CHAPTER 7

MODEL VALIDATION

In this chapter the Dynamic Track Deterioration Prediction Model and the Static Track Deterioration Prediction Model are validated against measured results. The Dynamic Track Deterioration Prediction Model is validated in terms of its dynamic behaviour as well as its ability to predict differential track settlement. The Static Track Deterioration Prediction Model is only validated in terms of its ability to predict differential track settlement. After validating the models the assumptions and simplifications that were made during the development of these models are once again listed and discussed in terms of their overall influence on the calculated predictions.

7.1 DYNAMIC BEHAVIOUR

With respect to the dynamic behaviour of the vehicle/track system the vertical displacement across the secondary suspension and the dynamic wheel load were used to compare simulated and measured results. In the comparative analysis, the vehicle and track parameters as given in Table 7.1 were used. Note that the wheelsets in the model effectively have the mass and rolling inertia of two wheelsets. Furthermore, the vertical stiffness of the primary suspension has been lowered to compensate for deflections in the side frame and the adaptor frame.

In Figure 7.1 and Figure 7.2 simulated and measured wheel loads are compared for vehicle speeds of 30 km/h and 70 km/h respectively. It can be seen that the predicted results agree reasonably well in terms of the frequency content, average wheel load and the dynamic wheel load range, with measurements taken during on-track tests when both track geometry and track stiffness variations were used as input into the vehicle model. See Table 7.2 for a summary of the dominant wheel load frequencies.

Table 7.1: Vehicle and track parameters.

Description	Symbol	Value
Mass of vehicle body	m_1	93920.0 kg
Mass of bogie frame	m_2	2620.0 kg
Mass of two wheelsets	m_w	2420.0 kg
Vehicle body moment of inertia in roll	I_1	360000.0 kgm^2
Bogie frame moment of inertia in roll	I_2	660.0 kgm^2
Vehicle body moment of inertia in pitch	I_p	1000000.0 kgm^2
Two wheelsets moment of inertia in roll	I_w	732.0 kgm^2
Vertical track damping	ρ_2	1000000.0 N/m/s
Vertical damping of primary suspension	ρ_p	20000.0 N/m/s
Vertical stiffness of secondary suspension	k_1	3881600.0 N/m
Vertical stiffness of primary suspension per bogie side	k_p	30000000.0 N/m
Stiffness of two stabilizer springs	k_{ss}	358120.0 N/m
Stabilizer spring pre-compression	x_{ss}	0.077 m
Wedge damping slope	C_{slope}	30000000.0 N/m/s
Half distance between secondary suspension	b	0.838 m
Distance between axles of one bogie	a	1.83 m
Half distance between wheel/rail contact points	l	0.55 m
Half bogie centre distance	b_{cc}	4.155 m
Wedge friction coefficient	μ	0.35

Table 7.2: Dominant wheel load frequencies.

	30 km/h			70 km/h	
Measured	0.02 Hz	0.1 Hz	0.45 Hz	0.03 to 0.1 Hz	0.23 and 0.45 Hz
Simulated	0.02 Hz	0.1 Hz	0.4 Hz	0.03 and 0.1 Hz	0.25 to 0.45 Hz

In Figure 7.2, the effect of excluding the nonlinear spatially varying track stiffness is illustrated and it can be seen that the spatially varying track stiffness has a significant influence on the dynamic loading of the vehicle on the track. What is even more important is the fact that the spatial track stiffness variations have a significant influence on differential track settlement. This is shown in Section 7.2.

In Figure 7.3 and Figure 7.4, a comparison between the simulated and measured vertical displacement across the secondary suspension is given. From these two figures it can be seen that the overall vertical displacement across the secondary suspension is approximately 3mm in both the measured and simulated cases. Although the patterns are different, higher simulated displacement generally occurs at the same point in time as in the measured results.

From the comparison between the measured and the simulated results it can be seen that the dynamic magnitude of both the dynamic wheel load and the vertical displacement across the secondary suspension compares very well with measured values. Although deviations do occur in the results, predictions are accurate enough to predict and evaluate the influence of dynamic wheel loading and spatially varying track stiffness on differential track settlement. A discussion of the assumptions that were made and why the given results are adequate for the prediction of track deterioration is given at the end of this chapter.

