The development of gravel deterioration models for adoption in a New Zealand gravel road management system

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Central Otago, Grey District, Hastings, Otorohanga, Selwyn, South Taranaki, Southland, Tasman, Thames Coromandel and Waimakariri

Contents

Executive summary

This report provides the outcomes from research based on the Land Transport NZ monitoring programme that commenced during 2002 and included the cooperation of 51 local authorities. A summary of the main deliverables from this project is presented in Table E.1 and these are discussed further in subsequent sections.

Table E.1: Deliverables from research.

Study objectives	Outcome / results	Comments
Propose some strategic level best practice guidelines for managing gravel roads from a performance perspective	Part A of this report provides comprehensive guidelines	
Interrogate the gravel loss data with the purpose of developing condition deterioration models such as gravel loss	General models were developed and are presented.	Given some data limitations, site specific model could not be developed.
Investigate the need and practicality of incorporating other/new condition performance measures such as gravel profile shape index (GrPSI) into a GRMS	A shape loss index is proposed and promising results were obtained.	More work is required on site specific data
Develop a framework for adopting the deterioration models and/or other practical consideration into a decision framework for the GRMS	Framework options are provided – discussed further in following sections	

Construction and maintenance best practice

Understanding the performance of unsealed roads and the factors that influence gravel loss is important for two reasons.

1. to assist asset management processes, ie to plan re-gravelling at the appropriate time
2. to reduce gravel loss through improved construction and maintenance practices.

Part A of this report focuses solely on the improvement of unsealed road performance through construction and maintenance processes. Reducing gravel loss can have significant benefits – not only in lowering maintenance costs, but in placing less demand on winning gravel, reducing dust emissions, less surface ravelling, better ride qualities and improved road safety.

While the gravel loss model is based on existing management practices, it is important that practitioners apply latest scientific practices relating to all aspects of unsealed road management to ensure that gravel loss is minimised.

The primary purpose of these notes is to provide practical guidelines on how best to handle the various factors contributing to gravel loss. Addressing some or all of these aspects will lead to a considerable reduction in gravel loss and in time the deterioration models can be calibrated to reflect the application of best practices.

Attention has to be given to a wide range of engineering practices (listed below) to ensure gravel loss is kept to a minimum:

- road geometry
- drainage
- pavement design and materials
- maintenance practices
- stabilisation practices
- performance evaluations.

Findings from the gravel experimental data

The data from the past five years was analysed and the results are presented in Part B of this report. It is important to recognise the original objective of this experiment, which was to derive only a gravel loss model for application in New Zealand. Furthermore, the monitoring programme was constrained in terms of finances, which did not allow for a full-scale testing programme such as those undertaken in South Africa and Australia (Paige-Green 1989 and Giummarra et al. 2007). Taking these factors into account, the general gravel loss models delivered might not necessarily be applicable to all site-specific applications.

Proposed models for gravel and slope loss

This research was successful in the delivery of general gravel loss and slope loss (crossfall) models given by:

$$DeltaGL = 2 \times \left[25.6 - F_1 \times Width - F_2 \times Pi + F_3 \times P265 - F_4 \times TLB + F_5 \times ADT\right)]$$

Equation E.1

Where	Delta GL	is the annual change in surface thickness
	WIDTH	surface width
	PI	plasticity index
	P265	percentage aggregate passing the 26.5 mm sieve
	TLB	number of days since last blading
	Fi	model coefficients

and

$$dSLOPE = 2 \times \begin{bmatrix} 0.04 + F_1 \times ADT + F_2 \times P265 - F_3 \times Grade - F_4 \times Pi \\ - F_5 \times Rain - F6 \times Width - F7 \times TLB) \end{bmatrix}$$

Equation E.2

Where	dSlope	is the annual change in profile slope
	ADT	average daily traffic

P265	% of particles passing through the 26.5 mm sieve
PI	plasticity index
Grade	longitudinal slope (if moderate =1, otherwise 0)
Rain	average annual rainfall
Width	surface width
TLB	number of days since last blading
Fi	model coefficients

Both these models will require calibration and refinement based on some site-specific data. This data will include monitoring of the gravel quantity and crossfall on a regular basis, plus before and after maintenance.

Lessons learned from the data collection

Some limitations were identified but these did not bear any reflection on the quality of data collection performed by the individual councils. However, the data analysis highlighted some important considerations for future studies of this nature including:

- The data collection should only be undertaken by one party. However, if different data collectors are used, their measurement technique must be cross-correlated in order to achieve a consistent outcome. By having different data collectors involved, different measurement practices introduce an additional layer of variability that cannot be explained by the data.
- More frequent measurements are needed, as a minimum, before and after measurement of blading cycles are performed. Figure E.1 illustrates this concept. It is easy to underestimate the impact blading has on the shape of the road profile in a longitudinal and transverse direction. The gravel profile is restored with each blading cycle, and with some blading the gravel level is significantly improved through material gain from the side ditch or from a longitudinal location next to the site. As displayed in the figure, the limited survey points in this experiment also limited the type of model that could be developed.
- The dataset was not always complete, thus limiting the amount of effective data on which the analysis was undertaken.

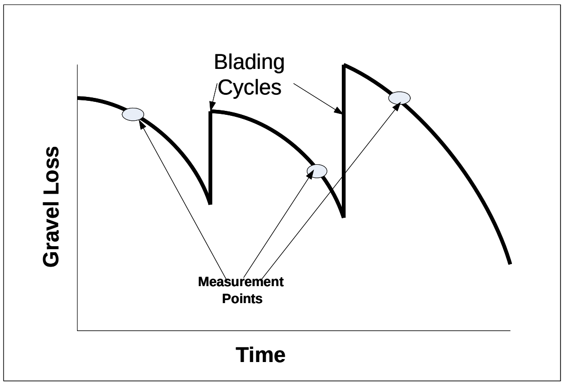


Figure E.1 Typical deterioration curve for gravel roads.

A new performance measure for unsealed roads

A newly proposed performance measure was investigated by this study. The need for such a measure originated from the fact that, in operational practice, re-gravelling is not necessarily a response to actual gravel loss. In most cases, an unsealed road is re-gravelled based on poor performance of the road, such as too high blading frequency and fast loss of slope or shape. For this reason, a shape loss index was developed based on the following figure.

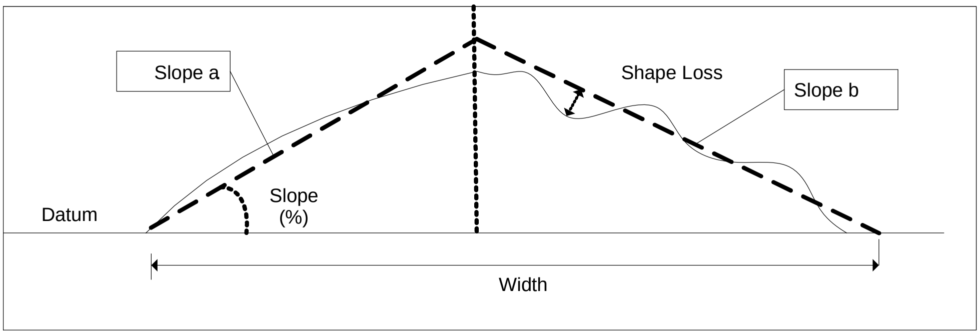


Figure E.2 Definition of slope and shape indices.

The figure indicates two parameters. The first is a simple slope of the crossfall, which is determined from a theoretical line that best fits the crossfall.

$$ShapeIndex = 10 \times \left(Slopefactor + StdDevFactor\right) \qquad \textbf{Equation E.3}$$

Where

$$SlopeFactor = 3 \times Slopecum$$

and

$$StdDevFactor = \max(-0.5, (1/(\log_e(stdevslopea) + \log_e(stdevslopeb))$$

Slopecum is obtained from Equation 11.1

Stddevslope a and b are the standard deviations for the respective slopes

The index showed some promising results and should be further refined based on site specific data.

Decision framework for unsealed roads

Decision frameworks for unsealed roads are normally a combination of practical and theoretical approaches.

Managing unsealed roads often involves operational issues, because unsealed roads change rapidly and when defects appear they must be addressed within a short response time. For that reason, most routine and cyclic maintenance is planned and scheduled according to routine inspections and experience from road operators.

However, longer-term maintenance activities, such as re-gravelling and surfacing of unsealed roads, need a more sophisticated process that includes predictive models. A major consideration during these analyses involves the economic appraisal of different maintenance options and timings of intervention.

This report has made a number of recommendations that will assist road managers in optimising the performance of unsealed roads through appropriate construction and maintenance practices.

Unfortunately, the current models developed in this study are not adequately developed to be incorporated into an asset management system. Further required work is discussed in the next section.

Recommended further work

The research achieved the stated objectives, but somewhat disappointing results were obtained from the regression analysis. The data collected did not allow for site-specific information such as maintenance effects, and for that reason only generalised models were developed. It also appears that these models are not sufficient for adoption within a management system. Further work requirements are presented in Table E.2.

Table E.2: Further research work on unsealed roads.

Recommended further work	A strategy to achieve the further work
Refine and further develop the existing gravel, slope and shape loss models based on frequently measured data	An incremental approach is recommended to improve both the model and measurement process according to the following steps: Step 1 – Attempt to improve the current dataset by incorporating more council data on selected sections such as Central Otago Step 2 – Conduct a survey on selected sections based on a short measurement frequency.
Refine shape loss performance measure	Conduct a network level survey of data and maintenance records in order to establish the KPM based on actual intervention criteria
Continue the gravel loss experiment with advanced measurement principles	Much has been learned from this study and this confirms that continued monitoring of unsealed roads is essential for New Zealand. Many aspects have been identified to suggest that unsealed roads are not maintained at optimal level. The only way to continue gaining knowledge is to have appropriate data available.

Abstract

This report provides the outcomes from research based on the Land Transport New Zealand gravel road monitoring programme that commenced during 2002 and included the cooperation of 51 local authorities. These sections were monitored on a six-monthly basis and all relevant data such as maintenance, rainfall where available and evaporation were incorporated into a national database.

This research project included the provision of practical guidelines for the construction and maintenance of gravel roads. In addition, the gravel road data were analysed and outcomes are presented. The resulting models are effective indications of gravel loss on a network scale but further research would be required for more detailed models. This can be achieved by collecting more information on the impact of routine maintenance such as blading.

One of the main outcomes from this research is the addition of a key performance measure that indicates the change in cross profile or shape over time.

1. Introduction

During 2002, Transfund New Zealand (now Land Transport New Zealand) established a gravel loss experiment in cooperation with 10 local authorities. This experiment consisted of data collection on 51 sections for a period of five years (years one to four have now been completed). MWH was responsible for the management and quality assurance of the data collection project. Part of this project delivered an integrated database for all the data collected.

In addition to this, a gravel road management system (GRMS) strategy undertaken for the RIMS Group (Furlong et al 2003) suggested developing a simple and pragmatic system for local authorities to use. Part of the recommendations also included the development of new deterioration models for New Zealand, as indicated in the objectives of this study.

This report contains the findings from the model development and provides users with a practical guideline for the construction and maintenance of unsealed roads.

1.1 Objectives of the study

This research topic sets the basis of the New Zealand GRMS. It was realised that it was important to develop the system framework and the predictive models hand-in-hand. For example, roughness deterioration models could be developed on gravel roads; however, work in New Zealand suggested that blading cycles were not optimised using roughness measures but through other drivers. Roughness models were, therefore, not crucial in this study. The purpose of this study was to develop the deterioration models within the framework of the intended GRMS. Once the research was completed, the models and the system framework could be directly applied within a management system.

The specific **objectives** of this research were to:

1. interrogate the gravel loss data, with the purpose of developing condition deterioration models such as gravel loss
2. investigate the need and practicality of incorporating other/new condition performance measures such as the gravel profile shape index (GrPSI) into a GRMS – (note that some roads fail because of a loss in shape rather than a loss of aggregate)
3. develop a framework for adopting the deterioration models and/or other practical considerations into a decision framework for the GRMS
4. propose some strategic level best practice guidelines for managing the performance of gravel roads.

1.2 Scope of the report

Gravel and/or shape loss of gravel roads are important to road managers for two reasons:

1. Understanding the interaction between the environment, traffic and local material assists the road manager to plan maintenance better, for the short-, medium- and long-term. As part of the required asset management processes, the engineer has to predict expenditure on gravel or unsealed roads. This expenditure is a combination of periodic and routine maintenance such as grading or blading. It also includes more costly maintenance activities such as re-gravelling.
2. Once there is a better understanding of the behaviour of material within a region, a number of activities or measures can be applied in order to reduce or delay the deterioration of the unsealed road.

This report addresses these aspects in two parts:

- **Part A** contains the practical guidelines for the construction and maintenance of unsealed roads. This part is largely based on existing documentation and experience in both New Zealand and Australia.
- **Part B** depicts the results from the analysis based on the gravel loss experiment. This part also contains the recommended gravel loss models to be adopted within the GRMS.

1.3 Terminology

The use of terminology is not consistent in New Zealand – in particular on unsealed, gravel or metal roads. For that reason, this report standardises terminology according to the following scheme (adopted from Henning et al. 2005).

Table 1.1 Terminology of unsealed roads used in this report.

Term	Description
Unformed roads	Unformed roads, also referred to as earth roads, have a natural alignment on the terrain without any engineering input.
Formed roads	Formed roads usually have a reasonably well defined cross-section, including drainage.
Gravelled roads	These roads are built and designed to certain engineering principles, including the importation of high quality gravel from borrow pits.

Part A: Gravel road construction and maintenance best practice

2. Understanding the rate of gravel loss

Understanding gravel loss and the factors that influence it can:

- assist in asset management processes, ie plan re-gravelling at the appropriate time
- reduce it through improved construction and maintenance practices.

The latter area is the predominant topic of this part of the report. The primary purpose of these notes is to provide practical guidelines on how best to handle the various factors contributing to gravel loss. Addressing some or all of these aspects will lead to a considerable reduction in gravel loss, and in time the deterioration models can be calibrated to reflect the application of best practices.

Reducing gravel loss can have significant benefits – not only in lowering maintenance costs, but by placing less demand on winning gravel, reducing dust emissions, less surface ravelling, better ride quality and improved road safety.

Gravel loss on unsealed roads can be attributed to a range of factors, with the main ones being traffic movement creating dust emissions and stone whip off, and climatic factors causing erosion of the road surface due to wind and rainfall.

Estimating gravel loss is an essential requirement in the better management of unsealed roads. Knowing the amount and extent of gravel loss along a road is necessary for:

- asset management systems requiring information on the extent of asset consumption (ie gravel loss) as a way of estimating depreciation
- estimating future gravel re-sheeting quantities, costs and programming re-gravelling operations
- prioritising allocation of often limited gravel resources, in terms of quantity and location of re-sheeting
- helping to evaluate alternative gravel surfacing materials and maintenance practices.

If you cannot measure it
you cannot improve it

Loss of surface material is particularly critical for unsealed roads, where the loss or replacement of lost gravel represents substantial costs. Loose surface material also creates a safety hazard as it has very low surface friction and generates higher dust emissions affecting visibility and health. The loss of fines adversely affects the ability of the pavement to provide a tightly bound surface for longer wear.

Rates of gravel loss are influenced by a number of factors depending on road geometry, material quality, traffic numbers and type, climatic conditions, construction standards and maintenance practices. As these factors can vary through the day, months and years – creating the dynamic nature of unsealed roads – it is difficult at times to provide reasonable estimates of gravel loss at the project level.

Of greater interest is the recently developed gravel loss deterioration model, which is based on New Zealand road conditions. Details of this model are discussed elsewhere in this document. The model is a useful guide to practitioners in providing, at the road network level, a measure of gravel loss for the better management of the unsealed road network.

While the model is based on existing management practices, it is important that practitioners apply latest scientific practices relating to all aspects of unsealed road management to ensure that gravel loss is minimised.

3. Improving the performance of the road surface

This section deals with the basic maintenance practices that affect the performance of the road surface. The purpose of maintenance activities is to preserve the road in a condition close to its intended or as-constructed state, or to ensure an acceptable level of service. This can be achieved through the control of various deterioration models such as ride quality, gravel loss, cross-section shape and dust emissions.

The deterioration of unsealed roads is mainly due to traffic loading – especially heavy vehicles and climatic conditions (rain and dry periods). The rate of deterioration is due to other factors relating to the geometry of the roadway, quality of road materials used, and construction and maintenance standards. As little can be done to influence traffic volumes and climatic conditions, practitioners need to concentrate on the other factors that contribute to deterioration. The aim is not to stop deterioration, but to reduce the **rate** of deterioration so that grading, for example, is extended (say) to every 10 weeks rather than four weeks, and gravel re-sheeting (say) every six years instead of every two years.

By addressing – where possible – existing road deficiencies, the practitioner can begin to influence the rate of pavement deterioration, thereby prolonging the need for maintenance of the road surface.

Listed below are the key practices for better management of unsealed roads. They serve as a basis to assess existing roads, and to highlight what deficiencies exist and how any upgrading may best be achieved. Further details may be found in ARRB (2000).

3.1 Geometric road requirements

3.1.1 Road hierarchy

The primary purpose of a road hierarchy is to ensure that appropriate management, engineering design, construction standards and maintenance practices are applied to a road, based on its function. It also enables more efficient use of limited resources by allocating funding to those roads that are in greater need, and on which expenditure is better justified and higher returns obtained.

Without an adequate road hierarchy for local roads, there may be inefficient allocation of resources, road user expectations may vary, and the scheduling of road works and priorities made more difficult.

A functional road classification should be established in each district which outlines, for each road class, the appropriate geometric design standards, performance criteria and maintenance intervention levels. There is also a need to improve these items in RAMM.

In developing a road hierarchy system, the following guiding principles should be used:

- The classification system should link, and be consistent with, other adjoining road authorities and local government standards.
- The classification system needs to be functionally based. Traffic volumes and vehicle type should not affect the road classification.
- The width of a road, or whether it is sealed, are not necessarily criteria that influence a classification.
- Special purpose roads, ie quarry, logging or tourist roads, should be made to fit existing classifications rather than establish a separate classification.
- Unused road reserves, or paper roads, are to be ignored and used only for mapping purposes.
- For a local road network up to four functional road categories could be used for rural roads as listed in Table 3.1.

Table 3.1 Proposed road classifications in rural areas.

Road class	Class type	Service function description	Brief description	Typical photographs (for unsealed roads)
A	Local arterial road	Provides primarily for the main connection from town centres and local areas to the wider state main road network or state highway system.	Two-way, two-lane, mainly sealed	
B	Collector road	Provides for collecting and distributing traffic and acting as a feeder service to local arterial roads.	Two-way, sealed or unsealed road.	
C	Access roads[1]	Provides predominantly for direct access to properties, recreational areas and industries in urban and rural zones.	Two-way, mainly two-lane sealed or unsealed road.	
D	Limited access tracks[2]	Provides primarily for limited access and using four-wheel drive vehicles. In New Zealand these are often considered as part of the local road network	Two-way, unformed single-lane track with possible access restrictions imposed.	

[1] Commonly referred to in NZ hierarchies as 'local roads', their function is local access and not to be confused with the wider definition of local roads used in the ARRB (2000) manual.

[2] In New Zealand, limited access roads (LAR) have a different meaning – typically, these are busy arterial roads where access is controlled to minimise the potential adverse effects of multiple access points to a single property.

Experience has shown that too often a council has limited road classification information about its unsealed road network, associated geometric design standards and maintenance intervention level. Decisions relating to the required maintenance are left to individual plant operators.

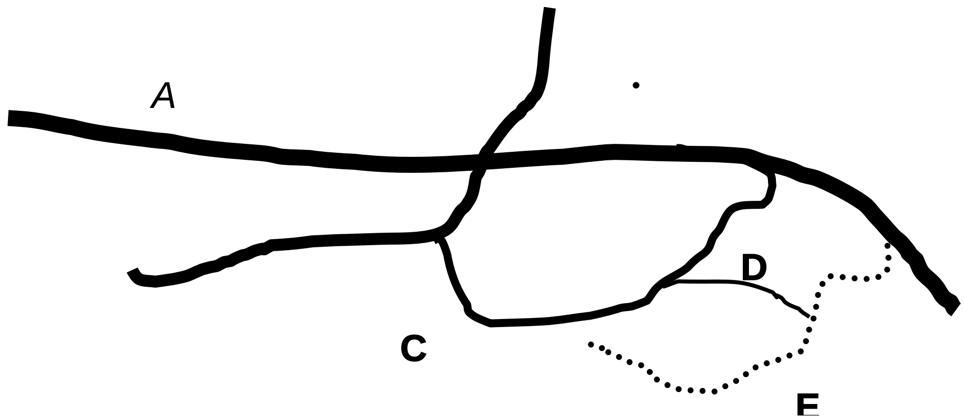


Figure 3.1 Schematic diagram of DSE and PV road classification system.

