Evaluating Sensitivity of Parameters in Predictive Pavement Deterioration Modelling

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Evaluating Sensitivity of Parameters in Predictive Pavement Deterioration Modelling

Nabin Pradhan
HTC Infrastructure Management Ltd.

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PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone 64-4-473-0220; Facsimile 64-4-499-0733

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Contents

Executive Summary

Objective

The main objective of this Transfund funded research project is to identify the sensitive parameters which will affect the output of the analysis using the NZ dTIMS system. This will help the user on deciding which data item should be given higher priority in terms of accuracy level.

Methodology Used

The study was based on NZ conditions. The RAMM databases for five different road controlling authorities were analysed to define:

- Range of various input data available in RAMM database; and,
- Homogeneity of treatment length.

The following two analysis methods have been used:

- Traditional *ceteris paribus* (TCP) method; and,
- Factorial latin hypercube (FLH) method.

The traditional *ceteris paribus* [Lat. other things being equal] method is based on changing a single factor while holding all other constants. The advantage of this method is that it reduces the number of the parameters. However, the major disadvantage of this method is that it does not consider the interactions between different factors. This method was used to screen out the less sensitive parameter before using Factorial method.

On the other hand, factorial experiments combine all the levels of one factor with all the levels of other factors. A large number of combinations are needed to be considered while carrying out analysis. The factorial latin hypercube (FLH) method of experiment design was used because of its capability to drastically reduce the number of combinations.

The sensitivity analysis was carried out separately for the following three consecutive stages related with the predictive modelling of road maintenance management:

- Simulation of pavement deterioration prediction;
- Maintenance strategy generation based on the intervention criteria; and,
- Optimisation to select a optimum strategy for each section.

Outcomes

The study showed that:

- Establishment of the homogeneous treatment length was very important to ensure that the average condition parameter represents the section. The study shows that poorly defined treatment lengths could result in improper use of the condition parameters measured by highly precise instruments. A optimum length of treatment length should be defined based on accuracy level of parameters required for dTIMS analysis. A further study is needed on this issue.
- The sensitivity analysis showed that only a limited number of input data were found to be sensitive to dTIMS analysis. However the sensitivity level of these parameter varies a lot depending upon the years of the analysis period considered, traffic level, existing network condition and the output parameter in response to which sensitivity is considered. A table of sensitive parameters with the level of sensitivity has been prepared together with the recommendation on the process of the acquisition of the data.
- The traditional *cetrius paribus* (TCP) method based on effect of individual parameters was found to be very useful in defining which of the input parameters were sensitive. However, for prioritising/ranking the level of sensitivity, the factorial analysis method (FLH), considering the inter-reaction between parameters, was found to be more desirable.
- The stagewise approach (sensitivity to predictive modelling, sensitivity to strategy generation and sensitivity to economic optimisation) taken for the sensitivity analysis was found to be very successful in carrying out the analysis with a large number of parameters.

Recommendations

The principal recommendations from this research are as follows:

- Most of the system currently used in NZ for collection of the pavement condition data are found to be accurate enough for predictive modelling purposes as source data are smoothened by averaging to a treatment length. However, the RAMM databases analyses have shown that repeatability of the data in consecutive years are not found to be very good. Hence, more emphasis should be given to the quality control during data collection and processing including proper calibration of the instruments so that the trend analysis could be carried out.
- The way in which maintenance treatment length are generated in RAMM should be reviewed with the objective of establishing a more homogeneous section. Treatment length sections should be generated based on a number of condition parameters highly sensitive to the treatment selection procedure. Research is needed to define the parameters to be considered and a methodology to define optimum range of each parameter (based on the existing network condition and long-term performance standard) for the treatment length generation .
- There is a need to understand the sensitivity of various data items. For the missing information the RCA will have to give preference to highly sensitive data items (traffic volume, cracking, roughness, flushing, surface age,

pavement width, trigger limits and cost parameters). For less sensitive data a regional default value can be applied. For non sensitive data the national default values available in the system is generally adequate.

- The long-term performance standard, which is represented by the trigger levels in NZ dTIMS system, is found to be quite sensitive in the maintenance strategy generation and optimisation. As trigger levels are found to be influenced to a great extend on the existing network condition it is essential that proper customisation of the trigger level is done before proceeding with the dTIMS analysis.

Abstract

This report describes the results of a project to investigate sensitivity of the input parameters used for NZ dTIMS system. The objective was to identify the sensitive parameters affecting the output of the dTIMS analysis which will help the user on deciding which data item should be given higher priority in terms of accuracy level with which data are to be acquired. It was also envisaged that the study will establish which of the parameters are effectively inactive in the pavement deterioration and maintenance programme generation process.

Five RAMM databases from different road controlling authorities were used to define the range of values for the data item used in NZ dTIMS system. The tradition *ceteris paribus* method (considering sensitivity of one parameter without inter-reaction with other parameter) and the Factorial Latin Hypercube method (considering the sensitivity of input parameters with inter-relation with other parameters) were used for the analysis. The analysis was done in three stages: pavement deterioration prediction, strategy generation and economic optimisation. Non sensitive parameters related to the each stage were eliminated from the consideration in the next stage. The results showed that not all the parameters are sensitive to the modelling and only a few are quite sensitive. A list of the sensitive parameters with the magnitude of the sensitivity together with the recommendation on the data acquisition method was prepared.

Glossary

AC Agency Cost
ACA Area of all cracking
ACW Area of wide cracking
ADT1 Traffic - car
ADT2 Traffic - LCV
ADT3 Traffic MCV -I
ADT4 Traffic HCV -I
ADT5 Traffic HCV -II
ADT6 Traffic Bus
AFL Area of Flushing
AGE2 Surface age
AGE3 Base course age
APH Area of patching
APT Area of potholes
ARV Area of raveling
ASH Wheel path length of shoving
C_AM Unit rate for asphalt mix ($\$/m^3$)
C_ANC Unit rate for Ancillary works (road furniture) ($\$/m$)
C_BRN Unit rate for burning, bleeding ($\$/m$)
C_CRFL Unit rate for Crack Fill ($\$/m$)
C_CRSL Unit rate for Crack Sealing ($\$/m^2$)
C_DIG Unit rate for Digout ($\$/m^2$)
C_DRN Unit rate for Drain Improvement ($\$/m$)
C_EWRK Unit rate for Earthwork ($\$/m^3$)
C_GRAD Unit Rate for Grading ($\$/km$)
C_GRBN Unit rate for Granular Base new ($\$/m^3$)
C_GRBR Unit rate for Gran. Base reworked ($\$/m^3$)
C_GRSN Unit rate for Gran. Subbase new ($\$/m^3$)
C_GRSR Unit rate for Gran Subb. reworked($\$/m^3$)
C_GRV Unit cost of Regravelling ($\$/m2$)
C_KC Unit cost of K&C ($\$/m$)
C_MILL Milling Pavement ($\$/m^3$)
C_PTH Unit rate for patching ($\$/m2$)
C_RIPP Ripping Up The Pavement ($\$/m^3$)
C_RTFL Unit rate for rut filling ($\$/m$)
C_RTN Routine Maintenance ($\$/m^2$)
C_RTNX Routine Maintenance ($\$/m^2$)
C-SAMI SAMI Layer ($\$/m^2$)
C_SLDB Unit rate Double chip
C_SLLG Large Chip Seals ($\$/m^2$)
C_SLSM Small Chip Seals ($\$/m^2$)
C_SLSP Unit rate Special chip
C_STAB Stabilisation ($\$/m^2$)
CHIP Chip Size
CMOD Base modulus
CQ Construction quality indicator
CV Curvature
dTIMS Deighton's Total Infrastructure Management System
EA Economic Analysis
FLENGTH Length
FLH Factorial Latin Hypercube method
GROWTH_H Traffic Growth - heavy
GROWTH_L Growth of light traffic
GRVL Granular Overlay need
HDM-III Highway Design and Maintenance Standards Model
HDM-4 Highway Development & Maintenance
HBASE Depth of stabilised base
HNEW Thickness of new surfacing
HOLD Thickness of old surfacing
IRI International Roughness Index
KCI Calib. Coeff. – crack initiation
KCP Calib. Coeff. – crack progression
KGE Calib. Coeff. - environment
KGP Calib. Coeff.– roughness progression
KPI Calib. Coeff. – pothole initiation
KRO Calib. Coeff. - texture depth
KPP Calib. Coeff. – pothole progression
KRP Calib. Coeff.– rutting progression
KVI Calib. Coeff. – ravelling initiation
KVP Calib. Coeff.– ravelling progression
LANE No. of lane
M_ACA_A0 Trigger coeff. – cracking smoothing
M_ASH_A0 Trigger coeff. – shoving smoothing
M_IRI_A0 Trigger coeff. – roughness smoothing
M_RDM_A0 Trigger coeff. – rutting smoothing
MCOMP Relative compaction
MMP Mean monthly precipitation
MOIST_EFF Moisture Effect
PANA Performance Based strategy
PAV_WID Pavement Width
PBA Performance Based analysis
PCA Area of previous cracking
PCW Previous area of wide cracking
R_HS_A0 Trigger coeff.–surf.thickness resurfacing
R_IRI_A0 Trigger coeff. – roughness resurfacing
R_SC_A0 Trigger coeff. - seal cycle resurfacing
R_SFC_A0 Trigger coeff.– SFC resurfacing
R_SII_A0 Trigger coeff.– SII resurfacing
R_TD_A0 Trigger coeff.– texture depth resurfacing
R_TS_A0 Trigger coeff.- AWPT treatment
RAISE Raise and fall
RDM Mean Rut Depth
RDS Std. deviation of rut depth
RF Rise and fall
RTN Routine Maintenance only strategy
S_GOV_A0 Trigger coeff. – Granular overlay need
S_IRI_A0 Trigger coeff.– Roughness strengthening
S_MCI_A0 Trigger coeff.– MCI
SFC Side force coefficient
SII Surface Integrity index
SNP Pavement structural number
TCP Traditional Ceteris Paribus method
TD Texture depth
VOC Vehicle Operating cost

1. Introduction

The NZ dTIMS System has been implemented throughout NZ for predictive modelling of forward maintenance works programmes.

Although the NZ dTIMS analysis was designed to accommodate the existing data available, not all of the Road Controlling Authorities have all of the required data, or sufficiently accurate data for dTIMS analyses.. It is generally accepted that more comprehensive data will benefit model credibility. With limited resources available it is therefore in the interest of all users to prioritise and develop data improvement plans for given budget constraints.

This research report has the following objectives:

1. Analyse the RAMM databases to define the range of input parameters for the sensitivity study;
2. Analyse the sensitivity of input parameters used in the NZ dTIMS system for ranking of data input parameters in terms of their impact;
3. Determine which parameters are effectively inactive in pavement deterioration prediction and optimisation process, and,
4. Make recommendations with respect to prioritising the data quality enhancement process.

The report comprises the final report of the study and includes the description of the fundamental aspects of prediction modelling and economic optimisation; the methodology used to carry out the research study; and discussion on the output of the study and recommendations.

The author would like to express his appreciation to the following individuals whose support made the project possible:

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- Dr Christopher Bennett and Mr Theuns Henning of HTC for review and guidance;
- Mr Zuwei Deng for customised software development,
- the road controlling authorities who provided data for the project: Mr. Indra Gyawali of North Shore City; Mr. Alan Roland of Auckland City Design; Mr. Ian Marshall of Southland District Council and Mr. Dave Robertson of Transit NZ.

2. Overseas Experience on Sensitivity of Model Parameters

2.1 Introduction

It is important that predictive modelling users are aware of the level of sensitivity of the models to each of the input parameters so that appropriate emphasis can be given to important parameters and less emphasis to second or third order factors. That is why various studies to define sensitivity of the various parameters in HDM predictive modelling were carried out overseas. This chapter summarises the available information on the sensitivity analysis of the input parameters for predictive modelling.

2.2 HDM-4 Calibration Guide and Impact Elasticity

For the HDM-4 Calibration Guide, Bennett and Paterson (2000) defined the "Impact elasticity" on the measure for assessing the sensitivity of modelling parameters. The impact elasticity is simply the ratio of the percentage change in a specific result to the percentage change of the input parameter, holding all other parameters constant at a mean value.

For example, if a 10 per cent increase in traffic loading causes a 5 per cent increase in roughness developed after 15 years, the impact elasticity of traffic loading for that roughness is 0.5. If there were a 5 per cent decrease, the value would be –0.5.

Using the HDM-III pavement deterioration model, since HDM-4 was not completed, Bennett and Peterson presented the result in Table 2.1. These are based on the ceteris paribus method, which showed one parameter varied while all others held constant.

The higher the elasticity, the more sensitive the models predictions. Those data items with moderate and high impacts (S-I and S-II) should receive the most attention. The low to negligible impact (S-III and S-IV) items should receive attention only if time or resource permit. One usually assumes the default HDM values for S-III and S-IV items since these generally give adequate results.

The deficiency of the *ceteris paribus* method used for the above study is that it does not consider the interaction between different factors.

2.3 Mrawira, *et al.* (1998)

Mrawira *et al.* (1998) describes the results of using the factorial approach for a sensitivity analysis on HDM-III models. The factorial experiments combine all the levels of one factor with all the levels of all the other factors. A Latin hyper cube experimental design was used to investigate the sensitivity of the link characterisation input factors for several HDM-III outputs - the net present value, agency, and user life-cycle costs. The agency and user lifecycle costs were found to be dominated by very few input factors, but sensitivity and factor set are specific to the rehabilitation and maintenance strategy.

Table 2.1 Sensitivity of Various Parameters on Optimisation Process.

Sensitivity Level	Impact Elasticity[1]	Parameter	Outcome most Impacted		
			Pavement Performance	Resurfacing and Surface Distress	Economic return on maintenance
S-1	>0.50	Structural Number	●	●	●
		Modified structural number	●	●	●
		Traffic volume			●
		Deflection	●	●	●
		Roughness	●		●
S-II	0.20-0.50	Annual loading	●	●	●
		Age		●	●
		All cracking area		●	●
		Wide cracking area		●	●
		Roughness-env. factor	●		●
		Cracking initiation factor	●	●	●
		Cracking progression factor		●	
S-III	0.05-0.20	Subgrade CBR (with SN)	●		
		Surface thickness (with SN)		●	●
		Heavy axles volume		●	●
		Potholing area	●	●	●
		Rut depth mean	●	●	●
		Rut depth standard deviation	●		
		Rut depth progression factor	●		
		Roughness general factor	●		●
S-IV	<0.05	Deflection (with SNC)		●	
		Subgrade compaction	●		●
		Rainfall (with Kge)	●		
		Ravelling area		●	
		Ravelling factor		●	

Source: Bennett and Paterson (2000)

The most sensitive factors in the net present value (NPV) predictions were found to be the rutting calibration factor (KRP), the pavement strength parameters (SN, DEF), the carriageway width (W) and the initial pavement distress level (ACRA, ACRW, APOT and ARAV). This group accounted for close to 64% variability in the NPV. The next most sensitive factors in the NPV are, the roughness-environmental calibration (KGE), the level of rutting and its variability (RDM, RDS), the altitude and the pavement construction and treatment history (AGE1, AGE2, AGE3). road roughness (IRI0), cracking calibration factors (KCI, KCP) and the base layer thickness (HBASE) were also found to be active in NPV.

It should be noted that an analysis was done for the traffic level of ADT 500 veh/day and 1000 veh/day. The reason given in the Mrawira *et al.* (1998) on high sensitivity of the rutting calibration factor was that it was evaluated over a wide range and is affecting the NPV through rut depth variation and roughness, but within a normal range it would be less influential.

The study showed that the HDM-III model exhibits strong factor interactions, as well effects which are moderately non-linear, and therefore, simple sensitivity tests can not be used to separate these effects. Results also seem to be strongly dependent on the factor ranges explored. Findings show that the data requirement can be streamlined without significant compromise in the quality of the lifecycle cost.

2.4 South Africa

A sensitivity analysis study was carried out on the South African Gautrans Road Network (Wolmerans I., *et al.* 1999) by Africon Consulting Engineers. A Latin hypercube experimental design was used to create a sample database. A dTIMS setup with HDM prediction models was used to test the following response variables:

- Change in pavement condition (in terms of a composite index) after 10 years; and,
- Change in roughness after 10 years.

The same dTIMS setup was used for testing the optimisation process. The response variables used were:

- Maximum benefit in terms of condition using Area Under Curve (AUC) objective function; and,
- Maximising benefits in terms of total transportation costs using vehicle operating cost (VOC) objective function.

It was found that the variables had a moderate to high impact on the HDM prediction models (Table 2.2):

- Annual average daily traffic (AADT) and percentage heavy vehicles (PERHVY);
- Visual assessment of cracks (CRACK);
- Calibration factors for roughness progression (KGP and KCP); and,
- Structural number derived from deflection and structural information (SNC).

Table 2.3 shows that the variables ranked highest for affecting the optimisation process were:

- Annual average daily traffic (AADT) and percentage heavy vehicles (PERHVY);
- Visual assessment of cracks (CRACK);
- Mechanical measurement of roughness and rutting (HRI and RUTM);
- Calibration factors for roughness and crack progression (KGP and KCP); and,
- Structural number derived from deflection and structural information (SNC).

Table 2.2 Sensitivity of Various Parameters on Performance Prediction.

Response variable	**Chip seal**		**Asphalt**	
	Condition	**Roughness**	**Condition**	**Roughness**
Ranked Highest	KCP	AADT	KCP	AADT
	AADT	KGP	AADT	SNC
	CRACK	SNC	CRACK	KGP
	SNC	KCP	SNC	CRACK
	KPP	PERHVY	PERHVY	PERHVY
	LANES	CRACK	KPP	KGE
	PERHVY	KPP	LANES	LANES
	KRP	RUTS	MMP	HRI
	KGP	LANES	KGP	KPP
	MMP	KGE	KRP	RUTS
	PCRW	MMP	RUTM	KRP
	RAVL	KRP	DEF	MMP
	POTH	HRI	KCI	E80_FACTOR
	KCI	RUTM	SEALAGE	RUTM
	DEF	E80_FACTOR	KGE	DEF
	HRI	POTH	RUTS	PCRA
	SEALAGE	KCI	PTCH	
	E80_FACTOR			
	RUTS			
Ranked Lowest	RUTM			
Kept out	BASETYPE	BASETYPE	BASETYPE	BASETYPE
	KGE	DEF	E80_FACTOR	KCI
	KRP2	KRP2	HRI	KRP2
	KVI	KVI	KRP2	KVI
	PCRA	PCRA	KVI	PCERW
	PTCH	PCRW	PCRA	POTH
		PTCH	PCRW	PTCH
		RAVL	POTH	RAVL
		SEALAGE	RAVL	SEALAGE

Source: Wolmerans I., et al. (1999)

However it was noted that the impact of traffic on the optimisation process is far greater than any other parameters considered.

2.5 Conclusions

- The studies carried out overseas with HDM models showed that various parameters have different levels of sensitivity to pavement deterioration prediction models and economic optimisation process.
- These studies showed that sensitivity depends on the range of input values of parameters. In NZ this range varies greatly on road networks in RCAs.
- The influence of each parameter differs according to the particular parameter and also values assigned to other parameters. Hence, the sensitivity of the models are dependent on the local circumstances affecting the input parameters.

Table 2.3 Sensitivity of Various Parameters on Optimisation Process.

Response variable	**Chip seal**		**Asphalt**	
	Condition	**Roughness**	**Condition**	**Roughness**
Ranked Highest	AADT	AADT	AADT	AADT
	CRACK	PERHVY	CRACK	HIRI
	KCP	HRI	KCP	PERHVY
	HRI	SNC	HRI	SNC
	SNC	KGP	RUTM	CRACK
	RUTM	KCP	SNC	KGP
	KPP	CRACK	PERHVY	KCP
	PERHVY	KPP	KRP	KPP
	LANES	KRP	POTH	RUTS
	RAVL	RUTS	KGP	LANES
	KRP	LANES	LANES	MMP
	KGP	KCI	DEF	POTH
	KCI	RUTM	KPP	
	PCRW	KGE	E80_FACTOR	
Ranked Lowest	RUTS	RAVL		
Kept out	BASETYPE	BASETYPE	BASETYPE	BASETYPE
	DEF	DEF	KCI	DEF
	E80_FACTOR	E80_FACTOR	KGE	E80_FACTOR
	KGE	KRP2	KRP2	KCI
	KRP2	KVI	KVI	KGE
	KVI	MMP	MMP	KRP
	MMP	PCRA	PCRA	KRP2
	PCRA	PCRW	PCRW	KVI
	POTH	POTH	PTCH	PCRA
	PTCH	PTCH	RAVL	PCRW
	SEALAGE	SEALAGE	RUTS	PTCH
			SEALAGE	RAVL
				RUTM
				SEALAGE

Source: Wolmerans I., et al. (1999)

- As the impact of traffic on the optimisation process was far greater than any other parameters, to improve the analysis it would be necessary to carry out additional sensitivity analyses of the input parameters for different levels of traffic (excluding traffic as independent variable).
- No specific information on the study of sensitivity of costs and the performance standard was given in the study reports. However, it was mentioned that both cost and standard (defined by intervention criteria and level) affects pavement deterioration predictions and economic optimisation.

3. Data Collection Issues and Methods

3.1 Introduction

There are a wide range of the data required for dTIMS analyses. Some of the data required are static in nature, whereas others have to be collected at regular intervals (annually or once in a couple of years). The frequently collected data includes:

- Traffic data;
- Road condition data; and,
- Strength data.

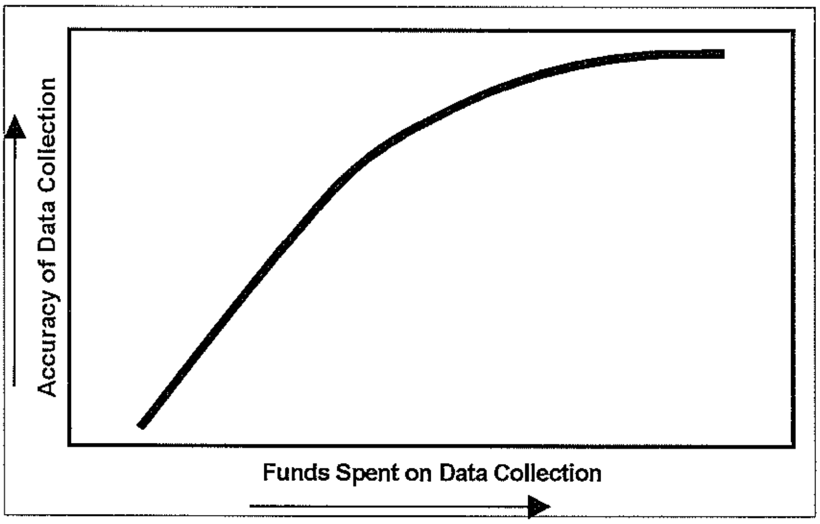
3.2 Data Quality Issues

3.2.1 Accuracy *v.* costs

RCAs have limited funds for data collection. It is therefore very important to understand what accuracy of data is actually required for a given purpose so that their funds can be effectively targeted.

One often finds that the cost of data collection has an asymptotic relationship with the resulting accuracy achieved. Figure 3.1 shows that initially an increase in the expenditure on data collection will result in an improvement in data accuracy, up to a certain point.

Figure 3.1 Relationship of Funding vs Data Accuracy.

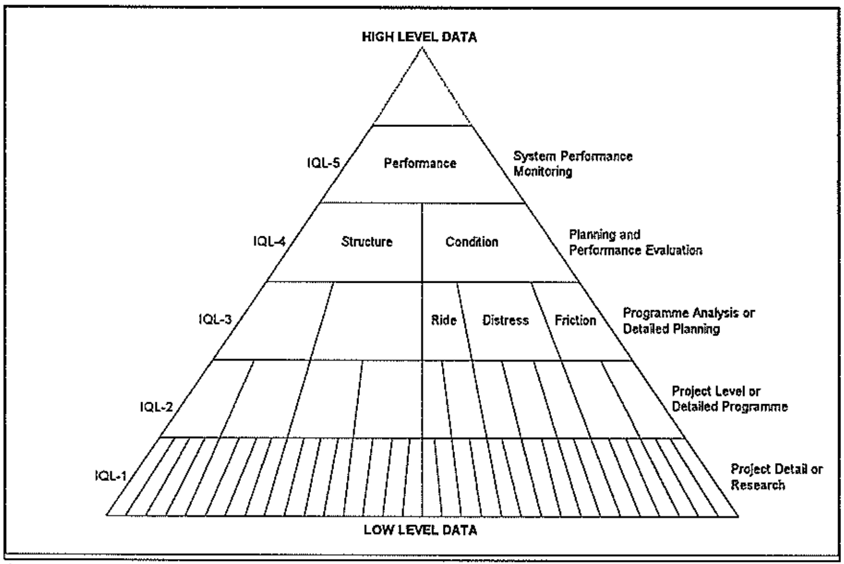


The rate of accuracy increase reaches a point where it will cost significantly more money only to gain a marginal increase in data accuracy. It is often said that one can get 80 per cent of the data quality for 20 per cent of the cost. The challenge is to find the balance between data accuracy and funding needed to achieve this. As mentioned above, this decision will be different for individual data items depending on the type and importance.

3.2.2 Data quality levels

As described in Bennett and Paterson (2000), an item of information can be presented in either simple or detailed terms. Viewed through a lens, the image of an object from a distance or great height will be seen as an outline and in general features. Close-up or at low heights, the amount of detail seen increases and other features or 'attributes' of the object can be identified. The object, or information, is the same but the quality of information has been enhanced. In some instances the general outline or overall situation is the quality of information which is required—that is the high-level or macro-level information—whereas in other instances the greater detail (micro-level) is what is required.

Figure 3.2 Information Quality Levels in Road Management.



Source: Bennett and Paterson (2000)

Hence, the information quality level to be adopted will depend on the purpose of the data collection itself.

Data collection is a costly exercise. Hence, the decision on what data should be collected, with what accuracy and frequency it should be collected, will depend on the purposes the data will be used for now and in the near future.

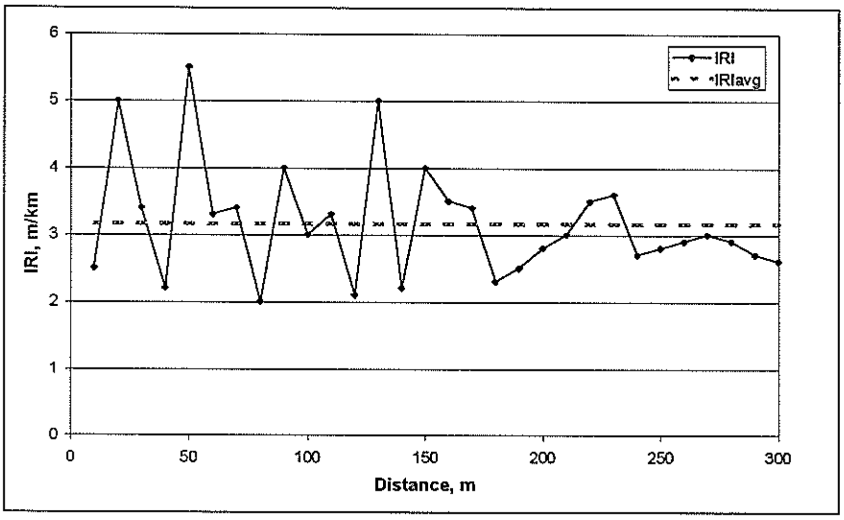
For example, pavement condition data could be used for:

- Assessing the network condition and its deterioration trend;
- Predictive modelling using PMS software such as dTIMS; and,
- Trend analysis for model calibration.

In the case of accessing the network condition for network level reporting purposes it is not essential to have the data collected with very accurate methods.

Even in the case of predictive modelling using dTIMS data collected, based on short sections, are averaged to the treatment length and, hence, data are already smoothed (Figure 3.3). Hence, only reasonably accurate methods will be required as input parameter for the models. Also, the level of analysis will affect the data. For example, programme level analysis with the aim of preparing forward work programme for five years will require less accurate data than project level analysis.

Figure 3.3 Averaging the Data to a Treatment length Section.



On the other hand trend analysis of the condition indicators *eg.* for calibration purposes, very accurate data are usually required. Benchmark monitoring sites or long-term pavement performance sites are generally used and the data collected with very high precision tools.

3.2.3 Repeatability issues

The data collection methods used should be repeatable (*ie* small differences between repeat measurements). In addition to the repeatability of the data between successive years plays a major role in the trend analysis. However, it is not economically justifiable to carry out the survey for programme level planning using the instruments and procedure used for calibration level purposes.

Bennett (2001) incorporating the study of Karamihas, *et al.* (1999) gave the comparison of the precision of roughness instruments as shown in Table 3.1. It was concluded that the standard response type measurement has a standard deviation of 3% and laser profilometers 2%.

Table 3.1 Precision of Profilometers.

Instrument	S. Dev (%)	% Within 2%	% Within 5%
Optical	2.95	72.6	95.0
ROMDAS response type meter	2.17	68.5	94.5
Laser	3.23	58.3	91.2
Ultrasonic, Commercial	5.32	42.2	77.7
Ultrasonic, Agency-built	6.47	36.4	67.1

Source: Bennett (2001)

Karamihas, *et al.* (1999) in discussing profilometers gave a number of factors affecting the repeatability of measurements including:

- Surface shape'
- Temperature variations, particularly with PCC pavements;
- Seasonal variations which affect the volume of the subsurface layers;
- Transverse variations in the roughness;

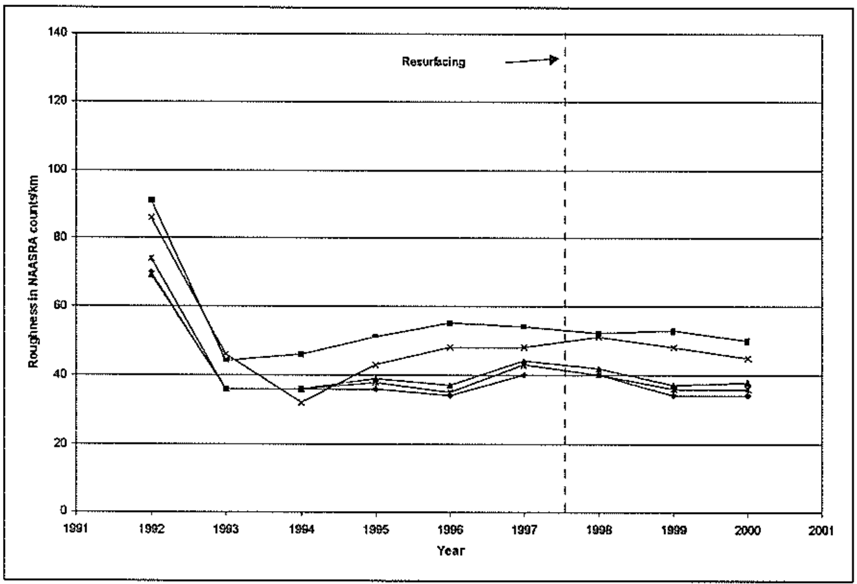
cont.

- Pavement distresses such as cracking and rutting;
- Lateral positioning of the vehicle during measurements; and,
- Profile driver and operation.

In addition, it is common for different systems to be used for collecting the network condition data in different years. The data processing procedures used by various data collection contractors may be different and this may affect the repeatability. However correct calibration of equipment should give a consistent output.

Bennett (2001) studied the roughness progression trends using the RAMM data for a number of road networks. Figure 3.4 illustrates a typical example of variation of the roughness data collected for State Highways[1] at five representative sites. The roughness data were summarised in 100 m intervals for analysis purposes.

Figure 3.4 Example of State Highway Roughness Progression.



Source: Bennett (2001)

The data shows relatively little variability and are generally consistent between years. There was a decrease in roughness after the resurfacing in 1997. Information about earlier maintenance in 1992-93 was not in the database.

The local authority data tended to show much more variation than the State Highway data which suggests a lower level of quality control. Figure 3.5 gives an example of typical RCA data. As with the State Highway data, there were situations where maintenance had obviously been done, but was not recorded in the RAMM database.

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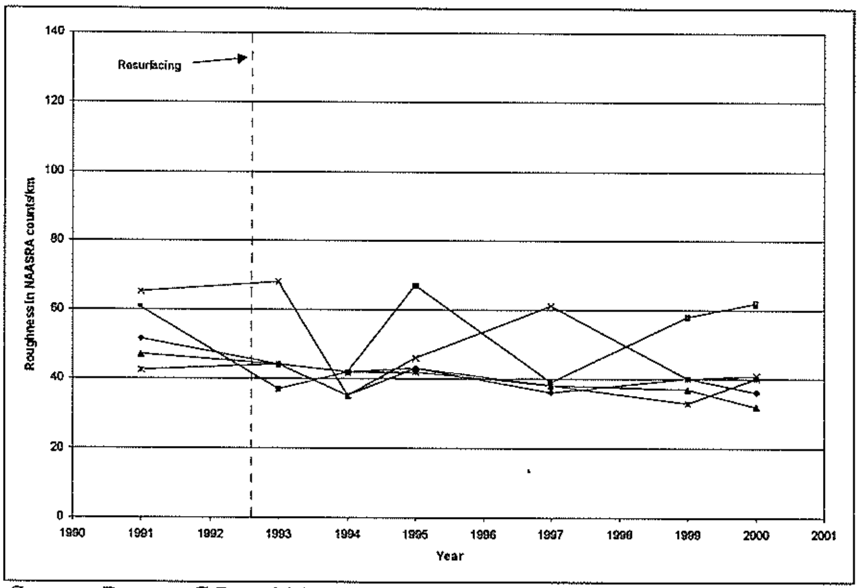
[1] The State Highways had data recorded with the NAASRA meter before 1994; an ARRB laser profilometer 1994-96; a WDM profilometer 1997-2000.

Figure 3.5 Example of RCA Roughness Progression.



Source: Bennett C.R. (2001)

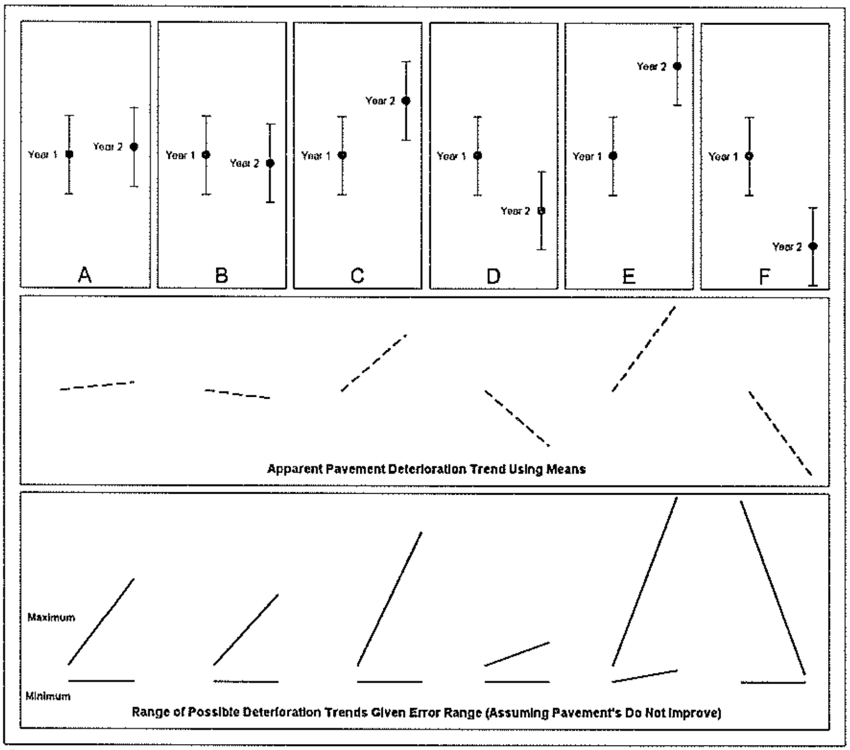
Bennett (2001) illustrates the implications of repeatability on the observed pavement deterioration (see Figure 3.6) which shows six situations drawn from the databases. There is a mean measurement and hypothetical error bars representing the confidence intervals around the measurement. On the basis of the mean there are six different cases for the trend in pavement deterioration, shown by the broken lines in the middle of the figure –

- ☐ **case A:** slight increase
- ☐ **case B:** slight decrease
- ☐ **case C:** large increase
- ☐ **case D:** large decrease
- ☐ **case E:** major increase
- ☐ **case F:** major decrease

The bottom of the figure shows the possible deterioration associated with the confidence intervals, assuming that pavements do not improve over time.

It is apparent from the examples in Figure 3.6 that the only way to obtain a reliable measure of pavement condition is by having measurements as precisely as is practical. This serves to decrease the size of the confidence interval thereby allowing for trends to be clearly observed. However, analyses of time series data from RAMM databases of various authorities showed that repeatability of the data are quite different even when the same type of equipment is used. This shows the importance of proper quality control procedure including appropriate equipment calibration and data processing to make sure that trend analysis can be done.

Figure 3.6 Implications of Confidence Intervals on Observed Deterioration.