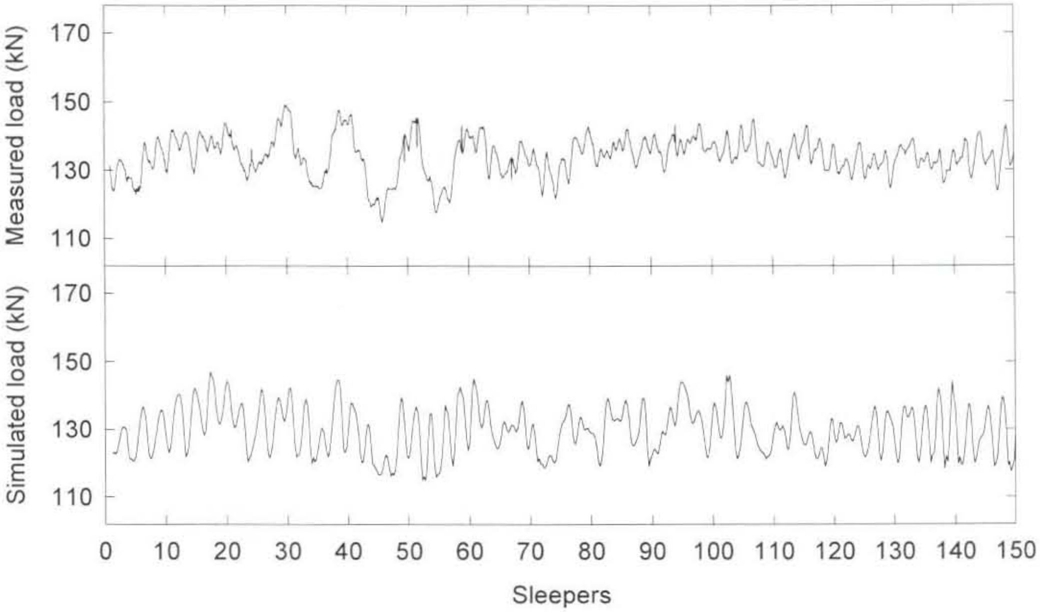


Figure 7.1: Wheel load comparison at 30 km/h.

