

A TRACK MAINTENANCE MODEL FOR HIGH-SPEED RAIL:  
A SYSTEM DYNAMICS APPROACH

by

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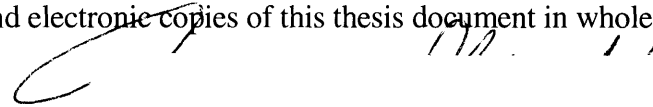
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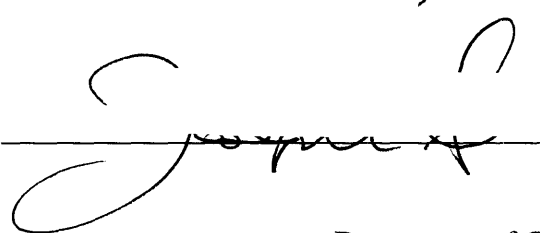
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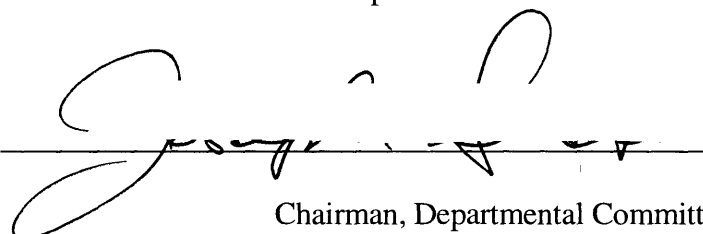
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**Abstract**

Track maintenance of High-Speed Rail is critical for its safe and reliable operation. Although the track maintenance costs are regarded as unavoidable fixed costs, the reduction of the costs gives an impact to the running of railroad business. A track maintenance model enables track engineers to try “virtually” multiple maintenance policies. This will help track engineers choose better maintenance strategies with lower costs still maintaining the required quality of the facilities.

A track maintenance model of High-Speed Rail is proposed in this study. The system dynamics approach is applied to the model. The model aims the prediction of physical behavior of the track. The model focuses on a one kilometer section of the High-Speed Rail track with conventional ballast track on the compacted subgrade, heavy welded rails, concrete ties and elastic support between ties and rails. The model is based on the ballast deterioration theory and newly proposed method of designing of ballast track. The variables used in the model are linked together to organize feedback loops. The model calculates various parameters over 250 months of simulation period, such as the dynamic wheel loads, standard deviation of track irregularity, and total maintenance cost.

The simulation results show that the model runs are consistent with reality, in terms of track settlement and the growth of track irregularity. This research studies cases with various sensitivity analysis with both pro-active maintenance and periodic maintenance. The results of the cases show that pro-active maintenance of MTT tamping is more economical than periodic maintenance, since the model performs maintenance when the conditions of the track is still satisfactory for the periodic maintenance. The combination of management of track data using advanced information technology and the application of this model that predict the track condition will enable substantial cost reduction.

Thesis Supervisor: Professor Joseph M. Sussman

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## **1. Introduction**

### **1.1 Motivation and problem statement**

Track maintenance<sup>1</sup> in the railroad industry is a long standing issue. The methods and the standards of track maintenance have developed through a number of trials and errors. Track maintenance dominates a significant part of expenditures in the railroad business. Railroad companies have sought an optimum level of maintenance so that economic efficiency and safety/ reliability of operation can balance each other.

Modern railroads load much more stress on the track because of high speed operation in the passenger railroad companies and heavy axle loads in the freight railroad companies. Track maintenance contains some specialized characteristics: time constraints of work during the intervals between trains, difficult labor conditions that include overnight labor, and strict standards of completion that are not required in common civil engineering structures. The quality of the facilities affects safety and reliability of the operation of passing trains. Although we regard the track maintenance cost as an unavoidable fixed expenditure, it used to be cut easily by the railroad companies with the short-term point of view. That led railroad lines to be more vulnerable to deterioration of the facilities and caused decreased productivity of operation.

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<sup>1</sup> In its narrow meaning, it represents track geometry alignment. (Profillidis) In this thesis research, I include this term as a continuous activities of inspection of track, and repair and replacement of track materials.

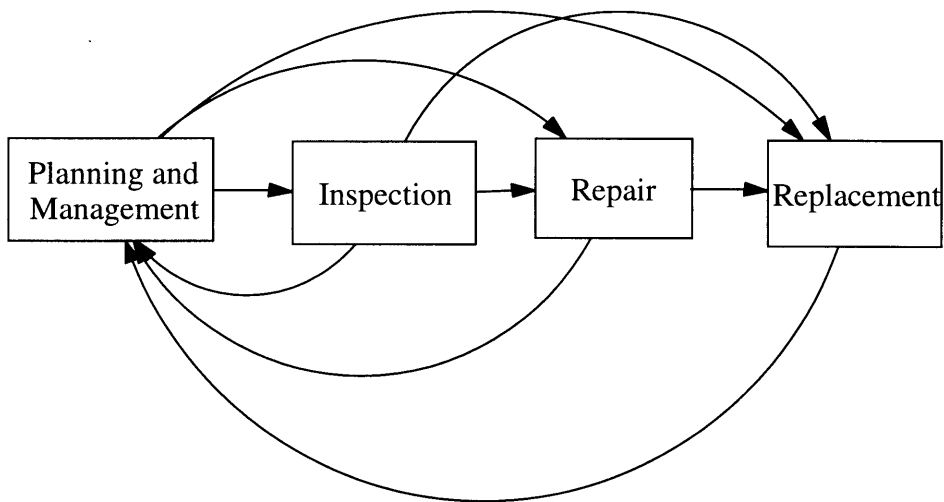


Figure 1.1 The cycle and the feedback of track maintenance

Track maintenance is a series of activities to improve or sustain the quality of the facilities for railroad track. There are mainly four components. They are: planning and management, inspection, repair, and replacement.

Track maintenance is a cyclical process of these four activities, and they interact with each other. This process can be considered a feedback system. Figure 1.1 shows a diagram of track maintenance activities. Although this is a very simplified form of track maintenance, it shows the feedback process of track maintenance activities. Figure 1.2 shows the causal loop of track maintenance. Various factors of track maintenance activities, quality, and budget interrelate with each other. It is important to seek not only effectiveness but also efficiency in the maintenance practices. Tradeoffs between effectiveness and efficiency have been overcome by new technologies and new methods of management. The differences of the target on the level of service has produced the diversity of the

organization and the method of maintenance. The optimization of effectiveness and efficiency is the most critical problem in the track maintenance activities.

It is helpful to model the track maintenance activities in order to find the optimum maintenance policies that will have efficient activities with substantially lower costs. By using this track maintenance model, track engineers will be able to try various cases that cannot be performed in actual maintenance activities. From the trials and errors by exercising the model, track engineers will be able to find a better method of maintenance.

Figure 1.2 shows a causal loop diagram of a general track maintenance. This is a very conceptual diagram and is made on the basis of experiences and intuitions from the view points of track engineers. Flows of information, work forces, materials and money within the scope of track maintenance is shown in this diagram. This diagram is modified to more sophisticated diagrams that are based on the scientific theories of track engineering in Chapter 4.

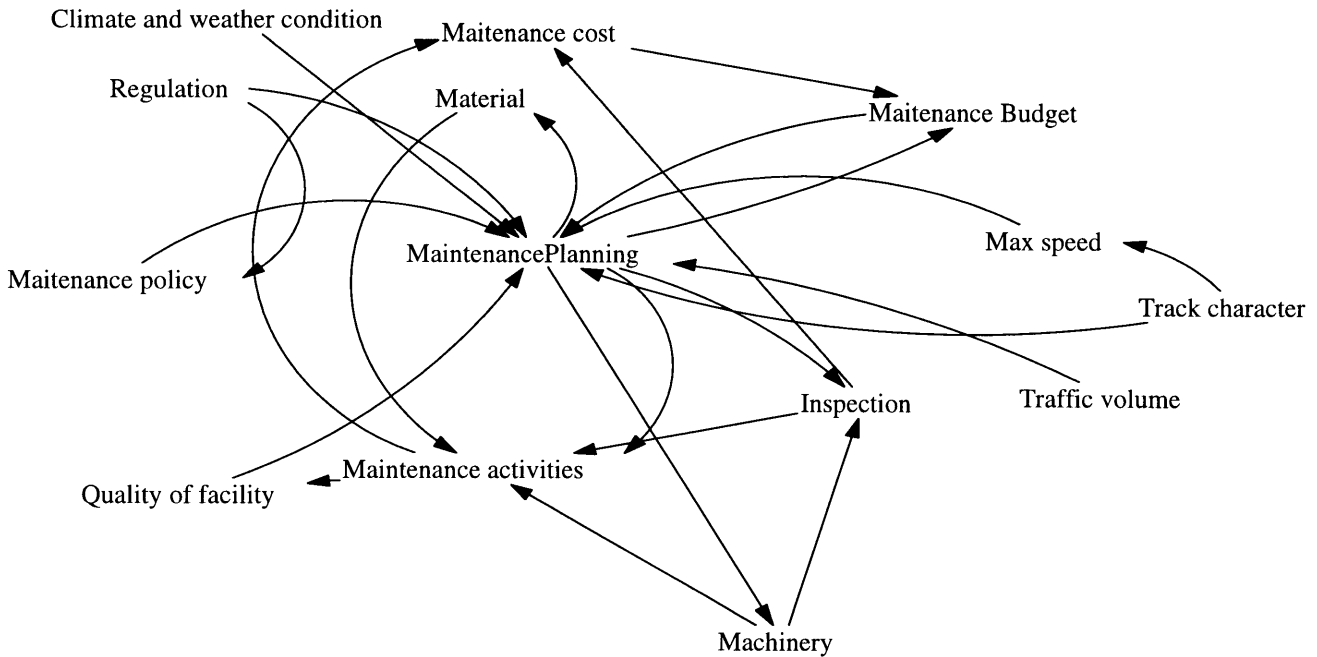


Figure 1.2 A causal loop of track maintenance

## 1.2 Scope of the Study

The main objective of this study is to reveal the conditions of the High-Speed Rail track that change over time and train loads. Even in a simple track of a railroad line, many variations exist on and around the track. For example, in the structures that support the railroad track, there are cuttings, landfills, viaducts, tunnels, bridges, and so on. Many variations on the types track exist, such as conventional ballast track and concrete slab track. In addition, many kinds of materials exist on the track, such as switches, joints, expansion joints, and glued insulated joints on the railroad track. This study focuses on a modeling of a simple track structure with ballast track and compacted soil subgrade. Therefore the model

constructed in this study does not account for other variations. In track maintenance, many factors must be considered, such as the quality of machines, laborers, and constraints that restrict the maintenance activities. However, this research examined physical behaviors of the track, rather than many other endogenous constraints.

This study focuses on the railroad tracks of High-Speed Rail with conventional ballast track. To explain the change of the conditions of the track, this study constructs a computer model using the system dynamics approach. The model simulates and predicts the quality of the facilities over time in two main parameters: a geometrical parameter and a mechanical parameter. The model predicts the change of conditions over time, such as dynamic wheel loads, track irregularity, and total maintenance costs.

The scope, the budget, and the purpose of track maintenance are quite different for various railroad companies. Therefore it is not practical to generalize the model for all kinds of railroad companies. To make the simulation model practical to use in the actual railroad line, the simulation model developed in this study focuses on High-Speed Rail. The model looks at a section of a high speed railroad line, with a unit length of one kilometer, and observe the change of the quality of the facilities.

The model simulates a one kilometer track with ordinary combinations of track materials. The model accounts for the use of ballast, concrete ties, elastic support between ties and rails, subgrade made of compacted soil, and heavy welded rails. These specifications resemble those of the Tokaido Shinkansen. The model places more weight on the physical behavior of the track, including both the geometrical parameter (track irregularity, track

settlement, rail roughness) and the mechanical parameter (the change of materials' characters over time, caused by the cumulative train loads and the cumulative tonnage).

The model also predicts the track maintenance costs.

The term of calculation of the model is set to 250 months, The model simulates both a straight and curved section. The model assumes the use of welded rails.

### **1.3 Study Approach**

This study reviews technology of track maintenance in order to investigate what kind of technology to introduce in modelling track maintenance. Then this study briefly reviews the system dynamics approach and its history. The model aims to predict the physical behavior of the track. Therefore, this study introduces theories to determine the track's physical behavior, whose theoretical base depends upon the ballast deterioration theory. This study compares the output of the model on the simulation runs with the data of real tracks from the Tokaido Shinkansen, which runs between Tokyo and Osaka.

Chapter 2 investigates technological advances in the materials, the maintenance methods, the machines, and the inspection.

Chapter 3 discusses the System Dynamics approach as a feedback model.

Chapter 4 first defines the qualities of the facilities at first. Then the chapter discusses the structure of the model, followed by explanations in detail.



Chapter 5 performs the validation of the model in comparison with data of Shinkansen track. Specifically, this chapter examines the track settlement and the growth of track irregularity.

Chapter 6 studies seven cases that are changing variables which influence behaviors of the model.

Chapter 7 concludes this study as a result of careful examinations of cases, recommends better maintenance policies and gives recommendations for further research.

## **1.4 Terminology**

The following terms that appear in the text are defined as follows:

**Track maintenance** This word refers to continuous activities of track inspection, repair and replacement.

**Shinkansen** This is the Japanese High-Speed Rail, operated by privatized three Japan Railway Companies. Total length of 4 operating lines is 2,034 km. Maximum operating speed is 300 km/h (in 1997).

**Tokaido Shinkansen** This track is Tokaido's new trunk line, which runs between Tokyo and Osaka. It is owned by JR-Central, which provided data for the validity analysis.

**MGT** This abbreviation stands for million gross ton, a unit used to measure the cumulative tonnage of traffic.

## **1.5 Typographical conventions**

*Italicized words* in this document refer to variables used in the model.

## **2. Review of technology in track maintenance**

### **2.1 Introduction**

Railroad track is also called the "Permanent Way". The term "Permanent" suggests that it is durable and lasts almost forever. At the first stage of the development of railroad, this might have been regarded as very convincing, because the traffic volume was far less than the modern railroad lines and it seemed to last for a very long time. The deformation of track caused by the train load was negligible in that stage of the railroad.

However, in the modern railroad which deals with heavy haul traffic or high speed traffic, we have to take into account track maintenance, as the emergence of wear and tear of materials and geometrical defects became substantial problems.

In track maintenance, there are two different types of parameters.<sup>2</sup> The first parameter is the deformation of geometry of the track. These defects in this parameter are caused by deformation of supporting materials of the track, such as subgrade, ballast, ties, and tie pads. One method of correcting these defects is tamping ballast using either a tamping machine or manual tamping.

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<sup>2</sup> Profillidids, V. A., Railway Engineering, Chapter 11, Avebury Technical, Aldershot, UK, 1995

The second parameter is the mechanical parameter which in most cases cannot be restored without parts replacement. All track materials are repeatedly replaced in turn, depending on how long the life span is. Due to years of train loads and environmental conditions, wear and tear of materials that may reduce the performance of track takes place. Replacement of the facilities is the main way of correcting these defects. Table 2.1 shows methods of track maintenance in each parameter of defects.

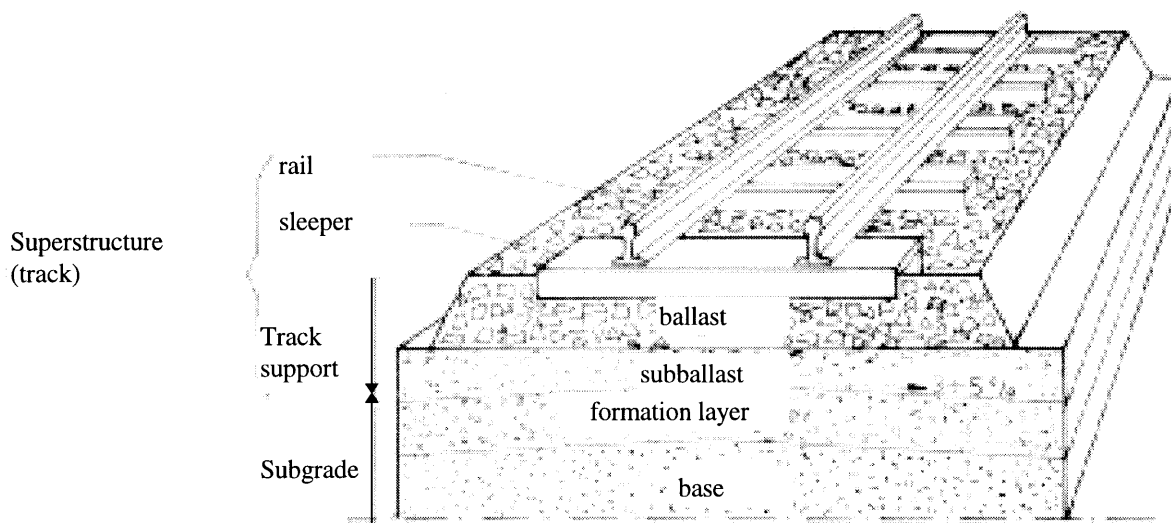


Figure 2.1 A Track layout of typical railroad

When the two parameters are observe, the geometrical parameter degrades much faster than the mechanical parameter. This chapter reviews the technologies of track maintenance briefly.

Table 2.1 Kinds of track maintenance in each parameter

Parameter	method of maintenance	Explanation in this chapter
Geometrical parameter	Track surfacing Tamping machine Stone blowing machine Rail grinding machine Ballast cleaner	2.2 Track geometry adjustment
Mechanical parameter	Ballast replacement unit Tie replacement machine Rail replacement unit	2.3 Material Replacement

## 2.2 Track geometry adjustment

Track geometry adjustment is a costly part of track maintenance. As mentioned in the last section, the defects in the geometrical parameter grow much faster than those in the mechanical parameter. In this section, machines that fix the defects for track surfacing are explained. The mechanism and abilities of tamping machine, stone blowing machine, rail grinding machine are briefly discussed.

### 2.2.1 Track surfacing

After a certain amount of time and train loads, the geometry of track will lose integrity both in longitudinal and horizontal dimensions. A traditional method of track surfacing is to loosen the ballast by tamping where track workers want to move the rail, then pushing the rail by using bars. This method is still used where labor resource is cheap, where capital investment for the tamping machines is unavailable, or where tamping machines cannot be used, such as near expansion joints, on the bridges, or in the grade crossings. However, it is becoming more difficult to rely on manual labor when fixing the defects of High-Speed Rail

lines, as track geometry needed for track maintenance for High-Speed Rail is quite precise. Human eyes and human labor cannot keep track of the required standards. Men can keep track of the track irregularity whose wavelength is up to 20 to 30 meters, so they cannot note the difference without using measuring devices. Recent technologies of tamping machines have made it possible to have geometrical correction during tamping. Thus it is inevitable to introduce tamping machines to have a geometrical correction of the High-Speed Rail track.

Table 2.2 shows a comparison of manual tamping and automated tamping. Automated tamping makes it possible to have much higher productivity, although operation is not as flexible as manual tamping. This is explained in the next section.

Table 2.2 Comparison of manual tamping and automated tamping in the surfacing

	Manual Tamping ( Handy tamper and bar)	Automated tamping (Tamping machine, MTT, 32 tamping tines)
required manpower (standard work)	One foreman six track men two watchmen (train)	One foreman one machine operator two watchers for the place of ballast two track men (for rearranging ballast) two watch men (train)
working speed	3 - 4 places/ hour ( 5-10 meters /place)	continuous 1500 meters /hour
required equipment	Manual tamper (powered by electricity using a generator), bar	Multiple tie tamper (MTT)
flexibility	flexible to train pass, easy to stay away from track	inflexible

### ***2.2.2 The Tamping machines (MTT)***

The tamping machine (MTT) is widely used for track maintenance in the railroad industry. Ballast provides support both in the horizontal and the longitudinal directions of the track, but it is crushed to smaller pieces of stones and packed into dirt. Then the settlement of the track occurs, and horizontal movement of the track occurs at the same time. These movements of track make geometrical defects of the track. Tamping machines are the most effective tool available for the track's geometrical alignment.

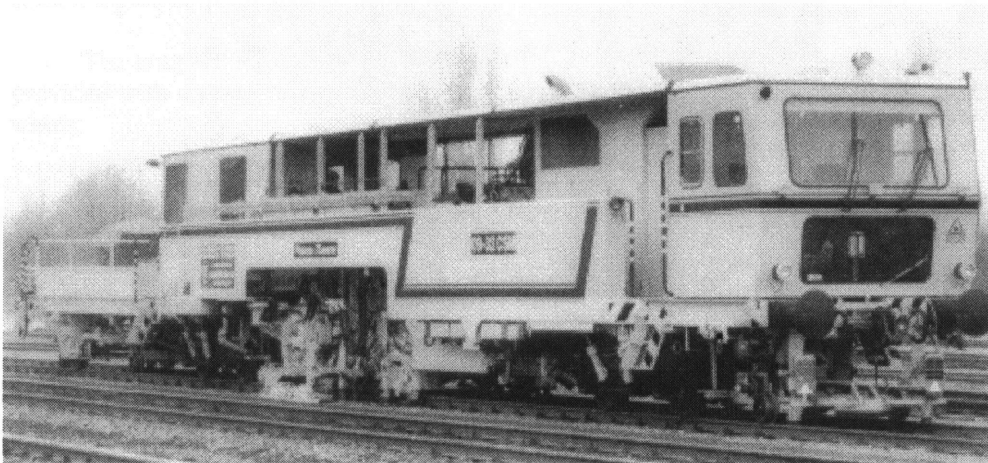
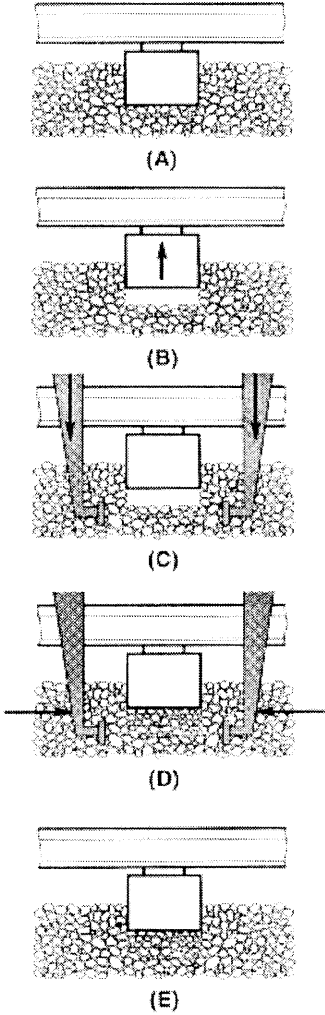


Figure 2.2 A multiple tie tamper (a self propelled tamping machine)

If the machines are able to tamp multiple ties simultaneously, they are also called Multiple Tie Tampers(MTT). Figure 2.1 shows a multiple tie tamper(MTT), which is equipped with 32 tamping tines. Most MTTs are equipped with a function of correcting lining and leveling of the rail. The tamping machine vibrates the tamping tine by a use of a motor powered vibrating unit. While the ballast is tamped, its resistance to movement is released

by the vibration and it enables the machine to move the rail that is clamped during the tamping. Figure 2.3 shows the movement of ballast when it is tamped. The following is the process of tamping:

- A. The tamping machine positions itself over the sleeper to be tamped.
- B. The lifting rollers clamp the rail, and the rail is adjusted to a targeted position.
- C. Tamping bars penetrate the ballast on either side of the sleeper
- D. The tamping bar vibrate and squeeze, then the ballast is filled into the void.
- E. Tamping bars are withdrawn and the machine goes forward to the following tamping position.



*“Tamping is the most effective way of correcting geometry faults, but this objective is accompanied by some ballast damage.” (Selig)*

There are many kinds of tamping machines available, from a tamping machine with a simple function which is used in

local lines with low density of trains, to a triple-tie-tamping machine equipped with ballast

Figure 2.3 Sequence of tamping by MTT<sup>3</sup>

<sup>3</sup> Selig, E. T. and Waters, J. M., Track geotechnology and substructure management, Chapter 15, Thomas Telford, London, 1994



regulators. A switch multiple tie tamper is able to tamp the ballast in the switch section as it can adjust the positions of tamping tines. Tamping ability per hour vary from 700 meters to 1600 meters depending on the ability of the machine.

Most MTTs are equipped with a measuring unit for the geometry of track, as it is necessary to align the rail. The newest machines measure track geometry before tamping by passing the tamping site, then calculating the amount of (horizontal) lining and (longitudinal) leveling movement in each position. This new function allows substantial reduction in time for measurement. The manual measurement is not precise enough to measure track geometry defects with a long wavelength. As a newly designed track geometry car, which can detect track irregularity with long wavelength, is not always available before the tamping, this function is very helpful to have reliable and economical operations.

### ***2.2.3 The stone blowing machine***

The stone blowing method was developed by the British Rail. A stone blowing machine adds small pieces of ballast, with a minimal particle size of 25mm. It blows particles beneath the ties where the track needs lifting. The process of stone blowing is similar to that of a tamping machine. Instead of vibrating the ballast and filling the void that is made by the lift, it blows stone into the void with air pressure.

Figure 2.4 shows the process of stone blowing. At first the rails are clamped and lifted, then the void space between the tie and the ballast is created(B). The stone blowing tube is injected into the ballast attached to the targeted tie (C). A measured quantity of stone that needs to make a desired residual lift is blown(D). The tube is withdrawn(E). Then the tie is

lowered onto the surface of the blown stone where it will be compacted by subsequent traffic (F).

The advantage of stone blowing is that it does not stir or destroy the existing ballast. Tamping causes some damage to the ballast, but the stone blowing method does not change the formation of ballast. The disadvantage of it is that the working distance per hour is much lower than that of the tamping machines. Another disadvantage is that small pieces of stone used in stone blowing promote breakage into smaller debris and loss of support. It may create dirt and thus mud pumping on the track in combination of water. The stone blowing machine is suited to the low lifts associated with the removal of short wavelength geometry alignment, while the tamping machine is suited to high lifts associated with the removal of long wavelength geometry alignment. Selig et. al says that stone blowing and tamping can be complementarily used. A small, hand held stone blower is now available for spot maintenance purposes. These machines are not used in Shinkansen, as the stone blowing is thought to promote mud-pumping.

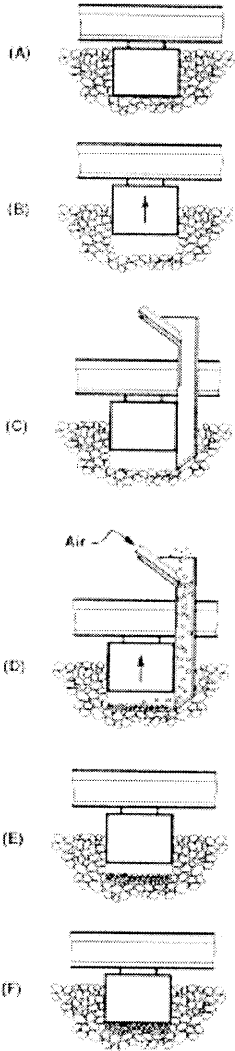


Figure 2.4 Process of stone blowing (Selig, pp. )

#### ***2.2.4 The Dynamic Track Stabilizer***

A dynamic track stabilizer is used after tamping to force the initial settlement before trains pass. After tamping or replacing ballast, it is usually necessary to have slow orders for trains.

The dynamic track stabilizer applies a combination of horizontal vibration and static longitudinal load to the track which results in the compaction of loose ballast. In the ballast deterioration theory, ballast is not compacted linearly over repetitive loads, but it has larger settlement in the initial stage of its compaction.<sup>4</sup> This machine intentionally settles the grade of the track by giving vibration and load to the ballast. The vibration frequency is adjustable from 0 to 45 Hz, depending on the track character. It will give the same settlement as is given as a result of 100,000 tons to 700,000 tons of train load.

The dynamic track stabilizer mitigates duration and speed limit of slow orders. In scheduled railroad operation, especially in High-Speed Rail, the number of slow orders is limited because of schedule consideration. By introducing this machine, the track maintenance side can make more flexible operation of tamping, material replacement and other track maintenance activities that affects ballast settlement, because it eliminates periods of slow orders and raises speed limit of the trains after the work.

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<sup>4</sup> For more information about the initial deformation process, see 4.4.4

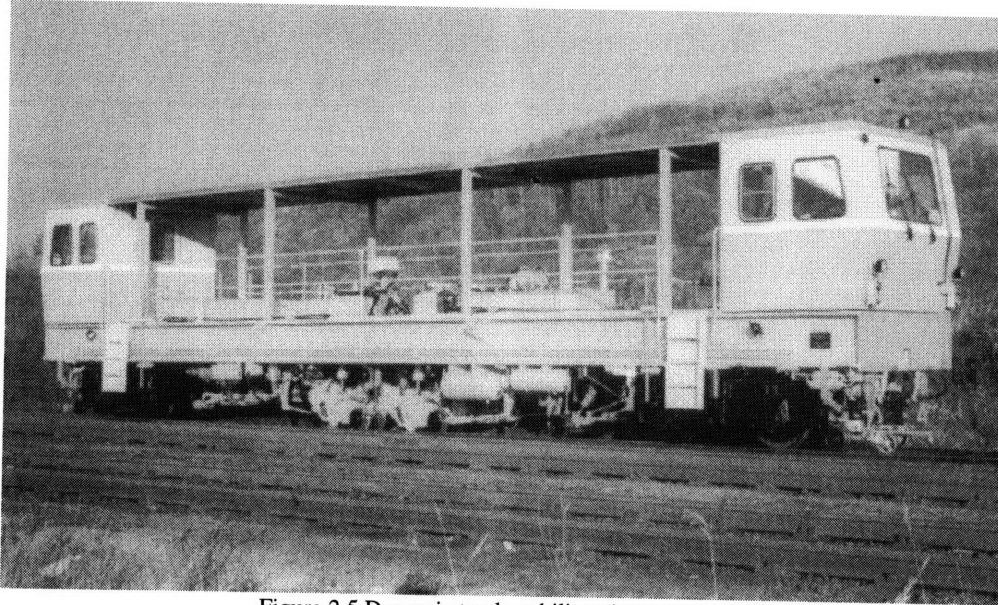


Figure 2.5 Dynamic track stabilizer (source: Selig )

### ***2.2.5 The rail grinding machine***

Rail grinding is a relatively new method to lengthen the life span of rail. Grinding is performed to remove excess metal after welding, to remove corrugations when they occur in rail, and to maintain a usable rail profile.<sup>5</sup> In the High-Speed Rail such as Shinkansen in Japan, corrugations, shelling and gauge corner wear are frequently observed. Corrugations are seen most in the braking section of the track. Their wave height increases in accordance with the increase of train loads, although the section where they appear does not change. Corrugations cause noise when in the contact with wheels, and increase short wavelength track irregularity.<sup>6</sup>

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<sup>5</sup> Romps, J. F. Modeling track maintenance and its effects on the reliability of a single track railroad line, p.26, Master's thesis, MIT, 1991

<sup>6</sup> Miyamoto, K. et al., Track (Japanese), pp.560 - 566, Sankaido Publishing, Tokyo, Japan, 1980

Shelling and gage corner wear are thought to occur when the contact of wheel and rail have repetitive train loads that damage and wear the rail head.<sup>7</sup> The appearance of shelling has black dots with areas of holes on rail surface, and inside small cracks run in the direction in which the trains pass with a depth of 3 to 8 mm and they hold branch cracks.

As the short wavelength irregularity which is shorter than 5 m belongs to the rail's inherent shape,<sup>8</sup> it is necessary to use a rail grinding machine to correct this irregularity. The short wavelength irregularity affects impact load of wheel to rail. Irregularity in the rail head shape causes high dynamic forces which are responsible for a rapid deterioration and a damage to the track.<sup>9</sup> On the other hand, the short wavelength irregularity bring about a point of loss of wheel longitudinal force, which may cause the loss of traction between wheels and rail and cause derailment.

Rail grinding prevents rail from raising shelling and corrugations. In Shinkansen operation, Kuroda<sup>10</sup> notes that rail shelling appears in 40 million gross tons. Therefore the rail should have a grinding every 40 million gross tons or less. As the spot maintenance of replacing one rail where rail shelling appears is very costly, we can reduce the maintenance cost and keep the safety of operation by introducing rail grinding. Table 2.3 shows the effect of rail grinding and its parameter to be discussed.

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<sup>7</sup> Miyamoto, K. et al.: Track (Japanese), pp. 560- 566, Sankaido Publishing, Tokyo, Japan, 1980

<sup>8</sup> Selig, E. T. and Waters, J. M.: Track geotechnology and substructure management, chap.15, Thomas Telford, London, 1994

<sup>9</sup> Esveld, C.: In track quality control and assessment of rails, Rail Quality and Maintenance for modern railway operation, Luwer Academic Publishers, Dordrecht, Netherlands, 1992

<sup>10</sup> Kuroda, Y.: Rail shelling of Shinkansen, Japan Rail Civil Engineering Association, December 1996, JRCEA, Tokyo, Japan

Table 2.3 Effect of rail grinding and related parameters

Topic	Effect of rail grinding	Parameter
Rail life	Reduction of spot replacement of rail due to removing shelling	gross million tons
Contact noise	Reduction of under floor noise level due to removing short wavelength track irregularity	under floor noise (dB)
Wheel load variance	Reduction of standard deviation of impact load, prevention of loss of traction	axle box acceleration (m/s <sup>2</sup> )
New rail roughness	remove of rail head roughness of new rail	short wavelength anomaly

### 2.2.6 Ballast cleaner

In time, ballast that supports track becomes crushed into smaller pieces and turns into dirt. That will damage the drainage of the track as well as the support of the track. It should be cleaned, or in time, replaced. The ballast cleaner is a machine to excavate ballast beneath the track, screen, clean and return it to the track. It is equipped with an excavating chain which passes beneath the track. As the ballast cleaner moves forward, the excavating chain removes ballast and conveys it up to vibrating screen to separate ballast from dirt. After being rinsed and cleaned up, the ballast goes back to the track for reuse. The dirt is thrown away to the track side or to a disposal wagon. This machine is used as a part of a ballast replacement unit that is mentioned in the next section.

The newest machine is equipped with laser detecting level control. As uneven depth of excavation results in the stirring of subballast and subgrade, precise depth control is necessary for the reduction of maintenance cost. If the ballast bed excavated by the

machine is even and flat, it gives a good chance of compacting uniformly under subsequent traffic load. This will give a stable track of high quality geometry.

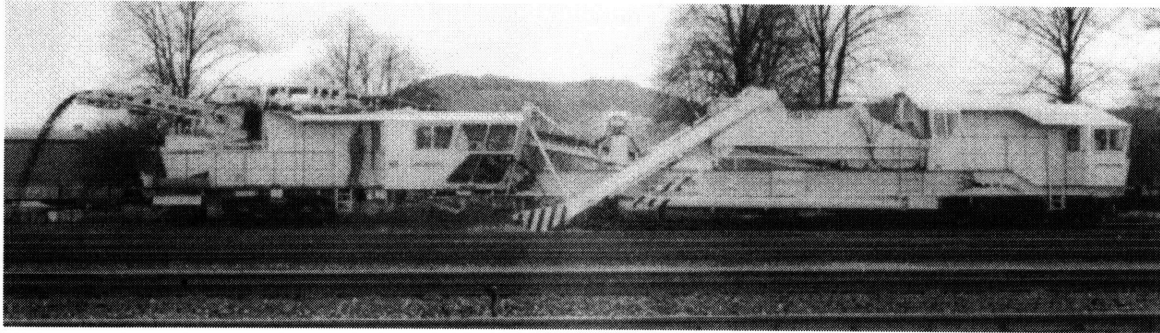


Figure 2.6 Ballast cleaner

## **2.3 Replacement**

In time we have to replace track materials because of wear and tear on them as a result of train loads and decay of materials after years of use. Of course, various materials have different life spans. Therefore the machines for the replacement of heavy track materials, such as ballast, rails and ties, have developed separately. This section presents currently used machines that are available in the modern track maintenance.

### ***2.3.1 The Ballast replacement unit***

The deterioration of ballast occurs when trains pass over the track, and ballast is crushed to small pieces and further into dirt. Thus, from time to time, ballast must be replaced. The ballast replacement unit consists of an excavating machine, ballast conveyors, and hopper wagons for new and old ballast. Train loads break the ballast into smaller pieces. The smaller pieces of ballast easily turn into dirt when mixed with water. The ballast is made

of crashed stone, and its design concept is to have a bigger internal friction angle than pebble and gravel. Therefore, handling ballast with manual labor is very difficult. Ballast replacement with manual labor is one of the hardest tasks in track maintenance. Due to the shortage and the aging of laborers, the mechanization of ballast replacement was developed in the railroad industry in Japan.

The ballast replacement unit consists of a ballast cleaner (changeable to a excavating machine), conveyor/hopper wagons and a tamping machine.

The process of ballast replacement is as follows. The excavating machine excavates the ballast where they want to replace it with new material. This feature of the machine is similar to that of ballast cleaners (See 2.2.6). Therefore the excavating machine can be replaced with the ballast cleaner. When the ballast cleaner is installed in the unit, it cleans the ballast with vibrating screens. Cleaned ballast goes back to hopper wagons. If the ballast is extremely dirty, the machine skip this step and convey the ballast to hopper wagons; then the ballast is cleaned elsewhere off the track for recycling. The new ballast is supplied from the hopper wagons, and the ballast falls down from the bottom of a bucket which is opened when the wagon arrives at the excavated place.

In Shinkansen, the working distance of the ballast replacement unit is up to 50m a day. As the unit cost of replacement of ballast is very high compared with other track maintenance activities, extending the replacement interval is critical in order to reduce the total maintenance cost.



### ***2.3.2 The Rail replacement unit***

This section reviews rail replacement for Shinkansen. Almost all the high speed section of track of Shinkansen uses welded rail in order to reduce noise and dynamic wheel loads. In Japan, a standard length rail is 25m long. On the Tokaido Shinkansen, which runs between Tokyo and Osaka, standard length rails are welded and made into a long rail with a length of 200m in the rail welding center. The welded rails are transported by a rail train, which can carry up to 32 long welded rails. The rails are brought down to the site before the installation. A rail exchanger, which inserts new rails that were put beside the track and take out old rails from ties, is used to change old rails with new rails.

## **2.4 Track Materials**

Technologically improved materials have contributed to the extension of life span of track components. It has also helped reduce maintenance costs. The rails and the ties are discussed in this section, as their characteristic are considered in the model and these technological advances have contributed to the change of maintenance policies.

### ***2.4.1 Rails***

The rails support train loads directly from wheels. Increasing traffic has encouraged the introduction of heavier rails. Tokaido Shinkansen used 50T rails, whose unit weight is 50kg/m, when it started operation in 1964. The 60 rail (60.8kg/m) was developed as the Shinkansen carried higher volume of traffic than it had been expected.

The life span of rails can be estimated using the following information: traffic, rail’s weight, curvature and other external conditions.

**The interval of replacement**

Table 2.4 shows the estimated cumulative tonnage over the life of the rail for various kinds of rails in France, Germany, Russia and Japan. Recently many railroad companies are trying to extend the average rail life to decrease costs for replacement. The heavier the rail are, the heavier tonnage the rails can support. However, it is possible rails can be replaced even before the tonnage reaches the number shown below. The rails are replaced to make the maintenance cost as low as possible. Low traffic lines in many local areas employ used rails from higher traffic (or higher class track) sections.

Table 2.4 Targeted rail replacement interval in four countries

Railway / Rail	Cumulative tonnage for replacement
SNCF (France) UIC 60	500 - 600 MGT
DB (Germany) S49 S54 UIC60	150 - 200 MGT 250 - 350 MGT 450 MGT
National Railway, (USSR) P50 P65 P75	350 MGT 550 MGT 600 MGT
Japan National Railway 50kgN 60kg	400 MGT 600 MGT

MGT: million gross tons

## Wear of the rail

In a straight section of track, wheels are usually rolling along the rail, so the friction between the rail and wheel is very small. In this condition there is a very small amount of wear on the rail. On the other hand, in a curved section of track, wheels are guided to the outer rail in many cases. Therefore, there is more wear on the rail head than on a straight section of track.

Figure 2.7 shows the relationship between the cumulative tonnage and the wear. It shows various radii, railhead profiles, and instances with or without lubrication. Amount of wear can be lessened by lubrication. There is approximately 1.5 mm of wear caused by the traffic of 100 MGT in a straight section.

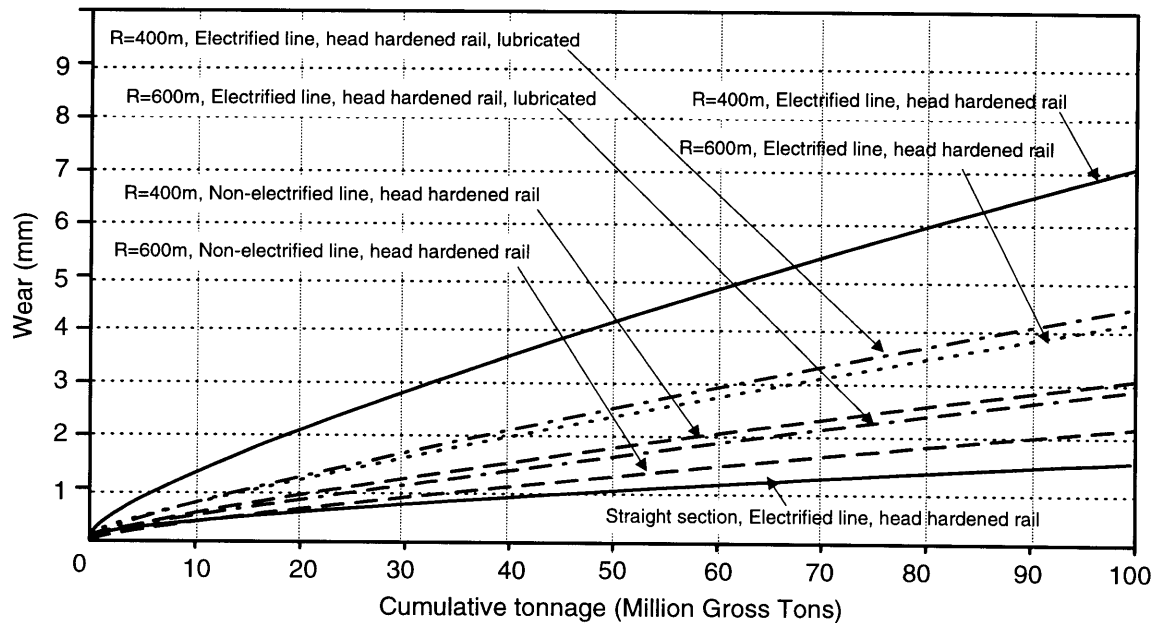


Figure 2.7 Wear of rail in various conditions, conventional lines, JNR  
(source: Miyamoto, K. pp.71)

### **Extension of rail life**

Besides the introduction of heavy rail, there are other methods of maintenance to extend the life of the rail. One is to grind the rail periodically. Aforementioned in the section on the rail grinding machines, the grinding of rail head is an effective method to extend rail life. Kuroda's study shows that the micro-cracks appear after traffic of 40 MGT.<sup>11</sup> Rail grinding avoids the growth of the micro-cracks and extends the rail life.

Another method is to have a good combination of wheels and rails. If you want to have more wear resistance for the rail, you should add more carbon in the process of making the steel for the rail. On the other hand, you will have more wear on the wheel when you choose the steel that has more carbon.

An interesting study was done in Sumitomo Steel Co. The study compared the wear produced by combinations of four kinds of wheels rolling on three kinds of rails with different percentages of carbon. The study showed that the best combination that had the least wear was not the combination of rail and wheel with high percentage of carbons. Therefore, the optimization of the life of the materials used both in rails and wheels requires a consideration of the design in both sides. It is usual that each manufacturer tries to make better products, but the results have to be evaluated by the overall performance of the system.

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<sup>11</sup> Kuroda, Y.: Rail shelling of Shinkansen, Japan Rail Civil Engineering Association, December 1996, JRCEA, Tokyo, Japan

### **Welded Rails**

Welded rail is a technological breakthrough for extending rail life. The joints of rail produce impact loads; then the loads encourage greater settlement of track. Welding of rails reduces the impact loads. It will reduce maintenance costs both due to reduced impact loads and less damages to rails and wheels. About half of the rail breakage is caused by the bolt-hole cracking; welding can avoid this breakage. However, welded sections of rail are weak points on the track. In rail welding, four main methods are used: electric flash butt welding, gas pressure welding, alminothermic welding and enclosed arc welding. The most reliable current method of welding is flash butt. When Tokaido Shinkansen was built in the 1960s, rails were welded with alminothermic welding. Then the main cause of the breakage of rail was the welding part until the welding was replaced with the flush butt welding.

By combining various methods of maintenance, it is possible to extend the life span of rail. In the system dynamics model, the rail life is dependent on the frequency of rail grinding (See 4.6.1).

#### ***2.4.2 The ties***

The ties, which are also called “cross ties” or “sleepers,” support the force from the rails.

There are several types of ties used in the railroad industry. There are three kinds of materials popularly used for ties: timber, concrete and steel. There are two tie types: mono-

block ties and twin-block ties. Each material and shape has its characteristic, and the material and the shape is chosen to suit the need of the railroad.

In the High-Speed Rail track, mono-block pre-stressed concrete ties and twin block concrete ties are usually used. Mono-block concrete ties were developed in United Kingdom(pre tension type) and Germany(post tension type). Eighty percents of concrete ties are mono-block.

In Japan, Shinkansen lines that were constructed after 1970's applied non-conventional concrete slab track. In this type of track, a concrete structure that supports the slab track is built. Rails are directly tied to the slab (see Figure 2.9). This was introduced to reduce maintenance cost, but European countries or the United States have not introduced the slab track so far for the High-Speed Rail, as they determined that the initial cost was too big to be economically feasible. The model in this research focuses on the ballast track, as the Tokaido Shinkansen uses ballast track.

