

**The Effect of South African Provincial Road Condition on the  
Efficiency of Forest Product Transport.**

by

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## **Declaration**

I the undersigned hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Signature:

Date:

## Abstract

*Nicholls, S.J. The Effect of South African Provincial Road Condition on the Efficiency of Forest Product Transport. MSc Forest Science Thesis. University of Stellenbosch. pp. 129.*

Keywords: Forest Transport, Network Analysis, Road Condition, Efficiency

The context of the study is concern over declining provincial road condition due to insufficient government funding of road maintenance. These roads are by their public nature used by a wide variety of commercial and private interests contributing a variety of axle loads. There was no information available on the use of these roads by forest companies and the road conditions. Consequently a survey was conducted to determine condition and length of each segment of provincial road in use by forestry companies and the volume of wood transported over them. In addition data was gathered on other users and their contribution to the volume transported over each section.

The questionnaire indicated that the provincial roads are in a poor state. The literature review suggested a significant reduction in total cost of transport can be achieved by maintaining or rebuilding these roads. South African forest companies provide the majority of the heaviest axle loading to these roads and must therefore take responsibility for damage caused to them. Also a variety of forest companies use the same roads and consequently collaborative studies between companies are needed.

A modified Dijkstra's algorithm was used to quantify the effect of the condition of South African provincial roads on the efficiency of the transport of forest products. The model requires digitised raster road and forest map layers combined with transport vehicle specification as input. The products of the model are optimum routes from all source points to a single exit point or sink, the total volume transported across all road nodes and the total cost to extract all wood from a map section. This output allows managers to identify critical roads for management

attention and make tentative estimates of possible reductions to total cost by altering the road condition. The manager is able to test the sensitivity of the solution to changes in variables and gain a better overall picture of the interactions within the system. The model results, and improved understanding, will provide input to more specific and collaborative studies.

South African forest managers can respond to the poor provincial road network by conducting *ad hoc* maintenance to these roads to prevent them becoming completely impassable or to rebuild them to their design state and maintain them at that state. The cost of taking no actions is that these roads would eventually become impassable. The road network model determined that, for the study area, a unilateral decision to rebuild and maintain all roads would result in a net increase in transport costs of R 2 million/year. When compared to the cost of *ad hoc* road improvements for the same area of R 8 million it is obvious that proper road management is a better option.

It was shown that 75% of the reduction in total cost is generated by improving only 31% of the provincial road surface. Consequently, by improving selected roads (20% of the total provincial road network for the area) it was possible to generate a net cost R 2.9 million lower than if the roads were left as they are.

If reductions in operating costs are included the net cost to the forest industry is R 3.1 million/year lower than leaving the roads as they are. In addition to the cost being lower, an improved road network would be in place and the current *ad hoc* spending would be unnecessary.

On a larger scale it was estimated that poor provincial road management costs the industry as a whole R 26 million or R 1.52/m<sup>3</sup>/year. This money can be used to offset the costs of maintaining and upgrading roads. It is therefore concluded that the South African forest industry needs to assess its policy on provincial road management and become more active in the managing of these roads. The tool developed and presented is intended as a prototype decision support tool in developing future policies.

## Opsomming

**Nicholls, S.J. Die invloed van die toestand van Suid-Afrikaanse Provinsiale paaie op die effektiwiteit van die vervoer van Bosbou produkte. MSc Bosbou Wetenskappe Tesis, Universiteit van Stellenbosch.**

Sleutelwoorde: Rondehout vervoer, sekondere vervoer; netwerk analise; toestand van paaie effektiwiteit

Die inhoud van hierdie studie handel oor die verval van provinsiale paaie as gevolg van die regering se onvoldoende fondse vir die instandhouding van die paaie. Hierdie paaie word as gevolg van hulle publieke aard deur 'n wye verskeidenheid kommersiële en private belange gebruik, wat bydra tot 'n verskeidenheid van asladings. Daar was geen inligting oor die bosbou maatskappye se gebruik van paaie of die toestand van die paaie beskikbaar nie. Gevolglik is 'n opname gemaak om die kondisie en lengte van elke segment van die paaie wat deur die bosbou maatskappye gebruik word, vas te stel, asook die volume hout wat oor die paaie vervoer word. Data oor ander verbruikers van die paaie is verder ingesamel, asook hul bydrae tot die volume wat oor die paaie vervoer word.

Die vraelys het aangedui dat die provinsiale paaie in 'n baie swak toestand is. 'n Literatuurstudie het getoon dat 'n beduidende daling in die totale vervoerkoste moontlik is deur hierdie paaie te onderhou of oor te bou. Die Suid-Afrikaanse bosbou maatskappye voorsien die meerderheid van die swaarste asladings op hierdie paaie en moet dus verantwoordelikheid neem vir beskadigde paaie. 'n Verskeidenheid bosbou maatskappye gebruik die paaie; gevolglik is gesamentlike studies tussen die maatskappye ook nodig.

'n Aangepaste Dijkstra algoritme is gebruik om die effek van die toestand van Suid-Afrikaanse provinsiale paaie op die effektiwiteit van die vervoer van bosbou produkte, vas te stel. Hierdie model benodig digitale inligting oor die hoof en bosbou paaie, asook die spesifikasies van die voertuie wat gebruik word. Die resultaat van die model is die optimale roetes vanaf alle bronpunt oorspronge tot by 'n enkele bestemming, die totale volume vervoer oor al die padnodusse en die totale

koste verbonde aan die verwydering van alle hout uit 'n afgemerkte seksie op die kaart. Hierdie produk of resultate stel bestuurders in staat om kritieke paaie vir aandag te identifiseer en om tentatiewe voorspellings van moontlike afname in die totale kostes te maak indien die toestande van paaie verbeter sou word.

Die bestuurder kan die sensitiwiteit van die oplossing vir variasie in die veranderlikes toets en sodoende 'n beter geheelbeeld kry van die interaksie binne die sisteem. Die resultate van die model en 'n beter begrip daarvan, kan instette lewer in meer spesifieke studies en gesamentlike studies tussen maatskappye.

Suid Afrikaanse bosbou bestuurders kan teen die swak provinsiale padnetwerk optree deur ad hoc instandhouding toe te pas op hierdie paaie om te voorkom dat hulle totaal en al onbegaanbaar word. Of hulle kan die paaie restoureer tot hul oorspronklike toestand en hulle dan in stand hou. Die kostes daaraan verbonde om nie op te tree nie, is dat hierdie paaie uiteindelik on-gaanbaar sal word. Die padnetwerkmodel het gewys dat vir die spesifieke studie area, 'n eenparige besluit om alle paaie te herbou en onderhou, 'n algehele toename in vervoerkostes van R2 miljoen/jaar tot gevolg sal hê. Wanneer dit vergelyk word met die R8 miljoen wat die ad hoc padverbeterings kos, is dit duidelik dat geskikte padbestuur 'n beter opsie is.

Daar is bewys dat 75% van die daling in totale kostes genereer kan word deur verbeteringe aan die oppervlaktes van slegs 31% van die provinsiale paaie te maak. Gevolglik was dit moontlik om netto kostes van R2,9 miljoen minder te genereer as wanneer geen instandhouding gedoen is nie. Dit is bewerkstellig deur verbeteringe aan geselekteerde paaie aante bring (20% van die totale provinsiale padnetwerk vir die area.)

As die daling in bedryfskoste ingesluit is, sal die netto koste vir die bedryf R3.1 miljoen/jaar minder wees as om die paaie so te los sonder enige aandag. Verder, tot laer koste sal daar 'n verbeterde pad netwerk in plek wees en die huidige ad hoc spandeering aan die paaie nie meer nodig wees nie.

Op groot skaal, is die benaderd voorspelling dat 'n swak provinsialepadbestuurstelsel die bosbou bedryf R26 miljoen of R1.52/m<sup>3</sup> uit die sak jaag. Hierdie misbruikte geld kan eerder teruggeploeg word in pad onderhoud en opgradeerings werksaamhede. Dit is dus nodig dat die bosbou bedryf sy beleid weer in oonskou moet neem in verband met die bestuur van provinsiale paaie en ook meer aktief die voortou sal moet neem in die instandhouding van provinsiale paaie. Die metodiek hier ontwikkel kan 'n inleidende doel dien in die ontwikkeling van toekomstige besluit neemings rakend die bestuur van provinsiale paaie.

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“But seek first his kingdom and his righteousness and all these things will be given to you as well. Therefore do not worry about tomorrow, for tomorrow will worry about itself.” Mathew 6:33-34

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# 1. Introduction

## 1.1. Context

The importance of timber transport in the forest industry is widely understood. The management of this transport has formed the basis of many studies in South Africa. Ackerman (2001) reports on several of these studies, which concludes that transport of forest products contributes 50-60% of the cost of wood delivered to the mill. The vehicle aspect of transport in South Africa is reasonably well managed by a variety of interests from small contractors to substantial, specialised transport contracting companies. As a result recent initiatives in transport management in South Africa have successfully focused on reducing tare weight to increase payloads and therefore productivity.

However, transport cannot be effectively considered or managed in isolation of roads. The interaction between vehicle and road is two way. A good quality road will facilitate cheaper transport. The volume and axle loads of traffic on a road, combined with maintenance policies, control the quality of the road. It is clear from the literature that road condition affects wear and tear on vehicles and tyres, as well as fuel and oil consumption. This has been observed both internationally (Larcombe, 1999) and locally (Jones & Paige-Green, 2000). Furthermore it is strongly suggested that road condition can affect travel speeds and therefore productivity.

South African forest companies manage a road network in excess of 100,000 km. More than 98% of this network is unsealed and minimal maintenance is the norm (Morkel, 1995a; Jones & Paige-Green, 2000). The average provincial road is considered to have 50% of its surface covered with defects sufficient to impede effective transport. Ackerman (2001) reported that most forest roads were unserviceable for 60% or more of their length. In some cases contractors would repair roads out of their own budgets in order to make roads passable. It would therefore seem an understatement to declare that the condition and management of South African forest roads are in a poor state.

This brings to light a conflict between management practices. Vehicle robustness has been reduced, while road management has been neglected, resulting in increased impacts on those vehicles. Lightweight vehicles require well-constructed and maintained roads in order for them to perform at sufficient speeds (Douglas, 1988; Marshall, 1989) with minimal wear and tear. Despite this, and despite the emphasis on road maintenance in the literature, both forest and provincial road conditions continue to decline. The decline in the latter is due to recent efforts by government to decommission provincial roads and withdraw government funding for these roads.

“The quality of our roads is declining and there is insufficient capital available to maintain and upgrade them...if we act swiftly and efficiently, we can build and reinforce the capacity of the industry itself to make investments necessary to continuously improve the service we offer to our passengers and goods.”

Mac Maharaj: Previous Minister of Transport (DOT, 1998).

In his forward to “Moving South Africa” (the guiding document for the Department of Transport’s strategy to meet the land transport needs of South Africa) Maharaj clearly indicates government’s intention. This is to concentrate scarce resources on critical transport corridors and to reduce spending on feeder roads. In addition it is expected that road costs, including externalities, are to be redistributed to the actual users of the road. Externalities include costs that, although accrued by society, are not factored into the financial determination of costs. Typically this includes costs incurred from pollution and physical damage to the environment (in the case of roads a major externality would be the cost of erosion).

From the above it is clear that the condition of roads in South Africa is an issue that requires attention. Jones and Paige-Green (2000) have conducted studies, under South African conditions, on the impact of road condition on transport costs. They conservatively concluded that poor road conditions could cause an increase on transport costs of 20%. In the same study they identified the need for further research into possible cost reductions by improving transport efficiency, an aspect that has not been studied in South Africa. Consequently it is this last aspect that

forms the main thrust of this investigation. The combination of the results from this study and those of Jones and Paige-Green (2000) will provide a more complete picture for managers in the South African forest industry.

The very nature of public roads is such that these roads are not owned by any specific interest. In addition because public roads have never fallen within forest company management structures, the available information on road conditions is vague and incomplete. Public roads are used by a variety of interests, with each contributing differing axle loads and traffic volume. Users of these roads will range from high axle load, industry based transport to low axle load users for tourism and access. It is difficult to determine who should pay for the maintenance of these roads and the extent to which interested parties should divide the costs. Furthermore, the government charges levies (through fuel taxes) for the maintenance of roads. It could therefore be argued that whenever forest companies pay for the maintenance of the public roads they use, they should receive a rebate on these taxes.

An additional aspect of road maintenance is that, due to the complex interaction of variables, there is no single management solution and using fixed standards is discouraged (Larcombe, 1999; Jones & Paige-Green, 2000). An efficient solution continually changes with time, as, amongst other factors, harvesting plans change to meet demand and this means that calculations must be repeated often. There are, however, sufficient guidelines to the direction management should take. It is evident that the problem within the South African industry is not a lack of information but a lack of skills and tools to aid the constructive application of this information.

The results of this research could be used by forest companies when assessing their policies on upgrading or maintaining decommissioned public roads. In addition, the information will provide an invaluable aid to groups engaged in negotiations with government bodies over rebates on taxes and levies. Edwards (2001) indicated that forest companies' ad hoc spending on provincial roads is in excess of R10 million. This money could be better channelled if spent within a well-prepared road management plan.

## **1.2. Scope**

A large amount of research in both South Africa and abroad has been done on the consequences of declining road condition on vehicle maintenance costs and fuel consumption. However, little research has been done on the effect on driving speeds.

The influences of the forest road can be grouped according to direct and indirect influences. The direct influences are the physical interaction of the elements while indirect influences include more esoteric aspects, such as drivers' perceptions of danger. The latter aspects are very difficult to model and are not part of the focus of this thesis. Instead the focus is on the direct influence of road condition.

The speed of a vehicle is ultimately determined by the state of the road on which it travels. The two main (non-alignment based) influences are road stiffness and road roughness. A stiffer road will result in lower rolling resistance and enable greater speeds for the same energy expenditure. In addition, a wet road will soften and therefore provide a greater rolling resistance as well as a loss of power through wheel slippage. Road stiffness is determined in the design and construction process of a road. Road roughness, a measure of irregularities in the road surface, causes unnecessary flexing of the tyres, which absorbs energy. For example, a provincial road will have a fixed specification for surfacing and road pavement structure strength (hardness). Road roughness is determined by the wear on the road and the frequency of appropriate maintenance procedures. Although pavement design and construction are not the focus of the study they do influence how a road will wear with use and thus road maintenance requirements. This study quantifies road surface condition by the occurrence of impediments to vehicle motion, such as potholes or washboards.

As a consequence of the trend to decommission provincial roads and because this aspect has received little attention in other studies, this paper focuses explicitly on provincial roads. Although gravel surfaced provincial roads account for a small percentage of a total trip they have a significant impact on cost (Morkel, 1995a). What is the effect of the decline in road condition on the South African forest

industry? Should the industry ignore the continued deterioration of provincial roads or should they be using private funds to maintain these public roads?

It is hypothesised that the effort and difficulty of conducting cost-benefit analyses discourages forest resource managers from conducting such analyses. Consequently, a decision support tool was developed. This programme has the additional benefit that it is cheap, user friendly and relatively simple to understand. It can therefore be used to assist in further studies of a similar nature.

Key indicators and the acceptable level of abstraction and generalisation of the data must be decided upon. Due to the complexity of the forest transport model and the need for generalisation (for computational convenience), optimality is not the objective of the model. Instead, a sense of the relative costs of various actions is desired. The results of such studies are meant to complement existing information and managerial aids for solving the overall problem (Pulkki, 1984).

The benefit of the programme being reusable is that it can be used in more focused studies aimed at determining accurate cost values. Ultimately the programme is presented as a prototype for a decision aid tool. The responsibility for the decision still rests on the manager who must also take into account less quantifiable aspects such as environmental considerations.

The model is kept simple and problem specific in order to facilitate technology transfer and to reduce costs. All inputs are user controlled, allowing rapid responses to changing managerial needs. In addition the problem addressed is too specific to warrant the investment in a larger, more general decision support system.

### **1.3. Objectives**

In the light of the management ethos and current condition of the road infrastructure the following two objectives were identified for this study.

**Objective one** was to determine the current state of the provincial road network as a basis for further analysis.

This involved identifying the roads in use by forest companies. In addition, it was necessary to gather certain critical information about these roads, specifically:

- How much of the total volume carried by those roads is contributed by forest product transport?
- What other enterprises use those roads?
- To what extent do different forest companies use the same roads and what is the potential for collaboration?
- What is the current condition of the roads?
- What is the change of condition of the roads when wet?

This first objective provides a general impression of the environment the forest companies engage in, as well as specific details on the state of the road network. Conducting and analysing an industry-wide survey or questionnaire achieved this objective.

**Objective two** was to assess the impact of the decline in provincial road condition on transport costs. It is hypothesised that this decline has a significant impact on timber transport costs. Apart from attempting to quantify the effect of road condition, a number of sub-objectives were investigated to serve as management guides:

- To determine the contribution of the most frequently used roads to the total cost, and to determine the importance of each road's contribution to total costs.
- To identify one or a few roads that, if isolated and improved, would significantly decrease the total cost.
- To determine the effect of changing moisture on the road on cost.
- To determine the effect of extreme changes in road condition.
- To provide a technique and tool for more specific studies.

This second objective was achieved by the development and application of a mathematical model, using a simple spreadsheet model and a more complex dynamic

(multi-stage) programming algorithm. This allowed the identification of key management variables and the quantification of costs within a road network.

#### **1.4. Limitations**

Within the above objectives the study is bound by the following limitations and assumptions:

- The study is confined to the effect of improving unpaved secondary/provincial/district road condition and, as a result, increasing transport vehicle speed. This will in turn realise cost reductions as a result of increased productivity.
- Only shortest routes were considered and no resource allocation was taken into account. In other words, one exit node was selected for each simulation, closest to the mills at Richards Bay and Durban. Two runs were therefore completed for each area to minimise a bias effect of using only one direction of transport.
- Due to the long planning horizons, the short term fluctuations in supply and demand cannot be modelled and are assumed to be constant and equal, and are estimated by long term averages (mean annual increment (MAI)).
- Trucks were assumed to run continuously and it was assumed that the truck could travel the whole trip without the driver taking a break during the shift.
- No roads were constructed and only the effect of reducing impediments by maintenance and rebuilding procedures were considered.
- Tree felling, extraction, timber preparation and loading costs were not included in this study.
- Only low tare weight highway trucks were considered (Rigid draw-bar trailer configuration).

The limitations on the model have the consequence that the cost data produced are not absolutely correct. However, the tactical nature of the study is to compare the validity of alternatives. It is not necessary to calculate absolute values, as approximately correct comparisons for the various alternatives will suffice, provided that their relative values are sufficiently precise (Hillier & Lieberman, 1986).

## 2. Literature review

### 2.1. *Forest road and transport interaction*

#### 2.1.1. Transport system

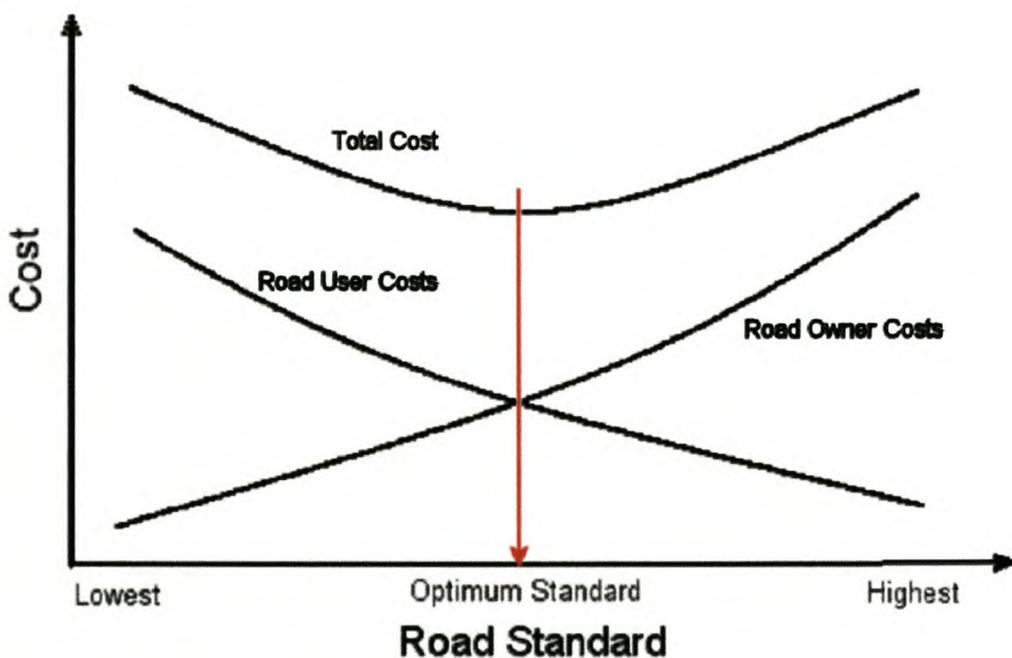
The transport system is made up of several interacting elements: the driver, road, vehicle and environment (Ljubic, 1984). Each of these components has a substantial impact on cost, reliability and durability of timber transport (Ljubic, 1983). Their interactions and impacts will be analysed in this section.

In order to understand and manage the above relationships it is appropriate to view the system in terms of cost. Costs associated with roads and transport can be subdivided into the costs associated with construction and maintenance of roads and those of using the road (Larcombe, 1999; Morkel, 1994).

- Road owner elements
  - Initial capital cost
  - Maintenance cost
  - Rehabilitation cost
  - Salvage value
- Road user elements
  - Traffic delay costs
  - User Operational costs
    - Vehicle operating costs
      - Fuel consumption
      - Tyre wear
      - Vehicle depreciation
      - Vehicle maintenance
      - Oil consumption
      - Parts replacement
    - Travel time costs

- Accident costs
- Discomfort costs

There is an inverse relationship between road owner costs and road user costs. As road owner costs increase, the condition and surface of the road improves and many of the vehicle operating costs decrease. A comparison of costs and benefits would determine what road condition level is most appropriate (Figure 1). The decision to upgrade or rebuild a road is simply a matter of conducting a cost benefit analysis by considering the location, condition, width and alignment that give the lowest combined cost for road construction, maintenance and haulage (Larcombe, 1999).



**Figure 1: Effect of road condition on cost (Larcombe, 1999)**

Road condition decline leads to increased repair and maintenance costs, increased fuel consumption, reduced travel speeds, lower productivity and reduced reliability of access (Morkel, 1994). Thus the manager must manage the interaction of all these factors in order to determine optimum road standards and to minimise total transportation system costs, including the cost of road construction and maintenance, plus vehicle operating costs (Douglas, 1988). In order to do so, a manager must understand how each component of the transport cycle affects the above costs. The

manager must also be aware of less quantifiable elements such as accident risk and discomfort costs (as the road worsens the jolting of the driver worsens and the road becomes less safe).

The transport of timber is dependent on a truck providing enough power to overcome the resistance to movement imposed by its own weight and that of its load to produce a forward motion of sufficient speed. Power is fed into the system by the engine of the vehicle and is consumed in the action of the vehicle and its interaction with the road and environment. Power is consumed in several ways:

- From the vehicle alone:
  - Accessories (Douglas, 1986, 1988) or parasitic losses (Smith, 1981)
  - Inertial (Smith, 1981) and churning resistance
  - Chassis friction (Douglas, 1986, 1988; Smith, 1981)
  - Air resistance (Douglas, 1986, 1988; Smith, 1981)
- As a result of vehicle/road interaction:
  - Grade resistance (Douglas, 1986, 1988; Smith, 1981)
  - Rolling resistance (Douglas, 1986, 1988; Smith, 1981)
  - Imposed performance standards by legal framework (speed limits) (Smith, 1981).

The loss of power in the vehicle is due to friction between the piston rings, pistons and bearings, losses through the drive line and accessory losses (*e.g.*, fan, compressor, generator, power steering). Engine losses, in a responsibly driven vehicle, represent the highest resistance that must be overcome (Ljubic, 1982). The management of vehicle resistance can be controlled in two ways: firstly, by selecting an appropriate transport vehicle configuration and secondly, by ensuring that the drivers are adequately trained.

The driver is the most important link between the machine and the road, and the most important factor influencing the performance and cost of any transport undertaking. The modern driver should be conscious of engine speed (rpm), be defensive, easy on the vehicle, energy efficient and environmentally conscious. Cost differences of 20% can be accounted for by driving technique alone (Nader, 1991) and fuel

consumption can differ by as much as 32.5% due to driver technique (Ljubic & Michaelson, 1986). A more conservative estimate is that through long term training programmes it may be possible reduce average fuel consumption by 5% through improved driving habits (Williams & Nader, 1993). Training should encourage the maintenance of a steady speed as one effective method of minimising fuel consumption, while at the same time sustaining a fairly high average road speed.

Correct vehicle specification can have a major and immediate impact on fuel consumption in the order of 10% to 20% (Williams & Nader, 1993). An increased fuel consumption of 4.5% was found when the axle spacing of a quad-axle trailer was increased from 4.21 to 6.03 m (Provencher, 1989).