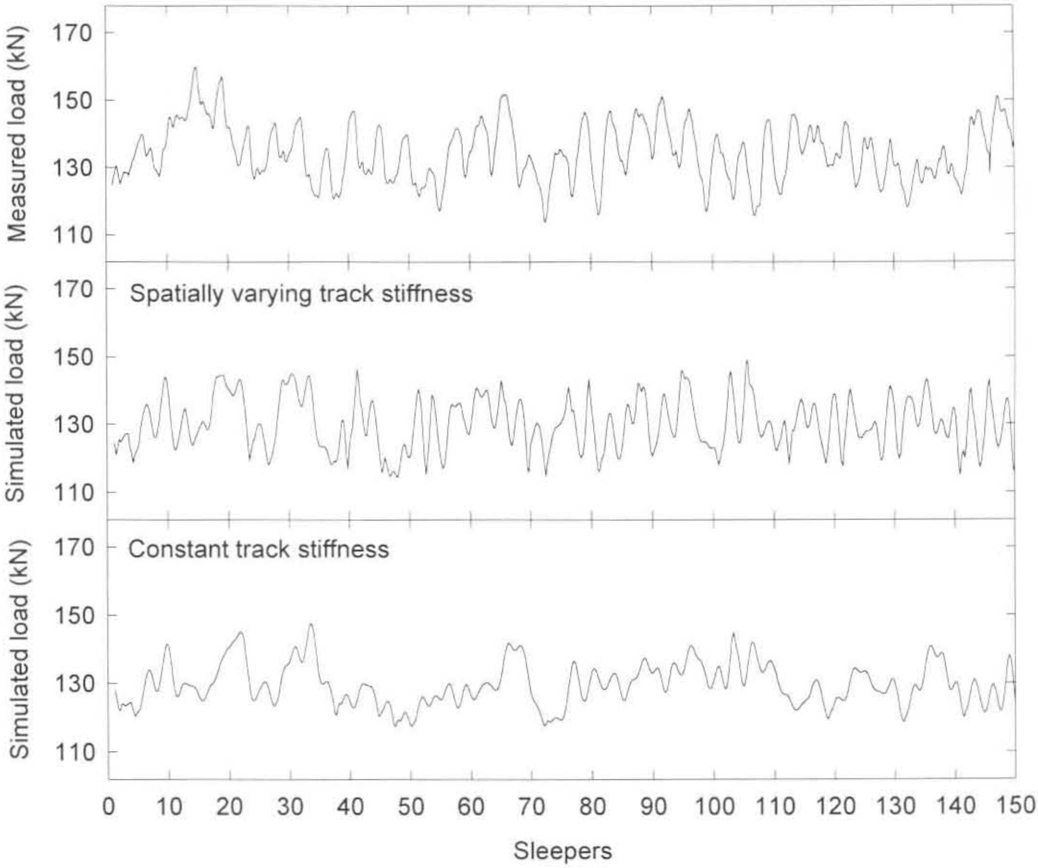


Figure 7.2: Wheel load comparison at 70 km/h.

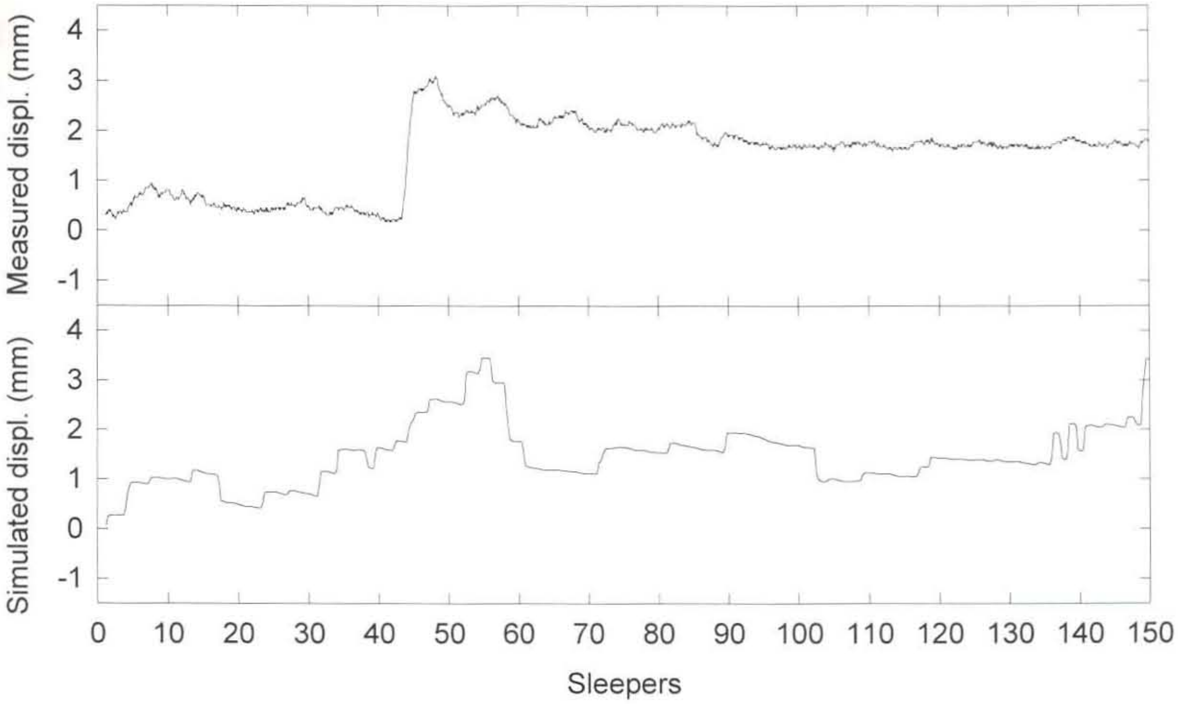


Figure 7.3: Displacement across secondary suspension at 30 km/h.