3.1.2 Design requirements

Most unsealed roads have developed over the years from routes that may have originally been built for the horse and cart, with little or no attention given to applying appropriate geometric designs to suit current motor vehicle requirements. As a result, there are many geometric design deficiencies on existing roads relating to narrow road widths, tight curves, poor drainage provisions and limited sight distances that can lead to higher gravel loss, increased maintenance costs and poor safety.

In some cases, original road reservations created in earlier subdivisions gave little consideration to the geometric requirements of roads. This has sometimes left little scope for developing roads to a good standard and alignment.

In order to improve the geometric design features of many existing unsealed roads with the limited resources available, attention should be given to rectifying – as a matter of priority – those sections of road where there are significant design inconsistencies or 'surprises' for the motorists along the alignment. This information can also be used to help identify those parts of an unsealed road which do not conform to appropriate geometric and safety requirements and highlight areas that, if corrected, will help improve pavement performance and reduce gravel loss (ie on tight curves). As a consistency check, design speeds should not normally differ by more than about 10 km/h on successive geometric elements.

The approach taken in the geometric design of an unsealed road differs from that used for sealed roads because of the highly variable nature of unsealed road surfaces in terms of material properties, climate and maintenance practices. These factors can have a significant effect on road surface friction values and directly influence the design parameters of stopping sight distance and horizontal curve radius. Because of the variability in surface conditions, higher design standards are often necessary to overcome lower longitudinal and sideways friction values.

The geometric design of an unsealed road should be the result of a careful balance between the purpose of the road, traffic volumes, terrain, design standards, costs and the standard of maintenance to be adopted. The wide variety of topography, vegetation, climatic, economic and community factors result in the designer needing to input local knowledge of conditions to any economic procedure used.

3.1.3 Road cross-section

In the majority of cases, unsealed roads are either one lane two-way or two lane two-way. The elements of a road cross-section are shown in Figure 3.2. The main deciding factor as to whether a road is one or two lanes depends on the average daily traffic (ADT) carried and vehicle types. Austroads (2003) suggests that the changeover point is when a projected ADT exceeds 150 vehicles. Suggested minimum desirable road cross-section width standards are listed in Table 3.2.

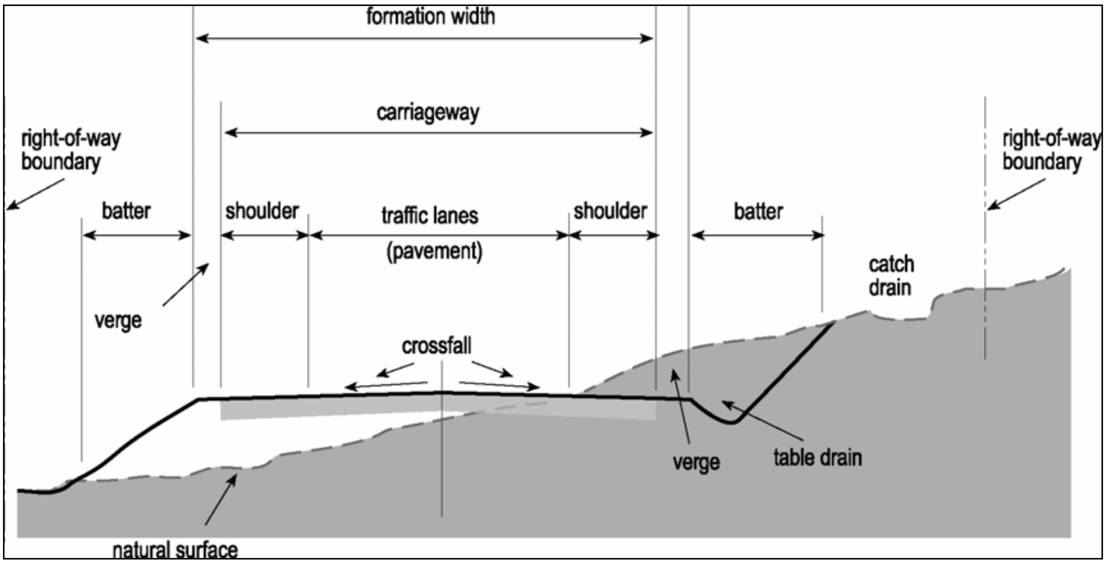


Figure 3.2 Elements of a road cross section.

Table 3.2 Suggested typical minimum unsealed road cross section widths.

Description	Two lane two-way road	One lane two-way road
Traffic lane	3.0 m	3.5 m
Shoulder	0.5 m	1.0 m
Carriageway	7.0 m	5.5 m
Table drain	1.0 m	1.0 m
Formation	9.0 m	7.5 m

If road widths fall between these values, then a road will exhibit a 'three wheel' effect, causing higher road maintenance and greater gravel loss due to the road crown having double the wear, as shown in Figure 3.3.

Figure 3.3 Road showing the 'three wheel' effect.

In some cases, road widths can become excessively high as the grader operator chases suitable fines material from the side of the road, thereby making the road wider than required (Figure 3.4). In these cases, extra maintenance passes are required to grade a wider roadway, and excessive loss of gravel occurs due to greater exposure to climatic factors and higher travel speeds. This situation should be avoided.

Figure 3.4 Avoid making unsealed roads too wide.

Practitioners should ensure that existing road widths comply with desired geometric design standards/road class to ensure efficient transport operations, improved safety and reduced maintenance requirements.

For roads carrying a high percentage of heavy vehicles – such as logging routes – special road widening requirements may be necessary, particularly around tight curves, to match truck configurations. Figure 3.5 shows road widening requirements on curves. Details can be found in Giummarra and Blanksby (2006).

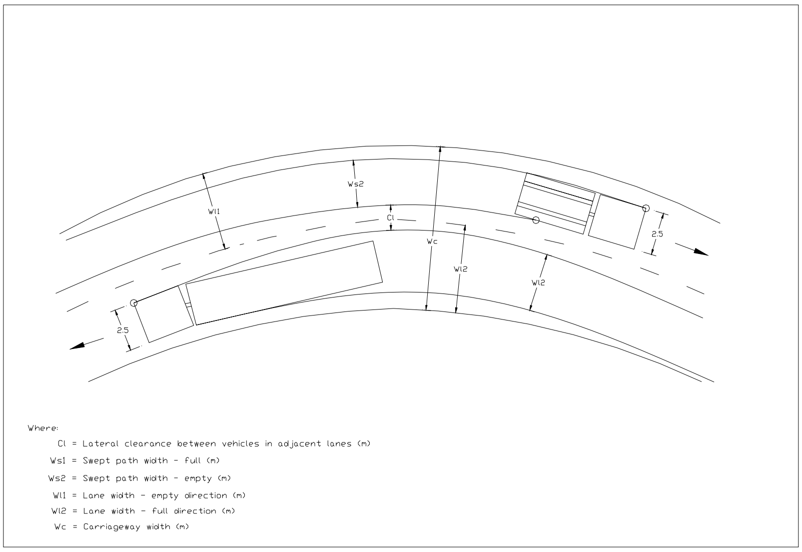


Figure 3.5 Vehicles passing on a typical curve.

3.1.4 Road crossfalls

For unsealed roads it is critical that the road surface has a crossfall of between 4–6% in order to quickly shed water from the surface. If the crossfall is allowed to go flat (< 4%), water is likely to remain on the surface, and the resulting ponding will lead to a weakening of the pavement structure and the rapid formation of potholes, as shown in Figure 3.6.

Figure 3.6 Creation of potholes due to flat crossfalls.

Crossfalls higher than 6% would have higher cross scour erosion and safety risks. Maintaining roads with the required crossfall will ensure better ride quality, lessen the risk of break-up of the road surface and considerably reduce routine maintenance operations.

The crossfall or cross section profile (cross shape) is often a maintenance driver on unsealed roads. Three considerations need to be taken account of including:

- in most cases shape loss or crossfall could be rectified by blading or shape correction processes
- some cases, such as frequent maintenance due to shape loss may be a result of poor material compaction or material properties. For such cases in-situ treatment of the material is required
- when the material is underperforming in the sense that it is not able to maintain the desired crossfall, more intensive maintenance is required. In such cases significant material testing will indicate the need for importing additional material and or treatment of existing material.

Re-gravelling is not always an answer to shape loss, especially if the shape is poor while there is adequate gravel on the road. Visser et al (1994) gives some guidelines of the decision process involved in determining appropriate maintenance for given situations.

3.1.5 Horizontal alignment

Poor road alignment – in terms of tight curves, insufficient super-elevation and high vehicle speeds – means that vehicles exert greater sideways force around a curve and cause the road surface to break up. This creates loose gravel which is more prone to ravelling, erosion, dust emission and gravel loss through whip-off, wind and rain action (Figure 3.7). Such conditions also increase the risk of vehicle accidents.

Figure 3.7 Tight curves with high road surface wear.

Horizontal curves that do not match the prevailing operating speed of drivers are more prone to greater gravel loss. Such curves should be identified and where minimum radius curves and associated super-elevation are below the minimum, alternatives such as increasing the radius of the curve, increased super-elevation, speed reduction or, in difficult cases, sealing the curve, should be considered. While sealing the pavement may be a high initial cost in terms of life-cycle costs, it may prove to be more cost effective, as ongoing maintenance is reduced considerably and road safety improved.

3.1.6 Vertical alignment

Steep vertical grades (>8%) should be avoided on unsealed roads, as the road surface does not have the binding properties to withstand the acceleration and deceleration forces exerted by heavy vehicle drive axles. Steep grades can also lead to drainage channels being formed down a road, causing the washing away of loose gravel (Figure 3.8).

Various techniques are available to minimise the amount of scouring caused by water that can occur on a steep grade. The reader is referred to the *Unsealed roads manual: Guidelines to good practice* (ARRB 2000).

Sections with steep gradients should also be candidates for sealing, which could reduce the whole life costs and possibly allow a decrease in routine maintenance cycles that would otherwise be dictated by such high-maintenance locations.

Figure 3.8 Longitudinal scour due to steep vertical grades.

Another important geometrical aspect is the importance of coordinating horizontal and vertical alignment. The example in Figure 3.9 indicates a wet spot at the bottom of the horizontal curve. This is because the crossfall at the curve-to-curve tangent point is flat to accord with a reverse horizontal curve, and this spot is also the bottom of the sag curve. There is nowhere for the water to run off the road and disperse. Such a situation will always lead to high gravel loss and a requirement for ongoing maintenance.

To overcome this problem, horizontal and vertical coordination needs to be arranged so that it will allow the road to be self draining. An option is to move the tangent point of the reverse curve up the slope so that water is able to flow off the road and be dispersed.

It must be remembered that most unsealed roads were probably constructed with few geometric design considerations. Therefore, if gravel loss is to be minimised because of poor geometric features, then practitioners must be aware of the matters raised above. This can be done by conducting an audit of the road geometry to help identify deficiencies.

Figure 3.9 Soft spot developed on road surface due to poor horizontal / vertical coordination.

3.2 Drainage

Drainage is one of the most important and critical factors in the ability of an unsealed road to withstand traffic loads and reduce ongoing maintenance. Water or excessive moisture reduces the strength of many surfacing and road foundation materials, so that rain and ground water needs to be dispersed away from the roadway as efficiently as possible.

The main road drainage system components are illustrated in Figure 3.10.

There are three key areas that need attention:

- Water that falls *onto* the road surface must be shed as quickly as possible by the use of a crowned crossfall of 4–6% on straight sections.
- Water collected *alongside* the road must be drained away from the road as soon as possible by the use of table drains, cut-off drains and cross drains.Water flows *approaching* a road from the higher adjoining countryside must be intercepted before flowing toward the road by catch drains, diverted into natural watercourses and taken across the road by suitable culverts/floodways.

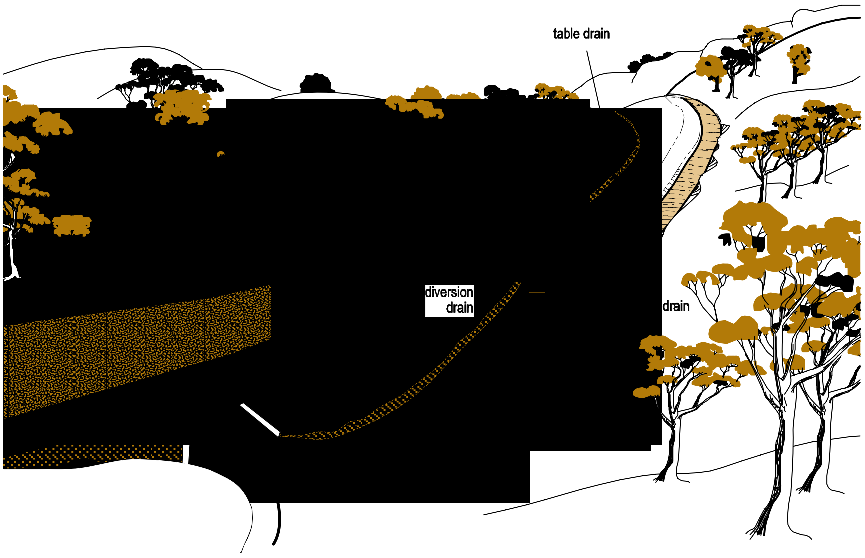


Figure 3.10 Typical drainage surface system.

There are two factors making drainage of higher importance on unsealed roads than on sealed roads. First, the materials used in low-volume unsealed roads tend to be of a lower quality than those used in sealed roads and are, therefore, more likely to be susceptible to water damage and surface scour. Second, due to the lack of a seal, the combination of traffic and water can erode the pavement more easily and do more structural damage than for sealed roads. **The importance of drainage should be kept in mind at all times.**

> **A wise old engineer once said that the three most important factors in the design of unsealed roads are drainage, drainage and drainage**

3.2.1 Surface drainage

Surface drainage consists of those elements that collect and remove water from the surface of the road and areas adjacent to the roadway. It includes culverts and any other drainage systems designed to intercept, collect and dispose of surface water flowing towards and onto the road surface from adjacent areas. The importance of providing adequate crossfall to allow surface water to run off the pavement is paramount for unsealed roads (Section 3.1.4).

It is highly desirable that, in all relatively flat or very gently undulating country except perhaps in arid areas, raised formations should be used. However, in areas of negligible slope which are prone to flooding, a raised formation may act as a dam for floodwaters. In such cases the alignment should be along any slightly higher elevated sections of the ground surface. If the ground level is such that the road formation will act as a dam, then the road should be designed so that the surface of the road is level with the natural surface level. This implies that the road will not be accessible when wet. The decision of when to re-open the road after flooding will depend on the likely initial deformation and other damage caused by traffic on the wet road. An alternative solution could be to raise the roadway on an embankment above flood level and provide low-cost drifts at natural ground level with hardened all-weather surface at regular intervals.

Road surface erosion can be reduced by:

- increasing the shear strength of the wearing course material by providing a well-graded, cohesive mix, with gravel size of up to 26.5 mm or using angular crushed stone and good compaction
- decreasing the shear stresses induced by the flow of water by retarding the rate of flow.

3.2.2 Surface scouring

Surface scour is the loss of surface material caused by the flow of water along and/or over the road. This often leads to considerable gravel loss as channels are cut into the road surface either laterally or down the grades. The problem is exacerbated if there is loose material on the surface, for example after a blading operation and before the surface is reconsolidated by traffic. The ability of the surface material to resist erosion depends on the shear strength under which the water flow occurs.

Pavements with a high content of fines and small aggregate are more inclined to scour than those with a well-graded mixture containing crushed stone of 19 mm or larger. Up to 40 mm stone size is appropriate in high rainfall environments.

Scouring is caused through lack of compaction, excessive longitudinal grades and the build-up of debris on shoulders, preventing surface water from flowing off the pavement.

Scouring includes both transverse and longitudinal scours. Transverse scours commence at the edge of the shoulder or on less compacted areas and tend to work towards the higher areas of the road pavement (Figure 3.11). Alternatively, lack of slope on the shoulders may lead to water standing on the road and eventually finding an escape route across it.

Figure 3.11 Transverse scouring on road.

Plant growth on shoulders – and the consequent entrapment of debris and earth – prevent water draining from the pavement, particularly in areas where longitudinal grades encourage water to flow along the pavement in preference to the direction of the crossfall. This gives rise to longitudinal scours. The scouring of the surface not only creates adverse driving conditions, but also leads to further deterioration of the pavement and gravel loss. Scouring can be pronounced when combined with material susceptible to rutting.

In the event of scouring, the use of high-quality aggregate that relies on mechanical interlock is the most suitable to minimise the problem. Stabilisation can also assist, particularly where longitudinal scouring occurs. Attention to drainage of the pavement and grading of materials helps to reduce the incidence of scouring. On longitudinal grades of 4% and above, crossfall may have to be increased to 5 or 6% depending on alignment and other factors, to ensure that the water finds the shortest possible route off the pavement. The most cost-effective precaution against scouring is to pay careful attention to drainage, material grading and road crossfall shape.

3.2.3 Soft surfaces

The selection of suitable material for the wearing course and base is essential if soft surfaces are to be avoided. Material containing a high percentage of fines may show signs of movement under the passage of vehicles. Lack of compaction, or water being allowed to enter the pavement, also contribute to soft surfaces.

To obtain maximum compaction, the material needs to be at optimum moisture content. The quality of binder in the material is crucial to the optimum performance. A simple field test can be applied to determine the optimum moisture content of the material (Figure 3.12). If the road material is at the optimum moisture content, it will stick together when squeezed in the hand. If moisture runs out of the material, it is too wet. If too dry, it will lack cohesion.

Materials with too much binder – even of good quality – should be avoided, as these will tend to become slippery, potholed and soft when wet. On the other hand, too little binder will cause both wet and dry weather problems. In wet weather, absorption or penetration of moisture will be excessive and in dry weather the surface will ravel. Stabilisation can be used to overcome soft surfaces.

Figure 3.12 Hand squeezing method to establish optimum moisture content.

3.3 Pavement design and materials

Providing a pavement thickness appropriate to future traffic loading and subgrade support is essential in ensuring a longer pavement life and reduced incidence of rutting.

Pavement designs are based on typical heavy vehicles (Figure 3.13).

Figure 3.13 Typical heavy vehicles used for pavement design.

The desired make-up of an unsealed road should be based on providing a base course – which provides the structural strength – topped by a wearing course (Figure 3.14).

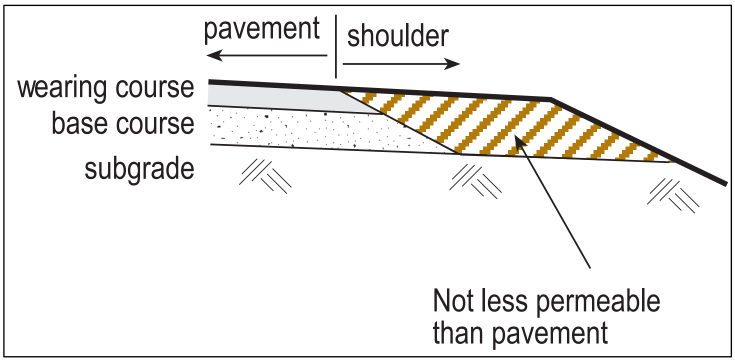


Figure 3.14 Diagram of pavement make-up and terminology.

To considerably reduce gravel loss, greater attention needs to be given by practitioners to pavement design requirements and the placement of a suitable wearing course.

Experience has shown that few unsealed road pavements are designed, even though the design procedure is relatively straightforward. Instead, they are more likely to be built according to the availability of material and other resources. This can sometimes lead to premature pavement failure and higher maintenance requirements of reshaping the road, eliminating rutting and poor ride quality.

A key requirement for an unsealed road is the provision of a wearing course to minimise ravelling, to better shed water run-off and to reduce gravel loss. The function of a wearing course is to provide a hard forming crust to resist wheel abrasion and minimise water penetration into the base course.

Trials conducted by ARRB (2000) have shown that the application of a wearing course (of appropriate specifications) can result in many benefits including:

- smoother roads providing better ride qualities
- improved road safety with road surfaces having a higher skid resistance
- reduced dust emissions as the pavement material will not ravel as much
- better road surface drainage as water can shed more readily
- reductions in gravel loss as material remains on the road longer.