Although the losses within the vehicle are significant and the effect of the driver paramount, in order to determine the effect of declining quality of provincial road systems, the vehicle-road interaction will make up the remainder of this literature review. The influence of the forest road on the vehicle can be grouped according to direct and indirect resistances. Indirect resistance refers to the characteristics of the road that impede the efficient passage of the vehicle, often as a result of the driver's perception of safety and comfort (Morkel, 1994). Direct resistances are those that retard the motion of the vehicle. The direct resistances associated with the road surface are:

- Rolling resistance (attributed to road stiffness and roughness)
- Grade resistance

Each of the above has an impact on transport costs and efficiencies. Grade resistance is the force required to move the load along a slope and is a function of the mass of the vehicle, the angle of the slope and gravity. Due to high costs of altering geometric characteristics of forest roads the existing roads should be accepted, in the short term, as they are (FAO, 1992). In some cases, however, as the volume of wood transported over the road increases it becomes justified to modify the alignment of the road.

The remaining sinks of engine power can all be managed to some degree. The most significant sink for the converted engine power is rolling resistance (Ljubic, 1983).

Roads, regardless of the quality of their construction, are flexible structures and deflect under the weight imposed on them by the vehicle. Consequently the tyre is always in a deflection bowl (Douglas, 1986) that moves continually with the vehicle. The force required to perpetually drive out of this deflection is a major component of rolling resistance. The magnitude of this force is dependent on the stiffness of the road structure; a tarred road will deflect less than an earth road. The stiffness is in turn dependent on the compaction of the material and the depth to which it is compacted (Morkel, 1994).

Road roughness can be divided between the state of the road according to its design level and the actual surface condition. Road roughness, a measure of irregularities in the surface (Ljubic, 1982), causes unnecessary flexing in the tyres (Douglas, 1986). The flexing of the tyre absorbs energy and gives rise to higher rolling resistance. Road roughness has been shown to be a significant contributor to all aspects of transport costs (Jones & Paige-Green, 2000; DOT, 1990). Ljubic (1983) showed a 20% reduction in fuel consumption purely from grading a stretch of gravel road. The roughness of a road is a controllable factor connected to the design specification of the road, and affects operating costs of transport vehicles (Anon, 1990). Road roughness decreases vehicle speed (affecting productivity) and increases the cost of maintaining the vehicle (Iwakawa, 1981) and its tyres (DOT, 1990).

An additional aspect of road roughness is surface condition, which refers to the frequency of defects on a road section (Morkel, 1994). Examples of defects would be potholes, washboard and erosion gullies. Defects have both a psychological effect on the driver, causing slower driving owing to a perceived lack of safety, as well as increased gearing as a result of slowing down for potholes and eroded areas. This increased gearing causes higher fuel consumption and greater wear and tear on the engine parts, while the slower driving speeds will affect productivity.

An additional benefit of improved road condition resulting from lower power losses is the option to select lighter trucks (Douglas, 1988; Marshall, 1989). The selection of lighter trucks has a number of benefits. Most obviously a lower initial investment

reduces the fixed costs and as a consequence of lower tare weights allows for greater payloads and fewer trips (Douglas, 1988). Reductions in tare weights have resulted in 20% lower operational costs (Williams & Nader, 1993). In addition a driver's opportunity to negatively influence transport costs is lowest during the period when the engine demands full power and smaller trucks will spend more time at full power (McCormack & Douglas, 1992).

There is considerable evidence that an improvement in road surfacing will reduce operating costs of transport enterprises. Tyre, maintenance and fuel costs are all reduced with an increase in road surface quality (FAO, 1992). Specific cost reductions noted are: 5% reduction in maintenance spending (Nader & Williams, 1993) and 10-20% reduction in fuel consumption (Nader & Williams, 1993; Ljubic, 1983). In South Africa, Jones and Paige-Green (2000) predicted a 20% reduction in total operating costs resulting from improved road maintenance.

Time reductions were investigated by Nader and Williams (1993) who found that increasing the number of shift hours resulted in a 10-15% increase in production. These gains could also be realised by increasing the efficient use of time by increasing driving speeds. However, transport costs are insensitive to travel speeds if the increase does not improve throughput. Scheduling is therefore essential with an aim to use the numerous origins and destinations and varying lead distances occurring in forest product transport to allow accumulated time reductions achieved during a shift to be converted into additional loads (Morkel, 1995a). In other words, trips of varying distance should be combined to keep the truck actively transporting throughout the shift.

In many cases the reductions in operational costs will offset the costs of road improvement (Paterson, 1971). Paterson's (1971) observations were confirmed in South African conditions by Jones and Paige-Green (2000): "The major proportion of the total cost of unsealed forest roads is the vehicle operating cost, which is normally several times the cost of initial road construction and maintenance." It is emphasised in the available literature that in many cases transport operation costs will be reduced by improving road condition and yet it is acknowledged that South

African roads are in an appalling state and continue to decline (Morkel, 1994, 1995b; DOT, 1998; Jones & Paige-Green, 2000).

### **2.1.2. South African road management**

The inadequate management of South African forest roads cannot be attributed to a lack of information but to a lack of understanding of cost-benefit analysis techniques and a reluctance to apply them. Morkel (1994) confirmed this lack of understanding or skills, when he discovered that only 4% of road managers had received any form of basic education in roads management. The situation is further complicated by the fact that the benefits of improved road condition are accrued by the transport company, while the costs of road improvement is borne by the road owner, forest company or provincial (state) authorities (Anon, 1990). In other words, it is unclear to what extent the roads should be improved and who should pay for it.

The number of variables and the variation in their values imply that there is no panacea that can be applied to all roads across all conditions. New Zealand's Logging Industry Research Organisation (LIRO) discourages "fixed standards" and depends on a needs analysis and economics to set individual road standards (Morkel, 1995b). Jones and Paige-Green (2000) state that the onus rests on the forest company to conduct cost-benefit analyses on the investment in the road network and to provide sufficient funding for its maintenance. The fundamental theory of such analyses is to evaluate the benefits, such as fuel, time and maintenance cost reduction, and the costs of providing alternative facilities (Anon, 1990), and to compare the net present value of the options (Larcombe, 1999).

The objective of efficiency is made even more elusive as a result of rapid changes in the planning environment. These rapid changes occur in economics (e.g. changing interest rates), technology (new equipment) and harvesting sites. In other words an optimal solution continually changes with time and the location of harvesting operations, and this means that calculations must be repeated often (Bradley & Winsauer, 1976). In addition, due to the number of variables, road management decisions are difficult to make without some form of aid or tool. The optimum road

standard and the construction cost of a particular road will be dictated by the following considerations (Morkel, 1995b):

- Total volume to be serviced by the road
- Market value of the wood
- Period over which the wood is to be harvested
- Total transport distance from roadside to mill
- Seasonal variations and constraints
- Environmental constraints and
- Terrain in which the road is to be built

In order to resolve the problem, vehicle simulation programming is needed to allow a forester to predict the impact of changes in road condition under a variety of projected conditions and variables (Douglas, 1988). The Forest Engineering Research Institute of Canada (FERIC) developed a vehicle simulation programme called OTTO, which is available to FERIC members. Cummins produces a product called Vehicle Mission Simulator (VMS), which predicts the performance of a truck for a specific road alignment. Unfortunately, the former is not available to non-FERIC members and the latter is not suited to this study.

Due to the interactive and repetitive nature of such a task, computers provide the ideal tool. Different alternatives can be considered at a fraction of the time and cost of one real experiment (Bradley & Winsauer, 1976) and a manager can visualise the interactions of the entire system. The ability to predict travel time is critical in estimating transport costs for various truck sizes and configurations (Marshall, 1989). In addition, the frequent changes in condition throughout the route would necessitate the constant recalculation of performance formulae, which further suits the application of computer-based models. A vehicle and route simulation programme would enable a study of the haul route and recommend the best road standard and vehicle type (Smith, 1981).

## **2.2. Operations Research (OR)**

Many different definitions of operations research (OR) are found in the literature. OR is a complex field and requires a broad knowledge of both modelling and the systems being modelled. The definitions can be distilled and OR can be thought of as a language or tool for formulating and communicating a problem, the function of which is to help managers better understand some part of their working lives (Robak, 1990a).

This is achieved by developing symbolic models that mimic the real environment. A model can be defined as a simplified representation of a part of the real world (the system of interest) which concentrates on certain elements, considered important for its analysis from a particular point of view (Ortuzar & Willumsen, 1994). The ability to choose and adapt models from a diverse range for particular contexts is an essential skill. In order for studies to be meaningful, an appropriate model of the problem at hand must be formulated, following which an effective algorithm must be selected (Golden & Assad, 1988).

### **2.2.1. The model**

Models in OR represent two things: firstly, a device for making predictions; and secondly, a statement of the beliefs and assumptions made by the scientist constructing the model (Mitchell, 1993). Model building can be a costly and perhaps an unrepeatable process. It is always worth giving thought to the choice of model types (Mitchell, 1993).

A model is comprised of three components: variables, restrictions or constraints, and objective decision criteria (Taha, 1997). The objective decision criteria define the basis on which the decisions will be made: for example, minimum cost, travel time, number of vehicles, or maximum turnover or throughput. The solution is subject to restrictions, for example, certain values may not be less than zero or production for a piece of equipment may not be greater than its capacity. The variables provide the

input and are representations of what is being studied. Certain parameters may represent managerial decisions, in which case the choice of the value of the parameter may be the issue to be studied (Hillier & Lieberman, 1986). An optimal solution is a feasible choice for decision variables with an objective value at least equal to or better than any other solution satisfying all constraints (Rardin, 1998).

Simple models can be solved with a high degree of precision and the objective function can accurately provide differentiating criteria. As the problem constraints become more complicated, the ability to base a decision on one quantifiable factor diminishes. In reality, it is difficult to extract one definite predictor from many variables (Mitchell, 1993). As the solution technique is composed of more and more interacting sub-models, the objective function starts to assume the role of a chosen control on the quality of the solutions, rather than an exact representation of the total operating costs (Golden & Assad, 1988). In the same manner, as the complexity of the problem increases, the likelihood of finding an optimal solution decreases (Pulkki, 1984). In any case a sensitivity analysis of the model is essential to determine which variables and constraints affect the objective function the most.

The degree to which a problem can be accurately modelled is largely based on the detail incorporated (Golden & Assad, 1988). There are several features that must be taken into account when specifying an analytical approach: the decision-making context (or level), the availability of suitable data (Ortuzar & Willumsen, 1994), the scope, the environment and the goal (Fortuin *et al.*, 1996)(Table 1). Naturally, real problems are not as easily classified and may form a hybrid of categories, but this provides a useful guideline.

**Table 1: Decision attributes (Fortuin *et al.*, 1996)**

Scope	Single component	Connected subsystem	Complex system
Level	Operational	Tactical	Strategic
Environment	Static	Evolutionary	Dynamic
Goal	Well-defined	Multiple Concerns	Fuzzy
Data-set	Small	Large	Huge

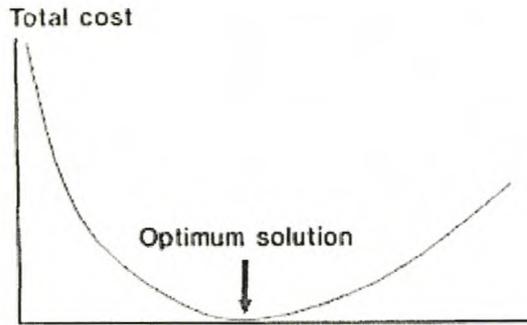
With each level in Table 1 comes a different level of detail. A project can be strategic, tactical or operational. With each level, assumptions must be made and the further right one moves in the table the more simplifying assumptions become. At a strategic level a company is concerned with direction and it is not necessary to include all the alternative courses of action considered. At the same time a strategic environment is more complicated than the others and will have larger data sets, requiring more dynamic and responsive models. Conversely, an operational model is concerned with more exact answers. For example, it may be concerned with optimum paper roll cutting patterns to minimise waste. The real system is simpler and modelled with high levels of accuracy. Data sets are small and relatively static.

It needs to be recognised that solutions are only optimal in respect to the model being used. Since the model is an abstraction of the real world, there is no guarantee that the solution will be optimum in the real world. However, if the model is well formulated, the resulting solution should tend to be a good approximation of the ideal course of action for the real problem. Therefore the test of the practical success of an operations research project should be whether it provides a better guide for actions than can be obtained by other means (Hillier & Lieberman, 1986).

Mathematical (i.e. symbolic) models are the cornerstone of OR studies. However, there is more to the solution than this. Specifically, decision problems include intangible variables that are less easily quantified (Taha, 1997), in this case the effect of the driver. Thus the mathematical aspect of OR should be viewed in the wider context of the decision-making process (Pulkki, 1984; Taha, 1997).

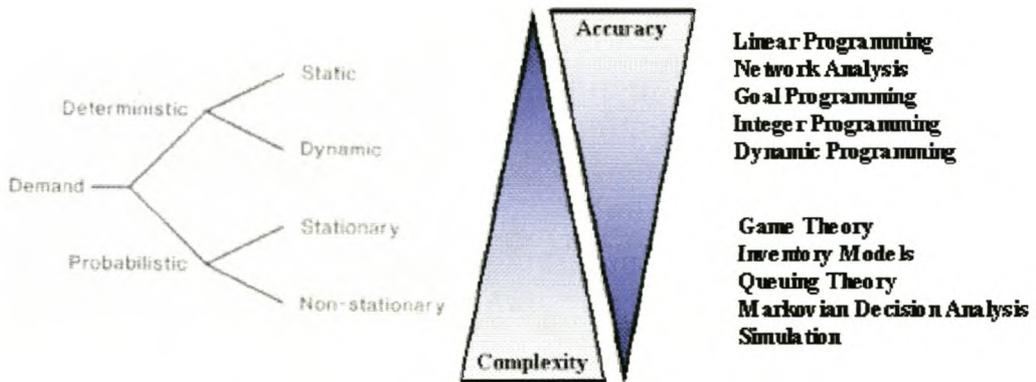
When developing a model, it is advisable to begin with a very simple version and move towards more elaborate models that more closely reflect the complexity of the real problem (Hillier & Lieberman, 1986). This process of enrichment continues until the cost of refining the model one step further exceeds the benefit of increased accuracy. If all inputs can be quantified, then mathematical optimisation techniques are appropriate. As more complex problems arise that require the consideration of less well-defined variables, simulation and/or heuristic techniques are required (Pulkki, 1984). Heuristics are intuitively designed procedures that work towards an

optimal solution in an iterative manner and determine a good sub-optimal solution. The heuristic solution will provide a solution somewhere near the optimum but not necessarily at exactly the minimum point. However if the nature of the solution area is fairly flat as in (Figure 2), the sub-optimal solution may be good enough and may be significantly cheaper to generate.



**Figure 2: The flat solution space (Pulkki, 1988).**

A representation of the variety of OR models and their classification is given in Figure 3 (adapted from Hillier & Lieberman, 1986; Taha, 1997). On the left hand side is a hierarchy of model types and on the right are OR tools used for the solution of that model type. The models and tools increase in complexity from top to bottom and at the same time the accuracy of their solutions becomes less well defined.



**Figure 3: OR models and their classification**

Considering the left side, or problem demands, two sub-divisions can be seen, deterministic and probabilistic. Deterministic models are where it is reasonable to

assume all problem data to be known with certainty, while probabilistic (or stochastic) models involve quantities known only in probability (Rardin, 1998). The power and breadth of available mathematical tools for stochastic models does not nearly match that available for deterministic models (Rardin, 1998). The nature of transport problems is that they are deterministic and are therefore quite solvable (Golden & Assad, 1998).

Deterministic solutions can be further broken down into static or dynamic problems. A static problem is when the assumed inputs of the problem do not change during the execution of the model (Golden & Assad, 1988). The values need not be estimated with complete accuracy but educated estimates are sufficient. In a static case there is no time, or scheduling, component of the problem: the information is assumed to be of the same quality irrespective of time. Dynamic problems, on the other hand, have a strong time component and the variables may change values frequently. For example, with a vehicle scheduling system there will be a real time change of orders that the model must accommodate. In the case of provincial roads, we are not concerned with the allocation of resources in the short term but rather the long-term usage of roads. Consequently, we can assume the system to be static.

Natural resource decision support systems (DSS) have evolved to encompass multi-component systems that include various combinations of simulation modelling, optimisation techniques, heuristics and artificial intelligence, geographic information systems, and user interface components (Todd, 1997). Each OR technique is designed to cater for a particular specification of a problem. Consequently, in order to choose the best modelling technique the characteristics of the transport system must be considered in detail.

### **2.2.2. Transport problem characteristics**

Transport simulation can be viewed as a three-tiered pyramid increasing in complexity from the base up (McCormack & Douglas, 1992). At the foundation is the physical interaction between the road and the vehicles, which have lower variation in behaviour, and can be modelled using equations. The second level is the

behaviour of the driver, which varies significantly and is extremely difficult to predict. Due to this unpredictable variability of potential impact, most transport models assume driver response to be robotic as is the case with the model presented in this paper. Consequently this kind of model is not appropriate where absolute performance is required (McCormack & Douglas, 1992). The final level is that of the interaction of the fleet with the road network and it is this level of consideration that forms the primary focus of this thesis.

Geographic Information Systems (GIS) combined with OR have proven to be promising in solving forest road network problems (Tan, 1992). The temptation is to develop an all-inclusive expert system for solving all road problems. However, a simulation model of this type would be expensive to develop. In addition the bigger a model, the more generalized its solutions become. Pulkki (1988) states that a universal software package for use as an operational tool is not practical, due to the fact that each company's transport requirements and criteria for decision-making are different. Robak (1997) confirms this and emphasises the need for modularised systems aimed at supporting single decisions.

The general transportation problem is concerned with distributing a commodity from any group of supply centres, called sources, to any group of receiving centres, called destinations or sinks, in such a way as to minimize total distribution costs (Hillier & Lieberman, 1986). Due to transport problems being quite tractable they are one of the most researched elements in OR (Golden & Assad, 1988). A number of specialised techniques have been developed in order to deal with different aspects of the transport problem.

Transport problems can principally be split into two forms: routing and allocation problems. Routing problems are concerned with the optimum route from one point to another along a network. Allocation problems are concerned with how much of a resource to ship from one point to another and to which end point the resource should be shipped. The two techniques are often used together with the routing problem used to generate costs to feed into the allocation problems (Rardin, 1998).

The characteristics of the transport problem determine what kind of solution algorithm is needed. The basic transport round trip of most commercial endeavours falls into one of the following categories, increasing in complexity (Golden & Assad, 1988):

1. Pure pick up and pure delivery
2. Pure pick up or pure delivery with backhaul
3. Combined pick up and delivery

In the first case, the transport moves from supply points to sinks without taking on more stock or dropping off at other points. It returns empty and the problem is only concerned with one-way routes and allocations. In the second case back-haul is considered, which complicates the model, as the back-haul route may not lead to the original source node. The final option adds complexity by allowing the transport to pick up or drop off stock on route and thus has changing payloads. In addition, as the number of supply points and delivery points increase so does the complexity of the problem. Forestry is distinctive in that it has many supply points (plantations, stands or individual trees) and few delivery points (pulp or saw mills). This is relatively simple to model as it is a pure pick up and delivery problem, usually with no backhaul.

The general transport problem is further complicated by temporal elements. In classical routing problems, all customers must be visited and served. In reality, however, the set of customer locations can be divided into three classes: those that must be served in this period, those that can be served and those that should be delayed until a future period. This necessitates knowledge of customer inventory levels in order to prioritise the customers (Golden & Assad, 1988).

Classical vehicle routing problems require demand to constantly equal supply. In reality, however, demand fluctuates over time (Golden & Assad, 1988). A further factor to consider is the start and end locations of the vehicles; e.g. do they end at a depot or do they end at the driver's home? The route duration and start times are also important. For example, some start times may have to be staggered when only one vehicle can be loaded at a time. When transporting over long distances, breaks for the driver must be scheduled (Golden & Assad, 1988).

An extension of the transport problem that allows routing to one point and then from there to another (say a depot) is called the transshipment problem. The transshipment problem can be described in general terms as being concerned with how to allocate and route units from supply centres to receiving centres through transshipment points (Hillier & Lieberman, 1986).

Pulkki (1984), Hillier and Lieberman (1986), Moore *et al.* (1988), Session (1992) and Kosir (1995) report that linear programming, network analysis, mixed integer mathematical programming, dynamic programming and heuristics have been used to solve transport problems in the forestry context.

The choice of technique is determined by the scope and required accuracy of the problem. Defining optimum road condition is a tactical level project and will require accurate results. Specific roads must be identified and maintained at a specific condition for a lengthy period of time. Heuristic techniques can therefore be deemed inappropriate. Furthermore, the variables in consideration are continuous and integer programming is not suitable. The decision must be made between the deterministic techniques of linear programming, network analysis and dynamic programming.

Linear programming is an important element in solving transport problems (Hillier & Lieberman, 1986). All transport problems can be solved with linear programming and the problem types arise frequently in practice in a variety of contexts. However, they usually require very large numbers of constraints and variables. A straightforward computer application of the simplex method may require an exorbitant computational effort. Thus special streamlined versions of the simplex method have been determined (Hillier & Lieberman, 1986). These special case solution methods are referred to as the transportation, assignment and transshipment problems. A basic assumption is that the cost of distributing units is directly proportional to the number distributed (Hillier & Lieberman, 1986), and that supply equals demand (although this is easily solved by creating a dummy source or sink).

Network analysis falls under mathematical programming and has important applications in information theory, cybernetics, and the study of transportation

systems (Hillier & Lieberman, 1986). One basic problem that often arises through the study of transportation systems is that of locating the shortest route. The reader is referred to Hillier and Lieberman (1986) for terminology and basics of network analysis and to Sessions (1992) for an introduction to network analysis for forestry applications. A disadvantage of network analysis is that skill and knowledge is required to draw the networks (Sessions, 1992). This means that for each specific road network a specific network must be drawn answering to situations requiring changes to the model and input.

Although it is possible to formulate shortest route problems with linear programming and network analysis, it is usually more efficient to use dynamic programming based methods (Rardin, 1998).

The name dynamic programming is assigned to a general approach to problem solving, with the particular equations used being developed to fit each individual situation (Hillier & Lieberman, 1986). Dynamic programming starts with a small portion of the problem and finds the solution for the smaller problem. It then gradually enlarges the problem, finding the current optimal solution from the preceding one, until the original problem is solved in its entirety (Hillier & Lieberman, 1986).

Transport problems, due to the fact that they form a network, can be represented as a matrix (raster grid). This allows an application of a special case of dynamic programming (Hillier & Lieberman, 1986), where the objective would be to locate the shortest or longest route through the network. These are the most specialized and thus the most efficiently solved of all broad classes of optimisation models (Rardin, 1998). Algorithms exist for the following situations: from all nodes to all others, and from one node to all others, with or without negative dicycles and negative costs.

Dijkstra's algorithm was selected for this study. The application of Dijkstra's algorithm requires there to be no negative dicycles (Rardin, 1998). Dicycles create circular dependencies in functional equations that preclude their solution by one-pass evaluation, even if the length of all dicycles is non-negative. A dicycle is a path that begins and ends at the same node, and a negative dicycle is a dicycle of negative total

length (Rardin, 1998). To cope with non-negative dicycles it is necessary to iterate. Each major iteration of the search evaluates the functional equation for each vertex  $v[k]$  using results from the preceding iteration. This ends when no result changes (Rardin, 1998). The consideration of scattered stands being harvested and their timber transported to one delivery point means that we want the shortest route from one point to all the others in the network. Distances and/or times represent the links in a road network and thus there are no negative values and no negative dicycles. The speed of this algorithm is accounted for by the fact it processes each arc only once, unlike other algorithms that evaluate all nodes in all iterations. For a detailed mathematical breakdown the reader is referred to Rardin (1998).

### **2.2.3. Map representation**

There are two major data formats for map data: raster and vector (Clarke, 1999). A raster model divides the terrain into a grid and assigns a value representing a particular feature contained in each cell to all cells within the grid. Vector models define all cartographic objects based on small lines defined by a beginning and end point. Table 2 summarises the characteristics of each type (Pulkki, 1984; Clarke, 1999; Demers, 2000).

**Table 2: Vector vs. raster data**

Vector Data Representation	
Vector refers to the representation of lines and shapes by a sequence of short lines defined by their end points (nodes) (Pulkki, 1984).	
Raster Data Representation	
A raster or grid organisation is where information is recorded at regular intervals in the smallest logical unit or cell (pixel) (Pulkki, 1984).	
Raster	Vector
All space is defined	No information exists for space between points
Greater generalisation of data	More accurate
Easier data manipulation	Working with data more difficult
Simple to conceptualise	More complicated
More bulky to store	Efficient storage
Fixed scale	Scaleable
Related to pixel based remote sensing	
Overlay operations are easier to perform	

Due to its computational convenience, raster data is used in this method. It is easy to work with, overlay and translate into a network (Pulkki, 1984; Tan, 1992; Clarke, 1999). It also facilitates the application of dynamic programming because it is already in a matrix format. Vector data does not explicitly define the intervening spaces between objects and consequently no calculations can be performed in these spaces (Demers, 2000). This does not suit this network model, as calculations need to be conducted at any point along a route or surface: for example, timber is dispersed along the road and not only at junctions.