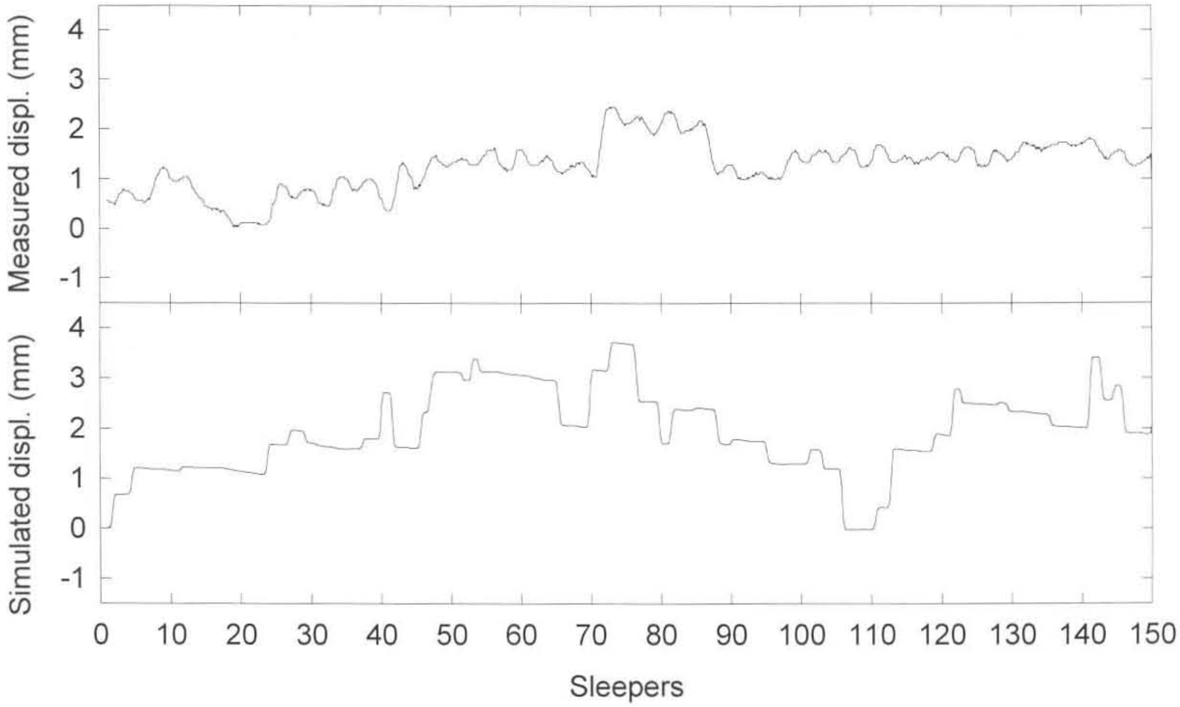


Figure 7.4: Displacement across secondary suspension at 70 km/h.

7.2 TRACK SETTLEMENT

In Figure 7.5, the measured and predicted average track settlement is shown as a function of accumulating traffic. Very little difference is observed between the two graphs, indicating a good prediction of the overall track settlement. The measured as well as predicted differential track settlement is shown in Figure 7.6. From the measured and predicted track settlement on both the left and the right hand rail it can be seen that the patterns of the differential track settlement in the latter half of both graphs is similar. The only difference is that the simulation predicted a higher overall track settlement. This difference is mainly due to the fact that only 26 ton axle loads were assumed for this prediction while in practice an axle load distribution as shown in Figure B1 in Appendix B occurred. If the lower axle load cycles would have been included in this particular simulation, the overall settlement of the track would have been predicted to be lower and thus closer to the measured settlement. The difference between the measured and predicted track settlement in the first part of both graphs can be due to a combination of the dynamic behaviour of the vehicle at the end of the transition curve, lateral track alignment deviations, and track stiffness measurements.