Source: Bennett (2001)

3.3 Traffic Data

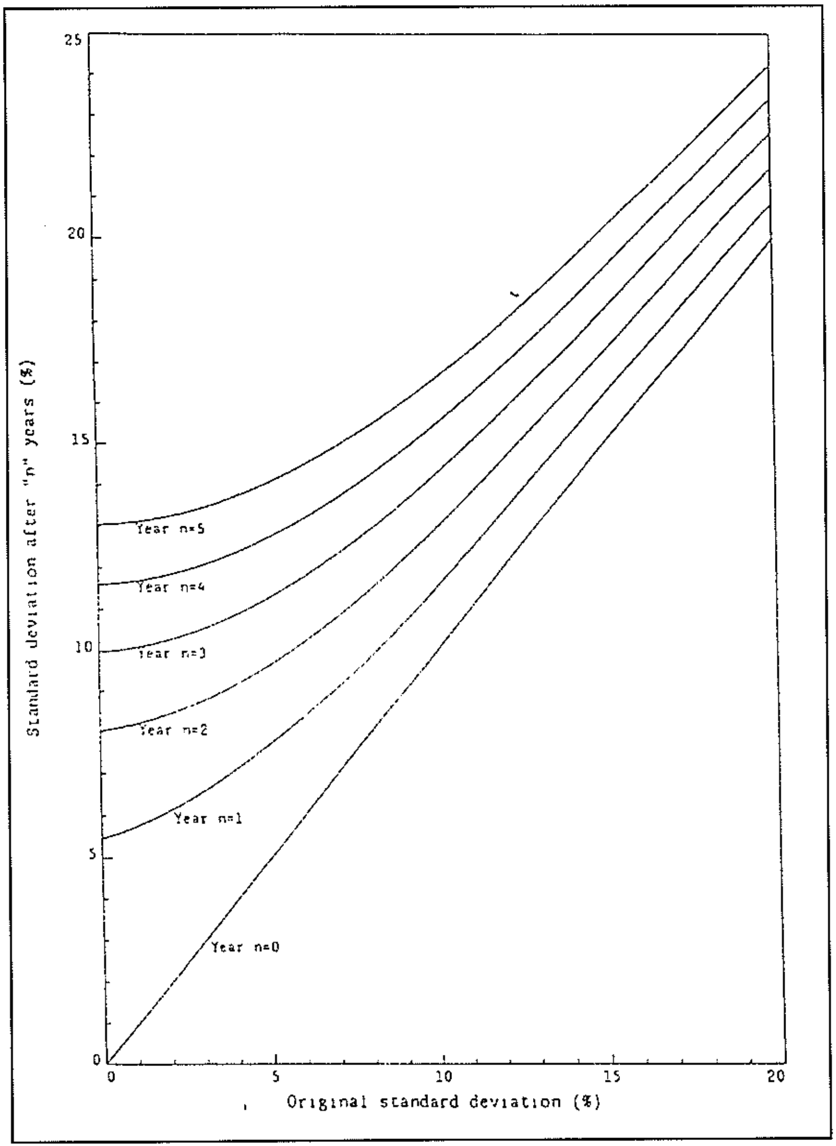
3.3.1 Traffic volume

The traffic volume data is one of the most important data items used in the dTIMS analysis. The normal practice of collecting the traffic data followed in NZ includes:

- Permanent counting stations are located at strategic points in the network whose main function are to determine trends of traffic flow in terms of daily, weekly, monthly and seasonal variations;
- Temporary counting stations cover other roads to give the traffic flow over a 7-day or 14-day period. The traffic variation for longer periods is obtained by extrapolating the permanent counting station; and,
- Temporary manual counts at intersections to determine traffic split and turning movements.

The standard deviation of the error indicates the accuracy of the historical traffic volume. Papenfus and Van As (1992) shows the relationship of the original standard deviation of the error against standard deviation after a number of years (see Figure 3.7).

Figure 3.7 Decline in Accuracy of Traffic Counts with Time.



Source: Papenfus and Van As (1992)

From this, one can conclude that roads with higher growth should be counted more often (1-2 years) than roads with low and steady growth (2-3 years). The use of traffic counts older than 3 years is not advisable. There are techniques such as moving car surveys which, when calibrated, will give reliable results for the entire network and can be collected quite rapidly.

3.3.2 Traffic growth

Traffic growth rates are not generally collected, but they are an important input to long-term pavement deterioration modelling and maintenance planning. Transit NZ gets growth rates from continuous traffic sites. However, determining the future traffic growth rate for a given road/network is a very complicated exercise. It should be based on the historical data together with the consideration of the future economic and social growth of the area.

Default values are provided by Transfund in the Project Evaluation Manual (Transfund, 1999). However, if a certain portion of the road network is facing a rapid growth it is recommended to determine the traffic growth for the subnetwork.

3.3.3 Traffic loading

Traffic loading has a influence on prediction models for pavement deterioration and can therefore also influence the long-term maintenance planning on a road network.
The axle loading on a network can be determined by the following methods:

- Permanent weigh-bridge stations;
- Portable weigh pads; and,
- Weigh-in-motion.

WIM (weigh-in-motion) stations can be temporary or permanently installed. Permanent weigh-bridge stations are expensive to construct and have limitations with regard to the coverage of the area and number of vehicles that can be weighed. For these reasons the WIM and portable weigh pads are much more popular to use for weight surveys. It must be appreciated that there is a trade-off between WIM and static surveys. WIM surveys have a lower accuracy than static surveys, but sample the entire traffic stream. Thus, there is a trade-off between precision and sample size. With the advent of low-cost portable WIM equipment they are becoming favoured by RCAs around the world for weight monitoring.

It is not required to perform axle-loading surveys on a total network. Many roads can be classified into categories of similar axle loading characteristics. A statistical sampling approach can be followed to perform these surveys on a representative portion of the network.

Provision is made in RAMM to enter the load factor in terms of the average ESAL (number of design axles) per vehicle type. Axle load factors given in Table 4.1 are used in the NZ dTIMS Setup. Although this will ensure that all road sections do have axle load data it must be emphasised that actual surveys should be conducted to establish reliable loading data. It is especially true for parts of the network where overweight vehicle permits have been issued.

3.4 Condition Data

Various road condition data are collected frequently by different road controlling authorities. The following two types of data collection methods are generally used:

- RAMM manual condition rating; and,
- Automated data collection.

3.4.1 Manual data collection

The surfacing data collected by RAMM manual condition rating and used by dTIMS analysis includes:

- Alligator cracking;
- Potholes;
- Scabbing;
- Flushing;
- Shoving; and, Rutting

The accuracy level of the manual data collection methods are usually not very good since they are based on subjective decisions. However if properly carried out this method is generally sufficient for programme and network level analysis. The data collected in the RAMM format (usually in terms of wheelpath length of defect) are converted into HDM format (usually in percentage of area) using the conversion expression developed under the NZ dTIMS project (HTC, 1999). However it should be noted that there was found to be very little correlation between RAMM wheel path length of rutting and mean rut depth.

3.4.2 Automated data collection

Automated condition data collection methods being used in NZ are given in Table 3.2.

Table 3.2 Automated Condition Data Collection Methods.

Condition Indicator	Method used	Remarks
Roughness	Response type meter Laser Profilometer	Used by most of Territorial RCAs Used by Transit and a few Territorial RCAs on arterial road
Rutting	RAMM Rating Transverse Profilometer	Used by most of Territorial RCAs Used by Transit and a few Territorial RCAs
Texture Depth	Sand Circle method Laser Profilometer	Not practical for network level Used almost exclusively by Transit for SH network
Side Force Friction	British Pendulum SCRIM Grip Tester	Not practical for network level Used almost exclusively by Transit for SH network Used for localised defects

Equipment being used in 2000 to measure roughness in NZ are as follows:

- Info 2000 - ROMDAS Bump Integrator;
- Info 2000 - ARRB 2 Laser Profilometer;
- Opus International Consultants - NAASRA meter;
- HTC – ROMDAS Bump Integrator;
- BECA - NAASRA meter;
- PMS – Greenwood Profilometer; and,
- WDM - WDM Profilometer.

The repeatability of the measurement by various instruments are given in Table 3.3.

Table 3.3 Roughness Data Collection Methods.

Instrument type	Repeatability in validation
Bump integrator	3%
NAASRA meter	3%
Laser Profilometer	2%

Source: Bennett (2001)

All of these systems give reasonably accurate results. However, recent experience has indicated that there are systematic differences in measurements, which may be attributed to different calibration procedures.

3.5 Strength Data

Pavement strength is difficult to establish on a network wide basis. The Pavement Strength program was developed by the NZ dTIMS project to assist the user in establishing pavement strengths for use with dTIMS. The data available to authorities differs and for this reason seven different methods were developed to calculate the SNC. They range from comprehensive FWD data and layer thicknesses to engineering judgement applied by the user. The methods are:

- Falling Weight Deflection (FWD) method with each layer thickness known;
- FWD method with total layer thickness known;
- FWD without layer thickness;
- Californian Baring Ratio (CBR) method;
- Benkelman Beam method;
- ARRB method; and,
- Typical Pavement method.

3.6 Treatment Length Summarisation

dTIMS analyses are carried out based on a uniformly performing 'homogeneous' section. In NZ a road is usually divided into a number of homogeneous sections called 'treatment lengths'. The available data collected based on different section lengths are summarised to the treatment length. Hence, as a treatment length cannot be absolutely homogeneous there will be a variation of road condition within the treatment length and the average value is usually taken as the representative data for that given section. Hence, the accuracy of the condition measurement after a certain limit will not give substantial improvement in the prediction of the dTIMS analysis. However, it should be noted that the data availability will also be used for the trend analysis of the road condition deterioration. In such a case a high accuracy of measurement could help to perform the trend analysis correctly.

4. Pavement Deterioration Models

4.1 Introduction

The pavement deterioration models predict pavement deterioration over time and under traffic. When maintenance work is carried out, the pavement condition is improved and the condition parameters are reset. The NZ dTIMS setup pavement performance is primarily based on the HDM III road deterioration and work effects (RDWE) models.

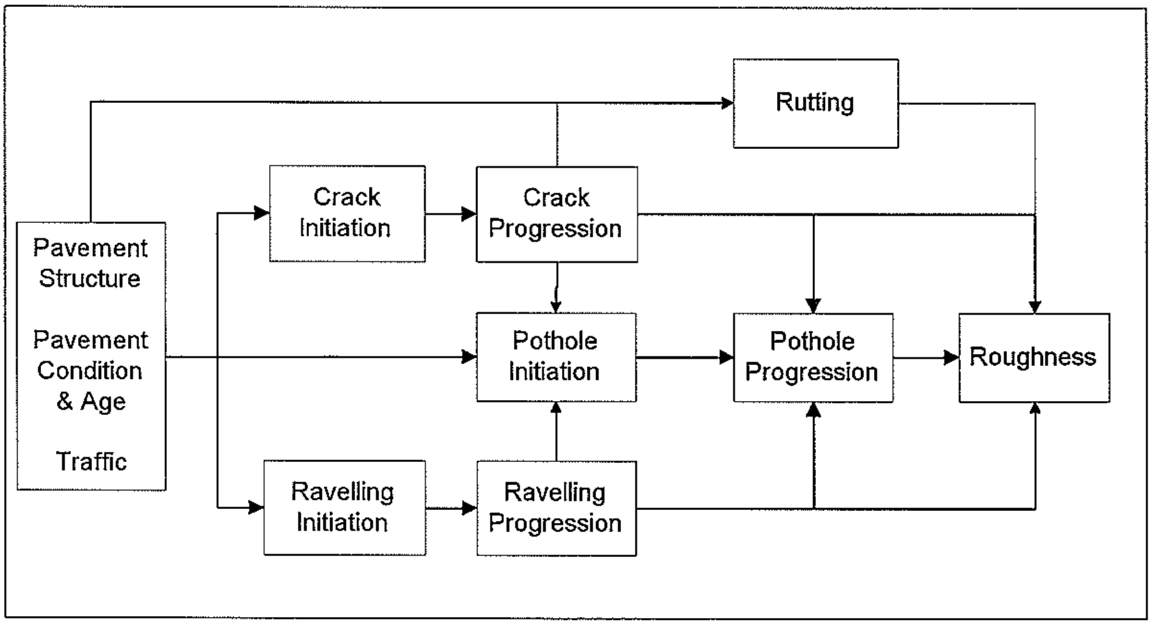
The condition parameters modelled in HDM-III models are:

- Cracking;
- Ravelling;
- Potholes;
- Rutting; and,
- Roughness.

It should be noted that ravelling (scabbing) progression is turned off in the current NZ dTIMS setup, as the HDM ravelling model did not give a reasonable prediction in the NZ situation.

There is an interaction between these distresses since they develop and progress from minor to major distresses (Figure 4.1).

Figure 4.1 Interaction of HDM-III Distresses.



In addition to the above, the following condition parameters using locally developed models are in the NZ dTIMS Setup:

- Texture depth; and,
- Side force friction.

Each of the condition models and major factors affecting the models are briefly described in this chapter.

4.2 Traffic Characteristics

Traffic data required for predictive modelling are characterised by:

YE4 – Number of equivalent standard axle load (ESAL) in million vehicles per year

YAX – Number of axles in million axles per year.

To define these parameters the following characteristics of the roads are required:

- Traffic volume;
- Traffic distribution/loading; and,
- Traffic growth.

Traffic in the NZ dTIMS Setup is classified into 6 different groups. Descriptions of the traffic groups and default equivalent axle loads are given in Table 4.1.

Table 4.1 Traffic Parameters in NZ dTIMS.

dTIMS parameters	Description	ESAL
ADT1	AADT - Car, veh/day	0
ADT2	AADT – Light Commercial Traffic, veh/day	0
ADT3	AADT – Medium Commercial Vehicle, veh/day	0.35
ADT4	AADT – Heavy Commercial Vehicle type 1, veh/day	0.83
ADT5	AADT – Heavy Commercial Vehicle type 2, veh/day	1.86
ADT6	AADT – Bus, veh/day	0.5
GROWTH_L	Traffic Growth Rate – Light vehicles (%p.a.)	N/A
GROWTH_H	Traffic Growth Rate – Heavy vehicles (%p.a.)	N/A

Source: HTC (2001)

4.3 Construction Quality

The performance of the pavement depends on the construction quality. Poorly constructed roads deteriorate faster. Construction quality, represented by CQ, in the NZ dTIMS setup, is taken equal to 0 for good construction and 1 for unsatisfactory construction quality.

4.4 Pavement Strength

The performance of the pavement depends on its structural strength. The modified structural number SNP is used as a means to quantify the pavement's structural number.

4.5 Calibration Coefficients

The rate of the pavement deterioration could be different between two roads in different locations even if the pavements have exactly the same characteristics. The calibration coefficients are used to customise the pavement deterioration models.

The calibration coefficients and their default values used in the NZ dTIMS setup are given in Table 4.2.

Table 4.2 Calibration Coefficients.

dTIMS Parameters	Description	Default Values
KCI	Calibration coefficient – crack initiation	1
KCP	Calibration coefficient – crack progression	1
KVI	Calibration coefficient – ravelling initiation	0
KVP	Calibration coefficient – ravelling progression	0
KPI	Calibration coefficient – pothole initiation	1
KPP	Calibration coefficient – pothole progression	1
KR0	Calibration coefficient – rut depth progression – year 1	1
KRP	Calibration coefficient – rut depth progression	1
KGP	Calibration coefficient – roughness progression	1
KGE	Calibration coefficient – environmental coefficient	1

4.6 Condition Parameters

4.6.1 Cracking

The Cracking model is the first model evaluated in the deterministic modelling sequence of the HDM-III model. Cracking is subdivided into two phases, namely:

- The time until the initiation of cracking, which was defined as an area of all cracking of 0.5% or more, over the pavement section under evaluation; and,
- The rate of progression of the area cracked.

Both the above phases are further subdivided into all cracking and wide cracking. The cracking progression used in the NZ dTIMS system is a time based model and primarily a function of the existing cracks. The cracking initiation is the function of:

- Traffic loading;
- Pavement strength;
- Construction quality;
- Surfacing thickness; and,
- Previous surface distress.

The expressions with the parameters mentioned above used in the NZ dTIMS setup to calculate the cracking are given in Appendix A.

The parameters used in the cracking expressions together with the corresponding dTIMS fields are given in Table 4.3 (*page* 34).

Table 4.3 Parameters Affecting Cracking Models.

Parameters	Relevant dTIMS Fields	Description	Composite[1] Index	Remarks
TYCRA	ICA	All crack initiation period (year)	•	
TYCRW	ICW	Wide crack initiation period (year)	•	
Kci	KCI	Calibration – crack initiation		
Fc		Occurrence distribution factor		Hard coded in NZ setup
SNC	SNP	Adjusted structural number		
YE4	YE4	Annual ESA per lane	•	Function of traffic
CQ	CQ	Construction quality indicator (0, 1)		
PCRW	PCW	Previous wide cracking (%)		
PCRA	PCA	Previous all cracking (%)		
HSNEW	HNEW	Thickness of last surfacing (mm)		
CRT		Crack retardation time		Not considered in NZ Setup
HSE	HBASE	Thickness of stabilised granular base (mm)		Function of HNEW, HOLD, KW
KW	KW	Wide cracks in old layer factor	•	Function of PCW
KA	KA	All cracks in old layer factor	•	Function of PCA
CMOD	CMOD	Modulus of Base (cemented only)		
DEF		Benkleman Beam Deflection		Automatically calculated from SNP value in NZ setup
ACR	ACA	All cracking (%)		
DACR	DCA	All cracking – increment	•	
CRP	KCP	Calibration – crack progression		

Note: 1/ No data input required for composite index as it is calculated based on other parameters

4.6.2 Ravelling

HDM III Ravelling (also known as scabbing) is also modelled in two phases, namely:

- The time before initiation of ravelling; and,
- The progression of the area ravelled once initiated.

The ravelling models are available in the NZ dTIMS Setup. But these models are turned off by assigning a calibration coefficient of 0.

4.6.3 Potholes

The potholing model is the third model in the modelling sequence. The reason for this being the fact that potholing was considered to develop from spalling of wide cracks or the ravelling of thin surface treatments (Watanatada *et al*, 1987). As with the previous two models, the potholing model is also divided into two phases, namely:

- The initiation of potholing defined as a function of the time since the initiation of the triggering distress, which is either wide cracking (>20%) or ravelling (>30%) for a surface treatment; and,
- The progression of potholes which is the result of new potholes caused by wide cracking or ravelling, and the enlargement of existing potholes.

The initiation period of potholes is a function of:
- Traffic volume; and,
- Thickness of bituminous layer.

The progression of the pothole is based on:
- Existing cracked surface;
- Traffic volume;
- Thickness of bituminous layer;
- Effective width;
- Construction quality; and,
- Pavement strength.

The expressions of pothole initiation and progression used in the NZ dTIMS setup are given in Appendix A.

Parameters required for the modelling of potholes in addition to that required for the Cracking models are given in Table 4.4.

Table 4.4 Additional Parameters for the Potholing Models.

Parameters	Relevant dTIMS Fields	Description	Composite[1] Index	Remarks
TMIN		Pothole Initiation Period (yr)		
HS	HBASE	Thickness of base (mm)		
YAX	YAX	Annual number of axle in millions per year per lane	•	Calculated based on other traffic data
W	PAV_WID	Pavement width (m)		
ELANES		Effective Lane Width		Effective width 3 m taken, ELANES not considered
MMP	MMP	Rainfall (m/month)		

Note: 1/ No data input required for composite index as it is calculated based on other parameters

4.6.4 Rut Depth

The rut depth progression modelling consisted of two models namely:
- Mean rut depth model; and,
- Rut depth standard deviation model.

The mean rut depth model is not used directly in the HDM III roughness model, but instead is used as a means to estimate the variation of the rut depth (standard deviation) which contributes directly to the roughness model.

The mean rut depth model and the rut depth standard deviation models used in the NZ dTIMS setup is given in Appendix A.

The parameters required for the modelling of rut depth are given in Table 4.5.

Table 4.5 Additional Parameters for Rut Depth Models.

Parameters	Relevant dTIMS Fields	Description	Composite Index[1]	Remarks
RDM	RDM	Mean rut depth (mm)		
DRDM	DRM	Mean rut depth – increment (mm)	•	
AGE3	AGE3	Years since (re)construction of base		
CRX	ACX	Indexed cracking – total	•	
DCRX	DCX	Indexed cracking – increment (mm)	•	
RH		Rehabilitation indicator		Hard coded in NZdTIMS setup
RDS	RDS	STD of rut depth (mm)		
DRDS	DRS	STD rut depth – increment (mm)	•	

Note: 1/ No data input required for composite index as it is calculated based on other parameters

4.6.5 Roughness

Roughness is the last model in the HDM-III modelling sequence. The model combines the predictions of all the previous models into a single value, which forms the basis for determination of vehicle operating costs.

All the parameters used in the roughness increment models were included in the other models described earlier.

4.6.6 Texture Depth

The Texture Depth model, although included in the NZ dTIMS setup, is not always giving reasonable results. Hence, sensitivity of parameters affecting the texture depth model has not been considered in this study.

4.6.7 Side Force Friction

The Side Force Friction (SFC) model, available in the NZ dTIMS setup, is not fully tested. No sensitivity of the SFC models has been carried out in this study.

4.7 Works Effect Models

When a treatment is applied, the condition of the network will have to be reset. The reset values could be based on:

- Absolute values;
- Percentage of the previous value;
- Ratio of the previous value; or,
- Based on an expression.

The reset values will have a considerable effect on pavement deterioration. However, as all the condition indicators are already considered as the original input parameters it was decided not to include the reset values in the sensitivity analysis.

4.8 Output Parameters for Comparison

The output parameter selected should be able to represent the overall response of the input parameters. Usually second level models which are used for this purposes.

All the condition parameters used in the HDM-III models effect the roughness value. Roughness (IRI) is used as a triggering parameter for maintenance treatment and also affects the road user cost, which has an effect on the optimisation process. Hence, roughness has been selected as one of the output factors for the sensitivity analyses.

Similarly, the surface integrity index (SII), can represent the overall condition of pavement surface. It is a function of cracking, scabbing, shoving, potholes, flushing and surface age, and represents the condition of the road surface. Hence, it can be used as an output parameter.

$$S11 = \text{Min}\,(100,\ (4\times ACA+0.5\times ARV+80\times APT+1.2\times AFL+3\times \text{Max}\,(0,\ AGE2-SLIF)))$$

where ACA is area of all cracking in %
ARV is area of ravelling in %
APT is area of potholing in %
AFL is area of flushing in %
AGE2 is surface age in years
SLIF is estimated surface in years

4.9 Conclusions

- All the pavement deterioration models based on HDM-III are related to each other and need to be analysed together.
- Texture depth and side force friction models are independent in nature and can be analysed separately. However, as the NZ models are not always giving reasonable results they were not considered in the study.
- All the condition parameters used in HDM-III models effect the roughness value and can be used as a output factor for the sensitivity analyses.
- The surface integrity index (SII) provides the information about the surface distress and hence can be used as an output parameter.

5. Maintenance Strategy Generation and Optimisation

5.1 Overview

NZ dTIMS, based on various parameters during the strategy generation period generates various alternative maintenance strategies for each section of the road based on the intervention criteria used. During the optimisation process one of the generated strategies is selected for each road section.

5.2 Analysis Modes in NZ dTIMS

The NZ dTIMS system operates in two fundamentally different modes:

- Performance based mode; and,
- Economic mode.

The performance based analysis (PBA) defines the funding required for maintaining a given road network based on a given long-term performance standard. Hence, by modifying the trigger limits (which defines the performance standard) the user can define the optimum long-term performance standard for a given road network. The budget is kept unlimited while conducting PBA analysis.

In the economic mode of analysis (EA) a number of maintenance strategies for a given road sections are generated, based on all potential first treatments for the road section. The subsequent treatments are triggered in response to the condition of the road. The selection of the optimum strategy under budget constraints for each given road section is usually based on the economic optimisation process.

5.3 Strategy Generation Process

5.3.1 Strategy for PBA

In the performance based mode only one maintenance strategy (excluding do nothing and routine maintenance only) is generated. When the condition of the road exceeds certain levels or trigger limits the given section will be flagged to carry out one of the following three levels/categories of maintenance:

- Strengthening;
- Smoothing; or,
- Resurfacing.

The intervention criteria based on constraints is used to choose one of the default treatments available for the given maintenance level.

Trigger limits are used to define the intervention level and, hence, determine the long-term performance standard in the NZ dTIMS system. In the NZ dTIMS system the following road condition parameters are used for defining the trigger limits for various treatments (*page* 40):

- Cracking;
- Scabbing;
- Rutting;
- Potholes;
- Roughness;
- Flushing;
- Shoving;
- Texture depth;
- Skid Resistance; and,
- Pavement Strength.

Parameters used as trigger limits used in the NZ dTIMS System are given in Table 5.1.

Table 5.1 Trigger Limit Parameters.

Strengthening	Smoothing	Resurfacing
Roughness (IRI)	Roughness (IRI)	Surface Integrity Index (SII)[1]
Maintenance Cost Index (MCI)	Rut depth (RDM)	Roughness (IRI)
Granular Overlay need (GOVL)	Shoving (ASH)	
	Cracking (ACA)	

Note: 1/ SII is a function of cracking, scabbing, potholes, flushing, surface age and surface life.

A continuous trigger limit is used in the NZ dTIMS system. The trigger limit for a given condition index is a function of traffic and is given by the following expression:

Trigger limit = a0 – a1×LOG (AADT)

where a0 and a1 are the trigger coefficients and LOG is the *natural* logarithm
AADT is the total average daily traffic in veh/day

Trigger coefficients are assigned to each road section through the dTIMS input file. Hence by varying the trigger coefficients it is possible to change the trigger limits for different types of treatment for a given road.

5.3.2 Strategy generation for economic analysis

In the case of the economic analysis (EA) mode, strategies with the first treatments representing strengthening, smoothing and resurfacing categories are generated for every year for the programme generation period. No consideration of the road network condition is made during this process and the treatment is selected based on the constraints for applying a given treatment. The following or the subsequent treatment will be triggered based on the trigger limits. Hence, trigger limits play an important role in EA analysis also.

5.3.3 Trigger limits *v* constraints

The trigger limits could affect the strategy generation process and define what level of maintenance should be applied to a given section. Hence, the long-term performance standard for a given road is basically defined by the trigger limits.

On the other hand constraints ensure the right treatment of given maintenance category level is applied (i.e. surface treatment not asphalt concrete is applied for the road with AADT 500 veh/day). As the cost as well as improvement from selecting one treatment rather than another for the same treatment category/ level does not vary too much the impact on predictive modelling is not as much as trigger limits.

Experience has shown that due to the following reasons it is essential to customise the trigger limits for a given road network:

- Existing condition of the road network will define what performance standard could be realistically achievable;
- Availability of funding will define how much money could be spent on the maintenance of the road; and,
- Policies of the given road controlling authorities and the expectations of the road users also defines the performance standard to be maintained.

As it will be necessary to change the trigger limits, it was considered to carry out sensitivity of the triggers to find out which of the triggers should be given higher priority in customisation.

5.4 Cost Factors

5.4.1 Agency Cost

The agency cost includes construction and maintenance cost during the analysis period. For an existing road it is maintenance cost. The maintenance cost could be:

- Strengthening cost (e.g. reconstruction, major rehabilitation);
- Smoothing cost (e.g. rehabilitation);
- Resurfacing cost (e.g. resealing, thin asphalt overlay); or,
- Routine Maintenance.

In the NZ dTIMS Setup agency cost is estimated based on the unit cost expressions. The estimated quantity of the various maintenance activities is multiplied by their unit cost to get the agency cost.

The unit cost for each treatment in the dTIMS setup is given in expression. For example the cost expression for recycling is:

$$\begin{gathered}\mathrm{F\_MYL} = \mathrm{FLENGTH} \times 1000 \times \mathrm{PAV\_WID} \times (\mathrm{C\_RIPP} \times 0.100 + \mathrm{C\_GRBR} \times 0.100 + \mathrm{C\_GRBN} \times 0.025 + \\ \mathrm{C\_STAB} + \mathrm{C\_SLLG}) + \mathrm{FLENGTH} \times 1000 \times \mathrm{C\_ANC} + (\mathrm{KC\_LEN} \times \mathrm{C\_KC}) \times 0.4\end{gathered}$$

The maintenance activities included in the cost expression are defined in Table 5.2 (*page* 42).

Table 5.2 Calculation of Treatment Cost.

Activity	Unit Cost	Quantity	Remarks
Ripping	C_RIPP * ($/m^3)	(FLENGTH * 1000) * PAV_WID* **0.1**	Ripping depth assumed **100** mm
Granular base rework	C_GRBR * ($/m^3)	(FLENGTH * 1000) * PAV_WID* **0.1**	Granular base rework depth assumed **100 mm**
Granular base addition	C_GRBN * ($/m^3)	(FLENGTH * 1000) * PAV_WID* **0.025**	New granular base assumed **25** mm
Stabilisation	C_STAB * ($/m^2)	(FLENGTH * 1000) * PAV_WID	Stabilisation of the base course
Sealing	C_SLSG * ($/m^2)	(FLENGTH * 1000) * PAV_WID	Seal with grade **4** chip
Extra items (site establishment)	C_ANC * ($/m)	(FLENGTH * 1000)	
Kerb & channel replacement	C_KC * ($/m)	(FLENGTH * 1000) * **0.4**	Assumed **40%** kerb and channel has to be replaced

Note: The coefficients in bold are the ones which might need some modifications based on the local maintenance practice

Agency cost is a part of the total transportation costs and, hence, affects the optimisation process. The total agency cost generally depends on:

- Existing condition of the road network;
- Long-term standard of the road followed by a given agency; an,
- Unit cost of various maintenance activities; etc.

As the agency cost directly affects the economic optimisation it is essential to find out the sensitivity of the unit costs of various maintenance activities to decide on which of the activities the user should give preference to customisation.

5.4.2 Road user costs

Road user costs are comprised of:

- Vehicle operating costs (VOC);
- Travel time costs; and,
- Accident costs.

Only VOC are considered in the NZ dTIMS setup. These comprised:

- Fuel consumption;
- Lubricating oil consumption;
- Tyre wear;
- Parts consumption;
- Maintenance labour hours;
- Depreciation;
- Interest;
- Crew hours; and,
- Overheads.

As the cost of each component varies with locality and time the VOC will also vary and could have a major impact on the economic optimisation process. The VOC for NZ are standardised by Transfund NZ to ensure that the same base is used for the whole country. The VOC for each vehicle km in the NZ dTIMS setup is based on the Transfund Project Evaluation Manual (PEM) (1999). The expressions used are provided in Annex D and were developed growth PEM data. It should be noted that only the vehicle operating cost, but not travel time cost or accident cost are considered in the PEM.

The total VOC are a function of:

- Roughness;
- Traffic volume; and,
- Type of vehicles.

Roughness itself is a function of the other condition parameters, and hence represents the cumulative effect of the road condition on the VOC.

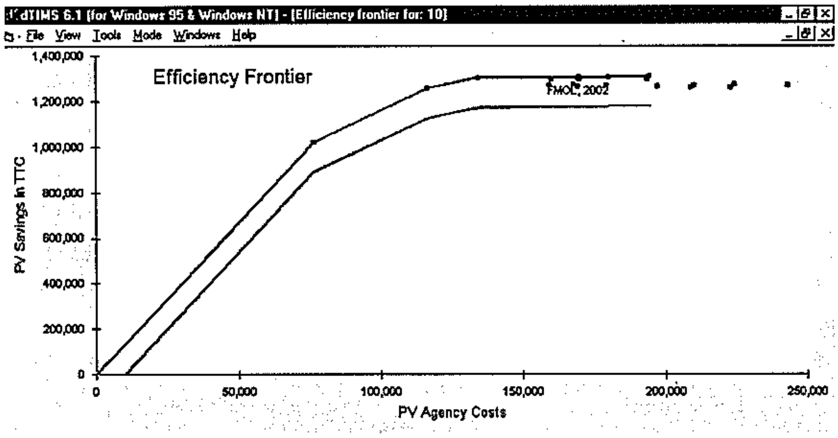
Since Transfund updates the vehicle operating cost rate from time to time, and, hence, it was considered necessary to carry out the effect of changing the VOC rates in the sensitivity of various input parameters.

5.5 Optimisation Process

5.5.1 Incremental benefit cost ratio optimisation

The optimisation technique used by dTIMS is based on the incremental benefit-cost ratio. The benefit-cost ratio is defined as the ratio between increase in benefit to the increase in cost for successive strategies. Figure 5.1 illustrates the efficiency frontier, which is also one of the outputs provided in dTIMS. The vertical axis shows the present value of benefits and the horizontal axis the present value of the costs. Each point on the graph represents a strategy. The segmented line connecting the uppermost points is the efficiency frontier. Note that the line starts at the do-nothing alternative and connects the dots in such a way that no line segment has a slope bigger than the slope of the previous segment. No points exist above the efficiency frontier.

Figure 5.1 Example of dTIMS Efficiency Frontier.



Optimisation of multiple treatments, sections and years involves some uncertainty in the results. Recognising the existence of uncertainty means that some treatment options lying close to the economic boundary should also be included in the analyses. To cope with this dTIMS creates an 'envelope' around the bottom of the economic boundary, and treatment options falling within this are included in the optimisation process. This increases the number of options available for selection, and can also result in producing a 'smoother' annual budget requirement than the deterministic approach.

The heuristic optimisation in dTIMS is performed the following steps (Deighton, 1998):

1. All strategies are sorted in descending order of incremental benefit cost regardless of the section they are on;
2. dTIMS starts at the top of the list and checks whether there is enough money in the budget in each year to cover the yearly cost of that strategy. If there is, that strategy is selected for that element;
3. The available budget in the respective category is reduced by the annual yearly costs of the treatments for the selected strategy; and,
4. dTIMS continues down the list doing the same process for each strategy on this sorted list.

5.5.2 Optimisation objective functions in dTIMS

The dTIMS program can carry out the optimisation based on the following 3 different objective functions:

- Total transportation costs;
- Vehicle operating costs; and,
- Area under curve.

In NZ dTIMS by default, the total transportation cost objective function is used while carrying out the economic optimisation. In the optimisation process the optimum strategy for each road section is selected based on minimisation of the total transportation cost of the whole road network for a given funding level. The same process is used during the sensitivity analysis in this study.

5.6 Conclusions

- Trigger coefficients define the long-term performance standard and hence have considerable effect on the sensitivity of the pavement deterioration prediction as well as on economic optimisation;
- A sensitivity analysis of the trigger limits needs to be carried out on the PBA mode. Only the most sensitive trigger coefficients should be considered during the sensitive analysis of the parameters affecting the economic optimisation.
- As the cost parameters affect the economic optimisation process, it is essential to analyse the sensitivity of these factors.
- As the road user cost rates are updated by Transfund from time to time, it is necessary to assess the effect of such changes on the sensitivity of the input parameters.

6. Research Methodology

6.1 Introduction

This chapter summarises the methodology used during the study. The project was carried out in four different phases:

- Desk study;
- Data acquisition and analysis;
- Sensitivity analysis; and,
- Preparation of reports.

For simplification of the sensitivity analysis phase, the analysis was carried out in three stages:

- **Stage1**: Sensitivity of the parameters affecting the pavement deterioration modelling (PDM).
- **Stage 2**: Sensitivity of the parameters affecting the maintenance strategy generation.
- **Stage 3**: Sensitivity of the parameters affecting the economic optimisation.

This approach has, by excluding the less sensitive variables in each stage, helped to keep the process manageable.

6.2 RAMM Database Acquisition and Analysis

RAMM databases representing the road networks with different traffic characteristics and geological conditions were acquired from several different RCAs. The following RAMM data tables were used for data processing:

- Roughness;
- Rating;
- Traffic;
- Loading;
- Carriageway surface;
- Treatment length;
- Pavement layer;
- HSD Rough;
- HSD Rut;
- HSD Texture depth;
- HSD SFC; and,
- FWD data.

Not all the RAMM databases available had all the above tables. The high speed data (HSD) and FWD data were available only for Transit network.

The RAMM database was analysed to define:

- Range of various input data available in RAMM database; and,
- Homogeneity of treatment length.

While defining the analysis range of input parameters 5th percentile data was considered as minimum and 95th percentile as maximum to ensure that outliers were not included. The range was used to develop the synthetic datasets for the sensitivity analysis. It was decided to carry out the analysis using synthetic datasets since no single real datasets can include all the possible range of the parameters to be considered.

The homogeneity of the treatment length was studied for two RAMM databases representing Transit and District Council road network. The homogeneity were tested based on:

- Roughness; and,
- Rutting (if available);

The high speed rut depth, texture depth and SFC data are only available for the Transit network. For the city and district council roads the homogeneity was tested in terms of roughness data only.

The following parameters were considered for defining the homogeneity of the treatment length sections:

- Standard deviation;
- 90th percentile value;
- Mean value
- 10th percentile value;
- percentage increase of 90th percentile value in comparison with mean; and,
- increase in value of 90th percentile value in comparison with mean.

These treatment length sections were further divided into 100m, 500m and 1000m sections. This was to check the possible variation of the values for a parameter in terms of minimum practical construction length.

6.3 Experimental Design Methods

6.3.1 Selection of methods for analysis

The literature review (Chapter 2) shows that the following methods have been successfully used overseas for the sensitivity analysis:

- Traditional *ceteris paribus* (TCP),
- Factorial Latin hypercube (FLH).