If a cell is completely represented by one feature then the cell is assigned that feature. Problems arise when only a small portion of the cell contains a particular feature. A number of decision strategies exist and each has its application, depending on the feature being digitised. These are summarised in Table 3.

**Table 3: Input strategies**

Method/Strategy	Description	Use
1. Presence/absence method	If the feature occurs in the cell it is assigned	All line features (roads)
2. Centroid-of-cell method	Entity is recorded only if it crosses the centroid of the cell.	Areas
3. Dominant type method	If the entity occupies more than 50% it is recorded	Areas (Forest)
4. Percent Occurrence	The actual percentage occurrence is recorded for each cell	Areas

Method one is the only practical method for line features that would cover a small portion of a grid cell. Methods two and four require more computation and consideration and thus method three is most commonly used for area features. The rough total area is conserved as cells with less than 50% coverage are left out and are balanced by those having between 50% and 100% coverage.

### **2.3. Decision Support Systems (DSS)**

Computers have revolutionised our approach to almost everything. Forestry is no exception and the opportunities appear limitless. Foresters must handle tremendous volumes of numerical and spatial information. Planning forest operations now span many parameters, including ecological, technical, regulatory and worker related parameters (Anon, 1996). These parameters become more complex, sensitive and volatile with time (Robak, 1990a). The application of sustainable management, driven by certification, relies on consideration of both timber and non-timber values. The latter includes the protection of water quality, wildlife and environmentally sensitive areas, and the provision of recreational opportunities (Robak, 1997), as well as social values. This implies that managers must also make decisions based on qualitative criteria (Robak, 1990a). At the same time the company must justify its use of resources by showing a significant return on investment (Robak, 1997) within a global decision-making environment characterised by increasing international competition and fluctuating world market prices for wood and paper products (Pavel *et al.*, 1999).

Despite the increasing complexity of the decision environment there is a concurrent international trend in corporations to form flatter, leaner organisational structures without providing the specialised support staff that such a structure demands (Robak, 1990a). This means that a manager has more to do both upstream and downstream within the company structure. For a forester this means more resources to manage.

Added to this trend is that of outsourcing. Contractors are smaller than corporations, with fewer organisational support structures to plan operations and provide services (Anon, 1996). This implies, at a corporate level, that managers have too much to do and tend to under-utilise information. On the other hand, at an operational level, smaller firms do not have the resources to adequately gather or utilise information. In such situations the lack of appropriate decision tools and evaluation criteria may tempt managers to use naive rules and large factors of safety in their decision-making. Alternatively, they simply stop making decisions at all (Robak, 1990a).

The complexity of making coherent, integrated, and inter-dependent management decisions within this intricate decision environment described above, challenges human capabilities (Todd, 1997). Companies can overcome these constraints by improving managerial access to expert knowledge by hiring more specialist consultants and/or using information technology to provide key knowledge (Robak, 1990a). Computerised systems present significant opportunities related to managing resources, landscapes and truck fleets, and for designing, constructing and rehabilitating roads (Anon, 1996).

Computers are not able to consider the problem on their own. Human scientists and managers need to formulate the problem in a language that computers can work with. Consequently the use of computers for problem solution is inexorably tied with OR. In addition, in practice all OR solution methods result in computational algorithms of an iterative nature (Taha, 1997). In other words the problem is solved in steps, with the number of steps required increasing with increasing problem complexity. This lends itself to the use of computers, as computers are faster and are not prone to calculation errors.

### **2.3.1. The implementation gap**

No research work is worth its time unless its target audience accepts it. Research has been conducted that has not been initially accepted by the target audience despite the fact that this information is highly useful. It seems that although managers express an interest in OR techniques, they rarely get around to actually using them. This is a pervasive trait of all management and is not limited to forestry (Robak, 1990a). This ambivalence is partially due to the models being too complex, such that the managers who need to understand them lack this understanding (Robak, 1990b). Consequently they put less confidence in the results. Additionally, research has shown that in complex decision situations where managerial decision-making is based on limited information, experience and intuition may yield better results than purely rational models (Robak, 1990b). This could be due to inefficiencies in the capacity to model complex environments and/or the human mind's esoteric ability to cope with large numbers of variables.

It is managers and not modellers who must justify, implement and control such solutions. Managers must be able to detect when solutions are invalid and when circumstances have changed to such an extent that the model should be updated or re-run with new data (Robak, 1990a).

There are two approaches to the implementation problem: firstly, providing a DSS or expert system and secondly, using OR and computers to solve a specific problem. Both have implications for development expertise and budgets. The former requires multi-disciplinary teams and considerable budgets, while the latter, although cheaper, has a life span that is limited to that of the project.

### **2.3.2. Scope of systems**

DSS applications combine the conclusions of research and practice into an effective system, the purpose of which is to improve the quality of decision-making (Robak, 1990b). Generally DSS applications are large programmes that are aimed at less structured, under-specified problems. They are often made up of smaller less sophisticated programmes and tools, which in their own right could be considered decision support tools. The larger systems focus is on all phases and levels of decision-making and emphasise flexibility and adaptability. They are used for modelling problems that are large and complex where the required precision exceeds the ability of the manager alone (Robak, 1990b). In order to accommodate the varied decision environments, the development of such a system requires large interdisciplinary teams and significant investment. The ultimate focus is on providing the manager with information that will aid decision-making and not to provide rules to dictate the decision.

The problem addressed by this thesis is too specific to warrant the high capital investment of developing a large DSS. In addition, the South African OR development environment is underdeveloped and there is insufficient communication between companies, and therefore, it is unlikely that there would be funding and acceptance for such projects. Thus South Africans should concentrate on developing

tools that provide managers with the most benefit at the least cost (Robak, 1990b). The focus should be on developing aids to decision-making and not on complete system modelling (Robak, 1990a). This frees managers who have a good sense of the whole system to make decisions based on intuition and improved information (Robak, 1990b). In addition the managerial problem space is so volatile that by the time complex models are developed, the data gathered and the solution generated, it no longer addresses the managers' concerns (Robak, 1990b). Generating smaller systems that are more problem specific allows the researcher to quickly respond to changes in the environment and the desires of the manager. Consequently it is this approach that is taken within this study and a simple problem specific model and programme was developed. It is possible that the small decision aid developed here can be incorporated into a larger decision support system.

### **2.3.3. Choice of programming language**

Within South Africa it is better to concentrate on solving a particular problem with smaller more adaptable computer-based aids. However, some of the principles used in the development of a full DSS cannot be ignored. In order for the model to be accepted and implemented the programme must be simple enough to be used by the forest and district personnel on a production basis and the solution time must be rapid enough to permit plan modification, alternative evaluation and frequent updating (Sessions & Sessions, 1988). The advent of low cost, powerful microcomputers in the 1980's, and their evolution into the personal computer in the 1990's, moved the location of the computer to the manager (Pritchard, 1990). This circumvents the problem of the user being isolated from complicated models, but has implications for development.

Durrstein (1992) summarises the experience and demands of the user in order to define the following criteria for effective computer aids (with specific reference to road planning):

- Suited to standardised software.
- Modular structure corresponding to traditional planning methods for utilising the engineers' experience in road planning.
- Simple handling based on clear screen menus, which avoid intensive training in the use of computer systems and increase acceptance by the forest engineer.

These objectives were met by the use of Visual Basic as the programming language of choice. Of personal computers worldwide, 90% run Microsoft's Windows<sup>®</sup> operating system (OS) (Dillinger, 2000), and most companies in South Africa use this OS or have access to it. Microsoft Visual Basic<sup>®</sup> (VB) is an object orientated programming language, a major aim of which is to generate Windows compatible programmes. VB was selected because of the relatively short learning curve required and the fact that it generates programmes according to a standard already generated by Microsoft. The programme produced, with pull down menus and familiar look, is therefore user friendly and standardised to common platforms.

The choice of developing the application for a Microsoft Windows platform is taken by many developers. Todd (1997), in a review of current DSS's available for environmental resource management, discovered that 79% of these systems were Windows compatible.

VB's power lies in text processing and not in mathematical processing like Fortran and C++ (Perry, 1998). However with the fast running speeds of modern day PC's, the computation time is still well below a few seconds, which is sufficient for this application. The use of VB has an additional advantage in that it is a language compatible with powerful GIS programmes such as ArcInfo<sup>®</sup>. It is hoped that if the project proves successful, it will be integrated with other road planning and GIS systems, and will be developed as a module within a DSS.

The selection of a DSS should be based on cost for the system, including computer hardware and software, the cost of installation and training in the use of the system, as well as the cost for its initial development, operation, maintenance and upkeep (Pulkki, 1988). The costs should be in favourable relation to the benefits. The focus on a single decision problem and the use of available, easy to implement technology keeps the above cost components at a minimum. The application has been developed cheaply but with sufficient quality of output. This enables its use by large companies, contractors and private landowners. The latter represent 24% of the plantation holdings in South Africa (FOA, 1998) and are a significant market segment.

### 3. Methodology

#### 3.1. Questionnaire

A survey of the current state of provincial roads in South Africa was conducted by means of a questionnaire. The goal of the questionnaire was to gather information not only about the state of the roads but about other factors concerning the management of these roads. These factors were other users of the roads, distribution of the axle loads by different users and the effect of water (precipitation) on these roads.

Forest enterprises are distributed throughout areas of high rainfall along the Eastern and Southern seaboard of South Africa beneath the escarpment. Consequently climatic and geographic differences are significant. This means that road alignments and construction materials used will differ markedly throughout the regions. In addition the use of the roads by other industries and agriculture can vary. Consequently it was necessary to send the questionnaires to representatives throughout the country.

The questionnaire, which has been included in appendix A, was sent to a company representative of seven forest enterprises, for distribution to and completion by strategically placed foresters. Completed questionnaires were returned by the following six forest companies:

- Sappi
- SAFCOL
- Mondi
- NCT
- Masonite and
- Northern Timbers

In total, responses were received from 25 separate foresters and transport managers. The only group not included in the survey was the Department of Water Affairs and Forestry (DWAF), which manages 11% of afforested land in South Africa (FOA, 2001). Detailed information on the response rate is given in section 4.1.

The decision to send the questionnaires to forest land and mill owners and not to contractors, the actual users of the roads, was based on the fact that the forest companies are the traditional managers of roads and consequently have the required access to data. In addition, were any improvements made to provincial roads it would be these enterprises that would have sufficient capital to contribute to the process.

Completing a questionnaire takes time away from already busy respondents. In order to encourage response it is necessary to convince the respondent of the necessity of the study and to make the process as simple and quick as possible. The representatives responsible from each company were therefore selected from members of the Forest Engineering Southern Africa's roads working group.

Each respondent was asked to identify all provincial roads in their management area and to locate these on a map (scale - 1:50 000). Each road was then analysed according to three criteria:

- Respondents were required to identify other road users that might impact on road condition, or that would be significantly affected by the road's condition. This provided some of the qualitative information that plays a role in land management within rural development and tourism areas. In addition it gave an indication of the stakeholders involved for distributing the costs of road maintenance or upgrading.
- Respondents were asked to indicate average annual volume transported over the roads and the lengths of each road segment.
- Finally estimations of road condition in both dry and wet states were requested. High moisture content in the structure of unpaved roads is a critical factor as it affects road traffic negatively (DOT, 1990) (note that there has to be some moisture in the road to bind fine materials and

reduce dust and material flying off to the side of the road). Five categories were presented.

- 1: 20% of the road is passable; the other 80% is not in a condition conducive to safe and economical transport of timber.
- 2: 40% of the road is passable and the balance as above
- 3: 60% of the road is passable and the balance as above
- 4: 80% of the road is passable and the balance as above
- 5: The total length is trafficable and in good condition for the time of year during which it is being used to haul timber.

These five categories were based on a standard used by civil engineers in Southern Africa to assess unpaved roads (Ackerman, 2001). The respondent was required to make a visual estimate of the section of road and classify the percentage considered to be passable. In other words what percentage of the road can sustain the quality of service it was originally designed for?

When the questionnaires, with accompanying maps, were received back from the respondents, the information was entered into a database (Microsoft Access©). The distances were confirmed by manually measuring the marked roads on each map. In cases where maps were not included or were on a scale different to the requested 1:50000 map set, the roads were located on appropriately scaled maps and re-measured. From Microsoft Access© the information was analysed and where necessary exported to Microsoft Excel© for further analysis and graphical representation.

The data was grouped and analysed by direct comparison or visual means (graphs and tables). The fact that the data is non-parametric and discrete ruled out simple statistical tests. The quality of information that would be gathered by these non-parametric tests would not warrant the time and effort required to conduct them. Furthermore, due to the large number of roads it was not possible to compare them individually. Therefore roads were grouped in 5 km categories starting at 0-5 and extending to 65 km to accommodate the longest road.

### 3.2. *Simple spreadsheet model*

Simple models often clarify a problem and it is a useful process to progressively build models iteratively from simple to more complex (Hillier & Lieberman, 1986). The benefit of starting with a simple model is that a manager or modeller builds understanding and insight into the system. However simple models are complicated by considering the system as a whole with its interacting elements (the actual road network). Consequently the mathematical model methodology section is divided into two portions: the simple spreadsheet model and the more complex road network analysis programme.

The foundation of the simple model is the physical interaction between roads and the vehicles, which have lower variation in behaviour, and can be modelled using equations (McCormack & Douglas, 1992). Consequently, initially a simple spreadsheet model was used to test the sensitivity of variables. The variables in these equations are altered within a range of possible values, while holding the other variables constant. This yields insight into how sensitive the objective function is to changes within the model parameters and constraints.

The cost of transport to remove the total volume from an area (excluding loading, unloading and queuing/waiting times) can be given as:

$$Total\ cost = \frac{volume}{payload} \times time \times rate \quad [1]$$

Where

- volume* the total volume of timber to be transported on the considered route (m<sup>3</sup>).
- payload* the payload of the vehicle transporting the timber (m<sup>3</sup>).
- time* the time for the round trip (hrs).
- rate* the charge out rate (R/hr) for the transport vehicle.

Consequently volume ÷ payload would yield the number for trips for a particular vehicle. This equation allows the variables volume, payload and charge out rate to be tested simply and meaningfully.

Time is, however, a more complicated variable as it is dependent on a number of other factors, namely the distance of the trip and the average speed attained over the round trip. In order to assess the time variable we need a more complicated equation that would factor in time saved. The equation for time saved per upgraded or rebuilt segment of the trip can be built from the following equations.

$$y_1 = \frac{a}{b_{out}} + \frac{a}{b_{in}} \quad [2]$$

Where  $y_1$  is the time for the trip in hours:

- $a$  the distance in km
- $b_{out}$  is the speed on the trip out, in km/hr (i.e. from the mill to the forest, normally empty and therefore faster)
- $b_{in}$  is the speed on the trip in, in km/hr (i.e. from the forest to the mill, in which case the vehicle is loaded and therefore slower).

$$y_2 = \frac{a}{b_{out} + c} + \frac{a}{b_{in} + c} \quad [3]$$

Where  $y_2$  is the time for the trip (in hours) after the road surface has been improved, given:

- $c$  the improved speed in km/hr due to road maintenance or improvement

The improvement in speed is acting as a proxy variable for road condition. Consequently the total time saved (in hours) will be

$$s = y_1 - y_2 \quad [4]$$

The complete equation for time saved in hours (combining equations 2 and 3) is represented as

$$s = \left( \frac{a}{b_{out}} + \frac{a}{b_m} \right) - \left( \frac{a}{b_{out} + c} + \frac{a}{b_m + c} \right) \quad [5]$$

Therefore, combining equations 1 and 5 produces the following equation:

$$\text{cost reduction } (R) = \frac{\text{volume}}{\text{payload}} \times \left( \left( \frac{a}{b_{out}} + \frac{a}{b_m} \right) - \left( \frac{a}{b_{out} + c} + \frac{a}{b_m + c} \right) \right) \times \text{rate} \quad [6]$$

The cost reduction equation (6) was tested for sensitivity by varying the following variable: the improved speed in both inward and outward bound travel (c).

The simple spreadsheet model is complicated by the relationship between variables. It is not possible to investigate the assumptions regarding the relationship between speeds in both loaded and unloaded states with a simple model. The following assumptions are therefore made:

- the relationship between the speeds loaded and unloaded is constant
- the improvement of road condition would lead to an equal increase in speed in both loaded and unloaded states.

In addition, a simple spreadsheet model is in no way able to predict a change in the behaviour of the entire system based on an improved performance in a section thereof. For example, improving a route may attract volume from other routes. In addition, such an analysis provides insight only into the management of the general system and not for any specific situation. Given an actual road network, the question remains of how to prioritise roads as they interact within the network. There are a number of possible interactions: firstly an improved road may draw traffic away from other roads, and secondly more cost reductions may be possible from improving a short road with high volumes than from improving a very long road with low volumes. The simple model's downfall is that it does not address the system interaction. Consequently a more complicated road network analysis model was developed.

### **3.3. GIS/OR road network model**

The majority of this methodology must be devoted to the description of this more complex GIS/OR model. Tan (1992) describes a GIS as being a computer-based system for handling geographically referenced data to support decision-making. It consists of four main processes:

1. Data input
2. Data storage and database management
3. Data manipulation and analysis
4. Data output

Although the tool presented here is not strictly a GIS (there is a limited database connected to the map data, as information is stored in unrelated flat files) the break down of the processes provides a useful layout for the methodology of the more complex road network analysis. The method will be broken down into four sections: data input, data manipulation, data output and experimental design.

In order to validate the model, it needs to be applied to a relevant South African managerial area. The road network analysis programme was applied to six map segments in the Kwazulu-Natal Midlands. This selection was based on the fact that:

- More complete questionnaire responses were received from the Kwazulu-Natal region.
- Many of the companies surveyed were represented in this region.
- It is the region with the second largest afforested area at 39% of the total afforested area in South Africa (FOA, 2001).
- Most of the expansion of the industry occurs in this region (41% of the total most recent afforestation) (FOA, 2001).

Due to memory limitations of the digitising programme (written in Fortran), grids were limited to a width of 256 cells. With a 500 m x 500 m grid size, this limited the map area to 128 km in width. Modern versions of Fortran and other programming languages are no longer constrained by this; and storing wider areas in two rows could also circumvent the problem. However it was not possible to modify the digitising programme used for this study, hence the somewhat artificial restriction in width to 256 cells. The Kwazulu-Natal Midlands was therefore divided into six

separate sections and digitised accordingly (Figure 4). The selection of this area covers 60% of the map sheets included in the questionnaire responses for the Kwazulu-Natal region.

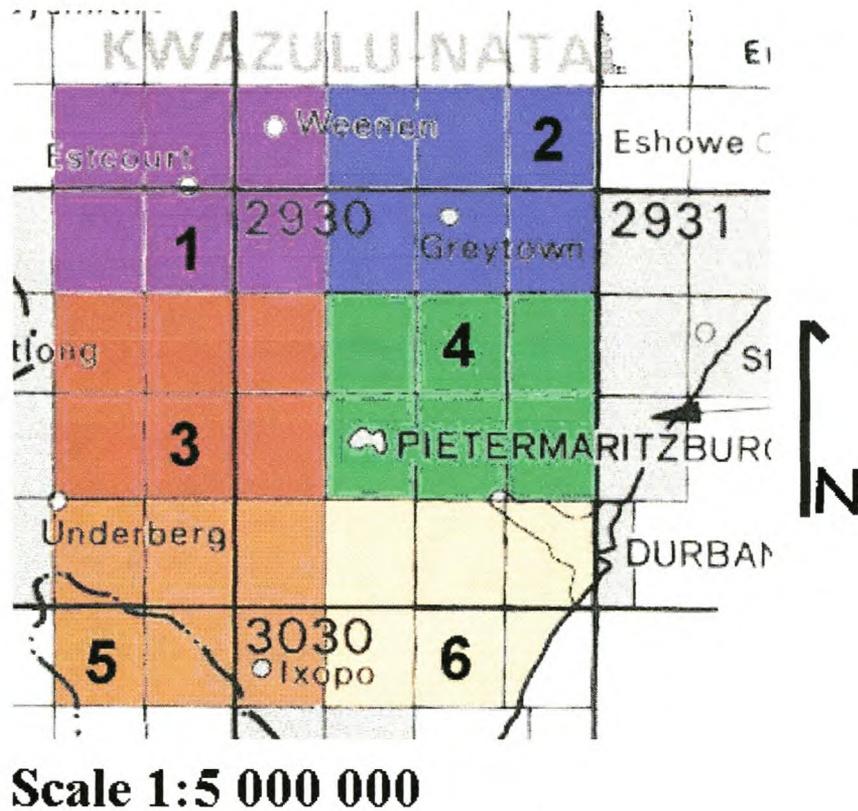


Figure 4: Study area

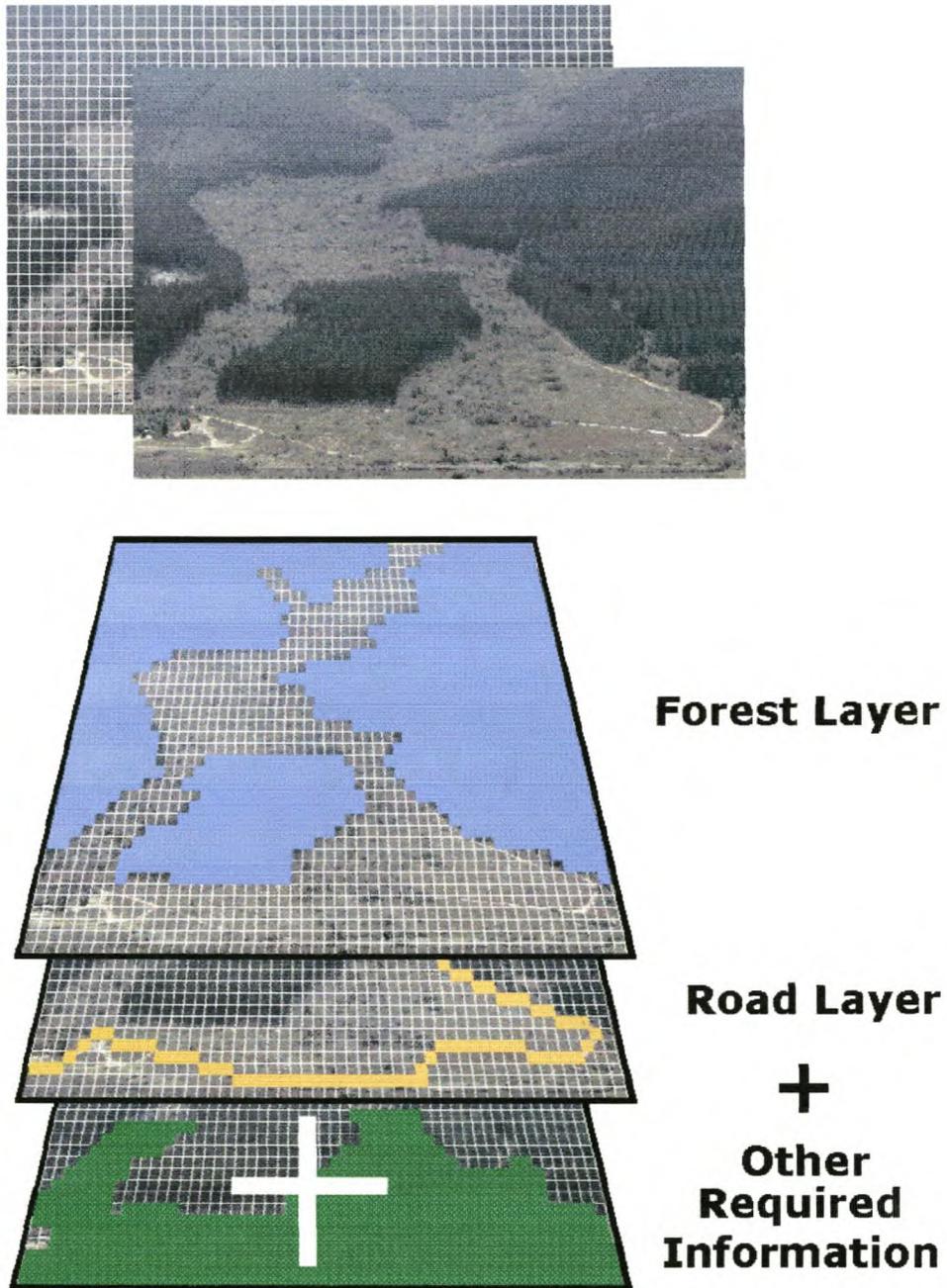
### 3.3.1. Data input

The model input was divided into two sets of data: transport specifications, and the road network and forest area layers. The latter are fed into the model in the form of digitised maps. The process of digitising and the pitfalls it presents are thus a critical part of the method. The effort to determine transport specifications is considerably less, but requires a greater knowledge of the forest transport industry. Experienced personnel must do the cost data estimation with great care, as the usefulness of the result is dependent on the quality of the input. In addition to all available documents and maps, further discussion with local foresters and visits to the field are essential

(Tan, 1992). As a result, industry experts and academic staff were consulted in the derivation of this data.

Any number of map layers can be fed into the model to continually improve accuracy, but due to time and cost constraints data input is limited to digitised road and forest maps (Figure 5). These are variables assumed to have the greatest impact on the solution, because they are both manageable and quantifiable. Some layers that could have an impact, but not included, are slope (considered to be part of road alignment and difficult to change) and soil types.