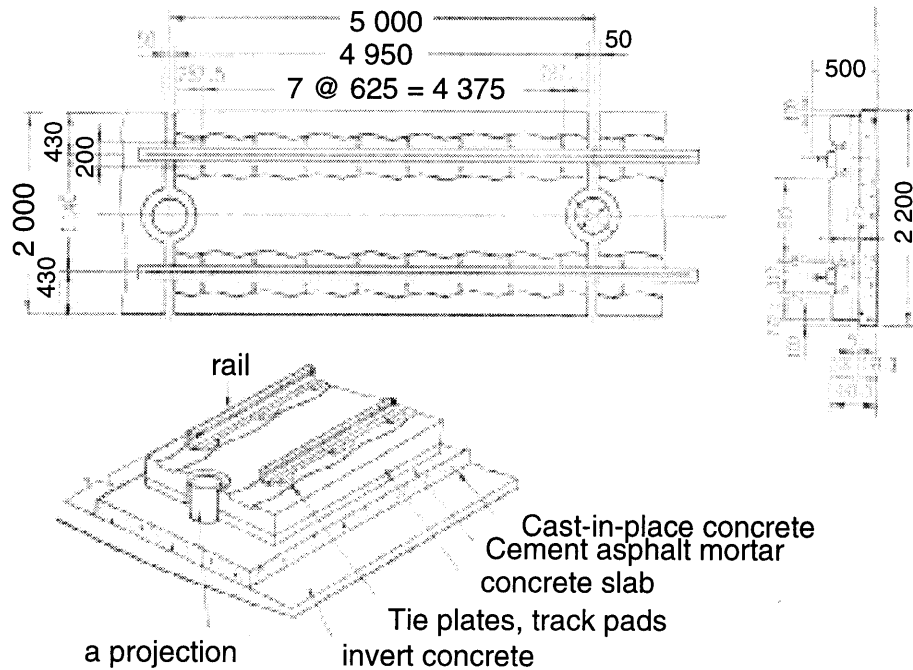


Figure 2.8 Concrete slab track, type A (Source: Miyamoto)

Tokaido Shinkansen uses mono-block prestressed concrete ties. The advantages of prestressed concrete ties are:<sup>12</sup>

1. Longer life (about 50 years) than timber ties
2. There is no decay in the life of installation.
3. There is more stability because of the heavy weight.
4. Double elastic fastenings are used, therefore the growth of track irregularity is smaller, and this enables to lower maintenance costs.

However, there are following disadvantages. They are:

1. The unit price of tie is higher than timber sleepers
2. Designing the fastening system is more difficult.
3. Insulation resistance is not big as the timber ties

<sup>12</sup> Miyamoto, K.: p.102

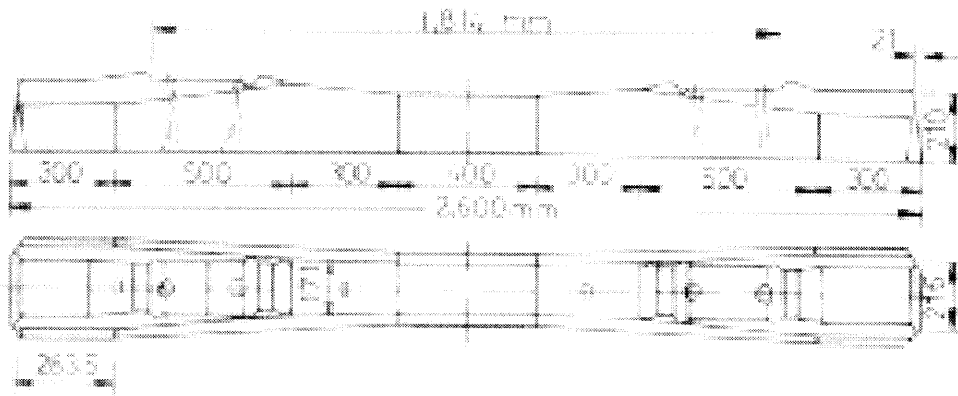


Figure 2.9 A mono-block tie of German Railway  
(source: Profillidis)

## 2.5 Inspection

There are many kinds of inspection in the track maintenance, such as: track geometry, track defect, rail defect, switch inspection, and so on. The track geometry car is an effective tool to detect track defects.<sup>13</sup> Development of computer technology allow us to store large amount of track information, such as geometry of track, age of materials, and cost information.

### 2.5.1 The Track Geometry cars

The High-Speed Rail requires high quality of track to sustain safe and reliable operations. As human eye cannot keep track of the track's geometrical defects in the long wavelength, track geometry cars are introduced to measure the defects of track for the High-Speed Rail.

<sup>13</sup> It can detect mainly track geometry defect, but newer vehicle installs a function of detecting rail defects by using ultrasonic detector in a certain amount of speed.



In Tokaido Shinkansen, a special train that measures the conditions of the track and the overhead electric trolley is run every ten days. The train is called “Dr. Yellow,” since it is painted yellow. The car output data both on paper and magnetic tape respectively. Data are measured every 0.3125 m. The basic method of the measurement of the irregularity is discussed in Chapter 4. The papers that record the track condition shown in Table 2.5 are distributed to track maintenance offices which exist every twenty five kilometer of the main line’s track. The data recorded on the magnetic tape are analyzed off the train by a main frame computer. These data are used to plan maintenance.

Table 2.5 Measured items for the track geometry car of Shinkansen

No	Measured items	recorded magnification	No	Measured items	recorded magnification
1	Longitudinal irregularity, left rail	1/1	14	Longitudinal defects of long wavelength	1 / 2
2	Longitudinal irregularity, right rail	1/1	15	Dynamic wheel loads, left	1t / 1 mm
3	Transverse defects	1/1	16	Dynamic wheel loads, right	1t / 1 mm
4	Gauge	1/1	17	Lateral force, left wheel	1t / 1 mm
5	Lateral irregularity, left	1/1	18	Lateral force, right wheel	1t / 1 mm
6	Lateral irregularity, right	1/1	19	Lateral force/ vertical force Q/P, left	0.05/ 1mm
7	Cross-level	1 / 2	20	Lateral force/ vertical force, right	0.05 / 1mm
8	Acceleration of vibration, vertical	0.02g/ 1 mm	21	Noise level	1 dB/ 1 mm
9	Acceleration of vibration, horizontal	0.02g/ 1 mm	22	Axle box acceleration, left	2g /mm
10	Longitudinal irregularity, 40m chord, left	1/1	23	Axle box acceleration, right	2g/ mm
11	Longitudinal irregularity, 40m chord, right	1/1	24	1 km place detection	
12	Lateral irregularity, 40m chord, left	1/1	25	10 km place detection	
13	Lateral irregularity, 40m chord, right	1/1			

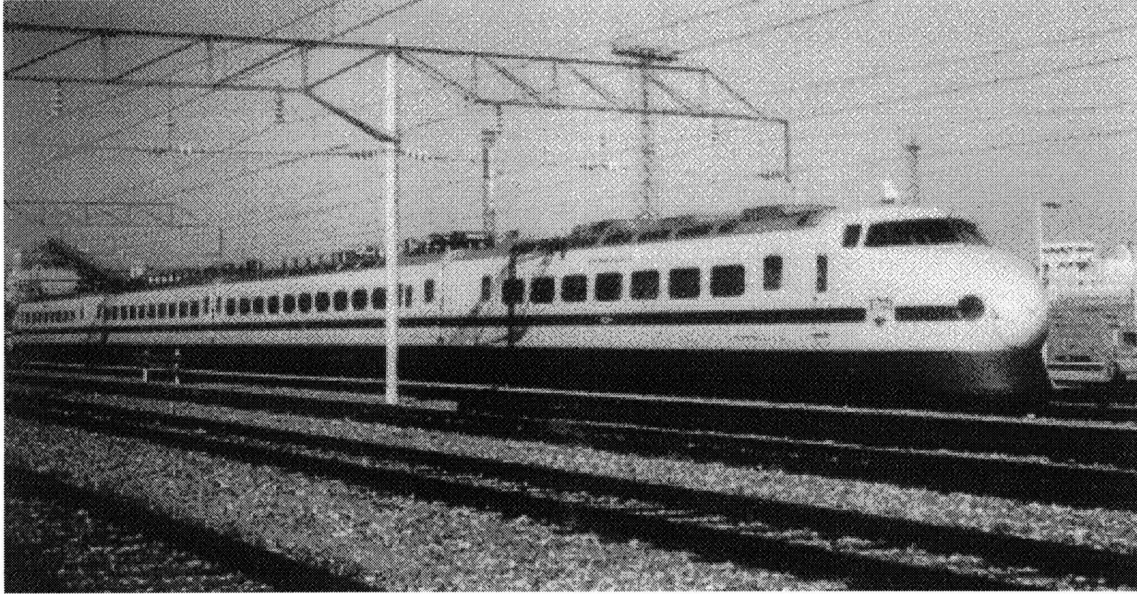


Figure 2.10 Dr. Yellow for the Tokaido Shinkansen (source: Semmens)

### ***2.5.2 The rail defects detector cars***

The rails on the track have to be inspected periodically to prevent accidents that are caused by the defective rails. There are many kinds of defects on rails: transverse cracking of railhead, horizontal cracking, shelling, bolt hole cracking, and corrugation.<sup>14</sup>

In Shinkansen, main lines have inspection twice a year, and in special sections, which are likely to have more defects, have inspection three times a year. The inspection is done using the rail defects detector cars, which are also called ultrasonic trains. If the defects are detected, they are reported to track maintenance offices and inspected precisely, using manual labor.

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<sup>14</sup> For more detail, see: Profillidis, V. A.: Railway Engineering, pp. 100-110 Avebury Technical, 1995

## **2.6 Summary of the chapter**

This chapter briefly reviewed technological aspects of track maintenance. Most machines and materials mentioned in this chapter are used in the High-Speed Rail operations.

In the track geometry adjustment, track surfacing is done using small tamping machines to have better productivity. The tamping machines enables to lift up track much more than manual tamping can do in a very efficient way. The rail grinding machines extend rail life and that contributes to the reduction of track maintenance cost.

The replacement of ballast and rail is also discussed in this section. Some breakthroughs of technologies are indispensable for the realization of High-Speed Rail. There are many other replacement activities actually done in the track maintenance, but this review focused on the activities related to the building of the model.

The materials used for the track are discussed in this chapter. The combination of materials, such as wheels and rails, is also an important factor in order to obtain higher performances. With this review as background, an approach to modeling track maintenance is discussed.

### 3. System Dynamics Modeling Approach

#### 3.1 Introduction

This chapter reviews the system dynamics approach briefly, since we will use this approach to model track maintenance.

System dynamics was first proposed as a development of industrial dynamics by Jay W. Forrester in the 1950's. Industrial dynamics<sup>15 16</sup> focused on the problems that happened in corporate settings. It was concerned with management problems such as instabilities in production and employment, slack or inconsistent corporate growth, and declining market share.<sup>17</sup> The term “system *dynamics*” replaced “*industrial dynamics*,” as the former approach covered a much broader range than the corporate settings. The study has been applied to wide range of problems, such as the growth and stagnation of urban areas,<sup>18</sup> corporate policies,<sup>19</sup> the dynamics of commodity markets,<sup>20</sup> management of large scale

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<sup>15</sup> Forrester, J.W.: Industrial Dynamics, Productivity Press, 1961

<sup>16</sup> Even more than 30 years after the first publication, it still is a bible for many enthusiasts of System Dynamics, called System Dynamists.

<sup>17</sup> Richardson, G., Pugh, A.: Introduction to System Dynamics Modeling with DYNAMO, Chapter 1, Productivity Press, Portland, OR. 1981

<sup>18</sup> Forrester, J.W.: Urban Dynamics. MIT Press, 1969

<sup>19</sup> Forrester, J.W.: Market growth as influenced by capital Investment. Industrial Management Review,. 9(2), pp.83-105

<sup>20</sup> Meadows, D.L.: Dynamics of commodity production cycles. Wright-Allen Press. Cambridge, MA. 1973

projects, and behavior of the world's ecological system,<sup>21</sup> and even to the modeling of scientific analyses.

### 3.2 System dynamics framework

System dynamics is a kind of philosophy that encourages systemic thinking when researchers analyze a system of interest. In this approach, researchers are required to see the relationship of the causes and results given in the system. Then they find the connections between them and make a diagram, which is called the causal loop diagram. When researchers deal with an abstract concept, or a difficult-to-quantify system, they use this process for brainstorming in order to clarify the concept of the system.

Figure 3.1 shows a simple diagram of the causes and results of settlement of track. The relationships in the shape of a heart are as follows: (dynamic) train loads influence pressure on rail, which positively influences the pressure on

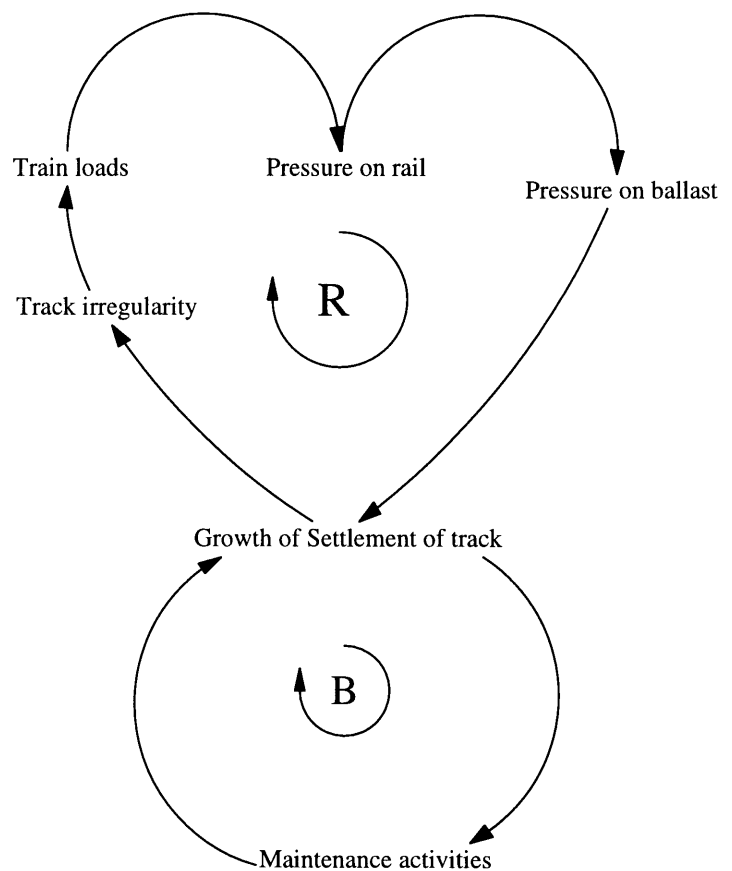


Figure 3.1 A simple diagram showing the track settlement

<sup>21</sup> Forrester, J.W.: World Dynamics. Wright-Allen Press. Cambridge, MA, 1971

ballast, which positively influences the settlement of track, which positively influences track irregularity, which positively influence train loads. All the factors in this loop increase over time. This is called a reinforcing loop. A clockwise loop with a letter “R” in the center of the heart shows the reinforcing characteristic. Another loop with a round shape at the bottom of the figure shows a balancing loop. Maintenance activities (the tamping of ballast) lift up the track and offset the settlement of track. A clockwise loop with a letter “B” in the center of the round loop shows the balancing characteristic. These signs are popularly used for the drawing of causal loop diagrams in system dynamics.

The system dynamic approach uses three kinds of variables: rates, levels and auxiliaries. The causal loop diagram shown in Figure 3.1 does not distinguish among these types, but they have to be identified when a researcher build up a model. For instance, “*settlement of track*” is divided into one level variable and one rate variable: “*cumulative track settlement,*” and “*growth of settlement of track.*” *Cumulative track settlement* often appears in units of mm (millimeter), while *growth of settlement of track* often appears in units of mm/month. Figure 3.2 shows a modified causal loop diagram which shows the types of variables. Variables surrounded by a rectangle are level variables. Variables written below a double line with a shape of double triangles (this shows a valve) are rate variables. Clouds described opposite the level variables show that the flows are supplied from somewhere outside of the system of interest. In a usual system dynamics model, level variables represent such diverse items as total assets, population, inventories, etc. In the model of this study, level variables include: the cumulative tonnage (of each material), the ballast deterioration, and the track irregularity (for more information, see Chapter 4).

Rate variables determine flows to level variables. Therefore, they have units of level variables per unit time. Rate variables include: revenue per year, number of birth per year, dividend payment per year, interest payment, and so on. In this model, most rate variables are physical values, such as growth of settlement, growth of track irregularity, tonnage per month, etc.

All other variables shown in the Figure are auxiliary variables. In many situations, it is necessary to explain the system besides level and rate variables. The auxiliary variables are used to simplify the modeling process that determines the rate variables. In Figure 3.2, it is necessary to explain the relationship between *track irregularity* and *growth of settlement of track*. “*Train loads*,” “*Pressure on rail*” and “*Pressure on ballast*” are derived from a theory that the model uses. The variable “*maintenance activities*” is a kind of function that defines the maintenance policies. Auxiliary variables aid in determining rate variables. Auxiliary variables can represent intermediate concepts about the state of the system that are important in their own right, and that have a bearing on the determination of the rate. They can also be used to represent a complex decision function (policy statement or rule) by a series of simple equations that makes the model easier to understand.<sup>22</sup>

This study uses a software of the System Dynamics called “Vensim.” This software enables users to help make a causal loop diagram. It greatly helps conceptualize the system of interest. The software enables users to output neat graphs and tables showing the results of simulations.

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<sup>22</sup> Luzzi, A. R.: A Systems Dynamics Model of U.S. railroad Industry. Chapter 2. Master’s thesis, MIT, 1976

The next chapter discusses how the system dynamics approach is used to model track maintenance.

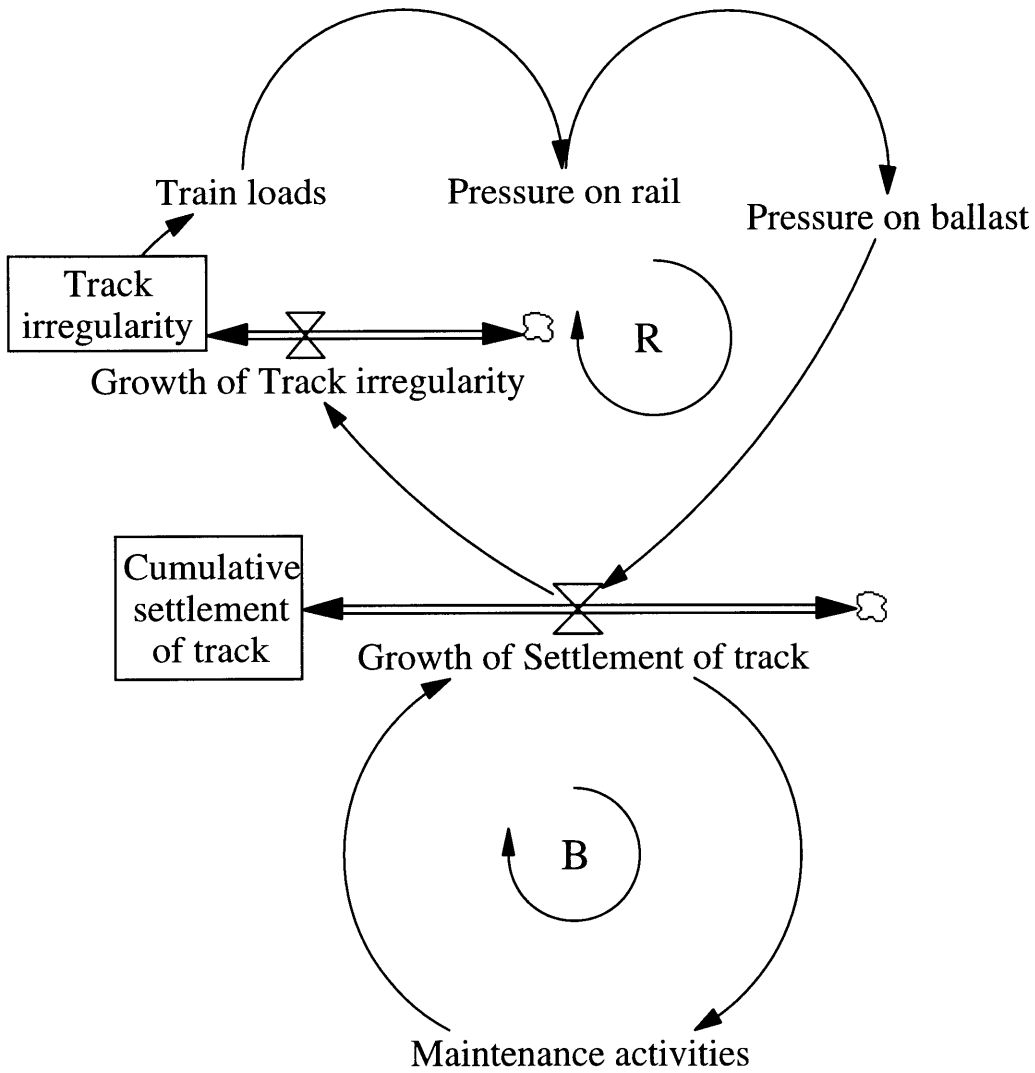


Figure 3.2 a causal loop diagram with variations of types of variables



## **4. Structure of the track maintenance Model**

### **4.1 Introduction**

Under train loads, the conventional ballast track has gradually increasing deterioration in the components of track materials and in the track's geometrical shape. The track qualities in both geometrical and mechanical parameters have cycles of degradation due to train loads and recovery due to track maintenance. A model that will predict the costs and the QF, which is defined in 4.2, will help track engineers choose maintenance policies and types of track structure when they maintain an existing line or construct new line. Ikemori proposed a track quality model that considers the deterioration of components of track materials using the system dynamics approach.<sup>23</sup> This study was inspired by his approach, as the system dynamics approach is appropriate to observe the change of conditions over time. However, this study uses a new method of designing the ballast track which takes into account the deterioration of track materials developed by Uchida and Miwa. Their study accounts for the growth of the rail roughness on the rail head, which in turn affects the deterioration of the track.

The main objective of this research is to predict the quality of the fixed facilities (QF) and the track maintenance costs, which are dependent on traffic, track geometry, maintenance

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<sup>23</sup> Ikemori, M., A model of time history of railway track irregularities and its applications, Journal of JSCE, No.365/IV-4, pp.145-154, January 1986

policy and other conditions. The system dynamics modeling approach makes it possible to observe the quantified values of the QF and the costs over time.

In this chapter, the quality of the facilities in this model is first defined. Then the macroscopic flow of the model is explained in 4.3. As the model consists of seven parts of modules, each module is explained briefly in the following sections.

#### ***4.1.1 Focus of the model***

This study focuses on the values of QF in each time period of the simulation. The length of simulation is 250 months. The model also calculates the total maintenance cost. It calculates total discounted cost for various values of discount rate. This study proposes a model that includes the following components for the QF. Indicators of QF are identified in 4.2. The indicators of QF that are measured in this research are as follows:

1. Track irregularity of the vertical dimension, due to the settlement of ballast and subgrade, and rail roughness on the rail head.
2. Track irregularity of the horizontal dimension of the track, due to the horizontal jolting of the train and the force of inertia.
3. Degradation of the ties due to the cumulative tonnage on each component. The life span of ties is set to 50 years, but there will be increasing probability of the necessity of replacement due to cracks.
4. Degradation of the tie pads. Cumulative tonnage of tie pads affects the spring coefficient, which influences dynamic wheel load on the ballast.

5. Degradation of the ballast. The quality of the ballast is affected by the cumulative tonnage and the works of tamping machines.
6. Degradation of the rail. The model will observe the cumulative tonnage of the rail and the rail roughness of the rail head. This model assumes that there will be increasing probability of the presence of cracks and shelling defects over the cumulative tonnage.

## **4.2 Identification of QF**

Then what is the Quality of the facilities? As this research focuses on the track maintenance of the High-Speed Rail system, “facilities” means fixed facilities of the railroad track, such as rail, ballast, ties, and tie pads. As is discussed in Chapter 2, two ruling parameters exist in track maintenance: the geometrical parameter and the mechanical parameter. The geometrical parameter shows the condition of linearity of the track. Over time and train loads, track geometry gets worse mainly because of the settlement of the track, which is primarily caused by the deterioration and rearrangement of the ballast. So the change of geometrical parameter is also related to the mechanical parameter, but maintenance to correct geometrical irregularities must be done more frequently than maintenance to correct degradation of the mechanical parameter. Therefore it is meaningful to distinguish between the two different components of QF.

Repetitive loads of trains on the track cause it to deteriorate, thus lowering both parameters of the QF. When the QF becomes lower than a predetermined level, the track materials have to be either repaired or replaced, depending on the character of the defects. The QF

changes in a cyclical manner due to track maintenance activities and deterioration resulting from track loads and various other conditions. It is very important to know the track condition and the maintenance cost over time. Using that information, we can make decisions about track structure, track maintenance planning, and the setting of the maintenance standard, so as to maintain QF while reducing costs. This research applies several variables for the measurement of QF.

#### ***4.2.1 QF in the geometrical parameter***

The geometrical parameter is related to the track geometry, or more specifically the geometry of the rail surface in both the horizontal and longitudinal dimensions. Table 4.1 shows indicators of QF in the geometrical parameter that are discussed in this Chapter.

Main concept of the QF in the geometrical parameter is “***track irregularity***.” Using the ***P-value*** is another method to express track irregularity. This index has been used for more than forty years in Japan, but it is not popular in other countries. This study uses this indicator because some data for the validity check in Chapter 5 from Shinkansen’s track uses the P-values.

The model does not use indicators of track irregularity and P-values using a 40m chord, as the method to predict these indicators is not currently established. Further research has to be performed in order to make the use of these parameters possible.

Table 4.1 QF in the geometrical parameter

Indicators of QF	Characteristics	Used in the model?	Sections to be discussed
track irregularity of longitudinal level(10m chord)	train safety, derailment	Yes	4.2.1.1, 4.2.1.2
track irregularity of longitudinal level (40m chord)	train's stability in the high-speed operation, passengers' comfort	No	4.2.1.1, 4.2.1.3
track irregularity of horizontal line(10m chord)	train safety, derailment	Yes	4.2.1.1, 4.2.1.2
track irregularity of horizontal line(40m chord)	train's stability in the high speed operation	No	4.2.1.1, 4.2.1.3
P-value, 10m chord, longitudinal level	percentage of irregularity greater than 3mm,	Yes	4.2.1.4, 4.2.1.2
P-value, 40m chord, longitudinal level	percentage of irregularity greater than 3mm	No	4.2.1.4, 4.2.1.3
P-value, 10m chord, horizontal line	percentage of irregularity greater than 3mm	Yes	4.2.1.4,
P-value, 40m chord, horizontal line	percentage of irregularity greater than 3mm	No	4.2.1.4

#### **4.2.1.1 Track irregularity**

Track geometrical defects are a main concern of track engineers. The difference between the designed geometry and the actual geometry is the issue. The ideal method of measuring the defects is to survey the track. Since it is not practical to survey the commercially operated railroad lines periodically, track engineers developed other ways of measuring geometrical defects of the railroad track. The most popular method is to measure the gap (versine) in the center of the chord which is strung along the edge of the rail. The value of the irregularity is equal to the gap (versine) between the rail and the string minus the versed sine value of the designed track geometry( in a curved or spiral section). They measure

horizontal and longitudinal values separately and use them as indicators of the quality of the track geometry. In Japan, a 10m chord is traditionally used, and in the US, a 31ft(9.4m) or chord is used.

There are some reasons why the US and Japan use a similar length of the chord. First it is easy to measure. In addition, the chord is short enough so that it does not become loose. Second, it is easy to measure manually. The measured defects are related to the danger of derailment, trains' stability and the comfort of passengers in the trains up to the middle range speed of trains and the safety of the train operation. The track irregularity of longitudinal dimension is also called "***track irregularity of longitudinal level***" or "***leveling defects***." The track irregularity of horizontal (lateral) dimension is also called "***track irregularity of line***," "***alignment defect***," or "***lateral distortion***."

#### ***4.2.1.2 The 10m chord track irregularity***

In the Japanese High-Speed Rail, the track irregularity is measured every ten days on the main track by the High-Speed track geometry car, which is called "Dr. Yellow." The measuring principle of Dr. Yellow is to measure the 10m chord irregularity value with its three measurement points . In the center point is a infra-red sensor to measure the gap to the rail head. In the coordinate  $n$  (units: meters. this represents a point on the track), the 10m chord versine value of the track are described as follows:

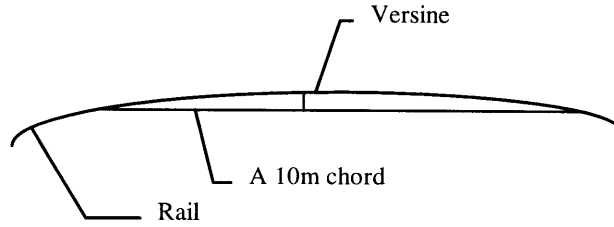


Figure 4.1 Rail and versine

$$v_{10}(n) = z(n) - \frac{z(n-5) + z(n+5)}{2} \quad (4.1)$$

where

$v_{10}(n)$  : the 10m chord versine in place n

$z(n)$  : coordinates of the point n

Figure 4.1 shows a simple picture describing the 10m chord measurement. The actual irregularity is equal to  $v(n)$  minus designed versine on the place. Thus the track irregularity in the 10m chord method is:

$$ir_{10}(n) = v_{10}(n) - DVS(n) \quad (4.2)$$

where

$ir_{10}(n)$  : The 10m chord track irregularity in the place n

$DVS(n)$  : Designed versed sign at n

When we observe track irregularity on the track as waves, the 10m chord method has uneven sensitivity of measuring irregularity with each wavelength. Figure 4.2 shows the relationship of wavelength and the sensitivity of the measurement in the 10m chord method. The waves with wavelength between 7m and 30m have the sensitivity more than 0.5, thus capturing the defects well in this range. Although the graph shows the wavelength more than 2.5m, in the wavelength of 10/2m, 10/3m, 10/4m..., the sensitivity becomes

zero. This is one of disadvantages of this measurement method. However, there are not many cases in which the actual track has cyclical waves of the rail head shape. It is possible to detect track irregularity with short wavelength, except for very short wavelength defects, such as corrugation on the rail head surface. In practice, this method is satisfactory to detect geometrical irregularity up to middle speed train operation.

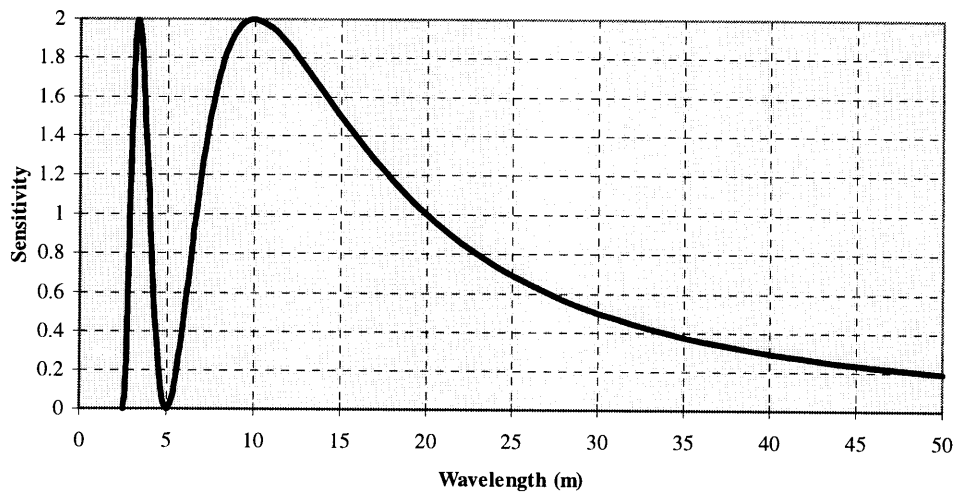


Figure 4.2 The 10m chord measurement sensitivity

#### 4.2.1.3 The 40m chord track irregularity

In the High-Speed Rail operation, the stability and passengers' comfort is very important in the High-Speed realm. The passengers' comfort depends on the train's inherent frequency of 0.6 to 2 Hz. When a high speed train runs at 220km/h to 270km/h, this frequency is equal to the wavelength of 40m to 120m. This means that a track irregularity with a very long wavelength, such as 100m, will influence passengers' comfort. In the Central Japan Railway Company, for the introduction of new type vehicle which allows the maximum



speed of 270km/h, the track maintenance side started using the measurement of the 40m chord irregularity in 1992. This method allowed railroads to detect track irregularity of the long wavelength up to 120m.

The 40m chord versine value can easily be calculated from the 10m chord versine value. In the place  $n$ , the 40m chord versine,  $b(n)$  becomes as follows:

$$v_{40}(n) = v_{10}(n-15) + 2v_{10}(n-10) + 3v_{10}(n-5) + 4v_{10}(n) + 3v_{10}(n+5) + 2v_{10}(n+10) + v_{10}(n+15) \quad (4.3)$$

where

$v_{40}(n)$ : 40m chord versine

$v_{10}(n)$ : 10m chord versine

Therefore the irregularity is shown as:

$$ir_{40}(n) = v_{40}(n) - DVS_{40}(n) \quad (4.4)$$

where

$ir_{40}(n)$ : 40m chord track irregularity

$DVS_{40}(n)$ : Designed 40m chord versine in the place  $n$

Figure 4.3 shows the relationship of wavelength to sensitivity in the 40m chord measurement method. This measurement has a sensitivity greater than 0.5 in the wavelengths between 30m and 120m. So this measurement is good for detecting the track irregularity which influence the passenger comfort in the high speed operation.

The Tokaido Shinkansen, which runs between Tokyo and Osaka, started its operation in 1964. There had been no standard to correct the long-wavelength track irregularity until 1993. Therefore track engineers did not always correct the irregularity, unless the track moved out of predetermined clearance limit relative to the civil structure. Over thirty years

of train loads and track works, the track irregularity with long-wavelength had been accumulated. Although Central Japan railway have been conducting to correct the long-wavelength irregularity, it has not been done in the entire main lines of the Shinkansen. However, this new standard has improved passengers' comfort substantially.

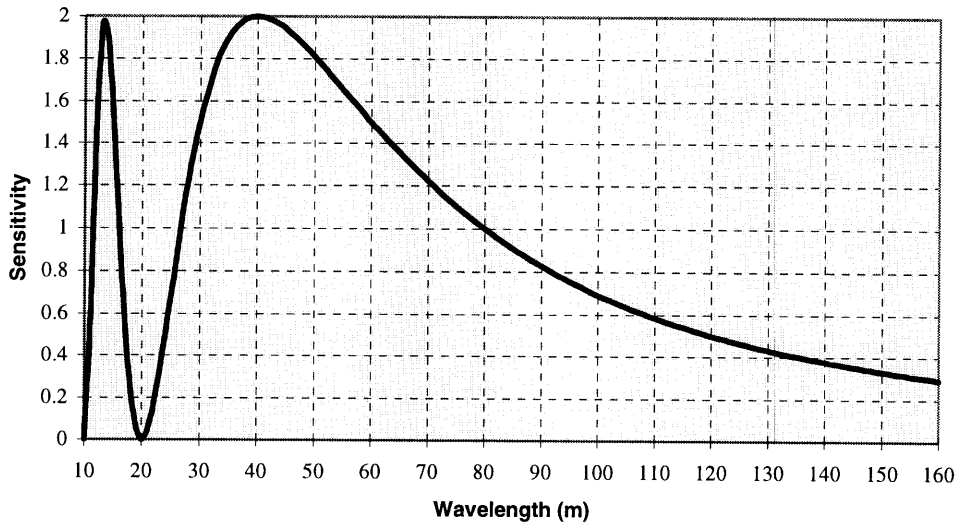


Figure 4.3 The 40m chord measurement sensitivity

#### 4.2.1.4 The P-values

The P-values are statistical values of track irregularity that have long been used in the Japan National Railway and later in the Japan Railway Companies Group. The P-values show the percentage of track irregularity which is greater than 3 mm in a section of track, whose length is usually from 500m to 1 km. The 10m chord P-value is a widely used statistical value of track irregularity in Japan. This value is convertible to the standard deviation of track irregularity, as the distribution of track irregularity is virtually identical to the normal

distribution. Like track irregularity, P-values are calculated in both longitudinal and horizontal(lateral) dimensions. The *P-value of longitudinal dimension* is also called *leveling P-value*, and the *P-value of horizontal(lateral) dimension* is also called *lining P-value*.

Figure 4.4 shows the relationship between the standard deviation of track irregularity and P-value, when the mean value is equal to zero. Figure 4.4 shows the relationship between the standard deviation of track irregularity and the P-value, when the mean value is equal to zero. The figure has a S shaped curve, which shows this measurement is not sensitive when value of the standard deviation of track irregularity is less than one millimeter. This value ranges between 10 to 40 for the track of conventional lines (10m chord values) in Japan. However, this value usually stays below 5 for Shinkansen's track, as it requires higher standard for the track geometry. Therefore, it cannot measure properly the track irregularity of High-Speed Rail, even though they still are mainly used indices

The 10m P-value shows track irregularity with the wavelength of 7m to 30m. It is correlated to train safety and derailment. The 40m P-value shows track irregularity with wavelengths of 30m to 100m. It is related to the comfort of passengers and the stability of train movement in the high speed operation. In both 10m and 40m chords, the P-values of horizontal dimension and longitudinal dimension are calculated for the Tokaido Shinkansen.

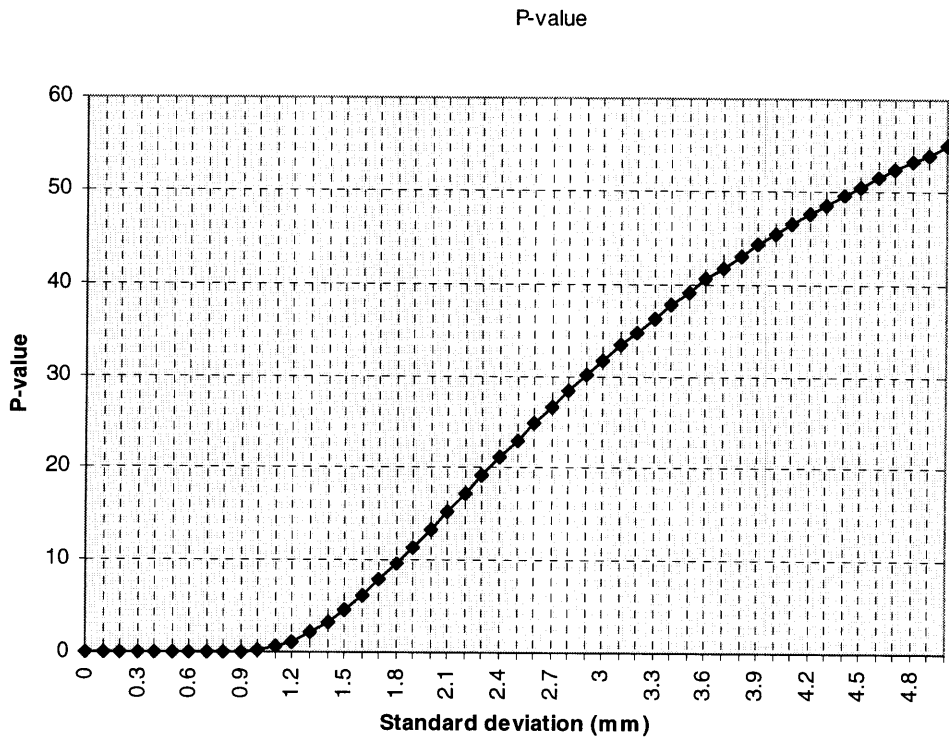


Figure 4.4 Relationship between P-value and Standard deviation of track irregularity

#### 4.2.2 The mechanical parameter of QF

The quality in the mechanical parameter is connected to fatigue, decay, wear and tear of materials. This study applies the material fatigue model that was developed in the Railway Technology Research Institute (RTRI) in Japan.<sup>24</sup> This research uses four main materials of the track structure: rail, ballast, ties, and tie pads. When the quality drops below the predetermined standard, the material is supposed to be replaced. Each material has its own deterioration behavior; that will be explained in the next section (4.3).

<sup>24</sup> Uchida M. et al.: A study on growth and restoration of the track irregularity considering material deterioration, RTRI Report, Vol. 11, No. 2, pp.1 - 6

Table 4.2 shows the variables that is used as indicators of QF in the mechanical parameter.

Table 4.2 QF in the mechanical parameter

Material	Indicators for QF
Rail	<i>Cumulative rail tonnage</i>
Rail	<i>Rail roughness</i>
Ballast	<i>Ballast deterioration</i>
Ballast	<i>Cumulative ballast tonnage</i>
Tie	<i>Cumulative ties tonnage</i>
Tie pads	<i>Cumulative tie pads tonnage</i>

### **4.3 The structure of the model (macroscopic description)**

This model will simulate a one kilometer section of High-Speed Rail track. The model will predict the change of the track qualities and maintenance costs over time under predetermined conditions. This model applies the ballast deterioration theory in the track geometry module of the model. Ballast movement and deterioration have been researched both at the experimental and practical level.

The characteristics of the model are described as follows:

1. This model will observe the track geometrical change over time in both vertical and horizontal dimensions. In the vertical dimension, this model will show the track settlement and track irregularity. In the horizontal dimension, this model will calculate the track irregularity and the movement of the track over time due to train loads.

2. From the track condition (designed geometrical shape of the track and track irregularity in each dimension) in the simulation, this model will calculate the dynamic train loads. When the model simulates a curved section, it will predict the dynamic wheel loads of inner rail and outer rail respectively. Then it will calculate track settlement (vertical dimension), and track movement (horizontal dimension) per transit of one wheel.
3. From the track settlement and the movement, it will calculate the growth of track irregularity over time.
4. This model uses a time interval of one month.
5. Simulation length is 250 months.
6. This model considers the change of elasticity of tie pad over cumulative tonnage, which will influence the values of dynamic wheel loads.
7. This model consists of six modules: the geometrical module (1), the geometrical module(2), the materials module, the maintenance policies module, the costs module, and the initial conditions module.

This model supports two different track maintenance policies, either pro-active maintenance, which is done when the track irregularity goes beyond a threshold level, or periodic maintenance at fixed intervals. The track maintenance that will improve the track irregularity is restricted to tamping by MTT, although in actual practice other methods, such as manual tamping, are also used.

Table 4.3 - 4.6 shows the variables used in the model. They are sorted with the order of respective modules. The model has 149 variables, which includes constants and look up functions.<sup>25</sup>

Figure 4.5 shows the causal loop diagram of the model. This figure shows the main flows of information within the model. Figure 4.5 includes the material module and the geometry module(1). It mainly explains the cause of vertical track irregularity and the QF of track materials. Main flows of information are from upper left hand side of the Figure to upper right hand side, then to the lower right hand side, and back to the upper left hand side. Each arrow shows a flow of information. For example,  $kv \rightarrow \sigma av$  shows that the variable  $kv$  is used in the variable  $\sigma av$ .