The majority of unsealed roads have a reasonable base course, but little provision for a wearing course. This has the adverse effect of allowing the base course to ravel very easily under traffic and water to enter the pavement. It would seem that practitioners have ‘lost the art’ of applying a wearing course – a practice used over 50 years ago. It is perhaps timely to revisit the need and reasons for applying a wearing course to unsealed roads, to achieve greater value.

3.3.1 Loss of surface material

The passage of vehicles and rainfall, combined with lack of strength and cohesion in pavement materials, leads to a loss of pavement materials. Surface material is lost by the actions of scouring, 'kick off', dust, attrition, stones breaking down through the passage of heavy vehicles and, on weak subgrades, traffic pushing pavement materials into the subgrade.

As aggregate replacement can be as high as 60% of total maintenance costs, losses – caused through dust emissions, breakdown of aggregate, scouring and erosion, poor maintenance practices and restricted selection of pavement materials – need to be minimised if maximum benefit is to be obtained from available resources such as finance, plant and labour.

Compaction, combined with the selection of suitable wearing course material with suitable grading, is an important factor in reducing gravel losses.

A well-designed wearing course should not readily produce loose material. Loose material on the surface is caused through the lack or loss of binder to hold the surface aggregate in place. Surfaces with loose material can have a major effect on vehicle operating costs and safety.

3.3.2 Wearing course specifications

Before laying the wearing course on top of the base course, practitioners must ensure that the base course has an adequate depth of material (about 150 mm), shaped to a crown, with crossfalls of 4–6%.

A soil aggregate consisting of a well-graded gravel sand mixture with a small proportion of clay fines will usually be the most desirable material as a wearing course for an unsealed surface. The aggregate should be well graded from coarse to fine and meet the requirements summarised in Table 3.3.

Table 3.3 Recommended wearing course specifications.

Item	Recommended range
Passing 19 mm sieve	100%
Passing 6.70 mm sieve	60–80%
Passing 2.36 mm sieve	40–60%
Passing 0.300 mm sieve	25–35%
Passing 0.075 mm sieve	10–20%
PI should be in the range of	8–12

(Source: Ferry 1986)

It is important that cohesive clay is added to the surface to help bind the aggregate particles together. For high rainfall areas (> 600 mm per year) a lower PI should be used. The wearing course should have sufficient water added at site and rolled with a multi-wheel roller to ensure high compaction. The minimum depth of a wearing course should be 70 mm.

This information should be used as a guide to good practice. Practitioners should monitor this mix and compare with existing procedures to determine the difference in maintenance requirements. Such an approach will establish whether the extra cost to produce a wearing course is economically justified in the particular circumstances being considered.

3.3.3 Selection of base course materials

The properties of pavement material affecting behaviour depend upon its grading, the hardness of the stone aggregate and the fine soil matrix. The principal factors affecting the performance of materials in relation to unsealed roads are:

- particle size distribution (PSD)
- plasticity (PI) and reactivity of clay and silt fractions
- hardness of stone aggregate
- surface permeability
- compressive strength of material when compacted (dry and wet).

In selecting a material specification for an unsealed pavement, these performance factors are of a lower order than those for sealed roads, because traffic intensities and capital investment are usually lower. However, it should be noted that some unsealed roads – even with low traffic intensities – serve as vital transport links which require higher levels of serviceability than might otherwise be considered.

In general, wear resistance and permeability are of greater importance to the performance of unsealed roads and consequences of loss of shape (ie subgrade rutting). An ideal material for an unsealed road will have properties which result in an even, tight, relatively impermeable (erosion-resistant) and wear-resistant surface. The PSD and PI will be such that there is sufficient coarse material to provide resistance to wear and adequate dry strength (through mechanical interlock), and low permeability to protect the material from loss of strength when the surface becomes wet. In addition, the soil fractions are required to have sufficient dry strength to hold the aggregate fractions in place to prevent ravelling and development of loose material on the surface.

There are two basic material requirements for unsealed roads – one for the base course and one for the wearing course.

Good gravel for the base course will generally have larger sized stone and a very small percentage of clay or fine materials. This is necessary for the strength and good drainability needed in base course gravels. However, this material will not be suitable for a wearing course, as it will not form a crust to keep the surface material bound together for an unsealed road.

A good base course material will have an appropriate grading distribution as listed below for natural gravels. Practitioners should undertake a sieve analysis of their local gravel pits to identify any deficiencies in grading and attempt to mix various materials – the aim being to try to achieve the grading listed in Table 3.4. Achieving the appropriate grading distribution will greatly enhance the performance of unsealed roads.

Table 3.4 Recommended grading limits for bases – natural gravels.

	Percent passing for nominal size (mm)		
Sieve size (mm)	**40**	**30**	**20**
53.0	100		
37.5	95–100	100	–
26.5	86–95	98–100	100
19.0	–	–	93–100
9.50	50–74	60–82	71–87
4.75	35–59	42–66	47–70
2.36	25–46	30–52	35–56
0.425	10–26	12–30	14–32
0.075	4–17	4–18	6–20

Source: ARRB (2000)

Materials for unsealed road pavements are usually selected on the basis of availability, material properties, cost and environmental factors. Often, the selection decision is a compromise between achieving the desired properties with available funds. Environmental factors may eliminate some sources of material and lengthy delays may occur while the approval of the environmental agency is obtained.

3.4 Construction requirements

The prime objective in road construction is to compact pavements and subgrades so as to limit, and if possible prevent, loss of shape from further compaction by traffic after construction. Before any gravel layers are laid the formation should be prepared and any soft spots attended to.

Compaction of fill or pavement material is usually specified to provide higher or predictable shear strength, higher bearing capacity, lower compressibility, lower permeability or reduced susceptibility to moisture content changes.

Compaction requirements may be specified as the number of passes with certain classes of roller, or by the use of a required density obtained for that material in a laboratory.

There is an optimum dry density achieved for given moisture content and compacted effort, known as the optimum moisture content (OMC) (Figure 3.15). However, with a higher compactive effort, a different OMC will result. In arid areas where water is likely to be scarce and possibly insufficient to achieve OMC, it may be better to compact the soil in its dry state by the use of heavy rollers.

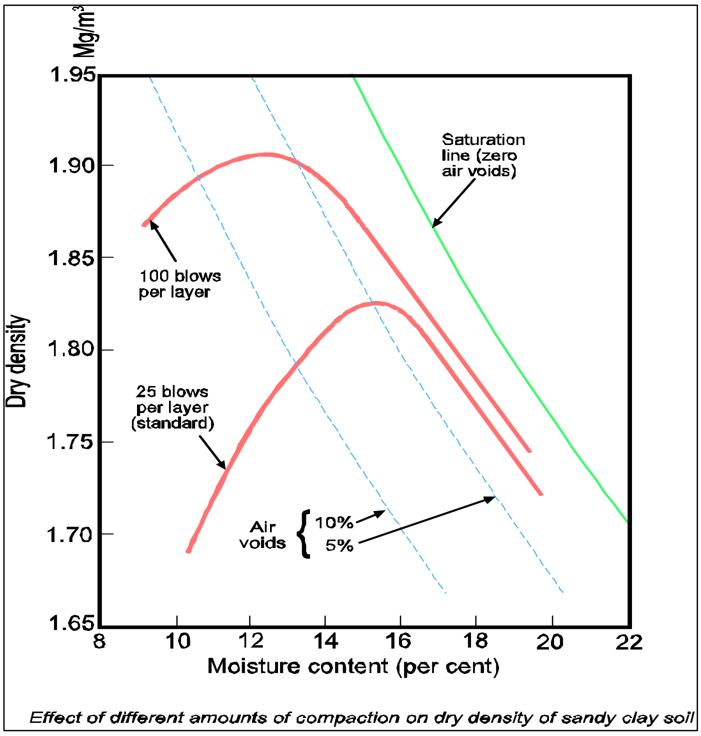


Figure 3.15 Optimum moisture design chart.

Compaction is achieved usually with a vibrating or non-vibrating steel drum roller. Pneumatic-tyred rollers may also be employed in an auxiliary role. Where a grid or cleated roller is used to break down a soft rock, it may also be used for the initial compaction passes. Rock busters can also be used to break down large rocks and provide a grading of road material.

Prior to commencement of compaction, the layer should be checked to ensure that the moisture content is uniform and that there are no patches of segregated material.

The following rolling procedures have been developed to achieve satisfactory compaction uniformly across the pavement, while maintaining the shape and evenness of the surface.

- Pavement material should be compacted in lifts not exceeding 200 mm loose layer thickness.

- The minimum loose layer thickness of material to be compacted is 2½ the nominal stone size (ie for a 40 mm nominal size stone the minimum loose layer thickness should be 100 mm).
- Rolling should generally commence at the outer (lower) edge of the pavement and progress towards the centreline (or lower edge if super-elevated). Rolling with passes progressing towards the lower edge will cause material to move downhill and result in loss of shape.
- A forward and reverse pass is made over the same section of pavement before moving to the adjacent section. It is important to check that this is done at the edges of the pavement. When changing direction, the roller should be on the previously compacted section.
- Each pass of the roller should overlap by up to 500 mm the previous pass so as to ensure complete coverage.
- Where the outside edge of the pavement is unsupported and squeezes out excessively, rolling should commence 200 to 300 mm from the edge and the 200 to 300 mm strip rolled later.
- Vibrating rollers should have the vibrator turned off when the machine is stopping or manoeuvring.
- All rollers should change direction without jolting. Sharp turns of the roller or sudden changes in direction should be avoided. Such practices can cause surface roughness.
- Static drum rollers should have the drive wheels leading on the initial pass to avoid pushing material ahead of the drum.
- The number of passes required to achieve a particular level of compaction depends on the roller, the layer thickness and the material. From studies undertaken on base course gravels after eight passes, the gain achieved is only minor. If four to eight passes do not achieve the required result then something has to change – the layer thickness, roller type or moisture content.
- The best roller speed is usually at normal walking pace, that is 4–6 km/h.
- When using vibrating rollers, a sequence consisting of a non-vibrating initial pass, followed by several high amplitude passes and finishing with low amplitude passes, has been found to achieve good compaction and surface evenness.
- Depending on weather conditions, light sprinkling of the surface with water will be necessary during compaction.

A satisfactory rolling process should be established during initial trials and that process maintained during the balance of the work for each material source.

4. Stabilisation practices

Pavement stabilisation is usually employed in unsealed roads to reduce maintenance costs, improve base course material properties and to provide a better all-weather surface. By rectifying deficiencies in materials, stabilisation allows otherwise unsuitable materials to be used to advantage in road pavements.

Stabilisation has the benefit of improved surface condition through less dust, rutting, potholes and corrugating. In addition to reduced maintenance costs, vehicle-operating costs may also be reduced.

However, some forms of stabilisation may be inappropriate or too costly for use in unsealed road construction. Problems can arise from either the selection of a stabilisation method which is inappropriate for the local material and conditions, or the use of incorrect techniques in an appropriate application.

The principal factors to be considered when selecting the most suitable method of stabilisation are as follows:

- type of material to be stabilised
- proposed use of the stabilised material
- relative costs
- the capabilities and experience of the construction personnel
- the availability of testing facilities for investigations and subsequent quality control.

Cost is a particularly important factor in relation to unsealed roads. Stabilisation is, therefore, only worthy of consideration if it is economical when compared with all other alternatives. For unsealed roads, it is more likely to be justified at particular problem locations.

The correct use of stabilisation requires that the material property to be improved be clearly identified. The most important properties are:

- abrasion resistance
- permeability
- strength
- volume stability
- durability.

Most stabilisation treatments will have an effect on all these properties. Each property, however, is influenced to differing degrees by the various stabilisers, which must be selected for the optimum response with respect to the material type. Stabilisation is effected by either modifying the properties of a paving material or by a cementing action.

For materials stabilised by modification, increasing their strength is not a principal design objective. However, stabilisation with appropriate quantities of a cementitious agent will increase strength and stiffness, in some cases enabling a reduction in pavement thickness with respect to that used for unbound materials.

To illustrate the difference between the modification and cementation processes, the addition of lime to many clay fines reduces plasticity and indirectly controls the range of variation in strength. The total increase in strength is often of secondary importance. On the other hand, where sand is stabilised by cement or a bituminous agent, the particles are bound together, providing an appreciable increase in strength.

Usually only stabilisation by modification is suitable for the wearing course of unsealed roads where maintenance of the surface is by routine grading and periodic reshaping. Pavements which are stabilised by a cementing action cannot be maintained in this manner.

Volume stability is a problem associated with clays that swell and shrink with seasonal moisture changes. By altering the clay minerals, stabilisation (eg with lime) can make such materials less variable in volume.

When a paving material is unsurfaced (ie no wearing course), it should have resistance to abrasion or ravelling caused by vehicle tyres. Stabilisation, by the addition of more cohesive fines that provide a better bonding of the materials, may be used so as to reduce ravelling, increase skid resistance or reduce dust.

If a material has too high a permeability, softening of the pavement or the subgrade may occur due to water penetration, resulting in damage by traffic loading.

To achieve the required desirable properties of a stabilised material, a detailed knowledge of the materials used for construction and their reaction to various stabilising agents is essential.

4.1 Method of stabilisation

The most common methods of stabilisation used in road works include:

- mechanical stabilisation
- lime stabilisation
- cement stabilisation
- bituminous stabilisation including emulsions
- geotextiles
- chemical stabilisation.

Extreme climatic conditions can have an influence on the correct choice of stabiliser, inhibiting the use of some and encouraging the use of others irrespective of cost.

Mechanical stabilisation – with some precautions – may be used under any conditions. Lime stabilisation is more suitable for hot, wet regions and bitumen for hot, dry areas. Cement stabilisation, while having a broad application, may encounter difficulties in any of these extreme conditions. In all cases, due consideration must be given to the availability of plant etc, and increased costs should be justified by the benefits of the stabilisation technique selected.

For unsealed roads, stabilisation other than by mechanical means usually becomes too costly except in isolated problem sections. In such cases it is generally applied to the subgrade or sub-base. Further details on the effectiveness of various stabilisation methods can be found in ARRB (2000).

4.2 Mechanical stabilisation

Where materials with a suitable grading and/or plasticity are unavailable locally, mechanical stabilisation may be possible by mixing two or more selected materials in the proportions required, to modify particle size distribution and/or plasticity. Typical requirements for particle size distribution and plasticity are given in Section 3.3.3. Mixing can be carried out on site, for example using a motorgrader, prior to final shaping and compaction. The alternative is to use grid rollers or rock crushers on site to arrive at an appropriate mix.

A common application of mechanical stabilisation is the blending of a granular material lacking in fines with a sand-clay mix. This blending of materials has the potential to improve strength, abrasion resistance, imperviousness and compactability. The technique is sometimes used as a 'rejuvenating' operation when binding fines have been removed from the surface by the action of traffic and/or weather.

The following points should be observed in proportioning and blending mixtures:

- Avoid complicated ratios. Field equipment cannot be used to the degree of accuracy maintained in a laboratory.
- Correction of grading below 0.075 mm sieve size is not feasible due to difficulties in obtaining such mixtures in the field.
- Extensive checking is needed on site to ensure the adequacy of granulation and mixing operations.

Where naturally occurring materials are to be mixed it is important to control the quality of the materials being delivered to the site, as well as the mixing, to ensure optimum particle size distribution and plasticity. Quality control may be less difficult if at least one of the materials is a by-product from production processes (eg scalpings, crusher dust or over/undersized material from crusher run).

Static or portable vibrating screens can be employed to separate the material into appropriate sizes and gradings prior to delivery and mixing on site.

Laboratory testing of the material to be treated and the stabilising material is necessary to ensure the desired end result will be achieved.

Visual inspections give a guide to the suitability of materials for optimum proportions of mixtures to be achieved. The design of mechanically stabilised mixtures involves testing the individual materials, proportioning them to meet the selected criteria, and making up a trial mixture to check that the preferred proportions do indeed provide the desired qualities.

Specifications (plasticity, particle size, distribution etc) for mechanical stabilisation should take into consideration the type of natural material available and climatic (environmental) conditions.

4.3 Dust control and suppressants

Dust from unsealed roads contributes significantly to total air-borne particulates. It can degrade agricultural produce, be a problem to households, affect health, reduce road safety, increase wear and tear on vehicles, and result in an increase in the rate of roadway deterioration.

Dust is caused both by the loss of fine particles (less than 0.075 mm) from road surfaces arising from a loosening of the pavement materials, and by disturbance of the wearing course caused by the action of traffic and climatic conditions.

The effect of the loss of fines is to increase the permeability and weakness of the surface, resulting in early pavement deterioration and accelerating the need for resurfacing. Loss of fines also exposes a coarser textured surface, creating higher levels of irregularities which, in turn, increase vehicle operating costs. Loss of fines incurs replacement costs of pavement material with subsequent social and economic costs. As the proportion of fines increases in the pavement, so does the potential loss. Good maintenance plays a major role in controlling fines loss by dust and erosion.

The amount of dust generated from a pavement surface depends on various factors including wind speed at the road surface caused by vehicle numbers, type of vehicles, travel speeds, grading and restraint of fines, and climatic conditions.

Short-term or seasonal dust suppression may be effected by the application of dust palliatives to the road surface. Longer-term solutions involve either sealing the pavement, or using materials with optimum plasticity limits to achieve cohesion in the wearing course material, without affecting its strength and resistance to skidding.

Although the remedies for dust emission problems can be expensive, dust palliatives may provide an alternative short-term solution to sealing the road. Where dust is the principal cause of accidents or degradation of primary produce, the use of dust palliatives may be justified in terms of the benefits occurring from the reduction in accidents and loss in value of primary produce. Any long-term improvement to the dust problem, however, is likely to come from either sealing the pavement or, alternatively, upgrading the gravel surfacing materials to the specifications listed above.

Experience also showed that dust suppressants mixed into the road surface and then rejuvenated by surface sprays were more effective than those simply sprayed onto the surface. The required maintenance approach would also have to be adjusted, since blading a section that has a surface spray will destroy any benefit.

4.4 Dust palliatives

Many products have been tried and evaluated as dust palliatives. These aim to stabilise the road surface only, rather than the entire pavement. Some have proved ineffective, while others – such as petroleum products – may have adverse environmental effects if used excessively.

Dust palliatives act as surface stabilisers, providing stability to otherwise unstable surface materials. They have the following important properties that:

- prevent particles becoming airborne
- improve resistance to traffic wear
- are retained in the pavement, ie not lost through evaporation or leaching
- resist ageing
- are compatible with the environment
- are easily applied with common road maintenance equipment
- are workable and responsive to maintenance
- are cost competitive.

Application rates of dust palliatives will depend on a number of factors, including type of product, degree of dust control required, type of wearing surface, traffic volumes, types of vehicles and speeds, frequency and maintenance procedure and climatic conditions. Manufacturers' recommended application rates should be adopted along with any specific site requirements and application procedures.

General procedures for applying dust palliatives include the following:

- Remove surface defects and add gravel as required to provide the correct shape, superelevation, crown and compact surface.
- Dampen the surface, except when using non-emulsified petroleum products.
- Apply the dust palliative uniformly to the surface.

- Lightly compact using a rubber-tyred roller when dust palliative is chloride or lignin sulphonates.

Traffic may use the surface immediately following application of chlorides; however, other products require time to be absorbed before traffic should be allowed to use the road.

The use of dust palliatives is primarily intended for low-volume low-cost roads. The first consideration in the cost-effective use of dust palliatives is to select low-traffic-volume roads with properly designed and constructed pavements, as the performance of the dust palliative is directly related to the performance of the unsealed road upon which it is applied. The properties of the subgrade, base course and wearing surface greatly affect the performance of the dust control programme.

A study of dust control techniques, including a performance evaluation of numerous chemical dust suppressants (Foley et al. 1996), concluded that the dust control methods available fell into three main categories:

- good construction and maintenance practices as outlined in ARRB (2000) *Unsealed roads manual: Guidelines to good practice*
- use of mechanical stabilisation to form a good wearing course that forms a hard surface crust
- use of chemical dust suppressants as an adjunct (not replacement) to the above methods.

The sequence of consideration of remedies should follow the order given above, with possibly all methods being used to reduce dust emissions to a satisfactory level. It is considered of little value to use a chemical dust suppressant if some of the basic road building requirements are not first addressed.

Short of sealing a road, there are **no** known ways to eliminate dust emissions effectively on a long-term basis by using a single process, or just one application of a dust suppressant (Foley et al. 1996).