To facilitate the manual encoding process, a transparent sheet with a grid of selected resolution is laid over the map sheet. The grid sheet permits the user to see which pixel is being digitised (Tan, 1992). Each block is assigned a value representing an attribute. For example a "6" could be used for forest, a "5" for riparian zones and a "4" for roads. Alternatively the area is divided into themes (or layers) each representing one feature (Figure 5). One layer would represent forest, another riparian zones and still another road surfaces. This is the preferred method as it allows an ordinal classification of a feature within a layer. For example, different road classes can be indicated (for example "1" for highways and "5" for forest roads). Within each layer any cell that does not contain the feature being mapped is given a value representing space (Demers, 2000). Caution should be shown during the digitising process. The document sheet must be firmly secured to the digitiser surface in order that the coordinate system remains constant to limit errors in data (Tan, 1992).



**Figure 5: Overview of digitising layers**

The advantage of using a separate forest layer is highlighted by the fact that roads are the primary focus of the study. If one layer were used, when both features appear in a cell you would be compelled to assign a road type to that cell resulting in an inaccurate loss of forest data. As these cells represent 25 ha this would represent a substantial reduction in total volume of timber.

Two map layers were used in this study. A road layer provided the transportation network and a forest layer was used to estimate volumes to be transported over this network. The forest layer represents forested area and thus the dominant type digitising method was used. Roads are line features and therefore the presence-absence method of digitising was used (Table 3).

Resolution refers to the size of the grid cells. As the resolution increases (more grid cells) the data becomes more accurate. However, the process becomes more complex and time consuming. Conversely, as grid cells get larger they represent a larger area and the data becomes more generalised. Raster data does not provide precise location information and the coarser the resolution, the less is known about the absolute position of points, lines and areas represented by the grid cell. There is a continual trade off between the level of acceptable generalisation, and the time and money available to gather, digitise and process data, as well as the cost of the required computer storage.

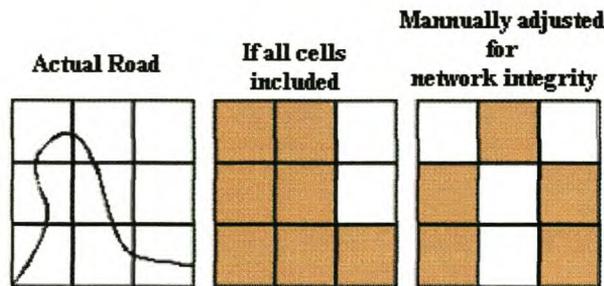
For this study 36, 1:50 000 topographic maps (a total area of 14 000 km<sup>2</sup>) were digitised to make up the study area shown in Figure 4. The Universal Transverse Mercator (UTM) projection forms the basis for these maps. This minimises distortion and provides for high resolutions (Demers, 2000). Pulkki (1984) states that UTM is the most appropriate projection for a raster based GIS. The roads were digitised according to the classification of those maps and given an ordinal rating from one to five according to Table 4. The focus of this study is therefore on class four or secondary/provincial roads. For this reason only essential roads of a lower class, linking forest area with provincial roads, were digitised.

**Table 4: Road classification**

Class	Road Type
1	National Freeway
2	Arterial Route
3	Main Road
4	Secondary or Provincial Road
5	Other or Forest Road

Manual digitising is the most tedious and time consuming of stages in the development process (Pulkki, 1984; Tan, 1992). Alternatively, digitised roads and vegetation cover data in vector format is available from the surveyor general at a considerable cost. This data would then have to be converted to raster format by standard GIS programmes and then corrected. At the resolution and extent to which this study was conducted, time and cost of this process would not be less than that of manual data capture. Therefore the data was manually digitised.

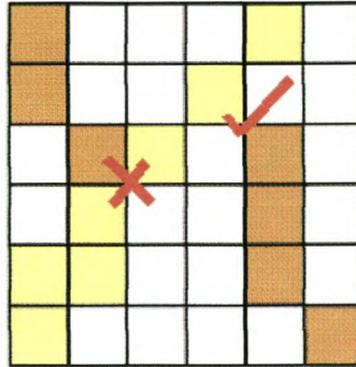
Digitising required some human judgement to prevent crossovers and to maintain the form of the road structure. A resolution of 1 cm by 1 cm was selected, in other words at a scale of 1:50000 each cell represents 25 ha (500 m x 500 m), and hence a road cell is 500 m wide. Thus roads that pass within 500 m of each other would touch if digitised together. This would cause a link in the network that, in reality, is not there. Consequently the digitiser must exercise discretion by manually adjusting the data to prevent this from occurring while minimising deviation (Figure 6).



**Figure 6: Crossovers**

Furthermore, due to complications in the computational process, a low road class (represented by the brown road in Figure 7) should not connect to a higher road class

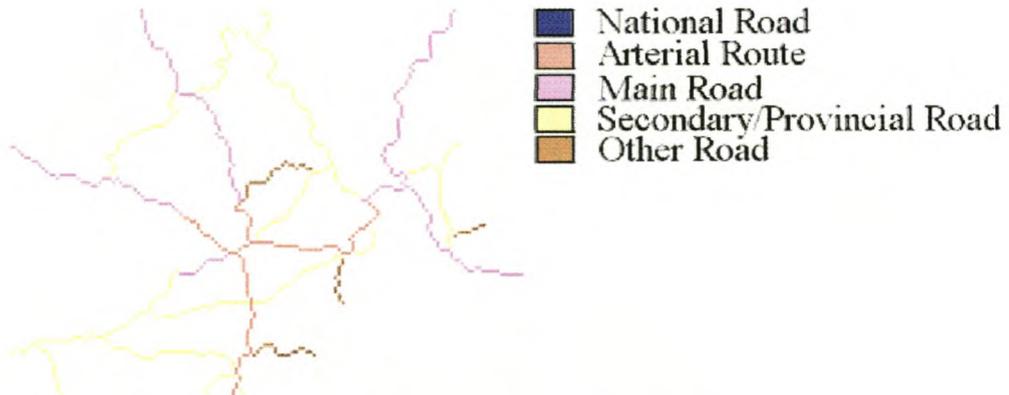
(represented by the yellow road in Figure 7) where it is touching the higher road class on more than 1 side. This case is seen on the left and should be adjusted to connect as on the right.



**Figure 7: Road class intersections**

Finally it is essential to ensure that all roads are connected to each other. An unconnected road will cause the computational process to stall or become stuck in a continuous loop.

A completed map would look like Figure 8, which represents Area 2 (Figure 4). The remaining map areas, including forest coverage, are shown in Appendix B.



**Figure 8: Area 2 road map**

Inputs to the model change with operating conditions, vehicle and time. The determination of model inputs requires experience and knowledge of the system. Due to the scope of the problem it was necessary to use industry averages. Thus

various professional and academic foresters were consulted to estimate the vehicle specification input data. The information required was truck payload, truck charge out rate, and speeds for varying road classes. The average payload for pulpwood trucks in South Africa is 37.8 tonnes (Morkel, 1999) and a payload of 38 tonnes was used throughout this study. The charge out rate of R355.00/hr was determined from a spreadsheet model based on Warkotsch (1994) and Grobbelaar (2000). The travel speeds per road class were determined from Shuttleworth (2000). The MAI for Natal Midlands/KwaZulu Natal of 21 m<sup>3</sup>/ha/yr was estimated from industry averages, published by Forestry Economics Services (1995), weighted by area under each species (DWAF, 1999). The input figures are summarised in Table 5.

**Table 5: Summary of vehicle specification inputs**

Truck payload		38 tonnes
Truck charge out rate		R355.00
MAI (m <sup>3</sup> /ha/year)		21
Driving Speed per road class		
Road Class	Empty	Loaded
1	80	70
2	75	60
3	55	45
4	50	40
5	30	25

An additional input is that of the exit node. It is assumed that all timber is transported towards major mills in Durban or Richards Bay. As only one exit point can be specified in the model, the programme was run twice for each area, using a different exit point on each occasion. This was done to remove the possibility of one exit point being uncharacteristically cheaper than any other. In addition, the average cost reduction would give a more accurate reflection of the actual transport routes used.

### 3.3.2. Calculation process and theory

The transport system in question is considered to be deterministic, pure pick up and delivery, static, and most appropriately solved by using dynamic programming algorithms modified for certain special characteristics of road network studies. It is a shortest route (or shortest time to complete the route) problem and does not consider allocation. Most models assume, as does this one, the driver response to be robotic and consequently absolute performance cannot be guaranteed. The level of problem is assumed to be strategic enough that relative figures will suffice. In this problem case, shortest routes are required from all source nodes to a single destination node. There are no transshipments and no backhaul. These are highly specialised and efficiently solved optimisation models and the most appropriate algorithm in this case is Dijkstra's algorithm modified by Pulkki (1994) for raster networks.

The prioritising of clients and the time value of expenses fall outside the scope of the project. Allocation is not an issue, as only one destination is considered. Operational aspects of scheduling and truck garaging also fall into a more detailed study. The focus is primarily on using shortest route algorithms to determine minimum times from sources to a specific sink.

Faster schemes can be developed if the given graph has special features beyond nonnegative features (Rardin, 1998), as is the case with our situation. The shortest route is determined by applying a modified Dijkstra's algorithm developed by Pulkki (1994). Generally this algorithm determines the minimum cost (shortest distance or travel time) from one node to all the other nodes in the network. Although solutions are found in a few seconds, the computational time does depend on the number of links in the network. In grid cell based networks, links are defined as the distance from the centre point of a cell to the centre points of all eight adjacent cells. To reduce computation time in road network problems the links are minimised by linking to only four adjacent cells (Pulkki, 1994). The nodes vertically and horizontally adjacent to the cell under consideration take priority when setting up links and then diagonally situated cells. This is possible as the nature of a road network is such that one must proceed to an adjacent cell. Computation time is

further reduced by only considering road nodes and not all other nodes (Pulkki, 1996).

Routes are tracked by using labels and recording distances or times as the process proceeds from node to node. A principle of optimality states that as optimal paths must have optimal sub-paths, the shortest path to any node is just one arc extension of the shortest path to a neighbour. This implies that a record of the last link is enough to recover the full path. It is necessary only to move to the indicated neighbour and to follow its optimal path (Rardin, 1998).

The cost of transport of all timber from a node can be represented by the number of trips required to remove all the timber from a particular node, multiplied by the time it takes for each round trip multiplied by the charge out rate per hour to give a total cost per node. The sum of all the nodes that hold timber would give the cost to extract all wood from the area. This is expressed in the following equation.

$$\text{Total cost to transport all the wood from an area} = \sum_{i=1}^n \left( \frac{\text{volume}_i}{\text{payload}} \times \text{time}_i \times \text{rate} \right), \quad [7]$$

where

- $i$  is the current road node being considered and
- $n$  is the last node

The first step in the algorithm is to assign a time to travel from the exit node to all other nodes in the road network. The shortest route algorithm starts at the selected exit node and proceeds outwards along the transportation network (Corcoran, Schiltz & Bryer, 1983). The shortest distance, and by a simple calculation the shortest time, between nodes is given as the connection between the source node and the next node in the network. By successively adding the times between nodes a total trip time is determined from the start node to the current node. The process continues until all nodes of the road network are connected to the source node.

The model calculates transport time based on the empty and loaded driving speeds for a particular road class. The time taken to travel between nodes is a function of the distance between node centre points and average travel speeds (empty and

loaded). The connections between nodes represent the links in the network. The addition of the time for each link would then give the total trip time. The distance between nodes is a function of the grid size in the raster database and of whether the link is to a horizontally adjacent node or to a diagonally adjacent node. In the horizontal case the distance will be equal to the grid spacing while in the diagonal case it would be equal to the hypotenuse of a right angled triangle with the remaining sides equal to the grid spacing. In this study that distance is 500 m for a horizontal link and 707 m for a diagonal link.

If there were no loops (or dicycles), one iteration would provide optimal routes. However as most road networks do form loops this process must be checked and iterations repeated. This is achieved by comparing the shortest route to each node, assigned in the first iteration, to its surrounding nodes. If the difference is greater than the time between the two nodes, then a more optimal route exists. The node is assigned the lower time and optimal times further along the route are reassigned. This is repeated until no further changes are necessary.

The transportation time between each two points is merely the decision variable most suitable for this study. It can be replaced with other decision variables, such as distance. More information on the mathematical workings of the algorithm can be found in Tan (1992) and Rardin (1998).

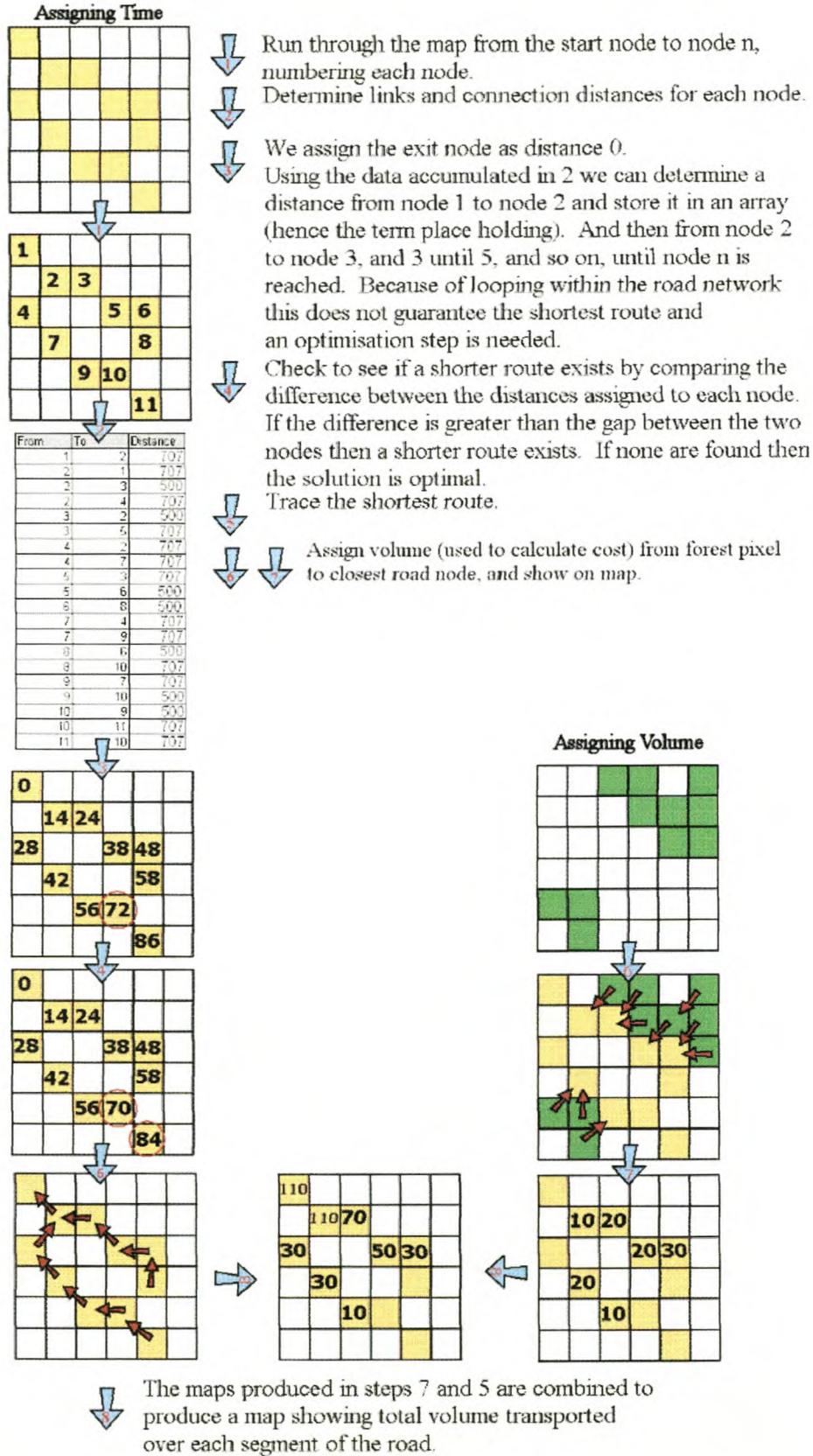
Once the time to travel from a node to the exit/sink node has been allocated to all the nodes it needs to be combined with the other variables. The volume available for transport is determined by considering each forest node and assigning its MAI to the nearest road node. This is achieved by comparing the geographic position of a forest node (forest layer) to the corresponding geographic position in the road layer. If the considered node in the road layer contains a road then the volume (25 ha multiplies by  $21 \text{ m}^3/\text{ha}/\text{year}$  equals  $525 \text{ m}^3/\text{node}/\text{year}$ ) is assigned to that node. If there is no corresponding road node then the eight adjacent cells are checked for road nodes and the volume is assigned to the closest road node. Obviously the road nodes perpendicular to the forest node are considered before the diagonal nodes as they are closer and would therefore reduce extraction costs. If there are more than one adjacent road nodes, ties are broken by choosing the node that has the lowest

distance or time to the exit point. If no road node is located, the next set of adjacent 16 nodes is considered and so on until a road node is located.

Once all the forest nodes have had their volume allocated to road nodes there is sufficient information to calculate total cost. The volume on the node is divided by the payload of the transport vehicle under deliberation, to determine the number of trips. The number of trips is multiplied by the total time to complete the trip to get a total time to transport all the volume available on that road node to the exit node. This total time is then multiplied by the charge out rate to get a total cost to extract the node. The sum of the total costs for each node will provide the net cost to transport all the available volume from the area to the exit node.

Further useful information can be gained by accumulating the volume along the route. This gives an indication of the volume transported over each segment and therefore the importance of the road.

This entire process, developed by Pulkki (1994, 1996) and described above, is illustrated in Figure 9.



**Figure 9: Network algorithm solution process**

### **3.3.3. Output**

The final output is the total cost of transporting all the timber from an area. Two solution files are produced; one with the cost and optimal routes from every cell to the exit point and another with the volume transported over each node. The latter solution file is obtained by adding the volume of each truck to all the nodes it passes through to get to the exit node. Included in the latter file is the total cost to extract the timber for that area. By changing input values and comparing these total costs, it is possible to determine the reduction in transport costs as a result of taking certain actions. Thus there are two files for each exit node across 40 scenarios for six areas giving a total of 640 output files. It is consequently essential that an appropriate directory structure be set up and utilised.

Verification determines the level of confidence or the accuracy of data manipulation in the model. This was done by a manual check of routes and times combined with results from a similar programme (previously verified) developed by Pulkki (1996). The times determined by the model were consistent with expected and experienced travel times for the same route. In addition the solutions were consistent with expectations across all the scenarios and areas.

### **3.4. *Experimental design to meet objectives***

The objective of the road network model was to assess the impact of the decline in provincial road condition on transport costs. In order to assess the assumption that speed changes have an effect on costs, the simulation programme was applied to each area indicated in Figure 4, each with two exit points. The two exit points helped to eliminate bias from selecting one exit point and the average results would approximate real conditions more appropriately. The model was applied in two ways, initially to get a general idea of the system behaviour and then to test the system response to likely management decisions.

In initial sensitivity analysis simulations, the estimated speeds achieved on provincial roads were adjusted by 5% intervals from -50% to 50%. These were compared to a control run with no adjustments had been made.

This would show the sensitivity of total cost to small and large improvements or degradations of the road network. The questionnaire results indicated that an increase in moisture on an average South African provincial road during wet weather causes a further 20% of the road surface to become poorly suited to effective transport. It was therefore assumed that the scenarios outlined above would also adequately cater for an investigation into the effect of poor drainage or lack of adequate surfacing.

In order to assess the possibility that certain key roads contributed most of the cost reduction, each pixel was given a volume rating. This was determined by dividing the volume transported over individual provincial road nodes by the total available volume for the area. The roads were then divided into five groups: roads that carry 80 - 100%, 60-79%, 40-59%, 20-39% and 0-19% of the volume.

This can be explained as follows: all the timber is funnelled towards a specific point, much like the tributary system of a river. Obviously the main road or river will carry all the timber or water that falls within the catchment area. This main road would therefore be the most important. However as the roads branch out towards individual forest stands, they carry less and less of the total volume available and consequently become less important roads.

In order to isolate these volume groups, they were improved by one road class (from road class 4 to class 3). Therefore, for the first simulation run, the class 4 roads that carried 80% or more of the available volume were changed to class 3 roads. The speed on these class 3 roads was then adjusted to investigate the effect of improved speed on only these sections. In further runs, the changing was cumulative, that is the first two groups were altered and so on until all the categories had been changed by one level (refer to graphs in appendix B). As a consequence of the change in road classes, a portion of the class 3 roads were in their natural state as they would occur in the control run and a portion would be the old class 4 roads whose impact we were

trying to measure. In order to remove the error introduced by other class 3 roads present, a separate run prior to the rebuild was conducted with the same variable changes. These roads introduce error because they are class 3 roads in their natural state and hence are not subject to the instituted changes in speed. This first run then establishes the reduction in cost that would be caused by improving class 3 roads that fall outside the scope of the study. The difference between this run and the control run was therefore subtracted from the reductions in total cost generated in the other scenarios.

It was assumed that the average speeds used as inputs for the control run were the design speeds for each road class. Consequently, in reality, it would be unlikely that speeds could be achieved much beyond the average and furthermore it would not be safe to do this. In addition the questionnaire results showed that most of South African provincial roads were covered by defects spanning at least half their surface. Morkel (1994) stated that there is a 38% to 48% reduction in speed when defects cover more than 50% of the road surface. Considering that the median road surface condition obtained from the questionnaire results was 3 (indicating that 50% of the road hinders traffic) this is not an unreasonable assumption to test. A calculation concluded that travel speeds currently experienced on South African Provincial roads are in the region of 23 km/hr and not the average 55 km/hr they should be achieving.

A second set of simulations is necessary in order to put the results into a management context. The possible courses of action in the provincial road context are:

- do nothing
- conduct *ad hoc* repairs
- rebuild and maintain the roads

If no action were taken, the roads would continue to decline up until the point where they became impassable. Obviously this would be impractical as timber must be transported. Realistic options are therefore the latter two. To conduct *ad hoc* repairs essentially means that money is spent keeping the roads passable by only conducting minor repairs when absolutely necessary. This means that the achievable speeds are kept to a minimum. Evidently this is the approach currently in use in South Africa. The last option would be to rebuild these roads to their intended design specification

and maintain them in that condition. Not to maintain them at this condition would mean a rapid return to the current state. A notable aspect of the environment, as mentioned in the discussion above, is that one can maintain or rebuild either all the roads or selected portions of the roads.

The reduction in total cost gained by such maintenance or rebuilding must be compared to the costs to rebuild and maintain the road surface for the distance of road in each map area. In South Africa the cost of maintenance is estimated at approximately R 500/km/yr while the cost of rebuilding the road surface is approximately R 75,000/km (Ackerman & Pulkki, 2001).

In all cases assumptions must be made about the effect of the rebuilt and maintained road surface on speed. In this study it was assumed that routine maintenance would prevent a decrease in speed of 10% and road rebuilding (from a very poor state to its original design level) would prevent a decrease in speed of 50% on the relevant section of road.

The 10% reduction in speed reflects the lower driving speeds that would be achieved, in the short term, due to road condition degradation as a result of insufficient road maintenance. Over the long term, with no maintenance, the road surface quality would be reduced to a point where there would be a 50% reduction in speed. After this point if the road were not rebuilt it would become impassable. So the cost of no maintenance would therefore result in the need to rebuild the road at extra cost in any case. In some cases it might even be beneficial to upgrade the road class, and thereby gain a further increase in driving speed.

Upgrading or rebuilding costs are however a once off payment and not an annual cost like maintenance costs. In order to make this comparison valid one must amortise the road rebuilding costs to get an annual fee and then add the maintenance cost. The amortisation was done using the present real interest rate of 4% and a time period of 16 years (the average rotation period in the study region within South Africa), assuming one annual payment at the end of each period. This resulted in R6,000/km/year.

In order to assess the impact of letting the roads decline to their poorest state, the speeds on the relevant road sections were reduced by 50%. This, when compared to the control run, would give an estimated additional cost due to losses in operational efficiency due to an *ad hoc* maintenance policy. The possible impact of rebuilding selected roads was tested by improving the speed in each volume group (roads that carry 80 - 100%, 60-79%, 40-59%, 20-39% and 0-19% of the volume).

Consequently there were 6 areas, each with two exit points and 5 volume groups (the last group being the rebuilding of all the roads that carry any volume of timber). The road distance in each volume group would provide the input for calculating the rebuilding and maintenance costs.

The above format was repeated for the same roads with speeds adjusted by 10%. This gave an indication of the effects and costs of road maintenance (assuming the roads to be in their design state).

The actual conditions in South Africa were indicated by the results produced from the lowest speeds and therefore the effect of rebuilding and maintenance were estimated by comparing this with the control run. This would estimate a reduction in total cost due to efficiency alone. The simulations outlined above were then repeated using an increased charge out rate to estimate the other benefits of improved road condition.

Each area needed 40 simulation runs and the total number of simulations were therefore 240. It is essential that the tool for conducting the runs is therefore user friendly and that a simple record storage system is in place. Screen shots of the user interface for the tool used in this study can be seen in appendix C.