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<sup>25</sup> The lookup function specifies an arbitrary nonlinear relationship. This is a function available in Vensim

Table 4.3 The variables used in the model (1/4)

No.	Variable's name	Units	Description
(001)	<i>Pr1</i>	kN	Forces applied to the outer rail
(002)	<i>Initial ballast deterioration</i>	** NA **	Ballast deterioration at time zero
(003)	<i>ballast replacement std 2</i>	** NA **	
(004)	<i>CorrectionCoefficient</i>	** NA **	Coefficient of ballast settlement that controls the influence of ballast deterioration
(005)	<i>MTT std2</i>	** NA **	Give zero one month after MTT standard = 1
(007)	<i>Psmean</i>	kN/m/m	Mean pressure applied to the subgrade
(008)	<i>Pr2</i>	kN	Forces applied to the inner rail
(009)	<i>a</i>	** NA **	Coefficient used to calculate the <i>ballast settlement</i>
(010)	<i>b</i>	** NA **	Coefficient used to calculate the <i>ballast settlement</i>
(011)	<i>day per month</i>	day/Month	Average number of days per month
(012)	<i>P sigma relation</i>	** NA **	A lookup function showing the relationship between the P-values and Sigma
(013)	<i>Pi</i>	** NA **	$\pi = 3.1415...$
(014)	<i>Pr12</i>	kN	Sum of <i>Pr1</i> and <i>Pr2</i>
(015)	<i>wheel load change</i>	kN	Change of wheel load
(016)	<i>Y2 K30 110</i>	** NA **	Lookup function when K30 = 110
(017)	<i>Y2 K30 30</i>	** NA **	Lookup function when K30 = 30
(018)	<i>Y2 K30 70</i>	** NA **	Lookup function when K30 = 70
***** <b>Geometrical(2) Module</b> *****			
(19)	<i>a max1</i>	mm	Initial horizontal movement
(020)	<i>aH</i>	m/s <sup>2</sup>	Horizontal acceleration of a train
(021)	<i>aHs</i>	m/ s <sup>2</sup>	Steady horizontal acceleration of a train
(022)	<i>b max1</i>	mm	Horizontal movement per axle
(023)	<i>Beta1</i>	1/m	$(K1*10^6/4/E/Iy/alpha)^{1/4}$
(024)	<i>daH</i>	m/ s <sup>2</sup>	Derivative of <i>aH</i>
(025)	<i>dQ</i>	kN	Derivative o f <i>Q</i>
(026)	<i>Irregularity growth1</i>	mm/Month	Growth of track irregularity per month
(027)	<i>K1</i>	MN/m	$-26.4+21.5/(a\ max1+0.0425)+mu*Pr12$
(028)	<i>kappa</i>	** NA **	Rate of <i>Qi</i> and <i>Qo</i>
(029)	<i>KH</i>	** NA **	
(030)	<i>KZ</i>	m/ s <sup>2</sup> /mm/(km/h)	Horizontal train vibration coefficient
(031)	<i>mu</i>	NA	Coefficient of friction resistance between ties and ballast
(032)	<i>P value line 10m</i>	** NA **	P-value of horizontal line
(033)	<i>Qi</i>	kN	Horizontal force applied to inner wheel
(034)	<i>Qmax</i>	kN	Maximum horizontal load
0	<i>Qo</i>	kN	Horizontal force applied to outer wheel



Table 4.4 The variables used in the model (2/4)

No.	Variable's name	Units	Description
(036)	$Qr1$	kN	Horizontal force applied to outer rail
(037)	$Qr2$	kN	Horizontal force applied to inner rail
(038)	$\sigma aH$	m/s <sup>2</sup>	Standard deviation of $aH$
(039)	$\sigma z$	mm	Standard deviation of the irregularity of the horizontal dimension
***** <b>Costs Module</b> *****			
(040)	<i>Rail replacement cost</i>	Yen	Aggregated cost of rail replacement
(041)	<i>MTT cost</i>	Yen	Aggregated cost of MTT cost for one activity
(042)	<i>discounted cost</i>	Yen/month	Discounted cost per month
(043)	<i>Tie replacement cost</i>	Yen	Cost required to replace the whole ties
(044)	<i>Unit cost of Rail</i>	Yen/m	
(045)	<i>Unit cost of Rail grinding</i>	Yen/km	10000 for contracting 50000 for the machine
(046)	<i>Unit cost of Rail replacement</i>	Yen/m	11400 for contracting 6000 for machine
(047)	<i>Unit cost of Tie pad</i>	Yen	
(048)	<i>Total discounted cost</i>	Yen	Total cumulative discounted cost up to a month
(049)	<i>Maintenance cost per month</i>	Yen	
(050)	<i>Ballast replacement cost</i>	Yen	Cost of ballast replacement for one kilometer
(051)	<i>Unit cost of ballast</i>	Yen/m <sup>3</sup>	
(052)	<i>Rail grinding cost</i>	Yen	Rail grinding cost for the whole section
(053)	<i>Unit cost of Manual tamping</i>	Yen/m	
(054)	<i>Unit cost of MTT tamping</i>	Yen/km	
(055)	<i>Total maintenance cost</i>	Yen	
(056)	<i>Unit cost of Tie</i>	Yen	
(057)	<i>Unit cost of Tie replacement</i>	Yen/tie	
(058)	<i>discount rate</i>	percent	6% is used in this study.
(059)	<i>Unit cost of Ballast replacement</i>	Yen/m	
(060)	<i>Manual tamping cost</i>	Yen	
***** <b>Geometrical(I) Module</b> *****			
(061)	<i>Track settlement</i>	mm	Cumulative track settlement
(062)	<i>Ballast settlement per axle</i>	mm	Settlement per transit of train's axle
(063)	<i>Beta</i>	** NA **	Changed: multiplied by 10 <sup>6</sup> to arrange dimension
(064)	<i>curve steady wheel load out</i>	kN	Steady wheel load of outer rail in a curved section
(065)	<i>curve steady wheel load in</i>	kN	Steady wheel load of inner rail
(066)	<i>D</i>	MN/m	Spring coefficient
(067)	<i>dI</i>	mm/kN	A coefficient of Rail roughness growth
(068)	<i>Db</i>	MN/m	Spring constant of ballast
(069)	<i>Dp1</i>	MN/m	Spring constant of tie pads from Ikemori
(070)	<i>Ds</i>	MN/m	Spring constant of subgrade
(071)	<i>Dynamic wheel load</i>	kN	Dynamic wheel load applied to a wheel
(072)	<i>Dynamic wheel load in</i>	kN	Inner rail side
(073)	<i>Dynamic wheel load out</i>	kN	Outer rail side
(074)	<i>Effective sleeper area</i>	m <sup>2</sup>	Effective area that carries the force from trains
(075)	<i>i</i>	** NA **	a coefficient to determine the influence of rail roughness to wheel load change out
(076)	<i>Initial Settlement</i>	mm	

Table 4.5 The variables used in the model (3/4)

No.	Variable's name	Units	Description
(077)	<i>kv</i>	m/s/s/mm/(km/h)	Coefficient for the vertical vibration of vehicles
(078)	<i>lift up</i>	mm/Month	Value of the lift up by tamping of MTT
(079)	<i>P value level 10m chord</i>	** NA **	P-value, 10m chord, longitudinal dimension
(080)	<i>Pt</i>	kN/m <sup>2</sup>	Pressure beneath tie
(081)	<i>Rail roughness</i>	mm	roughness on the railhead
(082)	<i>Rail roughness removal</i>	mm/Month	amount of removal due to grinding
(083)	<i>settlement per axle</i>	mm	Ballast settlement plus subgrade settlement
(084)	<i>Settlement per month</i>	mm/Month	track settlement change
(085)	<i>Sigma av</i>	m/s <sup>2</sup>	Standard deviation of av
(086)	<i>Sigma y</i>	mm	Standard deviation of track irregularity of level
(087)	<i>Static wheel load</i>	kN	Static wheel load
(088)	<i>Subgrade settlement per axle</i>	mm	Settlement of subgrade per transit of axle
(089)	<i>Track irregularity per month</i>	mm	Track irregularity growth
(090)	<i>wheel load change in</i>	kN	Change of wheel loads, inner rail side
(091)	<i>wheel load change out</i>	kN	Change of wheel loads, outer rail side
(092)	<i>Y2</i>	** NA **	Coefficient of acceleration due to ballast vibration
***** <b>Materials Module</b> *****			
(093)	<i>Ballast deterioration</i>	** NA **	Degree of deterioration of ballast. This value ranges from zero to one.
(094)	<i>Ballast Deterioration growth</i>	** NA **	Change of <i>Ballast deterioration</i>
(095)	<i>Ballast deterioration removal</i>	** NA *	Offset of ballast deterioration due to replacement
(096)	<i>Cumulative ballast tonnage</i>	tons	
(097)	<i>Cumulative rail tonnage</i>	tons	
(098)	<i>Cumulative tie pad tonnage</i>	tons	
(099)	<i>Cumulative tie tonnage</i>	tons	
(100)	<i>Delta d</i>	mm	Change of d
(101)	<i>Rail roughness growth</i>	mm/Month	
(102)	<i>Tie pad tonnage growth</i>	tons/Month	
(103)	<i>Tie pad tonnage removal</i>	** NA **	
(104)	<i>Tie tonnage per month</i>	tons/Month	
(105)	<i>Tie tonnage removal</i>	tons/Month	
(106)	<i>tonnage per month</i>	tons/Month	
(107)	<i>tonnage per month 2</i>	tons/Month	
(108)	<i>tonnage removal</i>	tons/Month	
(109)	<i>tonnage removal 2</i>	tons/Month	
***** <b>Initial Conditions Module</b> *****			
(110)	<i>Initial ballast tonnage</i>	tons	Tonnage of ballast at the beginning of simulation
(111)	<i>alpha</i>	m	tie spacing
(112)	<i>axle load</i>	tons	
(113)	<i>axle per veh</i>	1/veh	
(114)	<i>ballast height</i>	cm	Height between ballast and subgrade

Table 4.6 The variables used in the model (4/4)

No.	Variable's name	Units	Description
(115)	<i>Cant</i>	m	Cant
(116)	<i>CantDeficiency</i>	m	
(117)	<i>E</i>	N/m <sup>2</sup>	Young Coefficient of Steel
(118)	<i>g</i>	m/s <sup>2</sup>	Gravity acceleration
(119)	<i>Gauge</i>	m	Gauge between rails (1.435 m for Shinkansen)
(120)	<i>HG</i>	m	Height of center of gravity of a train
(121)	<i>Initial rail tonnage</i>	tons	
(122)	<i>Initial tie tonnage</i>	tons	
(123)	<i>I<sub>x</sub></i>	m <sup>4</sup>	Geometrical moment of inertia of rail
(124)	<i>I<sub>y</sub></i>	m <sup>4</sup>	Geometrical moment of inertia of rail
(125)	<i>K30</i>	MN/m <sup>3</sup>	ground reaction coefficient
(126)	<i>Radius</i>	m	Radius of a curve
(127)	<i>Tie length</i>	cm	
(128)	<i>Tie width</i>	cm	
(129)	<i>Traffic</i>	train/day	Number of trains per day
(130)	<i>Train speed</i>	km/h	Average train speed in the section
(131)	<i>vehicles per train</i>	veh/train	
***** <b>Maintenance Policies Module</b> *****			
(132)	<i>ballast deterioration limit</i>	** NA **	
(133)	<i>Rail replacement standard</i>	** NA **	Standard will give 1 when rail needs to be replaced.
(134)	<i>Rail replacement tonnage</i>	t	The tonnage that the rail life terminates Depending on grinding interval for simplification
(135)	<i>limit of Rail roughness</i>	** NA **	
(136)	<i>Rail grinding standard</i>	** NA **	
(137)	<i>Rail grinding policy</i>	** NA **	Choose 1 if you have periodic maintenance choose 0 if you have pro-active maintenance
(138)	<i>MTT policy</i>	** NA **	Choose 1 if you have periodic maintenance Choose 0 if you have pro active maintenance
(139)	<i>MTT standard</i>	** NA **	Give 1 when the model start MTT tamping
(140)	<i>Limit of Sigma y</i>	** NA **	Threshold level of <i>Sigma y</i> to start MTT tamping
(141)	<i>Ballast replacement standard</i>	** NA **	Model performs replacement when it is one.
(142)	<i>Grinding interval</i>	year	Used when Grinding policy = 1
(143)	<i>MTT interval</i>	year	Used when MTT policy = 1
(144)	<i>Life span tonnage of rail</i>	tons	Lookup function, depending on grinding interval
(145)	<i>Tie replacement standard</i>	tons	Tie replacement performed when it is one
***** <b>Control Parameters</b> *****			
<b>Simulation Control Parameters</b>			
(146)	<i>FINAL TIME</i>	Months	The final time for the simulation.
(147)	<i>INITIAL TIME</i>	Months	The initial time for the simulation.
(148)	<i>SAVEPER</i>	Months	The frequency with which output is stored.
(149)	<i>TIME STEP</i>	Months	The time step for the simulation.

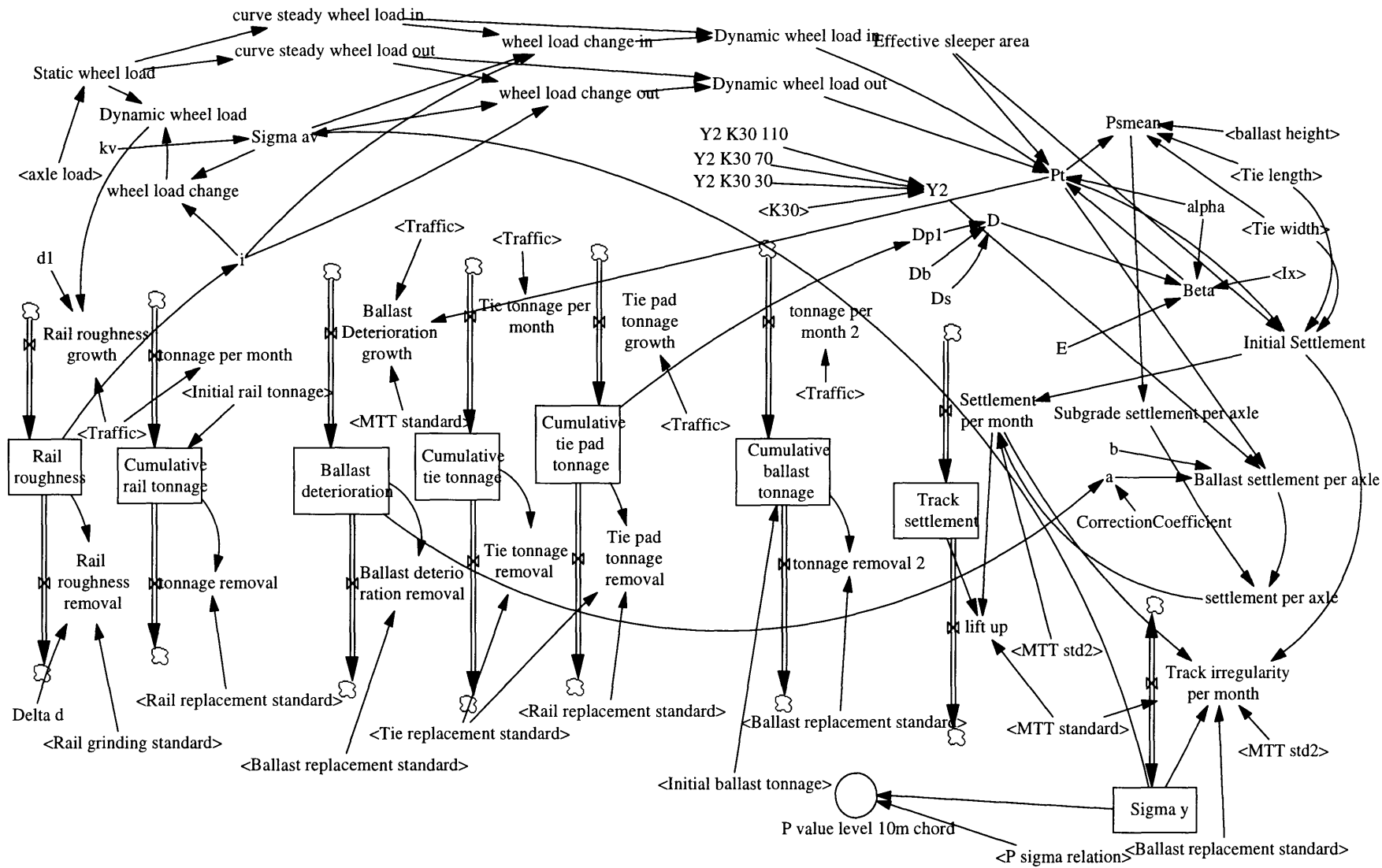


Figure 4.5 A causal loop diagram: overview of the model

#### 4.4 The Track Geometry Module (1)

This module deals with the track geometry of longitudinal dimension. The model calculates the 10 m chord P-value and the standard deviation of track irregularity in each time of the simulation.

Track conditions change over time due to various factors, such as initial track condition, track geometry, traffic, and maintenance policies. The basic concept of the geometry module of the model is as follows. Track settles due to the compaction of the train loads. This settlement is the sum of the ballast settlement and the subgrade settlement. The more the track has settled, the more the track irregularity increases. The model will calculate the force that will be applied to the track.

Figure 4.6 shows the causal loop diagram of the track irregularity module of the vertical dimension. Figure 4.7 shows a simplified diagram of the model.

There are two main feedback loops in Figure 4.6. The first loop is: *Dynamic wheel load in* → *Pt* → *Ballast settlement per axle* → *settlement per axle* → *settlement per month* → *Track irregularity per month* → *Sigma y* → *Sigma av* → *wheel load change in* → *Dynamic wheel load in* →... The second loop is: *wheel load change* → *Dynamic wheel load* → *Rail roughness growth* → *Rail roughness* → *i* → *wheel load change in* → *Dynamic wheel load*.

These two loops are both reinforcing loops that increase track irregularity.

# Longitudinal irregularity

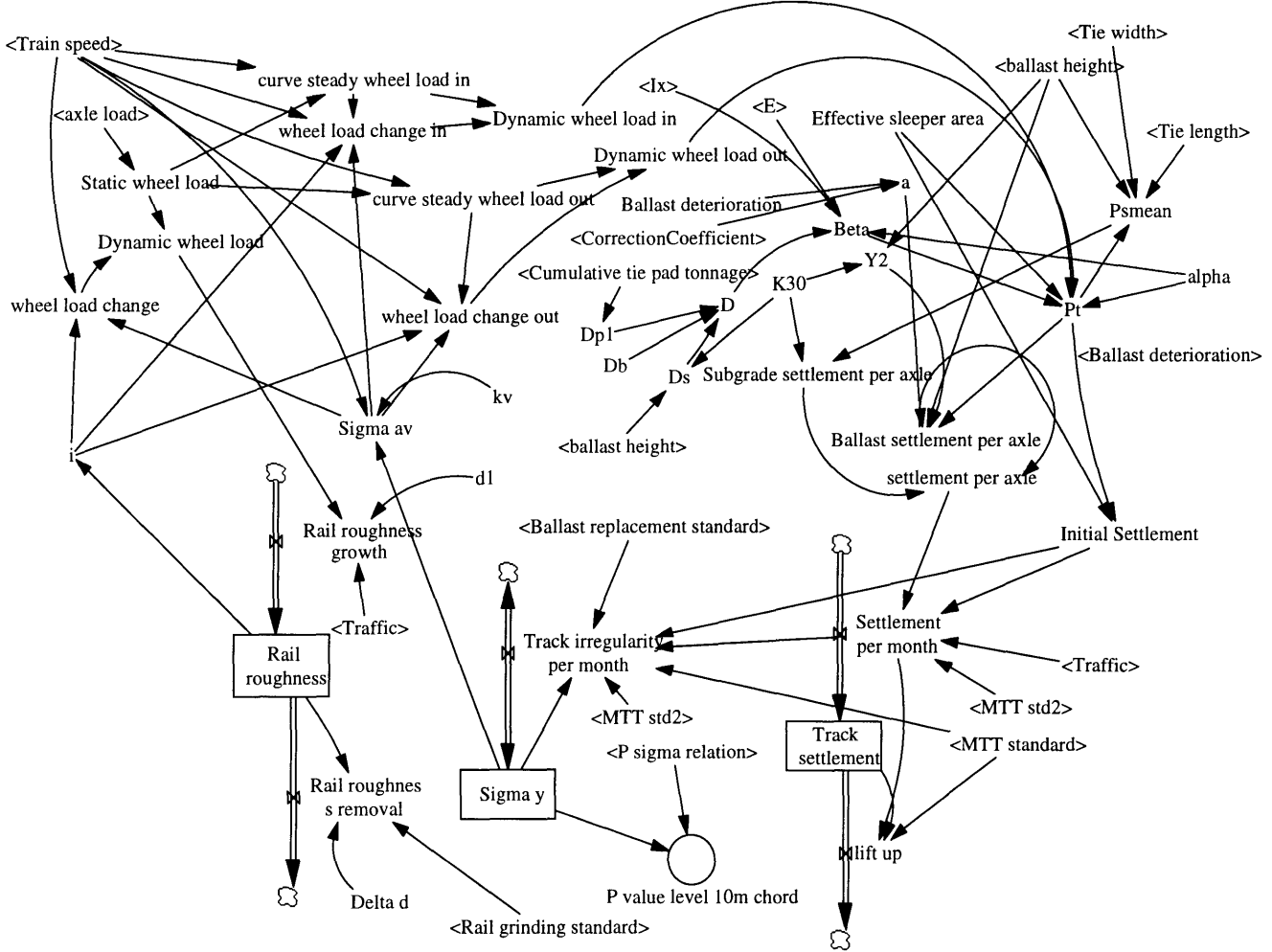


Figure 4.6 A causal loop diagram: track geometry module (1)

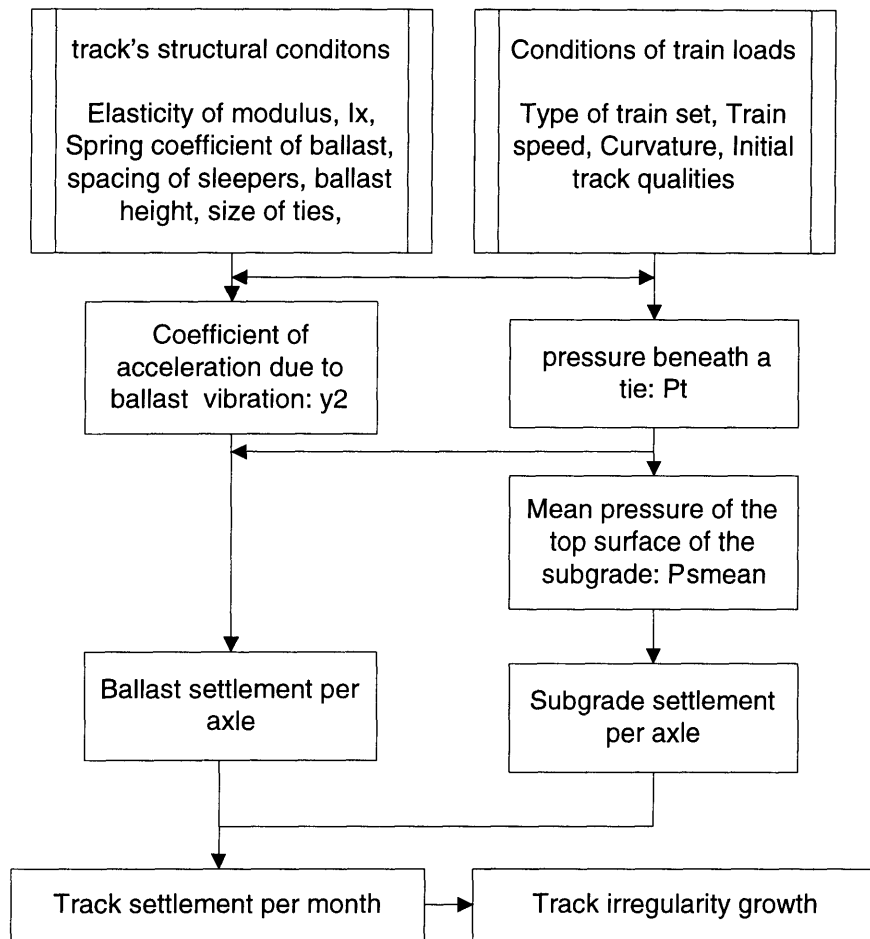


Figure 4.7 A simplified flow diagram for the calculation of track settlement and track irregularity

#### 4.4.1 The calculation of wheel loads on the track

The basic theory of the calculation of track settlement is taken from the new method of designing ballast track that was developed by Uchida et al.<sup>26</sup> From the initial data, dynamic wheel load is calculated. In addition to the static wheel load, the theory considers the wheel load change that is the results of the inertial force that is produced by the vibration of the

<sup>26</sup> Uchida, M., Ishikawa, T., Miwa, M. : New method of designing ballast track, Journal of Japan Railway Civil Engineering Association, pp.27-30, January 1996, (Japanese)

train. This vibration in turn results from the irregularity of the track. The dynamic wheel load is calculated using the following equations.

$$\begin{aligned} \text{Dynamic wheel load} &= \\ \text{Static wheel load} + \text{wheel load change} & \quad (4.5) \\ \text{Units: kN} & \end{aligned}$$

$$\begin{aligned} \text{wheel load change} &= \\ \text{Static wheel load} \cdot (3 \cdot \text{Sigma } av / g + i \cdot \text{Train speed} / 100) & \quad (4.6) \\ \text{Units: kN} & \end{aligned}$$

$$\begin{aligned} \text{Sigma } av &= \\ kv \cdot \text{Train speed} \cdot \text{Sigma } y & \quad (4.7) \\ \text{Units: m/s}^2 & \end{aligned}$$

Where

- $\text{Sigma } y$  : standard deviation of vertical track irregularity
- $i$  : rate of fluctuation of the wheel load caused by the vibration of the mass of the train below the suspension system
- $\text{Sigma } av$  : standard deviation of the vertical vibration of the train
- $kv$  : coefficient for the vertical vibration of the vehicle
- $g$  : acceleration of gravity ( $9.8 \text{ m/s}^2$ )
- $\text{Train Speed}$  : train speed (km/h)

The wheel load change in the equation (b) is described as a sum of the inertia force of the vertical movement of the train, which is related to the vertical track irregularity, and the inertial force of the train's mass below the suspension system, which is caused by the rail roughness. These forces increase in proportion to the train speed. The growth of rail roughness is dependent on the dynamic wheel loads.

The rate of fluctuation of the wheel load,  $i$ , is related to the rail roughness. The variable  $i$  is a coefficient given by the experimental simulation; it is a function of the rail roughness, the



spring coefficient of track, the mass of a vehicle below the suspension system, and so on.<sup>27</sup>

The variable  $i$  is described as follows.

$$i = 0.05 + 0.5 \cdot \text{Rail roughness} \quad (4.8)$$

Three kinds of dynamic wheel loads are defined in this model. The first is “*Dynamic wheel load*,” which is used to calculate rail roughness and the growth of rail roughness (rail roughness per month). The other two are used in the curved section; “*dynamic wheel load in*” is for the inner rail, and “*Dynamic wheel load out*” is for the outer rail.

$$\text{Dynamic wheel load} = \text{Static wheel load} + \text{wheel load change} \quad (4.9)$$

Units: kN

$$\text{Dynamic wheel load in} = \text{curve steady wheel load in} + \text{wheel load change in} \quad (4.10)$$

Units: kN

$$\text{Dynamic wheel load out} = \text{curve steady wheel load out} + \text{wheel load change out} \quad (4.11)$$

Units: kN

$$\text{wheel load change in} = \text{curve steady wheel load in} \cdot (3 \cdot \text{Sigma av/g} + i \cdot \text{Train speed} / 100) \quad (4.12)$$

Units: kN

$$\text{wheel load change out} = \text{curve steady wheel load out} \cdot (3 \cdot \text{Sigma av/g} + i \cdot \text{Train speed} / 100) \quad (4.13)$$

Units: kN

The variables “*curve steady wheel load in*” and “*curve steady wheel load out*” are steady wheel loads in a curved section which consider the excessive centrifugal force. They are described as follows.

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<sup>27</sup> Abe, N., Fukui, Y., et al., Management of the rail roughness of welded parts to extend the life span of rail, RTRI Report, pp.17-22, November 1994

$$\begin{aligned} \text{curve steady wheel load out} &= \text{Static wheel load} \cdot ( \\ &(1 + \text{Train speed} \cdot \text{Train speed} \cdot \text{Cant}/\text{g}/\text{Radius}/\text{Gauge} \cdot 1000/3600 \cdot 1000/3600) \\ &+ \text{HG} \cdot \text{CantDeficiency} \cdot 2/\text{Gauge}^2) \end{aligned} \quad (4.14)$$

Units: kN

$$\begin{aligned} \text{curve steady wheel load in} &= \text{Static wheel load} \cdot ( \\ &(1 + \text{Train speed} \cdot \text{Train speed} \cdot \text{Cant}/\text{g}/\text{Radius}/\text{Gauge} \cdot 1000/3600 \cdot 1000/3600) \\ &- \text{HG} \cdot \text{CantDeficiency} \cdot 2/\text{Gauge}^2) \end{aligned} \quad (4.15)$$

Units: kN

where

*Radius* : radius of the curvature (m)  
*Gauge* : gauge (1.435m for Shinkansen)  
*HG* : height of center of gravity of the train (m)  
*Cant* : cant (elevation) (m)  
*CantDeficiency*: cant deficiency (m)

#### 4.4.2 The calculation of the settlement of ballast

At first, forces applied to the bottom of rails are calculated using the dynamic wheel loads given in the previous subsection. They are calculated using the theory of an infinite beam on a uniform and continuous support.<sup>28</sup> Then the model will calculate the pressure beneath a tie (*Pt*). It is described as the sum of the force beneath rails divided by the effective sleeper area. *Pt* is described as follows:

$$\begin{aligned} Pt &= (\text{Dynamic wheel load in} + \text{Dynamic wheel load out}) \\ &/\text{Effective sleeper area} \cdot (1 - \text{EXP}(-\text{Beta} \cdot \alpha/2) \cdot \text{COS}(\text{Beta} \cdot \alpha/2)) \end{aligned} \quad (4.16)$$

Units: kN/m/m

where

$\text{Beta} = (D \cdot 1e+006 / (4 \cdot E \cdot I_x \cdot \alpha))^{0.25}$   
*Effective sleeper area* : mechanically effective sleeper area (m<sup>2</sup>)  
*alpha* : spacing between ties (m)  
*E* : modulus of elasticity (of rail) (N/m<sup>2</sup>)  
*I<sub>x</sub>* : geometrical moment of inertia (m<sup>4</sup>)

<sup>28</sup> Grassie, S.: Dynamic model of the track and their uses, Rail Quality and Maintenance for Modern Railway Operation, pp. 165- 183, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1993

$D$  : spring coefficient of the track (MN/m)  
 $1e+006$  : 1,000,000, multiplied to arrange units

The spring coefficient is given by the spring coefficients of ballast, tie pads, and subgrade (referred to in the description of equations in the Appendix). The ballast settlement per transit of axle is calculated using  $Pt$ . This model considers the degree of deterioration of ballast which influences life span of ballast and the settlement of ballast due to train loads. Settlement has a non-linear relationship to  $Pt$ .

(m) *Ballast settlement per axle =*  
 $a \cdot (Pt - b(\text{ballast height}))^2 \cdot Y2 \cdot (1 + \text{Ballast deterioration})$   
 Units: mm

where

$a$  : a coefficient (=2.7e-010)  
 $b$  : a coefficient that depends on the ballast height  
 $Y2$  : Coefficient of acceleration due to ballast vibration

A coefficient  $b$  shows that there is a domain of loads that does not cause plastic deformation of the ballast.  $Y2$  is dependent on the ballast height (between ties and subgrade) and ground reaction coefficient ( $K30$ ).  $Y2$  is described as the following table.<sup>29</sup>  $K30$  is a value derived from a penetration test of the subgrade.  $Y2$  is a coefficient that explains the change of ballast settlement, due to the decrease of friction between particle of ballast, and due to the increase of its deformation due to dynamic loads. This value is derived from the results of simulation tests for the vibration of the track (Table 4.1).<sup>30</sup>

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<sup>29</sup> Same as 26, PP.30

<sup>30</sup> Ishikawa, T., Namura, A., Cyclic Deformation characteristics of railroad ballast in full-scale tests, Journal of JSCE, No.512/IV-27, pp.47-59, May, 1995

Table 4.7 Y2 vs. ballast height and K30

Ballast height ( $h_B$ ) (cm)	ground reaction coefficient (K30) (MN/m <sup>3</sup> )		
	30	70	110≤
$15 \leq h_B < 20$	1.5	1.43	1.30
$20 \leq h_B < 25$	1.50	1.25	1.14
$25 \leq h_B < 30$	1.35	1.11	1.00
$30 \leq h_B$	1.20	0.97	0.88

The model will calculate the settlement of ballast per month using *Ballast settlement per axle*.

#### 4.4.3 The calculation of the settlement of the subgrade

This model considers the sinking of ballast into subgrade.<sup>31</sup> The settlement of the subgrade per axle is described as follows.

$$\begin{aligned} \text{Subgrade settlement per axle} = & \\ 6e-009 \cdot P_{\text{mean}}^{3.6} \cdot (3 \cdot 10^{(0.015 \cdot K30 + 1.192)})^{(-1.5)} & \quad (4.17) \\ \text{Units: mm} & \end{aligned}$$

where

$P_{\text{mean}}$  : mean pressure applied to the top surface of subgrade (kPa)  
 $K30$  : K30, ground reaction coefficient (MN/ m<sup>3</sup>)

From this value, the settlement of the subgrade per month is calculated.

#### 4.4.4 The initial settlement

According to the ballast deterioration theory, an initial settlement occurs after a lift due to loosened ballast by tamping activity (MTT in this model). In the initial deformation process, there is a domain of the settlement that does not change linearly to the number of

<sup>31</sup> Same as 26, pp.30

loads. Figure 4.8 shows the relationship between the number of loads and the settlement of track.  $C$  represents the initial settlement. The initial settlement is caused by the consolidation of ballast. It is thought to represent the initial rapid movement of ballast particles that fix uneven distribution of spacing between ballast particles. Initial settlement is described as follows.

$$\begin{aligned}
 \text{Initial Settlement} = & \\
 & 0.00076 \cdot (Pt \cdot \text{Effective sleeper area})^2 \\
 & \cdot (0.24 \cdot 2) / (\text{Tie length} \cdot \text{Tie width}) \cdot 100 \cdot 100 \qquad (4.18) \\
 & \text{Units: mm}
 \end{aligned}$$

Initial settlement is calculated to be proportional to the square of  $Pt$ .

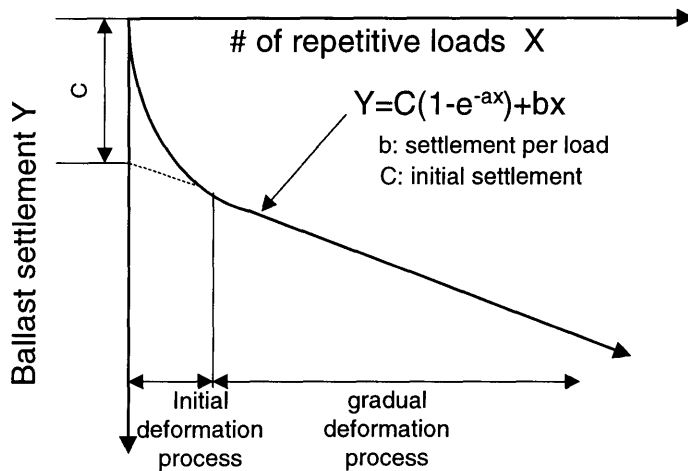


Figure 4.8 Settlement process in the ballast deterioration theory

#### 4.4.5 The calculation of track irregularity of longitudinal level

There are many studies about the relationship between the *ballast settlement* and the track irregularity. Although it varies over the characteristics of subgrade, ballast, cumulative tonnage, and so on, it is known that the standard deviation of track irregularity grows almost

proportionally to the track irregularity.<sup>32</sup> As the track irregularity over the dimension of rail can be assumed to have a normal distribution,<sup>33</sup> this model determines the value of the standard deviation of track irregularity ( $\sigma z$ ) to be one sixth of the *track settlement*. Tamping activity by MTT will remove the track irregularity by two thirds for the vertical dimension.<sup>34</sup> After the MTT's track maintenance, the initial settlement is added to the settlement section soon in order to suit the theory.

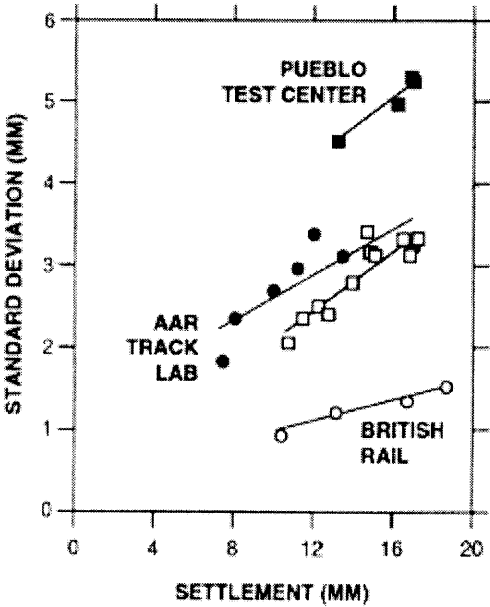


Figure 4.9 Relationship between the standard deviation of track irregularity and the settlement (source: Selig)

<sup>32</sup> Selig, T., Waters, J.: Track Geotechnology and Substructure Management, pp.168, Thomas Telford, 1994

<sup>33</sup> Miyamoto, T. Watanabe, K.: The track, pp.502, Sankaido Publishing, 1980 (Japanese)

<sup>34</sup> Uchida, M., Ishikawa, T., Miwa, M. : New method of designing ballast track, Journal of Japan Railway Civil Engineering Association, pp. 30, January 1996, (Japanese), pp. 30

## 4.5 Track Geometry Module (2)

This module calculates the track irregularity of lateral dimension and the lining P-value (10m) as outputs. The causal loop diagram of the horizontal track irregularity is shown in Figure 4.10. From the viewpoint of System Dynamics, there is one main reinforcing loop and one balancing loop. The symbol “R” in a circle written in the center of the Figure represents the reinforcing loop. This is a process of the increase of track irregularity. The symbol “B”, written beside “*sigma z*” shows a balancing loop. The activity of this loop is tamping using MTT.

The process of the growth of track irregularity is discussed below. Arrows in the Figure represent flows of information. Main flows are described as follows:

$\text{Sigma Z (horizontal track irregularity)} \rightarrow \dots \rightarrow aH \text{ (horizontal vibration)} \rightarrow dQ \text{ (change in the horizontal pressure on the rail)} \rightarrow Q_o, Q_i \text{ (lateral force in each rail)} \rightarrow Q_{r1}, Q_{r2} \text{ (horizontal pressure carried on the rail)} \rightarrow Q_{max} \text{ (maximum lateral force)} \rightarrow b_{max1} \text{ (horizontal movement of the track per transit of axle)} \rightarrow \text{Irregularity growth1 (growth of irregularity per month)} \rightarrow \text{sigma z.}$

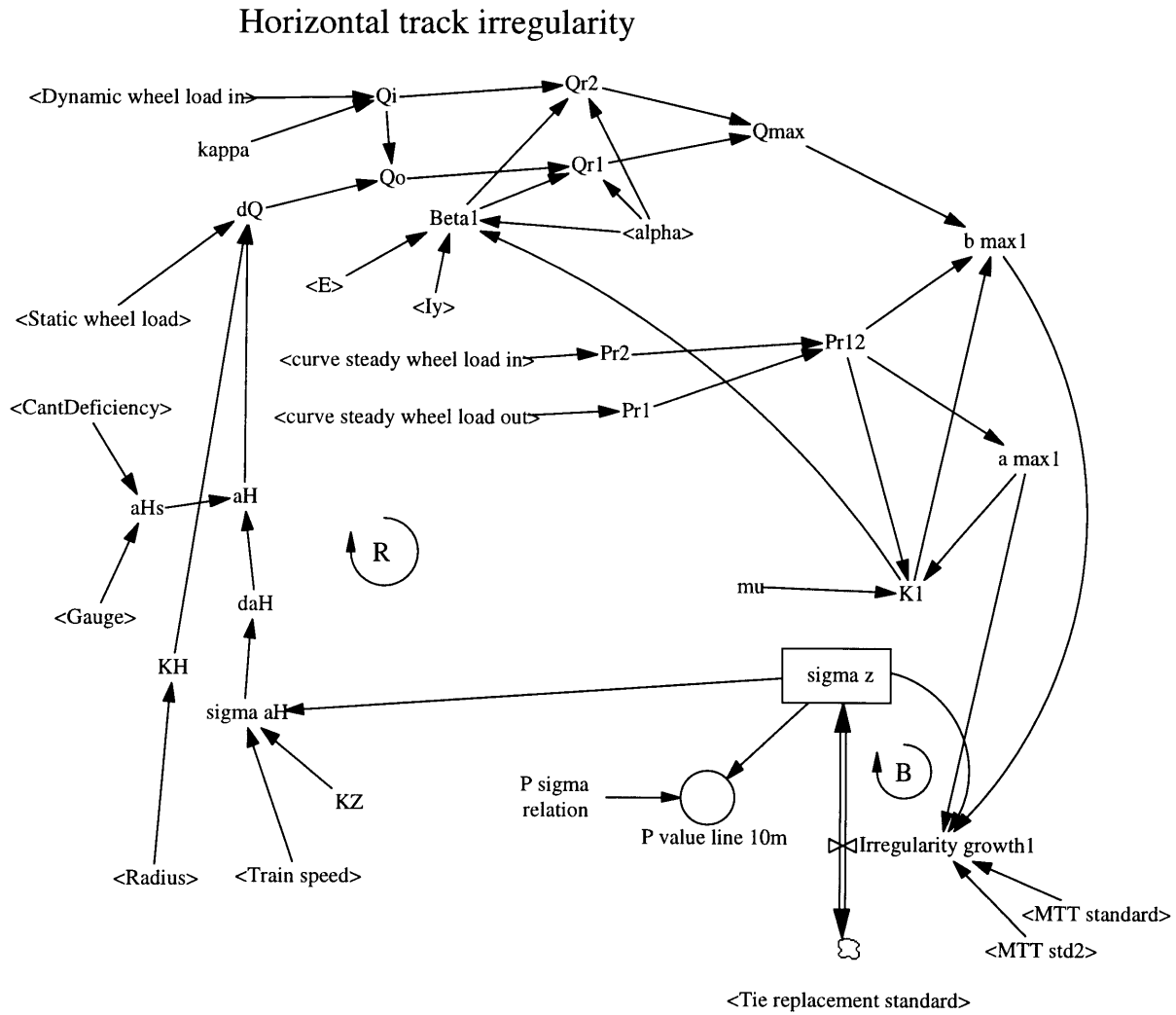


Figure 4.10 A causal loop diagram: Track geometry module (2)

#### 4.5.1 The calculation of wheel loads on the track

At first the model will calculate the lateral (parallel to the track surface) forces of the wheel of the outer rail side of the front axle of a bogie of a vehicle ( $Q_o$ ). It will also calculate the greatest value of the lateral force of the wheel and the axle ( $dQ$ ), which is the inertial force



of the vehicle due to horizontal vibration. Figure 4.11 shows the forces applied to wheels, axles and rails in a curved section.

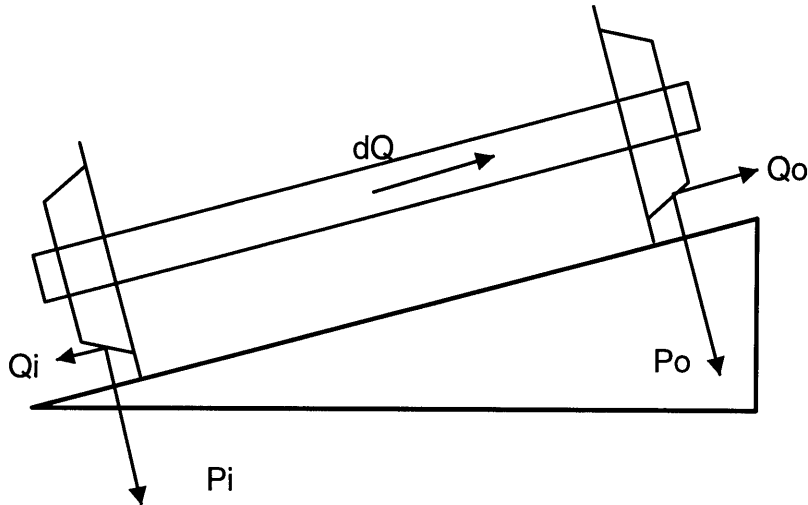


Figure 4.11 Cross section at the axle showing forces applied to rails, wheels and axles in a curved section

$$Q_o = Q_i + dQ \quad (4.19)$$

Units: kN

$$Q_i = \kappa \cdot \text{Dynamic wheel load in} \quad (4.20)$$

Units: kN

$$dQ = 4 \cdot \text{Static wheel load} / g \cdot aH \cdot KH \quad (4.21)$$

Units: kN

$$aH = aH_s + daH \quad (4.22)$$

Units:  $m/s^2$

$$aH_s = \text{CantDeficiency} / \text{Gauge} \cdot g \quad (4.23)$$

Units:  $m/s^2$

$$daH = 3 \cdot \sigma aH \quad (4.24)$$

Units: m/s

$$\sigma aH = KZ \cdot \sigma z \cdot \text{Train speed} \quad (4.25)$$

Units: m/s/s

$$KH = 0.6 + 80/\text{Radius} \quad (4.26)$$

where

$Q_o$	: lateral force applied to the outer rail
$Q_i$	: lateral force applied to the inner rail
$kappa$	: ratio of lateral force and wheel load
$aH$	: lateral acceleration of the vehicle (parallel to the track plane)
$aH_s$	: lateral acceleration of the vehicle (steady, not including influence of vibration)
$daH$	: lateral acceleration of the vehicle (a component due to the vibration)
$\sigma aH$	: standard deviation of $aH$
$KZ$	: horizontal train vibration coefficient (= 0.001) Units: $m/s^2/mm/(km/h)$
$\sigma z$	: standard deviation of horizontal track irregularity (mm)
$KH$	: coefficient for the horizontal vibration of the vehicle

The force applied to the outer rail ( $Q_o$ ) is equal to the sum of the steady lateral wheel load of inner wheel and change of load which is raised by the lateral vibrations.