During the numerous simulation runs that were done to predict track settlement it was seen that the predicted results were sensitive to the spatial variation in track stiffness. As an example, the same geometric track input was used but the track stiffness was kept linear and constant at the average liniarised track stiffness throughout the section. Figure 7.7 compares the resulting track settlement with the settlement predicted when using the spatially varying track stiffness. The simulation which included spatial track stiffness variations agrees better with the measured settlement. This emphasises the important relationship between spatially varying track stiffness and track deterioration.

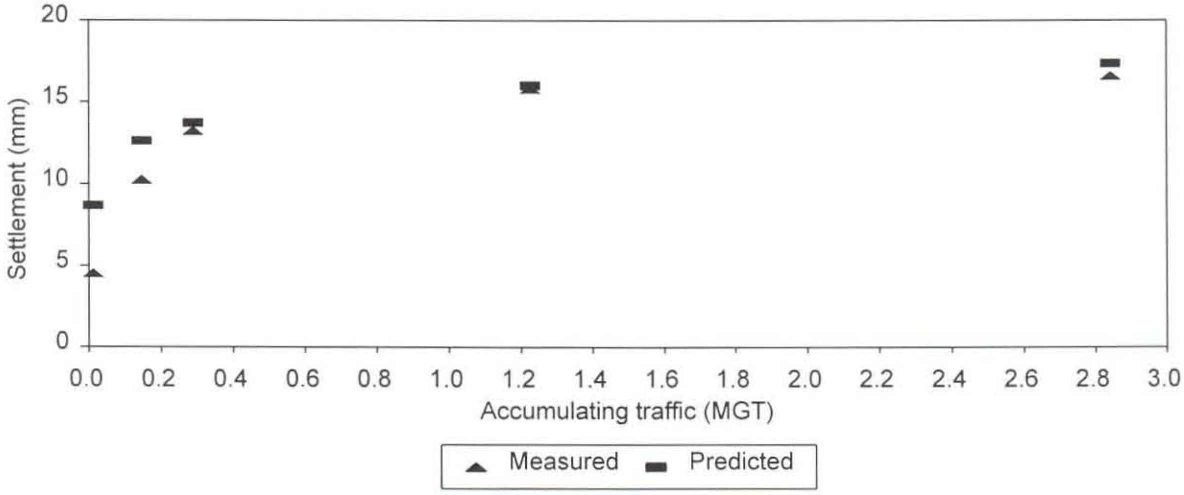
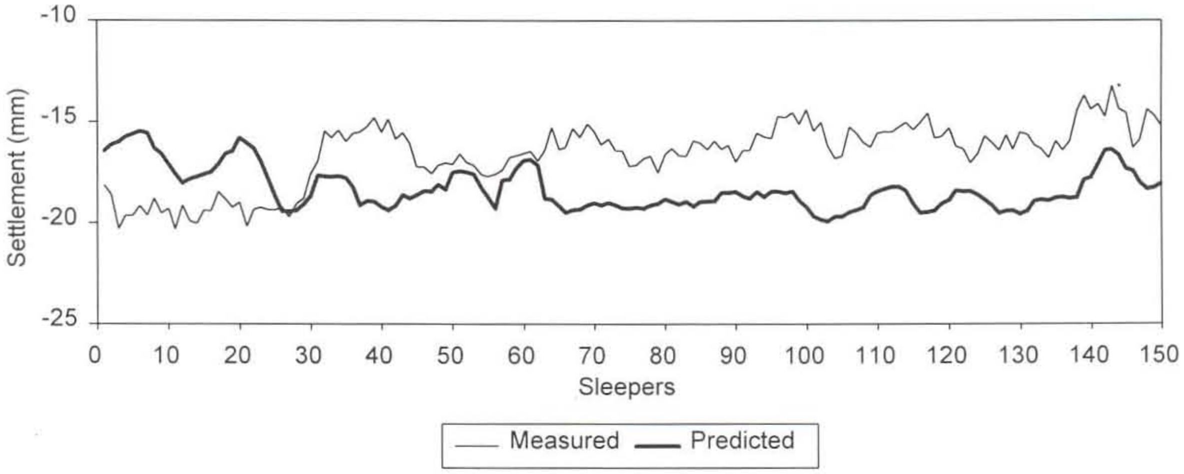
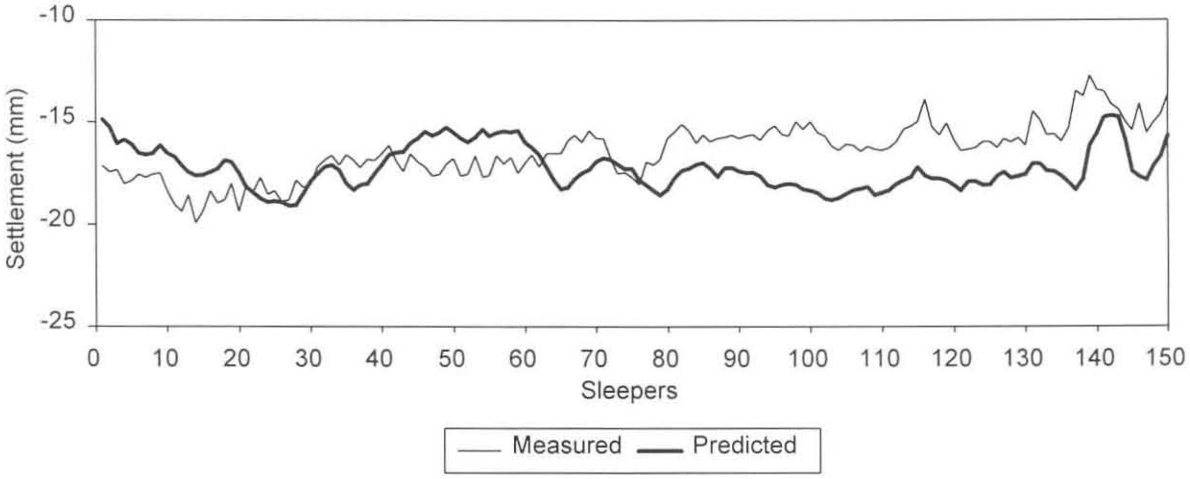