The TCP method is based on changing a single factor while holding all other constants. The advantage of this method is that it reduces the number of the parameters. However, the major disadvantage of this method is that it does not consider the interactions between different factors.

On the other hand, factorial experiments combine all the levels of one factor with all the levels of other factors. A large number of combinations are needed to be considered while carrying out analysis. The FLH method of experiment design can drastically reduce the number of combinations (Mrawira *et al.* ,1998). Even then the number of input variables must be limited to keep the number of combinations manageable (e.g. time taken for the dTIMS analysis due to a large number of combinations etc.).

Hence the TCP method was primarily used for preliminary analysis to filter out the parameters not very sensitive to the pavement performance and optimisation. The sensitivity analysis was then carried out based on the FLH method of experimental design.

Both of the methods require different ways of data preparation and analysis. The following sections describe in detail the methodology used in preparing the dataset for the analysis and processing of the results.

6.3.2 Data preparation and processing for TCP method

As described above, the TCP method is based on changing a single factor while keeping all others constant. Hence, for each factor five different levels within the defined ranges were considered while preparing the datasets. To consider the effect of traffic and pavement strength four different road conditions were considered for the analysis (Table 6.1).

Table 6.1 Matrix for Road Condition.

Condition Sets	Description	Traffic, AADT	Strength, SNP
LTNS	Low traffic (normal strength)	1,000	2
LTHS	Low traffic (high strength)	1,000	4
HTNS	High traffic (normal strength)	20,000	4
HTLS	High traffic (low strength)	20,000	2

A customised software program using Visual Basic was prepared for developing the datasets for the analyses. The data sets were used in the dTIMS analyses.

The analysis of the results of the dTIMS analyses was done using an MS Excel worksheet. Sensitivity of the parameters was calculated in terms of impact elasticity which is the ratio of the percentage change in a specific result to the percentage change of the input parameter, holding all other parameters constant at a mean value. The parameters were then grouped on the four sensitivity level based on the impact elasticity as defined in Table 2.1 (*page* 17).

6.3.3 Data preparation and processing for factorial method

For the analyses using the factorial method, the datasets required were prepared with the help of a special software program developed by HTC for generating datasets based on the Latin hypercube method of experimental planning. The range of each parameter, where possible, was divided into 10 levels and the number of the records in each dataset were usually limited to 4000.

The input variables of the dTIMS analysis were normalised between 0 to 1 by using the following expression:

$$X_{norm} = (X_i - X_{min})/(X_{max} - X_{min})$$

Where X_i is the value of a parameter for i^{th} record
X_{min} is the minimum value of the parameter
X_{max} is the maximum value of the parameter

The software STATGRAPHICS Plus 3.0 was used for the statistical analysis of the dTIMS output by using backward stepwise regression analysis. The backward elimination procedure proceeds one step at a time, by deleting the variable at each step with the larger *p*- value if that value exceeds the level of significance. The linear regression model was used for the analysis.

The results of the analysis were generally presented in the table with the regression coefficients of the input parameters ranked in the descending order. That means the parameter coming at the top was the most sensitive parameter. Besides, for comparison of the results of various analyses 'relative impact' was defined for each parameter. The relative impact is calculated by dividing the coefficient for a given parameter with the maximum coefficient available.

6.4 Performing dTIMS Analysis

6.4.1 Stagewise analysis

The analyses were carried out in these different stages are given in Table 6.2.

Table 6.2 Stages of the Sensitivity Analyses.

Stages	Description	Analysis Mode	Experimental Design	Strategy Considered
Stage I	Sensitivity of the parameters affecting the pavement deterioration modelling	PBA	• Ceteris Paribus • Factorial	• 'Do nothing' Strategy • Routine maintenance only (M&P)
Stage 2	Sensitivity of the parameters affecting the maintenance strategy generation	PBA	• Ceteris Paribus • Factorial	• Performance based analysis strategy (PANA)
Stage 3	Sensitivity of the parameters affecting the economic optimisation	EA	• Factorial	• Optimum strategy for each section selected based on minimisation of the TTC

Sensitivity analyses of the pavement deterioration without including any maintenance work can give the true sensitivity of different parameters in terms of the models prediction. However, in the NZ situation continuous routine maintenance is carried out to maintain surface defects. Hence, the sensitivity for both the do nothing and routine maintenance were the only cases considered during the sensitivity analysis for the pavement deterioration modelling stage.

Sensitivity analysis to the strategy generation process was carried out in the performance based analysis (PBA) mode. The TCP method was used to determine the sensitivity of all the trigger limits. The FLH analysis was carried out to investigate the more sensitive parameters affecting deterioration modelling and strategy generation process.

The sensitivity analysis of the economic optimisation was carried out in the economic analysis mode. The optimum strategy was selected from a number of potential strategies for a given section in the economic optimisation process. The effect on the sensitivity of the budget constraint and change in the vehicle operating costs were studied separately.

Table 6.3 summarises various analysis sets together with their objectives and the analysis method used for all three analysis stages during the study.

Table 6.3 Planning of the Sensitive Analysis Study.

Analysis Stage	Analysis Set	Objectives	Method Used	Dataset Used
Stage 1 Pavement Deterioration Modelling	Analysis #1	Define sensitivity of all parameters affecting pavement deterioration models	Cetrius Paribus	Dataset #1
	Analysis #2	Define sensitivity of all parameters affecting pavement deterioration models	Factorial	Dataset #2
	Analysis #3	Determine effect of traffic on sensitivity analysis	Factorial	Dataset #3
Stage 2 Strategy Generation	Analysis #4	Define sensitivity of all trigger coefficients	Cetrius Paribus	Dataset #4
	Analysis #5	Define sensitivity of all sensitive parameters affecting on strategy generation	Factorial	Dataset #5
Stage 3\ Economic Optimisation`	Analysis #6	Define sensitivity of all sensitive parameters affecting on economic optimisation	Factorial	Dataset #6
	Analysis #7	Define the effect of change in VOC rate on sensitivity of input parameters	Factorial	Dataset #6

6.4.2 Input parameters considered

The input parameters affecting the NZ dTIMS setup is summarised based on the sensitivity group in Table 6.4.

Table 6.4 Input Parameters for Various Stages.

Sensitivity groups	Affecting Deterioration Modelling	Affecting Strategy Generation	Affecting Economic Optimisation
Traffic	•	•	•
Condition	•	•	•
History	•	•	•
Inventory	•	•	•
Strength	•	•	•
Environment	•	•	•
Calibrations	•	•	•
Standard – triggers		•	•
Cost			•

The traffic, road conditions, history, environment and calibration parameters affect all the stages of the dTIMS analysis. However, as their primary effect is on the pavement deterioration modelling, the sensitivity of these parameters were studied in response to pavement deterioration and only those parameters found to be relatively more sensitive were considered in the next two stages.

On the other hand, performance standards (manifested by trigger limits) initially affect the strategy generation process and subsequently the economic optimisation process. Hence, the sensitivity of all the trigger limits were studied in response to the strategy generation process. Only the relatively more sensitive trigger limits together with the most sensitive parameters in response to pavement deterioration were considered further during the economic optimisation stage.

Table 6.4 shows that the cost (both agency as well as VOC) only affect the economic optimisation function. The agency cost, which is a function of the unit cost of various activities and could differ for different locations, is also time dependent. The VOC is defined by Transfund NZ and is stable throughout the country.

6.4.3 Output parameters

The sensitivity of input parameters are tested in response to different output parameters on different stages of dTIMS analysis. The output parameters should be representative so that they reflect the effects of various input parameters in different aspects of predictive modelling using the NZ dTIMS system.

Table 6.5 shows that in the analysis stage of predictive deterioration modelling the sensitivity in response to roughness (IRI) and the surface integrity index (SII) were carried out. In the HDM modelling process roughness is the function of the other condition parameters (i.e. cracking, ravelling, potholes, rutting). Also, roughness is the only road condition parameter used to calculate the vehicle operating costs in the NZ dTIMS setup. Hence, it is important that roughness should be taken as one of the output parameters. Similarly, the surface integrity index (SII) representing the surface distress is the function of various surface distresses, i.e. cracking, potholes, ravelling, flushing and surface age. As texture depth and side force friction prediction model are not yet well calibrated, SII is the only parameter triggering the resurfacing treatments. Hence, it is essential that SII should be taken as one of the output parameters.

Table 6.5 Output Parameters for Various Analysis Stages.

Output Parameters	**For Deterioration Modelling**	**For Strategy Generation**	**For Economic Optimisation**
Roughness (IRI)	•		
Surface integrity index (SII)	•		
Average roughness (IRI)		•	•
Average surface integrity index (SII)		•	•
Average granular overlay needs (GRVL)		•	•
Total length of different level of treatments		•	•
Total Agency cost (AC)			•
Total vehicle operating cost (VOC)			•

For the strategy generation stage the sensitivity of the input parameters in terms of average roughness (IRI), surface integrity index (SII) and average granular overlay needs (GRVL) were considered together with length of strengthening, smoothing and resurfacing treatments. The above mentioned output parameters showed the effect of the input parameters on the overall condition of the road network as well as the effect on treatment selection.

In the stage of the economic optimisation in addition to the output parameters considered for the strategy generation stage, the total agency costs and vehicle operating costs for the given period were considered. As the object function used in the NZ dTIMS system is based on minimisation of the total transportation costs both agency cost and VOC directly affect the economic optimisation process.

6.4.4 Analysis period

The period when the output is compared will affect the pavement performance prediction as well as the result of the economic optimisation. For example, most of the surface distress is corrected at the time of resurfacing which is done in about 4 to 16 year cycles. On the other hand, roughness and rut depth is corrected when the pavement is rehabilitated. The rehabilitation cycle is usually 20 to 40 years or more. Hence, the effect of various parameters in the pavement performance prediction was studied for year 5, 10, 15 and 20. A maximum of 20 years was used as dTIMS 6.1 keeps the data only up to 20 years in the output file.

7. RAMM Database Analysis

7.1 Background

Data are the most important component of predictive modelling. The road inventory and the condition data required for dTIMS analysis is made available from the RAMM database. The primary objective of analysing RAMM databases in this study was to define:

- The range of values for different input parameters; and,
- Variability of data within a treatment length section.

The range of each data item defined was used for developing input datasets for dTIMS analysis. Minimum possible variability of the data within the treatment length can be used to indicate the accuracy level to be considered in various analyses and data collection methods.

7.2 Database Acquisition

While selecting RCAs for the RAMM data, it was carefully chosen so that roads from different traffic and geological conditions with different levels of data collection were represented. For this project data were obtained from the following RCAs:

- Auckland City Council;
- Napier Transit Network;
- Northland Transit Network;
- Southland District Council; and,
- North Shore City Council.

The HTC IM proprietary software HIMS database system was used to store and analyse the data made available to the project.

7.3 Data Items Value Range

The dTIMS input files were prepared from the Treatment Length table extracted from the five different RAMM databases using the dTIMS Interface program. These files were processed to define the minimum and maximum values for each input parameters. The 5th percentile data was considered as the minimum and the 95th percentile was considered as the maximum to ensure that outliers were not considered.

The minimum, maximum and default values for the input parameters based on the above analysis and engineering judgement are given in the table found in Appendix C. The different datasets prepared for various analyses were based on these value ranges.

Traffic has a major influence on the pavement performance. District council, city council and Transit road networks have different traffic characteristics so it was decided to investigate the sensitivity based on road networks with high and low traffic roads separately.

7.4 Homogeneity of Treatment Length

dTIMS analyses are carried out based on a uniformly performing 'homogeneous' section. As stated earlier, the analysis of the homogeneity in this work was done to find the practical accuracy level of the data.

The homogeneity of the treatment length was studied for five sections, each from RAMM databases representing Transit and district councils. The treatment lengths of approximately 2km lengths were randomly selected from the databases and the homogeneity of the treatment length was tested based on:

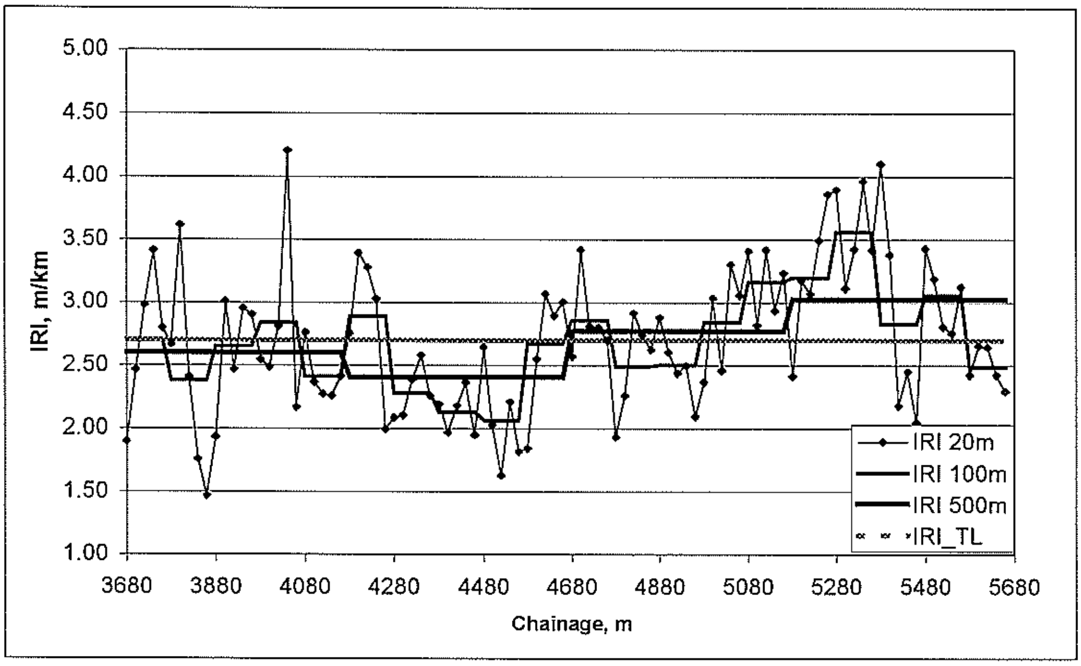
- Roughness; and,
- Rut Depth (for Transit network only).

These treatment lengths are further divided into 100m, 500m and 1000m sections to check the possible variation in the values for a parameter in terms of minimum practical construction length. The following parameters were considered for defining the homogeneity:

- Standard deviation;
- 90th percentile value;
- Mean value;
- 10th percentile value;
- Percentage increase of 90th percentile value in comparison with mean; and,
- value increase of 90th percentile value in comparison with mean.

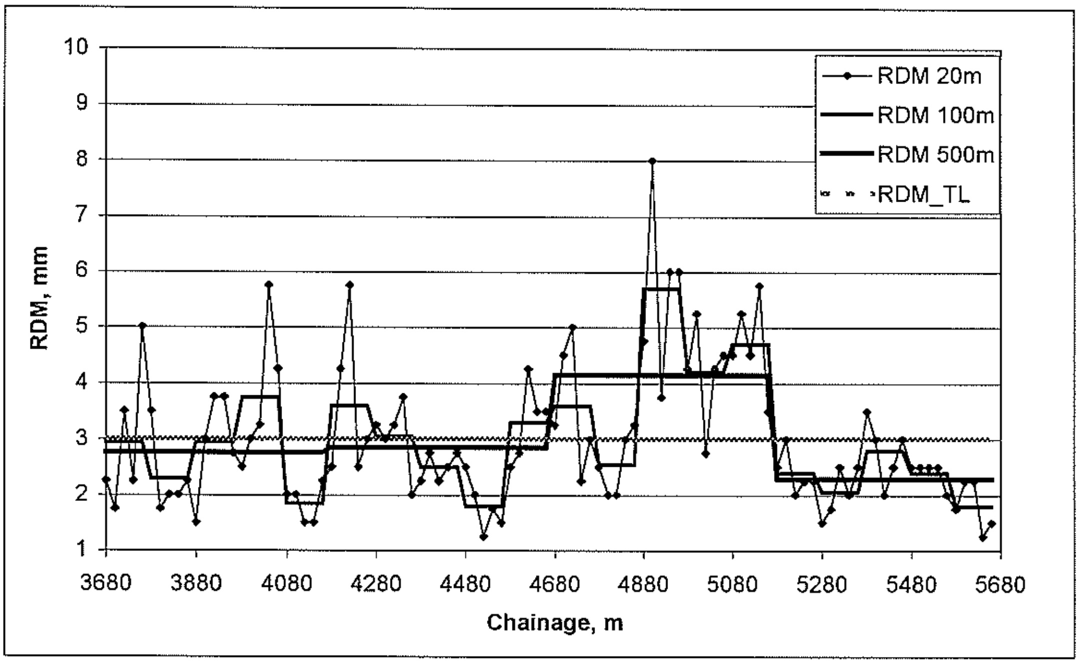
The analysis of the HSD roughness and rutting data showed that values of the roughness and rut depth varies considerably within a treatment length. Figure 7.1 shows the variation of roughness in a typical existing treatment length. Using a average roughness value for a treatment length of about 2.6 IRI actually represents the value from 1.5 IRI up to 4.2 IRI in individual 20m section.

Figure 7.1 HSD Roughness Variation in the Treatment Length.



Similarly, Figure 7.2 shows that average rut depth of about 3 mm actually represents rutting from 0.2 mm to more than 6mm in terms of 20 m sections.

Figure 7.2 HSD Rutting Variation in the Treatment Length.



Hence, correct breakdown of the treatment length is important to identify if the section was homogeneous enough so that a given treatment can be applied to the whole section. It is important to know the variability of the parameters for a minimum practical treatment length.

The treatment length was arbitrarily broken down to 100m, 500m and 1000m sections. Figure 7.1 and Figure 7.2 show that breaking down a 2km treatment length to smaller sections improves the homogeneity of the section. Not surprisingly, the shorter the section the more homogeneous it becomes. Figure 7.3 shows the sections increasing in length and shows the number of 20 m sections with higher differences from mean value will increase resulting it to be less and less homogeneous.

Figure 7.3 Distribution of the Difference from the Mean Roughness.

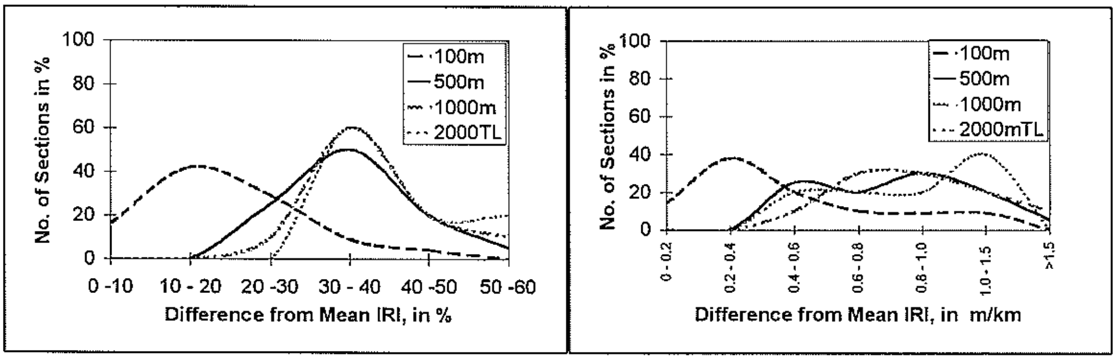
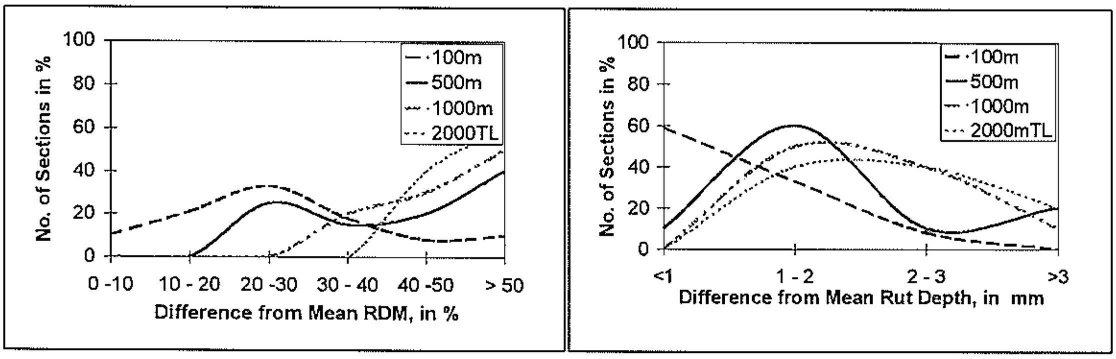


Figure 7.3 shows that for 100m sections (minimum practical length for TL breakdown) about 60% of the 20m sections the IRI values are less than ± 20 % from the Mean IRI. In the case of 500m, 1000m and 2000m sections almost all the 20m sections have IRI values greater than plus minus 20% from the mean roughness. Similarly, for about 60% of the 20m sections the IRI values are less than plus minus 0.4m/km from the mean roughness for 100m sections. For 500m, 1000m and 2000m sections almost all the 20m sections have IRI values greater than ± 0.4m/km from the mean roughness. The homogeneity of the sections longer than 100m sections can be improved by properly breaking down the sections based on the existing roughness condition.

Similar results were observed while analysing HSD rut depth data. Figure 7.4 shows that for 100m sections about 30% of the 20m sections the mean rut depth values (RDM) are less than plus minus 20% from the mean rut depth and about 60% of 20m sections with plus minus 30% from the mean rut depth. In the case of 500m, 1000m and 2000m sections almost all the 20m sections have rut depth values greater than plus minus 20% from the mean rut depth. While comparing the mean rut values it is observed that about 60% of the 20m sections the rut depth values are less than plus minus 1mm from the mean rut depth in the case of 100m sections. For 500m, 1000m and 2000m sections less than 10% of the 20m sections have rut depth values greater than ±1 mm.

Figure 7.4 Distribution of the Difference Level from the Mean Rut Depth.



7.5 Conclusions

The analysis shows that it is practically impossible to break down a road to the section/ treatment length level with the variation in the roughness and rutting less than 20–30% of the mean values. The accuracy of the instruments used for collecting data is much more precise (Table 3.1) than the possible minimum variation in a treatment length.

Obviously, in a lot of cases the variation within the treatment length is because the RAMM treatment length generation algorithm (TLGA) is based on carriageway sections or top surface rather than based on condition/performance parameters. Although, these can be amended /sub-divided further according to pavement behaviour observations and data analysis etc. Existing practice is user selection based on the information is available. There is a need to define a procedure or routine for treatment length generation based on a few most sensitive condition parameters. The selection and the values of parameters to be used for breaking down the treatment length should be defined carefully considering its sensitivity to predictive modelling and maintenance programming. The routine for further breaking down of the treatment length based on pavement performance will be needed to be included in the RAMM TLGA.

8. Sensitivity of Parameters in Pavement Deterioration

8.1 Introduction

Pavement deterioration models are the basis of predictive modelling. By simulating the progression of various distresses it is possible to predict the condition of a road and the various required maintenance works.

As described in Chapter 6, the following two different complementary methods were used for analysing the sensitivity of the input parameters in response to model predictions:

- TCP method which analysed the sensitivity of each parameter affecting pavement deterioration modelling without interactions with other parameters; and,
- FLH using those input parameters which are found to be sensitive to pavement deterioration modelling in consideration of interactions with each other.

Preliminary analyses showed that the traffic level considerably affected the sensitivity of the input parameters to the model prediction. Therefore, it was considered necessary to check the sensitivity of the input parameters for different traffic levels.

8.2 Sensitivity of the Individual Input Parameters

8.2.1 Dataset preparation and analysis

The sensitivity of the parameters in response to deterioration parameters were studied using the TCP method. A special software program developed for this purpose was used to generate datasets by varying the value of each parameter into five levels keeping all other values as default. The minimum and maximum ranges specified in Appendix C were used in preparing the dataset.

To determine the effect of traffic volume and pavement strength a matrix of different road conditions were used (see Table 6.1).

The sensitivity of the individual parameters on the roughness (IRI) and Surface Integrity index (SII) were studied for 5, 10, 15 and 20 years using the TCP method.

The dTIMS analysis for pavement deterioration prediction was carried out based on the Performance Based Analysis (PBA) mode. Only 'Do nothing' (without any maintenance case) and Routine maintenance only (M&P) strategies were considered.

8.2.2 Sensitivity to roughness for the 'without maintenance' case

To get a true picture of the sensitivity of various parameters on model predictions it was necessary to analyse the do nothing scenario, where it was considered that absolutely no maintenance works were carried out during the analysis period. This condition regime reflects pavement performance of sterilised long term pavement performance (LTPP) sites.

Roads with balanced pavement strength (properly designed road with a balance ratio between design traffic to required pavement strength) for high traffic and low traffic volume roads were analysed separately. Effects of the input parameters are ranked in order of the highest sensitivity on roughness prediction for a low volume roads are given in Table 8.1. It is observed that the effect of the various parameters in the model depends on the analysis period considered.

Table 8.1 Sensitivity to IRI for Low Traffic Road without Maintenance.

Impact Elasticity in Response to IRI for							
5 YEARS		**10 YEARS**		**15 YEARS**		**20 YEARS**	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
IRI0	0.99	KCI	1.55	KCI	1.72	KCI	1.42
CHIP	0.25	CHIP	1.26	CHIP	0.95	PAV_WID	0.92
ADT4	0.16	IRI0	0.90	PAV_WID	0.64	SNP	0.77
ADT5	0.15	AGE2	0.59	KGP	0.60	CHIP	0.48
KCI	0.14	ADT4	0.41	KPP	0.56	HNEW	0.39
KGE	0.12	ADT3	0.37	SNP	0.55	KCP	0.38
AGE2	0.12	ADT5	0.35	IRI0	0.53	KGP	0.36
ARV	0.11	KGE	0.25	AGE2	0.48	KPP	0.35
PCW	0.10	KCP	0.24	KCP	0.46	ADT1	0.32
ADT3	0.04	PCW	0.23	HOLD	0.46	AGE2	0.32
APT	0.04	ARV	0.22	ADT1	0.32	HOLD	0.31
KVP	0.03	ADT6	0.17	ADT2	0.31	KGE	0.27
ACA	0.03	KGP	0.15	CQ	0.31	IRI0	0.21
SNP	0.02	ADT1	0.14	ADT4	0.29	CQ	0.19
ADT6	0.01	SNP	0.11	ADT3	0.28	MMP	0.12
KGP	0.01	KVP	0.10	HNEW	0.25	ADT2	0.12
PAV_WID	0.01	ADT2	0.08	ADT5	0.25	ARV	0.11
RDS	0.01	APT	0.08	KGE	0.24	ADT6	0.10
KRP	0.01	PAV_WID	0.08	GROWTH_L	0.20	ADT5	0.10
		KPP	0.06	ADT6	0.18	PCW	0.09
		HOLD	0.06	ARV	0.16	ADT4	0.09
		CQ	0.04	PCW	0.15	ADT3	0.08
		ACA	0.02	KVP	0.07	GROWTH_L	0.08
		HNEW	0.02	APT	0.07	KVP	0.05
		GROWTH_L	0.02	MMP	0.06	APT	0.05
		RDS	0.01	GROWTH_H	0.02	GROWTH_H	0.04
		KRP	0.01	RDS	0.01	RDS	0.01
		AGE3	0.01	KRP	0.01	KRP	0.01
		GROWTH_H	0.01	AGE3	0.01	AGE3	0.01

Notes:	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.05 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

The study of sensitivity in the case of high traffic roads (see Table 8.2) in response to IRI0 showed that less parameters were sensitive in comparison with low traffic roads (see Table 8.1).

Table 8.2 Sensitivity to IRI for High Traffic Road without Maintenance.

Impact Elasticity in Response to IRI for							
5 YEARS		10 YEARS		15 YEARS		20 YEARS	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
KCI	3.57	KCI	4.32	KCI	3.05		
SNP	2.88	SNP	1.99	AGE2	0.46		
CHIP	1.60	PAV_WID	1.31	ADT1	0.03		
IRI0	0.99	AGE2	0.74				
AGE2	0.77	CHIP	0.66				
KVP	0.55	KCP	0.50				
PCW	0.47	KGP	0.40				
ARV	0.40	KPP	0.31				
APT	0.37	IRI0	0.30				
KGE	0.13	ADT1	0.26				
PAV_WID	0.03	CQ	0.25				
ACA	0.03	HOLD	0.20				
KGP	0.02	ADT3	0.19				
CQ	0.01	ADT4	0.19				
RDS	0.01	ADT5	0.19				
ADT6	0.01	KPI	0.18				
AGE3	0.01	ADT6	0.18				
ADT5	0.01	PCW	0.15				
KRP	0.01	HNEW	0.15				
		APT	0.13				
		ARV	0.13				
		GROWTH_H	0.12				
		KGE	0.10				
		MMP	0.02				
		ADT2	0.01				
		RDS	0.01				
		KRP	0.01				
		ACA	0.01				
		GROWTH_L	0.01				
		AGE3	0.01				

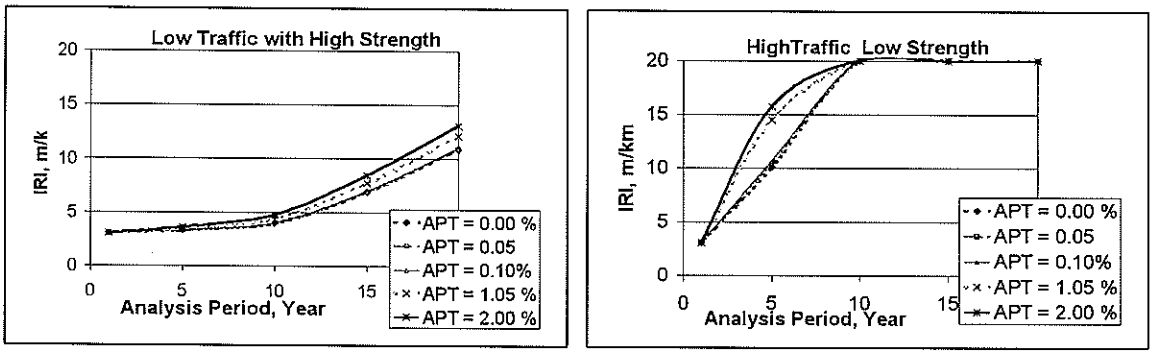
Notes:

Level 1	Impact Elasticity greater than 0.5
Level 2	Impact Elasticity greater than 0.2 and less than 0.5
Level 3	Impact Elasticity greater than 0.05 and less than 0.2
Level 4	Impact Elasticity less than 0.05

Similarly sensitivity to roughness prediction for roads with a strength higher and lower than required were also studied. In the case of high traffic roads with low pavement strength (refer to Table D.1 in Appendix D), it was found that most of the parameters identified as sensitive to the roughness prediction were found to be sensitive for the 5 year period, whereas, the number of the parameters found to be sensitive had decreased with time.

This observation is due to the fact that roughness can increase to a maximum value of 20m/km and then stay constant. For high traffic roads with low pavement strength the roughness progression is fast enough that it reaches its maximum limit within a short period, and without any maintenance, no sensitivity will be observed in terms of roughness even though the condition of the road continues to deteriorate. Figure 8.1 shows that for the given initial value of area of potholes (APT) roughness increases at a different incremental rate for different pavement conditions. In the case of high traffic roads with low pavement strength the progression is much faster and APT no longer impacts on the roughness increment after 10 years.

Figure 8.1 Roughness Progression for Various Road Condition.



This trend is proven by the sensitivity analysis in the case of the low traffic roads with high pavement strength (refer to Table D.2 in Appendix D) for which a lot of the parameters are sensitive even for the 20 year analysis period. Hence, it is essential to study the sensitivity for both 5 and 20 years in order that none of the parameters are accidentally overlooked.

8.2.3 Sensitivity of parameters on sii for the 'without maintenance' case

A sensitivity study of various parameters on the surface integrity index (SII) for the low traffic roads showed that:

- For SII on year 5 chip size (CHIP) was found to be the most sensitive parameter followed by calibration coefficients (KVP, KCI), ravelling (ARV) and traffic volume (ADT). In addition, the area of previous wide cracking (ACW), surface age (AGE2), initial flushing (AFL), potholes (APT) and all cracking (ACA) were also found to be sensitive.
- In the case when SII for 10 years and 15 years are considered only a few parameters (KCI, KCP, AGE2) were found to be sensitive.

The reason behind the reduction of sensitive parameters with increment in analysis period is due to the fact that the upper limit of SII is fixed to 100. For roads without any maintenance the SII values usually reaches 100 within 10 years in most cases.

The results of sensitivity analysis of the input parameters for the high traffic roads (see Table 8.4) showed that similar parameters as for the low traffic road is sensitive to SII (see Table 8.3), however the level of sensitivity is slightly different. The calibration coefficient for crack initiation (KCI) was found to be very highly sensitive followed by pavement strength (SNP). Similar to high traffic road number of the parameters reduced after year 5.

Table 8.3 Sensitivity to SII for Low Traffic Road.

Impact Elasticity in Response to SII for							
5 YEARS		**10 YEARS**		**15 YEARS**		**20 YEARS**	
Parameters	**Value**	**Parameters**	**Value**	**Parameters**	**Value**	**Parameters**	**Value**
CHIP	2.50	KCI	8.50	KCI	0.46		
KVP	1.82	AGE2	0.93	AGE2	0.30		
KCI	1.69	KCP	0.57				
ARV	1.46						
ADT3	1.29						
ADT4	1.21						
ADT5	1.21						
PCW	1.21						
AGE2	1.17						
AFL	1.00						
ADT6	0.61						
APT	0.50						
ACA	0.50						

Notes:	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5

Table 8.4 Sensitivity to SII for High Traffic Road.

Impact Elasticity in Response to SII for							
5 YEARS		**10 YEARS**		**15 YEARS**		**20 YEARS**	
Parameters	**Value**	**Parameters**	**Value**	**Parameters**	**Value**	**Parameters**	**Value**
KCI	10.32	KCI	3.30				
SNP	5.20	AGE2	0.67				
PAV_WID	3.40						
CHIP	2.09						
AGE2	1.00						
CQ	0.72						
ADT6	0.51						
AFL	0.46						
PCW	0.43						
APT	0.42						
ARV	0.42						
ACA	0.42						
KCP	0.31						
ADT3	0.28						
ADT4	0.28						
ADT5	0.28						
GROWTH_H	0.23						

Notes:	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5

8.2.4 Effect of routine maintenance

In NZ some kind of routine maintenance is generally carried out on a road section. It is assumed in the NZ dTIMS Setup that as a minimum:

- 50% of the narrow cracking are sealed;
- 20% of the wide cracking are corrected using digout; and,
- 90% of the potholes are patched.

Hence a sensitivity analysis of the individual parameters affect on roughness progression for low traffic roads with routine maintenance was carried out. The results showed that (see Table 8.5):

- The initial roughness (IRI0) was the most sensitive parameter (sensitive Level 1) 3 to 15 time more sensitive than other parameters depending on the period considered. This is contrary to the no maintenance case when the sensitivity of initial roughness decreased with an increase in the year of analysis considered.
- The chip size (CHIP) and traffic (ADT) were found to be the second most sensitive parameters (sensitive Level 3) for year 5 and 10. From year 15 calibration coefficients (KCP, KGP, KGE) were found to be more sensitive than these parameters. It is noted that sensitivity of these coefficients increases with the year considered.

The sensitivity analysis of the individual parameters on roughness (IRI) progression for high traffic roads with routine maintenance showed that parameters which were sensitive to low traffic roads are sensitive to high traffic roads as well, although some differences in the level of sensitivity was observed between the roads with different traffic levels. For example, the initial roughness (IRI0) was found to have the most impact on roughness progression for year 5 and was the only parameter with sensitivity level 1. The pavement strength (SNP) and calibration coefficients (KGE, KGP) were sensitivity Level 1 for year 10 and onwards. From year 15 these parameters were found to be more sensitive than IRI0. Please refer to Table D.5 in Appendix D for more information.

8.2.5 Comparison of sensitivity for road with and without maintenance

The sensitivity to IRI as well as SII for various road conditions and different years of analysis period has been summarised for both with and without maintenance case separately to access the overall impact (*refer* to Tables D.3, D.4, D.5 and D.6 in Appendix D for more details). The highest of the sensitivity levels of the input parameters for different years was taken as the representative for the given parameter.

The comparison of the results of the sensitivity analysis on roughness for the road networks with and without routine maintenance (*see* Figure 8.2) showed that most of the parameters sensitive to one case was sensitive to another also. However, the sensitivity of various parameters may vary a little, say up to 1 sensitivity level, if they are not in the same level.