The horizontal loads and movement are calculated using the conditions and methods described in

Figure 4.12. At first the model will calculate the vertical force applied to each rail, which is the same process as the calculation of the vertical track irregularity. However, this model considers only steady wheel loads for  $Pr1$  and  $Pr2$ , because this is a safer side of the design for the construction of the model. The bigger the vertical pressure on the rail, the smaller the movement of the track becomes. Therefore it is safer not to consider the influence of non-steady wheel loads. Then the model will calculate the horizontal spring coefficient of ballast, which is related to lateral ballast resistance force. Next the model will calculate the horizontal pressures applied to outer rail ( $Qr1$ ) and inner rail ( $Qr2$ ). The horizontal

movement per transit of axle is as follows. These equations are given by an actual experiment which uses a full scale model of the track.<sup>35</sup>

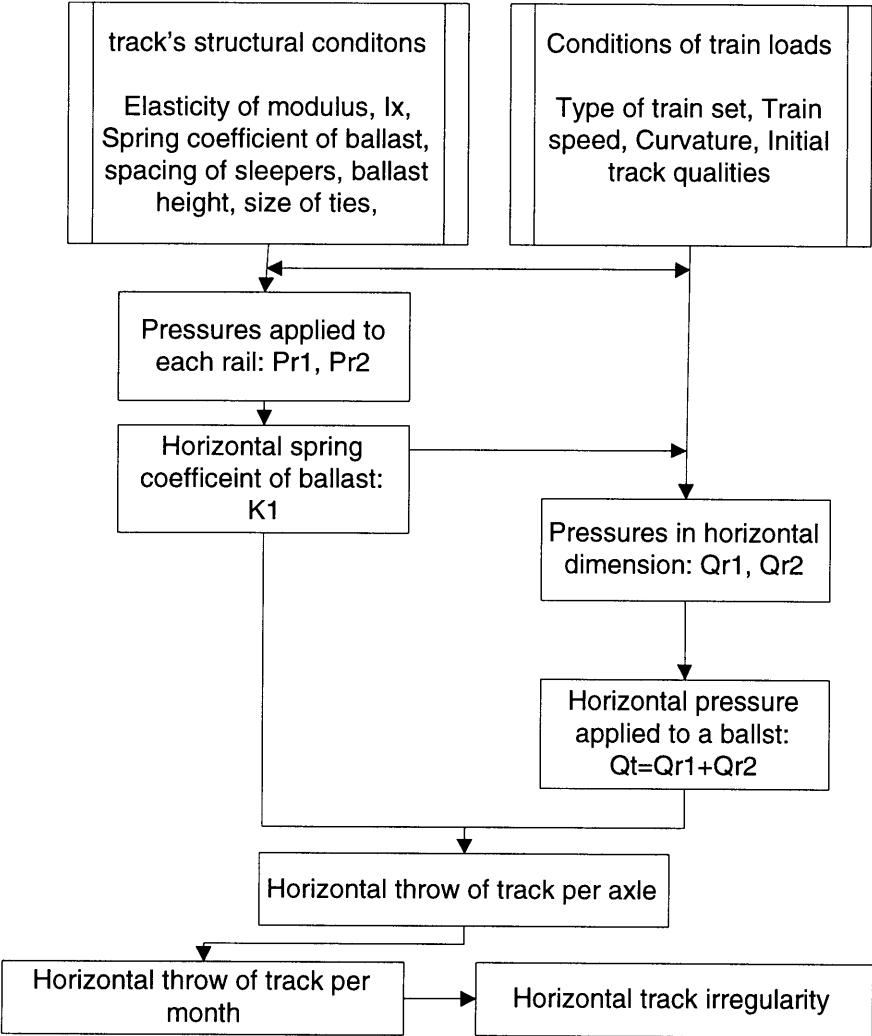


Figure 4.12 A simplified flow diagram of the calculation of horizontal track irregularity

<sup>35</sup> Same as 30,

Ishikawa, T., Namura, A., Cyclic Deformation characteristics of railroad ballast in full-scale tests, Journal of JSCE, No.512/IV-27, pp.47-59, May, 1995

Then the model will calculate the maximum pressure carried to rails ( $Q_{max}$ ) using  $Q_{r1}$  and  $Q_{r2}$ .  $Q_{r1}$  and  $Q_{r2}$  are lateral forces carried to rails (See Figure 4.11). They are calculated using the theory of an infinite beam on a uniform and continuous support, which is applied in the calculation of  $P_t$ .<sup>36</sup> The followings are the description of the variables.

$$Q_{r1} = Q_o \cdot (1 - \text{EXP}(-\text{Beta}1 \cdot \text{alpha}/2)) \cdot \text{COS}(\text{Beta}1 \cdot \text{alpha}/2) \quad (4.27)$$

Units: kN

$$Q_{r2} = Q_i \cdot (1 - \text{EXP}(-\text{Beta}1 \cdot \text{alpha}/2)) \cdot \text{COS}(\text{Beta}1 \cdot \text{alpha}/2) \quad (4.28)$$

Units: kN

$$Q_{max} = Q_{r1} - Q_{r2} \quad (4.29)$$

Units: kN  
Maximum horizontal load

#### 4.5.2 The calculation of the horizontal movement of the track

If the  $b_{max1} > 0$ ,

$$b_{max1} = (3.9e-005) \cdot Q_{max}/K1 - (8.38e-008 \cdot Pr12 - 1.67e-006) \quad (4.30)$$

else  $b_{max1} = 0$

Units: mm

$$Pr12 = Pr1 + Pr2 \quad (4.31)$$

Units: kN

$$Pr1 = \text{curve steady wheel load out} \cdot (1 - \text{EXP}(-\text{Beta} \cdot \text{alpha}/2)) \cdot \text{COS}(\text{Beta} \cdot \text{alpha}/2) \quad (4.32)$$

Units: kN

$$Pr2 = \text{curve steady wheel load in} \cdot (1 - \text{EXP}(-\text{Beta} \cdot \text{alpha}/2)) \cdot \text{COS}(\text{Beta} \cdot \text{alpha}/2) \quad (4.33)$$

Units: kN

$$K1 = -26.4 + 21.5 / (a_{max1} + 0.0425) + \mu \cdot Pr12 \quad (4.34)$$

Units: MN/m

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<sup>36</sup> See Chapter 4.4.1

where  
*b max1* : horizontal movement of the track per transit of axle  
*Pr1* : force applied to the outer rail  
*Pr12* : force applied to the inner rail  
*K1* : coefficient of spring for lateral dimension of the ballast  
*mu* : coefficient of friction between ballast and a concrete tie

#### ***4.5.3 The calculation of track irregularity of horizontal dimension***

The horizontal track irregularity grows as a result of the cumulative load of trains, in the same manner as the vertical track irregularity. The horizontal track irregularity has the normal distribution. As in the case of the vertical track irregularity, it is assumed that the growth of standard deviation of horizontal track irregularity per transit of axle becomes one sixth of *bmax1*. (The variable *bmax1* is the greatest value of horizontal movement of the track.)

In addition to the growth of track irregularity discussed above, we have to take into account the initial movement of the track after the tamping activity, which is the sole means of improving the track irregularity in this model.

## **4.6 The Material Module**

The material module of this model observes the QF of material over time. The easiest way of tracking the QF in this module would be to look at the cumulative tonnage of each

material, as many track engineers use it for an index of a replacement standard. As the measurement means of the QF, this model possesses six parameters. They are *Rail roughness*, *cumulative rail tonnage*, *Ballast deterioration*, *Cumulative ballast tonnage*, *Cumulative tie tonnage*, and *Cumulative tie pad tonnage*. Unfortunately, not all parameters are fully used in this research, but they can be used for an upgraded model which is supposed to be developed in the future for a further research. Figure 4.13 shows the causal loop diagram in the material module.

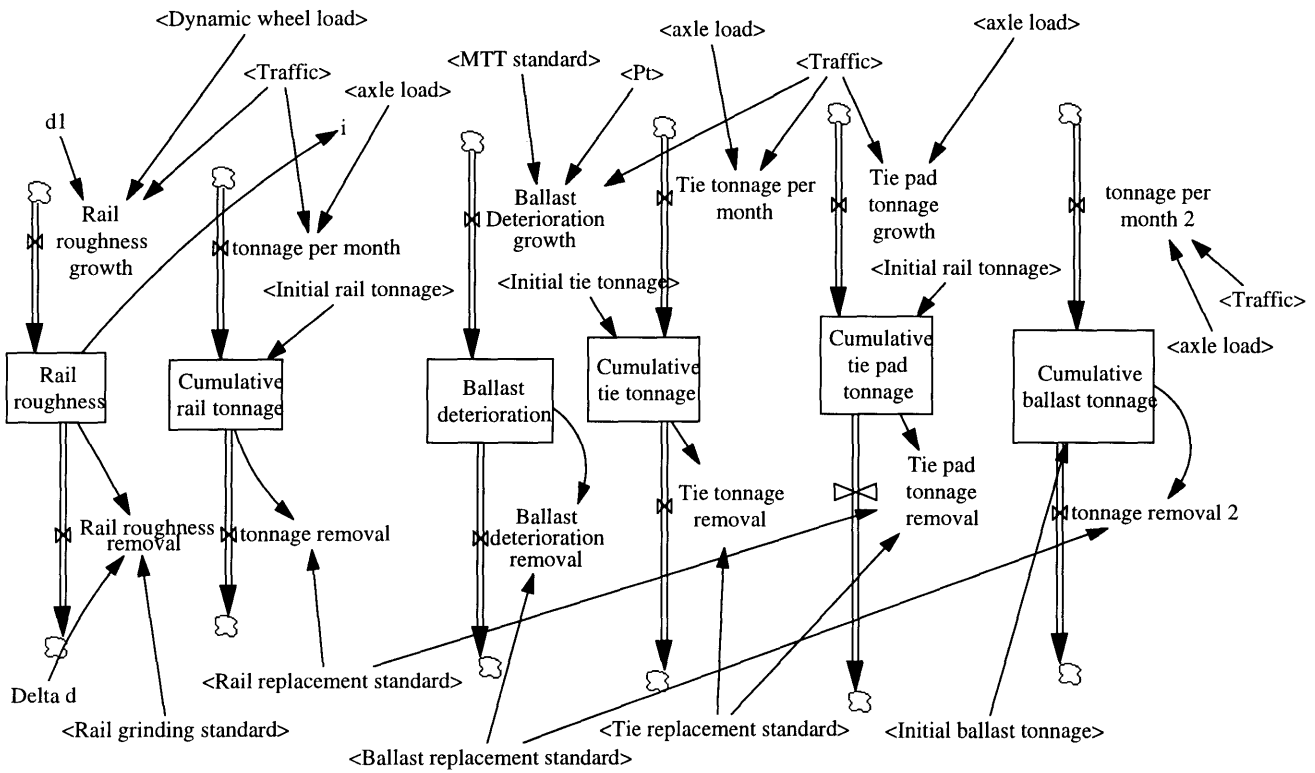


Figure 4.13 Causal loop diagram of the material module.

#### **4.6.1 The Rail Section**

There are three main factors that cause the rail to deteriorate. They are wear, tears and short wavelength roughness of the rail head surface. For simplification, this model considers the roughness of the rail head and the wear.

Basic theory of the deterioration of the rail is based on the study of Uchida et al.<sup>37</sup> The concept of their study is also applied in the track geometry module of this model.

Wear of the rail is mostly related to the cumulative tonnage of traffic on the rail. Some research reveals that the wear of the rail grows proportionally to the cumulative tonnage. This assumption is very common, as track engineers decide the period of the rail replacement with it. For simplification, the model considers only the cumulative tonnage in determining when to replace it with new one. The life span of the rail is dependent on the rail grinding frequency (internals between grinding maintenance).

#### **4.6.2 Rail Roughness Section**

This model predicts the rail roughness of welded section of the rail. The model considers the improvement of rail roughness due to rail grinding. It is assumed that the growth of rail roughness is proportional to the cumulative wheel load (kN) on the welded section. This relationship is described as follows:<sup>38</sup>

$$d = d_0 + d_1 \sum P \tag{4.35}$$

where

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<sup>37</sup> A study on growth and restoration of the track irregularity considering material deterioration, RTRI Report, Vol. 11, No. 2, pp.1 - 6

<sup>38</sup> Uchida et al.: A study on growth and restoration of the track irregularity considering material deterioration, pp.1-6

- $\sum P$  : cumulative wheel load
- $d_0$  : initial rail roughness (mm)
- $d_1$  : roughness growth per a unit of wheel load (mm/kN)
- $d$  : rail roughness; it is called “*rail roughness*” in the model(see Appendix)

$P$  represents dynamic wheel load, which is defined in 4.4. It is found that the roughness of rail grows approximately 0.1mm per 100 gross million tons of traffic. The variable  $d_i$  is computed from the preceding value. The variable  $d$  influences the rate of fluctuation of the wheel load caused by the vibration of the mass of the train below the suspension system ( $i$ ). The variable  $i$  is used in the dynamic wheel loads.

#### **4.6.3 The Ties Section**

The life span of cross ties used in Shinkansen is supposed to last 50 years in the stage of their design. There are increasing probabilities of appearance of cracks that needs replacement over the cumulative tonnage. However, this model does not take into account this probability. This model considers the tie replacement with the cumulative tonnage of 2 billion gross tons.

#### **4.6.4 The Ballast Section**

In the ballast section, two level variables, “*ballast deterioration*” and “*cumulative tonnage of ballast*” are considered.

The variable “*ballast deterioration*” shows the degree of deterioration which is influenced by cumulative dynamic train loads and maintenance activities. Although this is not proven



in the experimental level, this concept is introduced by Uchida and Miwa.<sup>39</sup> This concept should be refined to fit the actual behavior of the track, but this is supposed to be a reasonable concept for the degradation. Ballast deterioration is shown as follows:

$$s = s_1 \times M + s_2 (\sum P_i) \quad (4.36)$$

where

$s$  : deterioration of ballast ( $0 < s < 1$ )  
 $s_1, s_2$  : coefficients  
 $M$  : number of track maintenance by MTT  
 $\sum P_i$  : pressure carried beneath a tie

Next the relationship between  $s$  and the coefficient  $a$  used in the ballast settlement per axle are shown as follows.

$$a = a_0 \times (1 + s / c) \quad (4.37)$$

where

$a_0$  : a coefficient  
 $c$  : *correction coefficient*

A coefficient  $c$  is defined because the influence of deterioration in the track settlement has not yet been confirmed. This value should be determined precisely in a further research.

#### **4.6.5 The Tie pads section**

Tie pads are an important tool as an elastic support for the train in the track. Tie pads are usually made of rubber or similar component and they are usually replaced in the rail

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<sup>39</sup> Same as 37, pp.2

replacement. This model considers that the spring coefficient of tie pads is influenced by the their cumulative tonnage.<sup>40</sup> The spring coefficient of tie pads is shown as follows.

$$Dp1 = (89730 + 230.9 \cdot \text{Cumulative tie pad tonnage} / 10^6) / 1000 \quad (4.38)$$

Units: MN/m

#### 4.7 The costs module

In this model maintenance cost is calculated using the data of Shinkansen in 1997( Japanese Yen). In each maintenance activities, a unit maintenance cost multiplied by the amount of work is added. More precise information is referred to in the Appendix.

This model offers cumulative discounted cost that enables to observe the net present value of the maintenance cost. The discount rate can be changed in this model.

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<sup>40</sup> Ikemori, M. : A model of time history of railway track irregularities and its applications, Journal of JSCE, No.365/IV-4, April 1986, Japan Society of Civil Engineers

## Costs module

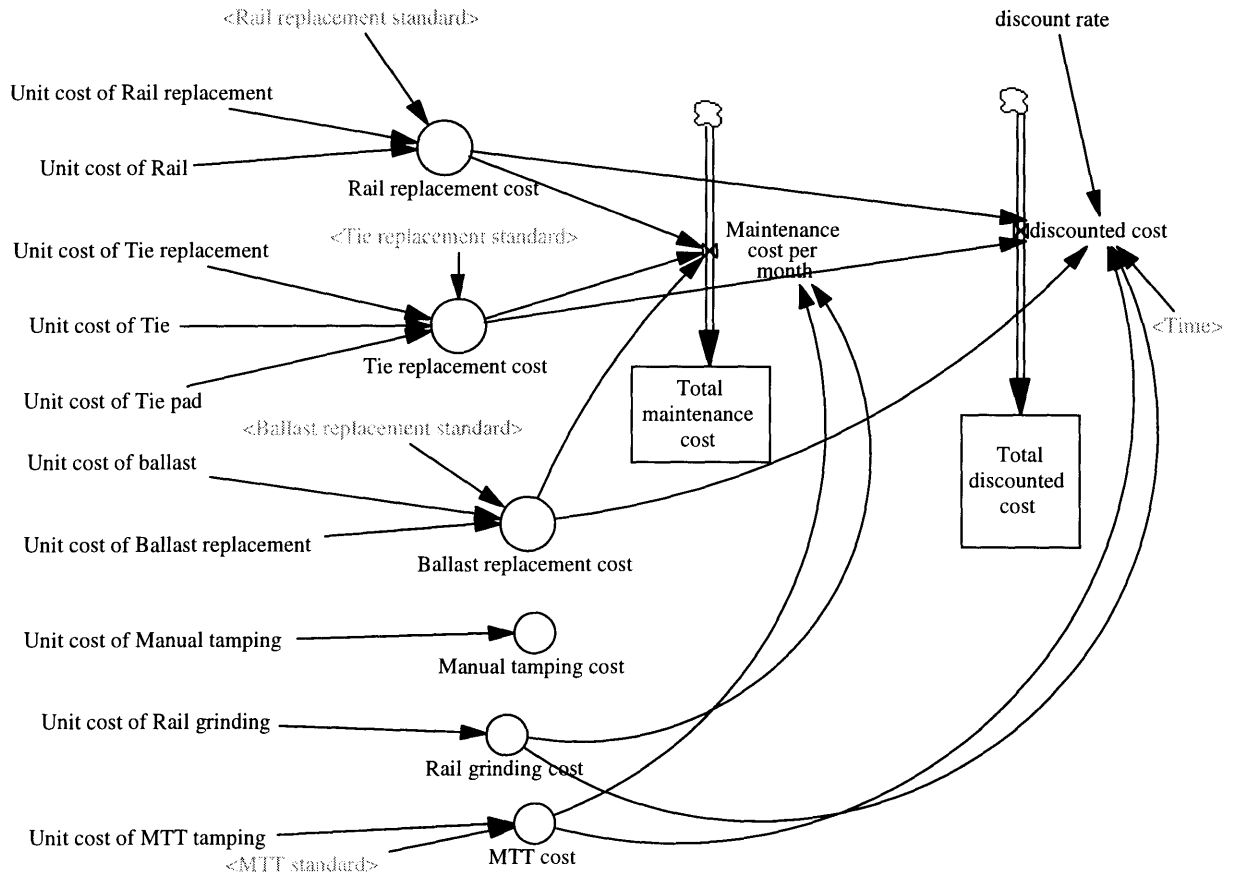


Figure 4.14 A causal loop diagram of the costs module

## **4.8 The maintenance policies module**

This model considers a maintenance standard in each material of main track components.

The model allows a user to choose either periodic maintenance or pro active maintenance in the tamping of ballast by MTT and rail grinding. When periodic maintenance is selected, the model performs maintenance in a predetermined interval. When pro active maintenance is chosen, the model executes maintenance when a value of defects, such as the standard deviation of track irregularity and roughness on the rail head, goes beyond a predetermined value.

In the rail replacement, the rail is replaced following a life span of rail which is a function of the interval of rail grinding. Tie pads are replaced at the same time when the rail is replaced.

For the replacement of ties, the model applies the replacement standard based on the cumulative tonnage on the materials. If the tonnage goes above the predetermined threshold, the replacement is swiftly executed. The ballast is replaced using the standard called “ballast deterioration,” which is discussed in 4.6.4.

Figure 4.15 shows a causal loop diagram of this module.

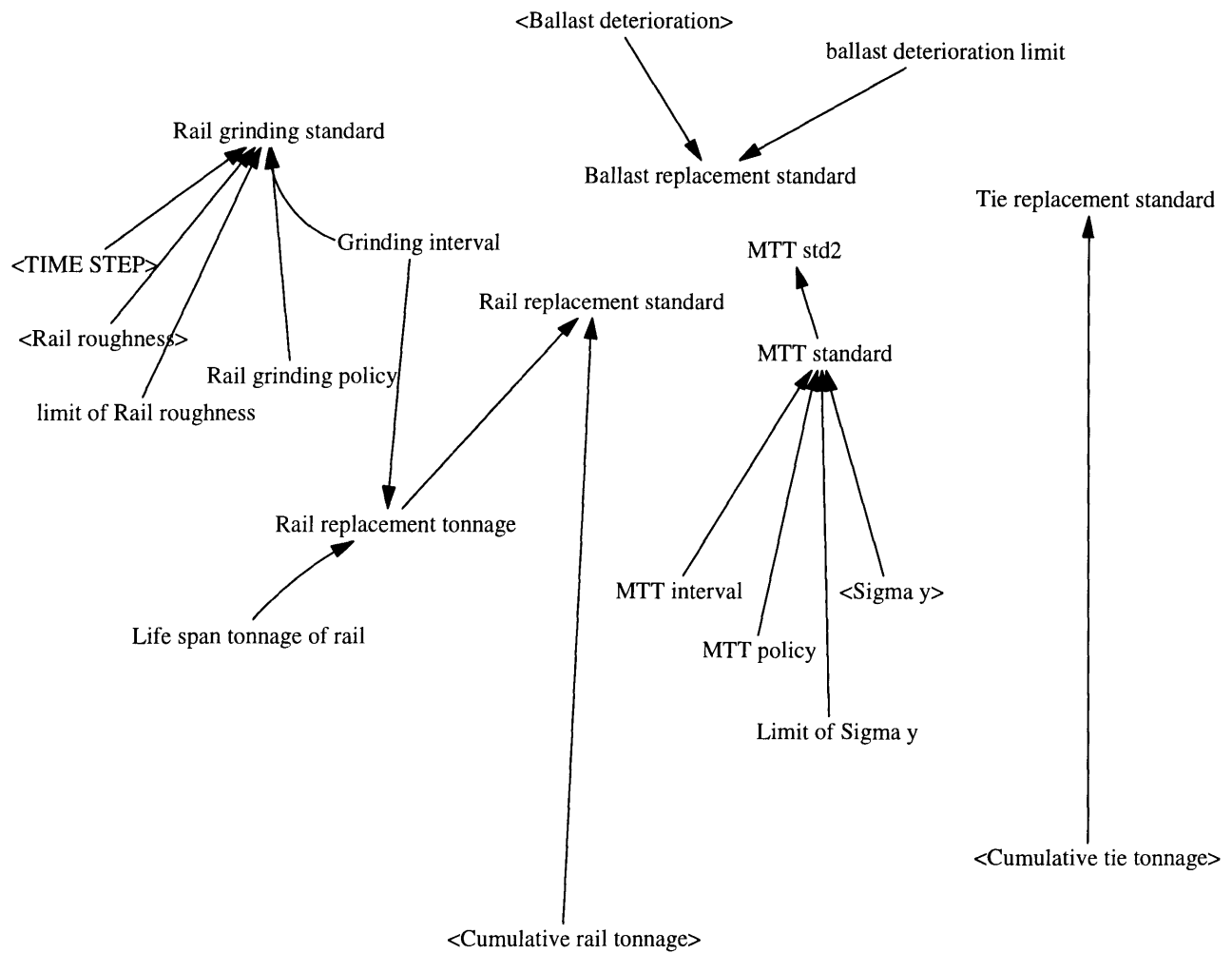


Figure 4.15 A causal loop diagram of the maintenance policies module

#### 4.8.1 MTT standard

This variable, which is described as an equation for a policy statement, determines how the tamping activities are performed using multiple tie tampers (tamping machines). In the model, this kind of standards gives the simulation runs triggers to perform particular maintenance activities.

As is shown in Figure 4.15, five variables (*MTT policy*, *MTT interval*, *Limit of Sigma y*, and *Sigma y*) causes the *MTT standard* to trigger tamping activities in simulation runs. *MTT policy* decides whether the model executes periodic maintenance (one is output) or proactive maintenance (zero is output). *MTT interval* gives the value of interval between tamping activities, and it is valid only when *MTT policy* is equal to one. *Limit of Sigma y* gives a threshold value which makes the model execute MTT tamping activities when the value of *Sigma y* reach the threshold. This variable is valid when the *MTT policy* is equal to zero.

#### **4.8.2 Rail replacement standard**

This variable determines how the rail is replaced. It is subject to *Cumulative rail tonnage* and *rail replacement tonnage*. When the *Cumulative rail tonnage* reach *rail replacement tonnage*, the variable gives simulation runs triggers to perform the rail replacement activity. When the rail replacement activity is performed, the cumulative rail tonnage is offset to zero.

Life span of rail is a function of *grinding interval*. A study shows that the life span of the rail that is shown as the cumulative tonnage on rail is dependent on the grinding interval.<sup>41</sup> This model uses modified data that fit the actual performance of rail life. Figure 4.16 shows the relationship of the life of rail and cumulative tonnage carried on the rail.

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<sup>41</sup> Ishida, M., Abe, N.: Prediction system of welded part of rail, JRCEA, March 1995.

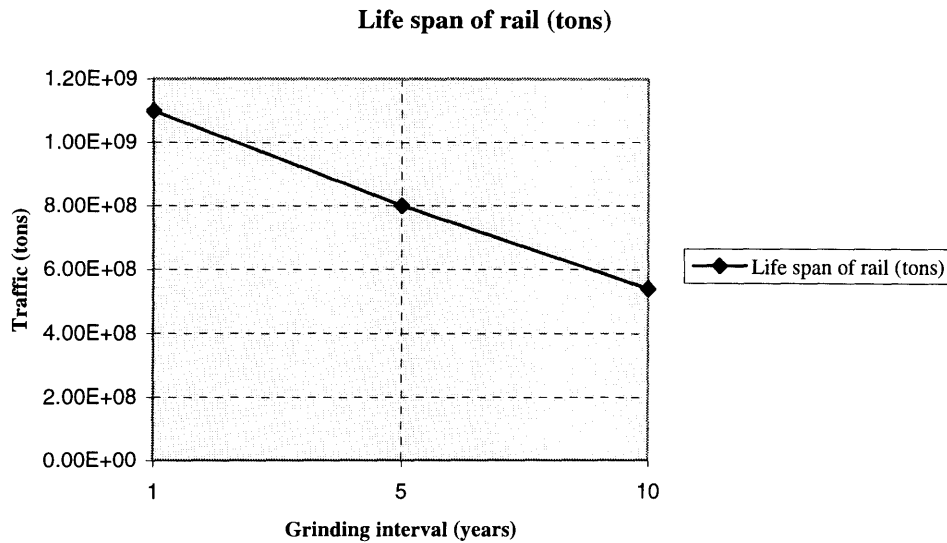


Figure 4.16 Life span of rail described as cumulative tonnage

#### 4.8.3 Rail grinding standard

This variable determines how the rail grinding activities are performed in the model. This variable allows users of the model to choose either periodic or pro-active maintenance. The variable *rail grinding policy* gives the policy of rail grinding (1 for periodic maintenance and 0 for pro-active maintenance). When users select the periodic maintenance, the model performs rail grinding with the intervals of *Grinding interval* (units: years).

#### 4.8.4 Ballast replacement standard

This variable determines when the model replace ballast in the simulation runs. As Figure 4.15 shows, the decision making of ballast replacement uses two variables: *Ballast deterioration* and *Ballast deterioration limit*. The variable *Ballast deterioration* shows the degree of deterioration which works as a coefficient of track settlement. The values of

ballast deterioration range from zero to one. When the *ballast deterioration* at the observed track in the model goes beyond the *Ballast deterioration limit*, the model executes ballast replacement. When the model performs ballast replacement, the value of ballast deterioration is offset to zero, as the new ballast is assumed to have no deterioration.

#### **4.9 The Initial conditions module**

This model requires the following input: the inherent characteristics of track components, the track geometry, the initial track conditions, and the maintenance policies.

The inherent characteristics of track components include the type of rail, the size of the ties, and the ballast height beneath the ties. Track geometry information includes the radius of the curvature (if the simulated section includes curves) and cant. The initial track conditions consist of the standard deviation of the track irregularity at the initial time, initial cumulative tonnage of individual track components, the subgrade's condition (K30 value), and initial degree of deterioration of the ballast. In actual track maintenance, each track component is replaced according to a replacement standard for each material. Therefore, we should take into account the tonnage or degree of deterioration of each material.

Traffic conditions include: number of trains per day, number of vehicles per train, number of axles per vehicle. For simplicity, the model considers only one type of train set, which is close to the actual situation of Shinkansen. It would be possible to improve the model to allow it to handle for variable train sets.



Maintenance policy decides how track maintenance is done. This model allows the choice either the pro-active maintenance or the periodic maintenance in the MTT work (tamping) and rail grinding. If pro-active maintenance is applied, the model will assume the performance of track maintenance if the QF of the components goes below some limit. In periodic maintenance, the model will simulate periodic track maintenance.

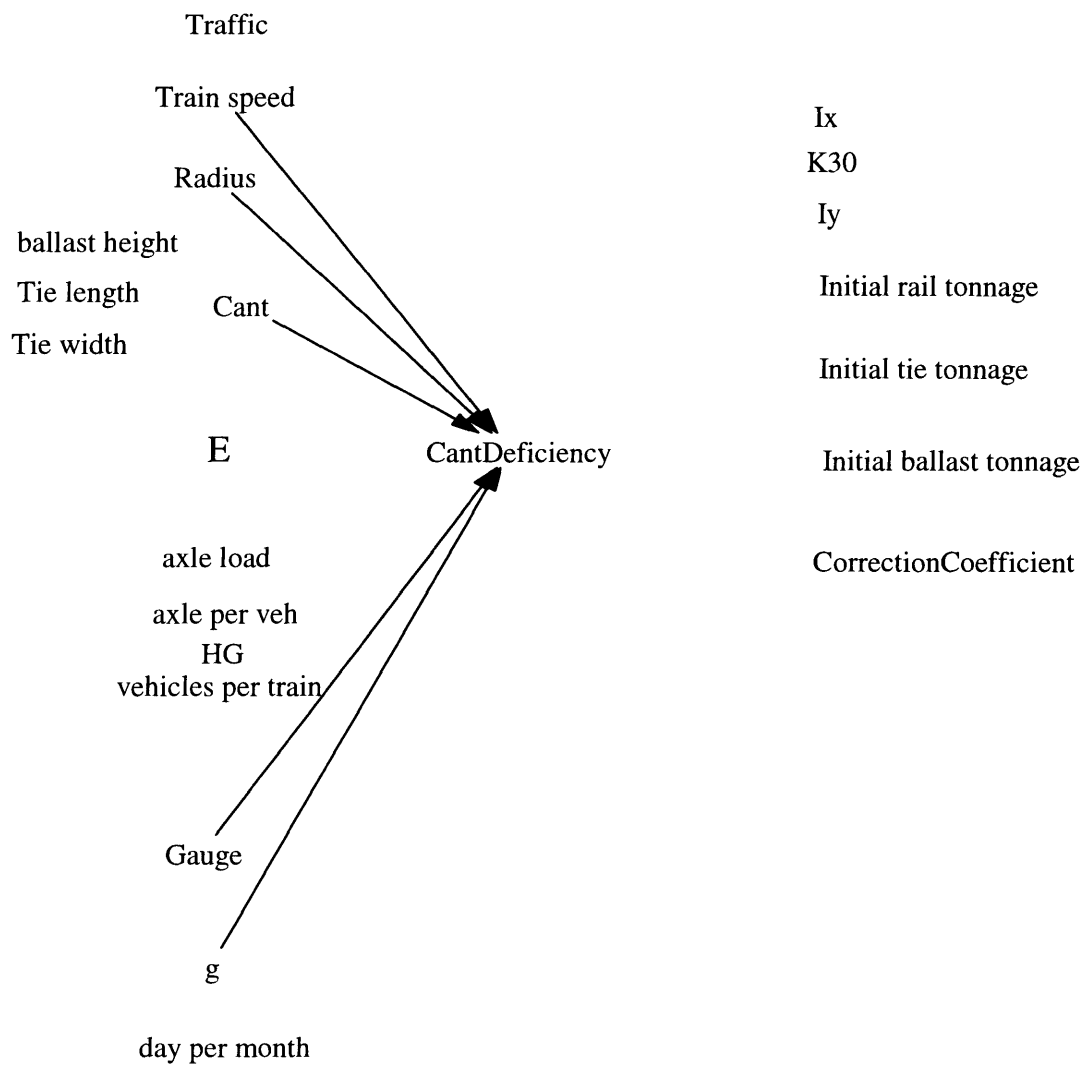


Figure 4.17 A causal loop diagram of the initial conditions module

## **4.10 Summary of the Chapter**

In this chapter, the focus of the model is discussed at first in 4.1. This model has a time interval of one month and simulates the period of 250 months, which almost covers the cycle of maintenance. The model calculates the track irregularity in both longitudinal and horizontal dimensions, cumulative tonnage of track component as indicators to see the quality of the facilities.

The quality of the facilities (QF) used in this model is defined in 4.1. As indicators of QF for the geometrical parameter, track irregularity and P-value were discussed. As indicators of QF in the mechanical parameter, the cumulative tonnage of materials and the ballast deterioration were defined.

A macroscopic explanation was made for the overview of the model in 4.3. This model possesses six modules: Geometrical (1), Geometrical (2), Materials, Costs, Initial conditions, and Maintenance policies.

The next chapter validates the model with actual track data.

## **5. Model Validation**

This chapter examines how well the model predicts actual track behavior.

Actual track maintenance activities are much more complex than activities assumed in the model. Even in a one kilometer section of track, the track condition is not uniform along its entire length because of factors such as local geometric conditions, subgrade conditions, and differences in the history of track maintenance activities. The model should have the ability to predict the trend that may be useful in choosing better maintenance policies. So the purpose of the modeling should not be to make a perfect predictor of the track, but to create an analytical tool that will help users explain the behavior that is comparable to the results of other maintenance policies. To validate the model, it is very important to check whether the variables in the model behave in a manner similar to actual circumstances.

This chapter describes the behavior of track settlement over time, and then examines the behavior of the P-value and the standard deviation of track irregularity in the longitudinal dimension ( $\sigma_y$ ).

## 5.1 The examination of the simulated data and actual data: High-Speed Rail in Japan

### 5.1.1 Track settlement

Railroad track settles over time due to train loads, centrifugal forces, impact loads on the welded sections, amplified inertial forces as a result of track irregularity, and so on. Due to track settlement, ballast needs to be added to keep the track level, since the pieces of ballast are pushed into the subgrade, crushed into smaller debris and further disintegrated into dirt. In addition, the loads of the trains also cause the ballast to slide to the sides of the track.

There is a study that calculates the necessary supply of ballast per year for the conventional tracks of Japan National Railway.<sup>42</sup> According to the study, the annual settlement in the first class track is equal to **7.1 mm**, and the necessary supply of ballast is 30 m<sup>3</sup>/km. This data was used to estimate the average settlement of all the first class track in Japan. Therefore this number is thought to be statistically reliable. The average tonnage on the first class tracks is 30 to 50 million tons, which is very close to the annual tonnage of the Tokaido Shinkansen near Nagoya station, where the data was acquired. The annual tonnage on the Shinkansen in this section is about 40 million tons.

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<sup>42</sup> Miyamoto. K.: The track. pp.199. 1980

Table 5.1 Conditions of the standard simulation

Condition of the simulation	Values	Units
<b>Varied variable in the sensitivity simulation runs: Correction Coefficient</b>	<b>1 - 10, step of 0.5, 21 runs 2 for the black line (base simulation)</b>	NA
train speed	255	km/h
radius	Straight section	meters
cant	0	meters
cars per train	16	cars/train
trains per day	140	trains
initial track irregularity (std. Deviation)	0.4	mm
axle load	12.5	tons
correction coefficient	2 (sensitivity analysis: 1-10)	NA
MTT policy	scheduled, 1 year-interval	
Subgrade's K30	110	MN/m
Initial rail tonnage	4e+008	tons
Initial ballast deterioration	0.6	NA

To check the behavior of the model, a sensitivity analysis is conducted under conditions shown in Table 5.1. In this simulation, the *correction coefficient*, which controls the influence of *ballast deterioration*, was varied from 1 to 10, for twenty one simulation runs. The initial conditions of the simulation are a straight track section with 255km/h of train speed. In this simulation, MTT tamping activities, which offset *track settlement* are scheduled annually (tamping ballast every twelve months). This makes it easy to check the annual settlement predicted by the model. The peaks in the graph of *track settlement* indicate the annual settlement values.

Figure 5.2 shows the result of the simulation with the initial conditions specified in Table 5.1. Figure 5.2 indicates the cumulative settlement of track over time. When the MTT tamping activities are performed, the settlement drops to zero, as the activities lift the track to the desired track level.

Large amounts of settlement follow the maintenance activities. These indicate the initial settlements after the tamping of the track. The initial settlement values range from 2.3 to 2.6 millimeters. The gradual deformation process occurs both during and after the initial settlement process (see 4.4.4). Gray (thin colored) lines show the results of the sensitivity simulation runs that change the values of *Correction Coefficient* from one to ten in steps of 0.5. Four thick lines with and without patterns represent four different values of *Correction Coefficient* ( $CC=1, 2, 5$  and  $10$ ).

When the *Correction Coefficient* is equal to 2 (shown in thick unbroken line), ballast is replaced in month 135, and rail is replaced in month 206. The range of gray lines is wider before month 135 than the range after month 136. As graph shows, the peak values gradually increase until month 131. This is because the variable *ballast*

$CC=2$       —————  
 $CC=1$       ·········  
 $CC=5$       - - - - -  
 $CC=10$      - · - · - ·

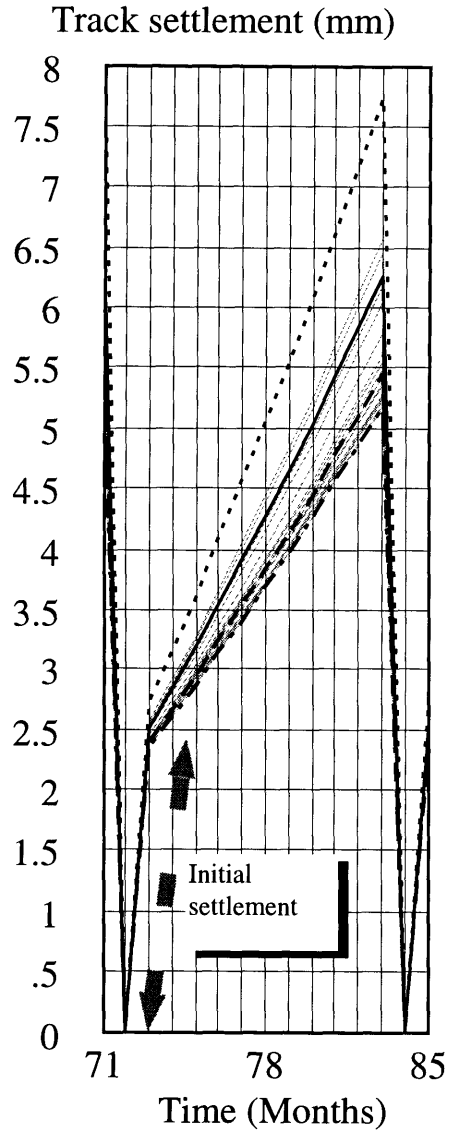


Figure 5.1 Magnified graph from Figure 5.2 between month 71 and 85

*deterioration* positively affects the growth of settlement (settlement per month). Therefore, the peak values increase in accordance with the values of ballast deterioration. The values of annual settlement range (peak values in the graph) from 5.3mm to 8.5 mm in the peak at month 131, 0right before the replacement of ballast. At that time, value of ballast deterioration is almost equal to one, thus having the biggest variation of peak values depending on the *Correction Coefficient*. This range of values includes average number on the first class real track, 7.1 mm/year. When the value of the *correction coefficient* is 2, the largest settlement becomes 6.3 mm at month 131. The wide variation of peak values in various month in the same value of *Correction Coefficient* implies that this model is able to calculate settlement values that depend on various factors.



CC=2: a base simulation

CC=1

CC=5

CC=10

Track settlement (mm)

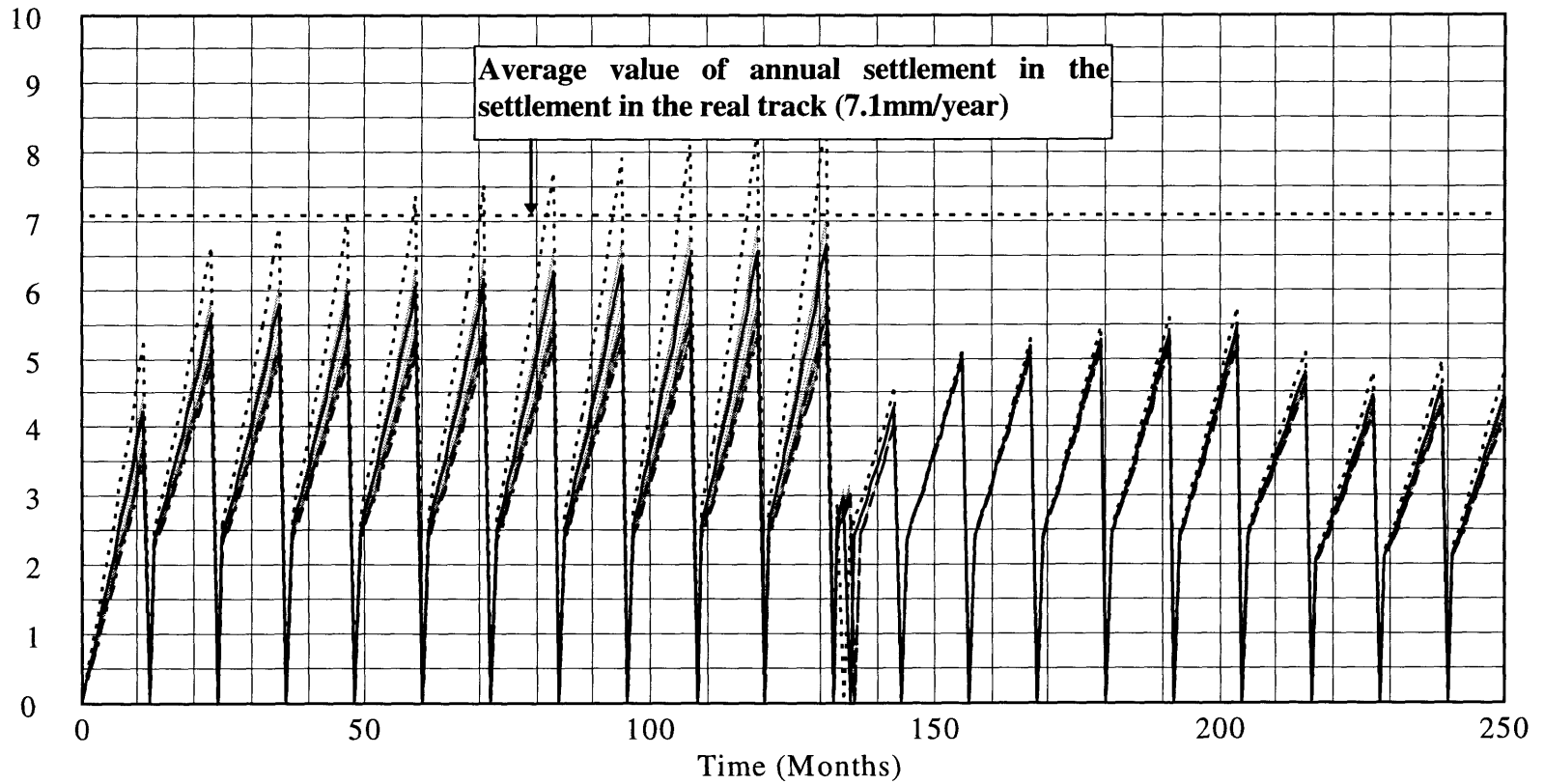


Figure 5.2 The result of simulation runs: Track settlement for various values of Correction Coefficient: CC=1,2,5,10 in thick lines

Figure 5.3 shows the change of *ballast deterioration* over time in three runs with different values of *K30*. *K30* indicates the ground reaction coefficient. It has the same units as that of the spring coefficient, so it shows how good the subgrade condition is. When the ballast deterioration drops to zero at month around 130, the ballast is replaced in the simulation runs. The graph shows that the simulation run higher value of *K30* has earlier month for the ballast settlement. This is because the variable *Ballast deterioration* is positively influenced by the pressure carried to ties (*Pt*), and *Pt* is bigger when the value of *K30* is bigger. That promotes *Ballast deterioration*.

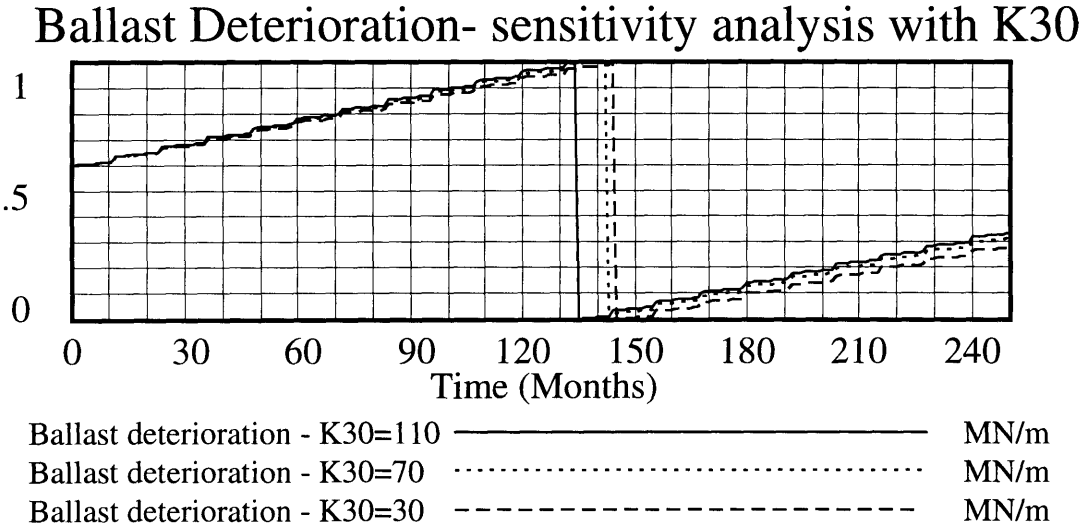


Figure 5.3 Ballast deterioration in three kinds of K30: 30, 70 and 110

Figure 5.3 is a result of sensitivity simulation runs showing *Track settlement* with the values of *K30* changed between 30 and 110 (MN/0m), with steps of every five MN/m. Thick patterned/non-patterned lines show representative runs, whose *K30* are indicated on top of

the graph. Before the replacement of ballast, the annual settlements range from 6 mm to 12.5 mm. The settlement values become bigger when the condition of the subgrade is worse. Therefore, the settlement of the subgrade is not negligible when the subgrade condition is not good.

Generally speaking, first class tracks are constructed in good conditions compared with lower grade tracks. Train loads over long period of time compact the subgrade and the value of  $K_{30}$  becomes relatively high. Therefore, the result given in this analysis is consistent with reality. More precise analysis should be performed to calibrate the model, using more data for the real tracks.

### ***5.1.2 Growth of track irregularity using data of the $P$ -values***

The  $P$ -values indicate the degree of track irregularity, which was explained in Chapter 4.