Benefits from dust control include extended periods between resurfacing, lowered levels of surface roughness and hence vehicle operating costs, reduced accidents, higher quality primary produce and an improved amenity for nearby residents. While dust palliatives have been used on roads carrying up to 500 veh/day, generally the life expectancy decreases as the traffic volume and the percentage of trucks increase. This is particularly so for products that create a hard surface crust, such as lignin sulphonates and most petroleum products. Consequently, economics will dictate the point where sealing becomes a more cost-effective treatment.

The selection of the type of dust palliative should be made bearing in mind the quantity of fines in the surface material or the subgrade (if there is no surfacing structure), climatic conditions and traffic volumes. As a general rule, total fines should range from 10 to 20%, to provide a dense compacted surface free from loose gravel. Figure 4.1 sets out guidelines for selecting dust control methods.

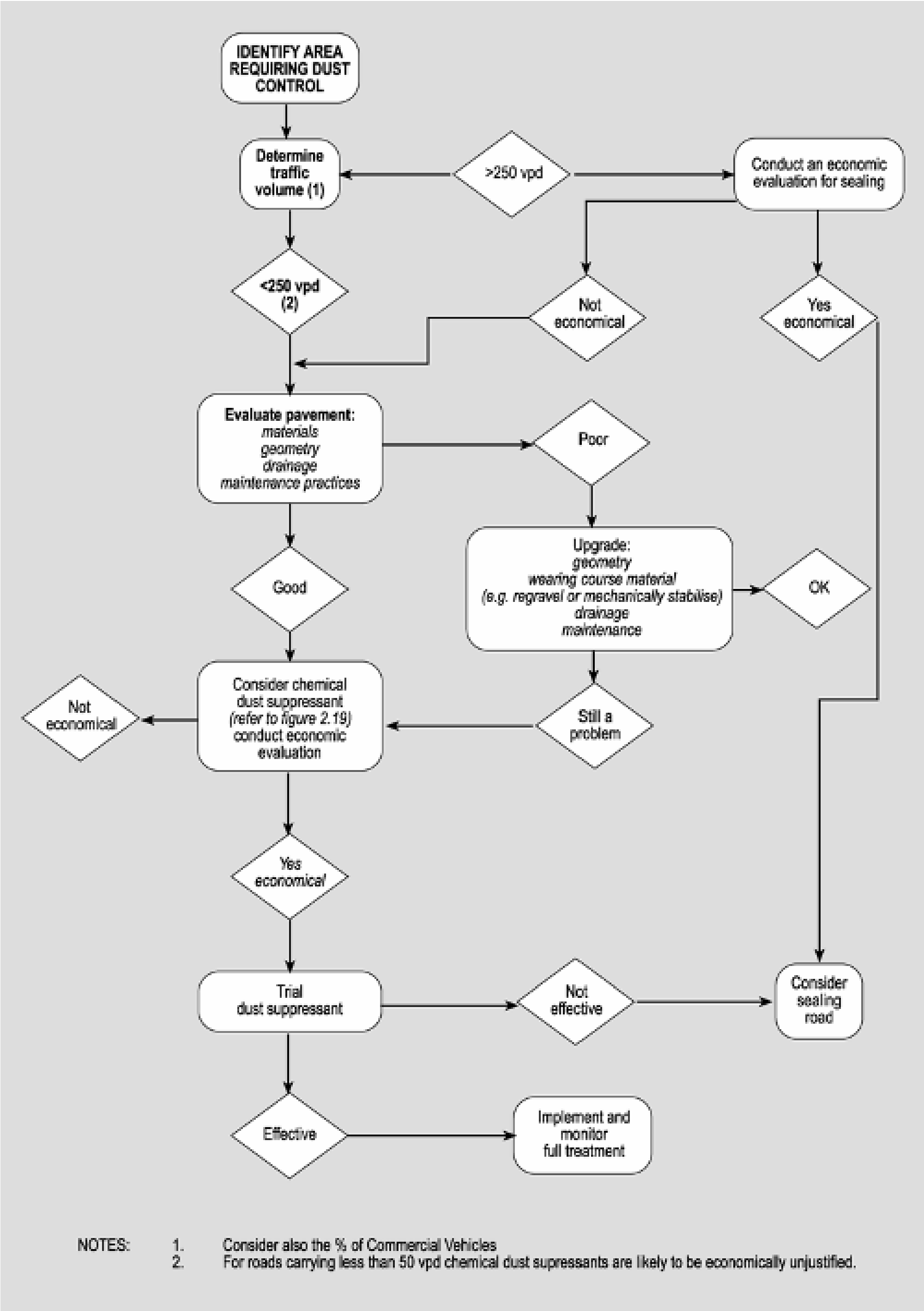


Figure 4.1 Guide to selection of dust control method (Source Foley 1996)

In selecting an appropriate dust suppressant product, two important factors to consider are climatic conditions and type of surface material.

4.5 Chemical dust suppressants

According to Foley (1996), most chemical dust suppressants are short-term bridging solutions and, short of sealing the road, there are no known ways to eliminate dust emissions efficiently. One particular problem is that most of the chemical additive suppliers have entered the market without recognised research.

The behaviour and performance of these additives are, in most cases, poorly understood, which has led to the application of some additives in the wrong locations (to inappropriate host materials), or under the wrong environment. According to Jones and Ventura (2003) these products are material and/or climate dependent, and the associated life-cycle cost may vary significantly. It is, therefore, important to investigate the performance under controlled experiments in order to understand the limitations and true life-cycle cost considerations.

There are some products that have been subjected to controlled tests – such as those undertaken in Southern Africa (Jones 1999) – and have performed well under the conditions they were designed for. Table 4.1 lists some of the generic additive products, with associated application potential.

Table 4.1 Summary of chemical additives and performance enhancing chemicals.

Category	Effect on unsealed material	Application
Dust palliatives		
Wetting agents (surfactants)	Surfactants reduce surface tension so moisture can wet particles. Due to the increased moisture, the binding with the soil improves. Natural water, detergents or soaps are typical wetting agents.	The action of surfactants is typically short term and they need to be applied regularly, even daily. Their use is limited and needs to be justified by special circumstances. Some applications may include mine haul roads and construction sites.
Salts/chlorides	Chlorides reduce the repulsive forces between soil particles by increasing moisture content. Chlorides typically draw moisture from the air due to their hydroscopic and deliquescent properties.	As the source of the moisture is the air, the underlying requirement for the effective working of these treatments is a relatively humid climate. None of the chlorides work in arid areas. Typically, calcium and magnesium require at least 30–40% humidity, while sodium ceases to be effective below 70% humidity (ARRB 2000). Consequently, sodium is used less frequently and it is less effective.
Natural polymers	They are based on lignosulfonate which is a by-product of the pulp milling industry. They act as a clay-dispersant, making the clay more plastic at low moisture content.	Polymers physically bind particles of the road material together. These products are highly soluble in water thus requiring re-application and could be an effective interim measure before a permanent surface is provided. Application areas include mine and forest haul roads. These products can be sprayed or mixed in during construction.

Category	Effect on unsealed material	Application
Modified waxes	Waxes are manufactured by the petrochemical industry. They act as a soil binder and can expel absorbed water from the soil and by doing so, the air voids decrease and compaction increases.	The performance is a function of road and ambient temperature. Above 35˚C, the wax softens and penetrates the road. Could be used in conjunction with calcium chloride and lignosulfonate to improve performance in wet weather
Petroleum resins	They usually are a blend of natural polymers and petroleum based additives. Some research has been conducted in the United States.	Has the potential as dust palliatives and stabilisers but cost is relatively high.
Bitumen and tar	Bitumen additives are often a by-product of the petrochemical and bitumen supplier's product line. Tar based applications are a by-product from the coal industry or synthetic fuel distillates.	Products are sprayed onto the road and in some cases blended with sand, which performs similarly to a sand seal, which can last for up to three years. Tar can perform similarly to the bitumen products but some countries ban the u e of tar products due to environmental and health concerns.
Compaction aids and stabilisers		
Synthetic polymer emulsions	Polymer dispersions are suspensions of synthetic polymers. Many formulations have been developed as soil 'conditioning' applications, which are potentially applicable for dust control and stabilisation of unsealed roads.	Most documented research originated from the agricultural industry. Limited research was done in road applications.
Bitumen and tar	See above	
Sulphonated oils	Consist of strongly acidic sulphur based organic mineral oils. These products were developed in the United States during the 1960s.	The stabilisation process is complex and material dependent. They have the ability to displace and replace exchange actions in clay and waterproof clay. They may also improve the soaked strength of high plasticity soils.
Enzymes and biological agents	Most of these product types will reduce the surface tension of water, thereby acting as a compaction aid. Some enzymes may result in a bond between particles due to crystallisation.	Little published material exists on the application of these material types.

Note: Based on Foley (1996) and Jones and Ventura (2003)

4.6 Reducing dust emissions

Dust control has major environmental, health safety and economic importance. Dust is caused by the loss of fine particles from the road surfacing due to traffic and environmental impact. The loss of fines increases the permeability of the surface and reduces the cohesion of the surfacing material at the same time. Reducing loss of fines increases the life of the surfacing, thus reducing maintenance demand.

Controlling dust will improve safety and comfort of the road users, reduce damage to the environment and improve socio-economic conditions. Reduced or no dust will allow higher speeds, thus improving transport efficiency. Dust is also a particular concern for certain farming areas. For example, dust can negatively affect the production of crop yield.

Short of sealing a road with a typically bituminous surfacing, there are no known ways to prevent dust emissions. For low-volume, low-cost roads carrying traffic volumes less than 250 vpd with about 10% commercial vehicles, sealing is often not economically feasible and less satisfactory methods must be used to help reduce the amount of dust emissions. Materials, haul distance, maintenance logistics, rainfall and gradient also affect this equation.

Good construction and maintenance practices are fundamental in providing for a longer life and appropriate level of service for an unsealed road. Provision of a crowned cross-section, well-graded materials, compaction and adequate drainage are all important in retaining a hard surface to reduce dust emissions. Existing roads that have a dust problem should first be checked to ensure the basic road building requirements are being met.

Mechanical or granular stabilisation involves the mixing of materials to ensure that locally available soils meet the requirements of a wearing surface, which has the correct grading and plasticity.

Mechanical stabilisation has proved over time that it can be used under various conditions as the road surface material can be readily reworked, whereas the chemical dust suppressants can leach out or break down over time.

Chemical dust suppressants should be considered as an adjunct to the other methods mentioned, if modifications by mechanical stabilisation cannot be achieved economically and high dust emissions persist. Under these circumstances a chemical dust suppressant may prove necessary.

Chemical dust suppressants have a limited ‘life’ and will require regular application to maintain a satisfactory control of dust emissions on a long-term basis. In such cases, careful attention must be given to whole-of-life costing, as other options involving the import of better quality road pavement materials – or even sealing a road – may become more cost effective.

5. Maintenance practices

The major task facing practitioners responsible for unsealed roads is the on-going maintenance – usually on very limited budgets.

Maintenance can be defined as those activities that are intended to retain the serviceability of a road, which may have deteriorated due to traffic and climate, at its original intended or as-built condition. However, as most unsealed roads have developed over time – probably originally from horse and cart tracks, with very little technical input to suit current motor vehicles – it is not surprising that maintaining roads to original conditions is not appropriate. Instead, to make better use of available maintenance funding, it may be necessary to try and correct the many design and construction features that go beyond just maintenance requirements.

This is why, in order to address the many maintenance requirements of unsealed roads, it is important to recognise that maintenance is only the outcome of the adequacy of the many components that make up a road. In other words, a road with little geometric design, poor use of local materials, and inadequate drainage and construction methods, will result in much greater maintenance demands than one designed in accordance with good practices. Therefore, in order to ensure that greater value is obtained from the limited funding available for maintenance, it is essential that deficiencies causing the problems are identified and remedied as resources become available, so that over time greater value is obtained from the funding allocated to maintenance.

Unsealed roads are, therefore, most susceptible to rapid deterioration as a result of loss of wearing course material and damage from water. Maintenance is carried out to ensure the safety of traffic, and to sustain the serviceability and appearance of the road.

Maintenance can vary from on-demand maintenance when a defect arises, to preventive maintenance which attempts to predict defects in advance of their occurring, and taking action to eliminate or reduce the occurrence or frequency of the defect.

Road maintenance involves remedying the relatively minor defects that occur in the roadway from time to time (routine maintenance), and providing substantial treatments such as re-gravelling, which rectify major defects and help retard the rate of deterioration (periodic maintenance).

Factors that have significant influences on gravel loss and can be reduced through improved maintenance practices include:

- drainage provisions
- wearing course specifications
- grading practices
- compaction requirements of the road surface.

Drainage: One of the most important aspects of road maintenance is protecting the road pavement from surface and ground water. Water penetrating the pavement weakens the structure, making the pavement more susceptible to damage by traffic. To reduce the adverse impact of water, the road must be regularly graded with a crossfall that effectively sheds surface water (4–6%). Further details are provided in Section 3.2.

Wearing course: The selection of suitable material for the pavement is essential if soft surfaces are to be avoided. Material containing a high percentage of fines may show signs of movement under the passage of vehicles. Materials with too much binder – even of good quality – should be avoided as these will tend to become slippery, potholed and soft when wet. On the other hand, too little binder will cause both wet and dry weather problems. In wet weather, absorption or penetration of moisture will be excessive and in dry weather the surface will ravel. Stabilisation can be used to overcome soft surfaces. Desired wearing course specifications are provided in Section 3.3.

Grading practices: Unsealed roads require regular grader maintenance, especially of the running surface, because of the effects of passing traffic and climate on an exposed aggregate surface. Maintenance is normally divided into routine and periodic maintenance.

Routine maintenance grading consists of light grading of the surface to keep the road surface in a good riding condition. It is often referred to as a smoothing operation and is usually done when aggregate and fines are moist. Smoothing can be done in dry weather to redistribute the loose gravel across the road, but the blade should not cut deep enough to disturb the hard crust (Figure 5.1). The risk in dry weather is that the redistributed loose material is not consolidated back into the road surface and traffic displaces this material to the side of the road or windrows, or into dust.

Figure 5.1 Periodic maintenance practice.

Periodic maintenance grading normally consists of both medium and heavy grading to restore the shape of the road, and is sometimes combined with re-gravelling operations.

Reshaping of the road involves more than just smoothing the surface. After periods of heavy traffic and wet weather, traffic will scatter the aggregate, flatten the crown, and make potholes and deep ruts in the road resulting in a rough surface. These conditions cannot be corrected by simply smoothing the surface – the gravel base needs to be reshaped.

Reshaping often involves scarifying the road surface and remixing the aggregate base to get a proper blend of fines and different sized aggregate, and blading this blended material into a properly crowned road surface with the required moisture content and compaction. This usually necessitates the use of watering and compaction equipment.

Compaction requirements: Lack of compaction, or water being allowed to enter the pavement, also contributes to soft surfaces. To obtain maximum compaction the material needs to be at optimum moisture content. The quality of binder in the material is crucial for an optimum performance. The most appropriate compaction equipment is the use of a multi-wheel roller (Figure 5.2). A simple field test can be applied to determine the optimum moisture content of the material. If the material is at the optimum moisture content, it will stick together when squeezed in the hand. If moisture runs out of the material it is too wet. If too dry it will lack cohesion. Details on optimum moisture content are covered in Section 3.4.

Figure 5.2 Multi-wheel roller.

6. Performance evaluation

6.1 Performance management

Performance management – a part of the overall requirement of an asset management system – is the method of obtaining, analysing and reporting information to indicate the adequacy of the pavement, roadside and safety features, and hence the works that are necessary for the road to fulfil its overall purpose. Performance indicators should incorporate structural adequacy, safety, defect identification and serviceability, ie the ability of a length of road to serve traffic in its existing condition.

A suggested format for establishing road performance criteria/defects to be monitored and intervention levels for a Class B unsealed road, is given in Table 6.1. This is only a guide, and each district will have to establish what are to be the key performance criteria and intervention levels, based on community expectations and available funding. Further details are available in Giummarra (2001a). Table 6.2 illustrates some performance standards adopted for Southland District Council. The table indicates the performance criteria plus standard response times the contractor has to rectify a defect. These response times are normally specified for different road classes, which are based on the traffic volume.

Table 6.1 Suggested maintenance intervention levels Class B road.

Class B – Secondary roads – unsealed				
Defect	**Intervention**	**Levels**	**Urgent maintenance**	**Typical action**
	Severity	**Extent (% /km)**	**(at isolated locations)**	
Rutting	depth > 70 mm	> 25	depth > 90 mm	medium/heavy grading
Loose material	depth > 50 mm	> 40	depth > 80 mm	reshape and compact
Corrugations	depth > 70 mm	> 35	depth > 90 mm	heavy grading and re shape
Drainage scours	depth > 70 mm	> 25	depth > 90 mm	reshape of cross falls 4–6%
Course texture/ride quality	NRM > 200 (envn. speeds < 70%)	> 45	NRM > 240 (envn. speed < 60%)	heavy grading and shaping
Potholes	potholes > 70 mm depth	> 40	potholes > 90 mm depth	restoration of crown and crossfalls
Gravel depth	< 50 mm	> 25	< 30 mm	re-gravelling
Table drain	Ponding > 150 mm	> 25	>250 mm	regrade
Batter clearing	Veg. > 500 mm	.>20	> 800 mm	slashing
Roadside vegetation	Veg. > 400 mm	> 20		
Culvert cleaning	Siltation > 200 mm	> 25	> 300 mm	clear out deposits

Table 6.2: Performance standards for unsealed roads (Southland Network Maintenance Contract – North Western Area. Contract no 05/02).

Contract standard	Road group	Response time	
		Cyclic	Notified
Surface defects			
No defect with a depth in excess of 75 mm	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
No more than 10 potholes over 200 mm dia and/ or 30 mm deep in any 500 m section of road	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Corrugations no more than 25 mm deep	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Smooth riding surface maintained in terms of comfort and roughness.	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Scours three metres long by 50 mm deep	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Longitudinal rutting 10 m long by 30 mm deep	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Loose windrows of aggregate between wheel tracks shall not exceed 50 mm in height	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Deep loose surface. Maximum: 50 mm deep over three metres of traffic lane	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
No soft areas or blowouts develop. Notified response time is time to get soft area repaired. Site shall be signed within one day of notification.	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
The wearing course does not wear out leaving the subgrade or sub-base exposed.	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days
Bound wearing course section maintained in bound, tight, compacted, smooth state.	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 day 5 days
Surface			
The maximum wearing course aggregate size is 25 mm	All	At all times	
All areas of roadway shed water	7 8 9	4 weeks 6 weeks 10 weeks	2 days 3 days 5 days

Performance management should be introduced into the unsealed road network in order to perform routine maintenance to a planned schedule and achieve greater efficiencies, rather than on the ad hoc or on-demand basis that is commonly used. If the value of the road asset is to be kept at a particular level, then some means of performance management are required to indicate the condition of the road network at a given point in time.

It must be understood that maintenance of unsealed roads is based on a dynamic situation in which road conditions can change significantly due mainly to climatic and traffic changes over a very short period of time.

Despite this difficulty, only by introducing an asset management system can an authority determine whether its maintenance practices are cost efficient and fully utilising the available maintenance resources to the best effect.

The basic steps involved are:

- establishing an inventory of the road assets
- monitoring the condition of the road network
- determining the maintenance effort required, based on adopted standards or intervention levels
- adopting appropriate deterioration models relating to gravel loss, ride quality and road crossfall change
- establishing a maintenance schedule – based on the above steps – taking into account priorities and available resources.

6.2 Performance monitoring

Monitoring the condition of the road network will cost money, so a manager must decide which is the most cost-effective method for the network.

Road condition data collected over a period can be used to determine the following:

- the present state of the network with respect to a desired standard(s)
- the maintenance resources required to maintain the network at the desired standard
- whether present grading and re-gravelling programs are cost efficient
- the efficiency and effectiveness of various maintenance activities.

Performance monitoring is undertaken in two instances that are described in more detail in the subsequent sections.

6.2.1 Routine monitoring

Given the rapidly changing nature of unsealed roads, regular monitoring programmes are undertaken in order to assess the effectiveness of routine maintenance. This monitoring could even be undertaken as part of contractual obligations, in order to monitor performance standards specified on a contract. Depending on the management contract, these monitoring programmes may be part of either the council's responsibility or that of the contractor.