## 4. Results and discussion

The results are divided into two sections. Firstly the results of the questionnaire and the implications thereof are discussed. Secondly the results of the mathematical analysis are considered. This later section is divided into the simple model (which builds a framework on which to work) and the more complex network analysis model.

### 4.1. Questionnaire

The total number of roads surveyed were 224. This represents a significant sample and representative sample for a cross section of South African provincial roads that serve forestry interests. Seven responses were spoilt due to human error, either owing to incorrect completion of the questionnaire or in the process of data capturing. Two of the spoilt responses were from Mondi estates and four from SAFCOL. One wet road condition response was spoilt and it was decided to remove it from the database. This reduced the total response from 224 to a final sample population (n) of 217. The responses by company are given in Figure 10 and are proportional to the sizes of the individual companies. As expected, the larger Sappi, SAFCOL and Mondi provided the majority of the data.

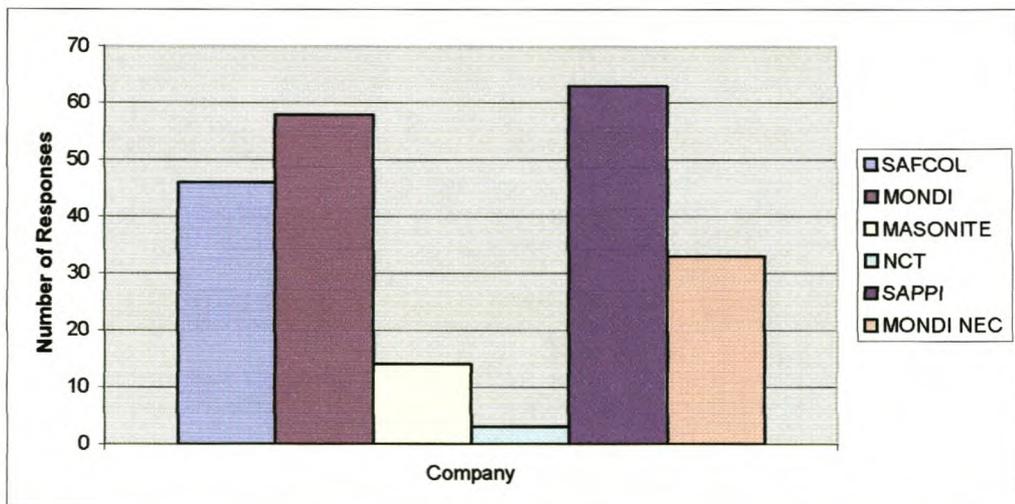


Figure 10: Responses divided according to company

Of the seven companies that were approached, six returned information on at least part of their operating areas. The total volume reported was 8.7 million m<sup>3</sup> transported over approximately 1,821 km. In the same year (1998/1999) 15.6 million m<sup>3</sup> was harvested from South African plantations (FOA, 2001). Therefore the sample represents 56.2% of the total volume harvested, which is a significant sample size. It is concluded that the discussion and conclusions derived from this data about distances, road quality and payloads are representative.

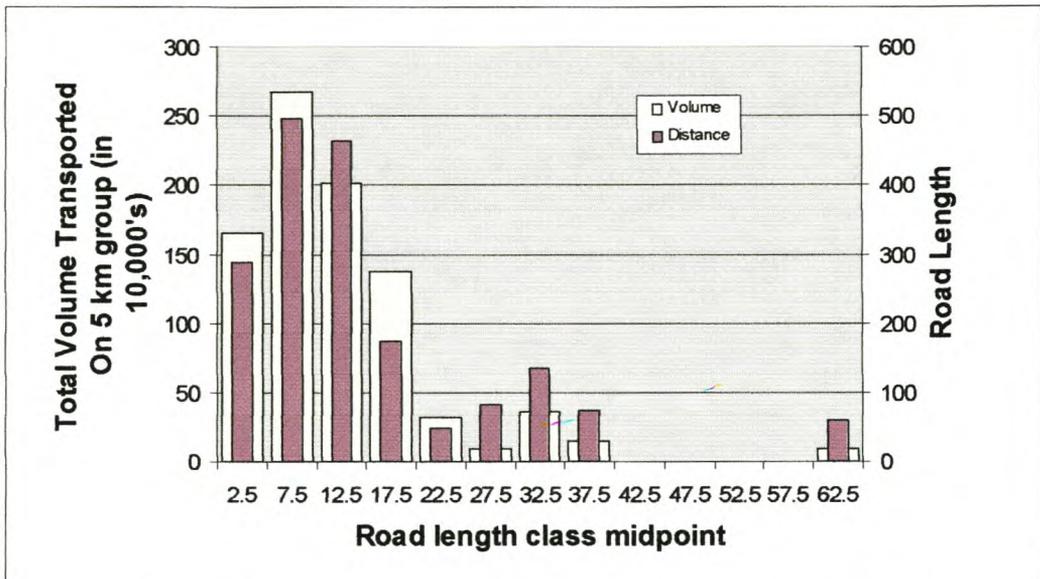
However, some caution should be exercised, as the questionnaire data is subject to human interpretation and error. For example, only one company in one region listed other users of the roads. This could either suggest that most forestry plantations are completely isolated from other industries, or that the remaining companies did not fill in the questionnaires properly. In another case it appeared that respondents did not understand the question regarding road length and condition. Many provincial road lengths are listed in the original questionnaire responses as 500 m. It is doubtful that the roads are of this length, and although it is possible that the road is only used for a short section, it is more likely that the respondents have only supplied information for the section of the road in its poorest state.

The results are summarised and presented in graphical format for ease of analysis.

#### **4.1.1. Road length and timber volume**

Both the lengths and volumes transported over the road segments have a large range and variation. In order to facilitate viewing the data the road data was aggregated into length class intervals (in categories incrementing by 5km). Figure 11 shows this variation for aggregated road classes. The left hand vertical axis shows the range in volume with the majority of the volume being transported over short roads. The right hand axis shows the total distance of roads for that road length interval. In other words the sum of the road lengths that fall between 5 and 10km is 525km. The average length of roads was 8 km and carried an average of 40,297 m<sup>3</sup> annually. One road was reported at 60 km carrying a volume of 100,000 m<sup>3</sup>. This was,

however, a distinct exception as the remainder of the roads were less than 25 km long with most roads being between 7 and 15 km. The descriptive statistics for road lengths and volumes are given in Table 6.



**Figure 11: Volume and road length distribution in 5 km classes**

**Table 6: Descriptive statistics on road distance and volume**

Statistic	Distance (km)	Volume (m <sup>3</sup> )
Minimum	0.5	100
Maximum	60.2	100,000
Average	8.4	40,121
Median	6.0	15,000
Total	1,823.7	8,746,360

The distribution across companies for provincial road length and volume transported are shown in Figure 12 and Figure 13, respectively.

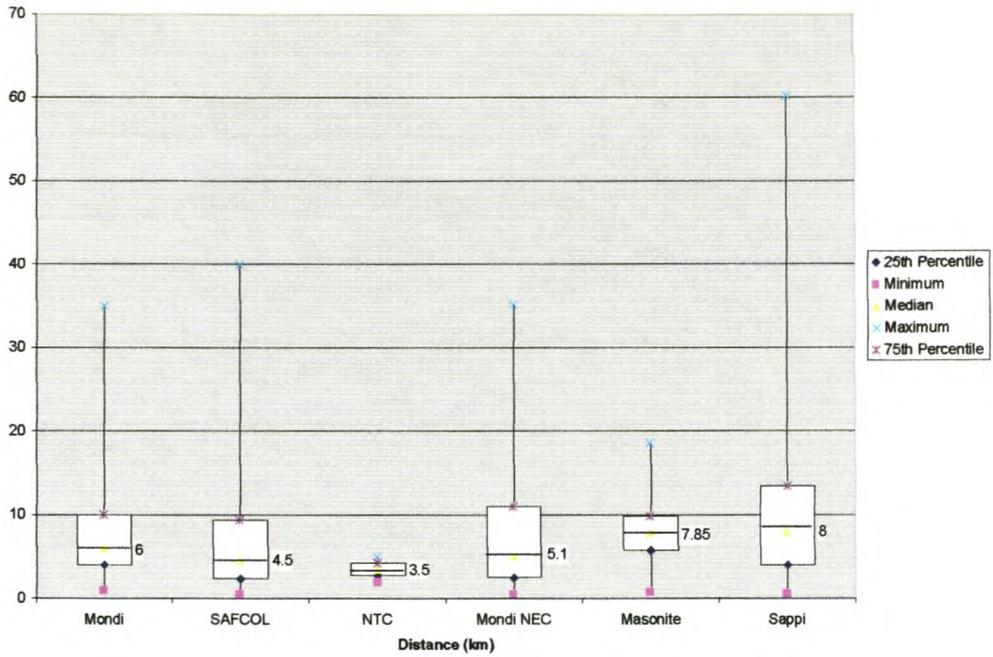


Figure 12: Box and whisker distribution of provincial road section length by company

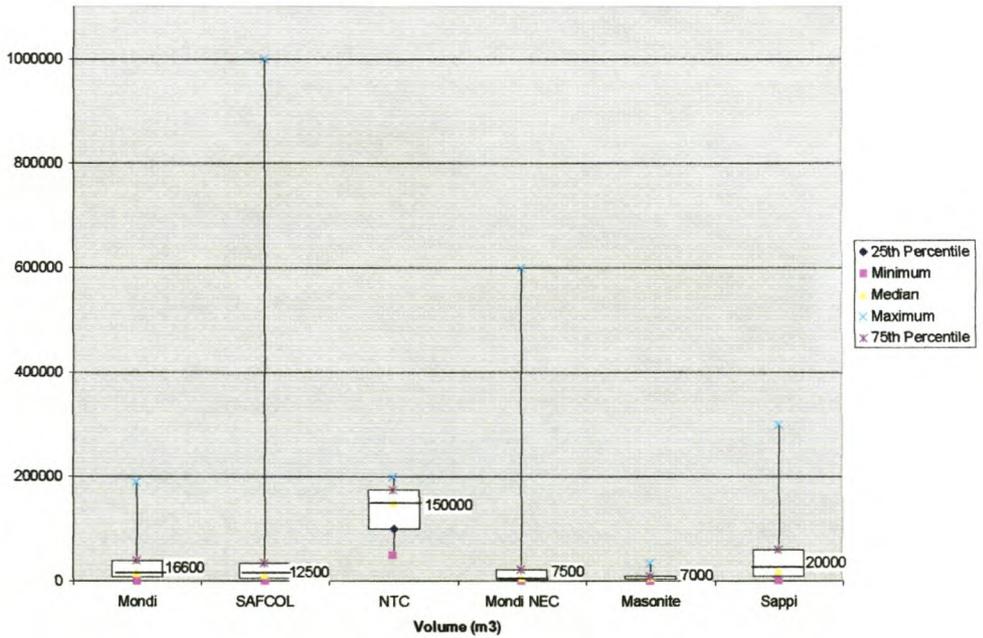


Figure 13: Box and whisker distribution of volume/road segment by company

It is clear that the maximum values, i.e. the top quartile, for each company are much higher than the majority. These are individual roads which may have a large

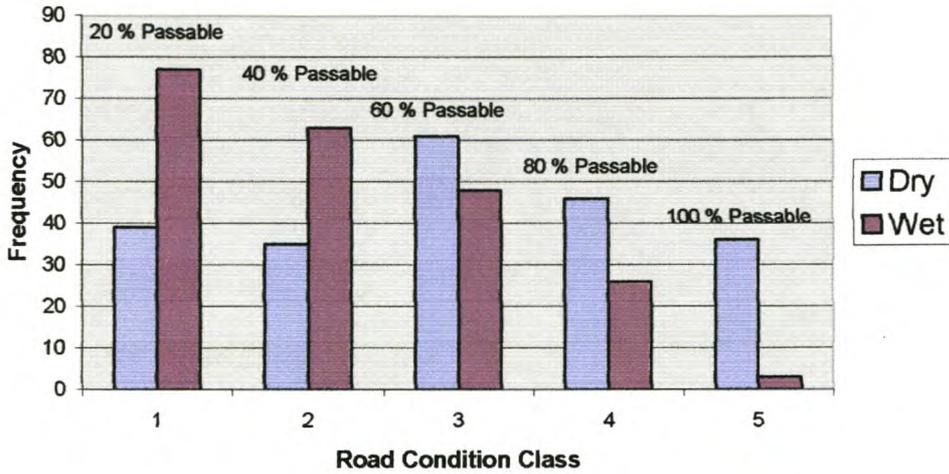
potential for reducing costs if correctly managed, especially in cases where the roads carry high individual volumes. The majority of the data however occur at much lower values and can be best described by their median values.

The median provincial road lengths do not show large variation and most of the road lengths fall around the forest industry median of 6 km. Sappi (8 km) and Masonite (7.85 km) have the longest median distances while NCT (3.5 km) has the lowest. Most of the company volume medians are aggregated around the median volume for the forest industry of 15,000 m<sup>3</sup> per reported road segment. The obvious exception is that of NCT, which represents a special case. NCT's median volume of roughly 150,000 m<sup>3</sup> is transported over three short roads. The implication for NCT is that there is a significant potential to reduce costs of transport by concentrating on the three roads that represent this sample. While NCT certainly has the greatest potential for cost reduction, there is no company that stands out as not using provincial roads. Consequently the results of this study are relevant to all the forest companies in South Africa.

For the remaining companies it would appear that provincial roads are used for short distances but carry relatively high volumes (the industry median of 15,000 m<sup>3</sup> would justify about 395 truck trips using a payload of 38 tonnes). However there is significant variation and each road should be investigated on its own merits. It is clear that there is great potential to generate large cost reductions from rebuilding short portions of road.

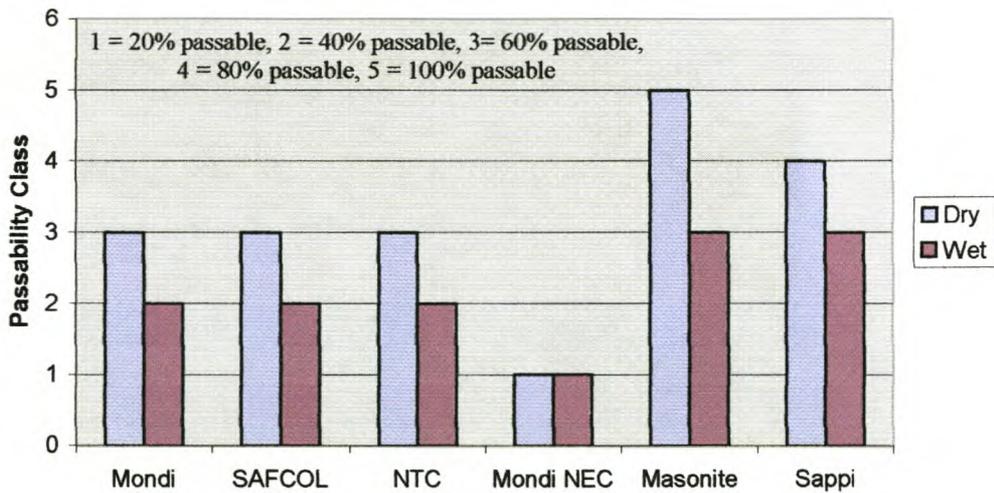
#### **4.1.2. Road condition: dry and wet**

The distribution of the dry road conditions is fairly uniform, with a peak at class 3 (refer to definition of road conditions in section 3.1) (Figure 14 and Figure 15). The median dry condition is 3, indicating that 50% of the road is not conducive to transport. Only 36 roads (12%) are listed as class 5 and are considered to be trafficable all year round. On the other end of the scale, 39 roads (18%) are considered to be in very poor condition (class 1) for transport.



**Figure 14: Frequency of road condition classes for wet and dry conditions**

The change in the distribution in wet conditions is marked. The median decrease in road condition is one condition level, resulting in a median condition of 2. Of the total roads, 158 roads changed by one condition level while 13 changed by two levels, and two changed by three levels. Only three roads maintained the best criterion of 5, while a total of 44 roads did not change condition in wet weather.

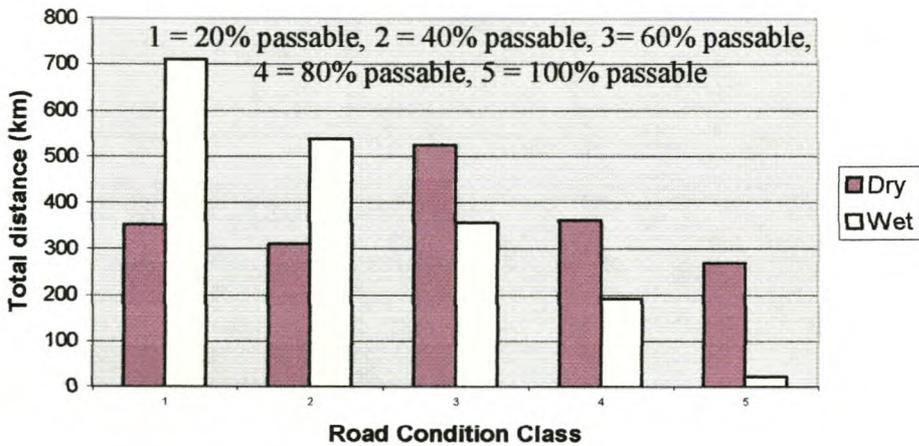


**Figure 15: Median road condition in both wet and dry states by company**

It is apparent that Mondi NEC has very poor roads, with their median road condition being 1 in the dry state. Hence it would not be possible for them to decrease further

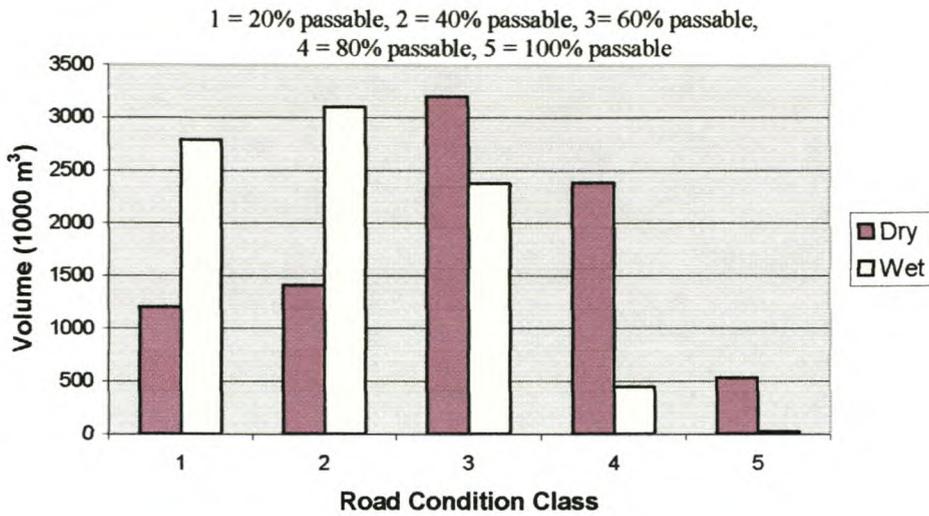
due to wet conditions. Although there is some decrease in passability due to moisture in the road, for most companies road passability decreases by 20% in wet weather. The fact that some roads in the sample do not change by one class suggests that this is a controllable factor. Masonite is most affected by poor drainage as provincial roads in their use deteriorate by two classes, or 40% passability, (they started from a higher surface condition 5 and went to 3, while Sappi moved from a lower condition 4 to 3 and others 3 to 2.)

If the same information is presented in terms of distance of each condition class (Figure 16) a similar picture is apparent. The majority of the road distance slips into the poor road class with very little road distance remaining in category 5.



**Figure 16: Road class grouped according to distance**

If the volume transported over each road class is considered (Figure 17), it is seen that the conditions are more favourable in the dry state. Most of the volume is carried over class three and four roads. In the wet state, however, the situation worsens considerably, with more than half (roughly 70%) of the volume being transported over poor (2) and very poor roads (1).



**Figure 17: Volume transported over the varying classes of road in wet and dry states**

It can consequently be concluded that poor road drainage is an issue requiring attention in the South African forest industry. None of the companies' roads showed adequate levels of drainage. Typically a road will deteriorate by one class or about 20% passability which would be acceptable for small forest roads but not for provincial roads.

#### 4.1.3. Other users

Two groups of other users were identified in the study. The first group consists of users who transport non-timber goods and add traffic at high axle loads. The second group includes lower axle load traffic that will not have a considerable impact on the road, but may have a high priority for qualitative reasons. Included in this second case are tourists and local communities who may use these roads for access. Their presence cannot be ignored, as they have an effect on safety, forest certification and the public image of forestry. Users in this second category range from other farmers to visitors of small nature reserves. The most common users of the roads surveyed are: other farmers (49%), rural communities (31%), general public (18%) and tourism (12%). Often more than one type of industry used a road segment and consequently there is some overlap between the previous four categories of user.

Only 5% or less of roads indicated in the survey were used by groups falling outside the previous four categories.

In terms of the total survey, the contribution of other road users to heavy traffic is insignificant. The four greatest contributors were sugarcane, maize, flour and citrus. Only 11.9% of the total length of roads surveyed had other users, and they contributed only 6% of the total volume of heavy traffic.

Looking at the data in terms of distance travelled by other users further emphasised the unimportant role that other users play. Only 126 km of road are shared with the transport of sugarcane, 107 km with maize, 62 km with bark, 18 km with citrus and 16 km with flour. Compared to a total road distance covered in the survey of 1,821 km. This represents 7% of the total distance for sugarcane and 6% for maize, with each of the remaining other users representing less than one percent of the total distance. Only five roads, totalling 50 km, had more than one non-timber product being transported on them.

If roads carrying other products are examined separately, a different picture is evident. In this case timber still contributes the greatest volume (62% of tonnes transported), followed by sugarcane (33%). The remaining users contribute 4% of the volume. Considering single roads it was revealed that certain roads are less dominated by timber. In these specific cases a far more collaborative effort in determining road maintenance funding will be needed.

#### **4.1.4. Sharing**

A further complication in determining budgets for road maintenance, rebuilding or upgrading is that some roads are shared by timber companies: 20% of the roads were used by more than one company. The average length of these roads was 9 km, carrying an average annual volume of 59,732 m<sup>3</sup>. The median serviceability in dry weather was 3 and when wet this degraded to a 2. This is contrasted to industry averages of 8 km and 40,297 m<sup>3</sup>/year. The roads' serviceability stays constant with medians of 3 dry and 2 wet.

#### 4.1.5. Observations based on the questionnaire

It is quite evident from the results of the questionnaire that the state of provincial roads is very poor. The majority of the roads are considered unserviceable for the greater portion of the length. This implies that they have been poorly managed and that they are in serious need of repair.

The roads are seriously affected by water, with most roads moving down a category of surface quality. In other words, after rain a further 20% of road length is not conducive to efficient transport. Clearly, effective drainage and surfacing are lacking in these roads. The unfortunate implication for the forest industry is that many of these roads will not merely require improved maintenance but in many cases also reconstruction.

An analysis of road condition with respect to wet and dry states within companies (Figure 8) reveals that SAFCOL, Mondi, Sappi and NCT have a similar distribution around the industry median. They have changes in condition of approximately one unit. Mondi NEC has considerably worse roads in both dry and wet states. The fact that there is no change in condition for Mondi NEC is most likely due to there being no lower road class available.

It appears that most of the traffic, in terms of axle loads, is contributed by forest companies. It can therefore be assumed that most of the damage to these roads is caused by forest companies. Forest companies must take on the responsibility of improving these roads partly for the benefit of their own transport operations and partly because they have a social responsibility to do so. Roads have a significant impact on the environment and local communities. It is feasible that in order to maintain environmental certification they should maintain provincial roads in their use. In addition, other users may contribute other non-financial benefits. Tourists, both local and international, who see well-run forests and environmentally conscious management, may help improve the reputation of an industry considered by many to be quite sinister. In fact, maintaining provincial roads may encourage tourists to use the better roads and therefore increase exposure and more rapidly spread positive

sentiment. In addition, relationships with local communities (the source of labour) who use the roads, may improve.

The decrease in government spending on, and the decommissioning of, South African provincial roads, has introduced a complex managerial issue. The nature of public roads is such that they are used by a number of commercial and private vehicles with varying axle loads. There is an inequality between the transport companies (who garner the benefits) and the road owners (who incur the costs). It is logical that users contributing high axle-load traffic would cause the most wear and damage and should provide for most of the budget.

An additional dimension to the problem facing the industry as a whole is that, although private companies are expected to maintain public roads, they are still expected to pay taxes and levies that are meant for the maintenance of public roads in use by forest companies. Consequently there should be an appropriate reduction of these fees in order to compensate for the forest industry's efforts. Forest companies, who may share some of these public roads, are faced with the problem of how they should manage these roads and whether it is worth managing them at all.

The South African government charges a tax on fuel that it uses for the maintenance of public roads. Decommissioned provincial roads do not become private roads as they remain on public land. Consequently, non-timber transport vehicles will still use these roads. This has the implication that if South African forest companies maintain these roads, not only will they be paying a tax that they do not use but they will also be paying for other users. It would seem logical and fair for some form of rebate to be granted to companies who actively maintain public use roads. The mechanics of calculating a rebate would be linked to the distance of road in the care of the forest company. Consequently the contribution of each provincial road segment to the total trip becomes a critical variable.