The track maintenance office at Nagoya of Central Japan Railway kindly provided almost complete data of track maintenance for the Shinkansen's track between April 1994 and January 1997 (Japanese fiscal year begins in April and ends in March). The data were collected from 15 km in the direction of Osaka. This section includes various conditions of both track geometry and train speed. This is basically an accelerating section for trains after leaving Nagoya Station. The train speed ranges from 0 to 255 km/h. This section includes both straight tracks and curved tracks.

The purpose of collecting data is to investigate the growth of track irregularity and the improvement of track irregularity due to the tamping of track. However, many kinds of

track maintenance activities are performed on the track and the activities are not uniform in the observed section. For example, in an inherently poor conditioned track, many kinds of track maintenance activities occur within a period of observation, and it is very difficult to extract the pure contribution due to train loads of the growth of track irregularity; some maintenance activities might worsen the value of track irregularity.

Figure 5.4 shows the change of P-values over time of a one kilometer section of real track at 349 km. This section has a good condition of the track and subgrade, thus needing fewer maintenance activities than other sections. The graph shows the P-values of 10m chord level (longitudinal dimension) for the right rail, 40m chord level of the right rail, 10m chord line (horizontal dimension) of the right rail, and 40m chord line of right and left rails. The P-values of 10m chord of leveling (longitudinal dimension) in the graph are rounded and appear as integers (the data were acquired only in this style). The graph shows that the 10m chord P-values in both level and line remains in very low level, from zero to two, while the P-values of 40m chord P-values of level stays bigger than 15.

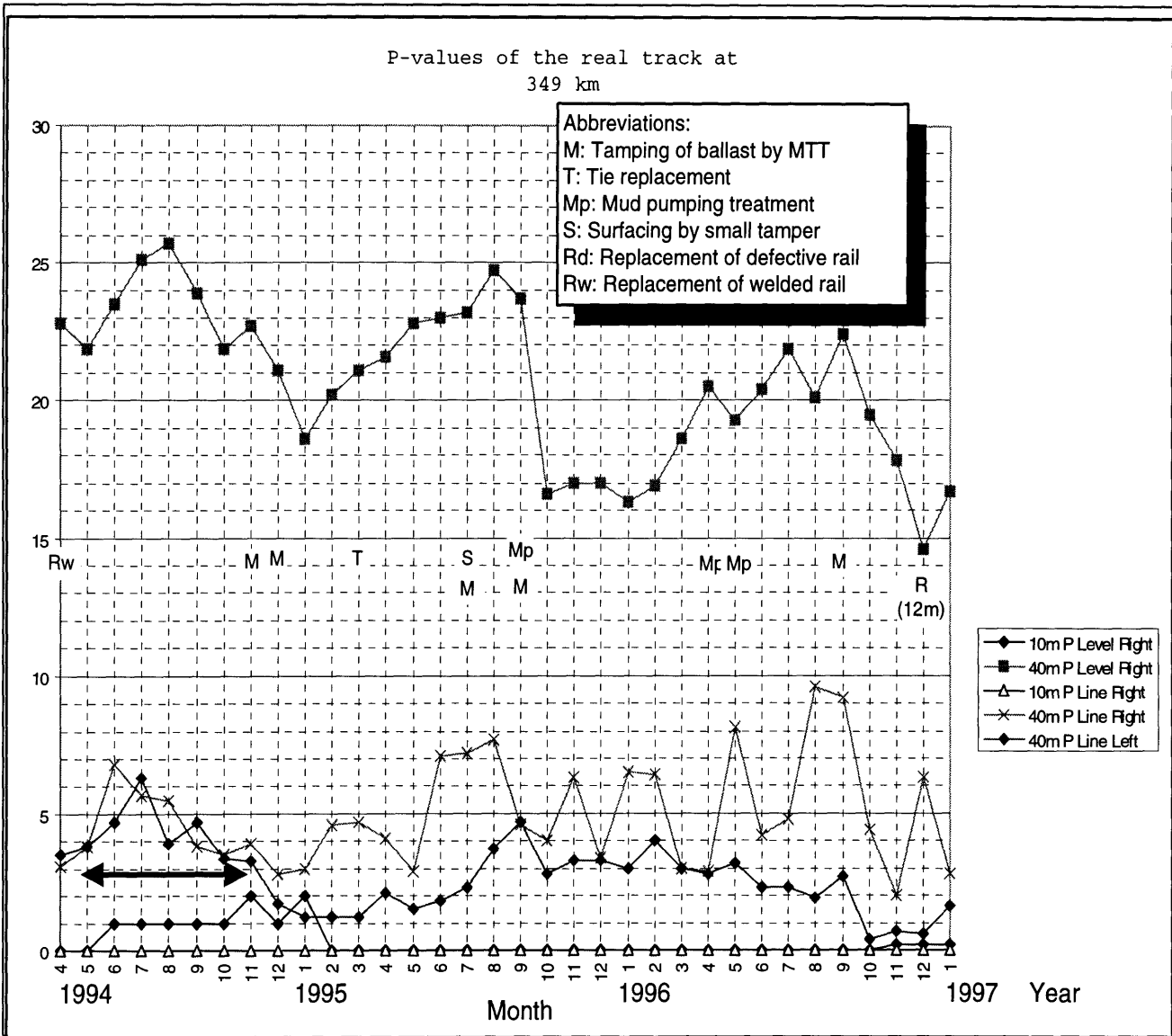


Figure 5.4 P-values measured over a one kilometer section of track

In the Tokaido Shinkansen's management of track maintenance, the measurement of the 40m P-values started in 1992 since Central Japan Railway started operating a new type of train sets, the type 300; its maximum speed is 270km/h. Before the introduction of the type 300, the maximum speed was 220km/h. As the 40m chord P-values of horizontal dimension are related to horizontal vibration of cars that is related to the passengers' comfort, the track maintenance section of Tokaido Shinkansen started a new method of

maintenance that intended to decreases the 40m chord P-values of horizontal dimension. The Tokaido Shinkansen’s track maintenance section does not currently execute track maintenance activities that is targeting to improve the 40m chord P-values of level, that is one of the reasons why they remain in larger values compared with other P-values.

Table 5.2 shows the geometrical conditions and train speed in the section. In this section, track maintenance activities executed in the period of the graph are shown as symbols such as “M,” “T,” and “Sp,” at the value around 13 and 14 of the graph. Symbols written in the graph are explained in Table 5.3. According to Figure 5.4, no maintenance activity was performed in the period where the thick lined arrow appears. In this period, the 10m chord P-value of right rail of the leveling (longitudinal dimension) increases from zero to two. Table 5.4 shows the relationship between the P-values and the standard deviation of track irregularity. The P-value of zero can be converted to the standard deviation of track irregularity ranging from zero to one millimeter, as the sensitivity of the P-value to the value of standard deviation of track irregularity is very low in this range(See 4.2.1.4).

Table 5.2 Conditions of the track 349km

Initial conditions of the simulation for 349 km	Values	Units
train speed	197 - 207	km/h
radius	2,500 (left curve)	meters
cant	0.18	meters
trains per day	140	trains

Table 5.3 Kinds of track maintenance activities in the real data

Types of maintenance	Specified work	Typical working distance/day	Symbol in the Figure
Tamping activities	Tamping by MTT	500-700m	M
Tamping activities	Surfacing by small tamper	100m	S
Tamping activities	Spot tamping of lining	20- 50m	Li
Tamping activities	Spot tamping of leveling	20- 50m	Le
Tamping activities	Removal of long wavelength irregularity by manual tamping	50- 100m	Lt
Tamping activities	Removal of long wavelength irregularity by MTT tamping	50- 200m	Lm
Ballast	Mud pumping treatment	5m	Mp
Ballast	Ballast replacement	25m- 50m	B
Rail	Rail replacement (welded rail)	100- 200m	Rw
Rail	Rail replacement (defective rail)	12- 25m	Rd
Rail	Rail grinding	6 - 8 km	Rg
Tie	Tie replacement	1 -20 ties	T
Expansion Joint	Replacement of expansion joint	1	E
Turnout	Turnout replacement	1	To
Subgrade	Improvement of roadbed (subgrade)	1	SI

Table 5.4 Relationship of P-value and standard deviation of track irregularity (source: Miyamoto K., Track, )

Standard deviation of track irregularity	P-value	Standard deviation of track irregularity	P-value
0	0	2.6	24.9
0.1	0	2.7	26.7
0.2	0	2.8	28.4
0.3	0	2.9	30.1
0.4	0	3.0	31.7
0.5	0	3.1	33.3
0.6	0	3.2	34.8
0.7	0	3.3	36.3
0.8	0	3.4	37.8
0.9	0.1	3.5	39.1
1.0	0.3	3.6	40.5
1.1	0.7	3.7	41.7
1.2	1.2	3.8	43
1.3	2.1	3.9	44.2
1.4	3.2	4.0	45.3
1.5	4.6	4.1	46.4
1.6	6.1	4.2	47.5
1.7	7.8	4.3	48.5
1.8	9.6	4.4	49.5
1.9	11.4	4.5	50.5
2.0	13.4	4.6	51.4
2.1	15.3	4.7	52.3
2.2	17.3	4.8	53.2
2.3	19.2	4.9	54
2.4	21.1	5.0	54.9
2.5	23		

Figure 5.5 shows the standard deviation of track irregularity at 349 km; its values are converted from Figure 5.4 using the relationship shown in Table 5.4. The conversion assumes that the standard deviation of track irregularity becomes 0.9 mm when the P-value is equal to zero. When we pay attention to “*sigma Level Right*,” which represents standard deviation of track irregularity for the 10 m chord, the Sigma was 0.9 mm in May 1994, and was 1.29 mm in November 1995. Therefore, the growth of track irregularity was about 0.4



mm in the period. The annual growth of track irregularity becomes 0.8 mm, or the growth per month becomes 0.67 mm in this analysis.

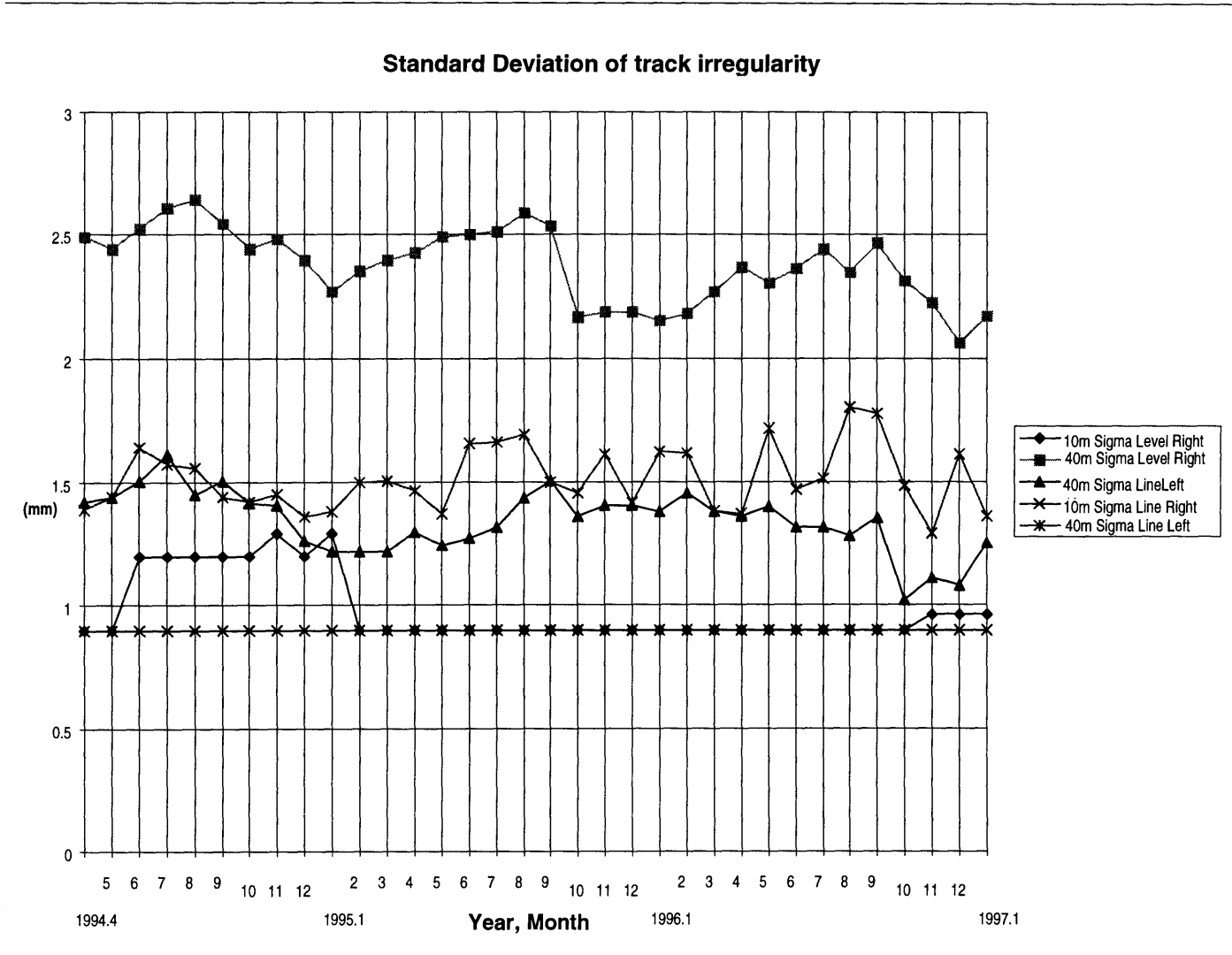


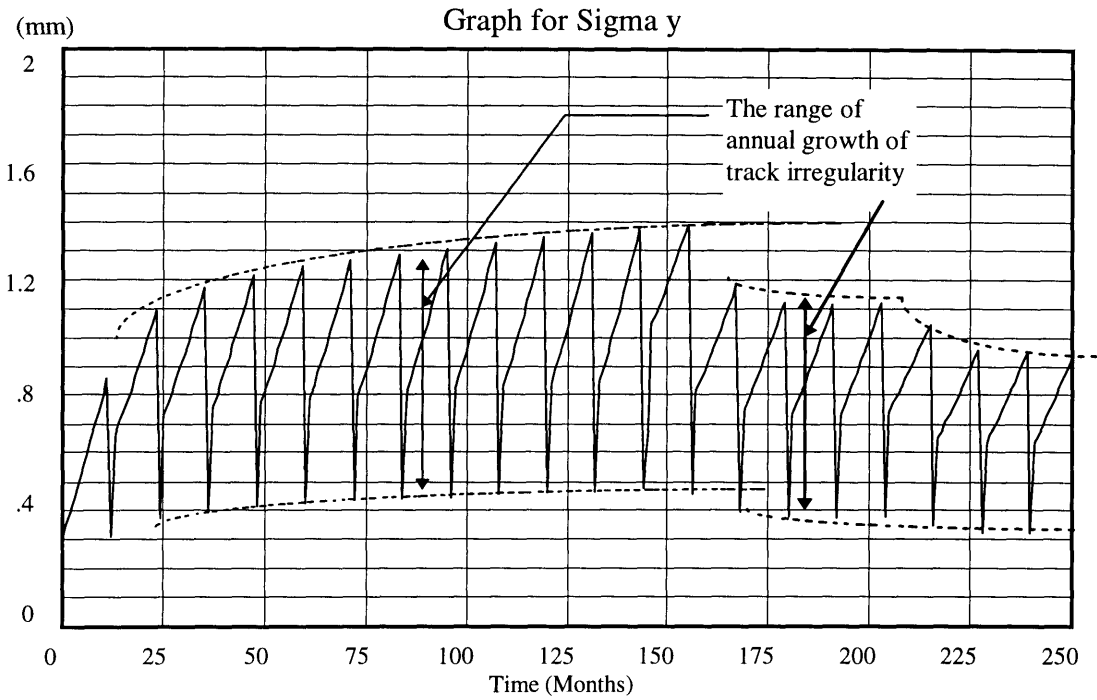
Figure 5.5 Standard deviation (sigma) of track irregularity at 349km for the real track between April 1994 and January 1997.

A simulation run is performed to check how much growth of track irregularity occurs in the computation of the model. The conditions of the track and traffic is based on those at 349 km (Table 5.2). Track maintenance policy for the tamping of ballast is periodic (once a year). This is mostly a curved section for left hand, with a radius of 2,500 m. Train speed

in the section ranges from 197-207 km/h. In the simulation run, train speed is assumed to be 200km/h. Figure 5.6 shows  $\Sigma y$  as a result of the simulation run. Figure 5.7 is also the simulation result showing the 10m chord P-value of leveling (longitudinal dimension). According to Figure 5.6, the annual growth of track irregularity (change of  $\Sigma y$  per year) range from 0.6 mm to 0.9 mm. This difference of range within the simulation comes from various factors in the model, such as the difference of force with the age (or cumulative tonnage) of track components, and the influence of ballast deterioration.

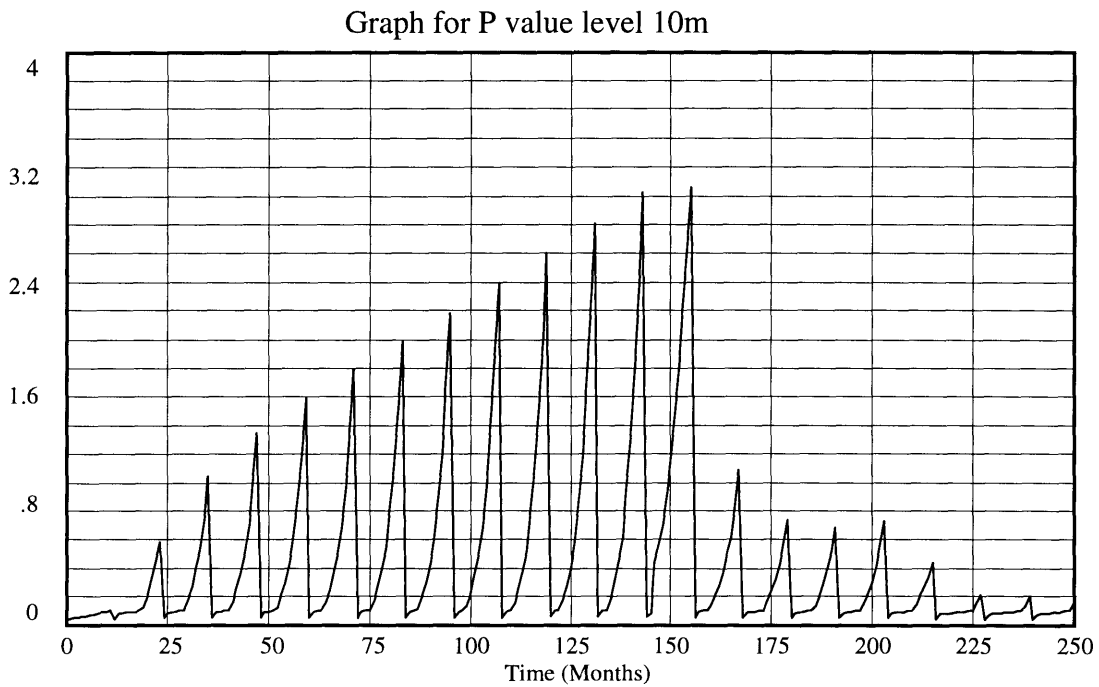
Regarding the simulation result more precisely, growth of track irregularity per month in the gradual deformation process ranges from 0.035 mm in month 216, to 0.076 mm in month 130, including 0.067 mm in month 92. The calculated value in the actual track, 0.067mm, stays within this range. As the tamping activities do not occur in April 1994, right before the period of observation, the growth of track irregularity in this period in the actual track does not include the initial deformation process. Therefore, this simulation result is close to reality in the sense of the growth of track irregularity.

Regarding Figure 5.7, P-value ranges from zero to three in the simulation. The change of the P-value that looks like an exponential growth comes from the biased sensitivity of the P-value to  $\Sigma y$ . The 10 m chord P-values of both longitudinal and horizontal dimensions for the Shinkansen's track are usually less than five, as a result of strict standards of track geometry. This result also makes sense compared with the real track.



Sigma y (mm)

Figure 5.6 A simulation result: the change of track irregularity (*Sigma y*) the conditions of 349km



P value level 10m chord - IRR-GRW1

Figure 5.7 A simulation result: the change of the 10m chord P-value of level in the condition of 349km

Figure 5.8 compares the result of simulation with the reality for the standard deviation of track irregularity of longitudinal level ( $\sigma_y$ ). The real data is given between April 1994 and November 1994, and the data from the model come between month 172 and 179. The sensitivity of the reality is poor as the rounded data of P-values are converted to  $\sigma_y$ . However, it is found that the model trace the real data well in the graph. If the raw data of  $\sigma_y$  is acquired from the real track, it will be possible to make a more precise validity analysis.

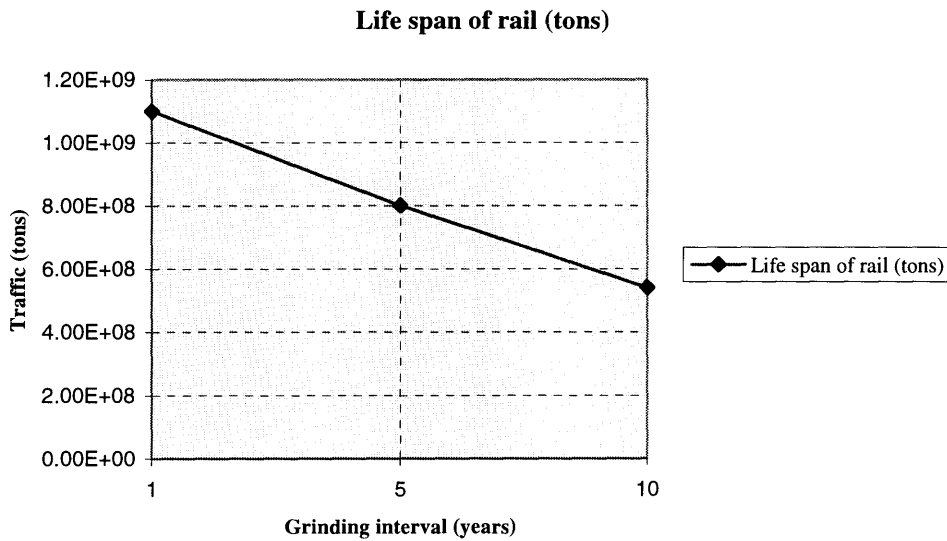


Figure 5.8 A comparison of the model and reality for track irregularity ( $\sigma_y$ )

## 5.2 Results of the validity analyses

The simulation runs executed in this chapter proved that the behavior of track settlement was close to the reality. As shown in the simulation results in this chapter, annual settlement values have a certain range that depends on various parameters used in the model, such as the ballast deterioration, the *correction coefficient*, the spring coefficient of

track materials, and the ground reaction coefficient ( $K30$ ). It is probable that combination of more complex factors correlate with each other in the actual process of the track settlement. However, the model succeeded in extracting dominant factors that cause the track to settle, thus giving results that are close to the settlement observed in the Shinkansen's track.

In terms of the growth of track irregularity of the longitudinal dimension, simulation runs showed that the values range from 0.035mm to 0.076mm, which are consistent with the value derived from the calculated data of the actual track. As the data obtained from the actual track did not include the history of ballast and rail replacement before 1994, the initial conditions, such as the initial tonnage of track materials, could not be specified precisely.

Both track settlement and the growth of track irregularity in the simulation runs showed satisfactory results that match the reality. Since the theories of the model are based on actual data derived from the experiments on full-scale models of track and statistical values of the various tracks, this model has a potential to be precise, even though the purpose of the model is to predict the trend of the behavior of the track given various maintenance policies.

Chapter 6 applies the validated model in several cases using the conditions that are typical in the High-Speed Rail operations.

## **6. Model Application: Case studies**

### **6.1 Introduction**

This chapter discusses seven case studies using the model described earlier.

In the simulation runs, conditions of the variables used in the model are changed to execute sensitivity analyses. The model incorporate two policies: periodic maintenance and pro-active maintenance. The model allows users to choose either pro-active or periodic maintenance policies for tamping of ballast by MTT and for rail grinding. The model also performs other maintenance activities following pro-active maintenance policies. In this model, some periodic maintenance occurs at intervals as a function of cumulative tonnage over time, but since the tonnage remains practically constant over time, this approach becomes a purely periodic interval. In a periodic maintenance policy, users of the model choose the interval between maintenance.

When a pro-active maintenance policy is chosen, the model executes maintenance activities if the values that indicate defects go beyond a predetermined standard.

Cases studied in this chapter include one periodic maintenance case, one case combining periodic and pro-active maintenance, four pro-active maintenance cases, and a case that compares periodic and pro-active maintenance policies.

Table 6.1 Case studies in Chapter 6

Case #	Topic	Section
1	Periodic maintenance: Sensitivity analysis of MTT interval	6.2
2	Sensitivity analysis of rail grinding interval while having pro-active maintenance of MTT	6.3
3	Pro-active maintenance: sensitivity analysis of ballast replacement	6.4
4	Pro-active maintenance: Sensitivity analysis of Sigma Z	6.5
5	Pro-active maintenance: Sensitivity analysis of train speed	6.6
6	Pro-active maintenance: Optimization analysis	6.7
7	Comparison between two maintenance policies	6.8

## 6.2 Case 1: Periodic maintenance: Sensitivity analysis of MTT interval

This sensitivity simulation runs change the value of intervals of tamping activities (Variable: *MTT interval*) from 0.5 year to 3 years. This case performs sensitivity simulation runs with the conditions shown in Table 6.2. These conditions are similar to the simulation runs at 349 km conducted in Chapter 5. This analysis becomes the base case of the simulation and other cases follow the initial conditions except for some changes. Figure 6.1 shows the change of *Sigma y* (Standard deviation of track irregularity of longitudinal dimension) where *MTT interval* is one year. The highest peak of *Sigma y* is less than 1.4 mm, so the condition of the track is very in the entire length of the simulation.



Table 6.2 The conditions for case 1

Variables for initial conditions	value	Units	Variables for initial conditions	value	Units
<i>Sensitivity runs: MTT interval</i>	0.5 to 3	years	<i>Limit of Sigma y</i>	1.5	mm
<i>axle load</i>	12.5	t/axle	<i>MTT interval</i>	1	years
<i>axle per veh</i>	4	axles/v	<i>MTT policy</i>	Periodic	NA
<i>ballast deterioration limit</i>	1		<i>Radius</i>	2500	meters
<i>ballast height</i>	30	cm	<i>Rail grinding policy</i>	Periodic, 1	year
<i>Cant</i>	0.18	m	<i>Rail replacement tonnage</i>	1.1E+09	tons
<i>CorrectionCoefficient</i>	2		<i>Rail roughness</i>	0.3	mm
<i>discount rate</i>	0.06	%	<i>Traffic</i>	140	trains/day
<i>Gauge</i>	1.435	m	<i>Train speed</i>	200	km/h
<i>Grinding interval</i>	1	years	<i>Unit cost of ballast</i>	3,000	Yen/m <sup>3</sup>
<i>HG</i>	1.5	m	<i>Unit cost of Ballast replacement</i>	108,000	Yen/m
<i>Initial ballast deterioration</i>	0.6		<i>Unit cost of Manual tamping</i>	4,840,000	Yen/km
<i>Initial ballast tonnage</i>	4E+08	t	<i>Unit cost of MTT tamping</i>	900,000	Yen/km
<i>Initial rail tonnage</i>	4E+08	t	<i>Unit cost of Rail</i>	14,700	Yen/m
<i>Initial Settlement</i>	1.885273	t	<i>Unit cost of Rail grinding</i>	150,000	Yen/km
<i>Initial tie tonnage</i>	8E+08	t	<i>Unit cost of Rail replacement</i>	17,400	Yen/m
<i>lx</i>	3.09E-05	m <sup>4</sup>	<i>Unit cost of Tie</i>	7,700	Yen
<i>ly</i>	5.12E-06	m <sup>4</sup>	<i>Unit cost of Tie pad</i>	500	Yen
<i>K1</i>	153.4649	kN	<i>Unit cost of Tie replacement</i>	57,300	Yen/tie
<i>K30</i>	110	MN/m	<i>vehicles per train</i>	16	cars
<i>kappa</i>	0.3		<i>Db</i>	200	MN/m
<i>kv</i>	0.001	m/s <sup>2</sup> /mm/(km/h)	<i>Dp1</i>	182	MN/m
<i>KZ</i>	0.001	m/s <sup>2</sup> /mm/(km/h)	<i>Ds</i>	85	MN/m
<i>limit of Rail roughness</i>	0.7	mm			

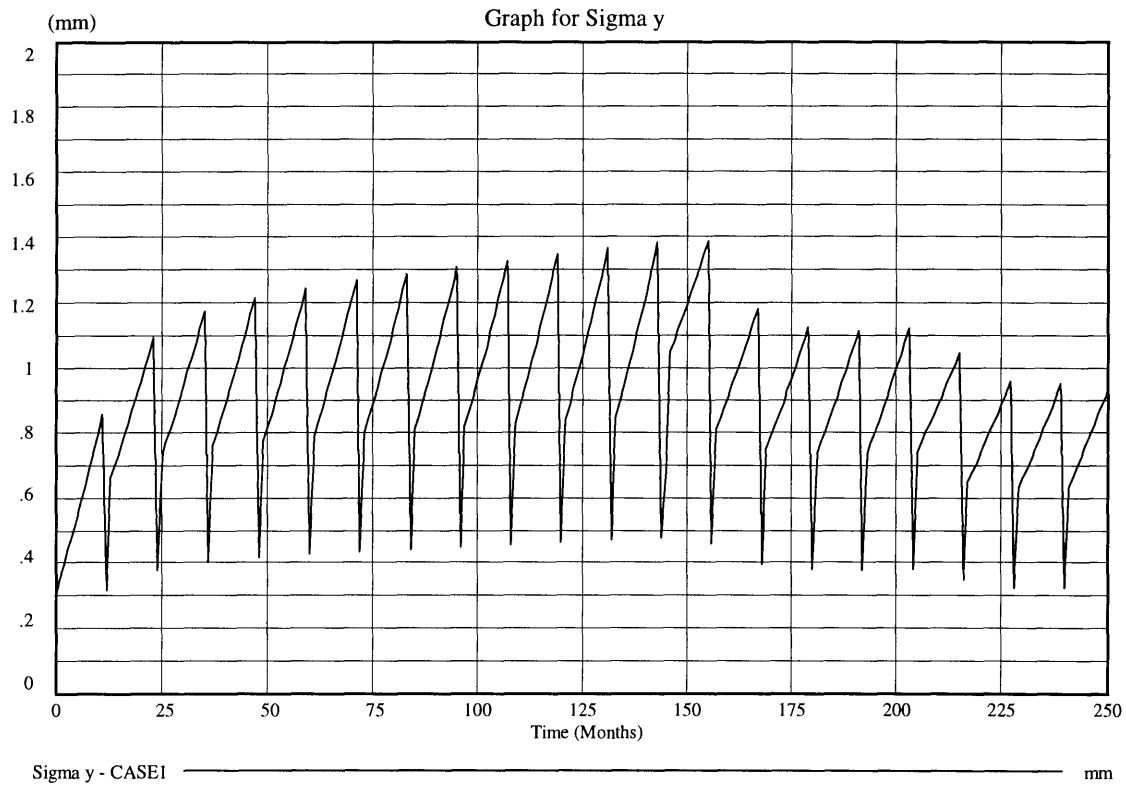


Figure 6.1 Case 1:  $\sigma_y$  in base simulation ( $MTT$  interval = 1year)

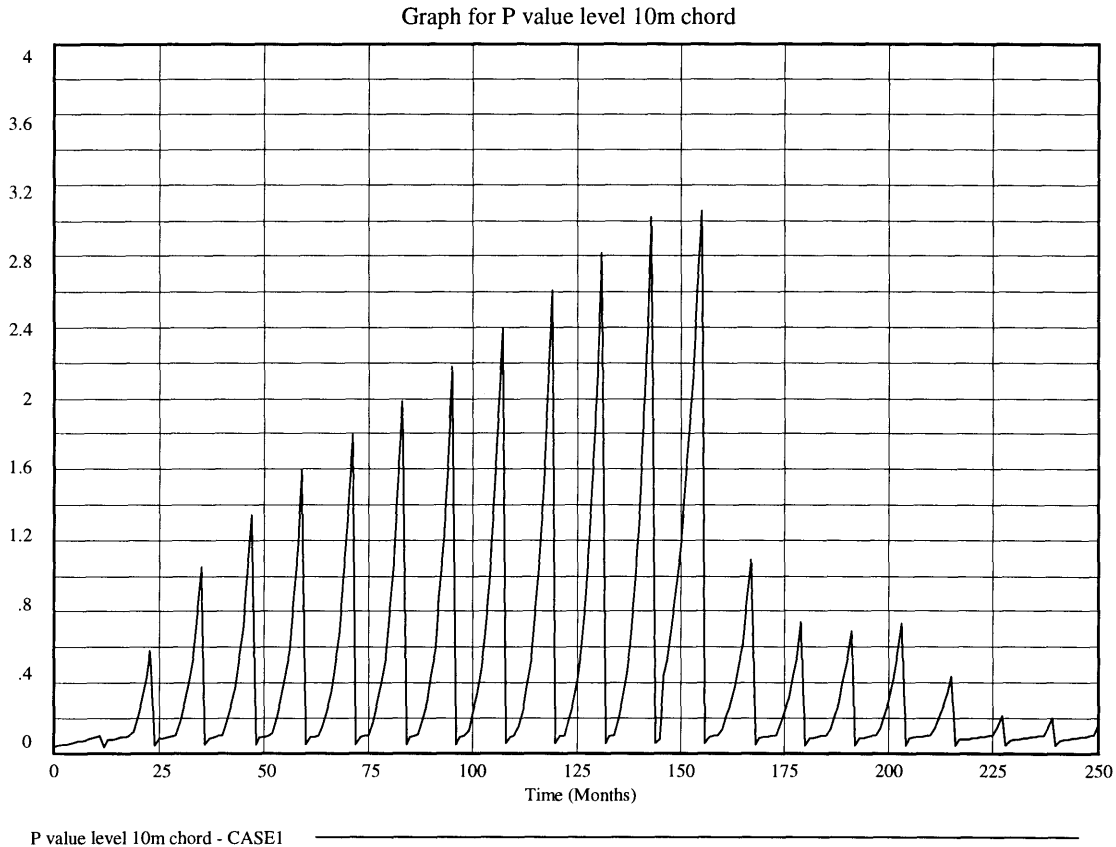


Figure 6.2 Case 1: *P-value* in: base simulation (*MTT interval* = 1 year)

Figure 6.2 shows the 10m chord *P-value* of longitudinal dimension. The *P-value* is lower than 3 in most months and this shows it is in a good condition. At around month 160, ballast is replaced in the simulation, and the increase of track irregularity slows down after that period, which can be found in both Figure 6.1 and Figure 6.2. At around month 205, rail is replaced and this also decrease the growth of track irregularity after the rail replacement because of the replacement of tie pad that is executed at the same time. The *cumulative tonnage of tie pad* influences the spring coefficient of tie pads (*Dp1*). The sensitivity simulation runs change the value of *MTT interval* from 0.5 year to 3.0 years in 0.1 month steps for 26 runs . Figure 6.3 is the results of the sensitivity runs showing *Sigma y* for representative values of *MTT interval*. Lines with or without patterns show four

simulations runs with different *MTT intervals*. The highest allowed limit of *Sigma y* is about 1.5 mm for High-Speed Rail operation, as the highest allowable value of track irregularity for Shinkansen is 9 mm (assumed that the largest value of track irregularity is six times as high as that of *Sigma y*, from the relationship of normal distribution). An *MTT interval* longer than 1.3 year goes beyond the limit. However, the value of *Sigma y* stay below the limit after the ballast is replaced. This implies that the *MTT interval* can be longer when the values of *cumulative ballast tonnage* or ballast deterioration are small.

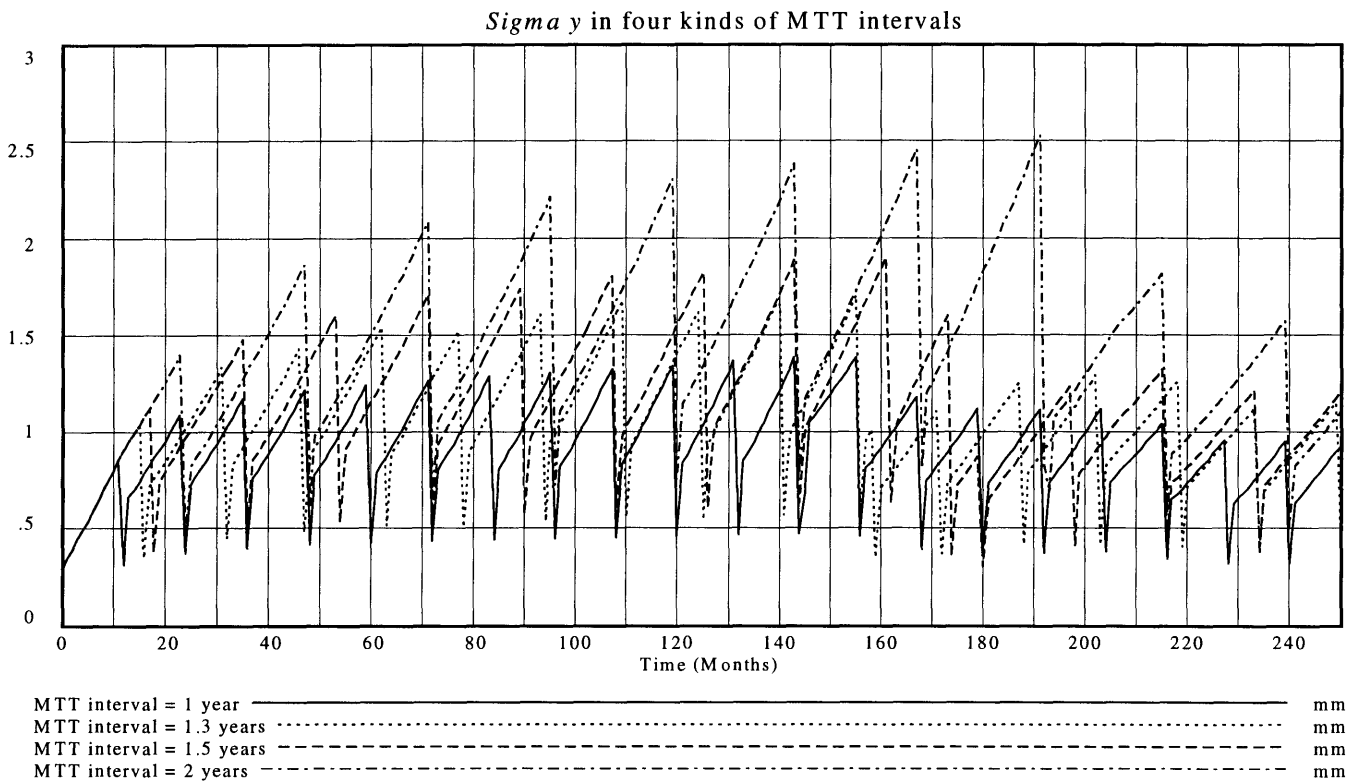


Figure 6.3 Case 1: Sensitivity simulation result of *Sigma y*. *MTT interval* = 3 years is eliminated it takes beyond the allowable limit of 1.5mm.

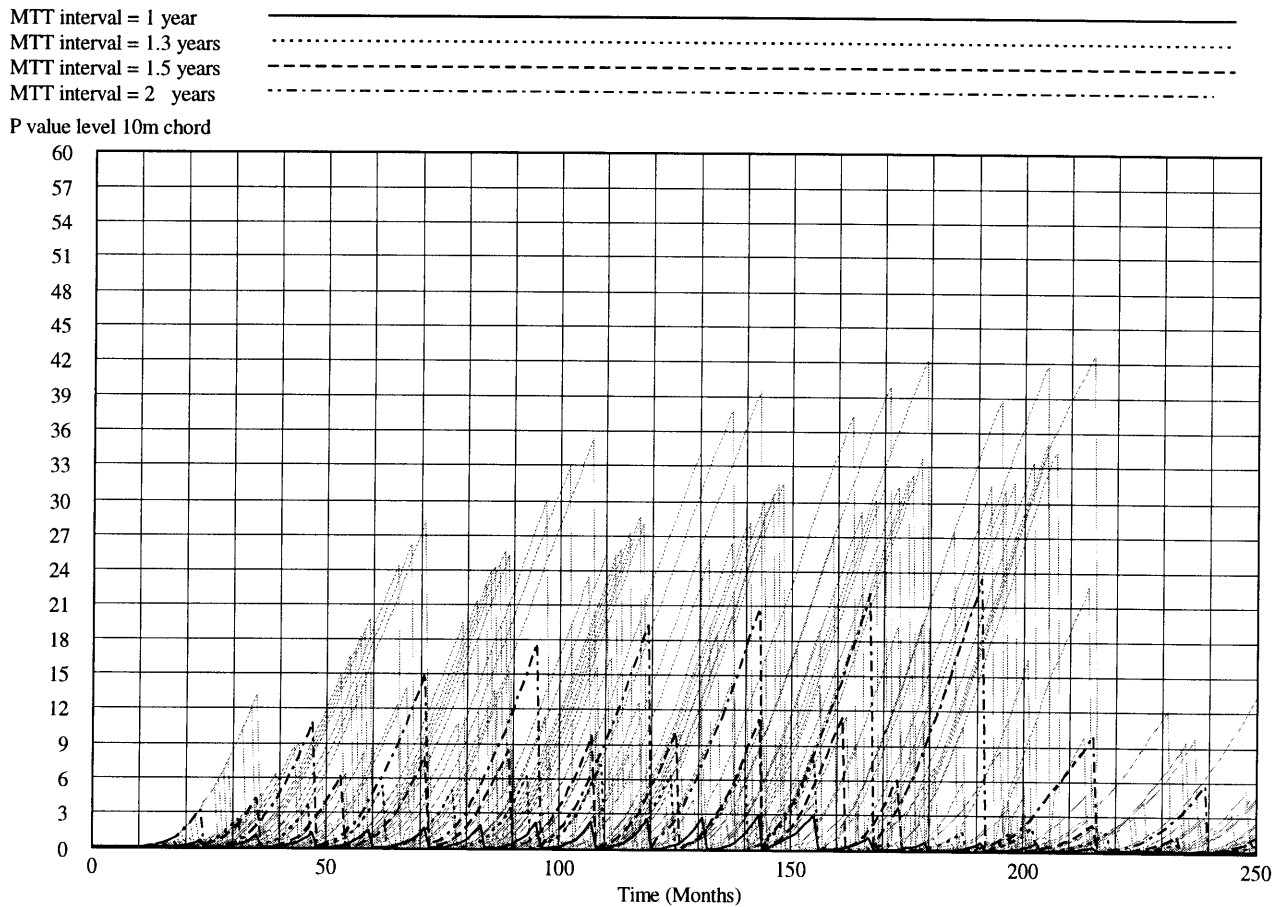


Figure 6.4 Case 1 : Sensitivity simulation result of *P-value(10m chord, level)*: MTT interval is changed between 0.5 to 3 years

Figure 6.4 shows the result of the P-values sensitivity runs. The variation of the P-values is from zero to 42, depending on the *MTT interval*. The P-values (10m chord, level) should stay below five in actual high-speed rail operations, as the P-value=5 is equivalent to the  $\Sigma y = 0.5$  (See Table 5.4). Therefore only *MTT interval = 1 (year)* meet this standard over entire simulation period.

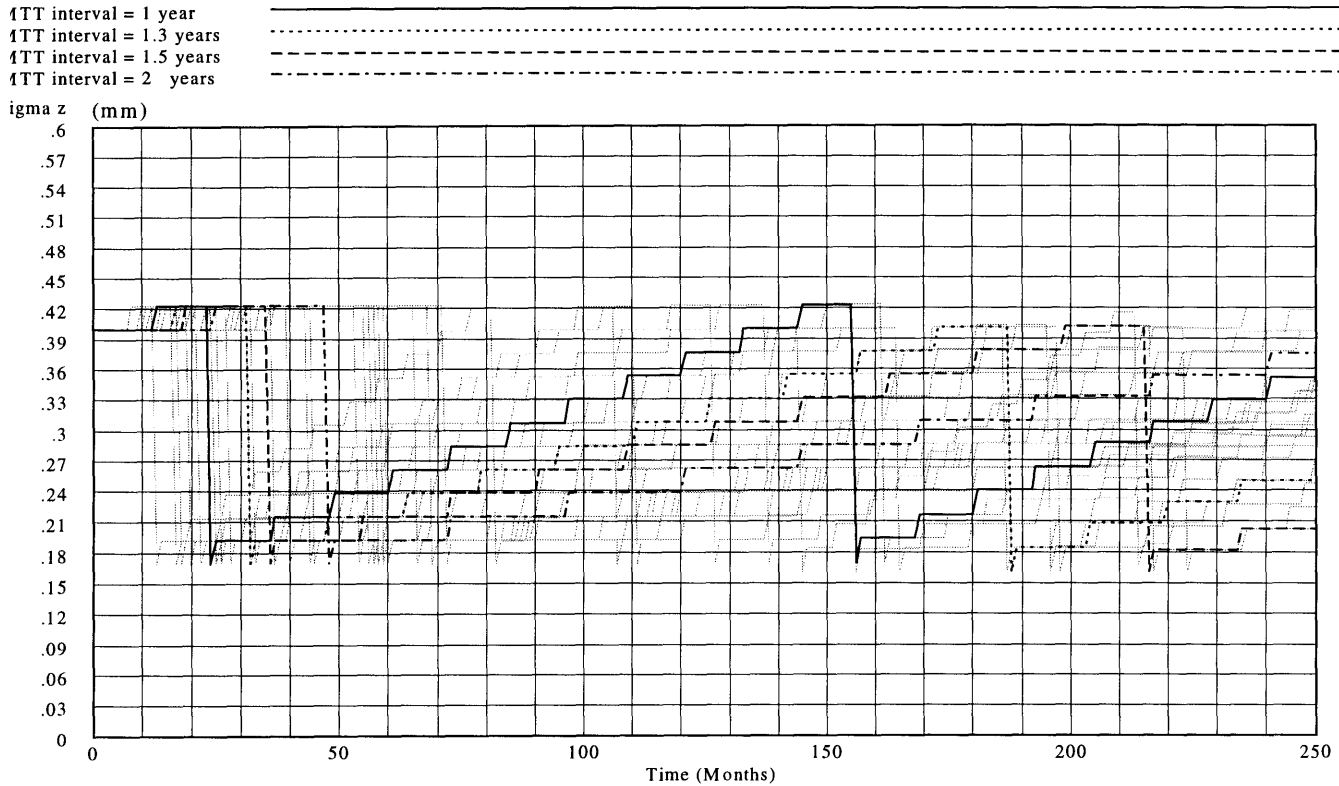


Figure 6.5 Case 1: Sensitivity simulation result of  $\sigma z$ :

Figure 6.5 shows the result of  $\sigma z$  (standard deviation of track irregularity in horizontal dimension). Thick lines with/without patterns show representative values of MTT intervals, while gray lines show other sensitivity runs. In these runs,  $\sigma z$  always stays below 0.42 mm. An interesting point in this result is that the increases in track irregularity occur only during the initial deformation process which immediately follows tamping activities by MTT. In the gradual deformation process, horizontal movement of track does not occur when the vertical force applied to the track is large compared with the horizontal force applied to the track (see Equation (4.30) in 4.5.2). This may be one of the reasons why the 10m chord P-value in the real track discussed in section 5.1.2 (p.113, Figure 5.4, P-value 10m chord line right) never varied from zero during the period of observation. As the

conditions of the simulation runs are similar to those at 349 km in the real track, and the 10m chord P-value of horizontal dimension stays at zero (see Figure 5.4).