The main purpose of the routine monitoring would be to assist with the operational planning of maintenance and blading crews. The degree of official reporting from these monitoring programmes varies, but in most cases recording this information in an official system is extremely useful in the analysis of the overall network performance.

6.2.2 Annual or bi-annual monitoring for asset management purposes

The annual or bi-annual monitoring of the entire unsealed road network is less frequently undertaken by authorities in New Zealand. This practice is, however, commonly found in other parts of the world such as South Africa. The purpose of this monitoring is to be able to have a snapshot of the condition of the entire network for comparison purposes between years. From this monitoring the asset management process could value the investment levels into the network, including re-gravelling and seal extension programmes. At a minimum, this monitoring should record some of the visual performance items noted in Table 6.2.

6.2.3 Data requirements for unsealed roads

Based on findings from Part B of this report, the minimum data requirements for unsealed roads in New Zealand include:

- a full inventory of unsealed roads that includes longitudinal and cross dimensions
- a full record of the material that is placed on the road – for the links to a given borrow pit, laboratory tests are sufficient
- classified counts of traffic that indicate the split between light and heavy vehicles
- annual monitoring performance data – (a visual assessment is sufficient, but any automated measurements are desirable).

7. Summary

Reducing gravel loss can have significant benefits, not only in lowering maintenance costs, but by placing less demand on winning gravel, reducing dust emissions, lowering surface ravelling, and improving ride qualities and road safety.

While the gravel loss model is based on existing management practices, it is important that practitioners apply latest scientific practices relating to all aspects of unsealed road management, in order to ensure that gravel loss is minimised.

The primary purpose of these notes is to provide practical guidelines on how best to handle the various factors contributing to gravel loss. Addressing some or all of these aspects will lead to a considerable reduction in gravel loss and, in time, the deterioration models can be calibrated to reflect the application of best practices.

Attention has to be given to a wide range of engineering practices (listed below) to ensure gravel loss is kept to a minimum:

- road geometry
- drainage
- pavement design and materials
- maintenance practices
- stabilisation practices
- performance evaluations.

Part B: Gravel loss experiment

8. Literature review

8.1 Gravel road deterioration models

A number of well-used gravel road deterioration models were reviewed during the literature review. The purpose of this review was to consider their formats and the variables used in them. The models were also reviewed in terms of their practicality concerning the required data needs.

Table 8.1 (Henning et al. 2005) presents a brief summary of the studies included in this literature review. The table indicates the objectives of the research, the design matrix for the experiment, and input variables such as traffic, material, and climate. Lastly, it also presents the main outcomes from the respective studies. The following sections deal with the resulting models from the respective studies in more detail.

8.1.1 An evaluation of unpaved road performance and maintenance (Visser 1981)

8.1.1.1 Roughness

Roughness predictions of unsealed roads are complex in nature, due to significant changes during seasons and will largely depend on the blading cycle adopted for a given road section. In his study, Visser (1981) considered two model formats for predicting roughness. He investigated a general linear model (GLM) and logit model. In his discussions, he recommended the GLM model for general use. The models give different roughness progressions for the wet and dry seasons, as indicted in Figure 8.1.

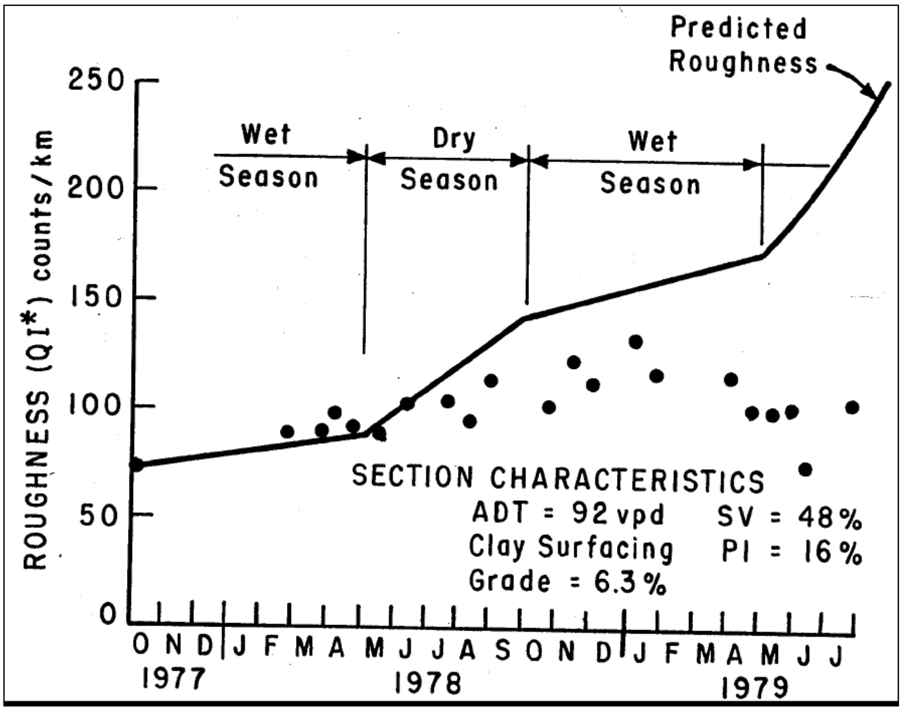


Figure 8.1 Illustration of predicted and actual roughness for a section that has not been bladed (Visser 1981).

The resulting GLM model is:

$$LDQ = D\begin{bmatrix} 0.4314 - 0.1705\times T_2 + 0.001159\times NC + 0.000895\times NT - \\ 0.000227\times NT\times G + S\begin{pmatrix} -0.1442 - 0.0198\times G + 0.00621\times SV - \\ 0.0142\times PI - 0.000617\times NC \end{pmatrix} \end{bmatrix}$$

Equation 8.1

Where
- LDQ is the change in log (roughness) in QI – counts/km
- D number of days since last blading in hundreds (days/100)
- T_2 surface type factor (1 if surfacing is clay, 0 otherwise)
- NC average daily light vehicles in both directions
- NT average heavy vehicle traffic in both directions
- G absolute grade in percentage
- S seasonal factor (S=0 for dry season and 1 for wet season)
- SV percentage of surface material passing the 0.074 mm sieve
- PI plasticity index of surfacing material (%).

8.1.1.2 Predicting rut depth

Visser (1981) also developed a model to predict the progression of rut depth on unsealed roads. This model was of particular interest to this study, as re-gravelling not only addresses gravel loss, but also loss of shape. It was also noted that the rut was not completely removed during the blading, but that some residual rut depth remained following a blading cycle. For the purposes of this study, only the rut progression model is included.

The rut depth model is:

$$DRD = D\begin{pmatrix} 9.85 - 1.03\times G - 0.21\times PI - 3.20\times T2 + 0.344\times NC + \\ 0.0081\times NT - 3.26\times RO - 3.23\left(\dfrac{NT}{R}\right) + 0.45\times G\times RO - \\ -287.6\left(\dfrac{L}{R}\right) + 0.0362\times L\times SV + 0.0487\times NT\times M1 + \\ 0.176\times NT\times M2 + S1\begin{pmatrix} -89.50 + 4.67\times G - 0.140\times NC + \\ 0.098\times NT + 6.463\times W \end{pmatrix} - \\ 0.0417\times S2 \end{pmatrix}$$

Equation 8.2

Where
- DRD is the change in rut depth in mm
- D number of days since last blading in hundreds (days/100)
- T_2 surface type factor (1 if surfacing is clay, 0 if otherwise)
- NC average daily light vehicles in both directions
- NT average heavy vehicle traffic in both directions
- G absolute grade in percentage
- S seasonal factor (S=0 for dry season and 1 for wet season)
- SV percentage of surface material passing the 0.074 mm sieve
- PI plasticity index of surfacing material (%)
- RO wheel path factor (RO=0 outer wheel path, RO=1 for inner wheelpath)
- L lane factor (L=0 for uphill and L=1 for downhill)
- W road width in m
- M1 maintenance frequency factor (M1=1 for fortnightly blading, 0 for otherwise
- M2 maintenance frequency factor (M2=1 for six weekly blading, 0 for otherwise.

8.1.1.3 Gravel loss

It was noted that the previous models presented had many independent variables and in some cases were relatively complex. Contrary to this, the gravel loss model is much simpler, with less dependant variables. The gravel loss model from Visser (1981) is:

$$GL = D\begin{pmatrix} 1.58 + 0.366\times G + 0.083\times SV - 0.210\times PI + \\ 0.0132\times NC + 0.0081\times NT + \dfrac{420.45}{R} \end{pmatrix}$$

Equation 8.3

Where
- GL is the gravel loss in mm
- D number of days since last blading in hundreds (days/100)
- NC average daily light vehicles in both directions
- NT average heavy vehicle traffic in both directions

G	absolute grade in percentage
SV	percent of surface material passing the 0.074 mm sieve
PI	plasticity index of surfacing material (%)
R	radius of horizontal curve.

Table 8.1 Summary of long-term pavement performance studies for unsealed roads (Henning et al. 2005).

			Study details				
Researcher	**Country**	**Study main objectives**	**Design matrix**	**Traffic range**	**Climate / rainfall**	**Material**	**Outcomes / status**
Visser (1981) and Paterson (1987)	Brazil	Development of deterioration relationships for unpaved roads and to evaluate different maintenance practices in a system analysis. This study and subsequent analysis by Paterson resulted in the unpaved road deterioration models as published for HDM-III.	The original study consisted of 48 sections. Design matrix factors: Surface material, traffic, vertical and horizontal alignment.	11 to 288 passenger car and 1 to 435 two axle trucks per day.	Rainfall – 1200 to 2000 mm/year Climate being classified between moist sub-humid to humid.	Laterite and Quartzite. Some earth roads (without wearing course) were also monitored.	Unsealed road deterioration models adopted in HDM-III and HDM-4 including: • roughness • material loss • passibility • rutting (not adopted in HDM).
Paige-Green (1989)	South Africa and Namibia	To develop performance-related specifications for gravel wearing courses. To develop unsealed road deterioration relationship for Southern Africa.	A total of 110 sections. Design matrix factors: Surface material, traffic, Weinert N-value.	Total traffic between 18 to 608 per day.	Rainfall – 300–1100 mm/yr. Dry arid to moist humid.	Acid and basic crystalline, high silica, arenaceous, argillaceous, pedocretes.	Performance related specification. Unsealed road deterioration models including: • roughness • material loss.
Giummarra (2001b, 2007)	Australia – Tasmania	To evaluate the performance of four different running surfaces as a function of maintaining the hard crust, minimising wear,	A single road of 2.7 km was divided into 300 m test sections in order to trial different treatment options.	A single traffic volume was used for the full experiment – ADT = 83.	Temperate climate. 1400–1600 mm/year.	Treatment A – applying current practices and served as the control section. Treatment B –	Demonstrated the different performance outcomes from each surface material in relation to: • roughness

			Study details				
Researcher	**Country**	**Study main objectives**	**Design matrix**	**Traffic range**	**Climate / rainfall**	**Material**	**Outcomes / status**
		ravelling and dust.				existing material with added clay. Treatment C – existing material with an overlay specially mixed wearing course (gravel clay mix). Treatment D – existing material with an overlay of specially mixed wearing course (oily scale material).	• gravel loss • loss of shape. In addition a cost effectiveness comparison was performed on each alternative.

8.1.2 World Bank HDM-III gravel loss models (Paterson, 1987)

Paterson (1987) describes the development of unsealed roads completed for adoption in the World Bank HDM-III and later in the HDM-4 models.

The primary principle behind these models (presented in subsequent sections) is based mainly on the material properties presented below:

$$MG = MIN(MGM, 1 - MGM, 0.36)$$ **Equation 8.4**

$$MGM = \frac{MG075 + MG525 + MG020}{3}$$ **Equation 8.5**

$$MG075 = \frac{LN(P075/95)}{LN(0.075/D95)}$$ If D95 > 0.4 **Equation 8.6**

MG075 = 0.3 otherwise

$$MG425 = \frac{LN(P425/95)}{LN(0.425/D95)}$$ If D95 > 1.0 **Equation 8.7**

MG425 = 0.3 otherwise

$$MG020 = \frac{LN(P020/95)}{LN(2.0/D95)}$$ If D95 > 4.0 **Equation 8.8**

MG020 = MG425 otherwise

Where MG is the slope of mean gradation
P075 percentage passing a 0.075 mm sieve
P425 percentage passing a 0.425 mm sieve
P020 percentage passing a 2.0 mm sieve
D95 maximum particle size in mm.

The dust ratio is given by:

MGD = P075/P425 if P425 > 0 **Equation 8.9**

MGD = 1 otherwise

8.1.2.1 Roughness

The roughness progression is provided for three cases, namely:

- minimum roughness
- maximum roughness
- average roughness.

The average annual roughness is given by:

$$IRIAV = \frac{IRI_{MAX} + (0.447 - 0.230 \times MGD)(1 - EXP(C \times BLFQ))(IRI_{MAX} - IRI_{MIN})}{(1 - (0.553 + 0.230 \times MGD)EXP(C \times BLFQ)) \times C \times BLFQ}$$

Equation 8.10

With

$$C = -0.001(0.461 + 0.0174 \times ADL + 0.0114 \times ADH - 0.0287 \times ADT \times MMP)$$

Where	IRIAV	is the annual average IRI in m/km
	BLFQ	grading interval in days
	ADT	annual average daily traffic
	ADL	annual average daily light traffic
	ADH	annual average heavy traffic.

8.1.2.2 Gravel loss

The annual loss of surfacing material is given by:

$$MLA = 3.65 \times (3.46 + 0.246 \times MM \times PRF + MAX[0,0.022 + \frac{0.969 \times C}{57300} + 0.00342 \times P075 - 0.0092 \times MMP \times PI - 0.101 \times MMP])$$

Equation 8.11

Where	MLA	is the annual material loss in mm
	PI	is the plasticity index
	MMP	is the mean monthly precipitation
	C	is the average horizontal curvature of the road (deg/km).

8.1.3 The influence of geotechnical properties on the performance of gravel wearing course materials (Paige-Green 1989)

Paige-Green (1989) developed unsealed roads models based on road sections established in South Africa and Namibia. The findings on his models for roughness and gravel loss are presented in the following sections.

8.1.3.1 Roughness prediction

The resulting model for the roughness is given by:

$$LnR = D \times \begin{bmatrix} -13.8 + 0.00022 \times PF + 0.064 \times S1 + 0.137 \times P26 + \\ 0.003 \times N \times ADT + GM \times (6.42 - 0.063 \times P26) \end{bmatrix}$$

Equation 8.12

Where	N	is Weinert N-value (climatic region)
	ADT	annual daily traffic
	PF	plastic factor
	P26	percentage passing a 26.5 mm sieve
	S1	Seasonal factor (1 for dry season and 0 for wet season).

8.1.3.2 Gravel loss

The resulting gravel loss model is given by:

$$GL = D \times \begin{bmatrix} ADT \times (0.059 + 0.0027 \times N - 0.006 \times P26) - \\ 0.367 \times N - 0.0014 \times PF + 0.0474 \times P26 \end{bmatrix}$$ **Equation 8.13**

Where	N	is Weinert N-value (climatic region)
	ADT	annual daily traffic
	PF	plastic factor
	P26	percentage passing a 26.5 mm sieve.

8.1.4 Establishing deterioration models for local roads in Australia (Giummarra et al. 2007)

Based on long-term pavement performance studies (LTPP) in Australia, Giummarra et al. (2007) has developed three models including:

- gravel loss
- roughness
- crossfall (loss of shape).

These models are presented in the following sections.

8.1.4.1 Roughness model

The resulting roughness model is given by:

$$\mathrm{IRI_{TG2}} = \mathrm{IRI_{max}} - \exp\{[-0.001 \times (F0 + F1 \times ADL + F2 \times ADT \times MMP/1000)] \times (TG2 - TG1)\} \times (\mathrm{IRI_{max}} - \mathrm{IRI_{TG1}})$$ **Equation 8.14**

Where:

IRITG1	is the roughness at time TG1, in m/km IRI
IRITG2	roughness at time TG2, in m/km IRI
IRImax	maximum allowable roughness for specified material, m/km IRI
TG1, TG2	time elapsed since latest grading, in days
ADL	average daily light traffic (GVW < 3500kg) in both directions, in vehicle/day
ADT	average daily vehicular traffic in both directions, in vehicle/day
MMP	mean monthly precipitation, in mm/month
F0, F1 & F2	model coefficients.

8.1.4.2 Gravel loss model

The resulting gravel loss model is given by:

$$GL = D \times (F1 \times ADT + F2 \times MMP + F3 \times PF)$$

Equation 8.15

Where:

GL	is the average gravel thickness loss (mm) across roadway
D	time period in hundreds of days (days/100)
ADT	average daily vehicular traffic in both directions, in vehicle/day
MMP	mean monthly precipitation, in mm/month
PF	plasticity factor (PI × P075)
P075	amount of material passing the 0.075 mm sieve, in percentage by mass
PI	plasticity index
F1 to F3	model coefficients.

8.1.4.3 Crossfall (loss of shape)

The change in cross-fall is given by:

$$SL = F0 + F1 \times ADT + F2 \times P075$$

Equation 8.16

Where:

SL	shape loss, ie percentage (%) change in crossfall per year
ADT	average daily vehicular traffic in both directions, in vehicle/day
P075	amount of material passing the 0.075 mm sieve, in percentage by mass
F0 to F3	model coefficients.

8.1.5 Model discussion

Based on the literature review, a number of observations were found to be pertinent from the models developed to date. The items of specific interest to this study are discussed in following sections.

8.1.5.1 Types of models to adopt

In all cases, the most complex models were the **roughness models**. This complexity resulted in all the models being dependent on a large number of data items. The value of adopting roughness models should be viewed from a perspective of data requirements, plus the ultimate use of the model. In most cases, the roughness model is an input into the following criteria within the management of unsealed roads:

- It gives an input into the determination of the optimal blading cycles.
- It can be used in the economic/financial analysis to upgrade unsealed roads to surfaced roads. For example, roughness is a primary driver in the HDM-4 models (see Section 8.1.2 and Henning et al 2005).

- It may indicate unacceptable performance of a given material, thus suggesting a re-gravelling need.

The New Zealand gravel loss trial excluded roughness measurements for the following reasons (see Fawcett et al 2001 and Furlong et al 2003):

- Roughness is not a common item collected on New Zealand unsealed roads.
- Blading frequencies are determined from standard processes that include responses to community complaints systems and in-house experience of blading requirements per material type and road class.
- A survey among network managers suggested that they were satisfied with current processes to determine blading frequencies and would not require a roughness model to assist in this regard.

Rightly or wrongly, the decision was made not to develop roughness models for New Zealand. Ultimately, modelling roughness would require considerable data collection for little gain in terms of efficiencies in the unsealed asset management process.

On the contrary, there is a great need for **gravel loss models** in New Zealand. The current long-term community consultation planning process (LTCCP) requires forecasted maintenance expenditure for a 10-year period. Although the estimate for annual blading is relatively simple to calculate, the re-gravelling is more complex, especially for those who are unfamiliar with a particular region. In addition to that, gravel loss is a more costly maintenance activity compared with blading thus increasing its importance. Better guidance is required and this includes having typical gravel loss functions available.

Loss of shape

This is an additional parameter that influences the decision to re-gravel roads (see Part A of this report). Some literature investigated had various formats either of indicated shape loss through the prediction of crossfall (Giummarra 2007), or through the prediction of rutting (Visser 1981). It was, therefore, considered important to develop a similar predictor for the New Zealand application.

8.1.5.2 Accuracy of models

The changing nature of gravel roads affects the predictability of the defects significantly. It is thus expected that gravel loss models will have a significant variability and consequently relatively low regression coefficients. The literature confirmed low predictability in findings with R^2 ranging from 0.2 to 0.6 for the gravel loss models. The factors that influenced the correlation included:

- the survey accuracy and frequency of measurements
- the number of variables included in the model. For the studies investigated, there was a relationship indicating that a higher number of variables resulted in higher R^2 values

- the model format adopted. Model formats varied between linear models, general linear models, exponential and logit models. It seemed that some alternative model formats yielded higher correlation.

With the New Zealand data collection frequency (see Section 9), it was anticipated that the model correlations would be relatively low and that the long survey frequency and inconsistent survey team (different councils) would remain limitations of this study.

8.1.5.3 Variables included to the models

The variables used in the respective models were vastly different. However, it was considered a useful review to steer the model development reported in this study. The variables are discussed in more detail in following sections.