Considering individual roads confirms a major conclusion drawn from the literature: that there is no single solution to any road problem and that each situation should be considered on its own merits. Some roads are shared by several forest companies, as well as transporting significant volumes of other products. In these cases it will be

essential for the parties to sit together and apportion maintenance, rebuilding and/or upgrade costs accordingly.

There is no company that is exempt from the poor condition of roads. It is clear from the lower than average road class that provincial roads should be a priority for Mondi NEC. Similarly, high volumes shipped over a few roads means that Masonite could benefit from road improvement. Accordingly, every forest company and stakeholder has a vested interest in the application of the information revealed in this paper.

While the forest companies should take responsibility for some aspect of the maintenance of all the roads that they use, the level to which they maintain these roads will be dependent on a number of factors. The most striking omission in the questionnaire is the portion of the total transport route that the provincial road represents. If the provincial road covers a very short section of the total route, it may not be necessary to maintain it to a very high level. In addition, because the roads are considered as part of a network, there is no way of predicting changes in routes based on rebuilt links. That is, by upgrading a certain road one could attract traffic volume from other routes intent on taking advantage of the improved road. As a result, the development of a model that considers the road network as a whole is essential. This will also provide input into calculating the division of costs amongst stakeholders.

The results of the questionnaire, combined with the conclusions made in the literature review, emphasise the need for a model that allows managers to combine their significant personal experience and intuition with an understanding of a larger network. The ability to vary user inputs allows the analysis of the effect of changing road condition and drainage quality.

## **4.2. Simple spreadsheet model**

By adjusting the variables in equation [1] by 5% increments (from -50% to +50%), one is able to determine the sensitivity of the equation to changes. Many of the results of the sensitivity analysis are mathematically intuitive. Changes in the variables (truck charge out rate, time/speed and volume at roadside landing) that are multipliers generate straight-line graphs. The variables that are denominators will produce indirectly proportional distributions because increasing these variables will cause smaller and smaller decreases in the quotient. What is important to garner from the analysis is the range and gradient of results produced for reasonable distributions of variable values. The steeper the gradient, the higher the effect will be and therefore the more important the variable. In the case of rate, time and volume their relationship is directly proportional and a percentage change in any one of these variables would cause an equal percentage change in total cost. This can be seen in Figure 18 where their lines overlap one another. Again this is mathematically intuitive as there are no coefficients so the weighting of the variable in the equations are the same.

What is important to consider is the likelihood of changes to these variables or their actual variation. For example it is quite likely that volume on roadside could differ from the control rate by 50%, whereas it is highly unlikely that the truck charge out rate would decrease below an economically viable value. The base values used in the sensitivity analysis are given in Table 7. Where possible (payload and truck charge out rate) the values are the same as used for the complex model (Table 5). The volume at roadside was based on the industry median determined from the questionnaire (15,000 m<sup>3</sup>) and the time for the round trip was estimated at 3 hours or 180 minutes.

**Table 7: Base rates for the simple mathematical model**

Variable	Base Rate
Volume at roadside	15,000 m <sup>3</sup>
Payload	38 tonnes
Time for round trip	180 minutes
Truck charge out rate	R355/hr

The change in payload is, however, not a linear graph and the total cost of transport decreases as the payload increases (Figure 18). It is important to note that as the payload reaches higher values the decrease in cost becomes less and less.

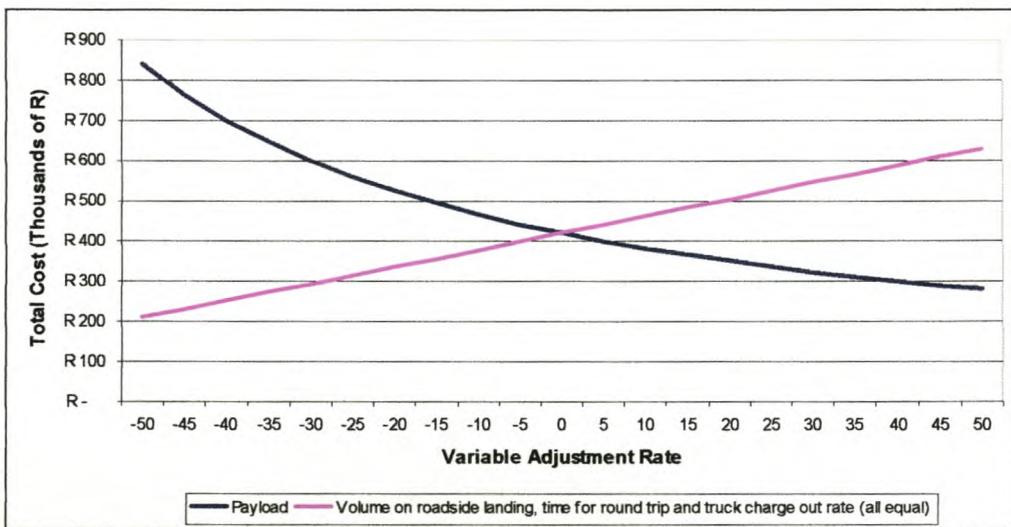


Figure 18: Sensitivity of solution to changes to variables

One can see from Figure 18 that the total cost, as a result of changes in payload, has a wider range (with the maximum cost) as well as, at low payloads, the steepest gradient than changes in volume. At low payloads this is therefore the most significant management variable. However, it is also evident from the shape of the graph that at top payloads the decrease in cost for an increase in payload becomes less and less. This indicates that, with current payloads (38-42 tonnes) at the top end of this range, this may not be the most appropriate driver for managing transport costs in South African conditions today.

Volume available at roadside is largely a variable controlled by the natural distribution of forest, and to a certain extent the location of the road. Also it must be borne in mind that timber is not extracted to one point on a road length but stacked continuously along the road side. It is tempting to conclude that by aggregating all the volume at one node (depot or landing) at the same time, by using extended primary transport or secondary intermediate transport, you could increase your potential for reducing costs. However, these transport techniques in use in South Africa are inefficient (Ackerman, 2001). Alternatively, depending on the required pre-processing form of the wood, considering a logging system (e.g., Cut-To-Length with forwarder) that would have a longer off-road transport lead distance (2x that of skidders) could get more volume/m of roadside landing.

The change in charge out rate is a significant contributor to cost and is also a highly manageable variable. This is, however, a considerably well-studied variable and has been the subject of many books, papers and other sensitivity analysis studies. It is not necessary to repeat those studies and it will suffice to mention that this is an important variable and that a forester should employ the arsenal of techniques available for reducing transport costs and therefore charge out rate.

Consequently, within the bounds of the current management environment and current road condition, it is concluded that time or the management thereof (the influence of driving speed) has the greatest potential impact on reducing transport costs. It is also the least well-known variable and hence represents a significant area for further study. Limitations of the study are that loading is not included and that terminal times are ignored, that is the round trip times are not as long as they should be. As distances increase this effect would be less significant but at short distances this may have a marked effect on results.

Time is made up of a combination of speed and distance (Equation [5]). Again, in this case it is plain that the multiplier variables (road distance or percentage of trip on that road class), would result in straight lines and a percentage increase in distance would result in an equal percentage increase in total cost. These are not really manageable variables but rather functions of the environment. Speed, however, is determined by the condition of the road, a highly manageable variable. Figure 19

shows the effect of increasing driving speed on total trip cost for a 40 km route, which equates to a 3 hr trip time using the same input speeds for provincial roads as the complex model (Table 5).

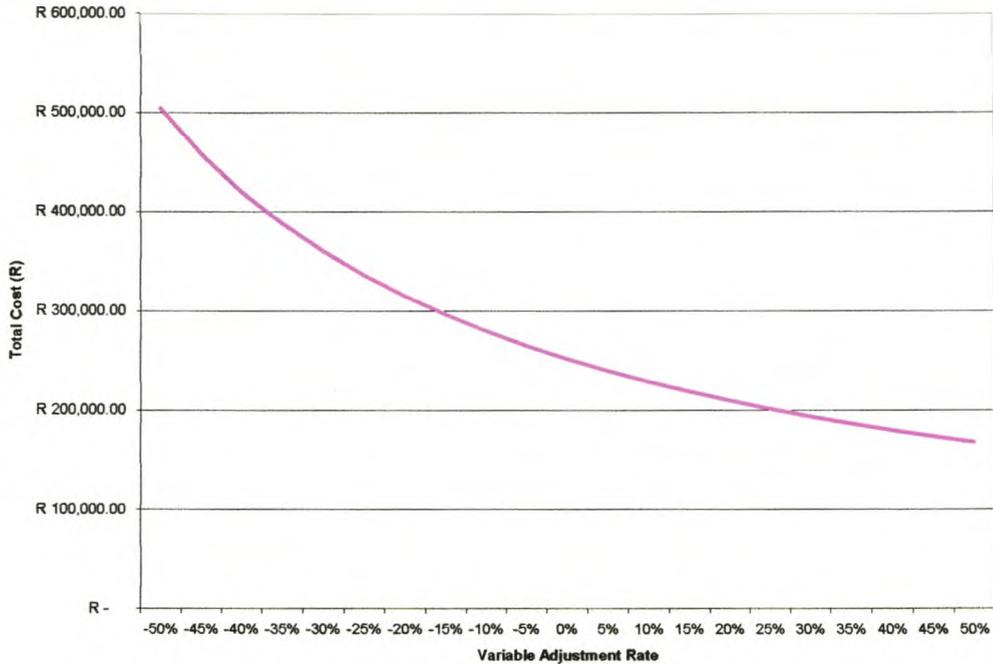


Figure 19: Sensitivity of solution to changes in driving speed

It is important to note that the gradient of the graph in Figure 19 is steepest at lower speeds. This is partly a function of more trips being necessary at very low speeds and partly mathematical. The driving speed differs for loaded and empty vehicles; therefore at low speeds the difference between the two would be less. At higher speeds, particularly if the speeds are determined by multiplying the base speed of 50 by a percentage factor (as is the case here), the differences become greater. Consequently the change in average driving speed is not linear. This would account for some of the curved nature of Figure 19.

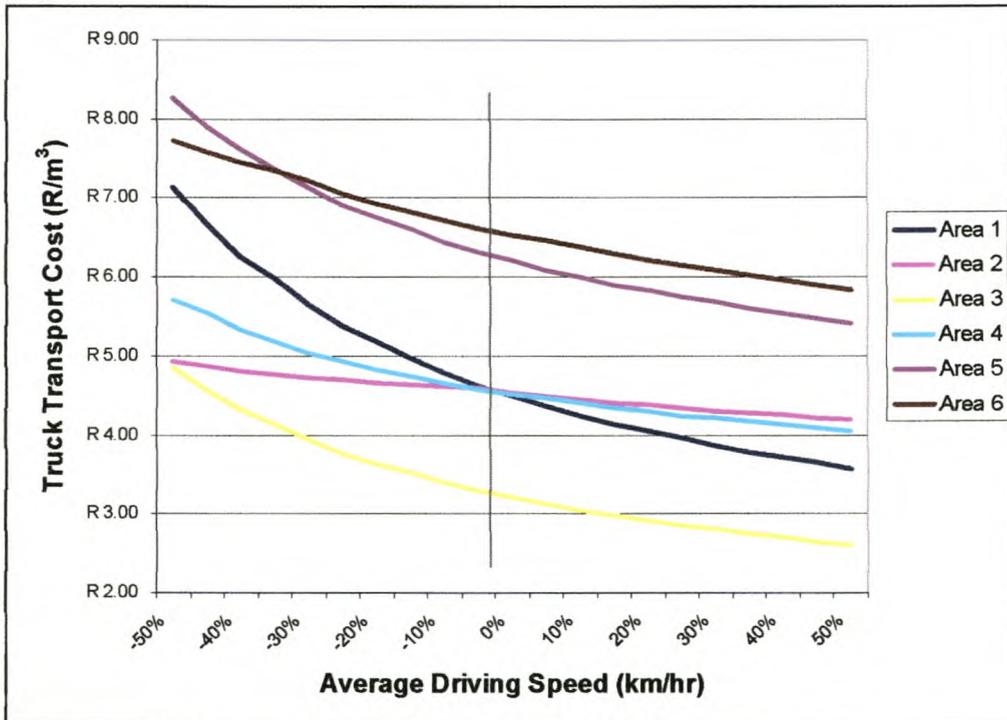
The implication of the curved graph is that the greatest improvements in total cost per unit speed increase occur at lower driving speeds. As the speeds get greater the marginal gains are reduced. We can therefore conclude that managing roads that are in poor condition (i.e. roads that would force the lowest driving speeds) would

generate the greatest reduction in transport costs. This is an encouraging discovery for the forest industry in the face of the poor state of provincial roads.

In summary, the following conclusions can be drawn when managing a single road.

- The time for the round trip is the variable deemed to be the most strongly influenced by management and consequently has the greatest potential impact on costs.
  - This is also the most under-managed variable
  - The time for the round trip is most dependent on the distance of the trip and the driving speeds along the route. The biggest improvements to the time can therefore be achieved by generally improving the surface of the road for as great a distance as possible. In most cases, however, distance is a function of the environment. In addition the volume of timber available for transport is very difficult to determine without the aid of a GIS based tool. The volume transported over the road must be sufficient to generate sufficient traffic to warrant rebuilding or upgrading.
- Payload has a large influence when dealing with small trucks but in the case of this study, where the focus is primarily on highway trucks that operate at maximum legal payloads, this influence is minimal.
- Charge out rate is an intensively managed variable and does not have the greatest impact on marginal costs. The implication for the forest industry is that this variable may be over-managed. The fact that industry leaders grind marginal prices from contractors instead of focusing on variables with greater effects on cost reduction is not constructive. In addition, by providing slightly more leeway to contractors, alternative benefits (improved morale, business stability and productivity) will be realised.
- The volume of timber available for transport is an important variable in determining total cost. However it is not a manageable variable in the short term.

As a form of validation the assumptions made in the simple model were tested with the more complex model. A simulation was run for each area using the basic values given in Table 5 and then adjusting them by 5% intervals until -50% and +50%. The results are presented in Figure 20. The actual results from these simulations are given in Appendix D.



**Figure 20: Truck transport cost/m<sup>3</sup> for each area as a result of changing speed**

The road network model confirms the observation made in the sensitivity analysis that the greatest impact on cost is at lower speeds. The shapes of the graphs (Figure 20) are very similar to the shape of the graph for speed adjustment in the simple analysis (Figure 19) and the explanation for the shape is the same. One can therefore assume that the output of the complex network model is consistent with other theoretical models and is therefore valid for the quality of input.

It is obvious from Figure 20 that there is a great variability and some areas have a greater potential for reducing total costs than others. Most of the variables are held constant during all runs (MAI, payload, rate and speeds for all other road classes except provincial roads). Consequently, the only variables that can account for these

constant during all runs (MAI, payload, rate and speeds for all other road classes except provincial roads). Consequently, the only variables that can account for these differences are the actual trip distance, the available volume (determined by forest area), and the percentage of the trip driven on provincial roads. The speed is adjusted for this latter portion and this speed determines any improvements in round trip time. This variability in the costs for each region is a pervasive trait of all the data produced in this thesis. This trend emphasises the need for a focused study in each area.

As a general guide we can deduce that by improving road quality and thus speeds, both by maintenance and rebuilding, costs will decrease. This can be seen in Figure 20 where the total cost decreases as the speeds increase (from left to right in the graph). The magnitude of the change is determined by the circumstance within each individual area. The average truck transport costs are reduced from R 6.44/m<sup>3</sup> (considering a 50% lower speed than the base) to R 4.92/m<sup>3</sup> (considering a 50% higher speed than the base), which is a cost reduction of R 1.52/m<sup>3</sup>. If we consider the total volume of timber harvested and transported annually in South Africa of 17 million m<sup>3</sup> (FOA, 2001) this equates to a lowering of the total cost for the industry by R 26 million/yr. This of course is prior to the costs of the road construction and maintenance being subtracted. Essentially this figure represents the amount of money the industry can spend annually on maintaining, rebuilding and/or upgrading strategic provincial roads in South Africa (it is assumed the current speeds achieved on these roads can be double, as discussed in section 3.4).

In order to determine the contribution of individual roads, each volume group was improved by one road class (an increase in speed of roughly 11%, roughly equal to the speed reduction maintenance would prevent). The results produced are given in Table 8.

**Table 8: Contribution of categories of road to total cost**

% of volume carried by roads	Distance Improved (km)	Total Cost (R)	Reduction in Transport Cost (R)	Percentage Change (%)	% of Total Reduction	% of Total Distance
80 - 100	90	R 30,737,468	R 252,971	1	25	6
60 - 100	154	R 30,554,927	R 435,512	1	43	11
40 - 100	200	R 30,472,513	R 517,927	2	51	14
20 - 100	445	R 30,227,181	R 763,258	2	75	31
0 - 100	1418	R 29,973,042	R 1,017,397	3	100	100
Control		R 30,990,439				

Table 8 shows that 75% of the reductions can be realised by maintaining 31% of the roads. This, however, does not consider the actual costs of rebuilding or of maintenance. It is therefore necessary to consider each area taking into account these costs.

At this stage our understanding of the equations is theoretical and provides a good indication as to how the system should behave. The more complicated road network model helps to put approximate numbers to real case scenarios in the hope of providing more accurate guidelines.

Because of the inherent variability in road transport costs, an average across all areas is a meaningless figure. Consequently each area is considered separately and then all the areas are considered together to give an overall cost reduction for the region. The results for each area, as well as totals across all areas, are given in Appendix D.

The net cost reduction because of road maintenance and rebuilding (after the deduction of relevant costs – R 6000/km/yr for road rebuilding i.e. returning the provincial roads to their design standard; and R 500/km/yr for maintenance to keep them at their design state) purely as a consequence of improved efficiency are given in Table 9. The top half of the table is for road maintenance (preventing a 10% decrease in speed) and the bottom half of the table is for road rebuilding (preventing 50% decrease in speed). The negative values are where the scenario would cause a net increase in total cost, where as the positive values are where there is a reduction in operating costs. The shaded cells represent the maximum reductions for a given scenario. It is clear that the increase in efficiency alone does not always justify improved maintenance or rebuilding. All the shaded areas in the table are the

scenarios that reduce the costs to the greatest degree. Where there are two cells shaded in one column, the top one is for road maintenance, while the bottom one is for road rebuilding scenarios. The maximum possible cost reduction can therefore be calculated by adding the shaded cells in the bottom half of the table.

**Table 9: Specific reductions from improved efficiency as a result of South African provincial road maintenance or rebuilding.**

	% of volume carried by roads	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Total
Maintenance	80% - 100%	R -11,855	R -3	R -2,489	R -2,011	R 729	R -3,615	R -19,244
	60% - 100%	R -12,181	R -997	R -9,636	R -6,644	R -566	R -3,615	R -33,639
	40% - 100%	R -12,683	R -997	R -18,666	R -10,465	R -2,769	R -3,615	R -49,195
	20% - 100%	R -13,543	R -6,790	R -64,933	R -34,888	R -17,759	R -10,670	R -148,583
	0% - 100%	R -37,695	R -54,855	R -172,128	R -138,592	R -143,707	R -63,450	R -610,426
Rebuilding	80% - 100%	R -101,758	R -11,459	R 39,465	R 85,059	R 797,020	R 226,094	R 1,034,420
	60% - 100%	R -104,746	R -46,241	R 68,736	R 302,666	R 1,328,707	R 226,094	R 1,775,216
	40% - 100%	R -110,098	R -46,241	R 56,360	R 368,888	R 1,573,116	R 226,094	R 2,068,119
	20% - 100%	R -120,565	R 7,730	R -373,210	R 455,493	R 2,045,454	R 360,237	R 2,375,140
	0% - 100%	R -423,757	R -335,197	R -1,363,006	R -387,251	R 982,065	R 163,492	R -1,363,654

Road maintenance will lower costs in one of the six areas and rebuilding will lower costs in five of the six areas. If we add the maximum possible reduction we get a total cost reduction of R 2.9 million/yr which is derived from gains in efficiency caused by improved road management.

The cost of doing *ad hoc* repairs can be calculated by comparing the control simulation with one where the speed on the provincial roads is decreased by the maximum of 50% across all the areas, which comes to a total of R 8 million/yr. In other words, if the South African forest industry does nothing about the decline in provincial road condition it will cost R8 million/yr in the study area in increased transport costs based on a loss in efficiency alone. This value does not include further increased transport costs the industry would incur from increased operating costs of the vehicles and increased accident rates.

There would be a net increase in cost, if all the roads were rebuilt, of R 1.3 million/yr (the total for the bottom row in Table 9). Consequently faced with a choice between doing nothing and doing everything, it would appear that doing everything is better. In other words a unilateral road management policy to rebuild all provincial roads would incur lower transport costs than the current unilateral policy of doing nothing about provincial roads. Therefore in the absence of qualified or motivated road managers the decision to maintain all roads is considerably better than the decision to do nothing.

The decision to instil a complete maintenance plan is further complicated by the fact that in order to realise the cost reductions from rebuilding, the roads must be maintained. Otherwise they would once again decline to their current state and the higher costs would be incurred. In actual fact the cost reductions gained from road rebuilding are inexorably tied to the costs of maintenance. Therefore, in the light of the above discussions, road maintenance is essential.

The decision to rebuild is more complicated. Due to the much higher cost/km to perform the rebuild there will never be a case where you can rebuild all roads. Mistakes, rebuilding a low axle load road for example, would cost a lot more than in the case of a maintenance policy. In order to justify the high expense of rebuilding there must be sufficient volume transported over that road to generate cost reductions. Area 1, for example, does not justify rebuilding as it has a small volume. When this volume was adjusted, by increasing the MAI to a very high value (50 m<sup>3</sup>/ha/yr), road rebuilding and even upgrading decisions were justified (Table 10).

**Table 10: Specific reductions from improved efficiency as a result of South African provincial road maintenance and rebuilding and an increased MAI (50 m<sup>3</sup>/ha/yr) in Area 1.**

% of volume carried by roads	Reductions
80% - 100%	R 17.114.85
60% - 100%	R 16.539.52
40% - 100%	R 13.501.52
20% - 100%	R 4.570.50
0% - 100%	R -277.752.50

However, in South African conditions, where provincial road conditions are so bad, many of the roads justify some rebuilding. Table 9 shows all areas, except area 1, justified some level of rebuilding. The total distance rebuilt would be 288 km (derived from adding the corresponding distances, from Table 11, for the shaded cells in Table 9) or 20% of the total provincial road surface (Table 11). The boundaries of this study have been rather coarse as 20% volume intervals are rather large. We could therefore further improve cost reductions by considering each road or each pixel.

**Table 11: The distance rebuilt or maintained in each area**

% of volume carried by	Area 1 (km)	Area 2 (km)	Area 3 (km)	Area 4 (km)	Area 5 (km)	Area 6 (km)	Total (km)
80 - 100	28	12	7	10	18	15	90
60 - 100	29	18	26	29	37	15	154
40 - 100	30	18	48	41	49	15	200
20 - 100	32	33	152	101	96	32	445
0 - 100	81	136	372	317	363	149	1418

In summary, it cannot be said of road rebuilding that a unilateral policy would suffice, quite the opposite. Such a policy would result in increased costs of R 1.3 million. Detailed studies must be made of the entire transport route and the areas that would justify cost reductions must be identified. In most cases only a portion of the total route would justify rebuilding. However accurate studies will most definitely identify those portions of roads that can be rebuilt and therefore reduce costs. As shown above, identifying these key roads would reduce costs by R 2.9 million.

The reductions in cost given in Table 9 are the reductions determined from gains in operating efficiency alone and do not account for other possible reduction to cost indicated in the literature. The literature review indicated a number of potential reductions that would result from good transport management.

- Selecting an appropriate transport configuration could account for 10 to 15% reduction in transport cost.
- Ensuring that vehicle drivers are properly trained could save 5% over the long term.
- Reducing the tare weight could result in up to 20% reductions.

- Reducing road roughness could result in a
  - 20% reduction in overall vehicle operating costs.
  - 5% reduction in maintenance costs.
  - 10-20% reduction in fuel consumption.
- Greater vehicle efficiency from fully utilizing shifts could result in cost reductions of 10-15%.
- There is an additional cost reduction in terms of improved driver comfort and a reduced accident rate.

Jones and Paige-Green (2000), in a study of South African road conditions, state that improvement in road surfacing will reduce operating costs by 20%. The operating costs portion of the total charge out rate is roughly 26% (Lowe, 1989). Consequently we can reduce the charge out rate by 5% (20% multiplied by 26%), which will further increase the potential to lower costs and may justify more road rebuilds. Consequently the simulations were repeated using an increased truck charge out rate of R373.00 (5% increase), only for the portion of the trip with poor roads. These results are summarised in Table 12 and the detailed results presented in Appendix D.