Figure 7.5: Average track settlement versus accumulating traffic.



UNDER THE LEFT RAIL



UNDER THE RIGHT RAIL

Figure 7.6: Measured and predicted track settlement.

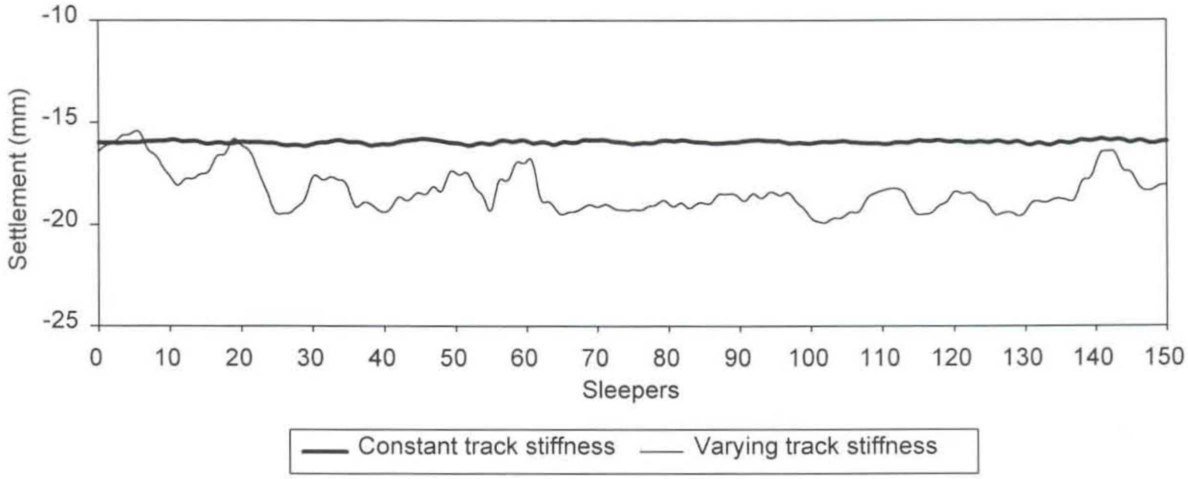


Figure 7.7: The influence of spatially varying track stiffness on track settlement.