8.2 Climatic description

All the models discussed in the previous sections contain variables describing the climatic factor. In most cases, the climatic factor will directly refer to the rainfall expressed in mean monthly precipitation. However, Paige-Green uses the Weinert N value, which takes account of the geological region in combination with the rainfall. Options considered for this study are presented in Table 8.2.

Table 8.2 Moisture index approaches.

Index	Description	Relevance to NZ
MMP	Mean monthly precipitation (MMP) is standard rainfall data that is readily available.	Directly relevant to New Zealand through NIWA records.
Weinert N value (Weinert, 1980)	Considered total rainfall figures, seasonal variation of rainfall in combination with potential evaporation. Further research classified soil behaviour as a function of the Weinert N value.	Developed in South Africa and may not be directly applicable to New Zealand.
Thornthwaite Index	Is a function of the rainfall and the monthly temperature.	This index is widely used in Australia and New Zealand.
Ratio of moisture/ wet soil strength (Cenek 2001)	In essence, this ratio gives the ratio between soil strength and moisture. It could be used as an indicator of soil sensitivity to moisture.	It was developed and used in the New Zealand LTPP Programme for sealed roads.

All the various methods have been noted and will form part of the analysis process discussed in later sections.

8.3 Defining the shape of unsealed roads

The only reference found on model loss of shape was the work completed by Giummarra (2007). Figure 8.2 illustrates the method that they have used to measure the profile on an annual basis. The loss of shape (crossfall) was then determined as a percentage of the original slope.

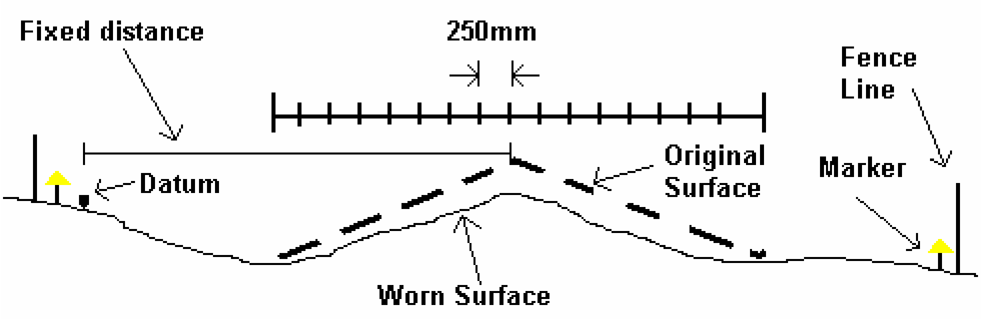


Figure 8.2 Unsealed roads measurement system for transverse profile (Guimmarra et al. 2007).

Merely considering the slope would not completely address the 'unevenness' of the road profile in a transverse direction. Other defects, such as rutting and loose material, would not be captured through the measurement of the slope. More research was undertaken to investigate alternative methods of describing the shape of unsealed roads, but none were found. It was recommended that this study should investigate potential measures to define the shape of the road as a function of crossfall, as well as look at unevenness of the surface.

8.4 Recommendations from the literature review

The literature review was extremely useful in setting the road map for this study. Only the model developments were discussed, since Part A covers most other items related to the construction and maintenance of unsealed roads. Recommendations resulting from the literature review include:

Models to develop:

- A roughness model is not a requirement on New Zealand unsealed roads at present.
- There is a great need for gravel loss models.
- In addition to the gravel loss, a shape loss model is required.

Part of the model development would also require special consideration of the climatic definition and the development of a shape index.

9. Experimental layout of the New Zealand gravel loss study

9.1 Experimental design

Planning for the New Zealand gravel loss experiment started in November 2001, with the site establishment and surveys commencing during February 2002. The experimental design matrix included three traffic levels and two road categories depending on grade or material difference. The latter categorisation was chosen by the authority based on the most significant factor within their area. Table 9.1 presents the detail categorisation used for the experimental design.

Table 9.1 Design matrix for the New Zealand gravel loss experiment (Fawcett et al. 2001).

Key attribute	**Description**
1. Traffic	
Low	Between 10 and 40 LVE
Medium	Between 80 and 120 LVE
High	Greater than 160 LVE
+ either	
2. Vertical grade	
Flat	0–1 %
Steep	> 6–8 %
or	
3. Material	
Type 1 eg Flood plain alluvial	Description, eg greywacke/quartz sandy gravels sourced from lower flood plain areas – generally clean with little silt
Type 2 eg Oreti Mataura	Description, eg 'Muruhiku Rocks', hard – moderately hard siltstone/sandstones with minor tuff (volcanic ashfall deposits)

Note: LVE is the light vehicle equivalent (Fawcett et al. 2001).

In addition to the above, the experiment aimed to establish gravel loss trials across New Zealand, thus incorporating all the climatic areas. Henning et al. (2004) found that New Zealand could be classified into four climatic areas if the rainfall, evaporation and CBR (Californian bearing ratio) were used as classification factors. Assuming that this classification was also applicable to unsealed, the resulting design matrix consisted of 24 (4*3*2) cells. Ultimately, a total number of 51 sections were established, thereby doubling the total number of sections required by the design matrix. However, given the variability of gravel road performance, it was necessary to follow a conservative approach in the site establishment.

9.2 Available data

9.2.1 Site make-up and gravel loss surveys

Each site was 60 m long and was surveyed in a grid pattern as displayed in Figure 9.1.

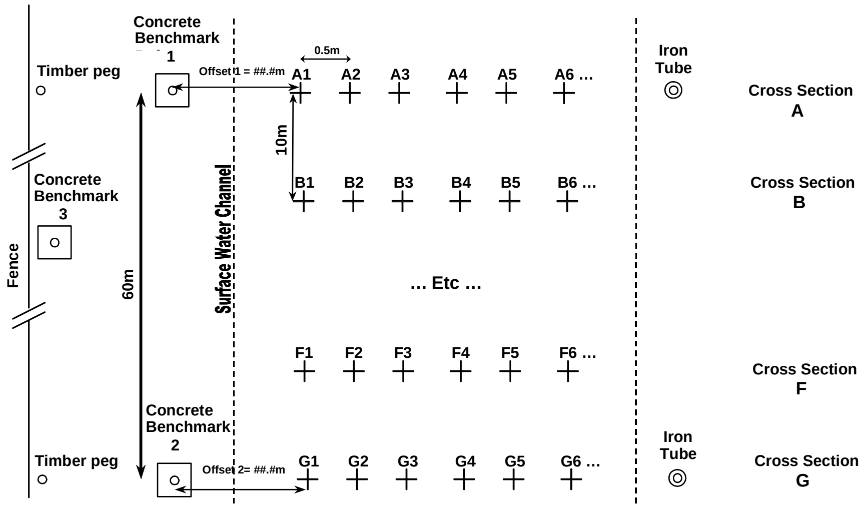


Figure 9.1 Layout of grid survey (Fawcett, et al 2001).

The surveys, therefore, resulted in measuring a total of seven cross sections, with each cross section consisting of a height measurement interval of 0.5 m. The gravel loss surveys were undertaken at six-monthly periods and a total of seven surveys were included in the analysis presented in this report.

Figure 9.2 Cross sections of surveys taken over seven surveys.

Figure 9.2 illustrates a typical output from the cross-sections for seven measurements taken in one location.

9.2.2 Data items

The data collected and available for the analysis can be grouped into the following categories (a full list of the data items used in this study is depicted in Appendix B):

- gravel loss or grid surveys
- rainfall and evaporation data sourced from NIWA
- material properties from laboratory tests
- traffic
- maintenance records.

10. Statistics of the gravel loss study

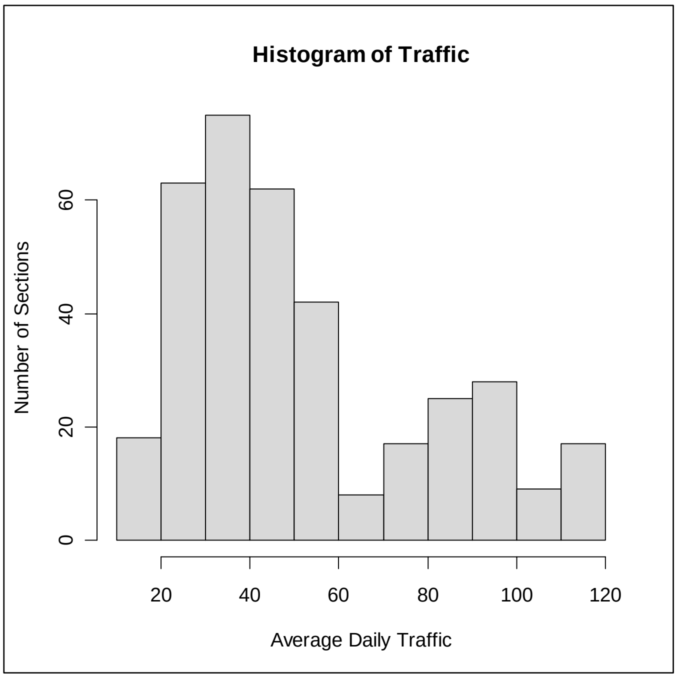
10.1 Descriptive statistics

The purpose of reviewing the descriptive statistics was to gain a better understanding of the data set. This understanding was then used to steer the research team during the model development presented later. Another reason for reviewing the descriptive statistics was to validate the data and to ensure any erroneous data was identified.

Appendix B contains descriptive statistics of all the data items, while this section graphically explores some of the items in more detail. Most of the data items seem to be in relatively good order. Note that there was an intensive data validation process prior to the analysis. The only concern raised related to some of the laboratory tests. For example, the percentage particles greater than 0.075 mm contained some values greater than 100%. These values were excluded from further analysis.

10.2 Traffic

The histogram of the traffic distribution on the sections is depicted in Figure 10.1. The traffic volumes in the sample are relatively low, with most being between less than 50 vehicles and a maximum of 100 vehicles per day.



Note: x-axes is limited to 120 vehicles

Figure 10.1 Traffic (all classes) distribution

Low traffic on gravel roads is typical for New Zealand roads as most authorities have very active seal extension programmes to upgrade unsealed to sealed roads. Figure 10.2 shows the distribution of light vehicles on the sections where it can be seen that most of the traffic consists of light vehicles. This highlights a potential gap in the data and any outputs containing heavy vehicles should be dealt with caution.

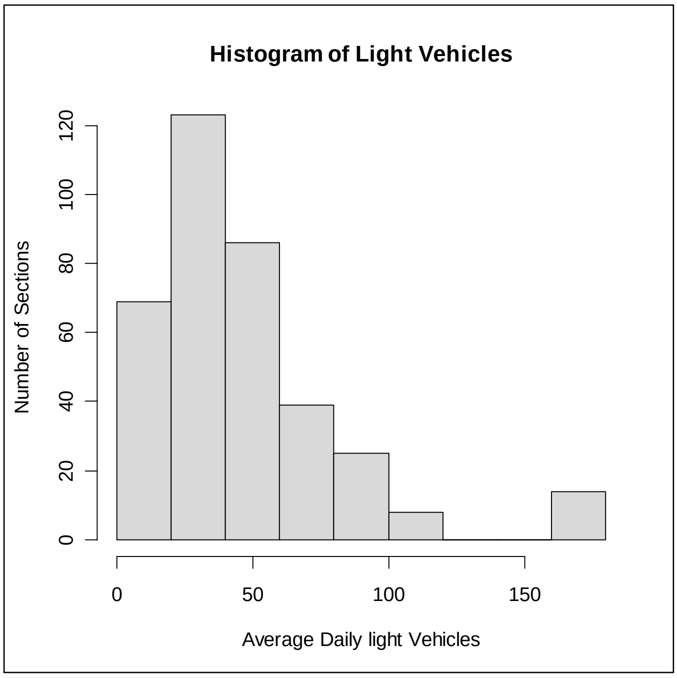


Figure 10.2 Light vehicle distribution.

10.3 Blading

As indicated in the literature review, any trends from gravel roads are a strong function of periodic maintenance, especially the blading cycles. It is further realised that the blading may be masking some of the independent variables used in predicting gravel or shape loss. For example, gravel roads in a certain rainfall area may lose their shape more quickly, suggesting a higher blading cycle, but a higher blading frequency does not necessarily suggest high shape loss rates. This section presents some plots between blading cycles and independent variables. Figure 10.3 presents the distribution of blading cycles for the data sample. It can be seen that most sections have a blading cycle of less than six blades between surveys (approximately monthly blading).

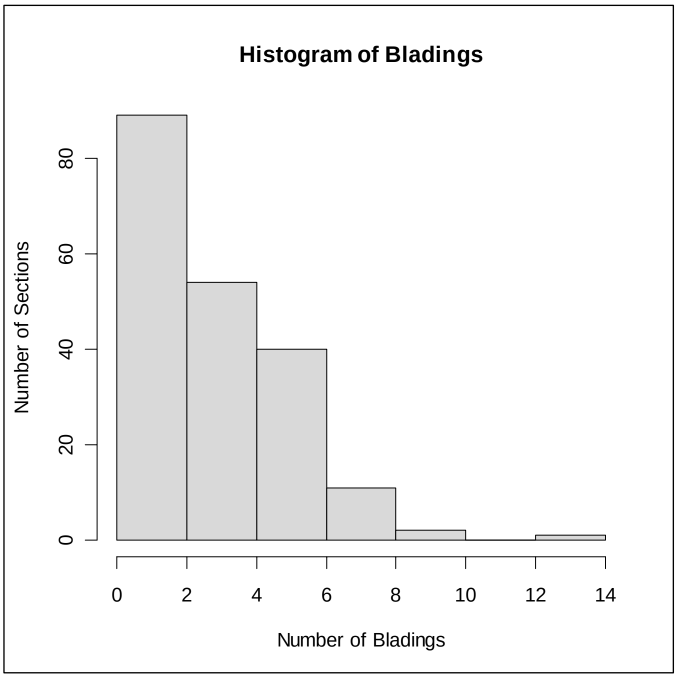


Figure 10.3 Distribution of bladings between surveys

Figure 10.4 depicts the blading cycle as a function of rainfall and large particle percentage. The negative relationship between rainfall and blading frequency suggests that higher rainfall areas generally require less blading. There is a positive relationship between the blading frequencies and particle size. An increase in particle size will result in a rougher surface, thus requiring frequent blading.

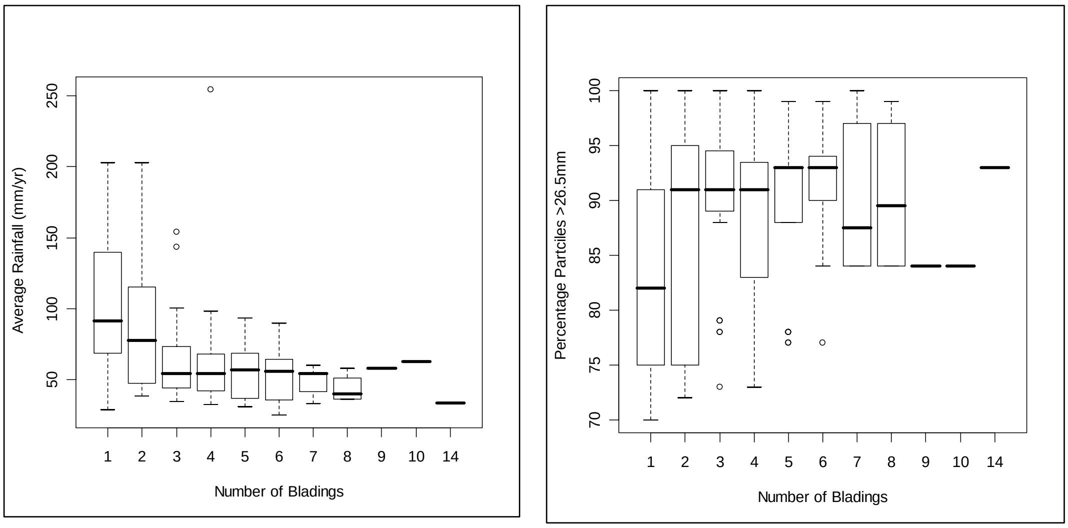


Figure 10.4 Number of bladings as a function of average rainfall (left plot) and percentage particles >26.5 mm (right plot).

Figure 10.5 illustrates the difference in blading cycles for given traffic (AADT). The relationship between traffic volume and blading cycles provides an opposite trend from what would be expected. It can be seen there is a negative trend between the traffic volume and blading cycles, suggesting that busier roads require less blading.

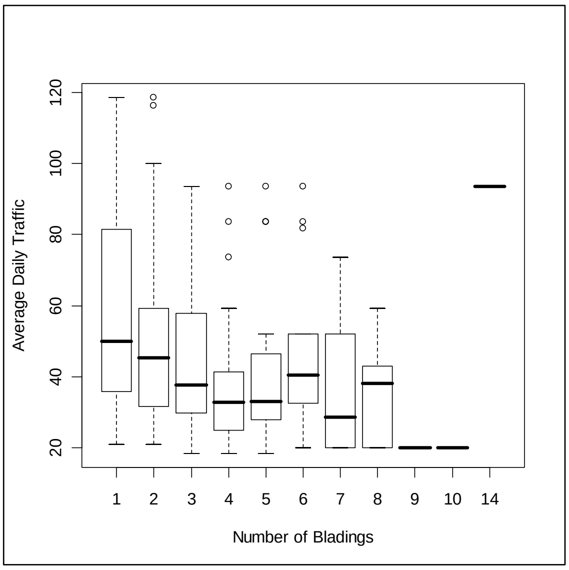


Figure 10.5: Number of bladings as a function of daily traffic.

The observations from this section suggest that for the sampled roads, blading cycles would be a function of climatic factors, material performance or socio-political considerations.

11. Gravel loss

11.1 Definition of gravel loss

There are a number of methods to describe the gravel loss quantity, including:

- each cross-section of the measurements can be expressed as a total area, thus allowing a total volume loss calculation
- one can take the measurement point and calculate an average height-loss.

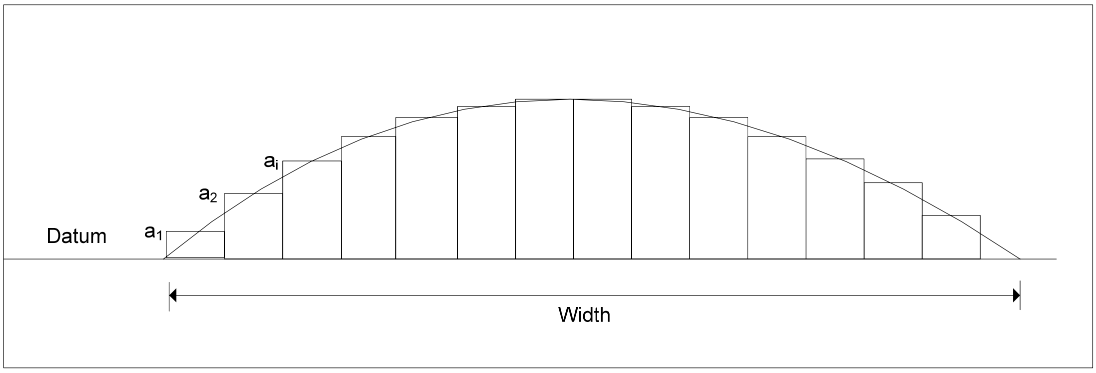


Figure 11.1 Gravel loss calculation for this study.

The gravel loss calculation adopted for this study is presented in Figure 11.1. Based on this scheme, the height is calculated as follows:

$$Area = \sum_{i=1}^{n}\left[\left(\left(\frac{a_{2-}a_{1}}{2} - Datum\right)\times 0.5\right)\right] \quad \textbf{Equation 11.1}$$

and,

$$SurfaceHeight = {Area}/{Width} \quad \textbf{Equation 11.2}$$

Note: the datum should be taken as the benchmark of the surveys.

Another aspect offering challenges in the modelling of gravel loss is the impact of blading on the measurements. The gravel loss trends are simple to interpret for a well-defined road profile, and for a grader operator who only uses the material from the profile. Although some points may gain height, others will reduce, with a net result of loss of material. In reality, this is often not the case, with grader operators often incorporating grade material from the side ditch into the profile. For that reason, the data often displays a gain in gravel without any additional material being put onto the road.

Unfortunately, the scope of this gravel monitoring programme did not include any 'before and after' maintenance measurements. It was, therefore, not possible to conduct the analysis on the absolute gravel loss quantities. The only method to overcome this limitation was to include 'days since last blading' as a field in the analysis dataset.