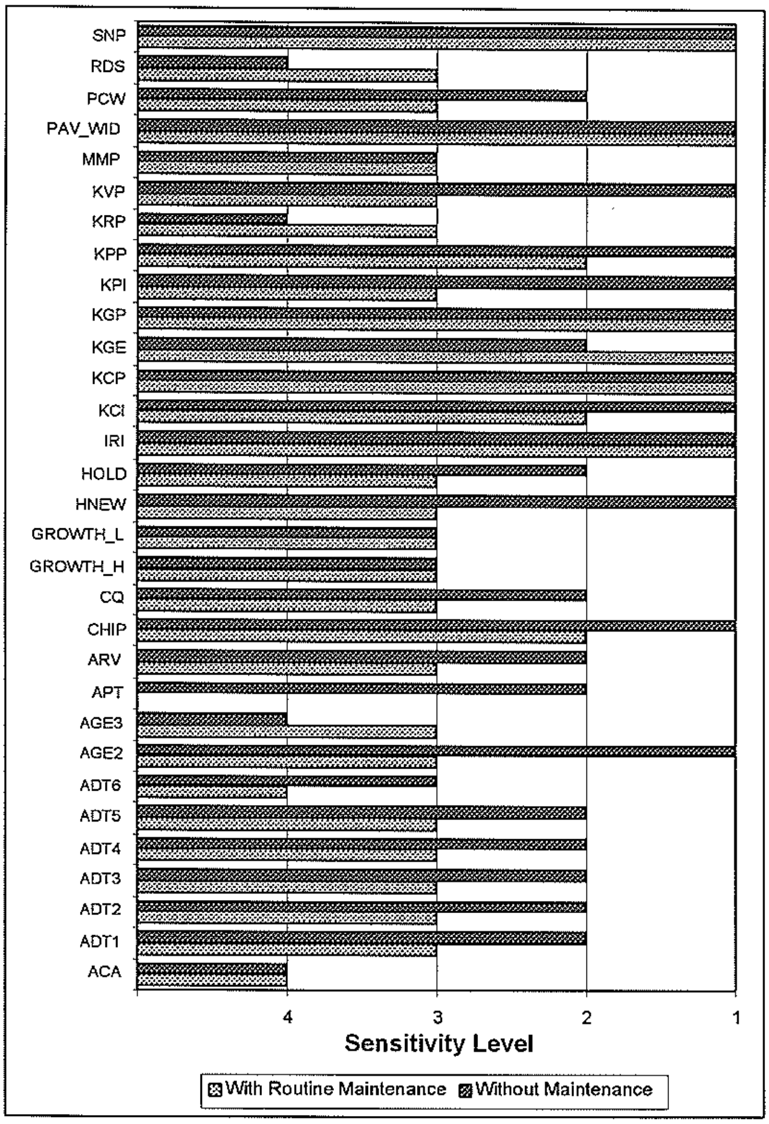
The comparison of the results of the sensitivity analysis on the surface integrity index (SII) for the road networks with and without routine maintenance (see Figure 8.3) showed that a few more parameters (KPP, KPI, MMP, HNEW, HOLD, CQ *etc.*) were sensitive to SII for roads with routine maintenance than without routine maintenance. Among those parameters old surfacing thickness (HOLD), pothole calibration coefficients (KPI, KPP) were found to be of sensitivity level 1.

Table 8.5 Sensitivity to IRI for Low Traffic Road with Routine Maintenance.

Impact Elasticity in Response to IRI for							
5 YEARS		10 YEARS		15 YEARS		20 YEARS	
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
IRI0	0.99	IRI0	0.96	IRI0	0.90	IRI0	0.85
CHIP	0.07	CHIP	0.18	KCP	0.24	KGE	0.36
ADT5	0.07	ADT5	0.13	KGE	0.23	KGP	0.36
ADT4	0.06	KCI	0.13	KGP	0.23	KCP	0.33
KCI	0.04	ADT4	0.13	CHIP	0.19	ADT5	0.20
ADT3	0.04	AGE2	0.09	ADT5	0.17	ADT1	0.20
AGE2	0.03	ADT3	0.09	ADT4	0.16	ADT4	0.19
SNP	0.02	KCP	0.08	KCI	0.14	CHIP	0.18
PCW	0.02	KGE	0.06	ADT1	0.13	KCI	0.16
ACA	0.01	KGP	0.06	ADT3	0.12	ADT3	0.14
ADT6	0.01	SNP	0.05	AGE2	0.09	SNP	0.12
KGE	0.01	ADT6	0.04	SNP	0.09	AGE2	0.09
KGP	0.01	PCW	0.03	ADT6	0.05	ADT6	0.07
ARV	0.01	ACA	0.03	PAV_WID	0.04	PAV_WID	0.05
PAV_WID	0.01	PAV_WID	0.02	PCW	0.03	PCW	0.03
RDS	0.01	ARV	0.02	ACA	0.03	ACA	0.03
KRP	0.01	ADT1	0.02	ARV	0.02	ADT2	0.03
		RDS	0.01	RDS	0.02	ARV	0.02
		KRP	0.01	KRP	0.02	RDS	0.02
		KVP	0.01	ADT2	0.01	KRP	0.02
		AGE3	0.01	AGE3	0.01	AGE3	0.02
				KVP	0.01	KPP	0.02
				GROWTH_H	0.01	GROWTH_H	0.02
				KPP	0.01	HOLD	0.01
				HOLD	0.01	CQ	0.01
				CQ	0.01	KVP	0.01
				KPI	0.01	GROWTH_L	0.01
						KPI	0.01

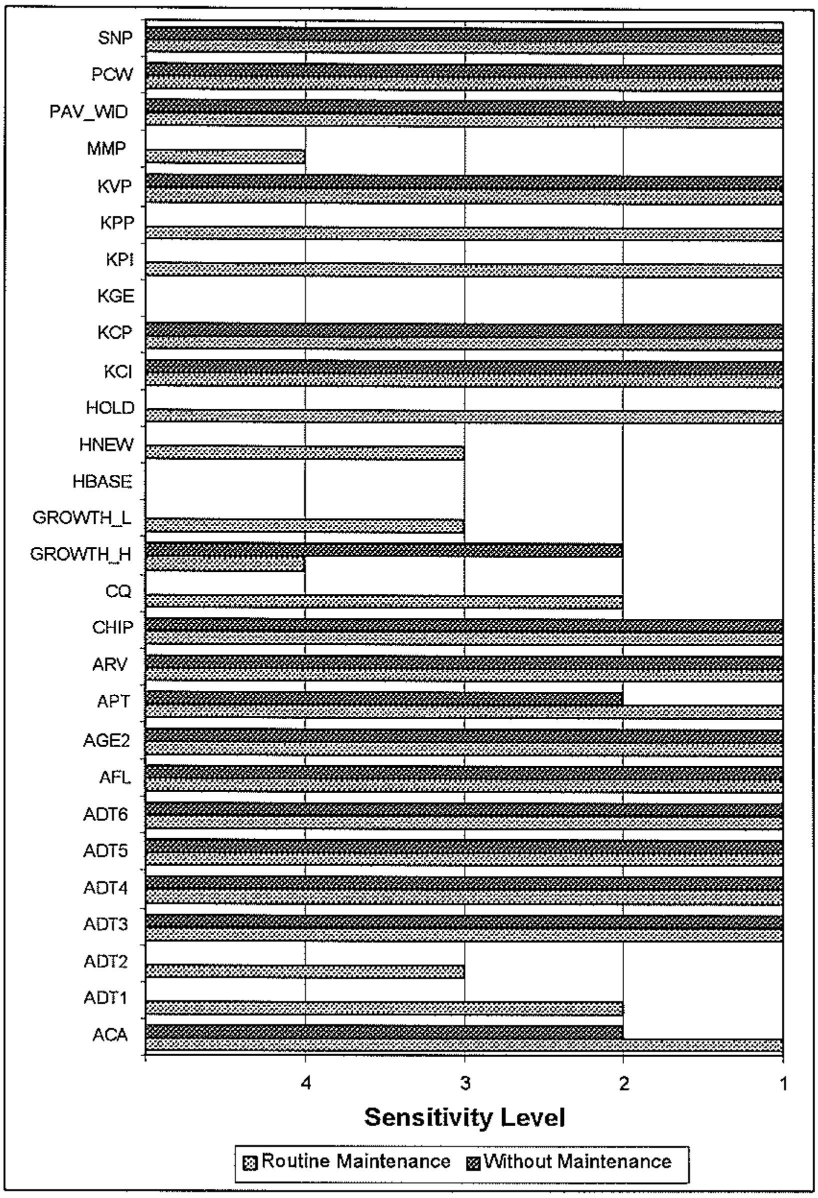
Notes:	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.05 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

Figure 8.2 Sensitivity on Roughness.



Note: 1 is the highest sensitivity level

Figure 8.3 Sensitivity on SII.



The study showed that it is preferable to carry out the sensitivity analysis based on routine maintenance, because:

- More parameters were found to be sensitive in the case of routine maintenance;
- Routine maintenance is always carried out in NZ.

8.3 Effect of the Interactions of Input Parameters

To study the sensitivity of the input parameters in interactions throughout each other the factorial experiment using the Latin Hypercube method (FLH) of the experimental design was used. The results were analysed using STATGRAPHICS Plus 3.0. Multiple regression analysis was carried out taking into consideration stepwise backward regression.

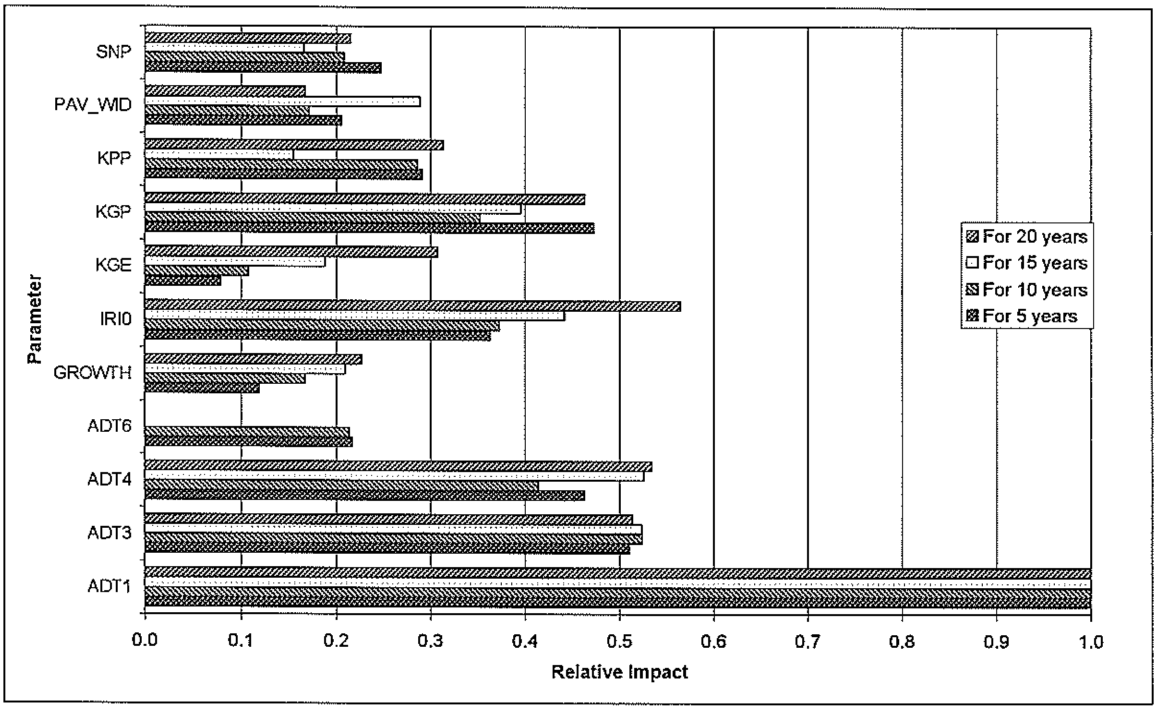
The tables with parameters ranked based on descending order of the sensitivity coefficients were prepared. For presentation on graphs the relative impact was calculated by dividing the sensitivity coefficient value for a given parameter by the maximum coefficient value.

8.3.1 Effect of the analysis period and routine maintenance

The effect of the analysis period on the sensitivity of inter-related input parameters on model predictions were observed to be similar to the effect of the individual parameters analysed earlier using TCP method (*see* Section 8.2).

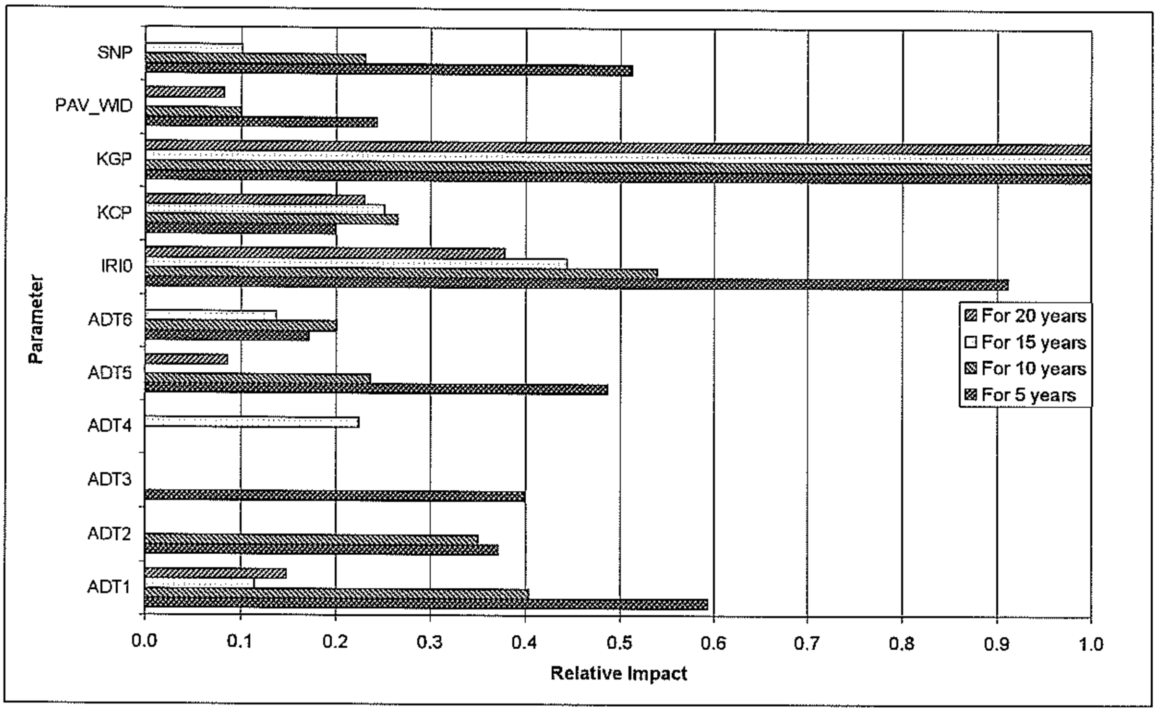
Figure 8.4 shows that there is some variation on sensitivity of various input parameters in response to roughness prediction for analysis periods of 5, 10, 15 and 20 years with no maintenance. Traffic was the most sensitive parameter for all the periods. In year 5 the calibration coefficients of roughness progression (KGP) was relatively more sensitive than initial roughness (IRI0), however for the year 10, 15 and 20 year of analysis period IRI0 was more sensitive than KGP. (refer to Table D10 in Appendix D for more detailed data).

Figure 8.4: Sensitivity on Roughness without Maintenance Case



A change in the relative impact of various input parameters for different year of analysis period was also observed in response to the roughness when routine maintenance is considered (*see* Figure 8.5 and refer Table D.11 in Appendix D for detail information). Calibration coefficient for roughness progression due to loading (KGP) followed by roughness (IRI0) was found to be the most sensitive parameter in this case.

Figure 8.5: Sensitivity on Roughness with Routine Maintenance.



A similar pattern was observed during the sensitivity of individual parameters observed in response to SII. In the case when no maintenance is applied, traffic volume (ADT) and existing surface condition (ACA, APT, ARV) are relatively high sensitive parameters (*see* Table 8.6). No input parameters except KCP (cracking progression coefficient) was found to be sensitive after five years.

Table 8.6 Sensitivity on SII for without Maintenance Case

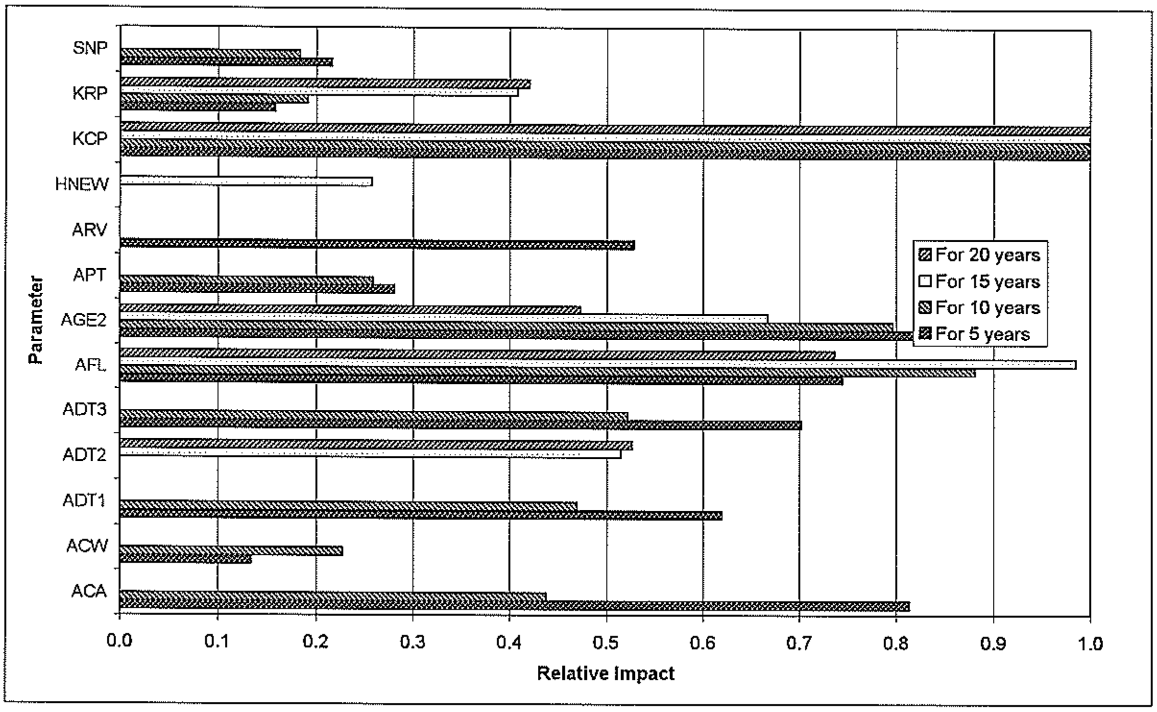
Sensitivity in Response to SII for							
5 Years		10 Years		15 Years		20 Years	
Parameters	Values[1]	Parameters	Values	Parameters	Values	Parameters	Values
KCP	0.49	KCP	0.03				
ACA	0.46						
APT	0.41						
ADT1	0.35						
ARV	0.3						
AGE2	0.27						

Notes: 1/ Regression coefficient

The number of sensitive parameters while analysing the sensitivity of the input parameters to SII for roads with ongoing routine maintenance work (see Figure 8.6) is much higher than without maintenance. As stated earlier, the main reason is that the SII value reaches its maximum limit of 100 quicker in the case of no maintenance option and continues to be 100 although the values of various individual components of the SII may still increase.

Most of the distress components in the composite index SII (ACA, ACW, APT, ARV, AGE2, AFL were found to be sensitive in this case (*see* Figure 8.6 and refer to Table D.12 in Appendix D for more detail).

Figure 8.6: Sensitivity on Roughness with Routine Maintenance.



The results highlight the fact that for the reliable output it is essential to consider the sensitivity for different years of the analysis period and it is preferable to use routine maintenance option for the analysis. Especially, in the case of SII it is better to analyse the sensitivity for less than 10 years period. This is relevant due to the fact that resurfacing triggered by SII is generally triggered within ten years.

8.3.2 Effect based on different traffic levels

The effect of the input parameters for different traffic levels were compared based on the effect on five years for SII and 10 years for IRI (Roughness). The analysis considered included routine maintenance work as some maintenance is carried out on NZ roads in NZ conditions.

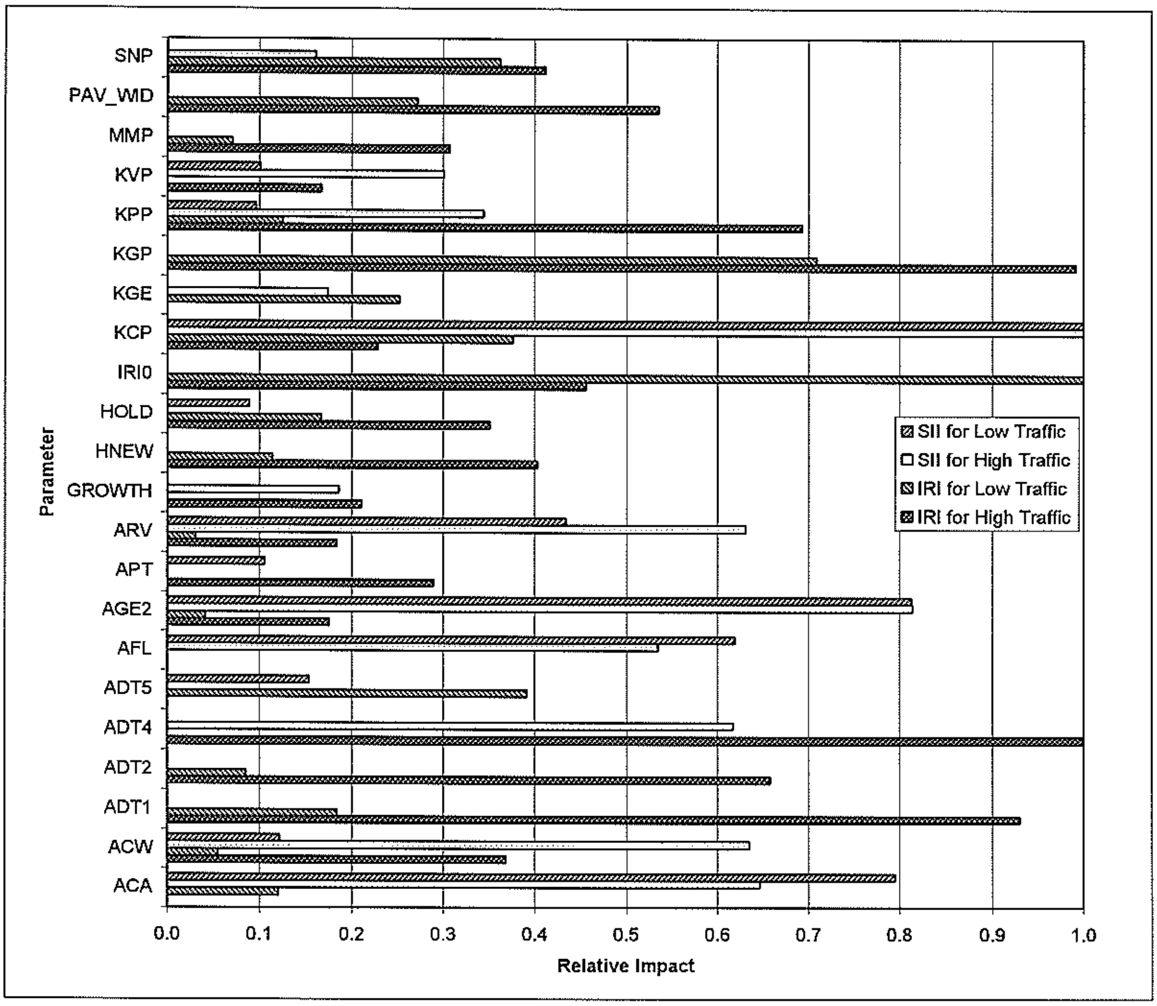
The traffic levels considered were:

- Low traffic road network; and,
- High traffic road network.

The result of the analyses in response to the roughness prediction showed (*see* Figure 8.7 and refer to Table D.13 in Appendix D for more detail) that:

- For lower traffic volume roads the existing roughness (IRI0) was the most sensitive parameter on the roughness. With higher traffic volume roads IRI0 was less sensitive than traffic and calibration coefficients.
- Calibration coefficient for roughness progression due to traffic loading (KGP) was relatively more sensitive for higher traffic load, whereas,. the calibration coefficient due to environmental factor (KGE) was more sensitive with lower traffic volume roads.

Figure 8.7: Comparison of the Sensitivity of Traffic Volume.



The results of the analyses for different traffic level in response to SII prediction showed (see Figure 8.7) that:

- For high volume traffic roads the calibration coefficient crack progression (KCP) was found to be most sensitive followed by surface age (AGE2), traffic (ADT) and condition parameters (ACA, ARV, AFL).
- In the case of low traffic roads also KCP was found to be the most sensitive followed by AGE2, ACA, AFL, APT and traffic. The pavement history i.e. chip size (CHIP), old surfacing thickness (HOLD) and previous wide cracking (PCW) not sensitive to high traffic roads were also found to be sensitive to SII modelling.

It can be concluded that the most of the parameters found sensitive with the high traffic volume road were also found sensitive with the low traffic road, however in the case of SII a few more parameters were found to be sensitive in low traffic road than high traffic road. It should also be noted that in most of the cases relative impact of input parameters varies for high traffic and low traffic roads.

8.3.3 Comparison of results using factorial and cetrius paribus methods

A comparison between the results of sensitivity analyses carried out using the factorial (FLH) and the cetrius paribus (TCP) methods was done in response to roughness prediction (IRI) for year 10 and surface integrity index prediction (SII) for year 5.

The results of the analysis are summarised in Table 8.7. The parameters are ranked based on sensitivity of parameters defined using the FLH method. The sensitivity level defined based on the impact elasticity using the TCP method is given for each input parameter.

The results of the study showed that:

- All the parameters found to be sensitive to the FLH analysis were found sensitive by the TCP method as well. Additional parameters which were found to be sensitive only for the TCP method could most probably be less sensitive when interaction of the parameters are considered. It should be noted that very few considered by the TCP method as most sensitive were not considered sensitive by the FLH method.
- Ranking of the parameters based on these two methods were found to be quite different, however it is more likely for more sensitive parameters for the TCP method to be in the higher ranking order on the sensitivity list for the FLH analysis.

8.4 Conclusions

- Not all of the parameters included in the expressions of the pavement deterioration models had major impacts on roughness and surface integrity index (SII) progression (*see* Table 8.7). For those parameters which were found not to be sensitive, a national default value may be adopted.
- Sensitivity of the input parameter differs based on:
  - Response to which condition parameters the sensitivity is studied;
  - Year of the analysis considered;
  - Traffic characteristics of the road network;
  - Method used to carryout the analysis.
- More input parameters were found to have an impact in the earlier years of the analysis period (5 years in the case of SII and 10 years in response to IRI), especially in the case of the 'do-nothing scenario'. This is due to the maximum limits of SII (100) and roughness (20 m/km) imposed on the system. When the application of the routine maintenance is considered, more parameters were found to be sensitive, especially, in response to SII.
- The ranking list of the sensitivity differed in different years. The initial values of the condition parameters are generally found to be more important in early years, whereas, calibration coefficients and other parameters were important more on later years. The traffic level of the network was found to have a major impact on the sensitivity ranking of the parameters for different years.
- All of the parameters found to be sensitive to the factorial analysis (FLH) were found sensitive by the cetrius paribus (TCP) method as well. A few additional parameters which were found to be sensitive only for the TCP method could most probably be less sensitive when interaction of the parameters are considered. It showed that the TCP is effective for carrying out the preliminary

analysis to filter out only the sensitive parameters before carrying out the analysis using FLH.

Table 8.7 Comparison of the Sensitivity of the Factorial (FLH) and Ceteris Paribus (TCP) Methods.

Sensitivity To Roughness (IRI) For				Sensitivity To Surface Integrity Index(SII) For			
High Traffic Road		Low Traffic Road		High Traffic Road		Low Traffic Road	
FLH Method Ranking[1]	TCP Sensitivity Level[2]	FLH Method Ranking	TCP Sensitivity Level	FLH Method Ranking	TCP Sensitivity Level	FLH Method Ranking	TCP Sensitivity Level
Parameters Sensitive to Both FLH and TCP Methods							
ADT4	3	IRI0	1	KCP	1	KCP	1
KGP	1	KGP	2	AGE2	1	AGE2	1
ADT1	3	ADT5	3	ACA	2	ACA	1
KPP	2	KCP	2	ADT1	2	AFL	1
ADT2	3	SNP	3	ARV	2	ARV	1
PAV_WID	1	PAV_WID	3	ADT4	2	ADT5	2
IRI0	1	KGE	2	AFL	1	CHIP	1
SNP	1	ADT1	3	KPP	1	PCW	1
HNEW	3	HOLD	4	KVP	1	ADT1	2
ACW	4	ADT3	3	CQ	2	APT	1
HOLD	3	KPP	4	GROWTH	4	KVP	1
MMP	3	ACA	4	SNP	2	KPP	4
APT	3	RDS	4			HOLD	4
KCP	1	HNEW	3			CQ	4
GROWTH	3	AGE3	4				
ARV	3	KRP	3				
KRP	4	ADT6	3				
AGE2	3	ADT2	3				
KVP	3	CQ	4				
CHIP	3	MMP	3				
CQ	3	ACW	4				
		KCI	3				
		AGE2	3				
		ARV	4				
		PCW	4				
Parameter Sensitive to TCP method only							
KGE	1	CHIP	2	CHIP	1	KCI	1
KCI	2	GROWTH	4	KCI	1	SNP	2
KPI	3	KPI	4	ACA	2	PAV_WID	3
AGE3	3	KVP	4	APT	2	KPI	4
RDS	3			HOLD	2	HNEW	4
ACA	4			PCW	2	GROWTH	4
PCW	4			KPI	3		
				HNEW	3		
				MMP	4		

Notes: 1/ Ranking based on regression coefficients from sensitivity analysis using FLH method

2/ The value indicate the Sensitivity level of the given parameter found using TCP method and level '1' has the highest sensitivity.

9. Sensitivity of Parameters in Strategy Generation

9.1 Introduction

The main objective of predictive modelling is to define the optimal long-term performance standard for a given road network and to prepare an optimised maintenance programme to maintain that standard for the minimum possible cost. Trigger limits, by defining the level to which a given road condition can be allowed to deteriorate to, ensure that the optimal long-term performance standard is met.

A number of condition parameters are used as triggers in the NZ dTIMS setup. If any of these parameters exceed the limit a relevant treatment is triggered. Trigger limits in the NZ dTIMS setup are defined by trigger expressions as a function of the traffic. Trigger coefficients A0 and A1 are supplied (refer to Chapter 5 for more detail). For simplicity the sensitivity analysis of the trigger limits were carried out by varying the value of the A0 coefficients only.

As stated in Chapter 6, the following two different complementary methods were used for analysing the sensitivity of the input parameters in response to various parameters in the strategy generation process:

- The traditional cetrius peribus method to analyse the sensitivity of the individual trigger limits without interactions with other parameters; and,
- A factorial Latin analysis for more sensitive trigger limits (defined from the TCP method) and sensitive parameters (defined in Chapter 9) on the deterioration modelling.

9.2 Sensitivity of Individual Trigger Limits

9.2.1 Dataset Preparation and Analysis

For the sensitivity analysis based on the TCP method the datasets were prepared using a customised software program. This program generated dTIMS input files by varying the values of the individual trigger limits to five different levels within a defined range. Separate datasets were prepared for low traffic volume roads (AADT 1000) and high traffic volume roads (AADT 20000).

A dTIMS analysis was carried out based on performance based analysis (PBA) mode keeping the discount factor of 0. Sensitivity of various trigger parameters in response to various output parameters were studied in 5, 10 , 15 and 20 years. Refer to Table 6.5 for the output parameters used for the analysis.

The sensitivity is presented in terms of impact elasticity or sensitivity level. (refer to Chapter 6 for definition of these parameters.)

9.2.2 Sensitivity of trigger limits for different analysis periods

A sensitivity analysis of the individual trigger coefficients was carried out in response to various condition parameters using the TCP method to determine the effect of the analysis period. The analysis showed (see Table 9.1) the trigger limits were not found very sensitive to the analysis period while analysing in response to average roughness.

Minor changes in the sensitivity level was generally observed. Similar results were observed in response to the surface integrity index (SII) and granular overlay need (GRVL) as well. Hence, as there was no major impact of the analysis period was found in the sensitivity analysis of the trigger limits in PBA, most of the further analyses for TCP method were carried out for a 20 years analysis period.

Table 9.1 Sensitivity of Trigger Limits on Average IRI for Different Periods.

Impact Elasticity in Response to Average IRI for							
For 10 Years Period		For 10 Years Period		For 15 Years Period		For 20 Years Period	
Triggers	Imp. El.	Triggers	Imp. El.	Triggers	Imp. El	Triggers	Imp. El.
S_MCI_A0	0.20	R_SII_A0	0.20	R_SII_A0	0.21	R_SII_A0	0.23
S_IRI_A0	0.20	S_MCI_A0	0.19	S_MCI_A0	0.18	S_MCI_A0	0.22
M_RDM_A0	0.20	M_RDM_A0	0.19	M_RDM_A0	0.18	M_RDM_A0	0.22
M_ACA_A0	0.20	M_ACA_A0	0.19	M_ACA_A0	0.18	M_ACA_A0	0.22
M_ASH_A0	0.20	M_ASH_A0	0.19	M_ASH_A0	0.18	M_ASH_A0	0.22
R_SII_A0	0.19	S_IRI_A0	0.19	R_IRI_A0	0.18	S_IRI_A0	0.21
R_SFC_A0	0.12	R_SFC_A0	0.11	S_IRI_A0	0.18	R_SFC_A0	0.13
M_IRI_A0	0.11	M_IRI_A0	0.09	R_SFC_A0	0.10	R_IRI_A0	0.11
		R_IRI_A0	0.09	M_IRI_A0	0.07	M_IRI_A0	0.09

Notes:

Level 2	Impact Elasticity greater than 0.2 and less than 0.5
Level 3	Impact Elasticity greater than 0.05 and less than 0.2

9.2.3 Sensitivity of trigger limits on deterioration models prediction

The results of the sensitivity analysis on pavement deterioration parameters (IRI, SII, GRVL) in terms of sensitivity level are summarised in Table 9.2.

Table 9.2 Sensitivity of Trigger Limits to Average IRI, SII and GRVL.

Trigger Coefficient	Trigger For	Sensitivity Level in Response to					
		IRI		SII		GRVL	
		Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic
S_GOVL_A0	Strengthening Granular base limits						
S_IRI_A0	Strengthening roughness limit	2	1	1	1	1	2
S_MCI_A0	MCI limit	2	1	1	1	1	2
M_ACA_A0	Strengthening cracking limit	2	2	1	1	1	2
M_ASH_A0	Strengthening shoving limit	2	2	1	1	1	2
M_IRI_A0	Smoothing roughness limit	3	2	1	1	1	2
M_RDM_A0	Smoothing rutting limit	2	2	1	1	1	2
R_HS_A0	Height of surfacing limit						
R_IRI_A0	Resurfacing roughness limit		3	1	1	2	3
R_SC_A0	Seal cycle limit						
R_SFC_A0	SFC limit	3	3	1	1	1	3
R_SII_A0	SII limit	2	3	1	1	1	3
R_TD_A0	Texture depth Limit		3		1[1]		3
R_TS_A0	Surfacing thickness limit						
D_IRI_A0	Do minimum roughness limit						
D_SII_A0	Do minimum SII Limit						

Note: 1/ Sensitivity of Texture depth progression is far greater than any other components

The results showed that the sensitivity to some of the parameters were found to be slightly different for low and high traffic roads. The following conclusions can be made from the results of the analyses (*see* Table 9.2):

- For high traffic roads the strengthening trigger limits (S_IRI_A0, S_MCI_A0) were found to be more sensitive in response to average IRI than for low traffic roads.
- Most of the trigger coefficients were found to be very sensitive (sensitivity level 1) for the average SII for both low and high traffic roads. However trigger limit for texture depth was found to be far more sensitive than other limits for high traffic roads.
- Sensitivity of the trigger limit in response to average granular overlay needs (GRVL) seemed to be more sensitive with low traffic roads than high traffic roads.

The following trigger limits were found not to be sensitive to the pavement deterioration prediction at all:

S_GOVL_A0	(granular overlay threshold for strengthening treatments),
R_HS_A0	(Maximum height of chip seal surfacing) ,
R_SC_A0	(maximum number of seal cycles),
R_TS_A0	(area wide treatment threshold
D_IRI_A0	(Roughness limit for Do-minimum strategy)
D_SII_A0	(SII limit for Do-minimum strategy)

9.2.4 Sensitivity of trigger limits on economic parameters

The total agency costs (AC) and total vehicle operating costs (VOC) were used as the economic output parameters to define the sensitivity of the trigger limits. As the strategy generation process in the performance based analysis (PBA) mode is based on performance of the road rather than economic optimisation, a study with variation of unit cost for various maintenance activities was not considered necessary here.

For high traffic roads the strengthening treatment triggers (S_MCI_A0, S_IRI_A0) were found to be the most sensitive trigger limits in response to AC and VOC followed by the smoothing treatment triggers (M_RDM_A0, M_ACA_A0, M_ASH_A0, M_IRI_A0) and resurfacing triggers (R_SII_ A0, R_TD_A0, R_SFC_A0, R_IRI_A0) (*see* Table 9.3 and Table 9.4), similar to that was observed earlier in response to IRI, SII and GRVL (*see* Table 9.2). This kind of ranking was not true in the case of the low traffic roads. However, most of the parameters sensitive to high traffic roads were found to be sensitive with low traffic roads as well.