The fact that differential track settlement is mainly a function of the spatial variation of the track stiffness can further be illustrated by looking at the wave length of spatial track stiffness variations and subsequent differential track settlement. Referring to Table 7.3, it can be seen that both the spatial track stiffness variation and the differential track settlement show dominant wave lengths of 8.1m and 32.5m. These two wavelengths also occur in the unloaded track geometry. When analysing the dynamic wheel loads, it was noticed that at the average speed of 40km/h these two wave lengths also occur but together with other shorter wave lengths which do not show up in the differential track settlement wave lengths.

In the remainder of this section the differential track settlement as predicted by the Static Track Deterioration Prediction Model is compared with that predicted by the Dynamic Track Deterioration Prediction Model. With all other conditions the same as used in the Dynamic Track Deterioration Prediction Model, the resulting differential track settlement is plotted in Figure 7.8. Comparing the track settlement that excluded the dynamic load component with that which included the dynamic behaviour of the vehicle, it can be seen that there is very little difference in the results. The reason for this small difference is the fact that the dynamic wheel load is only about 20% of the static wheel load. If the dynamic component would be higher, the influence of the dynamic wheel loading would contribute more towards the differential settlement of the track and the Dynamic Track Deterioration Prediction Model would have to be used.

Table 7.3: Wavelength analysis after 2.84 MGT.

	Wave length [m]	**Frequency at 40 km/h [Hz]**
Track stiffness	32.5	0.34
	4.64 to 8.1	1.37 to 2.39
Track settlement	32.5	0.34
	8.1	1.37
Vertical surface profile	32.5	0.34
	14.4	0.77
	8.1	1.37
Dynamic wheel load	32.5	0.34
	8.1	1.37
	4.64	2.39
	1.48	7.66
	1.14	9.75

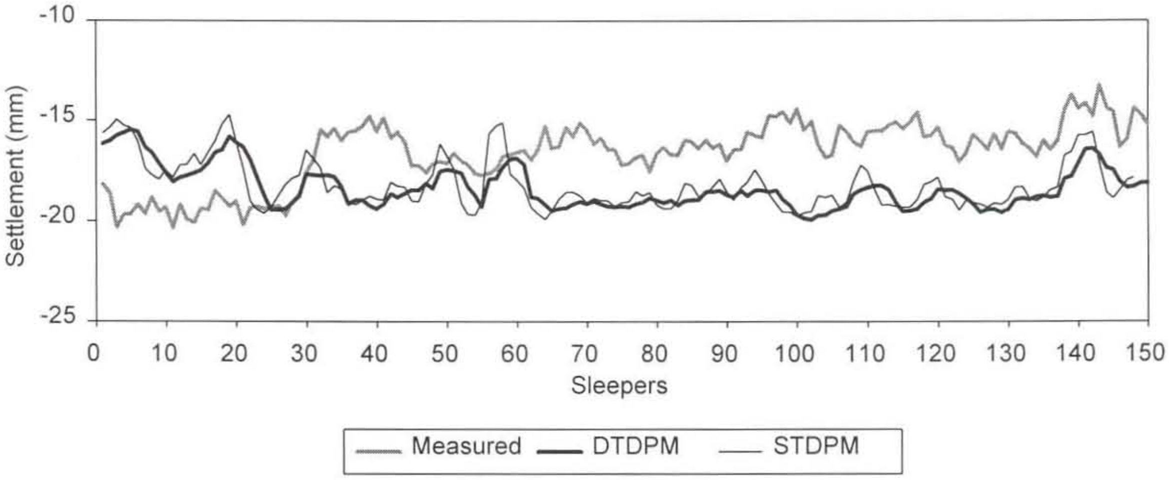


Figure 7.8: Measured and predicted track settlement including the STDPM.

Summary

As indicated, a good comparison is found between the overall envelope of predicted and measured dynamic wheel loading as well as differential track settlement. The models can thus be used to study the relationship between track stiffness, dynamic wheel load and track deterioration and to predict trends in track degradation. Specific applications are presented in Chapter 8.