**Table 12: Specific reductions from improved efficiency and reduced operating costs as a result of South African provincial road maintenance and/or rebuilding.**

	% of volume carried by roads	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Total
Maintenance	80% - 100%	R -12,965	R 292	R -2,427	R -1,862	R 1,215	R -3,422	R -19,169
	60% - 100%	R -13,291	R -599	R -9,462	R -6,237	R 338	R -3,422	R -32,673
	40% - 100%	R -13,791	R -599	R -18,394	R -9,965	R -1,672	R -3,422	R -47,844
	20% - 100%	R -14,650	R -6,301	R -64,381	R -34,093	R -16,221	R -10,405	R -146,051
	0% - 100%	R -38,790	R -54,186	R -171,419	R -137,571	R -141,798	R -62,885	R -606,649
Upgrading	80% - 100%	R -97,597	R -8,196	R 43,912	R 92,634	R 843,257	R 242,451	R 1,116,462
	60% - 100%	R -100,504	R -42,760	R 80,843	R 327,683	R 1,408,195	R 242,451	R 1,915,907
	40% - 100%	R -105,778	R -42,760	R 75,062	R 400,991	R 1,668,957	R 242,451	R 2,238,924
	20% - 100%	R -116,192	R 18,957	R -342,153	R 511,909	R 2,180,857	R 388,988	R 2,642,367
	0% - 100%	R -418,680	R -307,338	R -1,309,436	R -302,265	R 1,151,395	R 220,947	R -965,377

By including the cost reductions of 20% to operating costs you push the lowering of the total cost up to R3.1 million (once again the addition of the shaded cells in the bottom half of table 12, which includes the cost of maintenance). Although this does not seem a huge additional saving it reduces the net increase in cost of unilateral policies to just R 1 million/yr.

One of the sub-objectives to be addressed is the effect of drainage and poor surfacing on moisture in the road. If it is assumed that a 20% change (*i.e.* one road class – see section 4.2.) in road condition, the average change (indicated in the questionnaire) brought on by moisture on the roads, would account for an estimated 15% change in speed. Then correctly installed drainage and surfacing could therefore account for a 5% reduction in total transport costs. Rebuilt roads would not undergo such extreme changes in road condition and allow more uniform and lower costs. However no data was provided that could accurately estimate the expected change in driving speed from such a change in moisture content. The discussion around drainage must therefore be considered as estimation.

The final sub-objective of this study was to develop a tool to aid South African forest company managers with road management. The literature highlighted a number of factors that complicate the process of road management. In a flat corporate environment, company employees are spread very thinly and do not have the time for planning. On the other hand, contractors do not have the required resources for conducting appropriate planning and research, especially as contractors are often qualified by experience rather than training. Companies can overcome these constraints by improving managerial access to expert knowledge. This can be accomplished by hiring more specialist consultants and/or using information technology to distribute key knowledge. Decision support tools and specialised advice must be made available to operational staff. The implementation gap must be overcome by:

- Ensuring that models are not too complex.
- Not relying solely on computers; the environment must allow managers to test alternatives and make decisions.
- Involving managers in the problem selection and model development process, as manager intuition and experiential knowledge should provide the primary input.
- Developing staff skilled in sound modelling techniques and implementing their proposals in user-friendly software solutions. The main limitations to the applications of this type of study are no longer technological, but human.

The literature clearly showed that, within the South African environment, the vehicle aspect of transport management is reasonably well understood. Recent studies have focused on lowering tare weight to maximise payloads, as well as reducing variable transport costs. Unfortunately, it is equally clear that roads are severely neglected. Internationally, however, roads have been a major focus for forest research. There are a number of guidelines available for road management. The inadequate management of South African forest roads cannot be attributed to a lack of information or guidelines, but rather to a lack of understanding of analysis techniques and a reluctance to conduct said analyses to determine the financial impact of the decision to maintain or neglect these roads.

It must be emphatically stated, drawing from both the literature review and the variability in this study, that there is no general solution to all road situations. Fixed standards cannot be applied across the huge environmental variation existing in South Africa. South African managers need to weigh up the costs and benefits of improvements to road networks on a case-by-case basis. In cases where the benefits exceed the costs, the improvements are warranted.

As a consequence this paper cannot make recommendations to the industry in terms of appropriate condition levels. It does provide a background to the impact of road condition on transport costs and provides a model for the analysis of the impact of improving roads on transport costs. Forest managers are overworked and are not provided with full access to knowledge, skills and tools to complete such analyses. It is hypothesised that this is a major cause of poor road management.

This tool or model was developed following principles laid down in the literature and was therefore focused on a single problem and highly adaptable to simulate changes and their impacts on the system. All inputs are user defined and the manager controls the format of the output. This allows managers to input their considerable experience and intuition into the model.

The output allows managers to identify critical roads for management attention and to make tentative estimates of cost reduction that would be possible were road

condition to be altered. The manager is able to test the sensitivity of the solution to changes in the variables, and to gain a better overall picture of the interactions within the system. The model results and improved understanding of the system will provide input to more specific and collaborative studies.

The ease with which this model has been applied to a relevant South African road management issue and the usefulness of the results show that the final sub-objective given in the introduction has been met.

The model, as it is, is subject to a few limitations and restrictions. Firstly, "The cost of transport is insensitive to changes in travel speeds and terminal times, if the increase (or decrease) of the variables does not allow an extra load to be achieved (or lost) during the working day" Morkel (1995a).

This is true and in fact increased speeds can cause an increase in fuel consumption (Ljubic, 1983). Consequently drivers should be discouraged from driving faster for the sake of driving faster. Productivity and the quest for an efficient and safe extra load should be the primary goal.

Secondly, it is essential to consider the route as a whole, as this can make a significant difference to the total cost. Unfortunately, this study divided the entire route amongst map areas (Area 1 to 6). Consequently the absolute estimates conducted in this study could result in underestimates. This implies that there may be a greater potential to realise net cost reductions when road maintenance costs are included. In other words, if whole routes are considered, it may be justified to rebuild longer sections of provincial road.

Apart from focussing on the current inputs into the model, one can increase the number of inputs to enhance the accuracy of the output. For example, the model could be adjusted to determine the rate of fuel consumption, as well as wear and tear, based on road condition.

## 5. Conclusion

Objective one of this thesis was to determine the current state of the provincial road network and its management. The questionnaire confirmed a number of expectations built up from the literature review and personal experience. It was clear that provincial roads are in a poor state with more than 50% of them having only 50% of their length serviceable. It is an unfortunate fact that government will no longer be supplying adequate funds for the maintenance of these roads. In addition it is by no means clear who will become responsible for the future maintenance of these roads. In most cases it appears that the forest companies account for the greatest axle load traffic and should provide the largest portion of funds for road maintenance. Forest companies need to contribute to the funding of provincial road maintenance, partly due to the necessity to improve operating costs and partly as a result of their social responsibility to pay for the damage they cause to public roads. They cannot shirk this responsibility and should engage in studies and use a more collaborative approach to allocate funds for this purpose.

Different companies using the same roads to transport varying volumes further complicate the management environment. Fortunately, these volumes should be easy to quantify and hence a contribution ratio would be relatively easy to establish. The problem will arise with deciding between the levels to which these roads should be maintained to and therefore the total amount of money that should be invested. Different companies have different philosophies on road management. For some it is a priority and for some it is not.

Furthermore there is justification for some future benefit in the form of tax reductions where industry carries out public road maintenance. However there can be no hope of lobbying government to institute such reductions unless forest companies can form a united front backed up by accurate industry wide data and analysis models.

Objective two was to assess the impact of the decline in provincial road condition on transport costs. This was achieved by attempting to assign a quantitative figure to

the consequences of the decline of provincial roads in order to guide management decisions. By using a simple spreadsheet model and a more complex road network model relative measures of the consequences of various actions were generated.

From the simple mathematical model it was clear that volume, distance, payload and charge out rate are important variables, but they are either governed by the environment or are being successfully managed. The trip time variable, influenced by the controllable variable speed (based on road condition), is the variable with the greatest potential for improvement as it is not well understood and is difficult to calculate for a road network.

The road network model determined that for the study area a unilateral decision to rebuild and maintain all roads would result in a net increase in costs of R 2 million/yr but would also leave an improved road network. When compared to the cost of *ad hoc* repairs for the same area of R 8 million/yr it is obvious that proper road management is a better option. In addition the road condition would still be in a poor state and there would be an additional cost for the actual *ad hoc* spending. However, it was shown that 75% of the net reduction in total costs are generated by improving only 31% of the provincial road surface. Consequently by further analysis it was possible to generate cost reductions of R 2.9 million/yr for that study area by improving selected roads (20% of the total provincial road network for the area). These reductions were generated specifically from gains in transport efficiency and include the cost of maintaining and rebuilding the roads.

On a larger scale it was estimated that poor provincial road management costs the industry as a whole R 26 million/yr or R 1.52/m<sup>3</sup> in transport costs. This money, plus an additional cost reduction through reduced truck operating costs (a further 20% according to Jones and Paige-Green (2000)) from reduced efficiency, can be used to offset the costs of maintaining and rebuilding roads.

The road network model was then used to determine the change in costs if the effect of poor road condition on operating costs was included. The total possible cost reduction by rebuilding selected roads increased by a further R 200,000/yr, but more importantly the total net increase in cost of a unilateral road management policy was

reduced to R 1 million/yr. The implication of this is that more areas would generate cost reductions if the roads were studied at a finer resolution.

There were four sub-objectives that were also addressed: Firstly, the contribution of individual roads to total costs was determined to be significant. Secondly, the effect of drainage and surfacing in the current road state is also significant as road condition worsens considerably (in wet conditions an extra 20% of the surface is not passable). If proper drainage and correct surfacing is installed during the rebuilding process, then this would become less of a problem. Nevertheless poor drainage and surfacing could be costing the forest industry as much as an extra 5% on transport costs. Thirdly, the effect of extreme changes in condition such those indicated by the questionnaire, which is most relevant in South African poor provincial road conditions, was tested in the road rebuilding scenario. It is very clear that there is massive potential for rebuilding some of these roads. Finally, a tool for conducting such analysis was developed and validated by the study process and results. The ease of its use and the importance of the results indicate a scope for application of this or similar tools.

Possibly the most relevant conclusion that can be drawn from the results is that they are highly variable. It is clear that each area must be studied in detail and critical corridors identified. The tool presented here is a useful aid in this process. What is important is that in most cases there is a potential for reducing costs and the necessary studies should be carried out to identify the most important management areas. This type of study has the further benefit of identifying key transport corridors. For a provincial road to be considered important, it must be carrying a high volume over a short distance (in order to reduce maintenance and/or rebuilding costs) and providing the greatest portion of the total trip as possible. In many cases, in similar studies, the lowering of operational costs would offset the increased cost of road improvement (Paterson, 1971).

The analysis method and analysis tool presented in this paper may help to overcome the problem of difficult studies that must be repeated for each potential transport route. The tool is meant for use as a part of a cost-benefit analysis on these key road links and is meant to ease the burden of such an analysis and consequently improve

road management in South Africa. It must be stressed that this is a pilot study and that the model developed is a prototype and is not meant for commercial use.

There are a number of weaknesses in this study, and therefore opportunities for further study. There is some concern that focusing on driving speed, unless it results in more loads per shift or day, is less important than other variables (Morkel, 1995a). However the author felt that this study complemented international and local research and shows the potential that is available if truck driving speed and scheduling are better managed. In addition if forest logistics managers were to take advantage of scheduling techniques and use shorter lead distances towards the ends of shifts, they would be able to take advantage of time reductions and increase throughput.

It needs to be recognised that solutions are only optimal with regards to the information that is provided as input into the model. Within this application, the information was at a low resolution as the levels of results were tactical and relative results were required. A question that needs to be addressed is that of the acceptable level of information generalisation for economic analysis of roads at different planning levels (tactical, operational and strategic). The highest level of generalisation (therefore the cheapest data) that is acceptable in terms of output should be encouraged. In addition the high sensitivity of the model to the inputs implies that the inputs to the model must be as accurate as possible. As charge out rates, payloads and MAI are well defined, the key areas of focus would be accurately quantifying the effect of road condition on driving speed and improving the map input quality.

Consequently, collaborative efforts are needed in order to quantify and divide the costs among the different private, public and commercial stakeholders. Focus must be placed on fine-tuning the quality of inputs to the model as well as on a concurrent effort to develop accurate allocation models. This will then make scheduling models feasible, allowing managers to easily take advantage of the potential to reduce costs expressed here.

It is precisely the fact that the model can be enhanced and adapted that is the major worth of this study. The main limitations to the application of such modelling are now human. The system developed here can be modified for any number of spatial studies, including road upgrading, road location and spacing, locating processing facilities and many others. Pulkki (1988) stated the following: "The list of application is endless, with the major limitations being the imagination, skill and budgets of the research institutions." It is consequently the adaptability of the model and the expertise developed that is of most value to the South African forest industry.

In the introduction the question was posed: "Should the industry ignore the continued deterioration of provincial roads or should they use private funds to maintain these public roads?" Quite apart from the various benefits of improved road condition listed in the literature this study has indicated that there is, in most cases, a clear benefit in halting this decline.

By rebuilding selected road sections in the study area total costs could be reduced by roughly R 3.1 million/yr from reduced operating costs and reduced transport costs due to improved efficiency. This has the additional advantage that the road infrastructure is in an improved state. This must be compared to the cost of *ad hoc* repairs, where the road infrastructure will be in a poor state and continue to deteriorate. Costs in the latter scenario would increase by as much as R 8 million/yr in the study area. It is consequently essential that the South African forest industry review their provincial road maintenance strategy.

There is significant variation in forest and road structure within the South African environment which makes it difficult for parties to come together to decide on road management policy and budgets. It is, however, clear that it is not an option to let the roads continue to decline. Therefore, despite the difficulties involved, all forest interests and other users of the roads need to meet and consider these issues. It is also clear that, even if other users of the road refuse to cooperate, it is in the best interest of forestry companies to maintain these roads and allow free-riders. At a later date legislative avenues can be explored to reduce this effect. In fact, in the light of market-driven environmental pressures (like certification) it is the moral

obligation of forest companies to maintain these roads that may also be used for rural access and eco-tourism ventures.

The only obstacle to intra- and inter-industry cooperation is a lack of data and methods for road analysis. Unfortunately each and every road situation needs to be studied in detail and hence will require a small multi-disciplinary team. With the formulation of this technique and tool, and the expertise and knowledge available in the industry, it is possible for a case-by-case analysis of the South African provincial road system to be undertaken. The lowering of total costs that will be generated from improved fuel consumption, decreased wear and tear and increased efficiency should be ample compensation for improved road management initiatives.

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## Appendix A: The Questionnaire

### FESA Project: Funding of Provincial Road maintenance

During a Forest Engineering Southern Africa (FESA) strategic session held at Lakensvlei in 1998, the above mentioned project was identified as one of eight warranting investigation for the industry by FESA.

The project has its origins in the fact that over the past few years certain *unpaved* district/provincial roads, which are used to carry large volumes of timber are not being maintained by the responsible authorities for a variety of reasons. One reason being a lack of finances and secondly a shift in emphasis to more socially orientated responsibilities by the Department of Transport (DoT's) of the provinces. In some cases roads are even being de-legislated or denumbered, placing the responsibility for the maintenance of these roads squarely on the shoulders of the companies who are reliant on these roads for the movement of their timber.

The fact remains, whether the roads are numbered or not, that vast additional funding is required by the affected companies to maintain these roads in a suitable state of repair, which in the past had been the responsibility of the authorities. The aim of the survey is to attempt to quantify the problem in terms of identifying which roads are cause for concern, the lengths of these roads and what volumes they carry etc. This will enable the industry, through FESA, to approach the authorities with the aim of coming to an agreement on the future maintenance/management of the identified roads.

We would appreciate it if the completed questionnaire could be returned to the indicated address by the 1<sup>st</sup> of April 1999.

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Please complete, for each identified road separately, the points below. It is imperative that each and every road that falls into the above category, which is within your sphere of influence, be documented. Company roads within plantation/estate boundaries are excluded from this survey. Unpaved, secondary provincial/district roads are being singled out for the purposes of this questionnaire.

It would perhaps be best if you could use one page per route of description for points 2 to 4. This will assist analysis.

Please consult the attached notes on each question before completing the questionnaire. If you are unclear on how to proceed please contact your company representative who is associated with this FESA project or Pierre Ackerman at the address on the covering letter.

Point	Description
1.	Position and/or location of provincial road, road number or if denumbered old provincial road number.
2.	Indication of other road users.
3.	Average annual volume transported over the particular road.
4.	Degree of serviceability (indicate 1, 2, 3, 4 or 5)

**Notes:**

**Point 1:** It is important to have the exact location of these roads. Each road must be indicated on a 1:50000 Map and the map be submitted with the responses to the remaining points. This is important so that there can be no question to the exact placement or position of the said road (to prevent incorrect analysis). GIS will become an important tool for you to be able to indicate length and position of the roads in question. A particular road identified as fitting the requirements of the survey may have to be described by more than one provincial/district road number, please be aware of this.

**Point 2:** Indicate who the other road users are. We are in particular thinking of farmers, businesses and other formal enterprises who might have an inherent interest in improved road conditions and who forestry companies could perhaps lobby with for common gain. The public using the road to view particular tourist attraction can also be noted. If a rural community uses this road indicate as such. Please use your own discretion as to who to include as other road users bearing the above in mind. These users should use the road on a permanent basis, and not on only rare occasions.

**Point 3:** This point is self explanatory. Bear in mind, we are interested in the average annual volume of timber transported by your particular company only.

**Point 4:** Here we are looking for some indication on the present condition of the road. The following is a suggested way of doing so, please indicate as such.

- A 1 being: 20% of the road is passable, the other 80% is not in a condition conducive to safe and economical transport of timber;
- A 2: 40% of the road being passable, the balance as above;
- A 3 being: 60% of the road is passable the balance as above;
- A 4: 80% of the road being passable the balance as above;
- A 5: means that the total road length is trafficable and in good condition for the time of year that it is being used to haul timber etc.

We also need to know if the road is trafficable all year round or just in the dry season, or if it is capable of being used at all in any season!

## Appendix B: Area road and forest maps

### Area 1

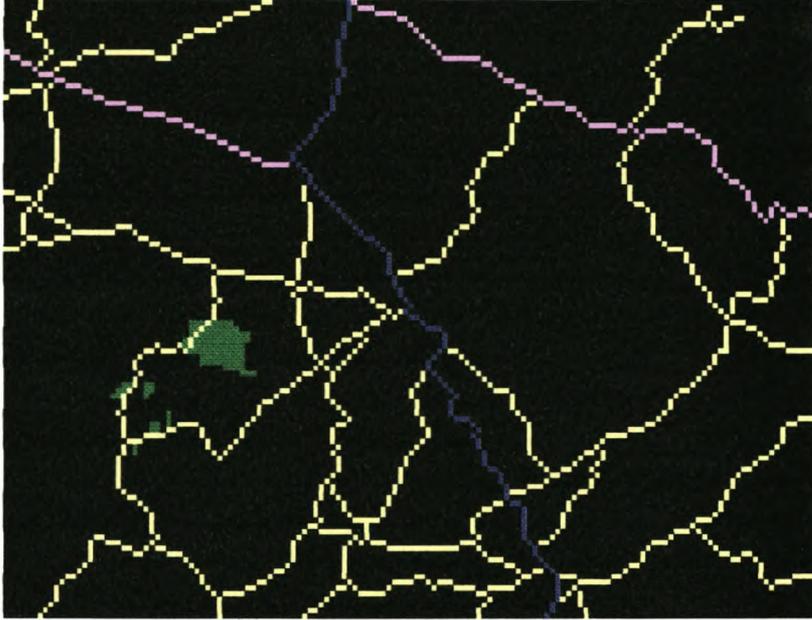


Figure 21: Area 1, All roads and forest

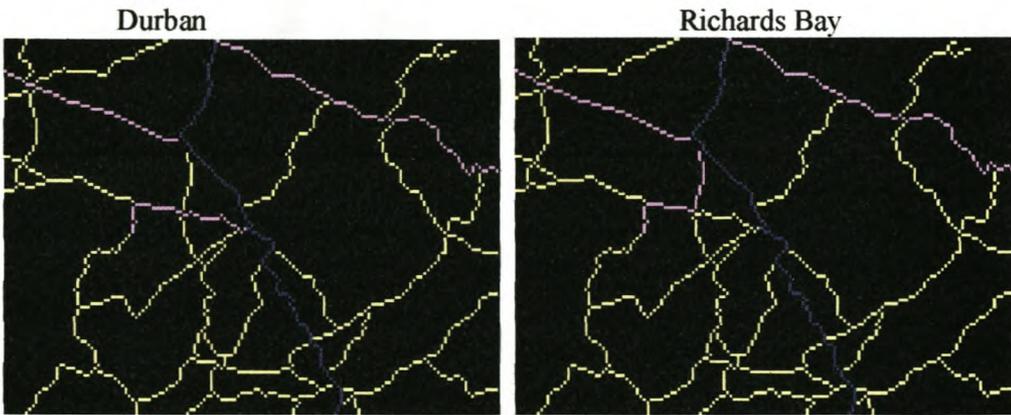
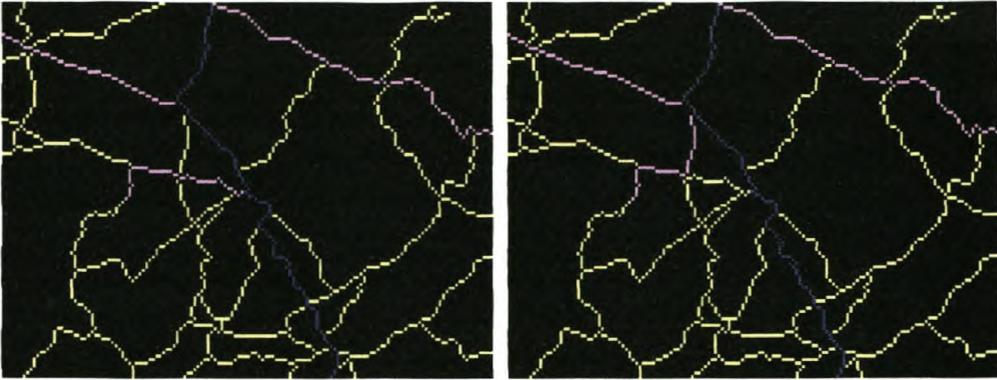


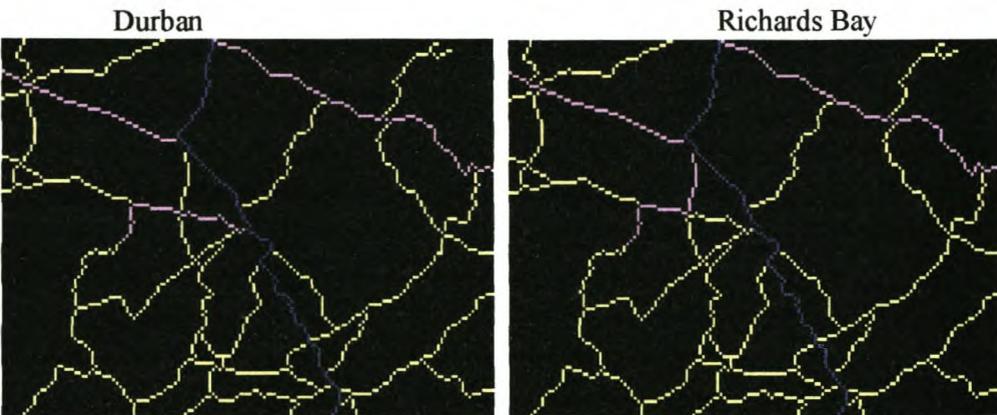
Figure 22: Area 1, provincial roads carrying 80-100% of available volume

Durban

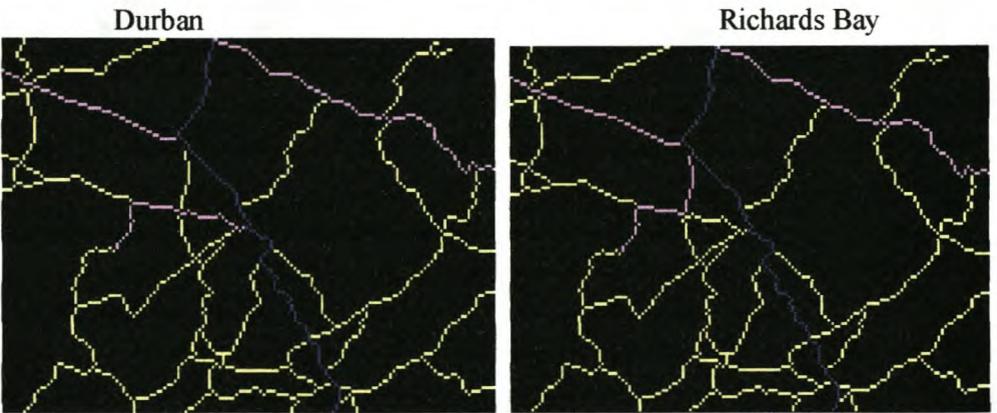
Richards Bay



**Figure 23: Area 1, provincial roads carrying 60-100% of the available volume**



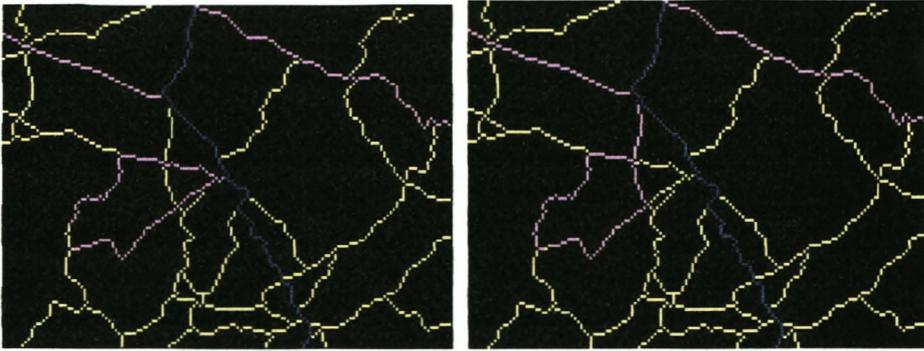
**Figure 24: Area 1, provincial roads carrying 40-100% of the available volume**