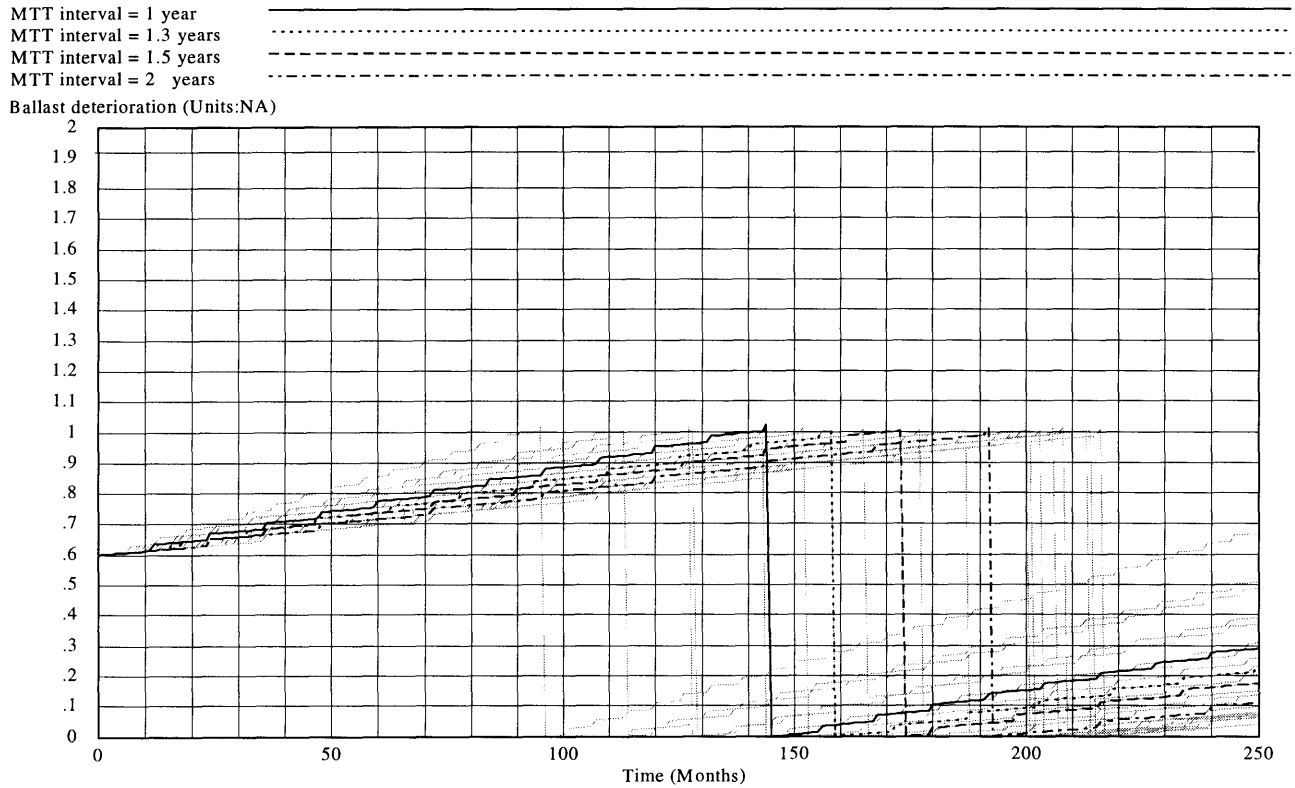


Figure 6.6 Case 1: Sensitivity simulation result of *Ballast Deterioration*

Figure 6.6 shows *Ballast Deterioration* sensitivity runs. It is found that the longer the MTT interval, the slower the progress of *Ballast Deterioration*. This fact implies that tamping activities should be performed as infrequently as possible in order to minimize the deterioration of ballast.

However, there is another factor. If the tamping activities are performed infrequently, the track will have more track irregularity (larger values of  $\sigma_y$ ,  $\sigma_z$  and  $P$ -values).

Then the ballast will have more deterioration because of the increased force applied to the track due to increasing dynamic wheel loads.

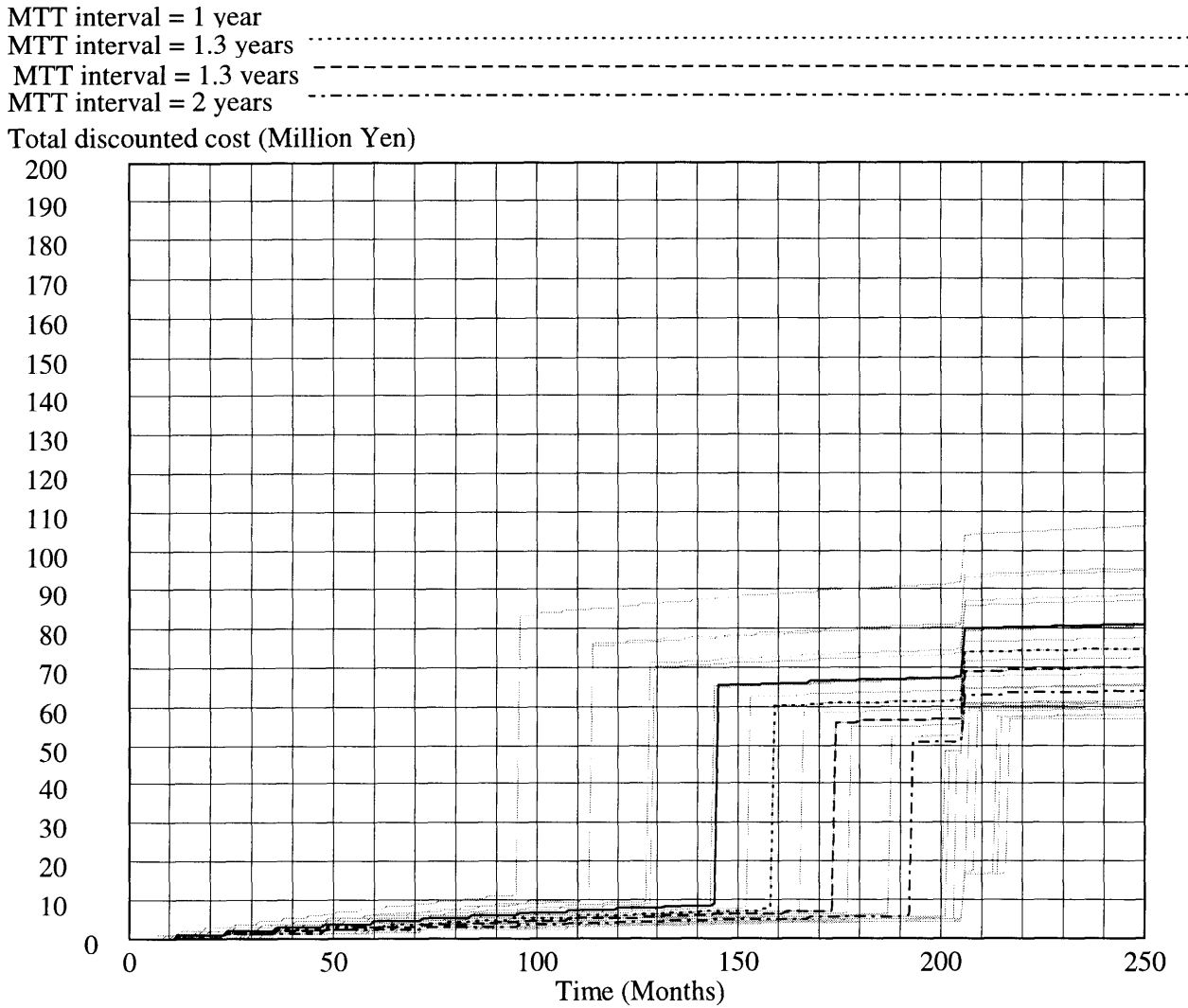


Figure 6.7 Case 1: Sensitivity simulation result of *Total discounted cost*

Figure 6.7 shows *Total discounted cost* sensitivity runs. The graph shows the cumulative values, so the cost shown for a particular month means the total discounted cost up to that month. The cost becomes low when the MTT interval is large. However, the bigger the



MTT interval, the lower the QF in terms of track irregularity becomes, as is shown in the graphs of Figure 6.3 and Figure 6.4. It should be reminded that higher values of both Sigma  $\sigma$  and P-value mean lower QF. Therefore, QF in terms of track irregularity and the *total discounted cost* must be traded off against each other. Lower QF can mean poor ride quality and even safety problem in extreme cases.

### **Summary of Case 1**

In terms of costs, the model gives an intuitive result; the better the quality, the higher the maintenance cost becomes. However, inefficiency often appeared in this case; the model sometimes performed tamping activities even though the track irregularity was below the desired level to start maintenance. If a good information system that stores the history of maintenance and track condition is available, track engineers can change the interval of tamping activities, thus reducing maintenance costs.

### **6.3 Case 2: Sensitivity analysis of rail grinding interval given pro-active MTT maintenance**

In this case study, the model changes the values of *grinding interval* as a sensitivity analysis. Rail grinding makes the railhead surface smooth. That reduces the forces applied to the track, and moderates the settlement and movement of track. Rail grinding eliminates short wavelength irregularity of track. It also lengthens the rail life, as it removes the minor shelling and cracks that can turn into larger defects that requires rail replacement. It also eliminates noise, which can be an environmental concern, by removing corrugations.

The initial conditions of the simulation runs are the same as those in base simulation of Case 1. However, the tamping of ballast is performed with the pro-active maintenance policy. So the tamping activities are performed when the value of  $\sigma_y$  goes above 1.3 mm, which is input as a threshold value described as the *limit of  $\sigma_y$* . In the sensitivity analysis, the value of rail grinding interval (*Grinding interval*) is varied from one year to ten years with steps of 0.5 years (19 runs). The life span of rail is determined by the cumulative tonnage (see p. 95).

Table 6.3 Conditions of Case 2

Name of the variable	Value	Units	Name of the variable	Value
<i>grinding interval (sensitivity runs)</i>	1-10	years		
<i>axle load</i>	12.5	tons	<i>MTT interval</i>	1 year
<i>axle per veh</i>	4	axles	<i>MTT policy (0: pro-active)</i>	0 NA
<i>ballast deterioration limit</i>	1	NA	<i>Radius</i>	2,500 m
<i>ballast height</i>	30	cm	<i>Rail replacement tonnage</i>	1.1E+09 tons
<i>Cant</i>	0.18	m	<i>Rail roughness</i>	0.3 mm
<i>CorrectionCoefficient</i>	2	NA	<i>Traffic</i>	140 trains/day
<i>discount rate</i>	6	%	<i>Train speed</i>	200 km/h
<i>Gauge</i>	1.435	m	<i>Unit cost of ballast</i>	3,000 yen/m <sup>3</sup>
<i>Grinding interval</i>	1	year	<i>Unit cost of Ballast replacement</i>	108,000 yen/m
<i>HG</i>	1.5	m	<i>Unit cost of MTT tamping</i>	900,000 yen/km
<i>Initial ballast deterioration</i>	0.6	NA	<i>Unit cost of Rail</i>	14,700 yen/m
<i>Initial ballast tonnage</i>	4E+08	tons	<i>Unit cost of Rail grinding</i>	150,000 yen/km
<i>Db</i>	200	MN/m	<i>Unit cost of Rail replacement</i>	17,400 yen/m
<i>Dp1</i>	182.09	MN/m	<i>Unit cost of Tie</i>	7,700 yen
<i>Ds</i>	85.05	MN/m	<i>Unit cost of Tie pad</i>	500 yen
<i>Ix</i>	3.09E-05	m <sup>4</sup>	<i>Unit cost of Tie replacement</i>	57,300 yen/tie
<i>Iy</i>	5.12E-06	m <sup>4</sup>	<i>vehicles per train</i>	16 cars/train
<i>K30</i>	110	MN/m	<i>Rail grinding policy</i>	1 NA
<i>kappa</i>	0.3	NA	<i>Initial Settlement</i>	1.885273 mm
<i>KH</i>	0.632		<i>Initial rail tonnage</i>	4E+08 tons
<i>kv</i>	0.001		<i>Initial tie tonnage</i>	8E+08 tons
<i>KZ</i>	0.001		<i>Db</i>	200 MN/m
<i>limit of Rail roughness</i>	0.7	mm	<i>Dp1</i>	182.09 MN/m
<i>Limit of Sigma y</i>	1.3	mm	<i>Ds</i>	85.05 MN/m

Figure 6.8 shows the *rail roughness* given various values of *grinding interval* from sensitivity runs. The longer the *grinding interval*, the more the peak values of *Rail roughness* become. In accordance with the behavior of rail roughness, the forces applied to the track (*dynamic wheel load out*) show a similar behavior (Figure 6.9). The increase of rail roughness promotes track irregularity due to the increase of forces applied to the track.

CASE2 \_\_\_\_\_  
CASE2-2 .....  
CASE2-3 - - - -  
CASE2-5 - - - -

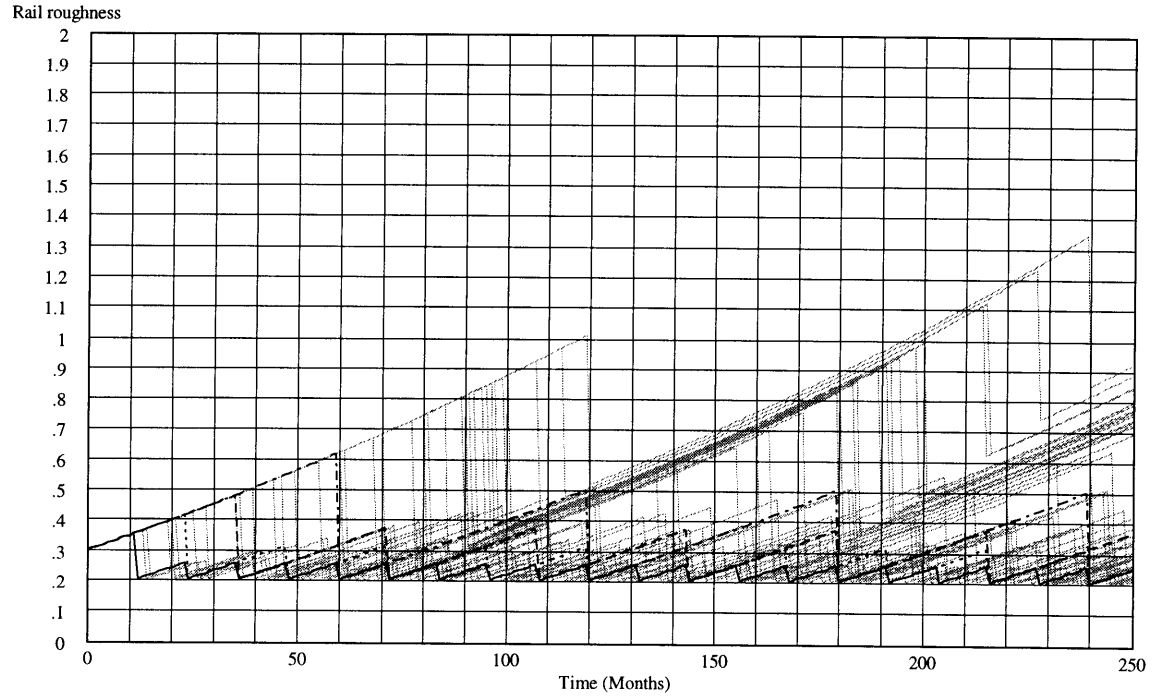


Figure 6.8 Case 2: Sensitivity simulation result of *rail roughness*: Thick lines show representative case with different grinding intervals, and gray lines are other simulation results

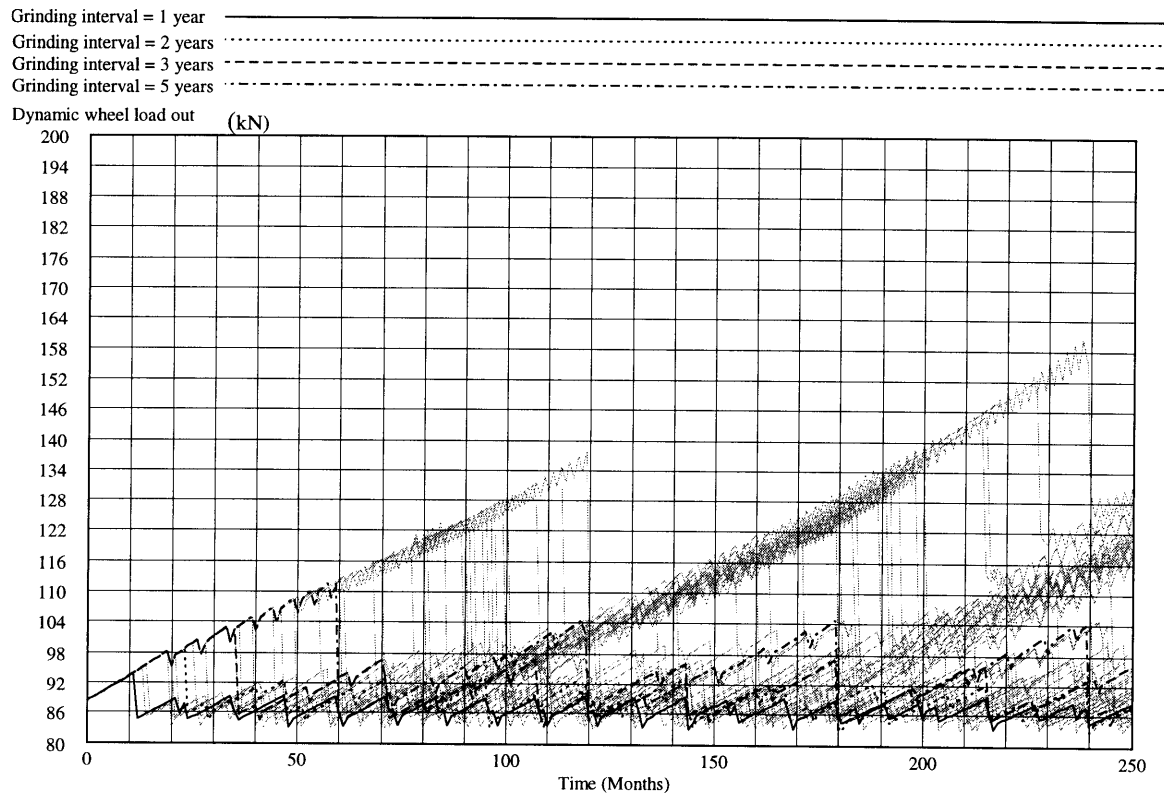


Figure 6.9 Case 2: Sensitivity simulation result of *Dynamic wheel load out*: When the grinding interval is long, the values dynamic wheel loads become bigger due to bigger rail roughness.

Figure 6.10 shows a simulation result showing the change of  $\sigma_y$  with four different values of grinding intervals: one, two, three and five years. As the graph shows, slopes of the curves for the longer period of grinding intervals are generally steeper in the gradual deformation process. For example, the slope of  $\sigma_y$  with *grinding interval* of five years is bigger in the gradual deformation process between month 160 and 180 than with smaller intervals, before the rail grinding is performed. This means that track irregularity progresses more rapidly when the rail roughness is larger, because of amplified forces applied to the rail due to the rail roughness.

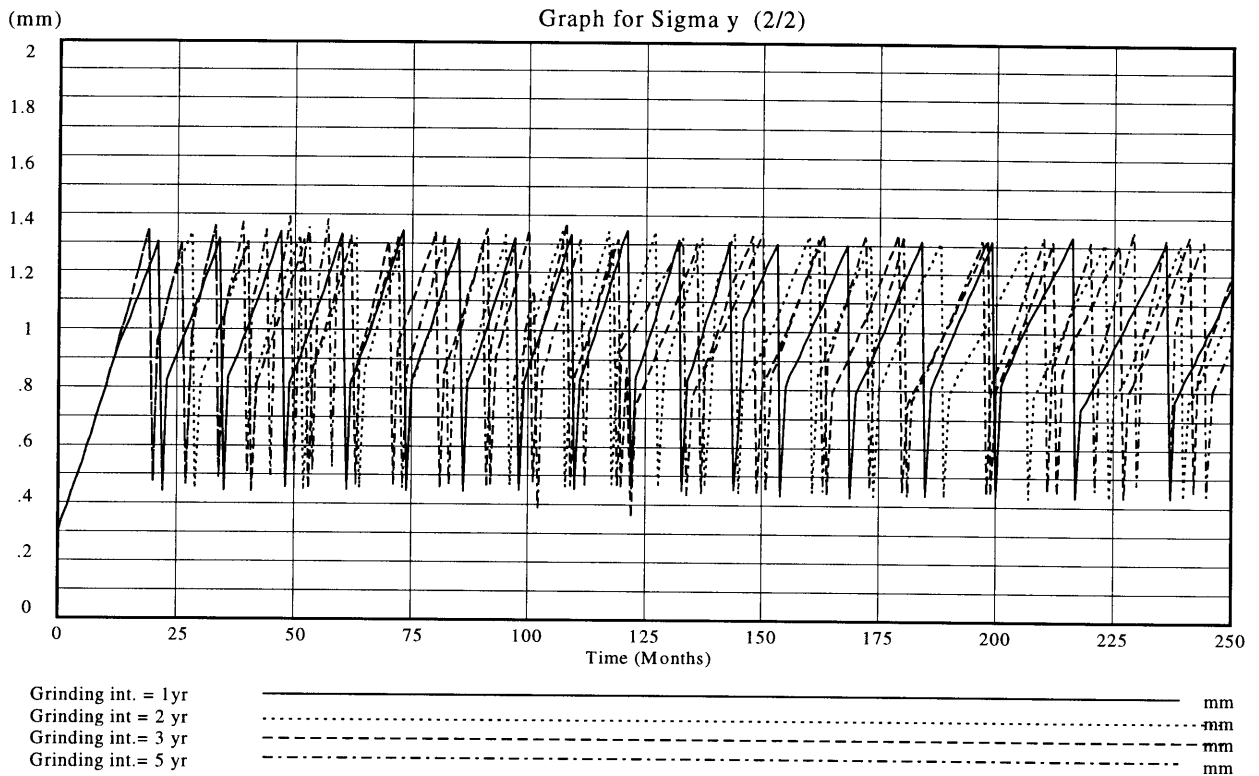
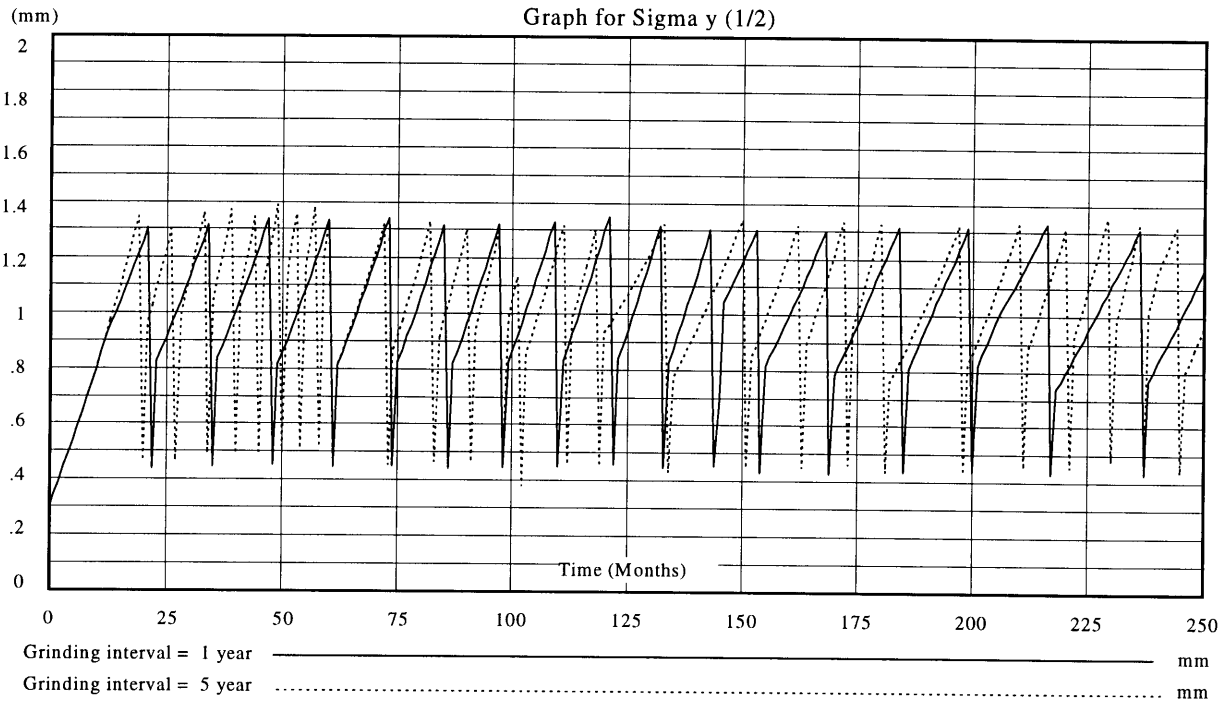


Figure 6.10 Case 2: A simulation result of Sigma y in four different grinding intervals

Figure 6.11 is a result of sensitivity simulation runs showing the values of *Ballast deterioration*. *Initial ballast deterioration* is 0.6 in all the runs in this case. However, the longer the grinding interval, the sooner the ballast deterioration reaches 1.0. Larger wheel loads due to rail roughness leads to faster increase in the track irregularity. Slopes of curves change over time even in one simulation run with a particular grinding interval. This is because *ballast deterioration* is influenced by  $Pt$ , which is also influenced by various variables, such as dynamic wheel load and the tie pads replacement policy.

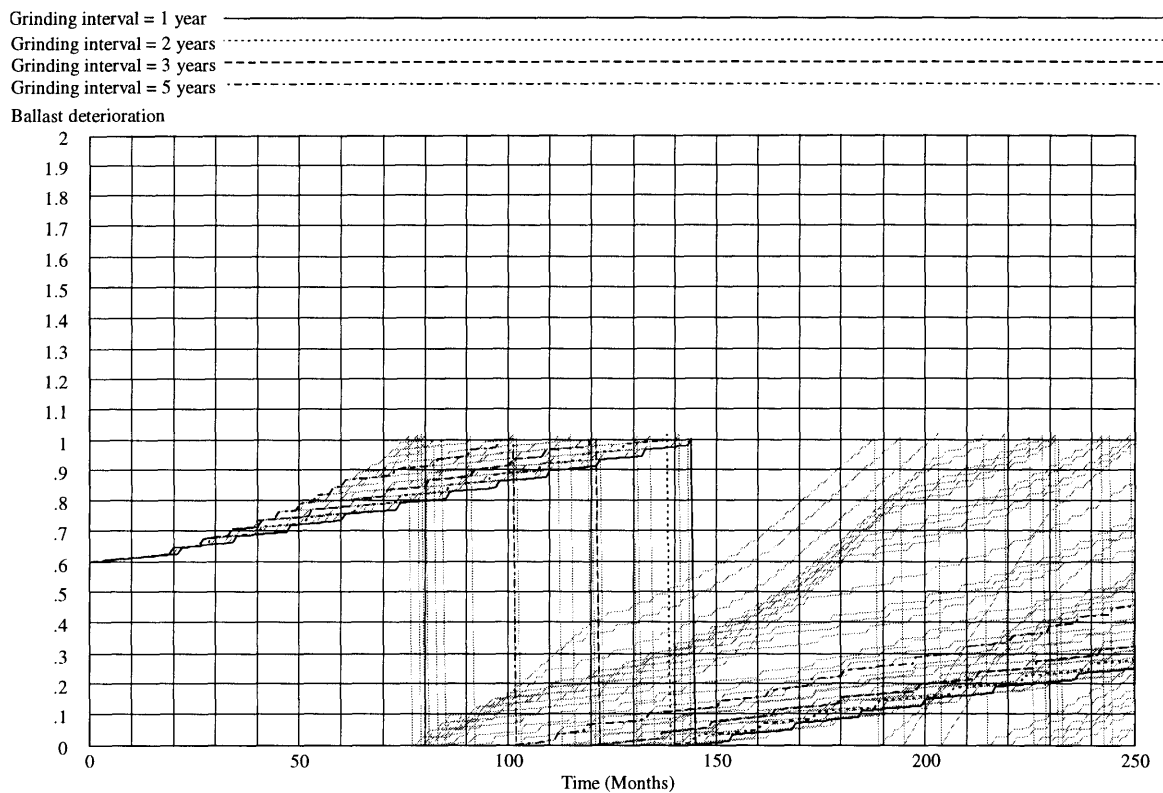


Figure 6.11 Case 2: Sensitivity simulation result of Ballast deterioration

Figure 6.12 shows the sensitivity simulation results of cumulative rail tonnage. The rail life depends on the grinding interval (discussed on p.95) in this model. So the model replaces the rail earlier if the rail grinding interval is longer.

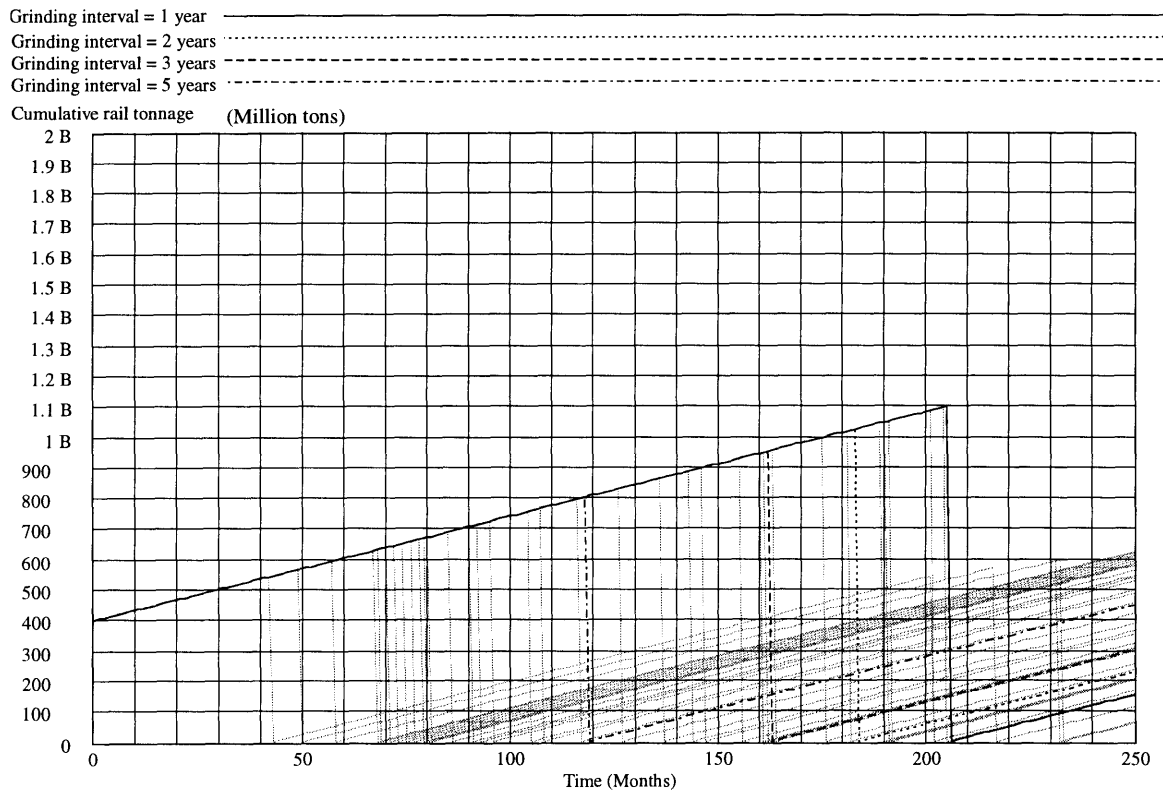


Figure 6.12 Case 2: Sensitivity simulation result of *Cumulative rail tonnage*

Figure 6.13 shows the *total discounted cost* over time in each simulation run. The cost is the smallest when the grinding interval is one year, in all runs and over all months of the simulation. Even though it takes a substantial amount of money to grind rail, rail grinding pays because of the reduction of costs for ballast replacement and rail replacement. This result is quite different from the result of case 1. In case 1, frequent maintenance (MTT tamping) is more costly than infrequent maintenance, although infrequent tamping leads to



the degradation of the track in terms of track irregularity. The rail grinding does not worsen the quality of rail but rather lengthens its life by eliminating causes of shelling and cracks. Kuroda reported that rail grinding should be performed every 40 million tons, as the initial stage of shelling that can be removed by rail grinding appears around that tonnage.<sup>43</sup> More frequent rail grinding will be costly, because increased operating costs due to rail grinding do not lead to significant cost reduction due to less frequent ballast and rail replacement.

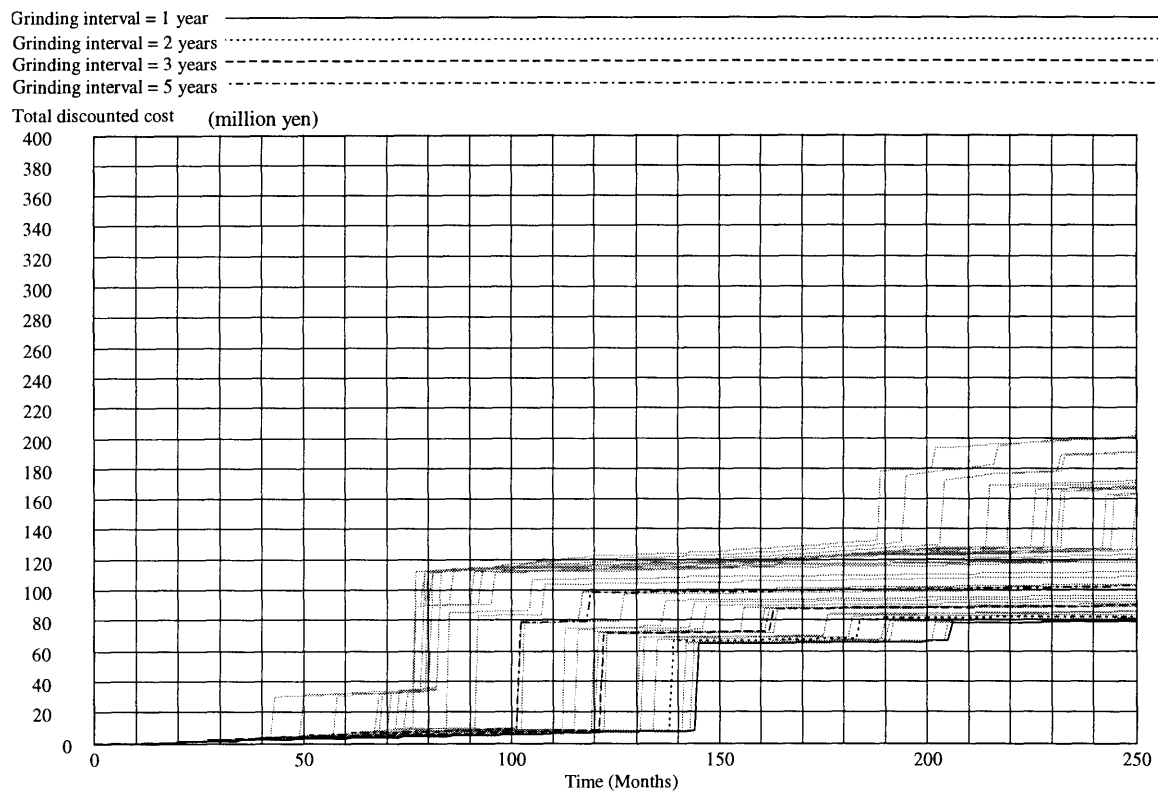
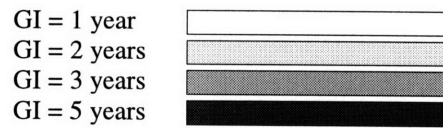


Figure 6.13 Case 2: Sensitivity simulation result of *Total discounted cost*

<sup>43</sup> Kuroda, Y.: Rail shelling of Shinkansen, Japan Rail Civil Engineering Association, December 1996, JRCEA, Tokyo, Japan

## Summary of Case 2

Unlike the result of Case 1, the most frequent grinding gave the most economical result. This is because the rail grinding does not harm the quality of the material (material), but rather improves it. That contrasts with tamping which improves track geometry but damages the ballast material. The influence of different parameters brought different results. Frequent maintenance is more economical than infrequent maintenance for rail grinding.



Total discounted cost @ Month250

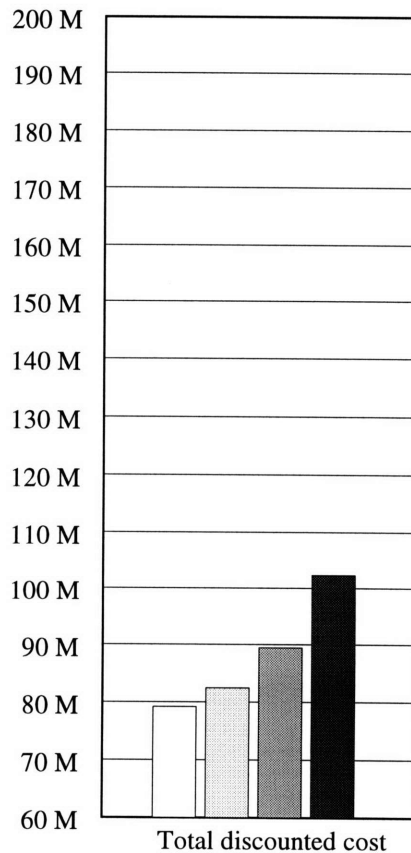


Figure 6.14 Total discounted cost at the end of simulation runs (Units: Yen, discount rate: 6%)

## 6.4 Case 3: Pro-active maintenance: sensitivity analysis of ballast replacement

In this case, the model changes the value of *Ballast deterioration limit*. *Ballast deterioration limit* is a threshold value of ballast deterioration that makes the model perform ballast replacement. The replacement of ballast is the most costly activity in the track

Table 6.4 Case 3: Initial conditions of the simulation

Variables for initial conditions(units)	initial value	Variables for initial conditions	value
axle load (tons)	12.5	kv (m/s <sup>2</sup> /mm/(km/h))	0.001
axle per veh (axles)	4	KZ (m/s <sup>2</sup> /mm/(km/h) )	0.001
Ballast deterioration (NA)	0.4	limit of Rail roughness (mm)	0.7
ballast deterioration limit(NA)	1	Limit of Sigma y (mm)	1.3
ballast height (cm)	30	MTT interval (years)	1
Cant (m)	0.18	MTT policy (0 for pro-active)	0
CorrectionCoefficient (NA)	2	Radius (m)	2500
discount rate (%)	6	Rail replacement tonnage (tons)	1.1E+09
Gauge (m)	1.435	Rail roughness (mm)	0.3
Grinding interval (years)	1	Traffic (trains/day)	140
HG (m)	1.5	Train speed (km/h)	200
l	0.2	Unit cost of ballast (yen/m <sup>3</sup> )	3000
Initial ballast deterioration (NA)	0.4	Unit cost of Ballast replacement (yen/m)	108000
Initial ballast tonnage (NA)	4E+08	Unit cost of MTT tamping (yen/km)	900000
Db (MN/m)	200	Unit cost of Rail (yen/m)	14700
Dp1 (MN/m)	182.09	Unit cost of Rail grinding (yen/km)	150000
Ds (MN/m)	85.05	Unit cost of Rail replacement (yen/m)	17400
lx (m <sup>4</sup> )	3.09E-05	Unit cost of Tie (yen)	7700
ly (m <sup>4</sup> )	5.12E-06	Unit cost of Tie pad (yen)	500
K30 (MN/m)	110	Unit cost of Tie replacement (yen/tie)	57300
kappa (NA)	0.3	vehicles per train (cars/train)	16
KH (m/s <sup>2</sup> /mm/(km/h))	0.632	Rail grinding policy (1 for periodic)	1

maintenance. However, *track settlement* gets larger when the ballast is old. That increases the cost of tamping of ballast to maintain the quality of the track geometry. These two factors, cost of ballast replacement and the cost of tamping, must be traded off against each other.

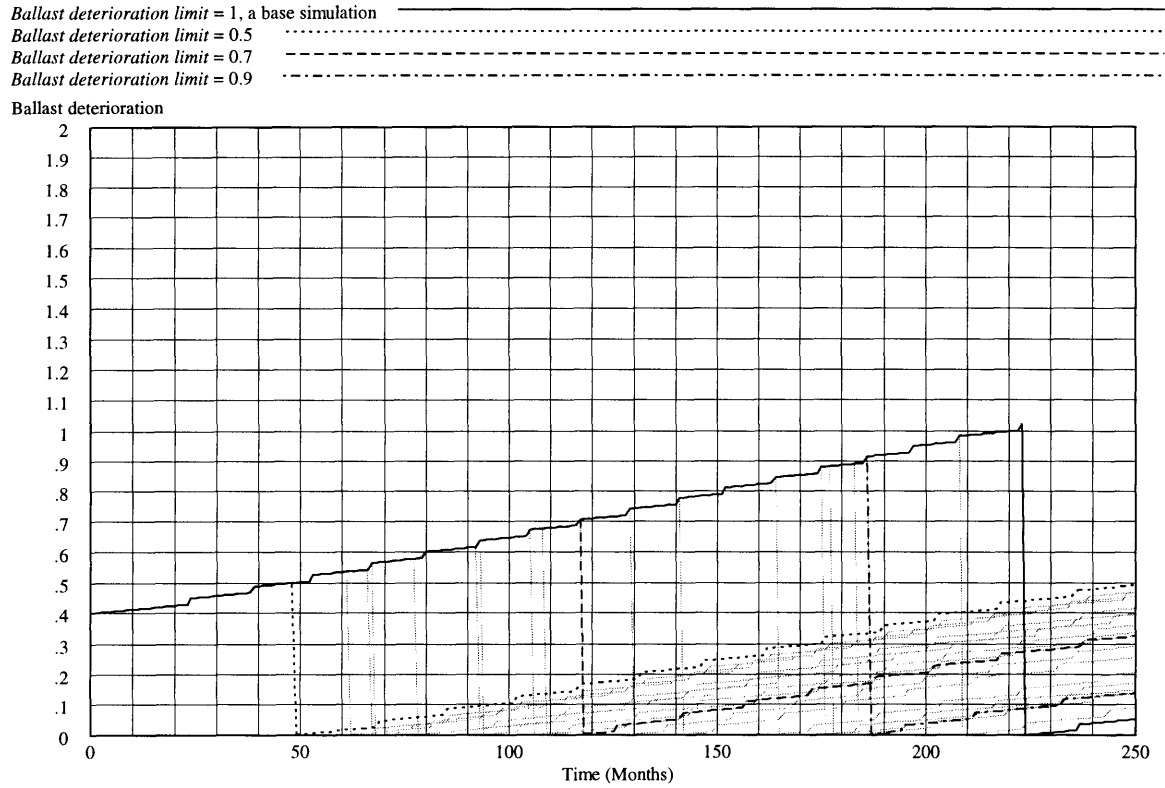


Figure 6.15 Case 3: Sensitivity simulation result of *Ballast deterioration*

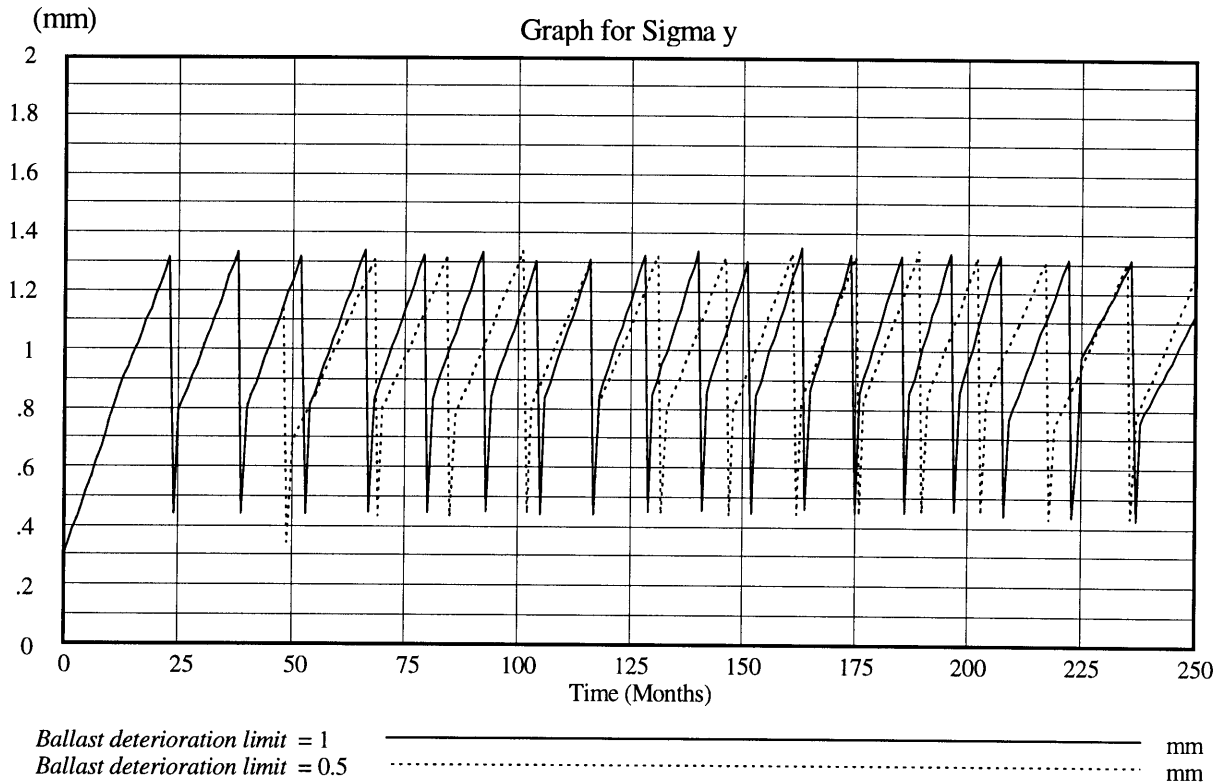


Figure 6.16 Sigma y when *Ballast deterioration limit* = 1, 0.5

Figure 6.16 shows a result of simulation runs with two different values of the *Ballast deterioration limit (LBD)*. When the *LBD* is 0.5, ballast was replaced at Month 49. After Month 49, slope of Sigma y is less steep in *LBD* = 0.5, as the ballast is newer than that of *LBD* = 1. Number of tamping activities is smaller for *LBD*=0.5 than for *LBD* = 1.