7.3 ASSUMPTIONS AND SIMPLIFICATIONS

Deviations between measured and predicted results can be due to a number of issues not included in the prediction model. The most important assumptions and simplifications are listed and discussed below in terms of their overall influence on the calculated prediction.

- *No lateral track input* is included although the test section was on the end of a transition curve where deviations in the lateral alignment of the track occurred. The influence of this type of track input was not included as it would have required additional degrees of freedom and the modelling of wheel/rail contact geometry and creep. The system is thus only excited by the vertical space curve of the track and spatial variations in the vertical track support stiffness.
- *No lateral dynamics* is included in the vehicle/track model.
- *Static track stiffness* as measured by the track loading vehicle was used and assumed to be correct and similar to the actual dynamic track stiffness.
- *Constant and linear track damping* was assumed as track dynamics is not investigated as such.
- The correct *traffic mix* was not used in the analysis.
- The *condition of the ballast* was assumed to stay constant.
- *Weather conditions* like rainy spells were not included.
- *Settlement induced by vibration* through the track superstructure to the ballast was not included.

- A constant *vehicle speed* was assumed.
- It was assumed that there are no changes in *track stiffness* with accumulating traffic.

The question is now: "How can the Track Deterioration Prediction Models still be applied to predict track deterioration?" The answer is found by considering the purpose of the prediction models, which is firstly to evaluate the relationship between spatial track stiffness variations and differential track settlement, and secondly to predict the envelope of the prevailing dynamic wheel load. For both these purposes it is not essential to have an absolute match between measured and predicted values, but to be able to predict trends in terms of the dynamic wheel loads and changes in the track roughness. With this information available, improved fatigue assessment of the track superstructure is possible, and the increase in track roughness can be predicted as a function of vehicle type, axle load, vehicle speed, and the geometric as well as structural condition of the track.

The relative influence of the predicted dynamic wheel load and the measured spatial variation of the track stiffness on differential track settlement can be seen by considering Equation (4.7) and investigating the relative influence of the given parameters. The influence of these parameters is summarised in Table 7.4.

The contents of the table can be explained as follows. A 20% increase in the dynamic wheel load, which corresponds with the upper limit of the measured dynamic wheel load, causes the differential track settlement to increase by 5.6%. A lowering of the dynamic wheel load by 20% reduces the differential track settlement by 6.5%. The total variation in the dynamic wheel load of 40% thus corresponds with a 12.1% variation in the differential track settlement.

Considering all the results given in Table 7.4, it can be seen that the predicted differential track settlement is more sensitive to variations in the spatial track stiffness than to prevailing dynamic wheel loads. Furthermore, the actual measured spatial variation in the track stiffness on the particular test section is higher than the measured variation of the dynamic wheel load. This further enhances the significant influence of spatial track stiffness variations on differential track settlement as against that of the dynamic wheel load.

Table 7.4: Influence of dynamic wheel load and track stiffness variations on differential track settlement.

Parameter variation	**Differential track settlement**	
	Variation	**Range**
Dynamic wheel load variations		
Actually measured variation: + 20% - 20%	+ 5.6% - 6.5%	12.1%
Maximum expected variation: + 50% - 50%	+ 13% - 19%	32.0%
Track stiffness variations		
Variation similar to dynamic + 20% wheel load variation: - 20%	+ 9.1% - 11.5%	20.6%
Actually measured variation: + 50% - 30%	+ 55% - 30%	68.0%

Summary

The purpose of the Track Deterioration Prediction Models is to predict the dynamic loading between the vehicle and the track, the differential settlement of the track, and to evaluate the importance of including spatial track stiffness variations in the analysis and prediction of track deterioration. Furthermore, the predicted dynamic wheel loads can now be compared to those assumed by amongst others Eisenmann (1972) for defining the design limits of various track components. In this respect a more realistic dynamic wheel load is now available to establish the rate of track component deterioration. On the other hand the predicted differential track settlement can be used to predict tamping cycles as a function of the prevailing dynamic loading as well as the spatially varying track stiffness.