The results of the sensitivity of trigger limits to AC and VOC are summarised in Table 9.5. It shows that the majority of trigger limits except S_GOVL_A0, R_HS_A0, R_SC_A0, R_TS_A0, D_IRI_A0 and D_SII_A0 are very sensitive (Sensitive level 1) to both total AC and VOC. The only exception was the Texture Depth Limit which was sensitive only for high traffic roads and in response to AC only.

Table 9.3 Sensitivity of Triggers to AC based on Traffic Level.

Sensitivity to Low Traffic Road				Sensitivity to High Traffic Road			
For 5 Years Period		For 20 Years Period		For 5 Years Period		For 20 Years Period	
Trigger	Imp. El.	Trigger	Imp. El.	Trigger	Imp. El.	Trigger	Imp. El
S_IRI_A0	20.90	S_IRI_A0	4.48	S_MCI_A0	57.23	S_MCI_A0	15.63
R_SII_A0	16.80	R_SII_A0	4.09	S_IRI_A0	38.24	S_IRI_A0	10.45
M_RDM_A0	15.14	M_RDM_A0	3.67	M_RDM_A0	23.93	M_IRI_A0	9.19
M_ACA_A0	15.14	M_ACA_A0	3.67	M_ACA_A0	23.93	M_RDM_A0	6.18
M_ASH_A0	15.14	M_ASH_A0	3.67	M_ASH_A0	23.93	M_ACA_A0	6.18
M_IRI_A0	8.08	R_SFC_A0	1.40	M_IRI_A0	23.93	M_ASH_A0	6.18
R_SFC_A0	5.60	S_MCI_A0	1.23	R_SII_A0	11.48	R_SII_A0	2.71
S_MCI_A0	1.09	M_IRI_A0	0.98	R_TD_A0	5.53	R_TD_A0	1.08
		R_IRI_A0	0.28	R_SFC_A0	3.36	R_SFC_A0	0.75
				R_IRI_A0	2.95	R_IRI_A0	0.33

Notes:		
	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5

Table 9.4 Sensitivity of Triggers to VOC based on Traffic Class.

Sensitivity to Low Traffic Road				Sensitivity to High Traffic Road			
For 5 Years Period		For 20 Years Period		For 5 Years Period		For 20 Years Period	
Triggers	Imp. El.	Trigger	Imp. El.	Trigger	Imp. El.	Trigger	Imp. El.
R_SFC_A0	1.95	R_SFC_A0	3.13	S_MCI_A0	4.19	S_MCI_A0	15.38
S_MCI_A0	1.09	R_SII_A0	1.37	S_IRI_A0	4.19	S_IRI_A0	15.38
S_IRI_A0	1.09	S_MCI_A0	1.23	M_RDM_A0	3.15	M_IRI_A0	6.08
M_RDM_A0	1.09	M_RDM_A0	1.23	M_IRI_A0	3.15	M_RDM_A0	6.07
M_ACA_A0	1.09	M_ACA_A0	1.23	M_ACA_A0	3.15	M_ACA_A0	6.07
M_ASH_A0	1.09	M_ASH_A0	1.23	M_ASH_A0	3.15	M_ASH_A0	6.07
R_SII_A0	1.06	S_IRI_A0	1.21	R_SFC_A0	2.95	R_SFC_A0	4.44
M_IRI_A0	0.66	M_IRI_A0	1.11	R_TD_A0	2.19	R_TD_A0	3.22
		R_IRI_A0	0.98	R_SII_A0	1.97	R_SII_A0	2.76
				R_IRI_A0	0.38	R_IRI_A0	0.38

Notes:		
	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5

Table 9.5 Sensitivity of Trigger limits to AC and VOC.

Triggers	Description	Sensitivity Level in Response to			
		Total AC		Total VOC	
		Low Traffic	High Traffic	Low Traffic	High Traffic
S_IRI_A0	Strengthening roughness limit	1	1	1	1
S_MCI_A0	MCI limit	1	1	1	1
M_ACA_A0	Smoothing cracking limit	1	1	1	1
M_ASH_A0	Smoothing shoving limit	1	1	1	1
M_IRI_A0	Smoothing roughness limit	1	1	1	1
M_RDM_A0	Smoothing rutting limit	1	1	1	1
R_IRI_A0	Resurfacing roughness limit	1	1	1	1
R_SFC_A0	SFC limit	1	1	1	1
R_SII_A0	SII limit	1	1	1	1
R_TD_A0	Texture depth Limit		1		1

9.2.5 Sensitivity of trigger limits to treatment selection

An analysis was carried out to find out the sensitivity of trigger limits to the treatment selection procedure. The sensitivity was studied in response to the length of one of the following categories/levels of treatments:

- Strengthening;
- Smoothing; and,
- Resurfacing.

Analysis of the results for high traffic roads (Table 9.6) amd for the low traffic roads (Table 9.7) have shown that:

- **Strengthening Length**: For both the high and low traffic roads, only strengthening treatment triggers (S_IRI_A0, S_MCI_A0) were found to be sensitive in response to the length of the strengthening treatment.
- **Smoothing Length**: For high traffic roads the smoothing trigger limit for roughness (M_IRI_A0) were found to be far more sensitive in triggering the smoothing treatments followed by other smoothing treatment and then resurfacing triggers. On the other hand, for low traffic volume roads all the earlier mentioned trigger limits affect the length of smoothing treatment generated, however their sensitivity does not differ considerably.
- **Resurfacing Length**: For high traffic roads only the resurfacing treatment triggers (R_TD_A0, R_SFC_A0, R_IRI_A0 and R_SII_A0) were found to be sensitive to the length of the resurfacing treatment. In the case of low traffic roads most of the trigger coefficients were found to be sensitive to the length of the resurfacing treatment and their sensitivity did not differ considerably.

Table 9.6 Sensitivity of Triggers Length of Treatments for High Traffic Road.

Sensitive to Strengthening Length		Sensitive to Smoothing Length		Sensitive to Resurfacing Length	
Trigger	**Imp. El.**	**Trigger**	**Imp. El.**	**Trigger**	**Imp. El.**
S_MCI_A0	0.80	M_IRI_A0	18.28	R_TD_A0	1.67
S_IRI_A0	0.80	M_ASH_A0	8.77	R_SFC_A0	1.67
		M_ACA_A0	8.77	R_IRI_A0	1.67
		M_RDM_A0	8.77	R_SII_A0	0.80
		R_SII_A0	1.68		
		S_MCI_A0	1.67		
		S_IRI_A0	1.67		
		R_TD_A0	0.75		
		R_SFC_A0	0.60		

Notes: Level 1 Impact Elasticity greater than 0.5

It must be noted that although there is some variation on the impact elasticity, most of the trigger limits (except S_GOVL_A0, R_HS_A0, R_TS_A0, D_IRI_A0, D_SII_A0 which are not sensitive at all) were found to be of sensitivity level 1 in response to the pavement deterioration, economic parameters and treatment selection process. Hence, proper customisation of these parameters should be done for different networks during dTIMS modelling.

Table 9.7 Sensitivity of Triggers Length of Treatments for Low Traffic Roads.

Sensitive to Strengthening Length		Sensitive to Smoothing Length		Sensitive to Resurfacing Length	
Trigger	**Imp. El.**	**Trigger**	**Imp. El.**	**Trigger**	**Imp. El.**
S_IRI_A0	6.25	M_ASH_A0	6.00	M_ASH_A0	4.50
S_MCI_A0	0.50	M_ACA_A0	6.00	M_ACA_A0	4.50
		R_SII_A0	6.00	S_MCI_A0	4.50
		M_RDM_A0	6.00	S_IRI_A0	4.50
		R_SFC_A0	2.00	R_SII_A0	4.50
		M_IRI_A0	1.60	M_RDM_A0	4.50
		S_MCI_A0	1.50	M_IRI_A0	1.60
		S_IRI_A0	0.80	R_SFC_A0	1.50

Notes:	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5

Chapter 8 showed that there are some differences in sensitivity of an input parameters in the case when only the individual parameter is considered and when the inter-relation of the parameter with other input parameters are considered. Hence, further analyses were carried out using the FLH method to study the sensitivity with varying the value of input parameters found sensitive to the pavement deterioration modelling in Chapter 8 and the sensitive trigger limits defined in this section.

9.3 Sensitivity to Strategy Generation Based on Factorial Analysis (FLH)

9.3.1 Dataset preparation and analysis in PBA

The sensitivity of various parameters affecting the strategy generation was studied using the FLH method to investigate the interaction between the parameters. The dataset used contained all the sensitive input parameters to the pavement deterioration models and the sensitive trigger limits defined earlier using the TCP method.

To consider the effect of the traffic level on the sensitivity of the parameters, the analysis was carried out for two levels of traffic:

- Low traffic road (200 to 2000 AADT); and,
- High traffic road (5000 to 30000 AADT).

The datasets based on the FLH method was prepared using the customised software program. For each parameter there were 10 levels of variations within the defined range. Separate datasets were prepared for high traffic volume roads and low traffic volume roads.

The dTIMS analysis was carried out based on the performance based analysis (PBA) mode keeping the discount factor of 0. Sensitivity of various trigger parameters in response to various output parameters were studied in 5, 10 , 15 and 20 years (refer to Table 6.5 for the output parameters used for the analysis).

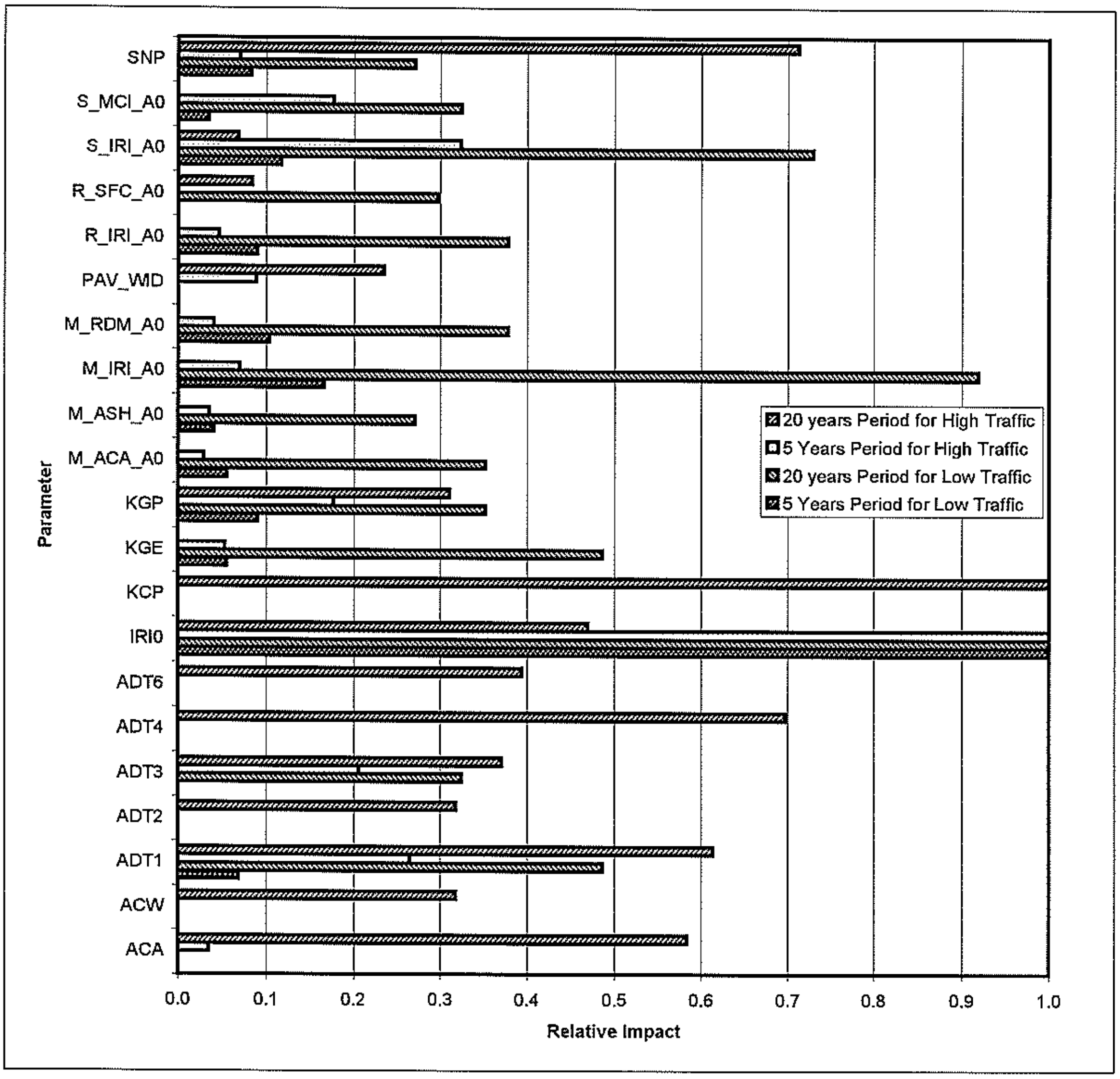
9.3.2 Sensitivity of deterioration predictions in PBA

The performance based analysis sensitivity on the pavement deterioration was studied in response to average roughness (IRI), the surface integrity index (SII) and granular overlay need (GRVL).

The sensitivity of the various input parameters on the average roughness in the performance based analysis showed that (*see* Figure 9.1 and refer to Table D.14 in Appendix D for more detail):

- There were slight variations on the relative impact of various input parameters in the case of high traffic and low traffic roads. However most of the parameters sensitive to the high traffic road is sensitive to low traffic road.
- The initial roughness (IRI0) was found to have the highest ranking in the sensitivity table. It should be noted that the sensitivity of IRI0 decreases with increase in the period in the case of high traffic road.
- The traffic volume and trigger limits for roughness were found to be relatively more sensitive than condition parameters.

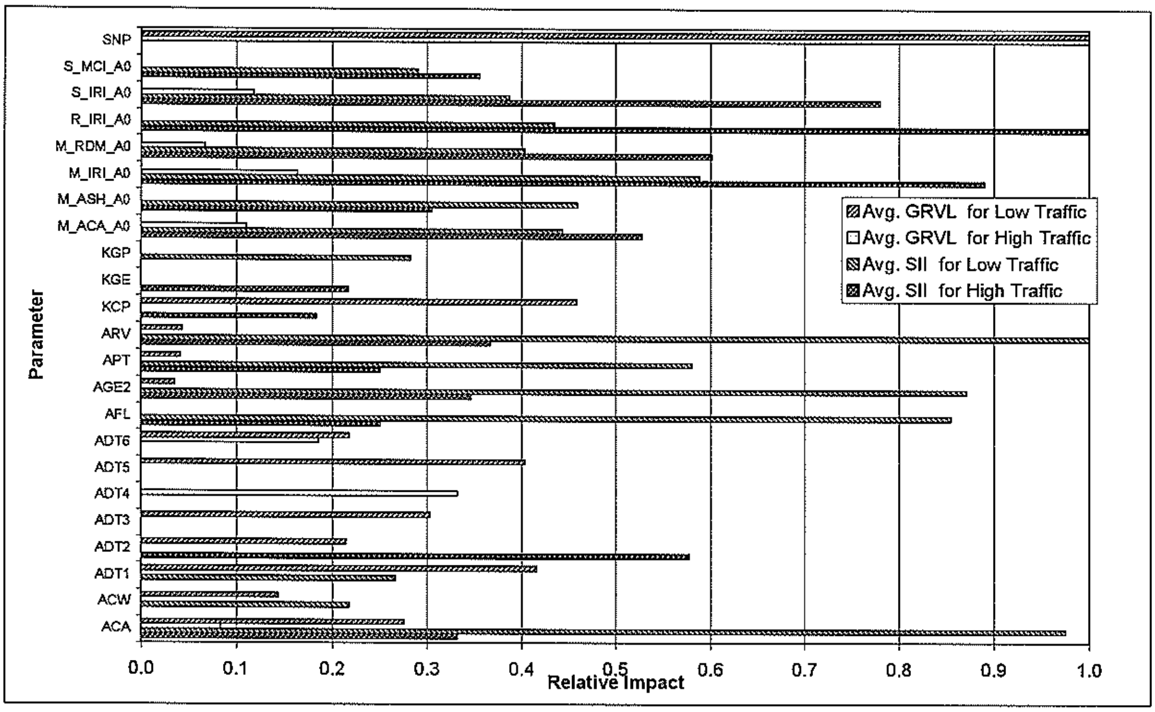
Figure 9.1: Sensitivity to Average IRI in PBA Analysis.



The analysis of results for different periods on the Surface Integrity index (SII) and Granular Overlay needs (GRVL) showed that there was a minor impact on the length of period for which results were considered. Hence, results of analyses carried out based on 20 years analysis period has been considered. The results of sensitivity analysis in response to Surface Integrity Index (SII) for 20 years (*see* Figure 9.2 and refer to Table D.15 in Appendix D for more detail) showed that:

- For **high traffic** roads the trigger limits (R_IRI__A0, M_IRI_A0, S_IRI_A0, M_RDM_A0, M_ACA_A0, S_MCI_A0, M_ASH_A0) were found to be very sensitive parameters. The other sensitive parameters were traffic volume (ADT2), condition parameters (ARV, ACA, AFL, APT), calibration coefficients (KGE, KCP) and pavement history (AGE2).
- For **low traffic** roads the condition parameters (ARV, ACA, AFL, APT) were found to be more sensitive than the trigger limits (R_IRI__A0, M_IRI_A0, S_IRI_A0, M_RDM_A0, M_ACA_A0, S_MCI_A0, M_ASH_A0).

Figure 9.2: Sensitivity to Average SII and GRVL in PBA Analysis.



The results of the sensitivity analysis in response to granular overlay need (GRVL) for 20 years (see Figure 9.2 and refer to Table D.15 in Appendix D for more details) showed that the pavement strength (SNP) was found to be the most sensitive parameter for both high and low traffic roads, the sensitivity of which was found to be much higher than for other parameters. The only other relatively sensitive parameters are traffic volume (ADT) and crack progression coefficient (KCP).

9.3.3 Sensitivity to the economic parameters in PBA

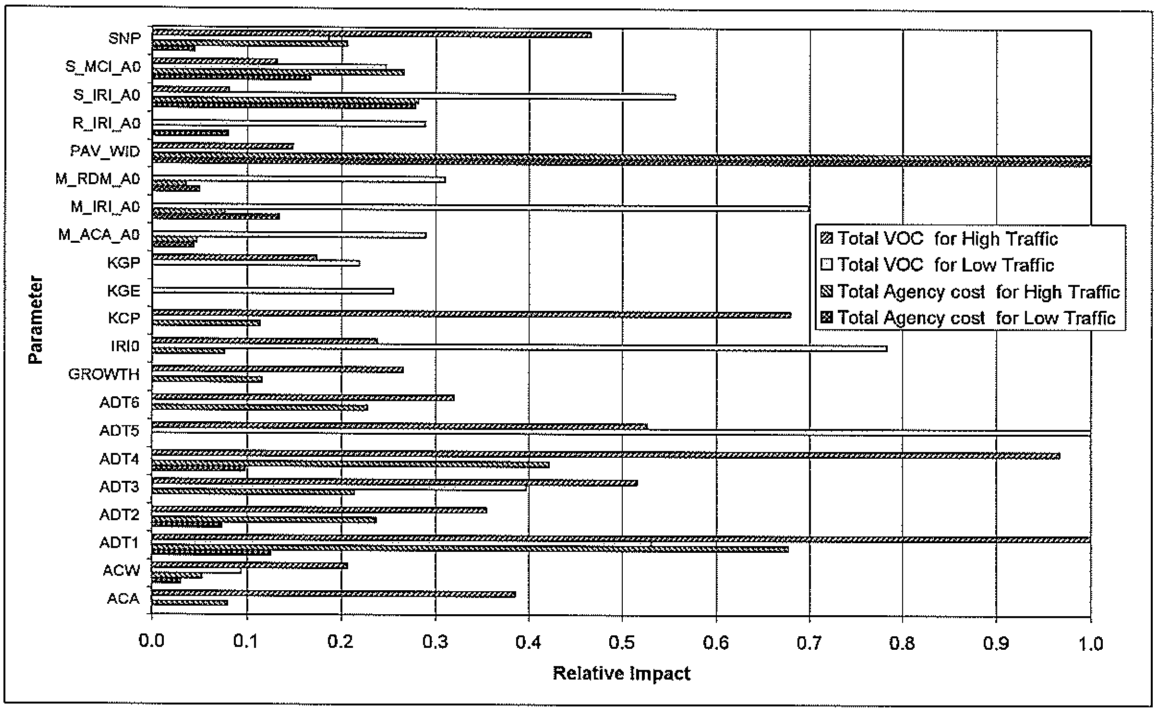
The sensitivity of various parameters in PBA in terms of economic parameters were investigated in response to the total agency cost (AC) and vehicle operating cost (VOC).

The analysis of the results in response to the sensitivity to the total agency cost (AC) showed that (*see* Figure 9.3 and refer to Table D.16 in Appendix D):

- The pavement width (PAV_WIDTH) was the most sensitive parameter for both low and high traffic roads. The reason behind this is that most of the unit cost for maintenance activities used in NZ dTIMS system is based on square metre area and, hence, any change in the width results considerable change in the cost for the maintenance work.

- The other quite sensitive parameter to AC include trigger coefficients and the traffic volume (ADT). Traffic seems to have slightly more influence in the case of the high traffic in comparison to trigger limits.

Figure 9.3: Sensitivity to Total AC and VOC for PBA.



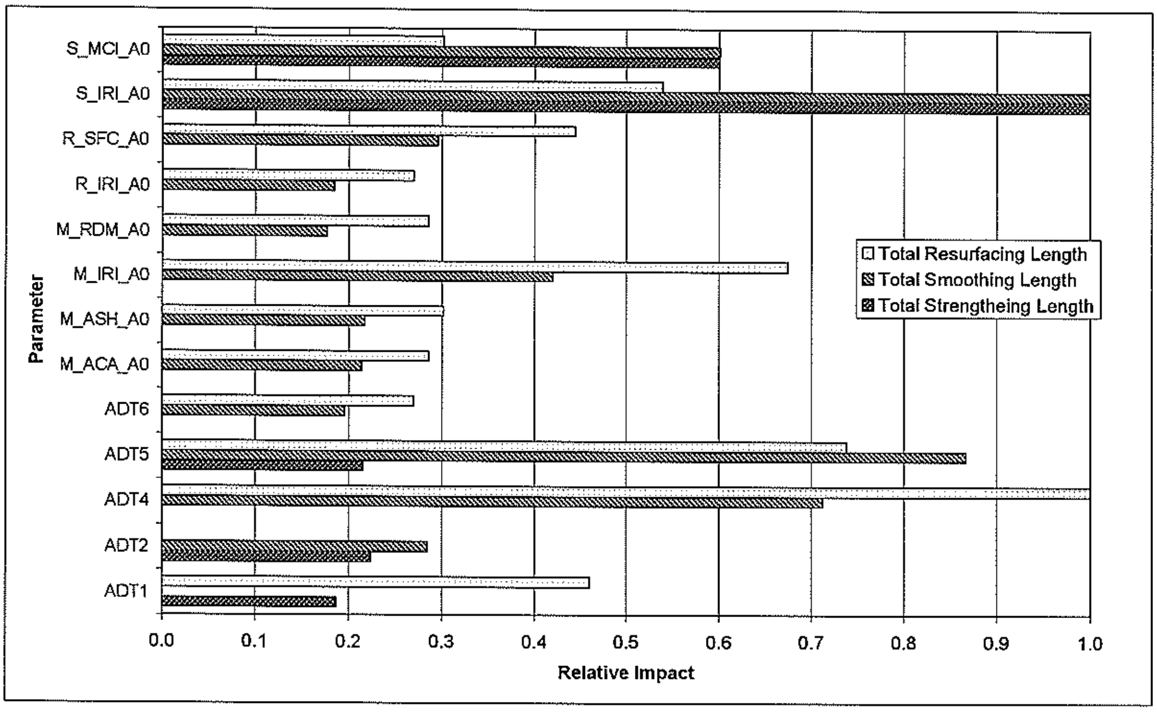
The analysis of the results in response to the sensitivity to the total vehicle operating cost (VOC) showed that (see Table):

- The traffic volume (ADT) is the most sensitive parameter for both low traffic and high traffic roads.
- In the case of low traffic roads initial roughness (IRI0) followed by trigger coefficients (M_IRI_A0, S_IRI_A0, M_RDM_A0, M_ACA_A0, R_IRI_A0, S_MCI_A0, R_SFC_A0, M_ASH_A0, R_SII_A0). The other sensitive parameters include calibration coefficients (KGE, KGP), pavement strength (SNP) and condition parameters like ACW.
- In the case of high traffic volume roads calibration coefficients (KCP, KGP) pavement strength (SNP) and some of the condition parameters (ACA, ACW) were found to be more sensitive than the trigger limits. The other sensitive parameters were pavement history (AGE2, AGE3, HNEW, HOLD).

9.3.4 Sensitivity to treatment selection in PBA

The sensitivity analysis for determining the impact of parameters in treatment selection was based on the performance based analysis for 20 years. The results in Figure 9.4 and Figure 9.5 (refer to Table D.17 and D.18 in Appendix D for more detail) shows that there are some differences with the impact of various parameters for high traffic and low traffic roads.

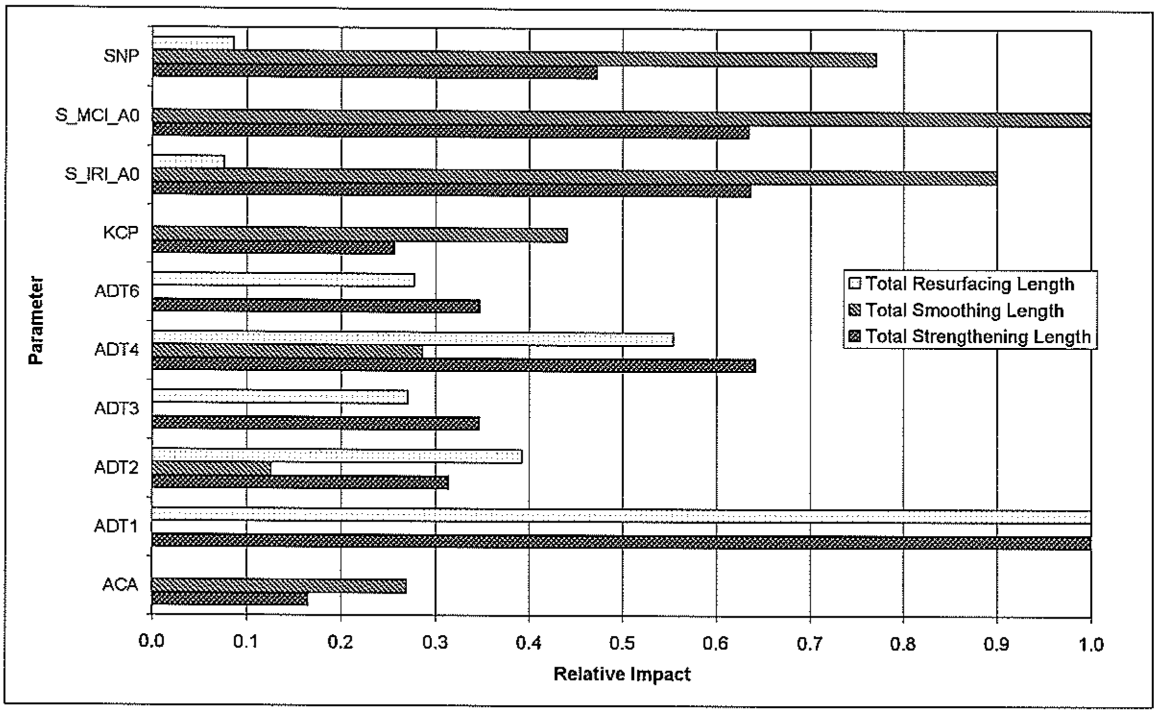
Figure 9.4: Sensitivity of Input Parameters to Treatment Selection for High Traffic Road.



It was observed that:

- **Strengthening Length**: For low traffic volume roads the trigger coefficients related to strengthening treatment (S_IRI_A0, S_MCI_A0) were the most sensitive followed by traffic volume (ADT), pavement strength (SNP) and existing roughness (IRI0). In the case of high traffic roads, traffic volume was the most sensitive parameter followed by the trigger coefficients related to strengthening. Other condition parameters, pavement characteristics, as well as trigger coefficients were found to be sensitive to the strengthening treatment for high traffic roads, whereas they are not so sensitive in the case of low traffic roads.
- **Smoothing Length**: Most of the trigger limits together with traffic volume were sensitive to the smoothing treatment length. In addition to that IRI0 and SNP were also found to be sensitive to smoothing. For high traffic roads in addition to the above mentioned parameters the condition parameters, for example ACA, ACW and pavement characteristic for example PAV_WID (carriageway width), HOLD (thickness of the old surfacing) will affect the smoothing treatment length.
- **Resurfacing Length**: Most of the parameters as in traffic volume, trigger coefficients, surface distresses and SNP (pavement strength) are affecting the smoothing treatment and are sensitive to the resurfacing treatment selection as well. This is true for both low volume and high volume roads.

Figure 9.5: Sensitivity of Input Parameters to Treatment Selection for Low Traffic Road.



It should be emphasised that the trigger limit is actually a function of the trigger coefficients and traffic volume. The analyses showed that the trigger coefficients and traffic volume are much more sensitive than the pavement condition and the calibration coefficients in determining what kind of treatment is applied. Hence, the proper definition of the long term performance standard is essential before carrying out any kind of analysis.

9.4 Comparison of Sensitivity of Performance Strategy with Routine Only

Comparison of the results of the sensitivity analysis in response to 20 years average roughness for performance based strategy ‘PANA’ and routine maintenance only ‘RTN’ showed that:

- For low traffic roads initial roughness (IRI0) had the highest sensitivity ranking for both cases. In addition, calibration coefficients (KGE, KGP), traffic volume (ADT), pavement strength (SNP) and environmental parameters were found to be sensitive. In the case of RTN, the pavement historical parameter (HNEW, HOLD, CQ, PCW, AGE2, AGE3) and condition parameters (ACA, ARV, ACW, RDS) were also found to be sensitive, whereas, these parameters were eliminated during the back analysis in the case of PANA.
- For high traffic roads traffic volume (ADT), calibration coefficients (KCP, KGP), initial roughness (IRI0), pavement width (PAV_WID), pavement strength (SNP), condition parameters (ARV, ACW) and historical parameters (HNEW, HOLD) etc. were found to be sensitive to both PANA and RTN. In the case of PANA there was some influence for trigger limits (S_IRI_A0, R_SFC_A0).

From the above example and overall assessment of the sensitivity analysis in response to PANA and RTN, it was found that most of the parameters found sensitive for routine maintenance were found to be sensitive to PANA as well. But as stated earlier, the trigger limits have a considerable influence only in the case of PANA. This is reasonable as 'RTN' strategy does not utilise the trigger limits, whereas, in the case of PANA, trigger limits define when to apply a certain level of treatment and the effect on other parameters depend on what level of treatment has been applied.

It should be noted that the reset values applied to various input parameters after applying a certain level of treatment also have considerable output from the dTIMS analysis. However, as the study of the sensitivity of the reset values was found to be a very complicated process it was not possible to carry out in this project. It is assumed that the sensitivity of the values used for resetting of a parameter will be similar to the sensitivity of the parameter.

9.5 Conclusions

1. The sensitivity of individual trigger limits based on the TCP method showed that:
   - the following trigger limits have very high sensitivity (Level 1):
     - Strengthening roughness trigger limit;
     - Strengthening MCI trigger limit;
     - Smoothing cracking trigger limit;
     - Smoothing roughness trigger limit;
     - Smoothing shoving trigger limit;
     - Smoothing rutting trigger limit;
     - Resurfacing roughness trigger limit;
     - Resurfacing SII trigger limit;
     - Resurfacing Texture trigger limit;
     - Resurfacing SFC trigger limit.
   - the following trigger limits are not found to be sensitive at all:
     - Granular overlay threshold limit;
     - Maximum number of seal cycle limit;
     - Roughness limit for do-minimum strategy;
     - SII limit for do-minimum strategy.
2. The results of the study using FLH method on sensitivity of the input parameters in response to condition deterioration prediction (average roughness, surface integrity index and granular overlay need) showed that trigger limits and the traffic level are quite sensitive and should be given due importance during the dTIMS analysis.
3. Most parameters found to be sensitive to routine maintenance only were also found to be sensitive to performance based strategy as well. However, unlike the routine maintenance case, the trigger limits had considerable influence in the case of performance based strategy.
4. Most of the parameters sensitive to pavement deterioration modelling were found to be sensitive in response to the total agency cost as well. However, the pavement width was found to be the most sensitive parameter due to its direct influence to the treatment cost.
5. Traffic volume was found to be the most sensitive parameter in response to total vehicle operating cost. Initial roughness and trigger coefficients were found to be more sensitive in the case of low traffic roads, whereas, calibration coefficients and pavement strength were more sensitive for high traffic roads.

10. Sensitivity of Parameters on Economic Optimisation

10.1 Introduction

Economic optimisation is used to select the best possible strategy for each road section to achieve a specified long-term performance standard of the road network for a given budget level. In the case of the NZ dTIMS system the optimisation is based on minimising the total transportation cost objective function. This means for the given budget constraint it will try to select those strategies which will result in the minimum total transportation costs for the analysis period.

The results of the analyses on the sensitivity of the various input parameters to economic optimisation are discussed in this chapter. The impact of the funding levels and effect on sensitivity due to changes in vehicle operating cost rates are also studied.

10.2 Data Preparation and Analysis

The analysis was carried out based on the factorial analysis as explained in Chapter 6 using the Latin hypercube experimental design method. Analysis of dTIMS was based on regression analysis using STATGRAPH 3.0. Relative impact to characterised sensitivity of a parameter is based on the normalised value obtain by dividing a coefficient for a given factor by the maximum coefficient.

The standard NZ dTIMS System was used with 5 years of programme generation period and 20 year treatment generation and benefit analysis period. dTIMS was run in the economic analysis mode with 10% discount rate as specified by the Transfund Project Evaluation Manual (Transfund, 1999).

10.3 Sensitivity to Deterioration Predictions in EA

The sensitivity of the various input parameters in response to the condition parameters were studied for different traffic levels and budget constraints in economic analysis mode (EA).

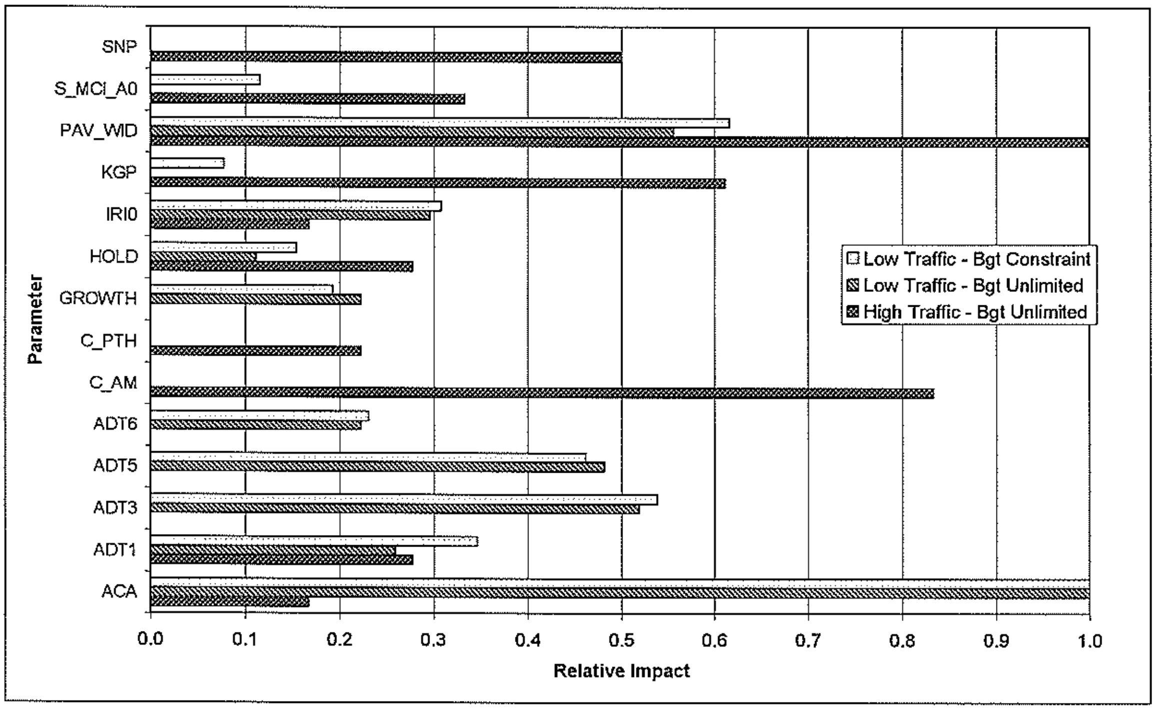
The sensitivity analysis in response to average roughness in EA mode showed that (*see* Figure 10.1 and refer to Table D.19 in Appendix D for more detail):

- For **high traffic** roads pavement width (PAV_WID) was found to be the most sensitive parameter followed by cost of asphalt mix (C_AM), calibration coefficient for roughness progression (KGP) and pavement strength (SNP). The other sensitive parameters were trigger limits (S_MCI_A0), traffic volume (ADT), calibration coefficient (KGP), condition parameters (ACA, IRI0) and pavement history (HOLD).
- On **low traffic** roads cracking (ACA) was found to be most sensitive followed pavement width and traffic volume (ADT, GROWTH).
- A comparison of the results for unlimited and constrained budget scenarios showed that there was not much difference in the sensitivity results between both scenarios in response to roughness prediction. The only exception was

that the trigger limits (S_MCI_A0, S_IRI_A0, R_SFC_A0) were found to be more sensitive in the case of the constrained budget.