Figure 6.17 shows the *total discounted cost* sensitivity runs. In this analysis, the total cost is the lowest when the value of *LBT* = 1. The decrease in the number of tamping activities as a result of earlier replacement of ballast for *LBD* = 0.5 did not fully compensate for the increased cost of ballast replacement because of the shift to the earlier period. The costs are discounted in six percent per year to calculate the present value.



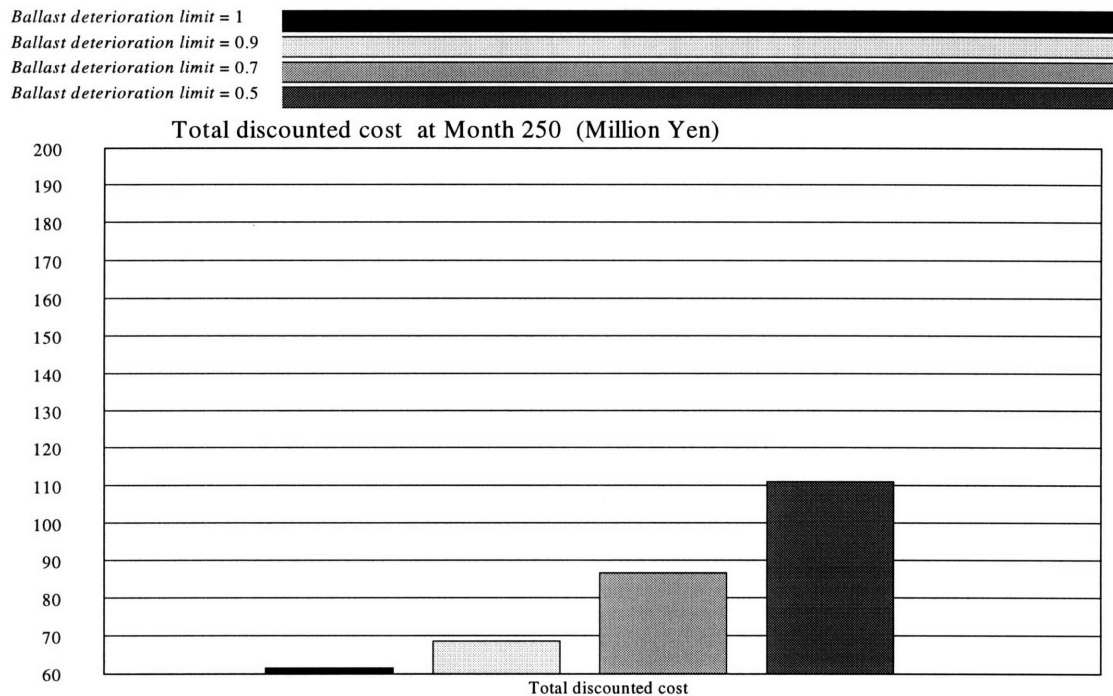


Figure 6.18 Case 3: Comparison of total discounted cost at the end of simulation runs for four cases

### **Summary of Case 3**

As the replacement of ballast is the most costly part of track maintenance, it is better to replace ballast as infrequently as possible. The lowest cost was given in the simulation runs when the *LBD* is equal to 1.0; the cost for ballast replacement is about 40 million Yen out of total cost of 63 million Yen. In other runs, the fraction of cost that is due to ballast replacement is even larger. As about two-thirds of the whole maintenance cost is spent for ballast replacement, cost reduction for the ballast replacement and extending the life of ballast is extremely important in order to attain lower maintenance cost.

However, gaining longer ballast life is very difficult, as railroad companies generally use cheap locally available materials for the ballast. The railroad track is then unavoidably damaged by the train loads. Then track engineers carefully select materials that are easy to

replace and maintain. When track engineers design a new type of track that is more resistant to the deterioration, they still have to be careful about maintenance and replacement.

The automation of ballast excavation and replacement mentioned in Chapter 2 helped reduce maintenance cost. However, the materials that support the track have not changed except for the unconventional track using concrete slab or solid bed track, which is used mainly in Japanese High-Speed Rail. The scope of this study does not cover the economics of unconventional track, but the analysis of track bed or ballast should be carefully examined in the design of the new tracks.



## 6.5 Case 4: Pro-active maintenance: Sensitivity analysis for the *limit of Sigma y*

In this case study, the model changes the values of the *limit of Sigma y* in a sensitivity analysis. *Sigma y* shows the standard deviation of track irregularity of level (longitudinal dimension) in the 10 m chord measurement. The main method of managing the quality of track geometry in Japan is the use of P-values, as it is easier to calculate values from the measurement of actual tracks. However, *Sigma y*, or the standard deviation of track irregularity, is a more useful method of managing the track's geometrical defects for the High-Speed Rail operations, because the track irregularity grows almost linearly over time in the measurement of *Sigma y* in the gradual deformation process. *Sigma y* is a variable that gives values to other variables in the model equations of this study, while P-value can be calculated only from *Sigma y*. *Sigma y* shows the condition of the track more directly than P-values.

In the sensitivity runs, the *Limit of Sigma y* is changed from 0.5 mm to 2.0 mm in steps of 0.05 mm over 31 runs<sup>0</sup>. The *Limit of Sigma y* is a threshold value that makes the model perform MTT tamping to improve track geometry. Other conditions are the same as those of Case 1, except this case takes a pro-active maintenance policy for MTT tamping. Figure 6.19 shows a result of simulation for *Sigma y* with four different *Limit of Sigma y*. It is found that the higher the limit of *Sigma y*, the higher the value of *Sigma y* right after the tamping activities by MTT. This model assumes that the track irregularity reduces by two thirds due to MTT tamping. Track engineers know from their experiences that tracks in

poor conditions are more difficult to recover to tracks in good conditions (of track geometry). It is consistent with this intuitive thought.

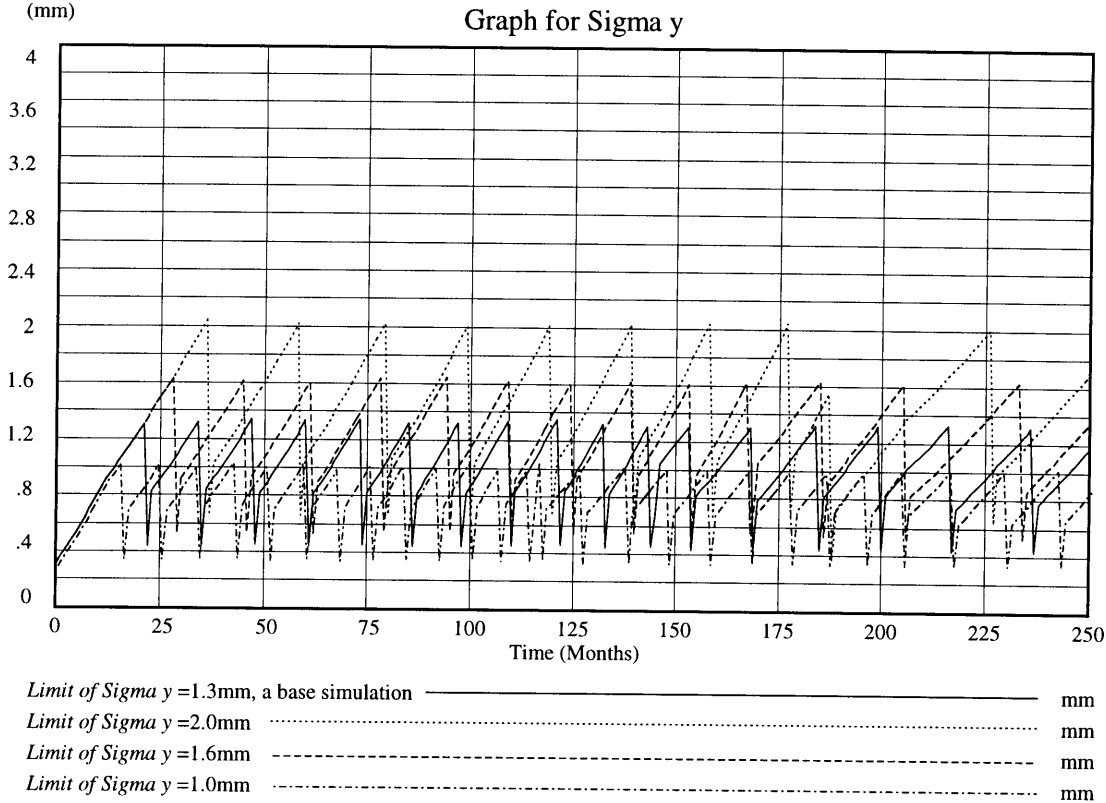


Figure 6.19 Case 4: Simulation result of  $\sigma_y$  different threshold values

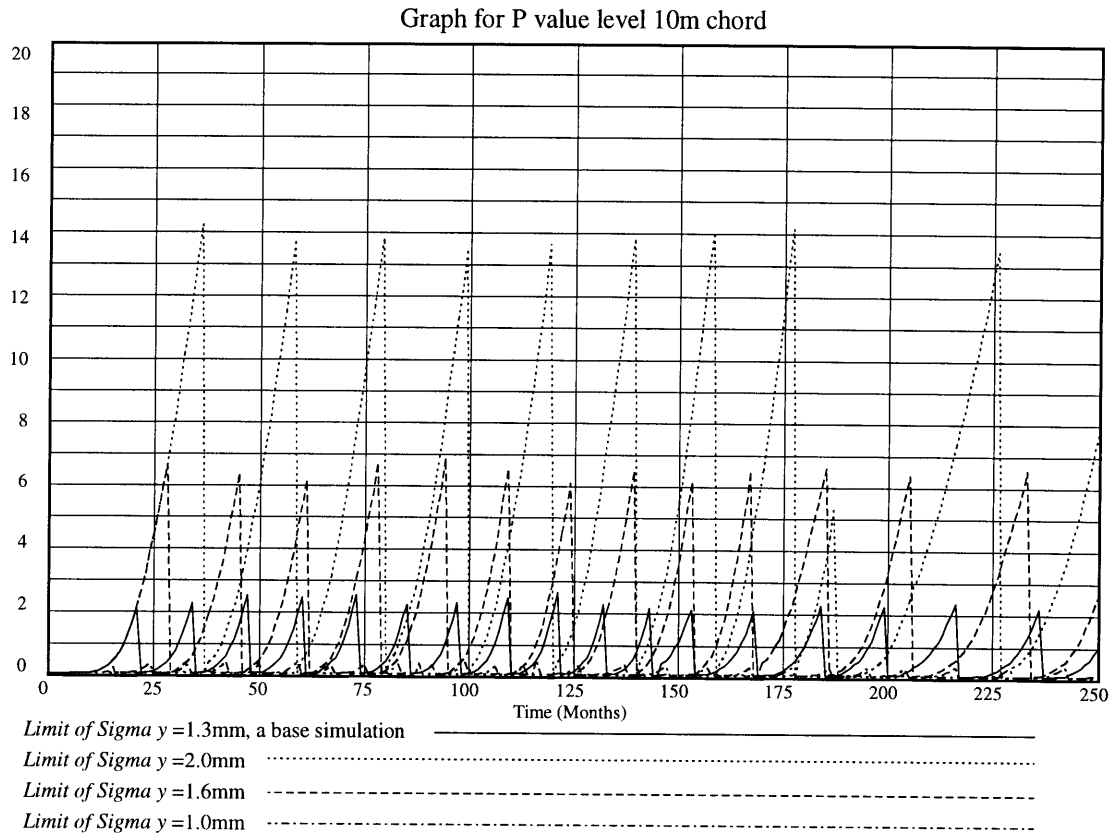


Figure 6.20 Case 4: Simulation result of  $P$ -value at different threshold values

As the above graph shows, the peak values of the  $P$ -values get larger when the *limit of sigma y* is larger. The maintenance activities of MTT tamping, which appears as sudden drops of  $P$ -values in the graph, are less frequent when the Limit of Sigma  $y$  is larger. This fact is also consistent with the intuition: the harder the standard of maintenance, the more frequently maintenance activities should be performed.

Limit of Sigma  $y = 1.3\text{mm}$ , a base simulation —————  
 Limit of Sigma  $y = 2.0\text{mm}$  .....  
 Limit of Sigma  $y = 1.6\text{mm}$  - - - - -  
 Limit of Sigma  $y = 1.0\text{mm}$  .....

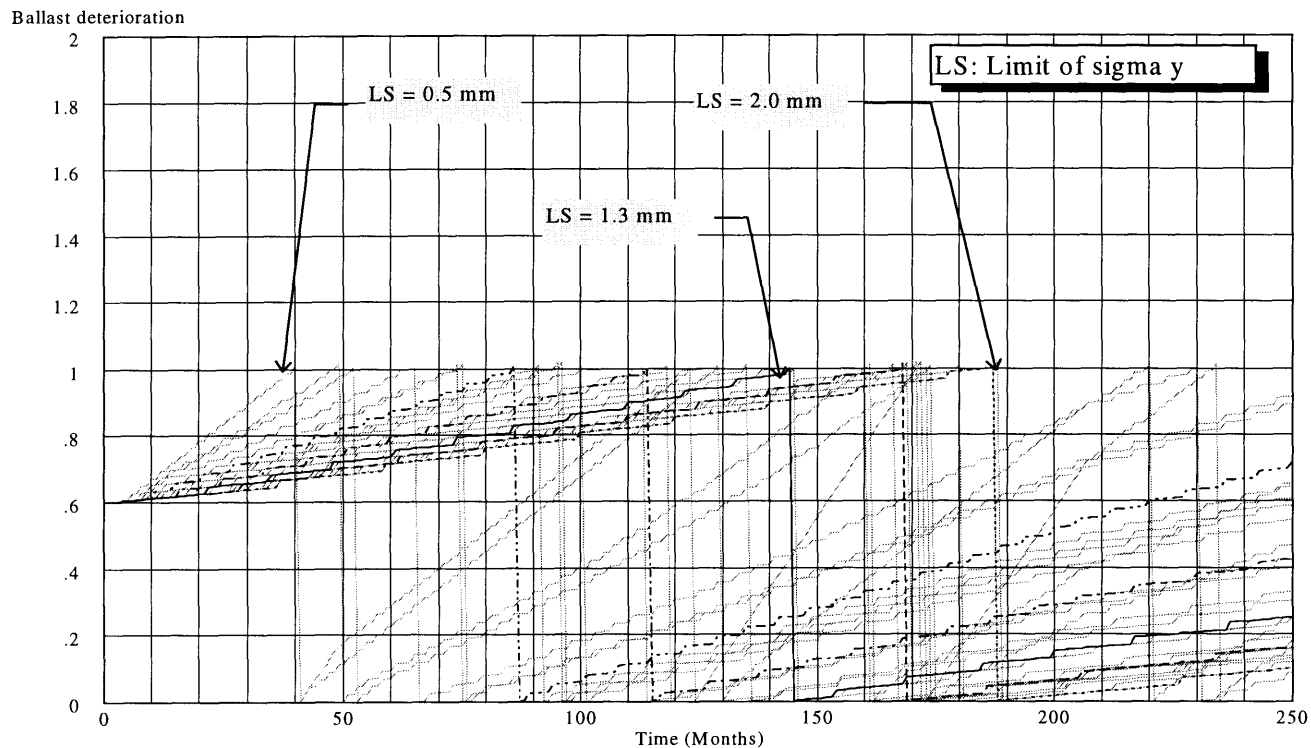


Figure 6.21 Case 4: Sensitivity simulation result of *Ballast deterioration*

Figure 6.21 shows the *Ballast deterioration* sensitivity runs. As a result of faster progress of *ballast deterioration* due to frequent tamping activities, the lower value of *Limit of Sigma y* (this means stricter standards for the track geometry) requires more frequent maintenance..

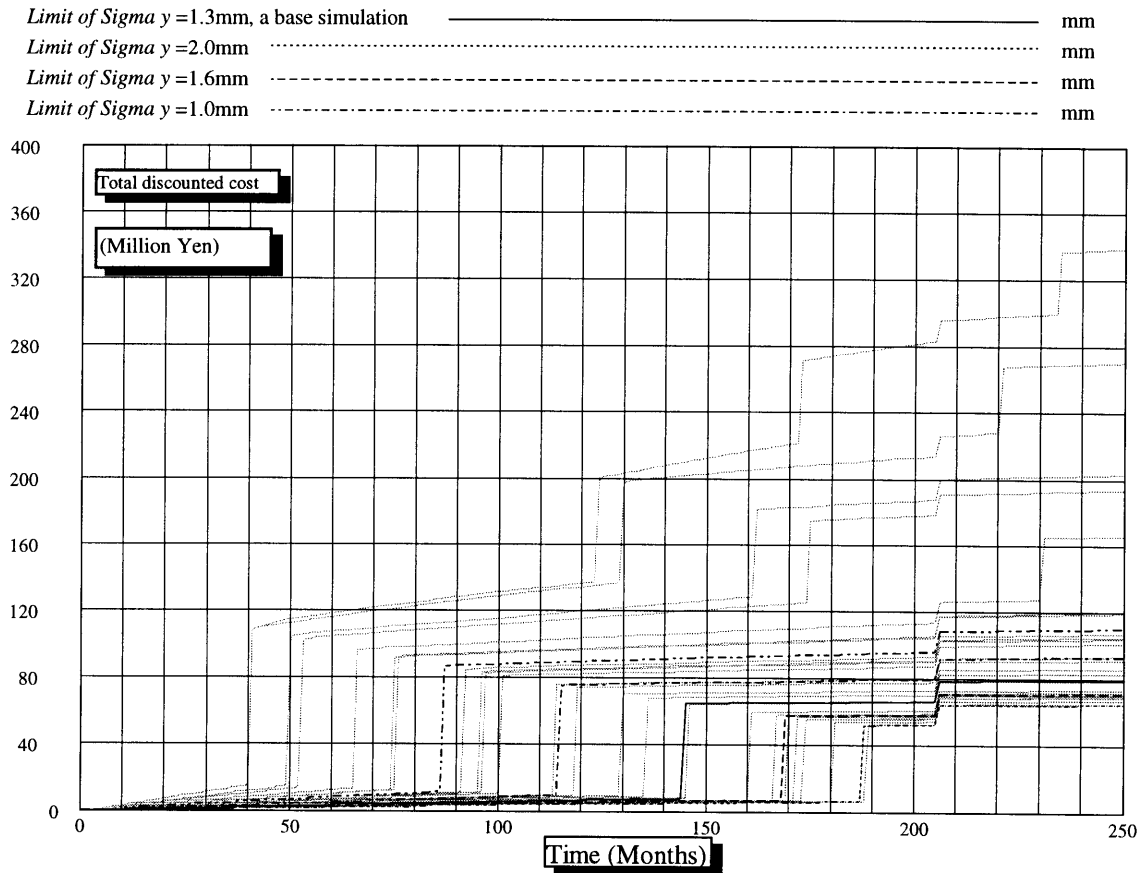


Figure 6.22 Case 4: Sensitivity simulation result of *Total discounted cost*

Figure 6.22 shows the *total discounted cost* of the sensitivity runs. The lowest total cost is given when the *Limit of Sigma*  $\gamma$  (*LS*) is 2.0 mm at month 250. Total cost at month 250 ranges between 64 million Yen (*LS* = 2.0) and 340 million Yen (*LS*=0.5). The total costs for *LS*=1.0 is 45 % higher than that for *LS*=2.0, but the total cost for *LS*=0.5 is almost five times as high as that for *LS*=2.0 (Figure 6.23). This means that *total discounted cost* rapidly increases if *LS* is smaller than 1.0; they are inversely related.

### Summary of Case 4

As Figure 6.22 and Figure 6.23 show, setting too strict a threshold is very inefficient in economic terms. On the other hand, it is not so costly to keep the quality of the facility at a certain level, although the costs gradually increase with the strictness of the threshold. This gradually increasing area is what the railroad companies ought to take into account, and where track engineers can make effective choices. The better the QF (in this context,  $\Sigma y$ ), the more benefit both passengers and the railroad companies can get in terms of passengers' comfort and increased safety.



Figure 6.23 Total discounted cost at the end of simulation period

## 6.6 Case 5: Pro-active maintenance: Sensitivity analysis of train speed

In this case study, the model changes *train speed* in a sensitivity analysis. This case deals with a track whose condition is similar to that of the real track at 349 km, which was discussed in Chapter 5. This case takes a pro-active maintenance policy and most conditions remain the same as the Case 1. These simulation runs select periodic maintenance policies for rail grinding (*grinding interval* = 1 year) and pro-active maintenance for MTT tamping (*limit of Sigma y* = 1.3mm). Then the model changes train speed from 160 km/h to 255 km/h as the sensitivity runs.

Table 6.5 Conditions of Case 5

Variable (units)	Value	Variable (units)	Value
Train speed (sensitivity runs) step: 5km/h, 21 runs	160-260		
ballast deterioration limit	1	MTT interval (year)	1
Cant (m)	0.18	MTT policy (0 for Pro-active)	0
CorrectionCoefficient (NA)	2	Radius (m)	2,500
discount rate (%)	6	Rail replacement tonnage (t)	1.1E+09
Grinding interval (years)	1	Rail roughness (mm)	0.3
Initial ballast deterioration(t)	0.6	Traffic (trains/day)	140
Initial ballast tonnage (t)	4E+08	Train speed (km/h) (base case)	200
Db (MN/m)	200	Unit cost of ballast (t)	3,000
Dp1 (MN/m)	182.09	Unit cost of Ballast replacement (t)	108,0000
Ds (MN/m)	85.05	Unit cost of MTT tamping (Yen/km)	900,000
lx (m <sup>4</sup> )	3.09E-05	Unit cost of Rail (Yen/m)	14,700
ly (m <sup>4</sup> )	5.12E-06	Unit cost of Rail grinding (Yen/km)	150,000
K30 (MN/m)	110	Unit cost of Rail replacement (Yen/m)	17,400
kappa (NA)	0.3	Unit cost of Tie (Yen)	7,700
KH (m/s <sup>2</sup> /mm/(km/h))	0.632	Unit cost of Tie pad (Yen)	500
kv (m/s <sup>2</sup> /mm/(km/h))	0.001	Unit cost of Tie replacement (Yen/ tie)	57,300
KZ (m/s <sup>2</sup> /mm/(km/h))	0.001	Rail grinding policy (1 for periodic)	1
limit of Rail roughness (mm)	0.7	Initial rail tonnage (t)	4E+08
Limit of Sigma y (mm)	1.3	Initial tie tonnage (t)	8E+08

Figure 6.24 shows a result of simulation runs with three different train speeds. The growth of Sigma y is generally largest in the run of 255 km/h and smallest in the run of 160 km/h. As a result, the number of tamping activities is thirteen times for 160 km/h over the entire simulation period and 26 times for 255 km/h. This simple fact shows that the influence of train speed to the track irregularity is significant.

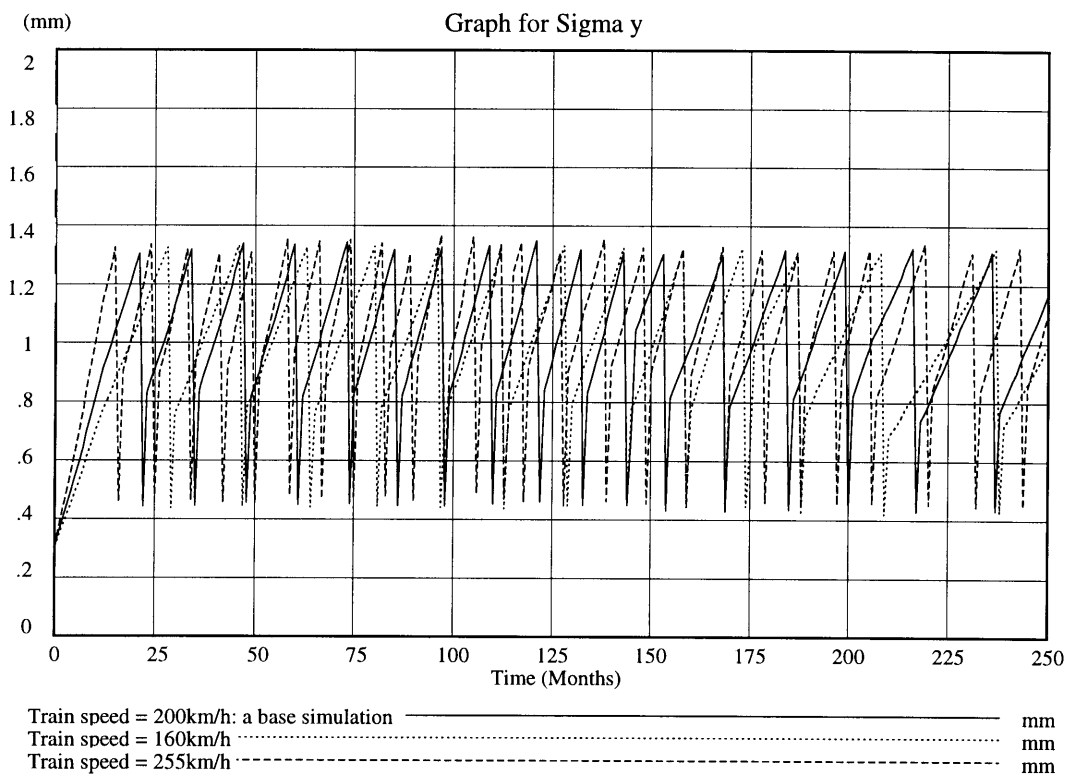


Figure 6.24 Case 5: Change of Sigma y in three different train speeds



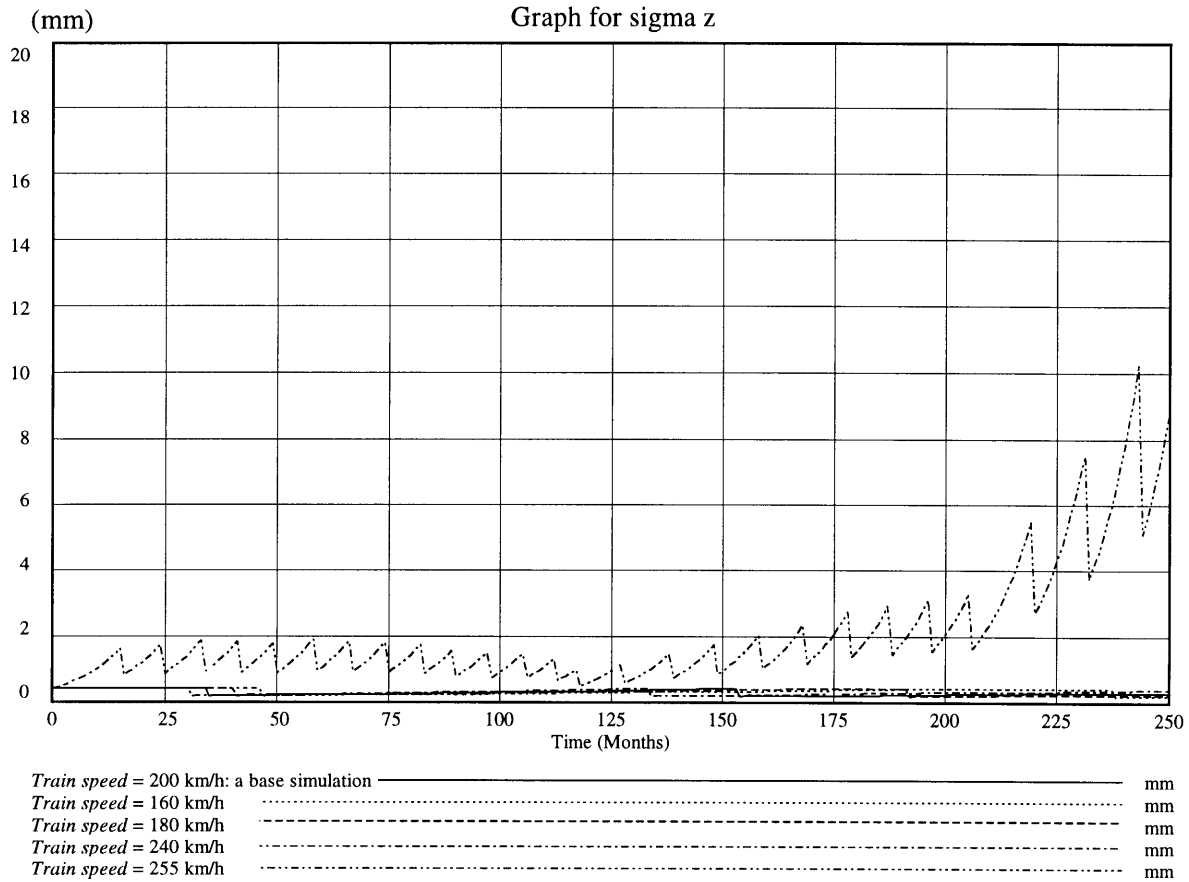


Figure 6.25 Case 5: Sigma z in 5 different train speeds

Figure 6.25 shows the  $\sigma_z$  in the simulation runs with five different train speeds. Except for the case of 255 km/h,  $\sigma_z$  stays below 0.5 mm in all the simulation runs. This means that no horizontal movement of track occurs in the gradual deformation process. However, when train speed is 255 km/h, the movement of track occurs in the gradual deformation process. There should be a speed between 240 km/h and 255 km/h where the movement of track occurs. The value of  $\sigma_z$  in 255 km/h diverges from the others at the later part of the simulation. Therefore, additional maintenance activities may be required to maintain the quality of the track.

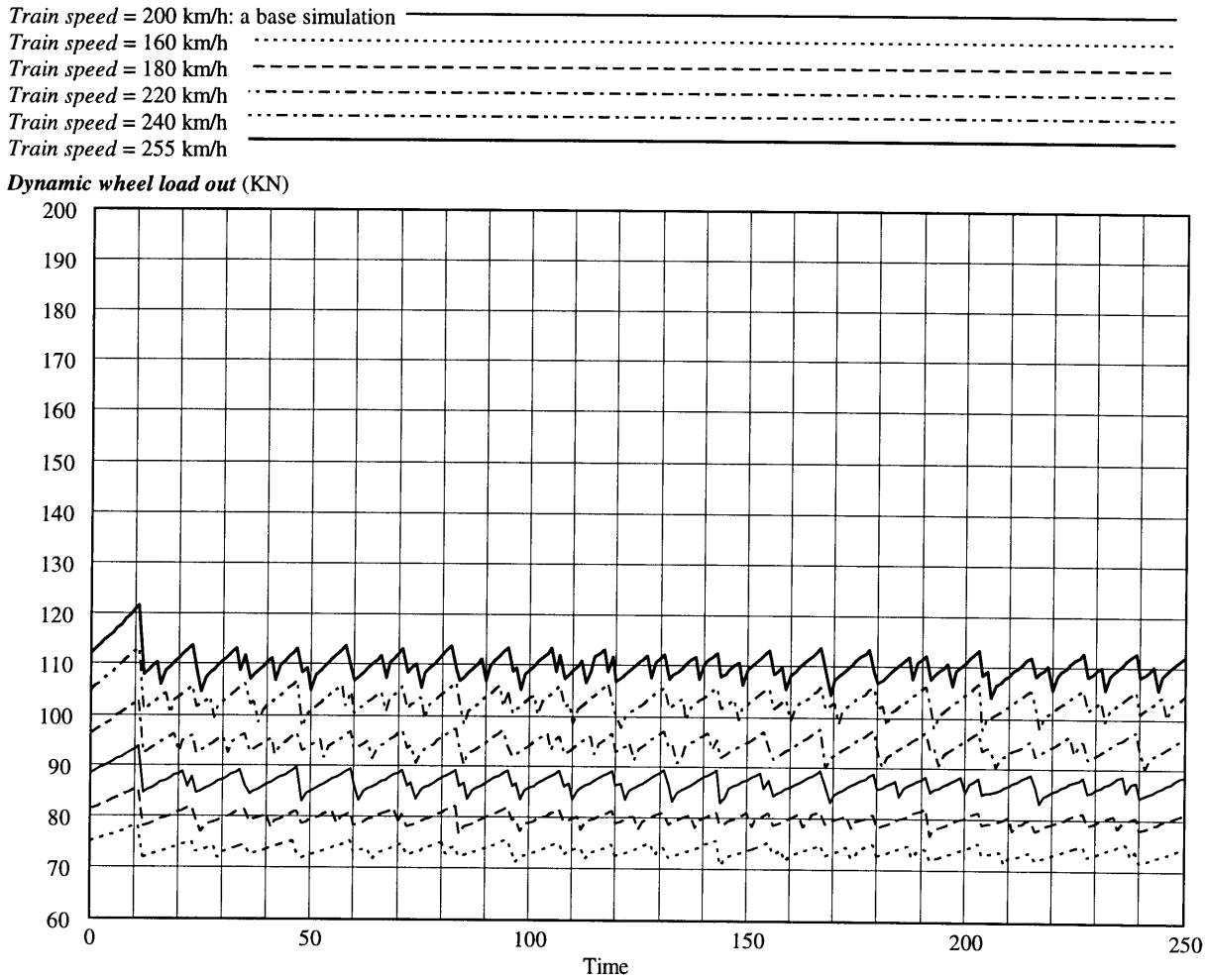


Figure 6.26 Case 5: *Dynamic wheel load out* in 5 different train speed.

Figure 6.26 shows a result of simulation runs for the *Dynamic wheel load out*. Train loads increase with increases in *train speed*. As the graph shows, the deviation of values in the entire length of simulation is larger when the train speed is faster. This indicates that the track irregularity influences *dynamic wheel loads* more when the *train speed* is higher. This gives a scientific basis to the fact that the High-Speed Rail requires stricter standards of track geometry.

Train speed = 200 km/h: a base simulation —————  
 Train speed = 160 km/h .....  
 Train speed = 180 km/h - - - - -  
 Train speed = 220 km/h - - - - -  
 Train speed = 255 km/h .....

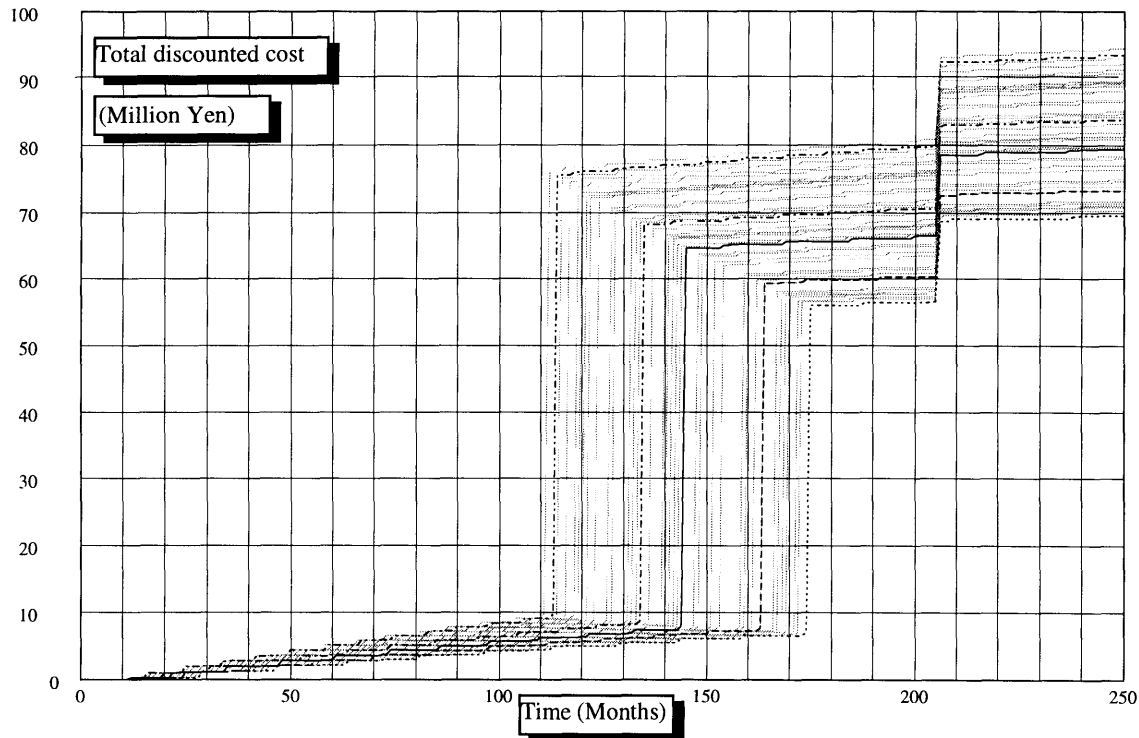


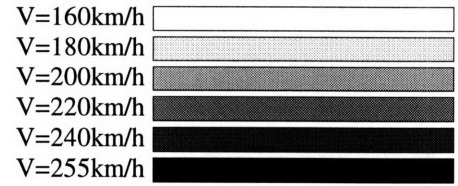
Figure 6.27 Case 5: total discounted cost sensitivity runs

Figure 6.27 shows the result of *total discounted cost* sensitivity runs over time. The differences in the total costs mainly come from the timing of ballast replacement and the frequency of tamping activities. Both factors raise track maintenance cost in higher train speeds. In the track maintenance of Shinkansen, tamping of ballast is performed periodically, usually once a year for all the main track. However, costs can be reduced by changing the cycle of maintenance depending on the train speed, the track geometry and the character of the subgrade and the track. This model will help track engineers to know the maintenance cycle that is appropriate for each section of the track.

### Summary of Case 5

As the results of the analysis for the total discounted cost show, maintenance costs vary in a large range, from 79 million Yen to 93 million Yen per kilometer, depending on train speeds. As this case used proactive maintenance policies, the total cost for lower speeds can be reduced to match the progress of deterioration of materials and geometrical defects.

As the first priority of the Passenger High-Speed Rail is safety, it is possible that railroad companies allow track engineers to spend the same amount of maintenance expense which does not depend on a particular character of track and traffic. By managing these conditions precisely, track engineers will be able to set appropriate maintenance level that fits the conditions.



Total discounted cost @ month 250

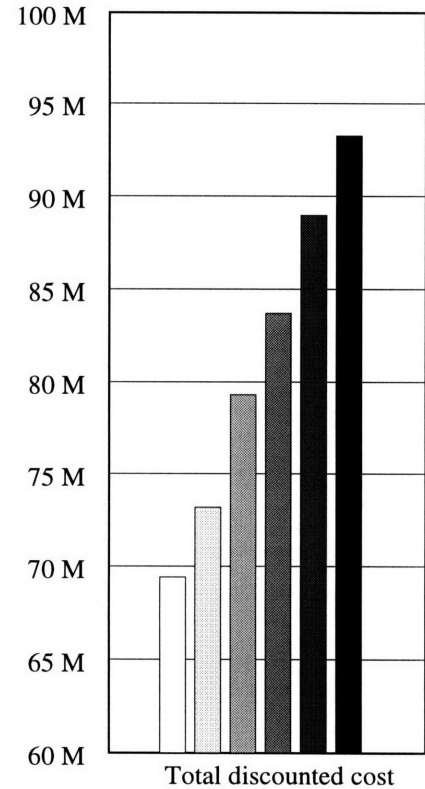


Figure 6.28 Case 6 Total discounted cost at the end of simulation runs

## 6.7 Case 6: Pro-active maintenance: Optimization analysis

In this case study, the model performs an optimization analysis that calculates the lowest possible cost within the standards of the quality of the facilities. In the optimization analysis, three variables are changed to obtain the best combination with the lowest cost.

The software used in this model, called “Vensim,” has a function to automatically calculate the best policies by changing selected variables.

This optimization runs vary the values of *Ballast deterioration limit*, the *limit of Sigma y* and *grinding interval*. The *Ballast deterioration limit* varies between 0.6 and 1.0. The

Table 6.6 Case 6: conditions of the optimization analysis

Variables (Units)	Value	Variable (Units)	Value
<b>Optimization: ballast deterioration limit</b>	0.5-1.0	KZ ( $m/s^2/mm/(km/h)$ )	0.001
<b>Optimization: Grinding interval</b>	1-10		
<b>Optimization: Limit of Sigma y</b>	0.5-1.4	MTT policy (0 for pro-active)	0
axle load (tons)	12.5	Radius (m)	1E+20
axle per veh (axles/car)	4	Rail replacement tonnage (t)	1.1E+09
ballast height (cm)	30	Rail roughness (mm)	0.3
Cant (m)	0.18	Traffic (trains/day)	140
CorrectionCoefficient (NA)	2	Train speed (km/h)	200
discount rate (%)	6	Unit cost of ballast (Yen/ $m^3$ )	3,000
Gauge (m)	1.435	Unit cost of Ballast replacement(Yen/m)	108,000
HG (m)	1.5	Unit cost of MTT tamping (Yen/km)	900,000
Initial ballast deterioration (NA)	0.6	Unit cost of Rail (Yen/m)	14,700
Initial ballast tonnage (t)	4E+08	Unit cost of Rail grinding (Yen/km)	150,000
Db (MN/m)	200	Unit cost of Rail replacement (Yen/m)	17,400
Dp1 (MN/m)	182.09	Unit cost of Tie (Yen)	7,700
Ds (MN/m)	85.05	Unit cost of Tie pad (Yen)	500
Ix ( $m^4$ )	3.09E-05	Unit cost of Tie replacement (Yen/tie)	57,300
Iy ( $m^4$ )	5.12E-06	vehicles per train (cars/train)	16
K30 (MN/m)	110	Rail grinding policy (1 for periodic)	1
kappa	0.3	Initial Settlement	2.135503
KH ( $m/s^2/mm/(km/h)$ )	0.6	Initial rail tonnage (t)	4E+08
kv ( $m/s^2/mm/(km/h)$ )	0.001	Initial tie tonnage (t)	8E+08

*Limit of Sigma y* varies between 0.5 and 1.4. The *Grinding interval* varies between 1 year and 10 years. The model calculates the combination of values of three variables that gives the lowest *Total discounted cost* in the optimization run.

Figure 6.29 is a result of the optimization run showing *Sigma y* with other base simulation in Case 4. The optimization run gave the values of *Ballast deterioration limit* = 1.0, *Limit of Sigma y* = 1.4 mm, and *Grinding interval* = 1.006 years (see Table 6.7 at p. 160).