11.2 Exploratory statistics

Some exploratory statistic plots were investigated, in order to understand the gravel loss trends. In addition, these plots were also used to identify any inter-dependencies of the independent variables. Only significant trends are presented in the following paragraphs.

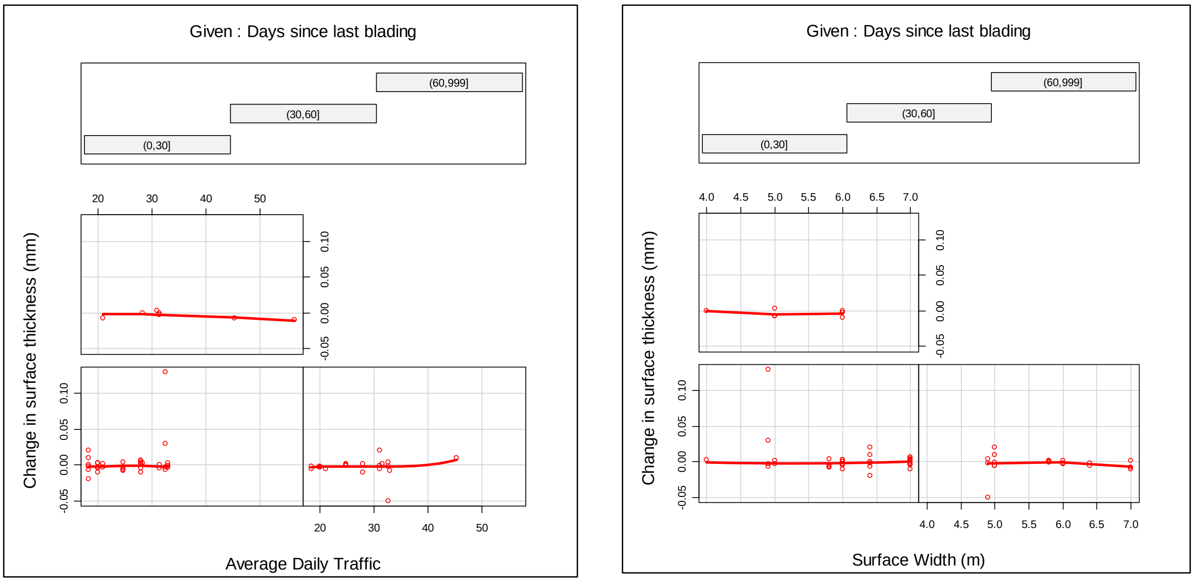


Figure 11.2 Co-plots for surface loss as a function of time since blading and traffic (left plot) and surface width (right plot).

Figure 11.2 illustrates some typical examples of co-plots for the surface loss. The plots depict the difference in gravel loss for the combined factors of time since blading and traffic and surface width. The time since blading is placed into three categories – shorter than 30 days, between 30 and 60 days and more than 60 days. For each of these categories, the trend between the gravel loss and traffic or surface width are displayed. Observations from these plots include:

- there is only a slight difference between the different blading periods
- within each category, there are also minor changes in gravel loss for the respective factors
- the most significant trends can be seen for the longer blading interval category
- for low blading cycles there is a slightly positive trend which correlates with expectations. For these plots there is some gravel loss with an increase in traffic and width.

The exploratory statistics highlighted that the following variables may be significant in predicting gravel loss:

- material grading properties (percentage passing the 0.075 and 26.5 mm sieves)
- plasticity

- rainfall
- traffic
- blading cycles
- surface width.

It should be noted that all of the variables indicated only minor trends in forecasting gravel loss, and the decision to include the variables in the final model depended on the regression analysis discussed in the following section.

11.3 Predicting gravel loss

11.3.1 Analysis approach

The analysis approach followed during this study involved the following steps:

1. Full stepwise regression: All possible variables were included to the regression in order to identify the significant variables for the prediction model.
2. Eliminate variables: In addition to the elimination of variables that took place automatically during the stepwise regression, a further variable elimination was undertaken manually. During this step, any illogical inter-effects of variables and variables with low significance were eliminated.
3. Factorise variables: Some variables lent themselves to be factorised within the model. For example, traffic could be factorised in low, medium and high classes. In some cases, factorised variables had a higher significance than a continuous variable, since some of the inhered variability was removed.
4. Select the final model: The final model was selected based on the remaining variables resulting from the prior steps. In addition, the model format was selected based on the review of the residual plots.

11.3.2 Regression results

The resulting model from the regression analysis is:

$$DeltaGL = 2 \times \begin{bmatrix} 108.53 - F_1 \times rain + F_2 \times \frac{BF}{2} - F_3 \times Width - F_4 \times Pi \\ + Grade\,\text{mod}(-F_5 + F_6 \times rain) + DLB(F_7 + F_8 \times pi - F_9 \times Plastl) \end{bmatrix}$$

Equation 11.3

Where	Delta GL	is the annual change in surface thickness
	Rain	average six monthly rainfall
	BF	annual number of blades
	TLB	number of days since last blading
	WIDTH	surface width
	Grademod	if longitudinal grade is moderate =1, otherwise 0
	Fi	model coefficients

The overall model regression coefficient is 0.22, with a model significance of 0.006. Therefore, although the model has a relatively low R^2, the model is significant. The significance of the individual factors are listed in Table C1. Figure 11.3 illustrates the residual plots for the developed model.

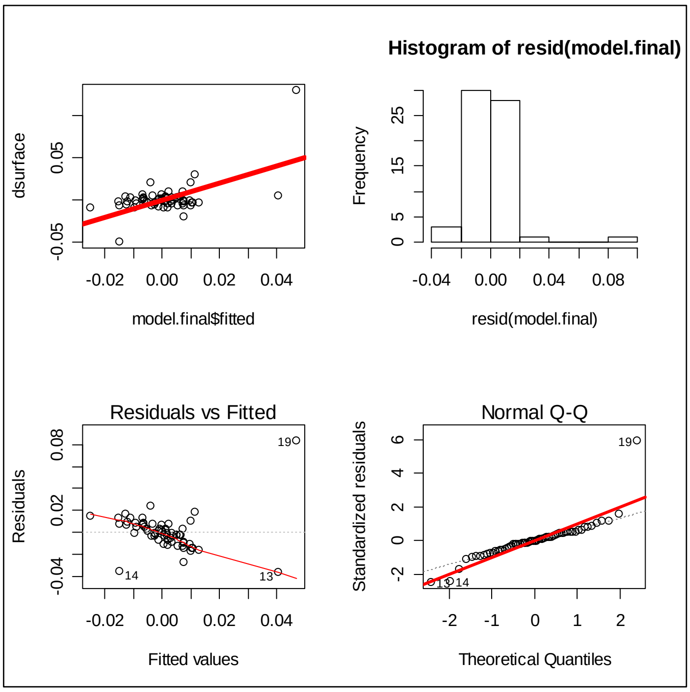


Figure 11.3 Residual plots for gravel loss model.

The following are observations from the residual plots.

- The plot comparing the predicted values versus the actual gravel loss points (top-left) suggests that the model has a reasonable fit with strong predictive power. There are some outliers observed though, that influence the over-all correlation of the model.
- The histogram of the residuals (top right) suggests a narrow distribution, except for the outliers that are indicated.
- The two bottom figures indicate that the model is adequately modelling the actual behaviour – ie the linear model format is appropriate. However, they also show the negative impact of the outliers in the overall fit of the model.

11.3.3 Suggesting a gravel loss based on averaged data

It should be appreciated that the model resulting from the regression analysis is an indication of general gravel loss only. For that reason it cannot be used on individual sections, because the experimental data did not include site-specific information such as maintenance effects and full blading cycle data.

In addition to the above, it can be seen that the model contains a large number of variables plus interdependencies between variables. Few of these interdependencies were observed in the exploratory statistics, thus calling into question the validity of the effects.

Based on the observations, a simpler approach was sought to derive a general gravel loss model based on average gravel loss for each site. In addition to taking the average gravel loss for each section, any significant gravel gain (>20mm) was removed from the data. This approach resulted in the following model:

$$DeltaGL = 2 \times \left[25.6 - F_1 \times Width - F_2 \times Pi + F_3 \times P265 - F_4 \times TLB + F_5 \times ADT)\right]$$

Equation 11.4

Where	Delta GL	is the annual change in surface thickness
	WIDTH	surface width
	Pi	plasticity index
	P265	percentage aggregate passing the 26.5 mm sieve
	TLB	number of days since last blading
	Fi	model coefficients

The overall model regression coefficient is 0.34, with a model significance of 0.196. The significance of the individual factors is listed in Table C2.

12. Profile slope and shape loss

12.1 Definition of profile indices

It is recognised that insufficient material may not always be indicated by gravel loss. Often insufficient material or marginal material behaviour manifests in the road profile or shape. With the material failing to meet cohesion and strength requirements, the ability to maintain the ideal profile will be lost. This result will require frequent blading, which still does not address the core failure mechanism. Poor riding quality and a poor draining surface cannot be addressed through the blading, plus there may be a drastic increase in blading and maintenance cost. As documented in the literature review, gravel loss models are seldom used in isolation. Roughness, rutting or profile models are used to supplement the gravel loss model, in order to capture some of the issues mentioned.

One of the objectives of this study was to develop and include additional profile or shape models for the same reasons. This section documents development of a slope model and considers a new shape model. The definition of these parameters is graphically illustrated in Figure 12.1.

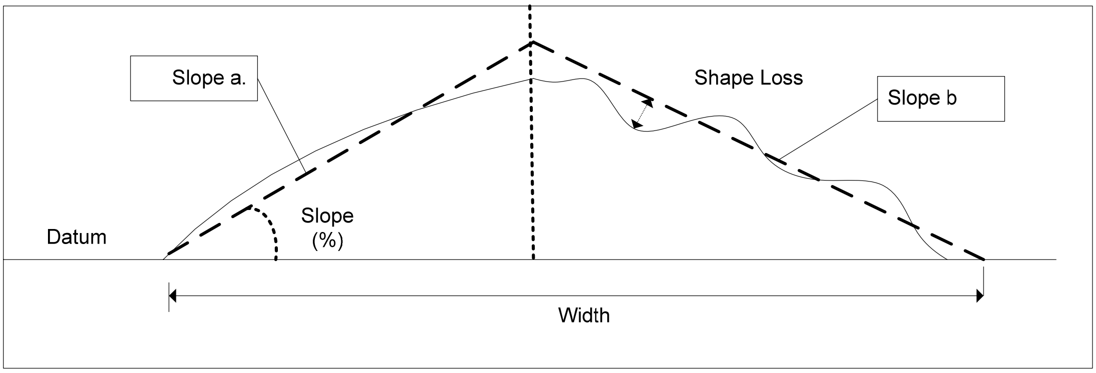


Figure 12.1 Definition of slope and shape indices.

The figure indicates two parameters. The first is a simple slope of the crossfall, which is determined from a theoretical line that best fits the crossfall. The cumulative profile slope is then defined as:

$$Slopecum = Slope_a - (-Slope_b)$$ **Equation 12.1**

Where	Slopecum	is the combined slope of the profile
	Slope a	the best fit positive slope
	Slope b	the best fit negative slope

Note that it is possible for the combined slope to have a negative outcome for instances where the road profile is shaped in the form of a trench or on a curve with a super elevation. With the ideal slope being between 4–6% any slopecum smaller than 12–8% will indicate a less desirable crossfall.

The slope is not the only parameter that represents the profile slope. As indicated in Figure 12.1, the right side of the road profile may have an adequate slope, but the unevenness of the surface will result in safety concerns and poor surface draining and normally signals loose material. In order to include this mechanism with the slope, the shape index was developed given by:

$$ShapeIndex = 10 \times (Slopefactor + StdDevFactor)$$ **Equation 12.2**

Where

$$SlopeFactor = 3 \times Slopecum$$

and

$$StdDevFactor = \max(-0.5, (1/(\log_e(stdevslopea) + \log_e(stdevslopeb))$$

Slopecum is obtained from Equation 12.1

Stddevslopea and b are the standard deviations for the respective slopes.

12.2 Exploratory statistics

The distribution of readings for both the slope and shape loss are indicated in Figure 12.2.

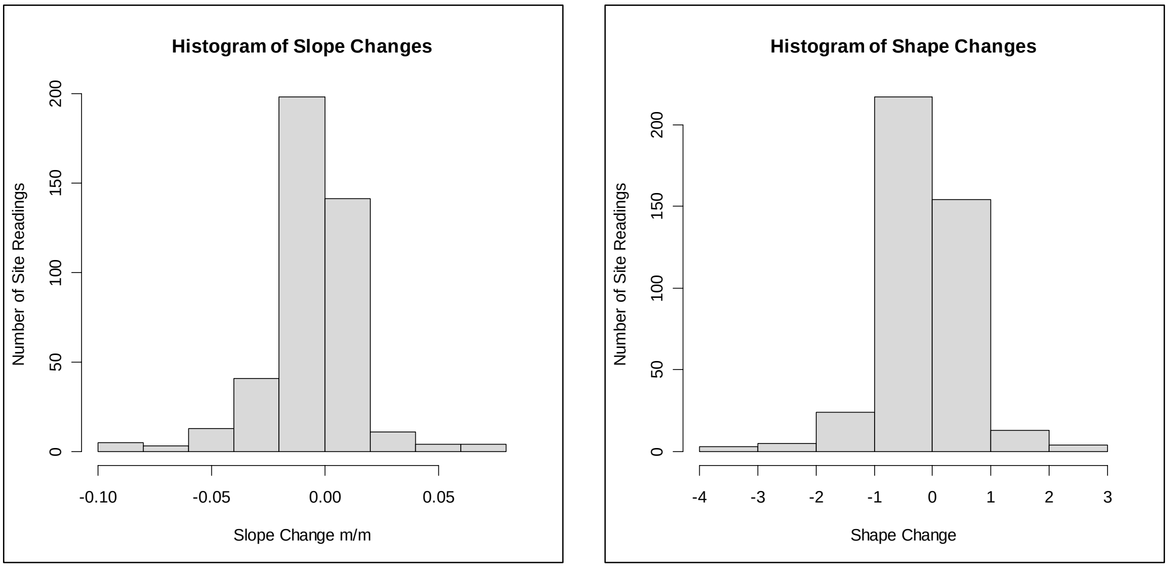
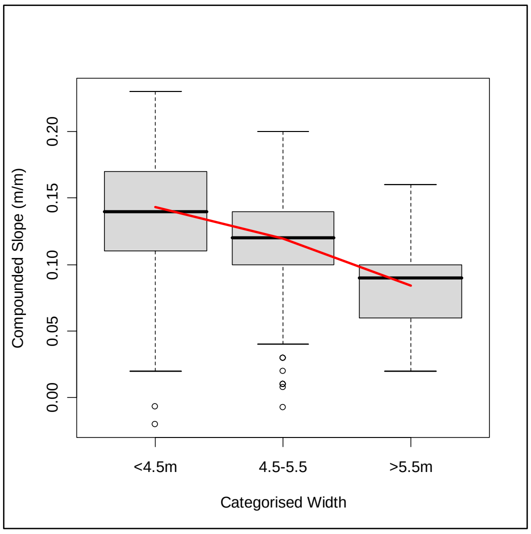


Figure 12.2 Distribution of readings for slope and shape loss.

Both the slope and shape loss show a predominant negative distribution, thus indicating that the majority of sections had a decrease in slope and shape over the study period. There were still a number of readings indicating a positive trend, which were explained by bladings that took place between surveys. However, the overall trend suggested that the road conditions deteriorated over time.

The aforementioned was a significant finding of this study and supported earlier claims that minor gravel loss was observed over time. However, gravel loss mostly involved losing fine material (%0.075 mm) – which might not be observed in net gravel loss – but it did change the performance of the gravel road significantly.

Another encouraging observation was that there were more significant trends between the slope and shape loss in relation to some variables. For example, viewing the condition of gravel roads revealed some significant trends that correlated with engineering expectations (See Figure 12.3).



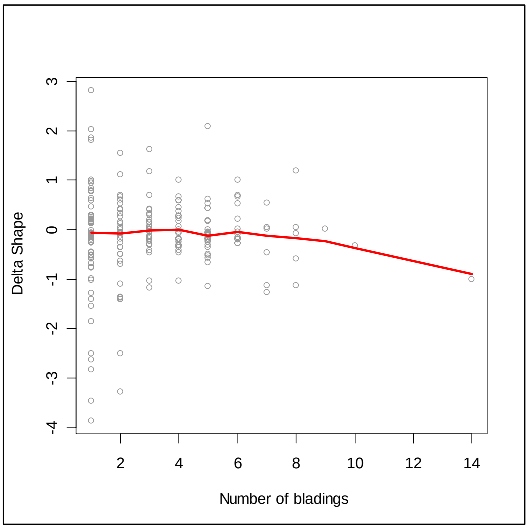


Figure 12.3: Trend plots between slope and pavement width (left plot), shape and bladings (right plot).

On the left-hand plot, the profile slopes at the beginning of the experiment are plotted as a function of the pavement width. As expected, it is observed that with an increase in pavement width, the slope decreases. This observation correlates with recommendations made in Section 3.1.3.

The right-hand plot indicates that there is a negative trend between the shape index and the blading cycle. This figure illustrates the change rate of the shape index and the blading cycle. The negative trend correctly suggests that with higher blading, the shape of the road also changes more quickly. It is unsure whether a higher blading frequency is maintained due to faster shape lost or vice versa, or higher traffic volume.

These observations also highlight the importance to view any potential relationships with the slope and shape as a function of the blading cycle, since there would always be a strong inter-correlation. Such examples are depicted in Figure 12.4. The figure illustrates the inter-relationship between the change in shape, days since last blading, percentage passing the 26.5 mm sieve and rainfall.

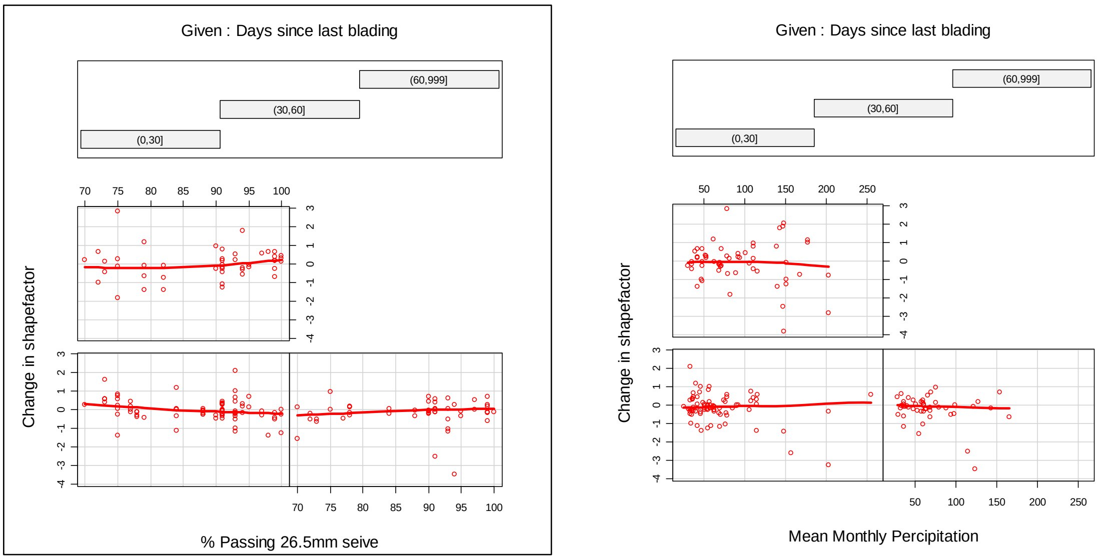


Figure 12.4 Co-plots between delta shape loss, days since last blading, percentage passing the 26.5 mm sieve (left hand plot), and rainfall (right hand plot).

It can be seen in both figures that the shape factor is significantly dependant on the days since last blading, percentage passing 26.5 mm sieve and the rainfall. Further observations include:

- Both independent variables have different trends for the various time periods since blading was undertaken. For example, the different blading categories on the left-hand plot have different trends in relationship to the percentage passing the 26.5 mm sieve. For recently bladed sections (less than 30 days) there is a negative relation to the shape change. That is, the shape is improving for increased percentage in material passing the 26.5 mm sieve. For any blading longer than 30 days ago, the trend is positive, thus a poorer shape. This observation correlates with expectations for the recent bladed sections, as one would expect a higher improvement of the shape for finer graded materials. However, for the sections where some deterioration has occurred, one would expect finer graded material to have a more significant shape loss.
- The trends observed confirm the necessity to include the time since blading in the prediction model.
- Overall, the shape index indicated more significant trends compared with the slope viewed in isolation. This confirms the validity of using this performance measure as a predictor of gravel road deterioration.