It should be noted that in the case of high volume traffic roads it was a much lower ranking whereas for low volume traffic roads it had the highest sensitivity. The reason could be that for high volume traffic roads the economic benefit in terms of VOC is already very high (road user cost is directly proportional to the traffic volume) which results in a high B/C ratio and selection of roughness correction treatments. As a result, after a certain traffic level is reached the traffic volume is not very sensitive to roughness prediction.

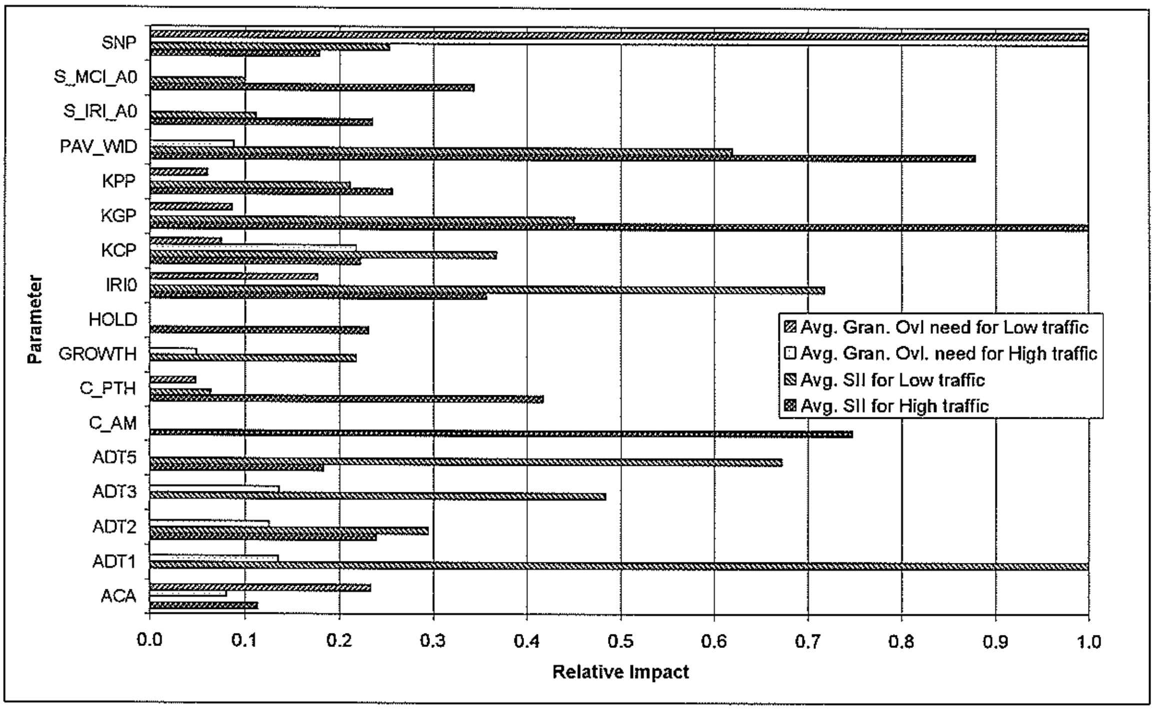
Figure 10.1: Sensitivity to Average IRI in EA.



The sensitivity analysis in response to the SII (surface integrity index) showed that (see Figure 10.2 and Table D.20 in Appendix D):

- For **high traffic** roads the most sensitive parameters were coefficients of roughness progression (KGP), pavement width (PAV_WID) and unit rate of asphalt mix (C_AM).
- For **low traffic** roads the traffic volume (ADT) was the most sensitive parameter followed by IRI0 (initial roughness), pavement width and calibration coefficients KGP and KPP).
- The comparison of the results for unlimited and constraint budget scenarios showed that there was not much difference between the sensitivity for various parameters to SII prediction.

Figure 10.2: Sensitivity to Average SII and GRVL in EA.



The sensitivity analysis in response to the GRVL (granular overlay need) showed that that pavement strength (SNP) is the most sensitive (much higher than other parameters) parameter for both high and low traffic roads (see Figure 10.2). A comparison of the results for unlimited and constrained budget scenarios showed that there was not much of a difference between the sensitivity for various parameters to GRVL prediction.

Therefore, it can be concluded that traffic volume had relatively high sensitivity in EA mode, especially for low traffic road. The cost parameters were also affecting the output of the dTIMS analysis. The effect of the trigger limits were much less than in the case of the performance based analysis. This is mainly due to the trigger limits related to roughness (S_IRI_A0, M_IRI_A0, R_IRI_A0) being found to be more sensitive. However, it should be noted that trigger limit related to maintenance cost (S_MCI_A0) was also found to be very sensitive on the economic analysis. Hence, if the MCI expression is not well customised to a given network it is generally recommended to turn off the MCI model.

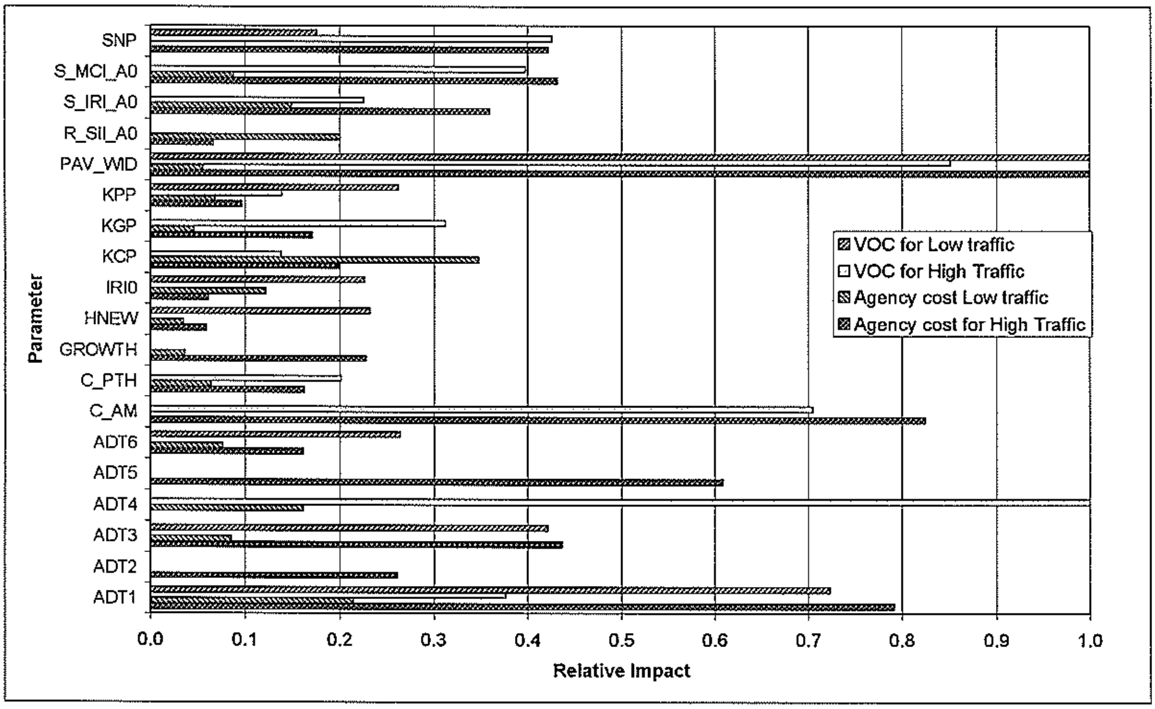
10.4 Sensitivity to Economic Parameters in EA

The sensitivity analysis in response to the economic parameters in EA mode were studied for total agency cost (AC) and total vehicle operating cost (VOC) for a 20 year analysis period. Although the analysis and optimisation were based on a discounted value using 10% the actual sensitivity to the cost parameters were based on real value.

The sensitivity analysis in response to the total agency cost (AC) for 20 years showed that (Figure 10.3 – for data see Table D.21 in Appendix D):

- For **high traffic** roads the most sensitive parameters are pavement width (PAV_WID), cost for asphalt mix (C_AM), traffic volume (ADT, GROWTH), pavement strength (SNP). Besides, trigger limits (S_MCI_A0, S_IRI_A0, R_SII_A0), and calibration coefficients (KCP, KGP, KPP) were also found to be sensitive to the predicted agency cost.
- For **low traffic** roads pavement width also was the most sensitive parameter with its sensitivity much higher than any other parameters. The other sensitive parameters were calibration coefficient for crack progression (KCP), traffic volume (ADT, GROWTH) and trigger limits (S_IRI_A0, S_MCI_A0, R_SII_A0).

Figure 10.3: Sensitivity to Agency Cost and VOC in EA.



The sensitivity analysis in response to the total vehicle operating cost (VOC) in economic analysis showed that (see Figure 10.3):

- For **high traffic** roads the most sensitive parameters were traffic volume (ADT) pavement width (PAV_WID), cost of asphalt mix (C_AM), pavement strength (SNP). However, trigger limits (S_MCI_A0, S_IRI_A0, R_SII_A0), and calibration coefficients (KCP, KGP, KPP) were found to be sensitive to the predicted VOC.
- For **low traffic** roads pavement width was the most sensitive followed by traffic volume. The other sensitive parameters were calibration coefficient (KPP), initial roughness (IRI0) and surface thickness (HNEW)

It should be noted that the high sensitivity of pavement width (PAV_WID) in response to the economic parameters are because the unit costs for various treatments in NZ dTIMS System are mainly based on the square metre which is obviously multiplied by pavement width.

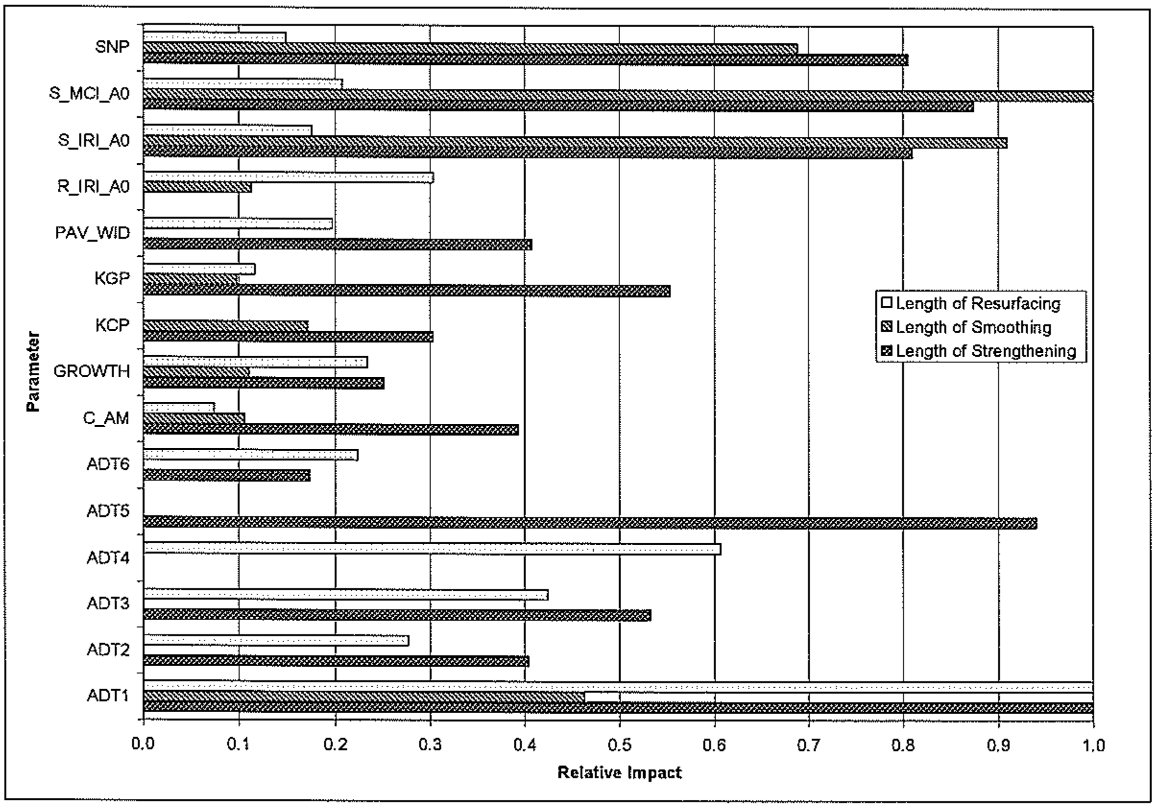
10.5 Sensitivity to Treatment Selection in EA

Sensitivity of various input parameters on the treatment selection based on the economic analysis (EA) was studied based on the length of the various treatments applied to the section for the analysis period of 20 years.

The analyses were carried out separately for the high traffic and low traffic roads. The results of the analyses for high traffic roads showed (*see* Figure 10.4 and refer to D.22 in Appendix D for more detail):

- **Strengthening Length**: The traffic volume (ADT1, ADT5) together with trigger coefficients for strengthening treatments (S_MCI_A0, S_IRI_A0) and pavement strength (SNP) were found to be the most sensitive parameters.
- **Smoothing Length**: The trigger coefficients for strengthening treatment were the most sensitive parameters followed by pavement strength and traffic volume.
- **Resurfacing Length**: Traffic volume (ADT) was found to be the most sensitive parameter to resurfacing treatment selection followed by trigger coefficients for resurfacing treatment (R_IRI_A0, R_SFC_A0, R_SII_A0), for smoothing treatment (M_IRI_A0) and for strengthening treatment (S_MCI_A0, S_IRI_A0).

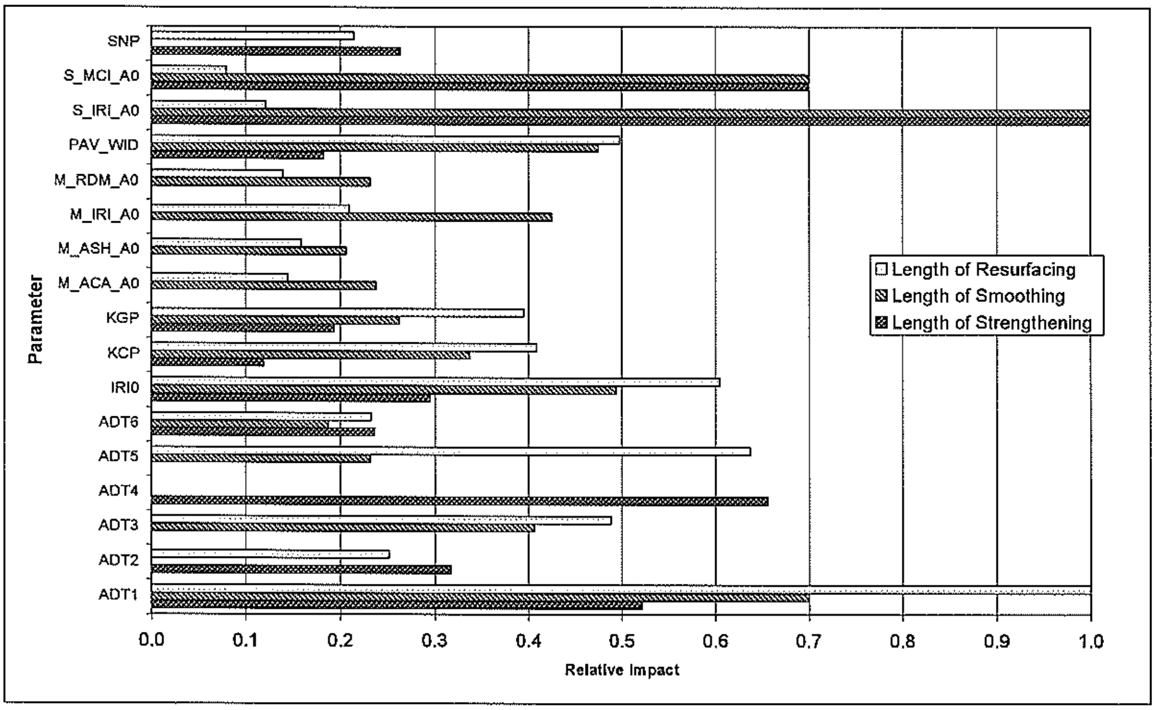
Figure 10.4: Sensitivity of Economic Analysis in High Traffic Road.



The results of the study for the sensitivity of the input parameters to the treatment selection in economic analysis for low traffic roads showed (*see* Figure 10.5 and refer to Table 23 in Appendix D):

- **Strengthening length**: Calibration coefficients for the strengthening treatment (S_IRI_A0, S_MCI_A0) together with traffic volume (ADT) were found to be most sensitive followed by initial roughness (IRI0), pavement strength (SNP) and calibration coefficients (KGP, KCP).
- **Smoothing Length**: Trigger coefficients for strengthening treatment (S_IRI_A0, S_MCI_A0), traffic volume (ADT), initial roughness (IRI0), pavement width (PAV_WID) were found to be quite sensitive.
- **Resurfacing Length**: Traffic volume (ADT) followed by initial roughness (IRI0) and pavement width (PAV_WID) were the most sensitive parameters.

Figure 10.5: Sensitivity of Economic Analysis in Low Traffic Road.

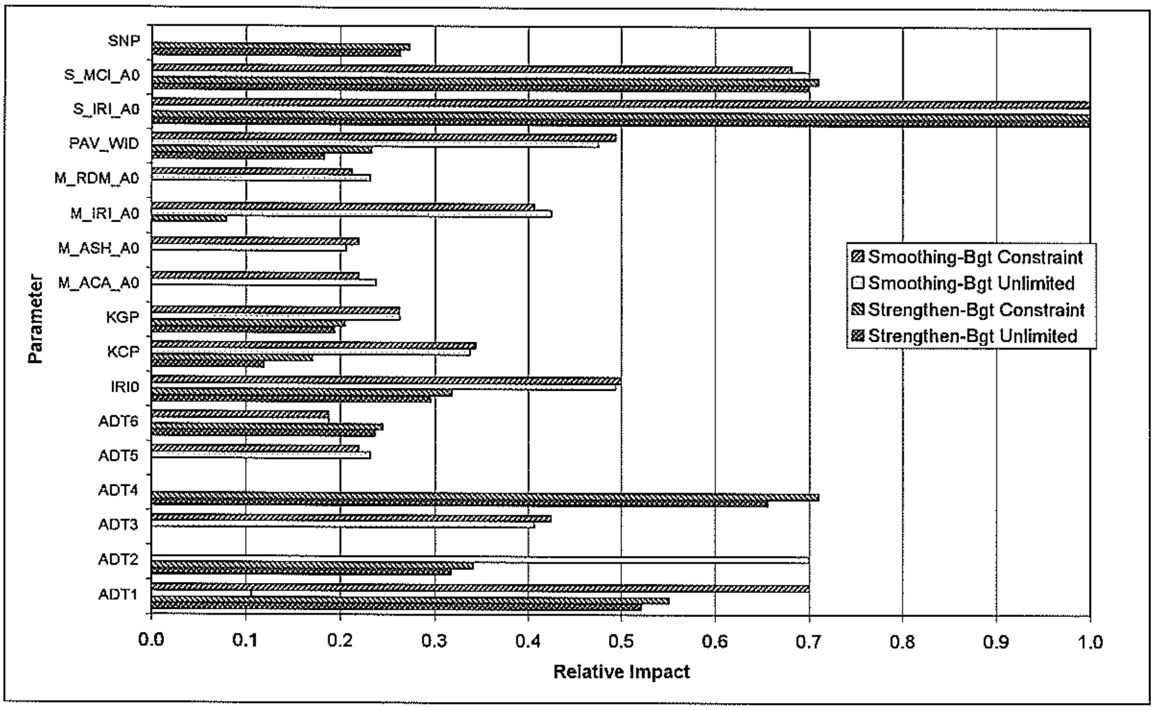


A comparison of the results of the sensitivity analysis showed that most of the parameters sensitive to high traffic roads were sensitive to low traffic roads. Traffic and trigger limits for strengthening treatments were the most sensitive parameters in the both case. However it was noted that cost parameters such as C_AM (cost of asphalt mix) were more sensitive to high traffic roads whereas C_SLDB, C_SLLG (cost of sealing) were sensitive to low traffic roads. Similarly with low traffic roads the effect of the environmental calibration coefficients (KGE) was found to be more sensitive.

10.6 Effect of Budget Constraint on Sensitivity to Treatment Selection

The study on the effect of the budget constraint on the sensitivity of various parameters showed that the sensitivity of various parameters in response to the length of treatments applied for the unlimited budget scenario and constraint budget was almost similar (*see* Figure 10.6 and refer to Table D.24 in Appendix D for more details).

Figure 10.6: Sensitivity of Budget Constraint in EA.



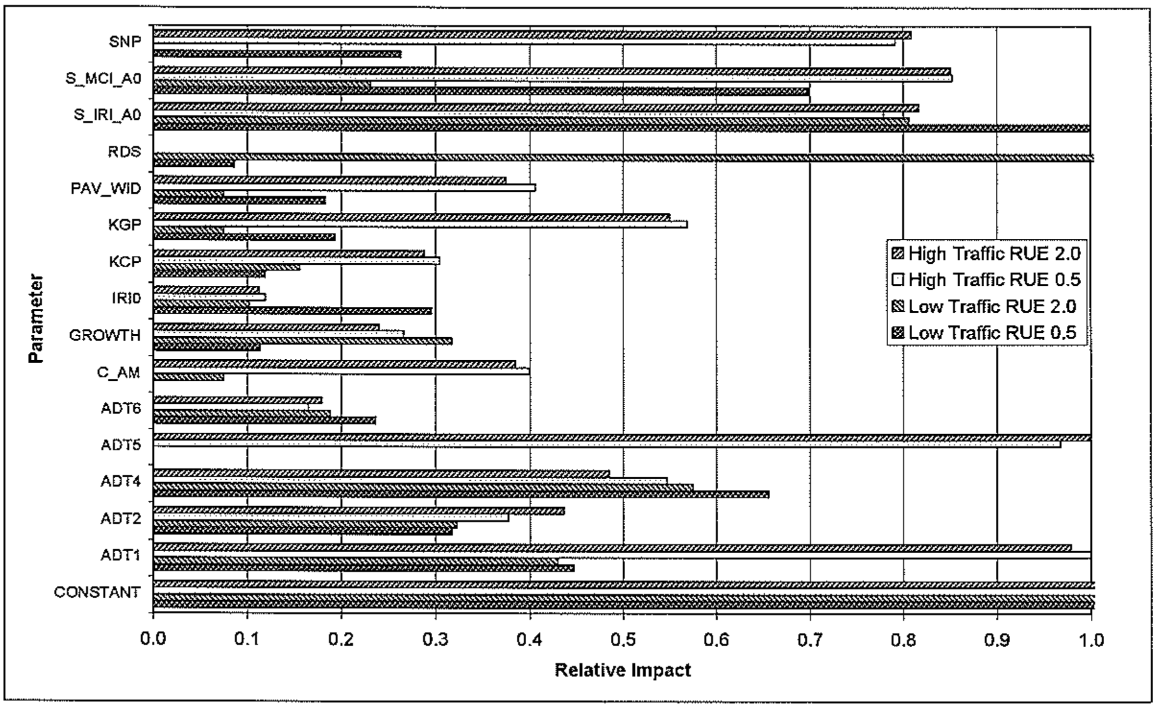
10.7 Effect of the VOC rate on Sensitivity to Treatment Selection

A study on the sensitivity of various input parameters to treatment selection for various level of VOC rate was carried out for 2 different levels:

- VOC rate of Transfund Project Evaluation Manual multiplied by 0.5; and,
- VOC rate of Transfund Project Evaluation Manual multiplied by 2.

The sensitivity for both high traffic roads as well as low traffic roads in terms of length of strengthening, smoothing and resurfacing treatment triggered were studied. Figure 10.7 (refer to Table D.25 in the Appendix D for more detail) shows the sensitivity of various parameters, in response to length of strengthening carried out, is similar for different levels of VOC rates. Similar results were found for the smoothing and resurfacing length cases also.

Figure 10.7: Effect of VOC Rate in Sensitivity to Strengthening Length.



10.8 Conclusions

- The economic optimisation process in the economic analysis (EA) mode results in the selection of a strategy from a number of strategies generated for each road section. Hence, the sensitivity of various parameters on the condition and economic parameters are indirectly related through the contribution of the input parameters in optimisation process.
- Cost parameters and trigger coefficients have a considerable impact on the economic analysis. Only a few condition parameters (ACA, ACW, IRI0) influenced the condition predictions in the economic analysis mode.
- No major impact was found in response to the sensitivity of parameters to treatment selection process whether the optimisation was carried out for an unlimited or constrained budget.
- No effect on the sensitivity of the input parameters on the treatment length selection was found by changing the project evaluation manual vehicle operating cost rate.

11. Summarising Sensitivity Results

11.1 Background

Sensitivity of different input parameters represents what could be the change in output parameters when the input parameters are changed by certain magnitude. The stagewise sensitivity analysis of the dTIMS input parameters in response to various output parameters for different road conditions and analysis periods showed that not all the input parameters had the same impact on the output of dTIMS analysis. For insensitive parameters, national default values provided with the dTIMS Interface program can be used. In the case of the sensitive parameters, users should collect the data to the required accuracy, customise and calibrate various parameters.

11.2 Summary of Analysis Results

As the level of sensitivity of the different input parameters varied in response to the various output parameters in different aspects of predictive modelling, it was found to be impossible to prepare a single recommended priority list. Based on the overall assessment and engineering judgement a table has been prepared where the sensitive parameter are defined as 'high' sensitive or 'low' sensitive in response to deterioration prediction, strategy generation and economic optimisation (refer to Table 11.1).

Table 11.1: List of Sensitive Parameters for NZ dTIMS System

Parameter	Description[1]	Model Prediction		Strategy Generation		Economic Optimisation	
		High	Low	High	Low	High	Low
Traffic Parameters							
ADT1	Traffic – car	•		•		•	
ADT2	Traffic – utilities	•		•		•	
ADT3	Traffic MCV –I	•		•		•	
ADT4	Traffic HCV –I	•		•		•	
ADT5	Traffic HCV –II	•		•		•	
ADT6	Traffic Bus	•		•		•	
GROWTH_H	Traffic Growth – heavy		•		•		•
GROWTH_L	Growth of light traffic		•		•		•
Condition							
ACA	Area of all cracking	•		•			•
ACW	Area of wide cracking	•		•			•
AFL	Area of Flushing	•		•			•
APH	Area of patching						
APT	Area of potholes		•		•		•
ARV	Area of ravelling		•		•		•
ASH	Wheel path length of shoving				•		
IRI0	Roughness	•		•		•	
RDM	Mean Rut Depth				•		
RDS	Std. Deviation of rut depth		•		•		•
SFC	Side force coefficient	•		•		•	
TD	Texture depth	•		•		•	

History							
AGE2	Surface age	•			•		•
AGE3	Base course age		•		•		•
CHIP	Chip Size		•				•
CQ	Construction quality indicator		•		•		•
CMOD	Base modulus						
HBASE	Depth of stabilised base						
HNEW	Thickness of new surfacing		•		•		•
HOLD	Thickness of old surfacing		•		•		•
MCOMP	Relative compaction						
PCA	Area of previous cracking		•		•		•
PCW	Previous area of wide cracking		•		•		•
Inventory							
CV	Curvature						
FLENGTH	Length						
LANE	No. of lane						
MMP	Mean monthly precipitation		•		•		
MOIST_EFF	Moisture Effect						
PAV_WID	Pavement Width		•	•		•	
RAISE	Raise and fall						
RF	Rise and fall						
Pavement Strength							
SNP	Pavement structural number	•		•		•	
Calibrations							
KCI	Calib. Coeff. – crack initiation	•		•		•	
KCP	Calib. Coeff. – crack progression	•		•		•	
KGE	Calib.Coeff.- roughness progression due to environment	•		•		•	
KGP	Calib.Coeff.- roughness progression due to traffic	•		•		•	
KPI	Calib. Coeff. – pothole initiation	•		•		•	
KRO	Calib. Coeff. for texture depth		•		•		•
KPP	Calib. Coeff. – pothole progression	•		•		•	
KRP	Calib.Coeff.- – rutting progression	•		•		•	
KVI	Calib. Coeff. – ravelling initiation						
KVP	Calib.Coeff.- – ravelling progression						
Standard – Trigger Limits							
M_ACA_A0 M_ACA_A1	Cracking trigger limit for Smoothing treatments			•		•	
M_ASH_A0 M_ASH_A1	Shoving trigger limit for Smoothing treatments			•		•	
M_IRI_A0 M_IRI_A1	Roughness trigger limit for Smoothing treatments			•		•	
M_RDM_A0 M_RDM_A1	Rutting trigger limit for Smoothing treatments			•		•	
R_HS_A0 R_HS_A1	Maximum surface thickness trigger limit for Resurfacing treatments						
R_IRI_A0 R_IRI_A1	Maximum roughness trigger limit for Resurfacing treatments			•		•	
R_SC_A0	Coefficient for seal cycle trigger limit for Resurfacing treatment			•		•	
R_SFC_A0 R_SFC_A1	Side force friction trigger limit for Resurfacing treatments			•		•	

R_SII_A0 R_SII_A1	Surface integrity index trigger limit for Resurfacing treatments			•		•	
R_TD_A0 R_TD_A1	Texture trigger limit for Resurfacing treatments			•		•	
R_TS_A0	Coefficient for trench patch and service cover						
S_GOV_A0	Granular overlay thickness threshold for Strengthening treatments						
S_IRI_A0 S_IRI_A1	Roughness trigger limit for Strengthening treatments			•		•	
S_MCI_A0 S_MCI_A1	Maintenance cost index trigger limit for Strengthening treatments			•		•	
Cost Parameters							
C_AM	Asphalt mix ($/m^3)					•	
C_ANC	Ancillary works (road furniture) ($/m)						•
C_BRN	Burning, bleeding ($/m)						•
C_CRFL	Crack Fill ($/m)					•	
C_CRSL	Crack Sealing ($/m^2)					•	
C_DIG	Digout/Heavy Patching ($/m^2)					•	
C_DRN	Drainage Improvement ($/m)					•	
C_EWRK	Earthwork ($/m^3)					•	
C_GRAD	Grading ($/km)					•	
C_GRBN	Granular Base imported ($/m^3)					•	
C_GRBR	Granular Base reworked ($/m^3)					•	
C_GRSN	Granular Subbase imported ($/m^3)					•	
C_GRSR	Granular Subbase reworked ($/m^3)					•	
C_GRV	Regravelling ($/m2)					•	
C_KC	K&C ($/m)					•	
C_MILL	Milling Pavement ($/m^3)					•	
C_PTH	Patching ($/m2)					•	
C_RIPP	Ripping Up The Pavement ($/m^3)					•	
C_RTFL	Rut filling ($/m)					•	
C_RTN	Routine Maintenance ($/m^2)					•	
C_RTNX	Routine Maintenance ($/m^2)					•	
C_SAMI	SAMI Layer ($/m^2)					•	
C_SLDB	Double chip					•	
C_SLLG	Large Chip Seals ($/m^2)					•	
C_SLSM	Small Chip Seals ($/m^2)					•	
C_SLSP	Special chip					•	
C_STAB	Stabilisation ($/m^2)					•	

A discussion of the sensitivity of various input parameters with recommendations on process for acquiring data are given in the following sections.

11.3 Traffic Parameters

11.3.1 Traffic volume

Sensitivity	HIGH

Traffic volume was found to be a very sensitive parameter in all aspects of predictive modelling. Collection of traffic data at least once every three years is recommended.

11.3.2 Traffic growth

Sensitivity	LOW

Traffic growth was found not to be very sensitive to prediction modelling whilst considering from 0 to 10% arithmetical growth per year. At the same time, in the case of NZ where the traffic growth is generally in between 0 to 3 %, sensitivity of this parameter to predictive modelling is very low. However, for specific roads in the network with high traffic growth, the estimation of traffic growth data could help improve prediction modelling.

11.3.3 Traffic composition (mix/distribution)

Sensitivity	LOW

The HDM pavement deterioration models were generally affected by the percentage of heavy vehicles. However as percentage of heavy traffic (medium and heavy commercial vehicles) was not taken more than 15 % of the total traffic volume considering general condition in NZ roads, the composition of the traffic did not show a considerable effect in predictive modelling. But there are roads in NZ with high volume of heavy vehicular traffic (*e.g.* logging traffic, container traffic) collecting traffic data and loading is essential for better prediction of the pavement deterioration.

11.4 Condition Parameters

11.4.1 Cracking

Sensitivity	HIGH

Existing alligator cracking data were found to be very important to pavement deterioration modelling, especially on SII prediction. It was noted that after the initiation the progression of cracking was found to be very fast, and, hence it is more important to define whether the cracking is initiated or not, whereas, error in cracking assessment to a certain degree does not have an effect too much. The current practice of RAMM manual rating of alligator cracking was generally satisfactory.

11.4.2 Ravelling

Sensitivity	LOW

The HDM Ravelling prediction models were found to be unsuitable for the NZ condition (HTC, 2000), and hence, turned off in the current NZ dTIMS Setup. However existing ravelling as a component of the surface integrity index (SII) will have some minor effect on the dTIMS output. The current practice of RAMM manual rating of scabbing was generally satisfactory for this purpose.

11.4.3 Potholes

Sensitivity	LOW

Existing potholes data were found to be quite sensitive to pavement deterioration modelling where no maintenance is considered. However, when considering the current maintenance practice which usually requires all potholes be patched within a certain response time, the existing potholes have a relatively low sensitivity in predictive modelling. Hence, it was considered that the current practice of RAMM manual rating for pothole data collection was satisfactory.

11.4.4 Rutting

Sensitivity	LOW

Rutting in pavement is assessed in terms of mean rut depth (RDM) and standard deviation of rut depth (RDS). Both of these parameters were not found to be too sensitive to predictive modelling. RDS was found to be relatively more sensitive being a component of roughness prediction model. On the other hand, existing RDM was found to be sensitive only on strategy generation period where if RDM is more than a certain limit it could trigger a surface correction treatment. It should be noted that the analysis of the available RAMM databases had shown that maximum average existing rutting is less than 11 mm.

The RAMM manual rating system based on the wheelpath length of rutting more than 30 mm rut depth does not correctly transferable to RDM and moreover calculates the RDS value. HSD rutting data collection method used to collect data for the Transit network can collect RDM and estimate RDS data with the required accuracy.

11.4.5 Current roughness

Sensitivity	HIGH

The roughness data were found to be very important in predicting pavement deterioration and strategy generation. Data collected by means of both laser profilometer and bump integrator were accurate enough to collect the data for predictive modelling. However, good quality control to ensure proper calibration of the equipment and a consistent location referencing system should be ensured as the analysis of data showed that there were some inconsistencies in roughness data for different years.

11.4.6 Flushing

Sensitivity	HIGH

The condition parameter flushing was not included in HDM modelling. However, as a component of the SII, it was very influential on the resurfacing treatment selection. The data collected using the existing RAMM manual rating system was generally adequate for this purpose.

11.4.7 Shoving

Sensitivity	LOW

The condition parameter shoving was not included in the HDM modelling neither was the component of the SII. Hence, shoving does not affect pavement deterioration prediction. However, as shoving represents a serious pavement defect and a strengthening treatment is triggered when shoving exceeds certain limits. The data collected using the existing RAMM manual rating system was generally adequate for this purpose.

11.4.8 Side force coefficients

Sensitivity	LOW

The side force coefficient (SFC) data are being collected only for the Transit road network and some other arterial roads using the SCRIM machine. Mean SCRIM usually does not necessarily reflect the SCRIM deficiency area requiring treatment. Also, SFC prediction modelling is not fully tested and generally turned off by the user. However, existing mean SCRIM warrants treatment if it is less than the trigger limit for SFC.

11.4.9 Texture depth

Sensitivity	LOW

The texture depth (TD) data is being collected only for the Transit road network and some other arterial roads using the HSD laser profilometer. The texture depth prediction model is not fully tested to NZ conditions and, hence is generally turned off by the user. However, existing texture depth warrants treatment if it is less than the trigger limit for texture depth.

11.5 Pavement History

11.5.1 Surface age

Sensitivity	HIGH

Surface age (AGE2) was very influential on the SII prediction and contributes to the resurfacing treatment selection. Surface data in RAMM should be updated at the time of resurfacing of the pavement.

11.5.2 Pavement base age

Sensitivity	LOW

Pavement base construction age (AGE3) was found to have low sensitivity in prediction modelling. The main influence of AGE3 in the NZ dTIMS modelling was found to be through the maintenance cost index prediction. Although accurate data on AGE3 are not generally required, a rough estimation within plus minus 5 years would be generally sufficient.

11.5.3 Chip Size

Sensitivity	LOW

The chip size (CHIP) was found to have very little impact. Its influence in the prediction modelling was mainly on the estimated surface life which is a component of the SII.