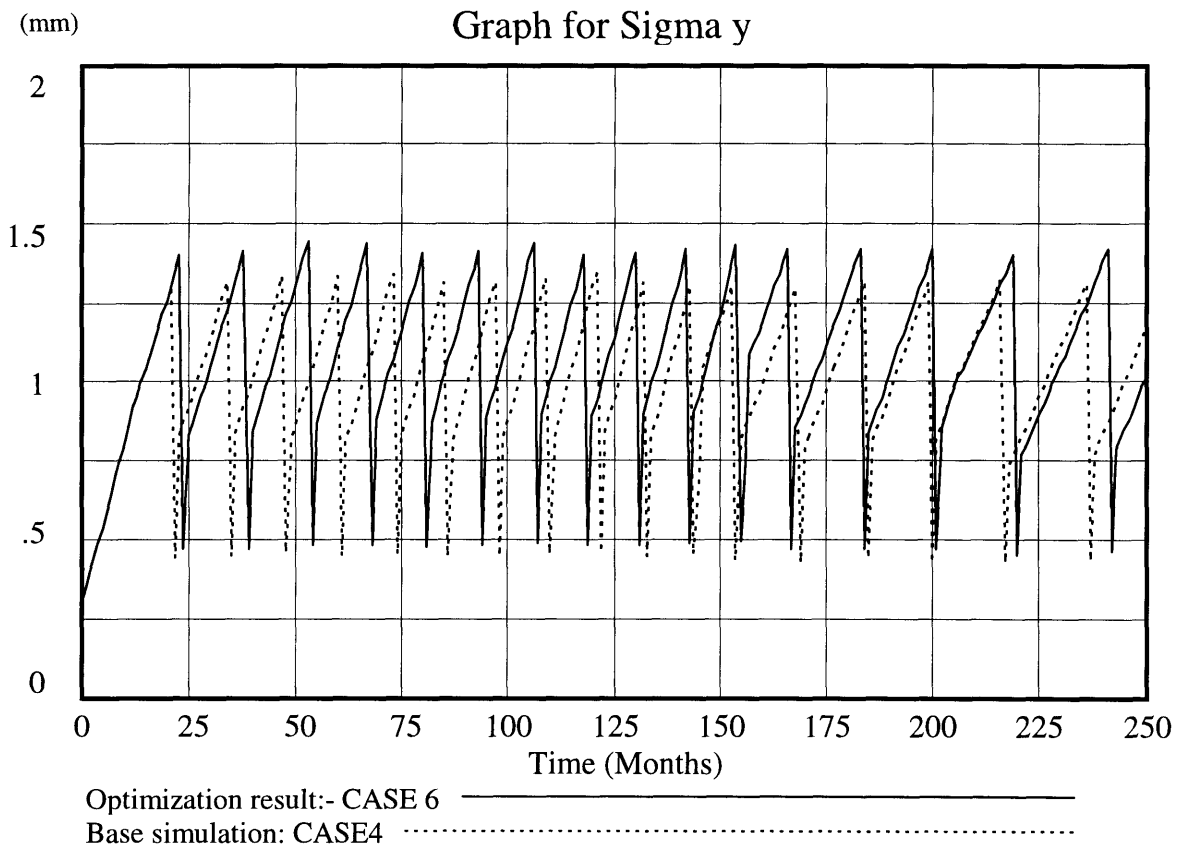
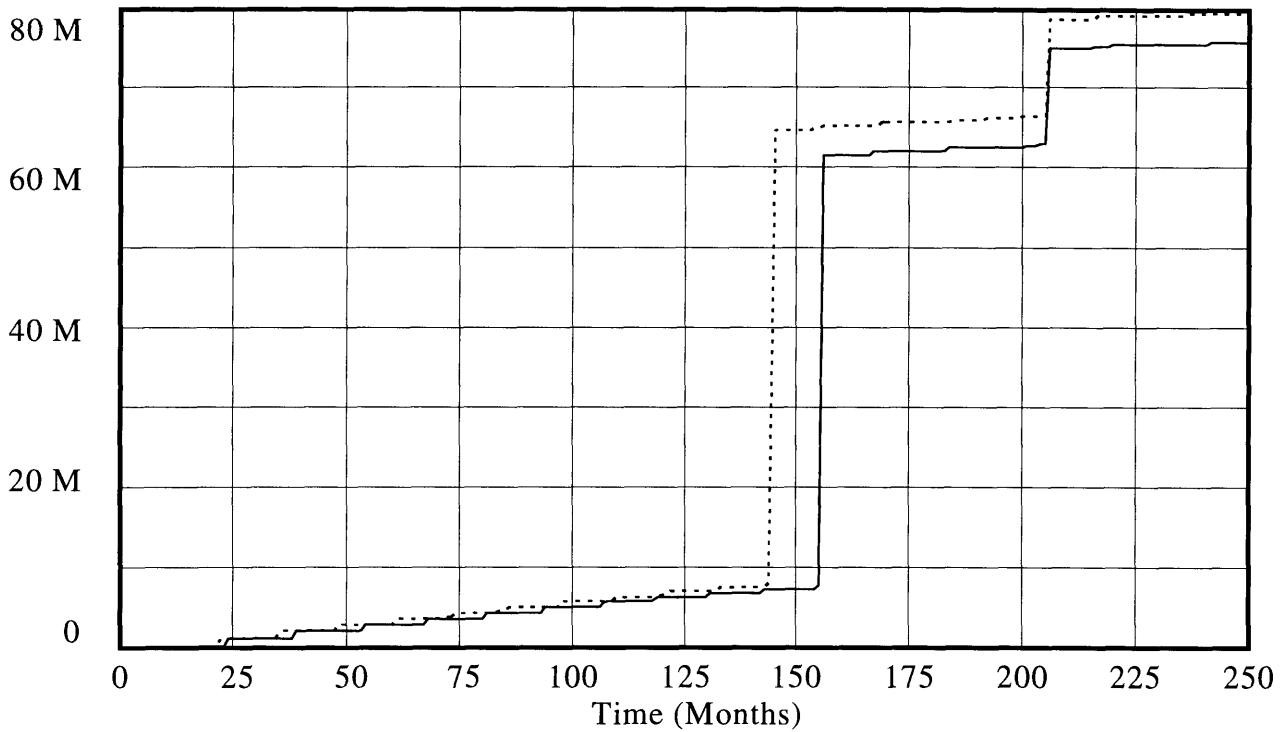


Figure 6.29 Case 6: *Sigma y* Comparison with Case 4 base simulation run

Graph for Total discounted cost



Optimization result:- CASE 6 \_\_\_\_\_  
 Base simulation: CASE4 .....  
 \_\_\_\_\_

Figure 6.30 Case 6: comparison of *Total discounted cost* with Case 4 base simulation

Figure 6.30 shows the Total discounted cost of the optimization run's result. Total cost becomes 75 million Yen at the end of the simulation period. The base simulation of the Case 4 shown in the graph has the total cost of 80 million Yen. The only difference of the conditions between the two runs is the *Limit of Sigma y*. The model calculated about 4% lower cost than the lowest possible cost of Case 4., This shows that it is possible to reduce the total maintenance cost by changing the threshold level of maintenance precisely.

## Summary of Case 6

This case study gave a optimized simulation run that gives the lowest maintenance cost for the pro-active maintenance policy for MTT tamping. This case did not give a surprising result, but rather a result consistent with the intuition of track engineers. The model offered the *lowest cost when the highest allowable value for the limit of Sigma z*, the shortest allowable value of *grinding interval*, and the highest allowable *tonnage on the ballast*.

Table 6.7 The result of the optimization run

```
Case 6-3
Initial point of search.
  BALLAST DETERIORATION LIMIT =          1.
  LIMIT OF SIGMA Y =          1.3.
  GRINDING INTERVAL =          1.
Simulations = 1.
Pass = 0.
Payoff = -8.1034e+009.
-----
Maximum payoff found at:.
  BALLAST DETERIORATION LIMIT =          1.
  LIMIT OF SIGMA Y =          1.4.
  *GRINDING INTERVAL =          1.0063.
Simulations = 45.
Pass = 3.
Payoff = -7.07807e+009.
-----
250
Done, the cumulative payoff is -7076552349.312500.
```



## 6.8 Case 7: Comparison between the maintenance policies in Case 1 and Case 6

This case study compares the optimized result given in Case 6 (pro-active maintenance for MTT tamping) with the periodic maintenance given in Case 1.

Figure 6.31 show the comparison of the change of  $\Sigma y$ . As the graph shows, peak values of  $\Sigma y$  for the periodic maintenance are smaller than those for the pro-active maintenance. Number of tamping activities are 21 for the periodic maintenance and 15 for the pro-active maintenance. Both policies are able to retain the quality of the facilities in terms of track geometry.

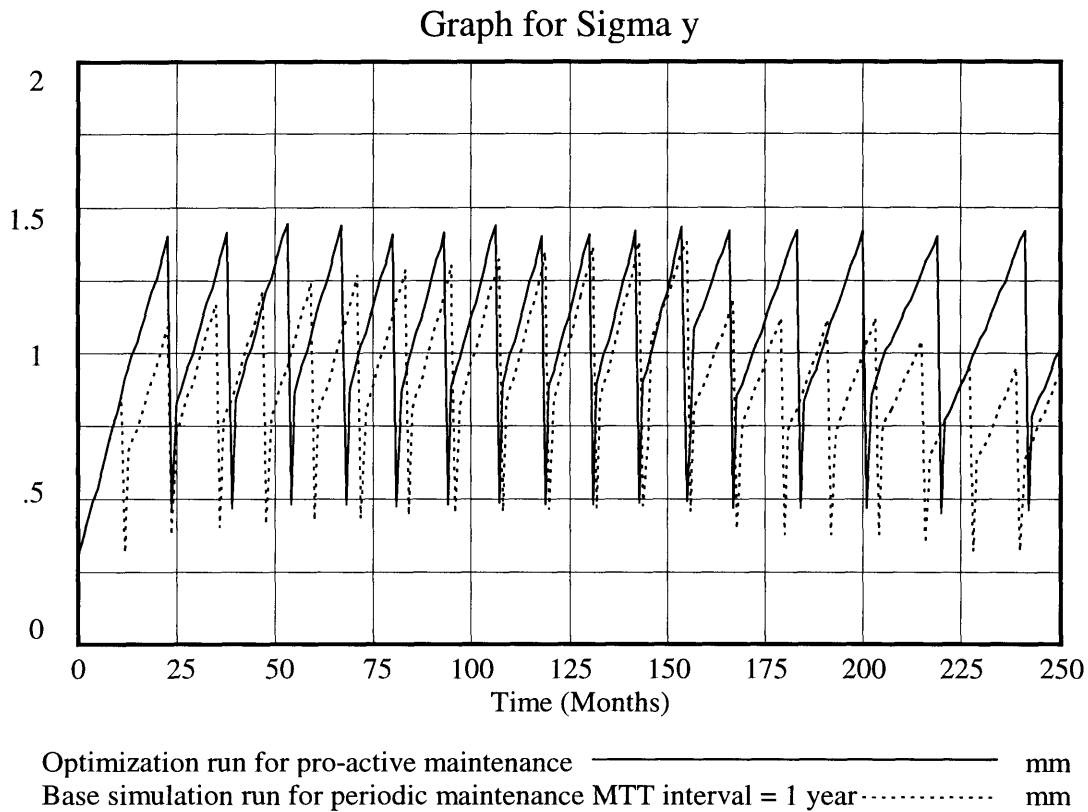
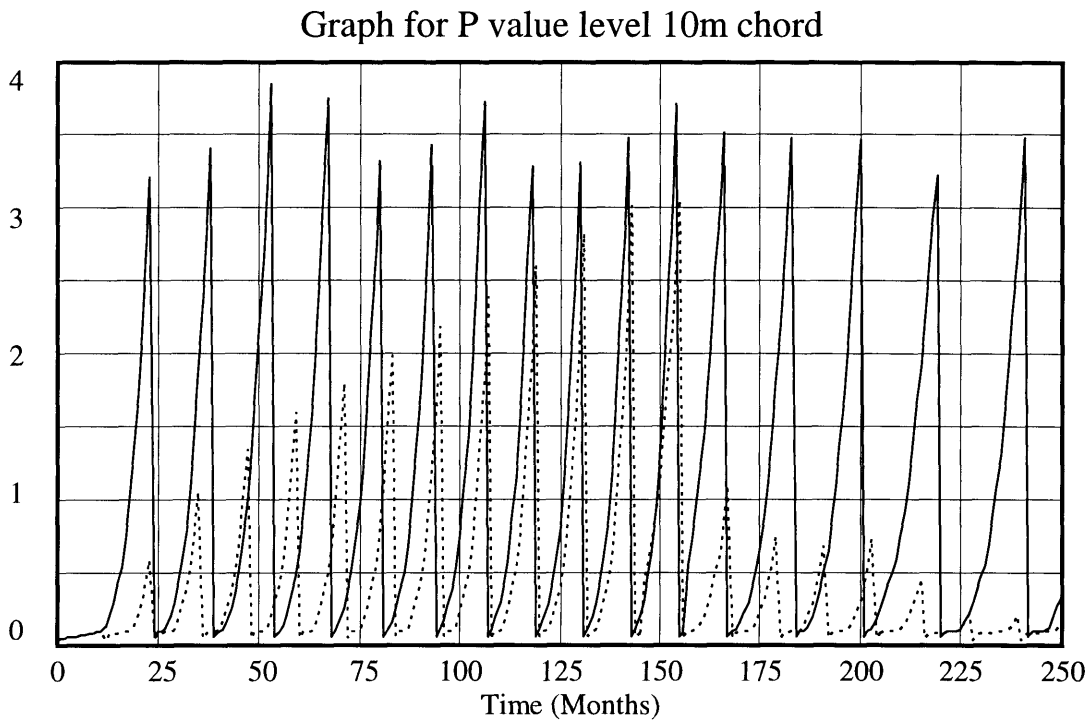


Figure 6.31 Case 7: Comparison of  $\Sigma y$  with two different policies



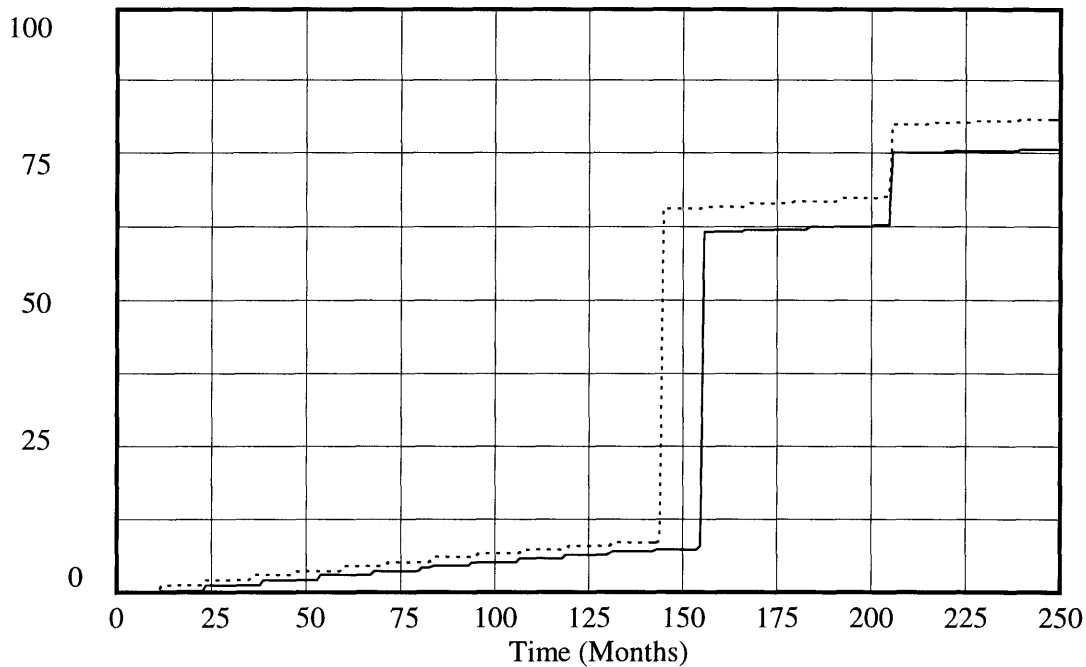
Optimization run for pro-active maintenance —————  
Base simulation run for periodic maintenance MTT interval = 1 year.....

Figure 6.32 Case 7: Comparison of P-values with two different policies

Figure 6.32 shows the comparison of P-value in each policy. As the rate of change for the P-values is not uniform, it is more difficult to predict P-values than *Sigma y*.

(Million Yen)

Graph for Total discounted cost



Optimization run for pro-active maintenance —————  
Base simulation run for periodic maintenance MTT interval = 1 year ·······

Figure 6.33 Case 7: Total discounted cost

Figure 6.33 shows the *Total discounted cost*. The pro-active maintenance costs about 75 million Yen, while periodic maintenance costs 80 million Yen. The difference of these costs are about 6%. This means that costs can be reduced by about six percent due to the change of maintenance policies.

### Summary of Case 7

The pro-active maintenance gave lower maintenance costs than the periodic maintenance. New economical methods of design for the materials, such as concrete beams, have been derived from more precise analyses of the (physical) behavior of the materials. Similar things happen in the design and analyses of the track. If track engineers can manage the

information on the track well, they can reduce costs substantially. It is more difficult to manage the pro-active maintenance than the periodic maintenance, as the pro-active maintenance requires more history of the track, more frequent update of the track information, more careful observation of real track, and more ability to predict the real track using this type of model.

About thirty billion Yen is spent for the track maintenance of the Tokaido Shinkansen per year for the entire length of double tracks, with a 515 post kilometer, 16 stations, 20 track maintenance offices, three train depots, and one factory for trains. If the cost reduction of three percent is obtained by the efficient maintenance policies, the company can save about nine hundred million Yen.

## 6.9 Overview and summery

This chapter carefully examined cases that change maintenance parameters. The results given by the case studies were not very surprising, but confirmed the intuition of track engineers.

Periodic maintenance Sensitivity analysis of *MTT interval* in Case 1 proved that the *MTT interval* and the track irregularity are traded off against each other. The results showed that frequent tamping activities cost more than infrequent maintenance activities.

A sensitivity analysis of *rail grinding interval* with pro-active MTT maintenance was performed in Case 2. frequent rail grinding is more economical than infrequent grinding. This result comes from the fact that this maintenance activity improves not only the geometrical parameter (rail roughness), but also the mechanical parameter (life span of the rail).

Case 3 dealt with a sensitivity analysis of ballast replacement for Pro-active maintenance. The result of the case showed that ballast replacement should be performed as late as possible, since the ballast replacement is much more costly than any other maintenance activities.

Case 4 performed a sensitivity analysis for the *limit of Sigma y* with the pro-active maintenance policy. The result of the case indicated stricter maintenance standards generate higher cost.

Case 5 studied pro-active maintenance with sensitivity analysis of train speed. The *total discounted cost* increases significantly over the increase of train speed. The variation of the maintenance cycles of ballast tamping given by the calculation of the model is large depending on the dynamic wheel loads.

Case 6 performed pro-active maintenance as an optimization analysis. The result that gave the lowest cost was consistent with the reality: largest allowable value of *limit of Sigma y*, shortest *grinding interval*, and largest *limit of ballast deterioration*.

Case 7 studied the comparison between two maintenance policies for MTT tamping: periodic maintenance and pro-active maintenance. This case showed that pro-active maintenance can be less costly than periodic maintenance, but pro-active maintenance requires stricter management of information, including the predictability of the track condition in the future.

These simulation runs performed in this chapter show the capability of the model. This model will help track engineer determine which kinds of maintenance policies they should take, and how long the maintenance cycle should be.

In the following concluding chapter, the author will explain the ability as well as the limit of the model.

## **7. Conclusions**

### **7.1 Conclusions**

#### ***7.1.1 Technology Review***

Chapter 2 reviews the technological advances in track maintenance. The mechanization and the automation of the maintenance activities are key factors in making advanced High-Speed Rail operations possible. Although the pace of development of technology in track maintenance is not as fast as other prospering industries, track maintenance has benefited from the development of technology in various manufacturing and information technology industries. Each item examined in this study, such as MTT and dynamic track stabilizers, helped support the track maintenance of the High-Speed Rail. Many assumptions used in the model use the fruits of advanced technologies.

#### ***7.1.2 The construction of the model***

The model in this study applies theories that have been studied for a long time and have gradually developed. One of the representative theories is the ballast deterioration theory. As the extension of the model has to be considered for further research, the model is divided into six modules: track geometry (1), track geometry(2), materials, costs, maintenance policies, and initial conditions. The track geometry (1) and the materials are the two main modules.

The track geometry (1) module calculates variables such as dynamic wheel loads, rail roughness, and track irregularity ( $\sigma_y$  and  $P$ -value). As the variables used in the model are interrelated each other, the new calculated values in a particular month becomes the conditions of the following months.

The materials module predicts the quality of the facilities in the mechanical parameter. The model calculates the cumulative tonnage of each materials and ballast deterioration.

### ***7.1.3 The validation of the model***

The model developed in this research is consistent with reality.

First, the annual settlement of track as a result of simulation runs are examined. The annual settlement values vary over the period of simulation runs, depending on time, ballast deterioration, cumulative tonnage of the materials, forces applied to ties, and so on. However, the average settlement calculated from the data of real tracks, 7.1 mm, is within the range of the simulation results.

Then this study compares the growth of track irregularity with the reality. The real data of tracks are given from the tracks of Shinkansen. The growth of track irregularity increases almost linearly over time in the gradual deformation process, which is consistent with reality. The model also accounts for the influence of initial deformation process. Large amount of settlement follows the lift of track by tamping activities of MTT.



#### 7.1.4 The case studies

Although simulation runs produce no surprising results, they indicate that the model can help track engineers choose maintenance policies by changing variables “virtually” on the simulations. Cases perform the sensitivity analysis by changing one or more variables which change the conditions of the simulation runs. The following list shows the summary of the results of simulation runs:

1. Sensitivity analysis of the *MTT interval* with periodic maintenance shows that only *MTT intervals* of less than about 1 year are acceptable in the entire length of the simulation. However, the *MTT interval* can be longer when the ballast deterioration is small, or when the rail is new. Periodic maintenance of MTT tamping is not economical, since the model frequently performs tamping when the track geometry (*Sigma y, P-value*) is satisfactory.
2. Sensitivity analysis of the rail grinding interval given pro-active MTT maintenance shows that the shortest grinding interval brought the lowest total discounted cost. This is because the rail grinding mitigates the forces applied to the track, and slows down the frequency of tamping activities. This is a totally opposite result from the tamping activities.
3. Sensitivity analysis of ballast replacement shows that the ballast should be changed as infrequently as possible in the simulation runs, since ballast replacement is the most costly part of track maintenance.

4. Sensitivity analysis for the *limit of Sigma y* (the threshold level to perform tamping activities) shows that the threshold should be as high as possible, if the standards of track maintenance permit. A higher limit produces lower maintenance cost.
5. Sensitivity analysis of trains speed with pro-active maintenance of MTT tamping shows that the influence of train speed is significant. The maintenance cost for 255 km/h is more than 30% higher than that for 160 km/h.
6. The optimization analysis that looks for the lowest cost with allowable standards of track quality shows that the optimum case takes the highest allowable value of *limit of Sigma y*, the most frequent rail grinding, and the largest *limit of ballast deterioration*.

#### ***7.1.5 The limits of the model***

This study shows that the model works consistently with reality. However, limits of the model exist. Here are examples.

1. This model represents the conditions of track for a one kilometer section of track. In the real track, there are many differences of conditions even within one kilometer, such as curvature, subgrade conditions and the existence of extension joints.
2. This model is good only for the ballast track with compacted soil subgrade. There are many types of track and its support, such as concrete slab track,

viaducts, bridges and tunnel. Even though the ballast track is prevalent for the Tokaido Shinkansen, other models have to be constructed for other kinds of track structures.

## **7.2 Recommendations for better maintenance policies**

This research reveals that the pro-active maintenance is more economical than the periodic maintenance. The periodic maintenance sometimes performs maintenance activities even when the track condition is satisfactory in the simulation runs. On the other hand, pro-active maintenance occurs only when needed. By introducing pro-active maintenance for MTT tamping, railroad companies will be able to lower the maintenance costs while maintaining the quality of the facilities.

Even though pro-active maintenance is more economical than periodic maintenance, the pro-active maintenance is harder to manage. Recent advancements in information technology can become breakthroughs for this bottleneck. In the measurement of track geometry or the defect detection of the rail, very large data must be stored and transferred, as the measurements are performed every meter, or sometimes every centimeter.

Until several years ago, track maintenance offices for the Tokaido Shinkansen could get the track information only as statistical information, such as *P-values* in every kilometer, or largest value of track irregularity and its location. Data must be limited because of the storage and transfer problem. Therefore, the track geometry car measures the Shinkansen's track every ten days, but before now the maintenance offices could not use the raw data of the measurement. Recent information technology has made it possible to bring all the track

data measured by the track geometry car through an online system. Computers in the maintenance offices now indicate the sites that should be maintained. They even can predict the track irregularity of the track, but the introduction of this model the system will make more secure predictions possible.

Efficient maintenance policies can be produced from the combination of good information systems and reliable prediction theories.

### **7.3 Recommendations for further research**

This model focuses on a the quality of the facilities and the costs. However, some topics of the research remain unexplored due to various constraints, such as time, difficulties of the acquisition of real track data, and further calibration of the model output. Here is a list of recommendations for further research:

1. Although this model provided many kinds of outputs calculated by the model, only three kinds of track irregularity (the *sigma y*, *10m chord P-value of level* and the *sigma z*) were examined in this study. The behavior of the 40m chord P-values of both longitudinal and horizontal dimensions, the 10 m chord P-value of horizontal dimensions, and improving effect of tamping activities to the P-values should also be examined in further research.
2. The examples used in the calibration of the model were not sufficient. Further research must be conducted to obtain more precision to the output of the model.

3. The effect of tamping that eliminates the track irregularity has to be validated to reality. Since this model considers the initial deformation process after the tamping of ballast, the model produces fairly large fraction of improvement (lessening) of the track irregularity that can cover the progress of immediate track irregularity due to initial deformation process.

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## Appendix Source code of the model

a = 2.7e-010\*(1+Ballast deterioration/CorrectionCoefficient)

~  
~ |

b [(0,0)-(40,50)],(15,37.5),(20,38.6),(25,39.6),(30,40.6)  
,(35,41.6)

~  
~ |

ballast replacement std 2 = DELAY FIXED(Ballast replacement standard,1,Ballast replacement standard)

~  
~ |

CorrectionCoefficient = 2

~  
~ |

day per month=

30.5  
~ day/Month  
~ |

Initial ballast deterioration = 0.6

~  
~ |

MTT std2 = DELAY FIXED(MTT standard,1,MTT standard)

~  
~ ~:SUPPLEMENTARY  
|

P sigma relation [(0,0)-(8,80)],(0,0),(0.9,0.1),(1,0.3),(1.1,0.6)  
,(1.2,1.2),(1.3,2.1),(1.4,3.2),(1.5,4.6),(1.6,6.1),(1.7,7.8)  
,(1.8,9.6),(1.9,11.4),(2,13.4),(2.1,15.3),(2.2,17.3),(2.3,19.2)  
,(2.4,21.1),(2.5,23),(2.6,24.9),(2.7,26.7),(2.8,28.4),(2.9,30.1)  
,(3,31.7),(3.1,33.3),(3.2,34.8),(3.3,36.3),(3.4,37.8),(3.5,39.1)  
,(3.6,40.5),(3.7,41.7),(3.8,43),(3.9,44.2),(4,45.3),(4.1,46.4)  
,(4.2,47.5),(4.3,48.5),(4.4,49.5),(4.5,50.5),(4.6,51.4),(4.7,52.3)  
,(4.8,53.2),(4.9,54),(5,54.9),(5.1,55.8),(5.2,56.7),(5.3,57.5)  
,(5.4,58.3),(5.5,59.3),(5.96289,63.1579),(6.09897,64.4976),(6.7134,69.0909)  
,(8.11546,79.0431)

~  
~ |

Pi = 3.14159

~  
~ ~:SUPPLEMENTARY  
|

Pr1 = curve steady wheel load out\*(1-EXP(-Beta\*alpha/2)\*COS(Beta\*alpha/2))

~ kN



```

~ |

Pr12 =
Pr1+Pr2
~ kN
~ |

Pr2 = curve steady wheel load in*(1-EXP(-Beta*alpha/2)*COS(Beta*alpha/2))
~ kN
~ Rail force
|

Psmean =
Pt*Tie width*Tie length
/(Tie width + 2*(ballast height-15))
/(Tie length+2*(ballast height-15))
~ kN/m/m
~ Subgrade pressure
|

wheel load change=
Static wheel load*(3*Sigma av/g+i*Train speed/100)
~ kN
~ ~:SUPPLEMENTARY
|

x = INTEG(1,1)
~
~ ~:SUPPLEMENTARY
|

Y2 K30 110 ((0,0)-(40,10)],(15,1.3),(20,1.14),(25,1),(30,0.88)
)
~
~ |

Y2 K30 30 ((0,0)-(40,10)],(15,1.65),(20,1.5),(25,1.35),(30,1.2)
)
~
~ |

Y2 K30 70 ((0,0)-(40,10)],(15,1.43),(20,1.25),(25,1.11),(30,0.97)
)
~
~ |

*****
.Control
*****~
Simulation Control Parameters
|

FINAL TIME = 250
~ Months
~ The final time for the simulation.

```

```

|
INITIAL TIME = 0
~ Months
~ The initial time for the simulation.
|

SAVEPER =
  TIME STEP
~ Months
~ The frequency with which output is stored.
|

TIME STEP = 1
~ Months
~ The time step for the simulation.
|

*****
.Costs
*****~
|

Ballast replacement cost = IF THEN ELSE(
Ballast replacement standard=1,
(Unit cost of ballast*2+Unit cost of Ballast replacement)*1000,0)
~
~ |

discount rate = 0.06
~
~ |

discounted cost =1/(1+discount rate)^(Time/12)*
( Ballast replacement cost+Rail replacement cost
+Tie replacement cost+MTT cost+Rail grinding cost)
~
~ |

Maintenance cost per month =Ballast replacement cost+
Rail replacement cost+Tie replacement cost+Rail grinding cost+MTT cost
~
~ |

Manual tamping cost = Unit cost of Manual tamping*1
~
~ ~:SUPPLEMENTARY
|

MTT cost = IF THEN ELSE(MTT standard=1,Unit cost of MTT tamping,0)
~
~ |

Rail grinding cost =IF THEN ELSE(Rail grinding standard=1, Unit cost of Rail grinding*1,0)
~

```

~ ~:SUPPLEMENTARY  
|

Rail replacement cost =IF THEN ELSE( Rail replacement standard=1,  
(Unit cost of Rail replacement+Unit cost of Rail)\*1000,  
0)

~  
~ |

Tie replacement cost = IF THEN ELSE(  
Tie replacement standard=1,  
(Unit cost of Tie replacement+Unit cost of Tie+Unit cost of Tie pad)\*44/25\*1000,0)

~ Yen  
~ |

Total discounted cost = INTEG(discounted cost,0)

~  
~ ~:SUPPLEMENTARY  
|

Total maintenance cost = INTEG(Maintenance cost per month,0)

~  
~ ~:SUPPLEMENTARY  
|

Unit cost of ballast = 3000

~ Yen/m/m/m  
~ |

Unit cost of Ballast replacement =108000

~ Yen/m  
~ 58000 for contracting  
50000 for machine

|

Unit cost of Manual tamping = 484

~  
~ ~:SUPPLEMENTARY  
|

Unit cost of MTT tamping = 900000

~ Yen/km  
~ 300000 for contracting  
600000 for the machine

|

Unit cost of Rail = 7350\*2

~ Yen/m  
~ |

Unit cost of Rail grinding = 150000

~ Yen/km  
~ 100000 for contracting  
50000 for the machine  
~:SUPPLEMENTARY

|  
Unit cost of Rail replacement = 17400

~ Yen/m  
~ 11400 for contracting  
6000 for machine

|  
Unit cost of Tie = 7700

~ Yen  
~ |

Unit cost of Tie pad = 500

~ Yen  
~ |

Unit cost of Tie replacement = 57300

~ Yen/tie  
~ |

\*\*\*\*\*  
.Geometrical(1)  
\*\*\*\*\*~  
|

Ballast settlement per axle =  $a \cdot (Pt - b(\text{ballast height}))^2 \cdot Y2$

~ mm  
~ |

Beta =  $(D \cdot 1e+006 / (4 \cdot E \cdot I_x \cdot \alpha))^{0.25}$

~  
~ Changed: multiplied by  $10^6$  to arrange dimension  
|

curve steady wheel load in = Static wheel load \* (  
 $(1 + \text{Train speed} \cdot \text{Train speed} \cdot \text{Cant} / g / \text{Radius} / \text{Gauge} \cdot 1000 / 3600 \cdot 1000 / 3600)$   
 $- \text{HG} \cdot \text{CantDeficiency}^2 / \text{Gauge}^2)$

~ kN  
~ |

curve steady wheel load out = Static wheel load \* (  
 $(1 + \text{Train speed} \cdot \text{Train speed} \cdot \text{Cant} / g / \text{Radius} / \text{Gauge} \cdot 1000 / 3600 \cdot 1000 / 3600)$   
 $+ \text{HG} \cdot \text{CantDeficiency}^2 / \text{Gauge}^2)$

~ kN  
~ |

$D = 1 / (1 / D_b + 1 / D_p + 1 / D_s)$

~ MN/m  
~ Spring coefficient  
|

d1 =

$2 \cdot 10^{-10}$   
~ mm/kN  
~ |

Db =200  
~ MN/m  
~ Ballast spring coefficient  
|

Dp1 =(89730+230.9\*Cumulative tie pad tonnage/10^6)/1000  
~ MN/m  
~ Spring constant of tie pads  
from Ikemori  
|

Ds =(Tie length+2\*(ballast height-15))\*(Tie width+2\*(ballast height-15))/100/100  
\*K30  
/2.2  
~ MN/m  
~ Subgrade spring coefficient  
240... Tie length, 33... Tie width in cm  
|

Dynamic wheel load=  
Static wheel load+wheel load change  
~ kN  
~ |

Dynamic wheel load in = curve steady wheel load in+wheel load change in  
~ kN  
~ |

Dynamic wheel load out = curve steady wheel load out+wheel load change out  
~ kN  
~ |

Effective sleeper area = 0.66632  
~ m\*m  
~ |

i=  
0.05+0.5\*Rail roughness  
~  
~ |

Initial Settlement=  
0.00076\*(Pt\*Effective sleeper area)^2  
\*(0.24^2)/(Tie length\*Tie width)\*100\*100  
~ mm  
~ |

kv=  
0.001  
~ m/s/s/mm/km\*h  
~ |

lift up =IF THEN ELSE(MTT standard=1 :OR: Ballast replacement standard=1,  
Track settlement+Settlement per month,0)

~ mm/Month  
~ |

P value level 10m chord = P sigma relation(Sigma y)

~  
~ ~:SUPPLEMENTARY  
|

Pt = (Dynamic wheel load in+Dynamic wheel load out)  
/Effective sleeper area\*(1-EXP(-Beta\*alpha/2)\*COS(Beta\*alpha/2))

~ kN/m/m  
~ Pressure beneath tie  
|

Rail roughness= INTEG (  
Rail roughness growth-Rail roughness removal,  
0.3)

~ mm  
~ |

Rail roughness removal=

IF THEN ELSE(Rail grinding standard=1 :AND: Rail roughness>0.7,Delta d,  
IF THEN ELSE(Rail grinding standard=1 :AND: Rail roughness<=0.7,Rail roughness-0.2,0))

~ mm/Month  
~ |

settlement per axle =Ballast settlement per axle+Subgrade settlement per axle

~ mm  
~ Ballast settlement plus subgrade settlement  
|

Settlement per month =

settlement per axle\*Traffic\*day per month\*vehicles per train\*axle per veh  
+IF THEN ELSE(MTT std2=1 :OR: ballast replacement std 2=1,Initial Settlement  
+settlement per axle\*Traffic\*day per month\*vehicles per train\*axle per veh,0)

~ mm/Month  
~ |

Sigma av=

kv\*Train speed\*Sigma y

~ m/s/s  
~ |

Sigma y= INTEG(Track irregularity per month,0.3)

~ mm  
~ |

Static wheel load=

axle load\*9.8/2

~ kN  
~ |

Subgrade settlement per axle =

+6\*10<sup>-9</sup>\*P<sub>smean</sub><sup>3.6</sup>\*(3\*10<sup>0.015</sup>\*K<sub>30</sub>+1.192)<sup>(-1.5)</sup>

~ mm

```

~ |

Track irregularity per month = Settlement per month/6 +
IF THEN ELSE(Ballast replacement standard =1,-Sigma y +0.3,
IF THEN ELSE(MTT standard =1,-Sigma y *0.7,0))
~ mm
~ |

Track settlement= INTEG (
Settlement per month-lift up,0)
~ mm
~ |

wheel load change in =curve steady wheel load in*(3*Sigma av/g+i*Train speed/100)
~ kN
~ |

wheel load change out = curve steady wheel load out*(3*Sigma av/g+i*Train speed/100)
~ kN
~ |

Y2=
IF THEN ELSE(K30>=110,
Y2 K30 110(ballast height),
IF THEN ELSE(K30>=70,
Y2 K30 70(ballast height),
Y2 K30 30(ballast height)))
~
~ Coefficient of acceleration due to ballast vibration
|

*****
.Geometrical(2)
*****~
|

a max1 =
0.00124*
(ABS(Pr12*0.3))^1.8
~ mm
~ Initial horizontal movement
changed: abs
|

aH = aHs+ daH
~ m/s/s
~ |

aHs = CantDeficiency/Gauge*g
~ m/s/s
~ |

b max1 =IF THEN ELSE(
(3.9e-005)*Qmax/K1-(8.38e-008*Pr12-1.67e-006)>0,
(3.9e-005)*Qmax/K1-(8.38e-008*Pr12-1.67e-006),

```

0)

~ mm

~ Horizontal movement per axle

|

$$\text{Beta1} = (K1 * 10^6 / 4 / E / I_y / \alpha)^{0.25}$$

~ 1/m

~ |

$$\text{daH} = 3 * \sigma * aH$$

~ m/s/s

~ |

$$\text{dQ} = 4 * \text{Static wheel load} / g * aH * KH$$

~ kN

~ |

$$\text{Irregularity growth1} = b \text{ max1} * \text{axle per veh} * \text{vehicles per train} * \text{Traffic} * \text{day per month} / 6$$

$$+ \text{IF THEN ELSE}(\text{MTT standard} = 1 : \text{AND} : \sigma z > 0.4, -\sigma z * 0.6, 0)$$

$$+ \text{IF THEN ELSE}(\text{MTT std2} = 1, a \text{ max1} / 6, 0)$$

~ mm/Month

~ |

$$K1 = -26.4 + 21.5 / (a \text{ max1} + 0.0425) + \mu * \text{Pr12}$$

~ MN/m

~ |

$$\text{kappa} = 0.3$$

~

~ |

$$KH = 0.6 + 80 / \text{Radius}$$

~

~ |

$$KZ = 0.001$$

~ m/s/s/mm/km\*h

~ Horizontal train vibration coefficient

|

$$\mu = 1.3$$

~

~ |

$$\text{P value line 10m} = \text{P sigma relation}(\sigma z)$$

~

~ ~: SUPPLEMENTARY

|

$$Q_i = \text{kappa} * \text{Dynamic wheel load in}$$

~ kN

~ |

$$Q_{\text{max}} = \text{ABS}(Q_{r1} - Q_{r2})$$

~ kN



```

~ Maximum horizontal load
|

Qo = Qi +dQ
~ kN
~ |

Qr1 =
Qo
*(1-EXP(-Beta1*alpha/2)*COS(Beta1*alpha/2))
~ kN
~ |

Qr2 =Qi
*(1-EXP(-Beta1*alpha/2)*COS(Beta1*alpha/2))
~ kN
~ |

sigma aH = KZ* sigma z* Train speed
~ m/s/s
~ |

sigma z = INTEG(Irregularity growth1,0.4)
~ mm
~ the Standard deviation of the irregularity of the horizontal dimension
|

*****
.Initial
*****~
|

alpha= 25/44
~ m
~ tie span
|

axle load=
12.5
~ t
~ |

axle per veh=
4
~ 1/veh
~ |

ballast height = 30
~ cm
~ |

Cant = 0
~ m
~ |

```

CantDeficiency = Gauge\*Train speed\*Train speed\*1000/3600\*1000/3600  
/g/Radius-Cant  
~ m  
~ |

E = 2.1\*10^6\*(9.8\*100\*100)  
~ N/m/m  
~ Young Coefficient of Steel  
|

g = 9.8  
~ m/s/s  
~ Gravity acceleration  
|

Gauge = 1.435  
~ m  
~ |

HG = 1.5  
~ m  
~ |

Initial ballast tonnage = 4e+008  
~ t  
~ |

Initial rail tonnage = 4e+008  
~ t  
~ |

Initial tie tonnage = 8e+008  
~ t  
~ |

Ix = 3.09e-005  
~ m\*m\*m\*m  
~ |

Iy = 5.12e-006  
~ m\*m\*m\*m  
~ |

K30 = 110  
~ MN/m/m/m  
~ ground reaction coefficient  
|

Radius = 1e+020  
~ m  
~ |

Tie length = 240  
~ cm  
~ |

Tie width = 33  
~ cm  
~ |

Traffic=  
140  
~ train/day  
~ |

Train speed=  
255  
~ km/h  
~ |

vehicles per train=  
16  
~ veh/train  
~ |

\*\*\*\*\*  
.Maintenance Policies  
\*\*\*\*\*~  
|

ballast deterioration limit = 1  
~  
~ |

Ballast replacement standard=IF THEN ELSE(Ballast deterioration>ballast deterioration limit,1,0)  
~  
~ |

Grinding interval=  
1  
~ year  
~ |

Life span tonnage of rail ((0,0)-(10,2e+009)],(1,1.1e+009)  
,(5,8e+008),(10,5.4e+008) )  
~ t  
~ |

limit of Rail roughness = 0.7  
~  
~ |

Limit of Sigma y = 1.5  
~  
~ |

MTT interval = 1  
~ year  
~ |

MTT policy = 1

~  
~ Choose 1 if you have periodic maintenance  
Choose 0 if you have pro active maintenance  
|

MTT standard =

IF THEN ELSE(MTT policy=1,  
IF THEN ELSE(modulo(Time+1,MTT interval\*12)<TIME STEP,1,0),  
IF THEN ELSE(Sigma y>=Limit of Sigma y,1,0)  
)  
~  
~ |

Rail grinding policy = 1

~  
~ Choose 1 if you have scheduled maintenance  
choose 0 if you have pro-active maintenance  
|

Rail grinding standard=

IF THEN ELSE(Rail grinding policy=1,  
IF THEN ELSE(  
modulo(Time+1,Grinding interval\*12)<TIME STEP,1,0),  
IF THEN ELSE (Rail roughness >=limit of Rail roughness, 1,0))  
~  
~ |

Rail replacement standard=IF THEN ELSE(

Cumulative rail tonnage>=Rail replacement tonnage,1,0)  
~  
~ Standard will give 1 when rail needs to be replaced.  
|

Rail replacement tonnage = Life span tonnage of rail(Grinding interval)

~ t  
~ The tonnage that the rail life terminates  
Depending on grinding interval for simplification  
|

Tie replacement standard =

IF THEN ELSE(Cumulative tie tonnage>=3e+009,1,0)  
~ t  
~ |

\*\*\*\*\*

.Material

\*\*\*\*\*~

|

Ballast deterioration=

INTEG ( IF THEN ELSE(Ballast deterioration<1:AND:Ballast deterioration>=0,  
Ballast Deterioration growth-Ballast deterioration removal,  
IF THEN ELSE(Ballast deterioration removal=0,  
0,-Ballast deterioration removal))

,Initial ballast deterioration)

~  
~ |

Ballast Deterioration growth=

IF THEN ELSE(MTT standard=1,0.02,0) +  
4.8e-011\*(Pt\*axle per veh\*vehicles per train\*Traffic\*day per month)

~  
~ |

Ballast deterioration removal =

IF THEN ELSE(Ballast replacement standard=1  
,Ballast deterioration,0)

~  
~ |

Cumulative ballast tonnage= INTEG (  
tonnage per month 2-tonnage removal 2,  
Initial ballast tonnage)

~ t  
~ |

Cumulative rail tonnage= INTEG (  
tonnage per month-tonnage removal,  
Initial rail tonnage)

~ t  
~ |

Cumulative tie pad tonnage = INTEG(Tie pad tonnage growth-Tie pad tonnage removal,  
Initial rail tonnage)

~ t  
~ |

Cumulative tie tonnage =INTEG(Tie tonnage per month-Tie tonnage removal,  
Initial tie tonnage)

~ t  
~ |

Delta d=

0.5

~ mm  
~ |

Rail roughness growth=

d1\*Dynamic wheel load\*Traffic\*vehicles per train\*axle per veh\*day per month

~ mm/Month  
~ |

Tie pad tonnage growth =

Traffic\*vehicles per train\*axle load\*axle per veh\*day per month

~ t/Month  
~ |

Tie pad tonnage removal =

IF THEN ELSE(Rail replacement standard=1:OR:

Tie replacement standard=1  
,Cumulative tie pad tonnage,0)  
~  
~ |

Tie tonnage per month =(Traffic\*axle load\*vehicles per train  
\*day per month\*axle per veh)  
~ t/Month  
~ |

Tie tonnage removal = IF THEN ELSE(Tie replacement standard=1,Cumulative tie tonnage,0)  
~ t/Month  
~ |

tonnage per month=  
Traffic\*vehicles per train\*axle load\*axle per veh\*day per month  
~ t/Month  
~ |

tonnage per month 2=  
Traffic\*vehicles per train\*axle load\*axle per veh\*day per month  
~ t/Month  
~ |

tonnage removal=  
IF THEN ELSE(Rail replacement standard=1,Cumulative rail tonnage,0)  
~ t/Month  
~ |

tonnage removal 2 = IF THEN ELSE(Ballast replacement standard=1,Cumulative ballast tonnage,0)  
~ t/Month  
~ |

## Biography of the author

The author was born in Hyogo Prefecture, Japan. He had lived in Osaka, Tokyo, Jakarta (Indonesia), Yokohama, Kamakura, and Osaka until he went to college. He went to the University of Tokyo and the Graduate School of Engineering at the University of Tokyo. He worked in the Central Japan Railway for three and a half years before he came to MIT. He worked in the track maintenance section of the Tokaido Shinkansen in Tokyo, the track maintenance office of the conventional railway lines at Nagoya, and the construction office of super conductive mag-lev (Linear Motor Car) experimental track.