Based on observations from the exploratory statistics, the following variables indicated a possible significance in predicting the change in slope and shape loss:

- plasticity
- rainfall
- traffic
- pavement width

- inter-relationships between the above with both the blading cycle and the time period since last blading.

12.3 Regression results

12.3.1 Regression results for slope loss

The resulting model from the linear regression of slope loss is:

$$dSlope = 2 \times \begin{bmatrix} -0.114 + ADT \times (F_1 - F_2 \times PlaticL) + BF \times \\ (F_3 \times PlaticL - F_4 \times ADT - F_5 \times CBR) + TLB \times (-F_6 + F_7 \times PI) \end{bmatrix}$$

Equation 12.3

Where	dSlope	is the annual change in profile slope
	ADT	average daily traffic
	PlasticL	plastic limit of fines
	PI	plasticity index
	BF	annual number of blades
	TLB	number of days since last blading
	CBR	Californian bearing ratio
	Fi	model coefficients

A low regression coefficient of 0.006 resulted from the analysis, plus the significance of the model was 0.48, which indicated that the model was not significant. The variable estimates and significance are indicated in Table C3. Figure 12.5 illustrates the residual plots for the slope loss model.

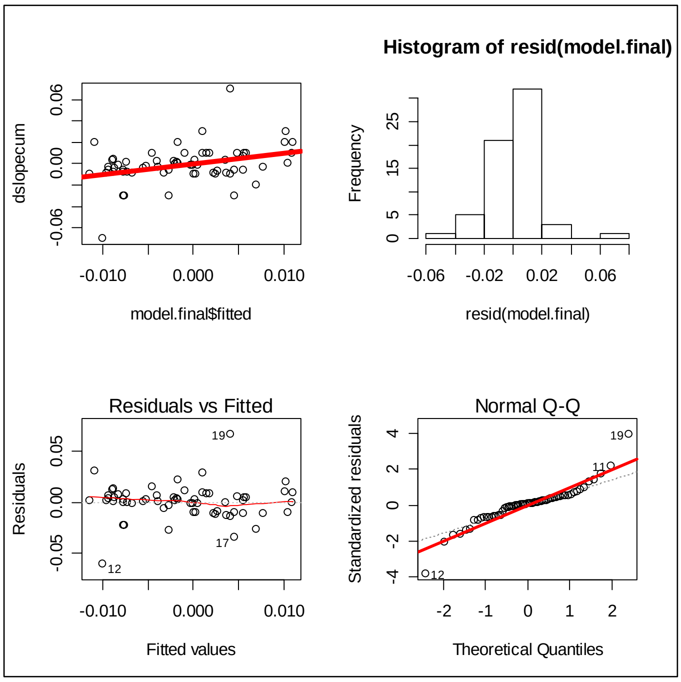


Figure 12.5 Residual plot for the slope loss model.

Observations from the residual plot are that:

- the plot comparing the predicted values versus the actual slope loss points (top left) suggests that the model has a reasonable fit, but weak predictive power. There is significant scatter of the data, which explains the relative low R2 and significance of the model
- the histogram of the residuals (top right) suggests a skewed distribution and there are also some outliers
- the residual plots bottom two figures indicate that the model is adequately modelling the actual behaviour, ie the linear model format is appropriate. However, it also shows the negative impact of the outliers in the overall fit of the model.

12.3.2 Regression results for shape loss

The resulting model from the linear regression of shape loss is:

$$dShape = 2 \times \begin{bmatrix} 2.32 + CBR \times (F1 - F2 \times ADT) - F3 \times p75 + F4 \times P265 + F5 \times Width + \\ PlastcL \times (-F6 + F7 \times BF - F8 \times Rain) + \\ BF \times (-F9 - F10 \times PI - F11 \times ADT - F12 \times CBR + F13 \times P75 - F14 \times P265) + \\ F15 \times PI \times Rain + DLB \times (F16 + F17 \times P75 - F18 \times PlasticL) \end{bmatrix}$$

Equation 12.4

Where	dShape	is the annual change in profile slope
	ADT	average daily traffic
	P75	% of particles passing through the 0.075 mm sieve
	P265	% of particles passing through the 26.5 mm sieve
	Width	surface width
	Rain	average annual rainfall
	PlasticL	plastic limit of fines
	PI	plasticity index
	BF	annual number of blades
	TLB	number of days since last blading
	CBR	Californian bearing ration
	Fi	model coefficients

A low regression coefficient of 0.014 resulted from the analysis and the significance of the model was 0.43, which indicated that the model was not significant. The variable estimates and significance are indicated in Table C4. Figure 12.6 illustrates the residual plots for the slope loss model.

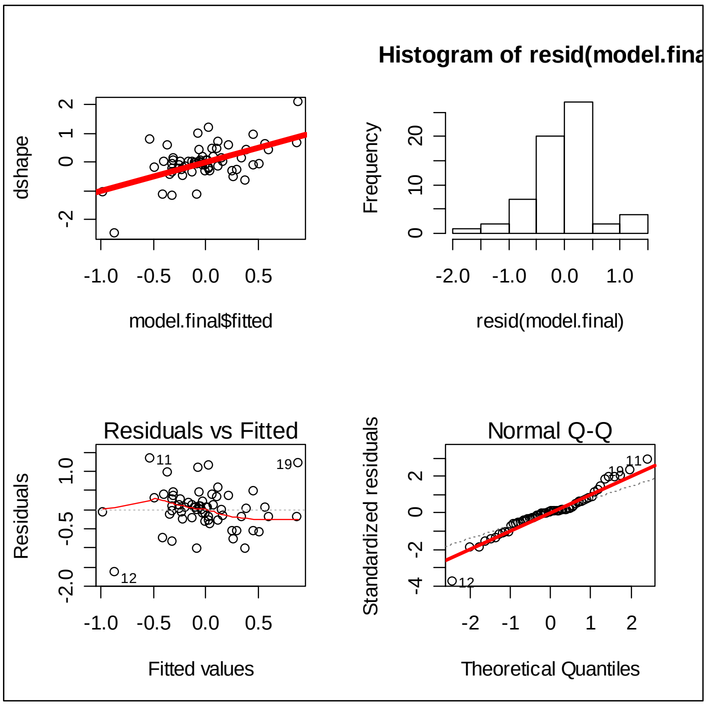


Figure 12.6 Residual plot for the shape loss model.

Given that the gravel shape is a strong function of the slope, the results in terms of the regression analysis are similar. A slightly better result was obtained because fewer variables were removed. Overall, the regression did not yield a satisfactory result.

12.3.3 Suggesting a slope model based on averaged values

Similarly to the gravel loss, the slope loss data was analysed based on averaged values for each section. Data indicating a significant slope improvement (>1%) was removed from the dataset. The resulting model from this data is:

$$dSLOPE = 2 \times \begin{bmatrix} 0.04 + F_1 \times ADT + F_2 \times P265 - F_3 \times Grade - F_4 \times Pi \\ - F_5 \times Rain - F6 \times Width - F7 \times TLB) \end{bmatrix}$$ **Equation 12.5**

Where	dSlope	is the annual change in profile slope
	ADT	average daily traffic
	P265	% of particles passing through the 26.5 mm sieve
	PI	plasticity index
	Grade	longitudinal slope (if moderate =1, else 0)
	Rain	average annual rainfall
	Width	surface width
	TLB	number of days since last blading
	Fi	model coefficients

The overall model regression coefficient is 0.75 with a model significance of 0.054. The significance of the individual factors is listed in Table C 5.

13. Recommendations

This report provides the outcomes from research based on the Land Transport NZ monitoring programme, which started during 2002 and included the cooperation of 51 local authorities. A summary of the main deliverables from this project is presented in Table 13.1.

Table 13.1 Deliverables from research.

Study objectives	Outcome/results	Comments
Propose some strategic level best practice guidelines for managing gravel roads from a performance perspective	Part A of this report provides comprehensive guidelines	
Interrogate the gravel loss data with the purpose of developing condition deterioration models such as gravel loss	General models were developed and are presented.	Given some data limitations, site specific model could not be developed.
Investigate the need and practicality of incorporating other/new condition performance measures such as gravel profile shape index (GrPSI) into a GRMS	A shape loss index is proposed and promising results were obtained.	More work is required on site specific data
Develop a framework for adopting the deterioration models and/or other practical consideration into a decision framework for the GRMS	Framework options are provided – discussed more in following paragraphs	

While the research achieved the stated objectives, somewhat disappointing results were obtained from the regression analysis. The data collected did not allow for site-specific information such as maintenance effects and for that reason only generalised models were developed. It is further suggested that these models are insufficient for adoption within a management system. Further required work is presented in Table 13.2.

Table 13.2: Further research work on unsealed roads.

Recommended further work	A strategy to achieve the further work
Refine and further develop the existing gravel, slope and shape loss models based on frequently measured data	An incremental approach is recommended to improve both the model and measurement process according to the following steps: Step 1 – Attempting to improve the current data-set by incorporating more council data on selected sections such as Central Otago Step 2 – Conduct a survey on selected sections only on a short measurement frequency.
Refine shape loss performance measure	Conduct a network level survey of data and maintenance records in order to establish the KPM based on actual intervention criteria
Continue the gravel loss experiment with advanced measurement principles	Much has been learned from this study and has confirmed that continues monitoring of unsealed roads is essential for New Zealand. Many aspects have been identify to suggest that unsealed roads are not maintained at optimal level. The only way to continue the knowledge gain is by having appropriate data available.

14. References

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Appendix A Abbreviations and acronyms

Some abbreviations and acronyms that are often used in Land Transport New Zealand Research Reports are listed here for quick reference.

AADT	Annual average daily traffic volume
ADT	Average daily traffic
AASHO	American Association of State Highway Officials (until Dec 1973)
AASHTO	American Association of State Highway and Transportation Officials (1974 on)
ARRB	Australian Road Research Board
Austroads	National Association of Road Transport and Traffic Authorities in Australia
B/C	Benefit/cost ratio
CBA	Cost-benefit analysis
CBR	Californian bearing ratio (an indicator of material strength)
GRMS	Gravel road management system
GrPSI	Gravel profile shape index
Land Transport NZ	Land Transport New Zealand (from 2004)
LTSA	Land Transport Safety Authority
NAASRA	National Association of Australian State Road Authorities
NCHRP	National Cooperative Highway Research Program
NRB	National Roads Board, New Zealand
OECD	Organisation for Economic Cooperation and Development
RAMM	Road assessment and maintenance management system
TeLIS	Technical Library and Information Service, Opus International Consultants Ltd
Transit	Transit New Zealand
Transfund	Transfund New Zealand (to 2004)
TRB	Transportation Research Board, Washington DC
TRL	Transport Research Laboratory, Crowthorne, United Kingdom (1992 on)
TRRL	Transport & Road Research Laboratory, Crowthorne, United Kingdom (until 1991)

Appendix B List of data items used in this study

Table B1: List of data items included to the study.

idno	Section ID
surveyno	Survey number
cbr	CBR
days	Period between surveys in days
panmm	Pan evaporation in mm
p75	Percentage passing 075
p265	Percentage passing 26.5
plasticl	Plastic limit (PL)
crush	Crushing resistance (kN)
pi	Plasticity index (PI)
rainmm	Average rainfall between surveys in mm
width	Surface width in m
grade	Longitudinal grade
adt	Average daily traffic
p_c	Percentage cars
p_bustr	Percentage bus traffic
p_at	Percentage articulated trucks
p_tt	Percentage truck and trailers
tot_LVE	Total light vehicle equivalents
days2blade	Number of days since last blading
blading	Text: Indicates blading action
numbladings	Number of bladings between surveys
days2gravel	Number of days since last metalling
re-gravel	Text: Indicates metalling action
numgravel	Number of metalling between surveys
surfacemm	Surface thickness in mm
slope_base	Transverse slope between edge points of cross section
slopecum	Cumulative cross slope
dsurface	Delta surface thickness between surveys
dslopecum	Delta cumulative slope between surveys
shapefactor	Calculated shape factor
dshape	Delta shape factor between surveys

Table B2: Descriptive statistic for complete dataset.

dsurface		dslope		dshape	
Min.	-1.01	Min.	-0.09	Min.	-3.86
1st Qu.	-0.01	1st Qu.	-0.01	1st Qu.	-0.29
Median	0.00	Median	0.00	Median	0.00
Mean	0.00	Mean	0.00	Mean	-0.07
3rd Qu.	0.00	3rd Qu.	0.01	3rd Qu.	0.24
Max.	1.00	Max.	0.08	Max.	2.81
cbr		**p75**		**pi**	
Min.	10.23	Min.	8.00	Min.	0.00
1st Qu.	33.21	1st Qu.	15.00	1st Qu.	3.00
Median	60.89	Median	23.00	Median	6.00
Mean	54.40	Mean	58.57	Mean	5.51
3rd Qu.	67.44	3rd Qu.	100.00	3rd Qu.	7.75
Max.	92.82	Max.	143.00	Max.	11.00
p26		**plasticl**		**bladings**	
Min.	78.00	Min.	0.00	Min.	1.00
1st Qu.	88.00	1st Qu.	17.00	1st Qu.	3.00
Median	91.00	Median	18.00	Median	4.00
Mean	90.26	Mean	15.30	Mean	4.18
3rd Qu.	93.00	3rd Qu.	19.00	3rd Qu.	5.00
Max.	100.00	Max.	21.00	Max.	14.00
rainmm		**panmm**		**width**	
Min.	25.26	Min.	48.66	Min.	4.00
1st Qu.	36.46	1st Qu.	68.90	1st Qu.	5.80
Median	46.95	Median	79.33	Median	6.00
Mean	48.48	Mean	85.46	Mean	6.12
3rd Qu.	57.88	3rd Qu.	101.00	3rd Qu.	6.40
Max.	140.01	Max.	156.80	Max.	7.30
adt		**crossfall**		**hcv**	
Min.	18.40	Min.	-0.02	Min.	0.08
1st Qu.	24.80	1st Qu.	-0.01	1st Qu.	1.89
Median	37.33	Median	0.00	Median	2.80
Mean	44.16	Mean	0.00	Mean	4.27
3rd Qu.	59.33	3rd Qu.	0.01	3rd Qu.	6.26
Max.	93.66	Max.	0.02	Max.	14.46

Appendix C Regression results

Table C1: Predicting gravel loss – regression outputs.

	Estimate	Std. error	t value	Pr(>|t|)	Significance
(Intercept)	1.09E-01	2.82E-02	3.845	0.000325	***
rainmm	-3.65E-04	1.98E-04	-1.842	0.071098	.
numbladings	2.74E-03	1.84E-03	1.494	0.141106	
width	-9.32E-03	4.04E-03	-2.307	0.024965	*
pi	-5.48E-03	1.57E-03	-3.49	0.000983	***
gradeModerate	-3.71E-02	1.46E-02	-2.55	0.013693	*
days2blade	2.78E-03	7.92E-04	3.504	0.000941	***
rainmm:gradeModerate	4.63E-04	2.31E-04	2.008	0.049741	*
pi:days2blade	1.71E-04	3.91E-05	4.377	5.68E-05	***
days2blade:plasticl	-2.20E-04	5.56E-05	-3.957	0.000227	***

Notes:

Residual standard error: 0.01695 on 53 degrees of freedom

Multiple R-Squared: 0.3344, Adjusted R-squared: 0.2214

F-statistic: 2.959 on 9 and 53 DF, p-value: 0.006352

Significance	Symbol
0	***
0.001	**
0.01	*
0.05	.
0.1	

Table C2: Predicting gravel loss (based on average loss rates for sections) – regression outputs.

	Estimate	Std. error	t value	Pr(>|t|)	Significance
(Intercept)	2.56E-02	3.64E-02	0.703	0.5082	
p265	4.80E-04	3.40E-04	1.411	0.2078	
pi	-5.56E-04	1.01E-03	-0.549	0.6029	
width	-9.17E-03	3.26E-03	-2.813	0.0306	*
days2blade	-3.35E-04	1.81E-04	-1.858	0.1126	
adt	1.94E-04	4.84E-04	0.4	0.7029	

Notes:
Residual standard error: 0.00815 on 6 degrees of freedom
Multiple R-Squared: 0.6389, Adjusted R-squared: 0.338
F-statistic: 2.124 on 5 and 6 DF, p-value: 0.193

Significance	Symbol
0	***
0.001	**
0.01	*
0.05	.
0.1	

Table C3: Predicting slope loss – regression outputs.

	Estimate	Std. Error	t value	Pr(>|t|)	Significance
(Intercept)	-1.15E-01	1.33E-01	-0.862	0.3923	
adt	4.26E-03	4.44E-03	0.958	0.3422	
plasticl	5.94E-03	7.78E-03	7.64E-01	0.4481	
days2blade	-5.07E-05	1.37E-04	-3.69E-01	0.7133	
plasticl:adt	-2.58E-04	2.52E-04	-1.02E+00	0.3111	
plasticl:numbladings	3.79E-04	3.60E-04	1.05E+00	0.2973	
adt:numbladings	-3.30E-05	2.17E-04	-1.52E-01	0.8795	
numbladings:cbr	-5.84E-05	2.97E-05	-1.97E+00	0.0545	.

Notes:
Residual standard error: 0.0178 on 54 degrees of freedom
Multiple R-Squared: 0.1235, Adjusted R-squared: -0.006302
F-statistic: 0.9515 on 8 and 54 DF, p-value: 0.4831

Significance	Symbol
0	***
0.001	**
0.01	*
0.05	.
0.1	

Table C4: Predicting shape loss – regression outputs.

Variable	Estimate	Std. error	t value	Pr(>|t|)	Significance
(Intercept)	2.32E+00	5.84E+00	3.98E-01	0.693	
Cbr	4.35E-02	4.41E-02	9.87E-01	0.329	
p75	-2.55E-01	1.79E-01	-1.43E+00	0.161	
Width	1.69E-02	2.68E-01	6.30E-02	0.950	
p265	3.87E-02	4.71E-02	8.23E-01	0.415	
Plasticl	-9.62E-02	2.48E-01	-3.88E-01	0.700	
days2blade	5.15E-02	4.02E-02	1.28E+00	0.207	
numbladings	-1.98E-01	1.38E+00	-1.43E-01	0.887	
cbr:adt	-1.59E-03	1.19E-03	-1.33E+00	0.190	
numbladings:plasticl	4.02E-02	5.84E-02	6.88E-01	0.495	
plasticl:rainmm	-1.94E-03	7.28E-04	-2.67E+00	0.011	*
numbladings:pi	-7.02E-02	3.49E-02	-2.01E+00	0.051	.
adt:numbladings	-4.66E-03	1.24E-02	-3.75E-01	0.709	
cbr:numbladings	-4.26E-04	4.85E-03	-8.80E-02	0.931	
p75:days2blade	1.94E-04	1.35E-03	1.44E-01	0.886	
rainmm:pi	3.44E-03	1.44E-03	2.38E+00	0.022	*
plasticl:days2blade	-3.00E-03	2.12E-03	-1.42E+00	0.164	

Notes:

Residual standard error: 0.6272 on 44 degrees of freedom

Multiple R-Squared: 0.3005, Adjusted R-squared: 0.01438

F-statistic: 1.05 on 18 and 44 DF, p-value: 0.429

Significance	Symbol
0	***
0.001	**
0.01	*
0.05	.
0.1	

Table C 5: Predicting gravel loss (based on average loss rates for sections) – regression outputs.

Variable	Estimate	Std. error	t value	Pr(>|t|)	Significance
(Intercept)	3.58E-02	1.92E-02	1.864	0.13583	
adt	1.21E-04	2.43E-04	0.5	0.64353	
p265	2.49E-04	1.68E-04	1.483	0.21222	
gradeModerate	-8.19E-03	3.42E-03	-2.395	0.07473	.
pi	-7.50E-04	6.18E-04	-1.214	0.29157	
rainmm	1.28E-04	6.08E-05	2.113	0.10213	
width	-8.73E-03	1.61E-03	-5.437	0.00555	**
days2blade	-2.14E-04	9.67E-05	-2.215	0.09113	.

Notes:
Residual standard error: 0.003614 on 4 degrees of freedom
Multiple R-Squared: 0.9103, Adjusted R-squared: 0.7534
F-statistic: 5.801 on 7 and 4 DF, p-value: 0.05432

Significance	Symbol
0	***
0.001	**
0.01	*
0.05	.
0.1	