11.5.4 Construction quality

Sensitivity	LOW

The construction quality indicator (CQ) was found to have low sensitivity in prediction modelling. If possible, a general estimate by an experience maintenance engineer is sufficient.

11.5.5 Thickness

Sensitivity	LOW

Both new surfacing (HNEW) as well as old surfacing (HOLD) thicknesses were found to have very little impact on the prediction modelling. Data on the estimated thickness for chip seal based on chip size should be kept in the RAMM database.

11.5.6 Previous cracking

Sensitivity	LOW

All previous cracking (PCA) and previous wide cracking (PCW) were found to have very little impact on the predictive modelling. The current procedure in RAMM to calculate previous cracking based on the cracked area before treatment is generally adequate.

11.6 Road Inventory

11.6.1 Mean monthly precipitation

Sensitivity	LOW

Mean monthly precipitation was found to have little impact on the predictive modelling. Hence, the regional default values provided in the dTIMS Interface program are generally adequate.

11.6.2 Pavement Width

Sensitivity	HIGH

The pavement width (PAV_WID) was found to have a major impact, due to its effect on distribution of loading and as the unit costs in NZ dTIMS setup are provided in square metre area. Accurate summarisation of pavement width is essential as it will significantly affect the agency cost estimation and consequently, on the strategy generation and outcome of the economic analysis.

11.6.3 Trigger Limits

Sensitivity	HIGH

All the trigger limits used as an intervention level for triggering strengthening, smoothing and resurfacing treatments were found to be very influential to the strategy generation and economic optimisation process. The analysis of the RAMM database showed that the average existing network condition varies greatly. Hence it is essential that trigger limits are well customised before carrying out prediction modelling.

It is generally recommended that if data of the required quality are not available or models for some condition parameters are not suitable for a given network, it is preferable to change the trigger limits in such a way that they do not affect the treatment selection procedure. For example, if MCI model is not calibrated to the network and the maintenance cost historical data is not good enough it is recommended not to use the MCI trigger level for strengthening treatment.

11.6.4 Cost parameters

Sensitivity	HIGH

Cost parameters are directly related with the estimation of agency cost and were found to be very influential on the economic optimisation. Hence, it is essential to customise the unit cost of the treatments to the given road network.

12. Conclusions and Recommendations

12.1 Conclusions

1. Analysis of various RAMM databases showed that treatment length are not homogeneous in terms of various sensitive condition parameters. Establishment of the homogeneous treatment length is very important to ensure that the average condition parameter represents the section. Poorly defined treatment lengths could result in improper use of the condition parameters measured by highly precise instruments.
2. The sensitivity analysis showed that only a limited number of input data were found to be sensitive to dTIMS analysis. The sensitivity level of these parameter varied a lot depending upon the years of the analysis period considered, traffic level and existing network condition and the output parameter in response to which sensitivity is considered. However grouping of the sensitive parameter to 'low' and 'high' sensitive category could be done based on the analysis.
3. The traditional cetrius paribus method based on effect of individual parameters was found to be very useful in defining which of the input parameters were sensitive. However for prioritising/ranking the level of sensitivity, the factorial analysis method, considering the inter-reaction between parameters, was found to be more suitable.
4. The stagewise approach (sensitivity to predictive modelling, sensitivity to strategy generation and sensitivity to economic optimisation) taken for the sensitivity analysis was found to be useful. By eliminating less sensitive parameters in each stage it made the sensitive analysis process manageable and more focused.
5. The highly sensitive parameters found during the study are listed in Table 12.1 below.

Table 12.1: Highly Sensitive Parameters in the NZ dTIMS System.

Parameter	Description[1]	Model Prediction		Strategy Generation		Economic Optimisation	
		High	Low	High	Low	High	Low
Traffic Parameters							
ADT1	Traffic – car	•		•		•	
ADT2	Traffic – utilities	•		•		•	
ADT3	Traffic MCV –I	•		•		•	
ADT4	Traffic HCV -I	•		•		•	
ADT5	Traffic HCV -II	•		•		•	
ADT6	Traffic Bus	•		•		•	
Condition							
ACA	Area of all cracking	•		•			•
ACW	Area of wide cracking	•		•			•
AFL	Area of Flushing	•		•			•
IRI0	Roughness	•		•		•	
SFC	Side force coefficient	•		•		•	
TD	Texture depth	•		•		•	

History							
AGE2	Surface age	•			•		•
Inventory							
PAV_WID	Pavement Width		•	•		•	
Pavement Strength							
SNP	Pavement structural number	•		•		•	
Calibrations							
KCI	Calib. Coeff. – crack initiation	•		•		•	
KCP	Calib. Coeff. – crack progression	•		•		•	
KGE	Calib.Coeff.- roughness progression due to environment	•		•		•	
KGP	Calib.Coeff.- roughness progression due to traffic	•		•		•	
KPI	Calib. Coeff. – pothole initiation	•		•		•	
KPP	Calib. Coeff. – pothole progression	•		•		•	
KRP	Calib.Coeff.- – rutting progression	•		•		•	
Standard – Trigger Limits							
M_ACA_A0 M_ACA_A1	Cracking trigger limit for Smoothing treatments			•		•	
M_ASH_A0 M_ASH_A1	Shoving trigger limit for Smoothing treatments			•		•	
M_IRI_A0 M_IRI_A1	Roughness trigger limit for Smoothing treatments			•		•	
M_RDM_A0 M_RDM_A1	Rutting trigger limit for Smoothing treatments			•		•	
R_IRI_A0 R_IRI_A1	Maximum roughness trigger limit for Resurfacing treatments			•		•	
R_SC_A0	Coefficient for seal cycle trigger limit for Resurfacing treatment			•		•	
R_SFC_A0 R_SFC_A1	Side force friction trigger limit for Resurfacing treatments			•		•	
R_SII_A0 R_SII_A1	Surface integrity index trigger limit for Resurfacing treatments			•		•	
R_TD_A0 R_TD_A1	Texture trigger limit for Resurfacing treatments			•		•	
S_IRI_A0 S_IRI_A1	Roughness trigger limit for Strengthening treatments			•		•	
S_MCI_A0 S_MCI_A1	Maintenance cost index trigger limit for Strengthening treatments			•		•	
Cost Parameters							
C_ALL	All cost parameters					•	

12.2 Recommendations

The principal recommendations from this research are as follows:

- Most of the systems currently used in NZ for collection of the pavement condition data are found to be accurate enough for predictive modelling purposes as source data are smoothened by averaging to a treatment length. However, more emphasis should be given to the quality control during data collection and processing including proper calibration of the instruments so that a trend analysis could be carried out.

- The way in which maintenance treatment length are generated in RAMM should be reviewed with the objective of establishing a more homogeneous section. Treatment length sections should be generated based on a number of condition parameters highly sensitive to the treatment selection procedure. Research is needed to define the parameters to be considered and a methodology to define optimum range of each parameter (based on the existing network condition and longterm performance standard) for the treatment length generation .
- There is a need to understand the sensitivity of various data items. For the missing information the RCA will have to give higher preference to highly sensitive data items (traffic volume, cracking, roughness, flushing, surface age, pavement width, trigger limits and cost parameters). For less sensitive data a regional default value can be applied. For non sensitive data the national default values available in the system is generally adequate.
- Longterm performance standard which is represented by the trigger levels in NZ dTIMS system are found to be quite sensitive in the maintenance strategy generation and optimisation. As trigger levels are found to be influenced to a great extend on the existing network condition it is essential that proper customisation of the trigger level is done before proceeding the dTIMS analysis.

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Appendix A: Pavement Deterioration Models

Cracking

Crack Initiation Expressions

<u>Granular and bituminous bases</u>

$$TYCRA = Kci\left\{\begin{matrix} Fc\max[a1\exp(a2SNC + a3\dfrac{YE4}{SNC^2}(1+CQ))\max(1-\dfrac{PCRW}{a4},0), \\ a5 + a6HSNEW] + CRT \end{matrix}\right\}$$

<u>Cemented bases</u>

$$TYCRA = Kci\left\{\begin{matrix} Fc[(a1KA + a2KW)(1 + a3HSE) + (1 - KA)(1 - KW) \\ (a4\exp(a5HSE + a6\ln(CMOD) - a7\ln(DEF) - a8YE4DEF)[+CRT \end{matrix}\right\}$$

$$TYCRW = Kci\ max(a1 + a2\ TYCRA,\ a3\ TYCRA)$$

Where TYCRA is the time in years to crack initiation
TYCRW is the time in years to initiation of wide cracking
Kci is a user-specified deterioration for crack initiation
Fc is the occurrence distribution factor for the sub-section
SNC is the modified structural number
YE4 is the annual axle loading in millions per lane
CQ is the construction fault indicator for surface treatments
1 if faults exist, 0 otherwise
PCRW is the area of wide cracks before resurfacing
PCRA is the area of all cracks before resurfacing
HSNEW is the thickness of the new surfacing in mm
CRT is the cracking retardation time if a preventive treatment has been applied
HSE is the effective thickness of surfacing layers defined as:
min[100, HSNEW + (1 - KW) HSOLD]
KW is a variable for indicating the presence of wide cracking in the old surfacing layers, defined as: min[0.05 max(PCRW - 10, 0), 1]
KA is a variable for indicating the presence of all cracking in the old surfacing layers, defined as: min[0.05 max(PCRA - 10, 0), 1]
CMOD is the resilient modulus of the cemented base in GPa
DEF is the deflection under a 40kN wheel load

Crack Progression Expressions

The crack progression model is incremental in form and uses three expressions, which give a symmetrical curve. The Brazil research, described in Paterson (1987) gave models based on time and traffic. The time-based models were selected for use in HDM-III and have the form:

For ACR < 50% and ACR + ΔACR < 50%

$$\Delta ACR = Kcp\ CRP\ (a\ b\ \Delta T + ACR^{b})^{1/b} - ACR$$

For ACR > 50%

$$\Delta ACRA = Kcp\ CRP\ [100 - ACR - max(-a\ b\ \Delta T + (100 - ACR)^{b},\ 0)^{1/b}\ ]$$

For ACR < 50% and ACR + ΔACR > 50%

$$\Delta ACRA = Kcp\ CRP\ [100 - (2\ 50^{b} - ACR^{b} - a\ b\ \Delta T)^{1/b} - ACR]$$

where ACR is the cracked area at the start of the year
ΔACRA is the increase in cracking during time ΔT
Kcp is a user-defined coefficient
CRP is the retardation due to preventive treatment, given by:

$$CRP = 1 - 0.12\ CRT$$

The parameters used in the above expressions together with the corresponding dTIMS fields are given below.

Potholes

The initiation period for potholing is a function of traffic and thickness of bituminous layers:

$$TMIN = max(a1 + a2\ HS + a3\ YAX,\ a4)$$

Where TMIN is the time in years from initiation of the triggering distress and the initiation of potholing
HS is the total thickness of asphaltic layers, including the base if bituminous

Pothole initiation is further constrained by setting a minimum area of primary distress - 20% for wide cracking and 30% for ravelling.

Annual increase in potholed area is the summation of the amounts derived from wide cracking, ravelling and enlargement of existing potholes:

$$\Delta APOT = min(\Delta APOTCR + \Delta APOTRV + \Delta APOTP,\ 10)$$

where ΔPOT is the total annual increase in percent area

The increases derived from wide cracking, ravelling and enlargement are given by:

$$\Delta APOTCR = Kpp \min\left(\frac{1.6ACRW * YAX * W(1+CQ)}{SNC * HS * ELANES}, 6 \right)$$

$$\Delta APOTRV = Kpp \min\left(\frac{0.32ARAV * YAX * W(1+CQ)}{SNC * HS * ELANES}, 6 \right)$$

$$\Delta APOTP = \min\{APOT * YAX\,(MMP + 0.1)\,\max(a1 + a2 * HS, a3), 10\}$$

where W is the pavement width in m
ELANES is the number of lanes
MMP is the rainfall in m/month

The coefficients in the enlargement component are dependent on the type of base.

Additional parameters required for the modelling are given in the table below.

Rutting

The mean rut depth in the first year after construction of a pavement is given by:

$$\mathrm{RDM} = \mathrm{Krp}\frac{39800(\mathrm{YE410}^{6})^{\mathrm{ERM}}}{\mathrm{SNC}^{0.502}\,\mathrm{COMP}^{2.30}}$$

The increment in mean rut depth in the second and subsequent years is given by:

$$\Delta RDM = Krp * RDM \left(\begin{array}{l} \dfrac{0.166 + ERM}{AGE3} + 0.0219 MMP * \Delta ACRX * \\ \ln(\max(1, AGE3 * YE4)) \end{array} \right)$$

$$\mathrm{ERM} = 0.09 - 0.0009\,\mathrm{RH} + 0.0384\,\mathrm{DEF} + 0.00158\,\mathrm{MMP} * \mathrm{CRX}$$

Where RDM is the mean rut depth
ΔRDM is the annual increment in mean rut depth
AGE3 is the time since construction in years
CRX is the area of indexed cracking in percent given by:
ACRA + 0.39 ACRW
ΔCRX is the annual increment in indexed cracking
RH is a rehabilitation indicator (1 if overlay, 0 otherwise)

The standard deviation of rut depth after pavement construction is given by:

$$RDS = Krp \frac{4390 \Delta RDM^{0.532} (YE4 * 10^{6})^{ERS}}{SNC^{0.422} COMP^{1.66}}$$

The increment in STD of rut depth in subsequent years is given by:

$$\Delta RDS = KrpRDS\left(\frac{0.532\Delta RDM}{RDM} + \frac{ERS}{AGE3} + 0.0519MMP^{*}\,\Delta CRX\ln(MAX(1, AGE3^{*}\,YE4))\right)$$

$ERS = -0.0086\ RH + 0.00115\ MMP \times CRX$

Roughness

HDM-III predicts the annual increment of roughness progression as several components (hence described as the component incremental model). These components are structural deformation, surface condition and environment. The expression is:

$$\begin{aligned}\Delta IRI = {} & 134 \exp(m\,t)\ YE4\ (1 + SNK)^{-5} \text{ (structural deformation)} \\ & + 0.114\ \Delta RDS + 0.0066\ \Delta ACRX + 0.42\ \Delta APOT \text{(surface condition)} \\ & + m\ IRI \text{ (environment)}\end{aligned}$$

All the parameters used in the roughness increment models are described earlier.

Appendix B: NZ VOC Expressions

Code	Expression
V_CAR	IF(NSRA <= 85, 0.0017 * (MAX(0, NSRA - 60)) ** 1.986, IF(NSRA <= 350, 0.0061 * (NSRA – 60) ** 1.564 + 0.13, 0.2014 * (NSRA - 28.84)))
V_LCV	IF(NSRA <= 85, 0.0019 * (MAX(0, NSRA - 60)) ** 1.966, IF(NSRA <= 350, 0.0064 * (NSRA – 60) ** 1.564, 0.2085 * (NSRA - 28)))
V_MCV	IF(NSRA <= 75, 0.012 * (MAX(0, NSRA - 60)) ** 1.210, 0.1986 * (NSRA - 60) ** 1.00 - 3.215)
V_HCV1	IF(NSRA <= 80, 0.0045 * (MAX(0, NSRA - 60)) ** 1.879, 0.4375 * (NSRA - 60) ** 1.00 - 7.530)
V_HCV2	IF(NSRA <= 80, 0.0052 * (MAX(0, NSRA - 60)) ** 1.87, 0.4098 * (NSRA - 60) ** 1.00 - 6.73)
V_BUS	IF(NSRA <= 80, 0.0003 * (MAX(0, NSRA - 60)) ** 2.657, IF(NSRA <= 350, 0.0614 * (NSRA – 60) ** 1.164, 0.2093 * (NSRA + 26.43)))
V_RUC_CM	0.8* VOC3 * ADT3 + VOC4 * ADT4 + VOC5 * ADT5 + VOC6 * ADT6 * 365/100
V_RUC_NC	0.8* VOC1 * ADT1 + VOC2 * ADT2 * 365/100

Source: HTC (2000)

Appendix C: NZ dTIMS Inventory Table with Data Value Range

Parameter	Description[1]	Default[2]	Max	Min	Model Prediction	Strategy Generation	Economic Optimisation
ACA	Area of all cracking	0	20	0	●	●	●
ACW	Area of wide cracking	0	10	0	●	●	●
ADT1	Traffic - car	830/16600	33200	40	●	●	●
ADT2	Traffic - LCV	100/2000	4000	5	●	●	●
ADT3	Traffic MCV -I	30/600	1200	2	●	●	●
ADT4	Traffic HCV -I	20/400	800	1	●	●	●
ADT5	Traffic HCV -II	10/200	400	1	●	●	●
ADT6	Traffic Bus	10/200	400	1	●	●	●
AFL	Area of Flushing	0	20	0	●	●	●
AGE2	Surface age	8	20	1	●	●	●
AGE3	Base course age	15	40	1	●	●	●
APH	Area of patching	0	20	0	●	●	●
APT	Area of potholes	0	2	0	●	●	●
ARV	Area of raveling	0	50	0	●	●	●
ASH	Wheel path length of shoving	0	10	0	●	●	●
C_AM	Unit rate for asphalt mix (\$/m^3)	300	600	150			●
C_ANC	Unit rate for Ancillary works (road furniture) (\$/m)	10	20	5			●
C_BRN	Unit rate for burning, bleeding (\$/m)	4	8	2			●
C_CRFL	Unit rate for Crack Fill (\$/m)	8	16	4			●
C_CRSL	Unit rate for Crack Sealing (\$/m^2)	6	12	3			●
C_DIG	Unit rate for Digout (\$/m^2)	30	60	15			●
C_DRN	Unit rate for Drain Improvement (\$/m)	20	40	10			●
C_EWRK	Unit rate for Earthwork (\$/m^3)	20	40	10			●
C_GRAD	Unit Rate for Grading (\$/km)	42	84	21			●
C_GRBN	Unit rate for Granular Base new (\$/m^3)	65	130	32.5			●
C_GRBR	Unit rate for Gran. Base reworked (\$/m^3	31	62	15.5			●
C_GRSN	Unit rate for Gran. Subbase new (\$/m^3)	55	110	27.5			●
C_GRSR	Unit rate for Gran Subb. reworked(\$/m^3)	30	60	15			●
C_GRV	Unit cost of Regravelling (\$/m2)	5	10	2.5			●
C_KC	Unit cost of K&C (\$/m)	80	160	40			●
C_MILL	Milling Pavement (\$/m^3)	74	148	37			●
C_PTH	Unit rate for patching (\$/m2)	80	160	40			●
C_RIPP	Ripping Up The Pavement (\$/m^3)	30	60	15			●
C_RTFL	Unit rate for rut filling (\$/m)	30	60	15			●
C_RTN	Routine Maintenance (\$/m^2)	0.2	0.4	0.1			●
C_RTNX	Routine Maintenance (\$/m^2)	0.2	0.4	0.1			●
C-SAMI	SAMI Layer (\$/m^2)	6	12	3			●
C_SLDB	Unit rate Double chip	5	10	2.5			●
C_SLLG	Large Chip Seals (\$/m^2)	3	6	1.5			●
C_SLSM	Small Chip Seals (\$/m^2)	3	6	1.5			●
C_SLSP	Unit rate Special chip	12	24	6			●
C_STAB	Stabilisation (\$/m^2)	5	10	2.5			●
CHIP	Chip Size	3	6	2	●	●	●
CMOD	Base modulus	0	1	1	●	●	●
CQ	Construction quality indicator	0	1	0	●	●	●

Parameter	Description[1]	Default[2]	Max	Min	Model Prediction	Strategy Generation	Economic Optimisation
CV	Curvature	150	300	20	•	•	•
FLENGTH	Length	1000	2000	50	•	•	•
GROWTH_	Traffic Growth - heavy	0	10	0	•	•	•
GROWTH_L	Growth of light traffic	0	10	0	•	•	•
HBASE	Depth of stabilised base	0	400	0	•	•	•
HNEW	Thickness of new surfacing	10	40	4	•	•	•
HOLD	Thickness of old surfacing	25	50	0	•	•	•
IRI	Roughness	3	8	1.5	•	•	•
KCI	Calib. Coeff. – crack initiation	1	2	0.5	•	•	•
KCP	Calib. Coeff. – crack progression	1	2	0.5	•	•	•
KGE	Calib. Coeff. - environment	1	2	0.5	•	•	•
KGP	Calib. Coeff.– roughness progression	1	2	0.5	•	•	•
KPI	Calib. Coeff. – pothole initiation	1	2	0.5	•	•	•
KRO	Calib. Coeff. - texture depth	1	2	0.5	•	•	•
KPP	Calib. Coeff. – pothole progression	1	2	0.5	•	•	•
KRP	Calib. Coeff.– rutting progression	1	2	0.5	•	•	•
KVI	Calib. Coeff. – ravelling initiation	1	2	0.5	•	•	•
KVP	Calib. Coeff.– ravelling progression	1	2	0.5	•	•	•
LANE	No. of lane	2	6	2	•	•	•
M_ACA_A0	Trigger coeff. – cracking smoothing	20	40	10		•	•
M_ASH_A0	Trigger coeff. – shoving smoothing	44.3	88.5	22.1		•	•
M_IRI_A0	Trigger coeff. – roughness smoothing	8.0	16.1	4.1		•	•
M_RDM_A0	Trigger coeff. – rutting smoothing	40	80	20		•	•
MCOMP	Relative compaction	95	100	80	•	•	•
MMP	Mean monthly precipitation	0.1	0.3	0.05	•	•	•
MOIST_EFF	Moisture Effect	1	2	0	•	•	•
PAV_WID	Pavement Width	8	20	6	•	•	•
PCA	Area of previous cracking	0	20	0	•	•	•
PCW	Previous area of wide cracking	0	10	0	•	•	•
R_HS_A0	Trigger coeff.–surf.thickness resurfacing					•	•
R_IRI_A0	Trigger coeff. – roughness resurfacing	7.63	15.26	3		•	•
R_SC_A0	Trigger coeff. - seal cycle resurfacing	0.5				•	•
R_SFC_A0	Trigger coeff.– SFC resurfacing	0.4	0.8	0.2		•	•
R_SII_A0	Trigger coeff.– SII resurfacing	67.5	100	12		•	•
R_TD_A0	Trigger coeff.– texture depth resurfacing					•	•
R_TS_A0	Trigger coeff.- AWPT treatment					•	•
RAISE	Raise and fall	1	1	0	•	•	•
RDM	Mean Rut Depth	1	20	0	•	•	•
RDS	Std. deviation of rut depth	1	10	0	•	•	•
RF	Rise and fall	25	100	5	•	•	•
S_GOV_A0	Trigger coeff. – Granular overlay need	100	200	50		•	•
S_IRI_A0	Trigger coeff.– Roughness strengthening	10.32	20.64	5.16		•	•
S_MCI_A0	Trigger coeff.– MCI	27250	54500	13625		•	•
SFC	Side force coefficient	0.55	0.6	0.4	•	•	•
SNP	Pavement structural number	4	10	1.5	•	•	•
TD	Texture depth	2.5	4	1	•	•	•

Note: 1/ Default values are taken for Coefficients A1 for all trigger expressions
2/ Traffic and SNP are taken in 2 levels in some cases

Appendix D: Results of Analyses on Pavement Deterioration

Table D.1 Sensitivity to IRI for high Traffic Low Strength Road without Maintenance.

Impact Elasticity in Response to IRI for							
5 YEARS		10 YEARS		15 YEARS		20 YEARS	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
SNP	2.88	KCI	4.02	KCI	1.96	GROWTH_H	0.04
KCI	2.45	SNP	1.99	GROWTH_H	0.02		
PAV_WID	2.21	AGE2	0.46				
HNEW	1.03	HOLD	0.20				
KPI	0.98	PAV_WID	0.10				
KGP	0.71	KGP	0.06				
AGE2	0.62						
CHIP	0.54						
KCP	0.43						
IRI0	0.42						
ADT5	0.37						
KPP	0.33						
CQ	0.32						
KVP	0.32						
ADT4	0.26						
ADT1	0.26						
ADT3	0.25						
ARV	0.23						
ADT6	0.17						
APT	0.16						
PCW	0.15						
KGE	0.08						
AGE3	0.04						
MMP	0.02						
ACA	0.02						
ADT2	0.02						
GROWTH_L	0.01						
RDS	0.01						

Notes:		
	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.05 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

Table D. 2 Sensitivity to IRI for Low traffic and High Strength Road Without Maintenance.

Impact Elasticity in Response to IRI for							
5 YEARS		10 YEARS		15 YEARS		20 YEARS	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
IRI0	0.99	KCI	1.55	KCI	1.72	KCI	1.42
CHIP	0.25	CHIP	1.26	CHIP	0.95	PAV_WID	0.92
ADT4	0.16	IRI0	0.90	PAV_WID	0.64	SNP	0.77
ADT5	0.15	AGE2	0.59	KGP	0.60	CHIP	0.48
KCI	0.14	ADT4	0.41	KPP	0.56	HNEW	0.39
KGE	0.12	ADT3	0.37	SNP	0.55	KCP	0.38
AGE2	0.12	ADT5	0.35	IRI0	0.53	KGP	0.36
ARV	0.11	KGE	0.25	AGE2	0.48	KPP	0.35
PCW	0.10	KCP	0.24	KCP	0.46	ADT1	0.32
ADT3	0.04	PCW	0.23	HOLD	0.46	AGE2	0.32
APT	0.04	ARV	0.22	ADT1	0.32	HOLD	0.31
KVP	0.03	ADT6	0.17	ADT2	0.31	KGE	0.27
ACA	0.03	KGP	0.15	CQ	0.31	IRI0	0.21
SNP	0.02	ADT1	0.14	ADT4	0.29	CQ	0.19
ADT6	0.01	SNP	0.11	ADT3	0.28	MMP	0.12
KGP	0.01	KVP	0.10	HNEW	0.25	ADT2	0.12
PAV_WID	0.01	ADT2	0.08	ADT5	0.25	ARV	0.11
RDS	0.01	APT	0.08	KGE	0.24	ADT6	0.10
KRP	0.01	PAV_WID	0.08	GROWTH_L	0.20	ADT5	0.10
		KPP	0.06	ADT6	0.18	PCW	0.09
		HOLD	0.06	ARV	0.16	ADT4	0.09
		CQ	0.04	PCW	0.15	ADT3	0.08
		ACA	0.02	KVP	0.07	GROWTH_L	0.08
		HNEW	0.02	APT	0.07	KVP	0.05
		GROWTH_L	0.02	MMP	0.06	APT	0.05
		RDS	0.01	GROWTH_H	0.02	GROWTH_H	0.04
		KRP	0.01	RDS	0.01	RDS	0.01
		AGE3	0.01	KRP	0.01	KRP	0.01
		GROWTH_H	0.01	AGE3	0.01	AGE3	0.01

Notes:		
	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.05 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

Table D. 3 Sensitivity to Roughness for Do Nothing.

Parameter	Description	LTNS[1]	LTHS	HTNS	HTLS	Sensitivity Level
ACA	Area of all cracking	4	4			4
ADT1	Traffic - car	2	2	2	2	2
ADT2	Traffic - utilities	2	2	4		2
ADT3	Traffic MCV -I	2	2	3	2	2
ADT4	Traffic HCV -I	2	2	3	2	2
ADT5	Traffic HCV -II	2	2	3		2
ADT6	Traffic Bus	3	4	3	3	3
AGE2	Surface age	1	1	1	1	1
AGE3	Base course age	4	4	4		4
APH	Area of patching					
APT	Area of potholes	3		2	3	2
ARV	Area of ravelling	2	2	2	2	2
ASH	Area of shoving					
CHIP	Chip Size	1	1	1	1	1
CMOD	Base modulus					
CQ	Construction quality indicator	2	2	2	2	2
CV	Curvature					
FLENGTH	Length					
GROWTH_H	Traffic Growth - heavy	3	4	3		3
GROWTH_L	Growth of light traffic	3	3	4		3
HBASE	Depth of stabilised base					
HNEW	Thickness of new surfacing	2	2	3	1	1
HOLD	Thickness of old surfacing	2	2	3		2
IRI0	Roughness	1	1	1	2	1
KCI	Calibration coefficients	1	1	1	1	1
KCP	Calib. Coeff. – crack progression	2	2	2	1	1
KGE	Calib. Coeff. - Environment	2	2	3	3	2
KGP	Calib. Coeff.– roughness progres.	2	1	2		1
KPI	Calib. Coeff. – pothole initiation			3	1	1
KRO	Calib. Coeff. for texture depth					
KPP	Calib. Coeff. – pothole progression	1	1	2	2	1
KRP	Calib. Coeff.– rutting progression	4	4			4
KVI	Calib. Coeff. – ravelling initiation					
KVP	Calib. Coeff.– ravelling progression	3		1	2	1
LANE	No. of lane					
MCOMP	Compaction					
MMP	Mean monthly precipitation	3	3	4		3
PAV_WID	Pavement Width	1	1	1	1	1
PCA	Area of previous cracking					
PCW	Previous area of wide cracking	2	2	2	3	2
RAISE	Raise and fall					
RDM	Mean rut depth					
RDS	Std. deviation of rut depth	4	4	4		4
RF	Rise and fall					
SFC	Side force coefficient					
SNP	Pavement structural number	1	1	1	1	1
TD	Texture depth					

Note: 1/ LTNS – Low traffic normal strength
LTHS – Low traffic high strength
HTNS – High traffic normal strength
HTLS – High traffic low strength

Table D. 4 Sensitivity to SII for Do Nothing.

Parameter	Description	Sensitivity Level in Response to SII				
		LTNS	LTHS	HTNS	HTLS	Final
ACA	Area of all cracking	2	2			2
ADT1	Traffic - car					
ADT2	Traffic - utilities					
ADT3	Traffic MCV -I	1	1	2		1
ADT4	Traffic HCV -I	1	1	2		1
ADT5	Traffic HCV -II	1	1	2		1
ADT6	Traffic Bus	1	1	1		1
AFL	Area of Flushing	1	1	2		1
AGE2	Surface age	1	1	1	1	1
AGE3	Base course age					
APH	Area of patching					
APT	Area of potholes	2	2	2		2
ARV	Area of ravelling	1	1	2		1
ASH	Area of shoving					
CHIP	Chip Size	1	1	1		1
CMOD	Base modulus					
CQ	Construction quality indicator					
CV	Curvature					
FLENGTH	Length					
GROWTH_H	Traffic Growth - heavy			2		2
GROWTH_L	Growth of light traffic					
HBASE	Depth of stabilised base					
HNEW	Thickness of new surfacing					
HOLD	Thickness of old surfacing					
IRI0	Roughness					
KCI	Calibration coefficients	1	1	1	1	1
KCP	Calib. Coeff. – crack progression	1	1	2		1
KGE	Calib. Coeff. - Environment					
KGP	Calib. Coeff. – roughness progress.					
KPI	Calib. Coeff. – pothole initiation					
KRO	Calib. Coeff. for texture depth					
KPP	Calib. Coeff. – pothole progression					
KRP	Calib. Coeff.– rutting progression					
KVI	Calib. Coeff. – ravelling initiation					
KVP	Calib. Coeff.– ravelling progression	1	1			1
LANE	No. of lane					
MCOMP	Compaction					
MMP	Mean monthly precipitation					
PAV_WID	Pavement Width			1	1	1
PCA	Area of previous cracking					
PCW	Previous area of wide cracking	1	1	2		1
RAISE	Raise and fall					
RDM	Mean rut depth					
RDS	Std. deviation of rut depth					
RF	Rise and fall					
SFC	Side force coefficient					
SNP	Pavement structural number			1	1	1
TD	Texture depth					

Note: 1/ LTNS – Low traffic normal strength
LTHS – Low traffic high strength
HTNS – High traffic normal strength
HTLS – High traffic low strength

Table D. 5 Sensitivity to IRI for High Traffic Road with Routine Maintenance.

Impact Elasticity in Response to IRI for							
5 YEARS		10 YEARS		15 YEARS		20 YEARS	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
IRI0	0.99	IRI0	0.91	KGE	1.24	KGE	1.86
SNP	0.48	SNP	0.89	KGP	1.24	KGP	1.86
CHIP	0.14	KGE	0.53	SNP	1.14	SNP	1.00
KCI	0.12	KGP	0.53	IRI0	0.81	IRI0	0.73
AGE2	0.07	CHIP	0.29	KCP	0.43	KCP	0.55
KVP	0.07	KCI	0.27	KCI	0.31	KCI	0.30
ARV	0.05	KCP	0.23	CHIP	0.27	PAV_WID	0.28
PCW	0.03	AGE2	0.14	PAV_WID	0.22	KPP	0.26
PAV_WID	0.02	PAV_WID	0.12	KPP	0.18	CHIP	0.24
KGE	0.02	CQ	0.09	CQ	0.14	CQ	0.17
KGP	0.02	ARV	0.09	AGE2	0.13	HOLD	0.17
ACA	0.02	KVP	0.09	HOLD	0.12	ADT1	0.16
CQ	0.01	KPP	0.06	ARV	0.11	ARV	0.12
RDS	0.01	PCW	0.05	ADT1	0.11	AGE2	0.12
AGE3	0.01	HOLD	0.05	KVP	0.07	GROWTH_L	0.11
KRP	0.01	ADT1	0.04	GROWTH_L	0.06	KRP	0.08
		KPI	0.03	HNEW	0.05	HNEW	0.07
		ADT5	0.02	PCW	0.05	RDS	0.06
		ADT4	0.02	RDS	0.04	MMP	0.06
		RDS	0.02	KRP	0.04	KVP	0.06
		ACA	0.02	MMP	0.03	PCW	0.04
		ADT3	0.02	ADT5	0.03	GROWTH_H	0.04
		KRP	0.02	ADT4	0.03	AGE3	0.03
		HNEW	0.02	GROWTH_H	0.03	ADT5	0.03
		GROWTH_L	0.02	ADT3	0.03	ADT4	0.03
		GROWTH_H	0.02	KPI	0.03	ADT3	0.03
		AGE3	0.02	AGE3	0.02	KPI	0.02
		ADT6	0.01	ACA	0.02	ACA	0.02
		MMP	0.01	ADT6	0.02	ADT2	0.02
				ADT2	0.01	ADT6	0.02

Notes:		
	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.05 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

Table D. 6 Sensitivity on IRI for Routine Maintenance Case.

Parameter	Description	Sensitivity Level					
		LTNS[1]	LTHS	HTNS	HTLS	Sensitivity Routine	Sensitivity DoNothing
ACA	Area of all cracking	4	4	4	4	4	4
ADT1	Traffic – car	3	3	3	3	3	2
ADT2	Traffic – utilities	3	4	4		3	2
ADT3	Traffic MCV -I	3	4	4	3	3	2
ADT4	Traffic HCV -I	3	4	4	3	3	2
ADT5	Traffic HCV -II	3	4	4	3	3	2
ADT6	Traffic Bus		4	4	4	4	3
AGE2	Surface age	3	3	3	3	3	1
AGE3	Base course age	4		4	3	3	4
APH	Area of patching						
APT	Area of potholes						2
ARV	Area of ravelling	4	4	3	3	3	2
ASH	Area of shoving						
CHIP	Chip Size	3	2	3	4	2	1
CMOD	Base modulus						
CQ	Construction quality indicator	4	4	3	3	3	2
CV	Curvature						
FLENGTH	Length						
GROWTH_H	Traffic Growth - heavy	4		4	3	3	3
GROWTH_L	Growth of light traffic	4		3	3	3	3
HBASE	Depth of stabilised base						
HNEW	Thickness of new surfacing			3	3	3	1
HOLD	Thickness of old surfacing	4	4	3	3	3	2
IRI0	Roughness	1	1	1	1	1	1
KCI	Calib. Coeff. – crack initiation	3	3	2	2	2	1
KCP	Calib. Coeff. – crack progression	2	2	1	2	1	1
KGE	Calib. Coeff. - Environment	2	2	1	1	1	2
KGP	Calib. Coeff. – roughness progress.	2	2	1	1	1	1
KPI	Calib. Coeff. – pothole initiation	4			3	3	1
KRO	Calib. Coeff. for texture depth						
KPP	Calib. Coeff. – pothole progression	4	4	2	2	2	1
KRP	Calib. Coeff. – rutting progression	4	4	3	3	3	4
KVI	Calib. Coeff. – ravelling initiation						
KVP	Calib. Coeff.– ravelling progression	4	4	3	3	3	1
LANE	No. of lane						
MCOMP	Compaction						
MMP	Mean monthly precipitation			3	3	3	3
PAV_WID	Pavement Width	3	4	2	1	1	1
PCA	Area of previous cracking						
PCW	Previous area of wide cracking	4	4	3	4	3	2
RAISE	Raise and fall						
RDM	Mean rut depth						
RDS	Std. deviation of rut depth	4	4	3	3	3	4
RF	Rise and fall						
SFC	Side force coefficient						
SNP	Pavement structural number	3	3	1	1	1	1
TD	Texture depth						

Note: 1/ LTNS – Low traffic normal strength
LTHS – Low traffic high strength
HTNS – High traffic normal strength
HTLS – High traffic low strength

Table D. 7 Sensitivity on SII for Low Traffic Road for Routine Maintenance Case.

Impact Elasticity in Response to SII for							
5 YEARS		**10 YEARS**		**15 YEARS**		**20 YEARS**	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CHIP	2.50	KCI	1.50	KCI	2.21	KCI	1.05
AGE2	1.73	AGE2	1.20	AGE2	0.50	KCP	0.44
KVP	1.40	KCP	1.05	KCP	0.49	AGE2	0.17
ADT3	1.13	CHIP	0.75	ADT1	0.16	AFL	0.05
ARV	1.04	AFL	0.40	ARV	0.15	ARV	0.05
PCW	1.02	ARV	0.23	CHIP	0.15	ADT1	0.04
AFL	1.00	ADT1	0.21	AFL	0.12	ADT2	0.04
APT	1.00	PAV_WID	0.17	PAV_WID	0.05	CHIP	0.03
ADT4	0.98	ADT4	0.17	ADT2	0.04	KPP	0.02
ADT5	0.98	ADT5	0.16	ADT4	0.04	HOLD	0.02
ADT6	0.61	ACA	0.16	ACA	0.03	PAV_WID	0.02
ACA	0.61	PCW	0.16	ADT5	0.03	CQ	0.02
		ADT3	0.14	ADT3	0.03	GROWTH_L	0.01
		ADT6	0.08	PCW	0.03	ADT3	0.01
		HOLD	0.04	KPP	0.03	ADT4	0.01
		KVP	0.04	HOLD	0.03	ADT5	0.01
		KPI	0.03	CQ	0.02	HNEW	0.01
				ADT6	0.02	ACA	0.01
				GROWTH_L	0.01	PCW	0.01
				HNEW	0.01		

Notes:		
	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.04 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

Table D. 8 Sensitivity on SII for High Traffic Road for Routine Maintenance Case.

Impact Elasticity in Response to SII for							
5 YEARS		10 YEARS		15 YEARS		20 YEARS	
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
SNP	1.93	KCI	3.62	KCI	2.00	KCI	0.56
CHIP	1.61	AGE2	0.71	KCP	0.50	KCP	0.32
AGE2	1.40	PAV_WID	0.52	AGE2	0.27	AGE2	0.07
PAV_WID	1.08	KCP	0.50	SNP	0.12		
KVP	0.66	SNP	0.44	PAV_WID	0.11		
AFL	0.49	CHIP	0.40	KPP	0.10		
ARV	0.45	KPP	0.31	HOLD	0.08		
CQ	0.39	CQ	0.26	ADT1	0.08		
ACA	0.34	HOLD	0.23	HNEW	0.07		
PCW	0.31	ADT1	0.19	ADT2	0.01		
ADT6	0.24	AFL	0.15	MMP	0.01		
KCP	0.19	ARV	0.15	CHIP	0.01		
ADT3	0.13	HNEW	0.10	ADT3	0.01		
ADT4	0.13	GROWTH_L	0.09				
ADT5	0.13	ACA	0.08				
GROWTH_H	0.11	KPI	0.07				
		PCW	0.07				
		ADT6	0.06				
		ADT3	0.06				
		ADT4	0.06				
		ADT5	0.05				
		GROWTH_H	0.03				
		MMP	0.03				
		ADT2	0.02				

Notes:	Level 1	Impact Elasticity greater than 0.5
	Level 2	Impact Elasticity greater than 0.2 and less than 0.5
	Level 3	Impact Elasticity greater than 0.05 and less than 0.2
	Level 4	Impact Elasticity less than 0.05

Table D. 9 Sensitivity to SII for Do Nothing.

Parameter	**Description**	**LTNS**	**LTHS**	**HTNS**	**HTLS**	**Sensitivity M&P**	**Sensitivity DoNothing**
ACA	Area of all cracking	1	1	2	3	1	2
ADT1	Traffic - car	2	3	3	2	2	
ADT2	Traffic - utilities		4	3	3	3	
ADT3	Traffic MCV -I	1	3	3	3	1	1
ADT4	Traffic HCV -I	1	1	3	3	1	1
ADT5	Traffic HCV -II	1	1	3	2	1	1
ADT6	Traffic Bus	1	3	2	4	1	1
AFL	Area of Flushing	1	1	2	2	1	1
AGE2	Surface age	1	1	1	1	1	1
AGE3	Base course age						
APH	Area of patching						
APT	Area of potholes		1			1	2
ARV	Area of ravelling	1	1	2	2	1	1
ASH	Area of shoving						
CHIP	Chip Size	1	1	1		1	1
CMOD	Base modulus						
CQ	Construction quality indicator	4	3	2	2	2	
CV	Curvature						
FLENGTH	Length						
GROWTH_H	Traffic Growth - heavy			4	4	4	2
GROWTH_L	Growth of light traffic	4	4		3	3	
HBASE	Depth of stabilised base						
HNEW	Thickness of new surfacing	4		3	3	3	
HOLD	Thickness of old surfacing	4	4	2	1	1	
IRI0	Roughness (IRI0)						
KCI	Calib.Coeff. – crack initiation	1	1	1	1	1	1
KCP	Calib.Coeff.– crack progression	1	1	2	1	1	1
KGE	Calib.coeff.icients- Environment						
KGP	Calib.Coeff.–rough.progression						
KPI	Calib.Coeff. – pothole initiation	4	4	3	1	1	
KRO	Calib.Coeff. for texture depth						
KPP	Calib.Coeff.–pothole progression	4	4	2	1	1	
KRP	Calib. Coeff.– rutting progression						
KVI	Calib. Coeff. – ravelling initiation						
KVP	Calib.Coeff.–ravelling progress.n	1	1	1	2	1	1
LANE	No. of lane						
MCOMP							
MMP	Mean monthly precipitation			4	4	4	
PAV_WID	Pavement Width	3	4	1	1	1	1
PCA	Area of previous cracking						
PCW	Previous area of wide cracking	1	1	2	4	1	1
RAISE	Raise and fall						
RDM	Mean rut depth						
RDS	Std. deviation of rut depth						
RF	Rise and fall						
SFC	Side force coefficient						
SNP	Pavement structural number		2	1	2	1	1
TD	Texture depth						

Note: 1/ LTNS – Low traffic normal strength
LTHS – Low traffic high strength
HTNS – High traffic normal strength
HTLS – High traffic low strength

Table D.10 Sensitivity on IRI to Do Nothing Case.

Sensitivity in Response to IRI for							
5 YEARS		**10 YEARS**		**15 YEARS**		**20 YEARS**	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	2.07	CONSTANT	9.96	CONSTANT	12.24	CONSTANT	13.7
ADT1	10.41	ADT1	6.78	ADT1	4.78	ADT1	3.35
ADT3	5.31	ADT3	3.55	ADT4	2.51	IRI0	1.89
KGP	4.92	ADT4	2.81	ADT3	2.5	ADT4	1.79
ADT4	4.81	IRI0	2.53	IRI0	2.11	ADT3	1.72
IRI0	3.78	KGP	2.39	KGP	1.89	KGP	1.55
KPP	3.03	KPP	1.94	PAV_WID	1.38	KPP	1.05
SNP	2.57	ADT6	1.45	GROWTH	1	KGE	1.03
ADT6	2.26	SNP	1.41		0.97	GROWTH	0.76
PAV_WID	2.14	ACW	1.20	ACW	0.91	SNP	0.72
HOLD	1.89	PAV_WID	1.16	KGE	0.9	KPI	0.67
ACW	1.88	HOLD	1.15	SNP	0.79	ACW	0.67
KCP	1.58	GROWTH	1.13	HOLD	0.78	HOLD	0.59
HNEW	1.35	HNEW	0.81	KPP	0.74	PAV_WID	0.56
ACA	1.28	KPI	0.78	ACA	0.6	ACA	0.49
GROWTH	1.23	ACA	0.74	HNEW	0.55	HNEW	0.43
ARV	0.94	KGE	0.73	AFL	0.43	AFL	0.37
MMP	0.91	CQ	0.53	CHIP	0.37	CHIP	0.35
KGE	0.82	APT	0.53	APT	0.37	KRP	0.33
CQ	0.78	KCP	0.50	CQ	0.34	CQ	0.21
APT	0.77	ARV	0.46				
KRP	0.58						
KPI	0.55						
AGE2	0.48						

Table D.11 Sensitivity on IRI for Routine Maintenance Case.

Sensitivity in Response to IRI for							
5 Years		**10 Years**		**15 Years**		**20 Years**	
Parameter	**Values**	**Parameters**	**Values**	**Parameters**	**Values**	**Parameters**	**Values**
CONSTANT	*-2.61*	*CONSTANT*	*-2.21*	*CONSTANT*	*0.58*	*CONSTANT*	*3.63*
KGP	6.67	KGP	9.33	KGP	9.80	KGP	9.52
IRI0	6.08	IRI0	5.03	IRI0	4.35	IRI0	3.60
ADT1	3.96	ADT1	3.77	KCP	2.46	KCP	2.19
SNP	3.42	ADT3	3.27	ADT4	2.19	KGE	1.88
ADT5	3.25	KCP	2.47	KGE	1.90	ADT1	1.41
ADT3	2.67	ADT5	2.20	ADT6	1.34	KPP	1.14
ADT2	2.48	SNP	2.15	ADT1	1.12	HOLD	1.09
PAV_WID	1.62	ADT6	1.87	RDS	1.07	HNEW	0.85
KCP	1.33	KGE	1.78	KRP	1.03	ADT5	0.82
KGE	1.23	RDS	1.20	SNP	0.99	KRP	0.82
ADT6	1.14	KRP	1.11	HOLD	0.66	RDS	0.80
HOLD	0.92	PAV_WID	0.93	HNEW	0.66	PAV_WID	0.78
KPP	0.84	ACA	0.83	ACA	0.60	ACA	0.46
AGE3	0.69	ACW	0.78	ACW	0.59	CQ	0.35
ACA	0.69	GROWTH	0.65	KPP	0.59		
RDS	0.67	MMP	0.62	ARV	0.47		
ARV	0.67	AGE3	0.56	MMP	0.42		
GROWTH	0.57	ARV	0.54				
KRP	0.54	CQ	0.28				
ACW	0.54						
MMP	0.47						
HNEW	0.46						
AGE2	0.44						
CQ	0.43						
RDM	0.36						
KVP	0.34						

Table D.12 Sensitivity on SII with Routine Maintenance Case.

Sensitivity in Response to SII for							
5 Years		10 Years		15 Years		20 Years	
Parameters	**Values**	**Parameters**	**Values**	**Parameters**	**Values**	**Parameters**	**Values**
CONSTANT	*80.81*	*CONSTANT*	*93.94*	*CONSTANT*	*98.71*	*CONSTANT*	*99.66*
KCP	6.34	KCP	2.51	KCP	0.66	KCP	0.19
AGE2	5.80	AFL	2.21	AFL	0.65	AFL	0.14
ACA	5.16	AGE2	2.00	AGE2	0.44	ADT2	0.10
AFL	4.72	ADT3	1.31	ADT2	0.34	AGE2	0.09
ADT3	4.45	ADT1	1.18	KRP	0.27	KRP	0.08
ADT1	3.93	ACA	1.10	HNEW	0.17		
ARV	3.35	APT	0.65				
APT	1.78	ACW	0.57				
SNP	1.37	KCI	0.50				
KRP	1.00	KRP	0.48				
CQ	0.95	SNP	0.46				
ACW	0.85	CHIP	0.39				
		CQ	0.22				

Table D.13 Comparison of the Sensitivity of the Traffic Level in PBA.

Sensitivity To Roughness (IRI) For				Sensitivity To Surface Integrity Index(SII) For			
High Traffic Road		Low Traffic Road		High Traffic Road		Low Traffic Road	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	*16.75*	*CONSTANT*	*-2.9*	*CONSTANT*	*85.71*	*CONSTANT*	*72.13*
ADT4	1.14	IRI0	8.32	KCP	4.36	KCP	10.18
KGP	1.13	KGP	5.90	AGE2	3.55	AGE2	8.27
ADT1	1.06	ADT5	3.26	ACA	2.82	ACA	8.09
KPP	0.79	KCP	3.13	ADT1	2.77	AFL	6.30
ADT2	0.75	SNP	3.02	ARV	2.75	ARV	4.42
PAV_WID	0.61	PAV_WID	2.26	ADT4	2.69	ADT5	1.56
IRI0	0.52	KGE	2.10	AFL	2.33	CHIP	1.51
SNP	0.47	ADT1	1.53	KPP	1.50	PCW	1.28
HNEW	0.46	HOLD	1.39	KVP	1.31	ADT1	1.24
ACW	0.42	ADT3	1.23	CQ	0.87	APT	1.07
HOLD	0.40	KPP	1.04	GROWTH	0.81	KVP	1.02
MMP	0.35	ACA	1.00	KGE	0.76	KPP	0.98
APT	0.33	RDS	0.96	SNP	0.70	HOLD	0.91
KCP	0.26	HNEW	0.95			CQ	0.71
GROWTH	0.24	AGE3	0.84				
ARV	0.21	KRP	0.76				
KRP	0.21	ADT6	0.72				
AGE2	0.20	ADT2	0.71				
KVP	0.19	CQ	0.64				
CHIP	0.17	MMP	0.59				
CQ	0.14	ACW	0.46				
		KCI	0.43				
		AGE2	0.35				
		ARV	0.26				
		PCW	0.23				

Table D.14 Sensitivity to Average IRI in PBA.

Sensitivity to Low Traffic Road				Sensitivity to High Traffic Road			
For 5 Years Period		**For 20 Years Period**		**For 5 Years Period**		**For 20 Years Period**	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	*2.19*	*CONSTANT*	*2.33*	*CONSTANT*	*1.60*	*CONSTANT*	*0.93*
IRI0	1.45	IRI0	0.37	IRI0	1.70	KCP	1.32
M_IRI_A0	0.24	M_IRI_A0	0.34	S_IRI_A0	0.55	SNP	0.94
S_IRI_A0	0.17	S_IRI_A0	0.27	ADT1	0.45	ADT4	0.92
M_RDM_A0	0.15	KGE	0.18	ADT3	0.35	ADT1	0.81
KGP	0.13	ADT1	0.18	KGP	0.30	ACA	0.77
R_IRI_A0	0.13	M_RDM_A0	0.14	S_MCI_A0	0.30	IRI0	0.62
SNP	0.12	R_IRI_A0	0.14	PAV_WID	0.15	ADT6	0.52
ADT1	0.10	M_ACA_A0	0.13	M_IRI_A0	0.12	ADT3	0.49
KGE	0.08	KGP	0.13	SNP	0.12	ADT2	0.42
M_ACA_A0	0.08	S_MCI_A0	0.12	HNEW	0.10	ACW	0.42
M_ASH_A0	0.06	ADT3	0.12	ARV	0.10	KGP	0.41
S_MCI_A0	0.05	R_SFC_A0	0.11	KPP	0.10	PAV_WID	0.31
RDM	0.05	M_ASH_A0	0.10	KGE	0.09	HNEW	0.13
		SNP	0.10	HOLD	0.08	AGE2	0.13
		MMP	0.05	R_IRI_A0	0.08	AGE3	0.11
		R_SII_A0	0.05	M_RDM_A0	0.07	R_SFC_A0	0.11
				MMP	0.07	RDS	0.10
				ACA	0.06	HOLD	0.10
				M_ASH_A0	0.06	ARV	0.10
				AGE2	0.06	S_IRI_A0	0.09
				CQ	0.06		
				M_ACA_A0	0.05		

Table D.15 Sensitivity to Average SII and GRVL in PBA.

Sensitivity in Response to SII				Sensitivity in Response to GRVL			
For High Traffic		**For Low Traffic**		**For High Traffic**		**For Low Traffic**	
Parameter	**value**	**Parameter**	**value**	**Parameter**	**value**	**Parameter**	**value**
CONSTANT	*-1.23*	*CONSTANT*	*-0.39*	*CONSTANT*	*16.14*	*CONSTANT*	*7.84*
R_IRI_A0	4.19	ARV	1.24	SNP	32.97	SNP	64.53
M_IRI_A0	3.73	ACA	1.21	ADT4	10.93	KCP	29.59
S_IRI_A0	3.27	AGE2	1.08	ADT6	6.12	ADT1	26.88
M_RDM_A0	2.52	AFL	1.06	M_IRI_A0	5.39	ADT5	26.03
ADT2	2.42	M_IRI_A0	0.73	PAV_WID	4.69	ADT3	19.55
M_ACA_A0	2.21	APT	0.72	S_IRI_A0	3.89	ACA	17.73
ARV	1.54	M_ASH_A0	0.57	M_ACA_A0	3.65	ADT6	14.05
S_MCI_A0	1.49	M_ACA_A0	0.55	ADT1	2.75	ADT2	13.83
AGE2	1.45	R_IRI_A0	0.54	M_RDM_A0	2.23	PAV_WID	7.40
ACA	1.39	M_RDM_A0	0.50			ACW	9.24
M_ASH_A0	1.28	S_IRI_A0	0.48			HOLD	4.27
AFL	1.05	S_MCI_A0	0.36			IRI0	4.07
APT	1.05	KGP	0.35			HNEW	4.04
KGE	0.91	ADT1	0.33			R_SFC_A0	2.95
MMP	0.81	ACW	0.27			ARV	2.79
KCP	0.77	KRP	0.21			APT	2.69
		IRI0	0.21			MMP	2.64
		R_SII_A0	0.19			KPP	2.47
						RDS	2.31
						AGE2	2.30

Table D.16 Sensitivity to Total AC and VOC in PBA.

Sensitivity in Response to Total AC				Sensitivity in Response to Total VOC			
For Low Traffic		For High Traffic		For Low Traffic		For High Traffic	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	*871071*	*CONSTANT*	*589648*	*CONSTANT*	*-145013*	*CONSTANT*	*-13105700*
PAV_WID	1354360	PAV_WID	4243630	ADT5	122588	ADT1	11645500
S_IRI_A0	376797	ADT1	2872380	IRI0	96008	ADT4	11252800
S_MCI_A0	226575	ADT4	1792480	M_IRI_A0	85602	KCP	7908280
R_SFC_A0	190346	S_IRI_A0	1193880	S_IRI_A0	68179	ADT5	6136200
M_IRI_A0	181712	S_MCI_A0	1130840	ADT1	65063	ADT3	6008550
ADT1	169600	ADT2	1005040	ADT3	48677	SNP	5434500
ADT4	133054	ADT6	967975	M_RDM_A0	38047	ACA	4493390
R_IRI_A0	108566	ADT3	908671	M_ACA_A0	35519	ADT2	4127240
ADT2	99356	SNP	875681	R_IRI_A0	35404	ADT6	3727250
M_ASH_A0	74853	GROWTH	490965	KGE	31334	GROWTH	3095260
M_RDM_A0	67429	KCP	481750	S_MCI_A0	30322	IRI0	2771050
R_SII_A0	67296	ACA	337180	KGP	26795	ACW	2401530
SNP	59971	M_IRI_A0	326152	R_SFC_A0	24217	KGP	2030140
M_ACA_A0	59888	IRI0	324099	M_ASH_A0	23758	PAV_WID	1732000
ACW	41068	APT	291146	SNP	22825	S_MCI_A0	1525260
APT	34856	M_ASH_A0	290801	ACW	11552	S_IRI_A0	945728
MMP	31109	AGE2	262145	R-SII_A0	11468	HNEW	885821
		ACW	223026			R_SFC_A0	824620
		HNEW	213566			RDS	757882
		M_ACA_A0	200583			AGE3	681354
		R_SFC_A0	194491			AGE2	670919
		AGE3	167544			HOLD	607045
		M_RDM_A0	149612				
		RDS	145760				

Table D.17 Sensitivity to Treatment Selection for Low Traffic Road.

Sensitivity to Strengthening Length		Sensitivity to Smoothing Length		Sensitivity to Resurfacing Length	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	*3.86*	*CONSTANT*	*1.42*	*CONSTANT*	*4.07*
S_IRI_A0	3.53	S_IRI_A0	2.71	ADT4	1.26
S_MCI_A0	2.12	ADT5	2.35	ADT5	0.93
ADT2	0.79	ADT4	1.93	M_IRI_A0	0.85
ADT5	0.76	S_MCI_A0	1.63	S_IRI_A0	0.68
ADT1	0.66	M_IRI_A0	1.14	ADT1	0.58
SNP	0.65	R_SFC_A0	0.80	R_SFC_A0	0.56
IRI0	0.33	ADT2	0.77	M_ASH_A0	0.38
		M_ASH_A0	0.59	S_MCI_A0	0.38
		M_ACA_A0	0.58	M_RDM_A0	0.36
		ADT6	0.53	M_ACA_A0	0.36
		SNP	0.53	R_IRI_A0	0.34
		R_IRI_A0	0.50	ADT6	0.34
		M_RDM_A0	0.48	R_SII_A0	0.23
		IRI0	0.33	MMP	0.15
		R_SII_A0	0.21	ACW	0.11
				SNP	0.09

Table D.18 Sensitivity to Treatment Selection for High Traffic Road.

Sensitivity to Strengthening Length		Sensitivity to Smoothing Length		Sensitivity to Resurfacing Length	
Parameters	**Value**	**Parameters**	**Value**	**Parameters**	**Value**
CONSTANT	*6.17*	*CONSTANT*	*0.87*	*CONSTANT*	*3.56*
ADT1	10.22	S_MCI_A0	5.20	ADT1	3.03
ADT4	6.56	S_IRI_A0	4.68	ADT4	1.68
S_IRI_A0	6.51	SNP	4.01	ADT2	1.19
S_MCI_A0	6.49	KCP	2.29	ADT6	0.84
SNP	4.83	ADT4	1.49	ADT3	0.82
ADT6	3.55	ACA	1.40	GROWTH	0.47
ADT3	3.55	M_ASH_A0	0.86	R_IRI_A0	0.28
ADT2	3.21	ACW	0.79	R_SII_A0	0.26
KCP	2.62	PAV_WID	0.76	SNP	0.26
ACA	1.68	ADT2	0.65	IRI0	0.25
GROWTH	1.59	M_ACA_A0	0.55	S_IRI_A0	0.23
IRI0	1.27	R_SFC_A0	0.45	AGE2	0.18
ACW	1.04	M_IRI_A0	0.41	APT	0.18
M_IRI_A0	0.94	HOLD	0.40	AFL	0.13
AGE2	0.88			M_RDM_A0	0.12
PAV_WID	0.84			M_ACA_A0	0.12
APT	0.82				
R_SFC_A0	0.76				
M_ASH_A0	0.71				
HNEW	0.60				
RDS	0.56				
HOLD	0.55				
AFL	0.53				
AGE3	0.51				

Table D.19 Sensitivity to Average Roughness in EA.

Sensitivity to Avg. IRI for					
High Traffic		**Low traffic**			
Unlimited Budget		**Unlimited Budget**		**Constraint Budget**	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	*2.00*	*CONSTANT*	*4.8*	*CONSTANT*	*4.7*
PAV_WID	1.8	ADT1	2.7	ADT1	2.6
C_AM	1.5	PAV_WID	1.5	PAV_WID	1.6
KGP	1.1	ADT3	1.4	ADT3	1.4
SNP	0.9	ADT5	1.3	ADT5	1.2
S_MCI_A0	0.6	IRI0	0.8	ADT2	0.9
ADT1	0.5	ADT2	0.7	IRI0	0.8
HOLD	0.5	ADT6	0.6	ADT6	0.6
C_PTH	0.4	GROWTH	0.6	GROWTH	0.5
KCP	0.3	KGE	0.4	HOLD	0.4
CQ	0.3	KPP	0.3	KGE	0.4
IRI0	0.3	HOLD	0.3	C_SLLG	0.4
ACA	0.3	C_STAB	0.3	KPP	0.4
KPP	0.3	C_SLLG	0.2	C_STAB	0.3
S_IRI_A0	0.2	HNEW	0.2	S_MCI_A0	0.3
C_STAB	0.2	APT	0.2	C_GRBN	0.2
C_MILL	0.2	CQ	0.2	KGP	0.2
C_DRN	0.2	CHIP	0.2	HNEW	0.2
				CQ	0.2
				R_SFC_A0	0.2
				KCP	0.2
				S_IRI_A0	0.2
				APT	0.2
				C_CRSL	0.2

Table D.20 Sensitivity to Average SII and GRVL in EA.

Sensitivity to Avg. SII				Sensitivity to Avg. GRVL			
High Traffic		**Low traffic**		**High Traffic**		**Low traffic**	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
CONSTANT	*32.43*	*CONSTANT*	*95.8*	*CONSTANT*	*40.6*	*CONSTANT*	*50.5*
KGP	23.0	ADT1	45.1	SNP	84.0	SNP	47.7
PAV_WID	20.2	IRI0	32.4	ADT4	27.8	ADT1	11.1
C_AM	17.2	ADT5	30.3	KCP	18.3	IRI0	8.4
C_PTH	9.6	PAV_WID	27.9	ADT6	11.4	C_GRBN	4.1
IRI0	8.2	ADT3	21.8	ADT3	11.4	KGP	4.1
S_MCI_A0	7.9	KGP	20.3	ADT1	11.3	KCP	3.6
KPP	5.9	KCP	16.6	ADT2	10.5	KPP	2.9
ADT2	5.5	ADT2	13.3	PAV_WID	7.4	C_GRSR	2.5
S_IRI_A0	5.4	SNP	11.4	ACA	6.8	M_ASH_A0	2.3
HOLD	5.3	GROWTH	9.8	GROWTH	4.1	C_PTH	2.3
KCP	5.1	KPP	9.5	ACW	3.1	KGE	2.3
CQ	4.3	HOLD	8.9	C_RTFL	2.4	KRP	2.3
ADT5	4.2	ADT6	8.4	R_IRI_A0	2.3	C_SLDB	2.2
SNP	4.1	HNEW	7.5	C_SLSP	2.1	AFL	2.1
C_DRN	3.2	KGE	6.0	C_DRN	1.9	HNEW	1.9
ACW	3.1	C_CRSL	5.5	C_CRFL	1.8	CQ	1.7
R_IRI_A0	2.6	C_STAB	5.3				
ACA	2.6	R_SFC_A0	5.0				
		S_IRI_A0	5.0				
		C_GRBN	4.5				
		S_MCI_A0	4.5				
		CQ	4.3				
		C_GRGB	4.0				
		C_SLLG	3.7				
		M_IRI_A0	3.5				
		CHIP	3.4				
		RDS	3.1				
		ACW	3.1				
		C_PTH	2.9				

Table D.21 Sensitivity to Agency Cost and VOC in EA.

Sensitivity to Agency Cost				**Sensitivity to Vehicle Operating Cost**			
Parameter	**High Traffic**	**Parameter**	**Low traffic**	**Parameter**	**High Traffic**	**Parameter**	**Low traffic**
CONSTANT	*-825393*	*CONSTANT*	*-297022*	*CONSTANT*	*-4440530*	*CONSTANT*	*52982*
PAV_WID	3077340	PAV_WID	1383280	ADT4	14850300	PAV_WID	334697
C_AM	2537560	KCP	480923	PAV_WID	12636000	ADT1	242215
ADT1	2435520	ADT1	296670	C_AM	10467100	ADT3	141097
ADT5	1873320	S_IRI_A0	277671	SNP	6330430	ADT6	88542
ADT3	1343190	C_GRBN	265250	S_MCI_A0	5912750	KPP	87732
S_MCI_A0	1328060	C_STAB	241919	ADT1	5598150	HNEW	77695
SNP	1298310	C_SLLG	231385	KGP	4639050	IRI0	75566
S_IRI_A0	1106570	ADT4	223199	S_IRI_A0	3340280	KGE	66605
ADT2	802612	C_CRSL	213857	C_PTH	2984710	HOLD	63694
GROWTH	700639	S_MCI_A0	205783	HOLD	2892010	SNP	58836
KCP	610866	IRI0	168224	CQ	2280920	C_SLLG	58735
KGP	525388	M_IRI_A0	162740	KPP	2052670	C_STAB	57950
C_PTH	501204	R_SFC_A0	143888	KCP	2045450	C_GRBN	53643
ADT6	495661	SNP	121976	ACA	1971090	ACW	40550
HOLD	309006	M_ASH_A0	121957	C_STAB	1955700	CQ	37292
KPP	298032	C_CRFL	121393	C_DRN	1468550	C_CRSL	36297
C_DRN	238990	ADT3	118115			R_SFC_A0	33924
M_ASH_A0	236405	M_RDM_A0	117524			C_GRGB	33056
R_SII_A0	205752	ACA	117524				
C_SLLG	190056	ADT6	106365				
IRI0	188828	C_GRGB	99481				
HNEW	182459	M_ACA_A0	94530				
C_CRSL	182217	C_PTH	88682				
C_RTFL	178599	R_IRI_A0	77363				
C_ANC	176960	C_RIPP	68569				
CQ	134769	C_DRN	67032				
		KGP	64359				
		C_ANC	54599				
		APT	53591				
		R_SII_A0	52560				
		GROWTH	50912				
		HNEW	48580				
		ACW	48190				

Table D.22 Sensitivity to Treatment Selection High Traffic Road in EA.

Sensitivity to Strengthening Length		**Sensitivity to Smoothing Length**		**Sensitivity Resurfacing Length**	
Parameters	**Values**	**Parameters**	**Values**	**Parameters**	**Values**
CONSTANT	*4.85*	*CONSTANT*	*-0.37*	*CONSTANT*	*2.34*
ADT1	6.36	S_MCI_A0	4.62	ADT1	1.88
ADT5	5.98	S_IRI_A0	4.20	ADT4	1.14
S_MCI_A0	5.56	SNP	3.18	ADT3	0.80
S_IRI_A0	5.15	ADT1	2.14	R_IRI_A0	0.57
SNP	5.12	M_ASH_A0	0.90	ADT2	0.52
KGP	3.52	KCP	0.79	GROWTH	0.44
ADT3	3.39	ACA	0.77	ADT6	0.42
PAV_WID	2.59	M_RDM_A0	0.72	S_MCI_A0	0.39
ADT2	2.57	M_IRI_A0	0.70	PAV_WID	0.37
C_AM	2.50	R_SFC_A0	0.69	S_IRI_A0	0.33
KCP	1.93	RDS	0.64	SNP	0.28
GROWTH	1.60	HOLD	0.62	R_SFC_A0	0.27
ADT6	1.10	R_IRI_A0	0.52	R_SII_A0	0.25
C_PTH	0.97	GROWTH	0.51	IRI0	0.23
KPP	0.88	C_PTH	0.50	KGP	0.22
IRI0	0.79	C_AM	0.49	C_PTH	0.17
C_GRSN	0.77	KGP	0.45	ACA	0.16
C_KC	0.75	M_ACA_A0	0.45	C_AM	0.14
		CQ	0.30	M_IRI_A0	0.14
				C_DRN	0.13
				C_RTN	0.12
				CQ	0.11

Table D.23 Sensitivity to Treatment Selection Low Traffic Road in EA.

Sensitivity to Strengthening Length		Sensitivity to Smoothing Length		Sensitivity Resurfacing Length	
Parameters	**Values**	**Parameters**	**Values**	**Parameters**	**Values**
CONSTANT	*1.05*	*CONSTANT*	*-0.80*	*CONSTANT*	*0.15*
S_IRI_A0	1.86	S_IRI_A0	1.60	ADT1	2.15
S_MCI_A0	1.30	ADT1	1.12	ADT5	1.37
ADT4	1.22	S_MCI_A0	1.12	IRI0	1.30
ADT1	0.97	IRI0	0.79	PAV_WID	1.07
ADT2	0.59	PAV_WID	0.76	ADT3	1.05
IRI0	0.55	M_IRI_A0	0.68	KCP	0.88
SNP	0.49	ADT3	0.65	KGP	0.85
ADT6	0.44	KCP	0.54	ADT2	0.54
KGP	0.36	KGP	0.42	ADT6	0.50
PAV_WID	0.34	M_ACA_A0	0.38	SNP	0.46
KCP	0.22	M_RDM_A0	0.37	M_IRI_A0	0.45
GROWTH	0.21	ADT5	0.37	GROWTH	0.39
KGE	0.21	M_ASH_A0	0.33	KPP	0.38
KPP	0.20	ADT6	0.30	M_ASH_A0	0.34
C_SLDB	0.18	C_RIPP	0.28	M_ACA_A0	0.31
C_GRBN	0.18	R_IRI_A0	0.27	M_RDM_A0	0.30
HOLD	0.18	C_GRBR	0.25	HOLD	0.29
RDS	0.16	R_SFC_A0	0.22	KGE	0.29
		GROWTH	0.19	S_IRI_A0	0.26
		C_SLDB	0.19	HNEW	0.25
		AFL	0.17	R_SFC_A0	0.23
		ACW	0.17	R_IRI_A0	0.23
		KPP	0.16	C_CRSL	0.22
		CQ	0.10	C_SLLG	0.20
				C_GRBN	0.19
				C_STAB	0.18
				ACA	0.18
				S_MCI_A0	0.17
				C_EWRK	0.17
				ACW	0.15
				CQ	0.15
				C_GRBR	0.14
				CHIP	0.14
				AGE2	0.12

Table D.24 Sensitivity of Budget Constraint in Economic Analysis.

Sensitivity to Strengthening Length				Sensitivity to Smoothing Length			
Unlimited Budget		Constraint Budget		Unlimited Budget		Constraint Budget	
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
CONSTANT	1.05	CONSTANT	0.93	CONSTANT	-0.80	CONSTANT	-0.76
S_IRI_A0	1.86	S_IRI_A0	1.76	S_IRI_A0	1.60	S_IRI_A0	1.60
S_MCI_A0	1.30	S_MCI_A0	1.25	ADT1	1.12	ADT1	1.12
ADT4	1.22	ADT4	1.25	S_MCI_A0	1.12	S_MCI_A0	1.09
ADT1	0.97	ADT1	0.97	IRI0	0.79	IRI0	0.80
ADT2	0.59	ADT2	0.60	PAV_WID	0.76	PAV_WID	0.79
IRI0	0.55	IRI0	0.56	M_IRI_A0	0.68	ADT3	0.68
SNP	0.49	SNP	0.48	ADT3	0.65	M_IRI_A0	0.65
ADT6	0.44	ADT6	0.43	KCP	0.54	KCP	0.55
KGP	0.36	PAV_WID	0.41	KGP	0.42	KGP	0.42
PAV_WID	0.34	KGP	0.36	M_ACA_A0	0.38	M_ACA_A0	0.35
KCP	0.22	KCP	0.30	M_RDM_A0	0.37	M_ASH_A0	0.35
GROWTH	0.21	HOLD	0.24	ADT5	0.37	ADT5	0.35
KGE	0.21	C_GRBN	0.22	M_ASH_A0	0.33	M_RDM_A0	0.34
KPP	0.20	RDS	0.20	ADT6	0.30	ADT6	0.30
C_SLDB	0.18	KGE	0.19	C_RIPP	0.28	R_IRI_A0	0.29
C_GRBN	0.18	KPP	0.19	R_IRI_A0	0.27	C_RIPP	0.27
HOLD	0.18	GROWTH	0.17	C_GRBR	0.25	C_GRBR	0.23
RDS	0.16	C_SLDB	0.16	R_SFC_A0	0.22	R_SFC_A0	0.23
		M_IRI_A0	0.14	GROWTH	0.19	C_SLDB	0.20
		C_SLLG	0.13	C_SLDB	0.19	KPP	0.20
		CQ	0.09	AFL	0.17	GROWTH	0.18
				ACW	0.17	AFL	0.17
				KPP	0.16	HOLD	0.15
				CQ	0.10	CQ	0.12

Table D.25: Effect of VOC Rate in Sensitivity to Strengthening Length.

Sensitivity for Low Traffic Road				Sensitivity to High Traffic Road			
For 0.5 RUC		For 2.0 RUC		For 0.5 RUC		For 2.0 RUC	
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
CONSTANT	1.05	CONSTANT	1.39	CONSTANT	4.58	CONSTANT	5.11
S_IRI_A0	1.86	S_IRI_A0	2.17	ADT1	6.43	ADT5	6.43
S_MCI_A0	1.30	S_MCI_A0	1.50	ADT5	6.22	ADT1	6.29
ADT4	1.22	ADT4	1.07	S_MCI_A0	5.48	S_MCI_A0	5.47
ADT1	0.97	ADT1	0.80	SNP	5.09	S_IRI_A0	5.25
ADT2	0.59	ADT2	0.60	S_IRI_A0	5.01	SNP	5.20
IRI0	0.55	IRI0	0.59	KGP	3.66	KGP	3.54
SNP	0.49	SNP	0.43	ADT3	3.52	ADT3	3.12
ADT6	0.44	ADT6	0.35	PAV_WID	2.61	ADT2	2.81
KGP	0.36	KGP	0.30	C_AM	2.57	C_AM	2.47
PAV_WID	0.34	KGE	0.29	ADT2	2.43	PAV_WID	2.41
KCP	0.22	PAV_WID	0.23	KCP	1.96	KCP	1.85
GROWTH	0.21	C_SLDB	0.22	GROWTH	1.71	GROWTH	1.54
KGE	0.21	KCP	0.19	C_PTH	1.09	ADT6	1.15
KPP	0.20	GROWTH	0.17	ADT6	1.06	C_PTH	1.06
C_SLDB	0.18	KPP	0.14	KPP	0.99	KPP	0.78
C_GRBN	0.18	RDS	0.14	C_GRSN	0.83	C_KC	0.73
HOLD	0.18	C_GRBN	0.14	C_KC	0.77	IRI0	0.72
RDS	0.16			IRI0	0.76	C_GRSN	0.68
				HNEW	0.56	HNEW	0.49