**Figure 25: Area 1, provincial roads carrying 20-100% of the available volume**

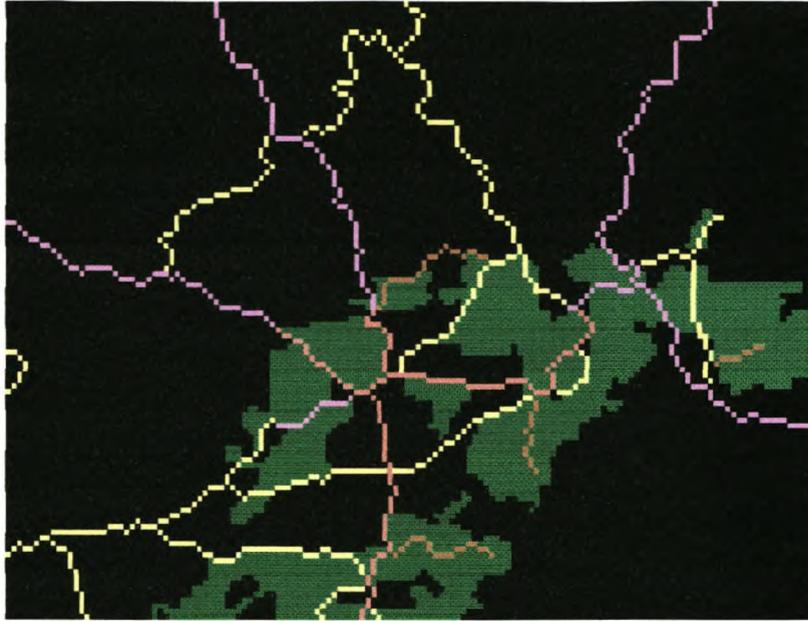
Durban

Richards Bay



**Figure 26: Area 1, all provincial roads used**

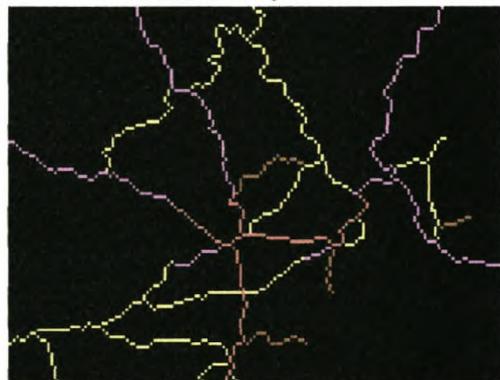
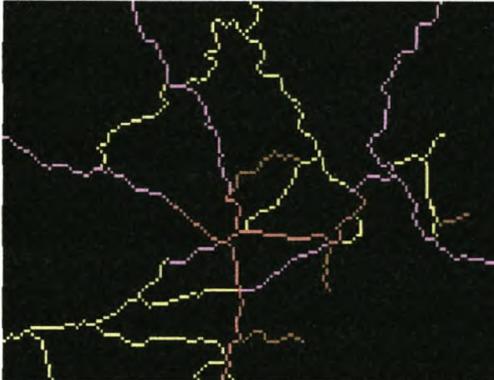
**Area 2**



**Figure 27: Area 2, all roads and forest**

Durban

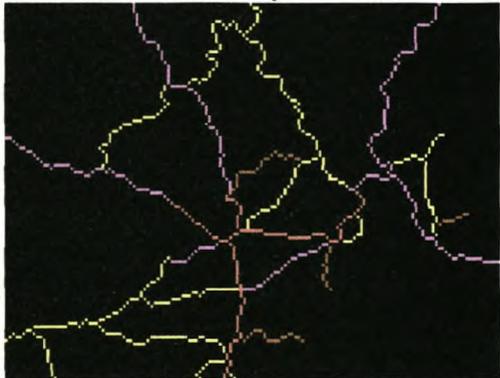
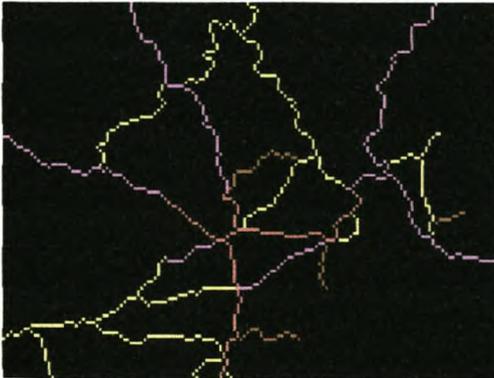
Richards Bay



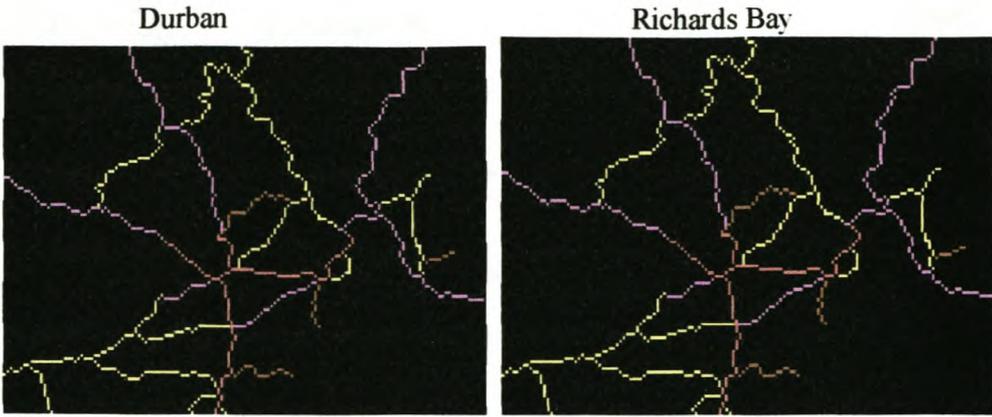
**Figure 28: Area 2, provincial roads carrying 80-100% of available volume**

Durban

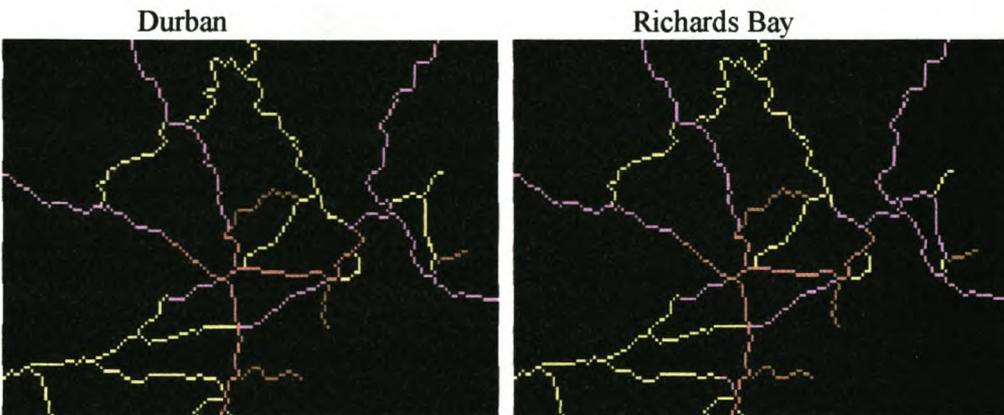
Richards Bay



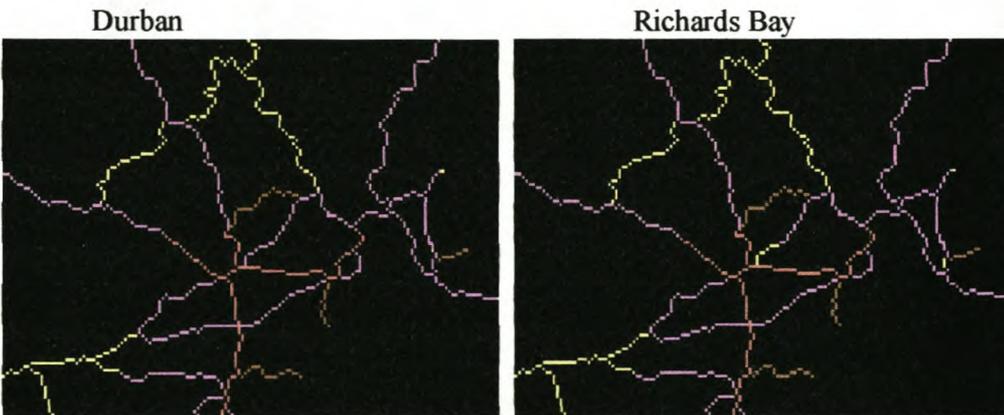
**Figure 29: Area 2, provincial roads carrying 60-100% of the available volume**



**Figure 30: Area 2, provincial roads carrying 40-100% of the available volume**

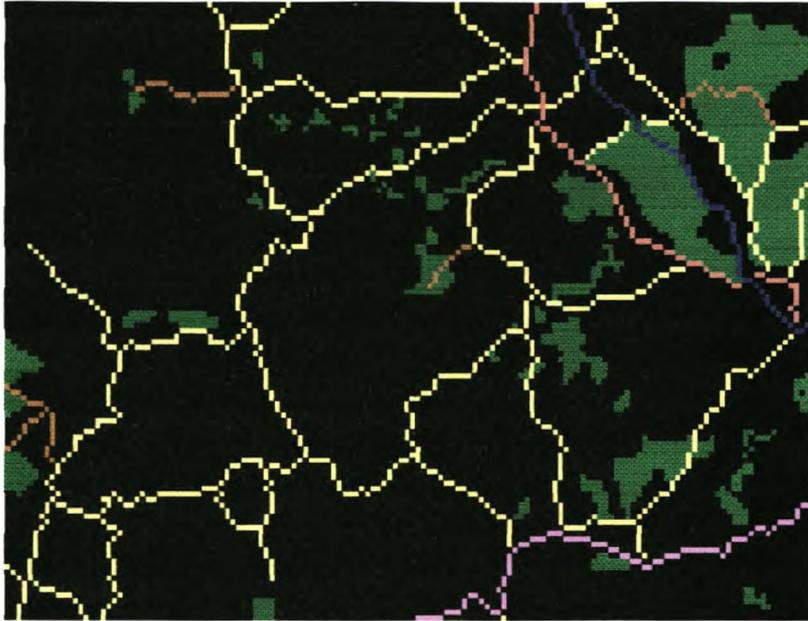


**Figure 31: Area 2, provincial roads carrying 20-100% of the available volume**



**Figure 32: Area 2, all provincial roads used**

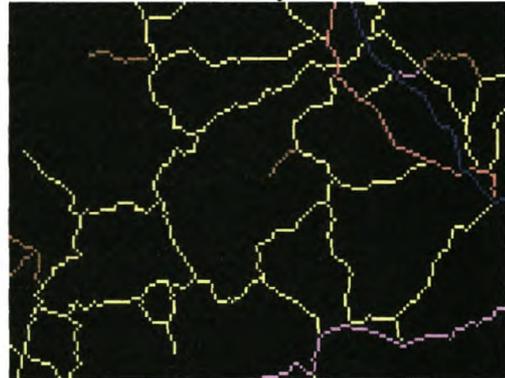
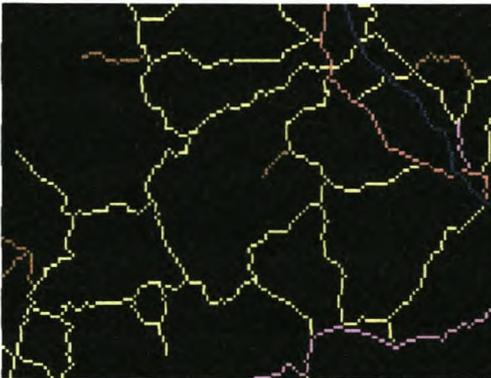
**Area 3**



**Figure 33: Area 3, all roads and forest**

Durban

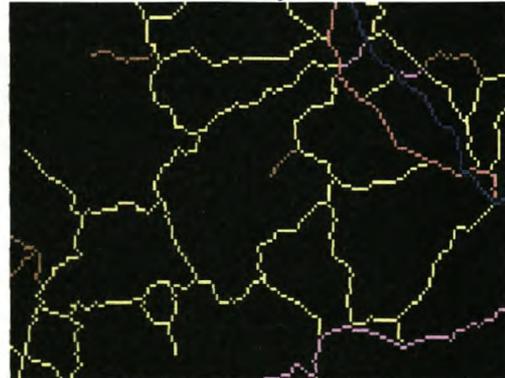
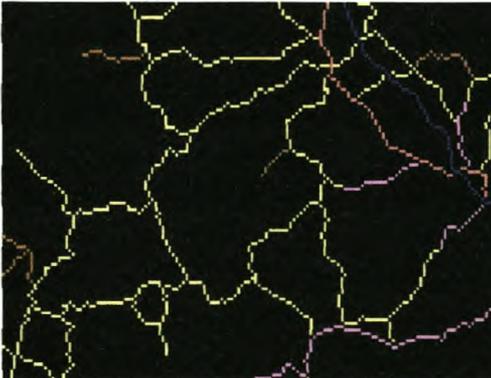
Richards Bay



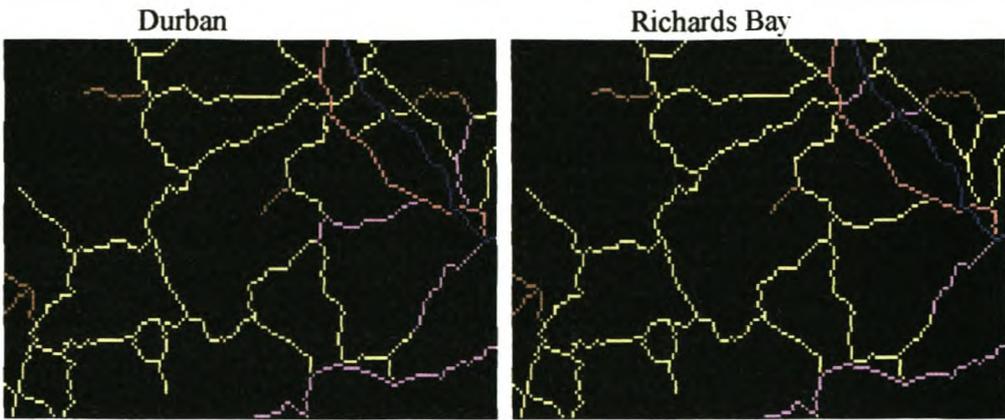
**Figure 34: Area 3, provincial roads carrying 80-100% of available volume**

Durban

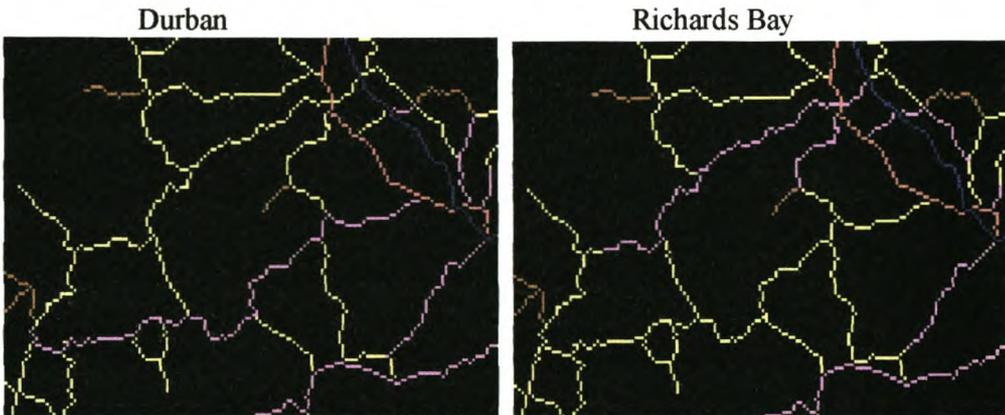
Richards Bay



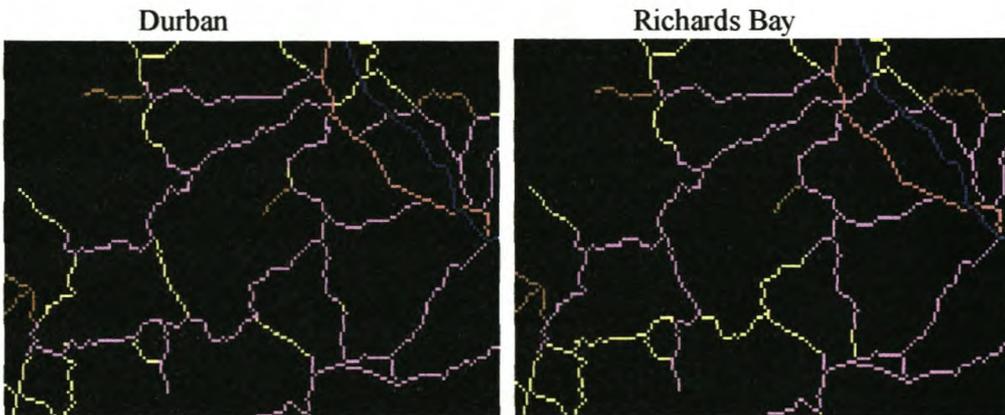
**Figure 35: Area 3, provincial roads carrying 60-100% of the available volume**



**Figure 36: Area 3, provincial roads carrying 40-100% of the available volume**

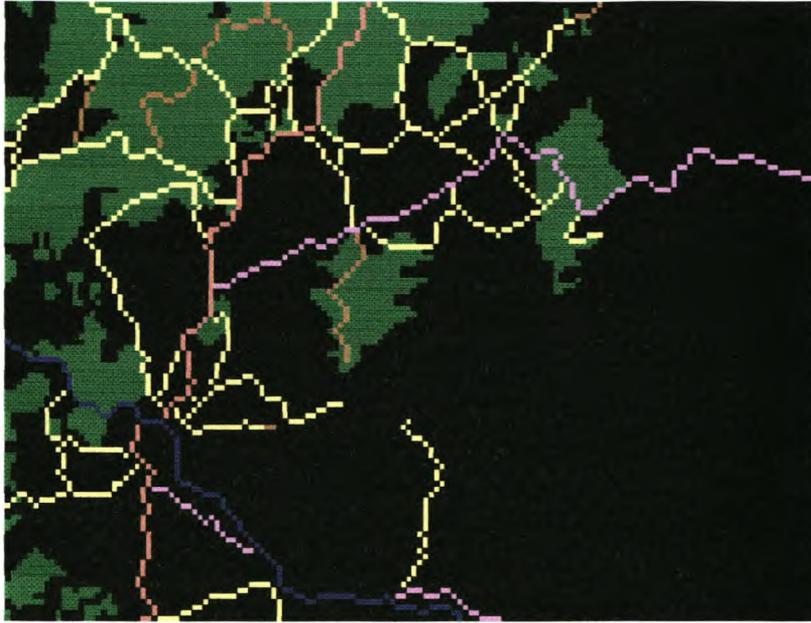


**Figure 37: Area 3, provincial roads carrying 20-100% of the available volume**

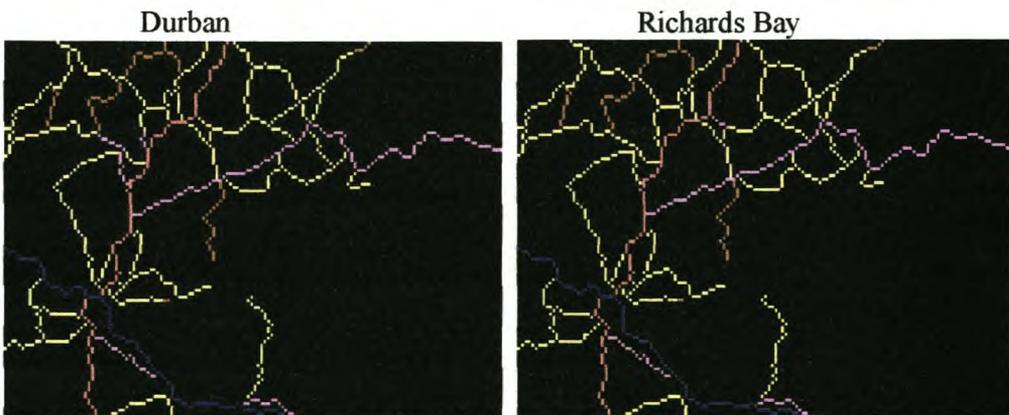


**Figure 38: Area 3, all provincial roads used**

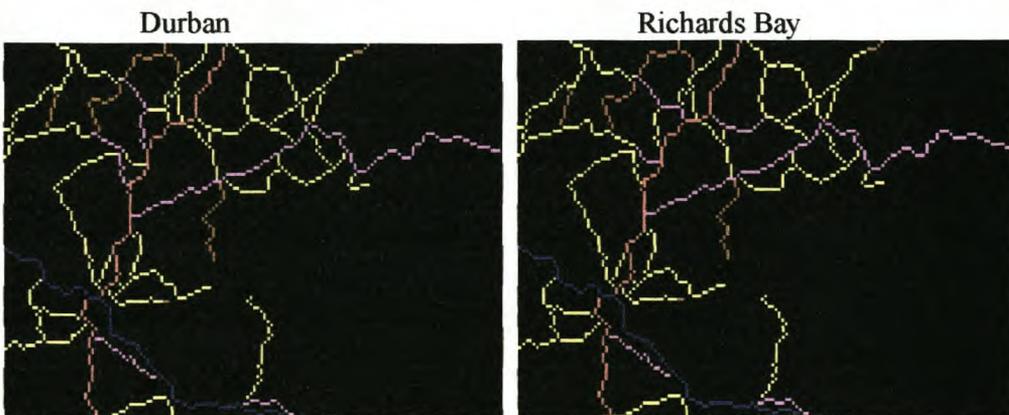
**Area 4**



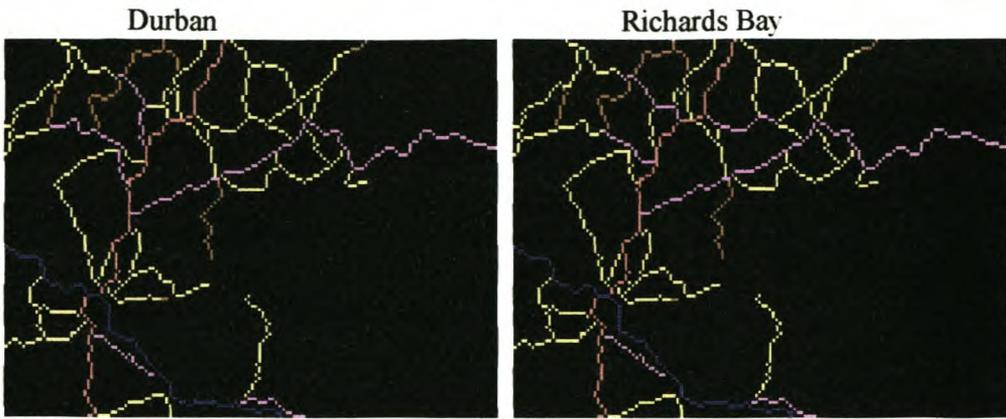
**Figure 39: Area 4, all roads and forest**



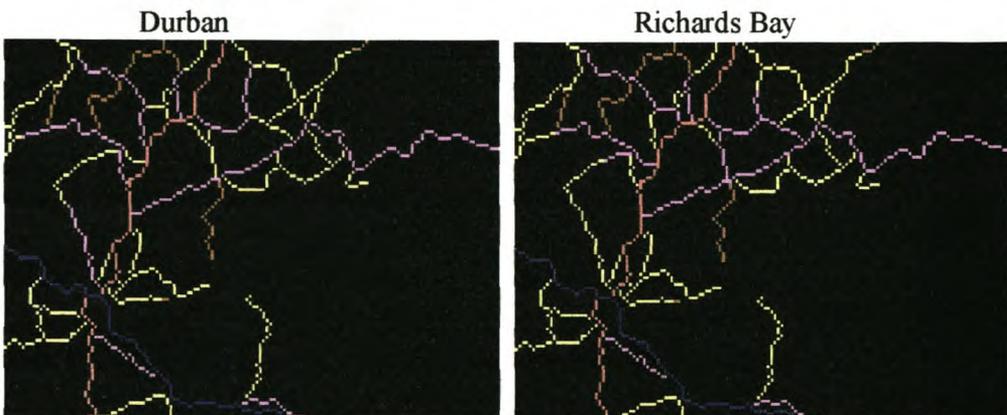
**Figure 40: Area 4, provincial roads carrying 80-100% of available volume**



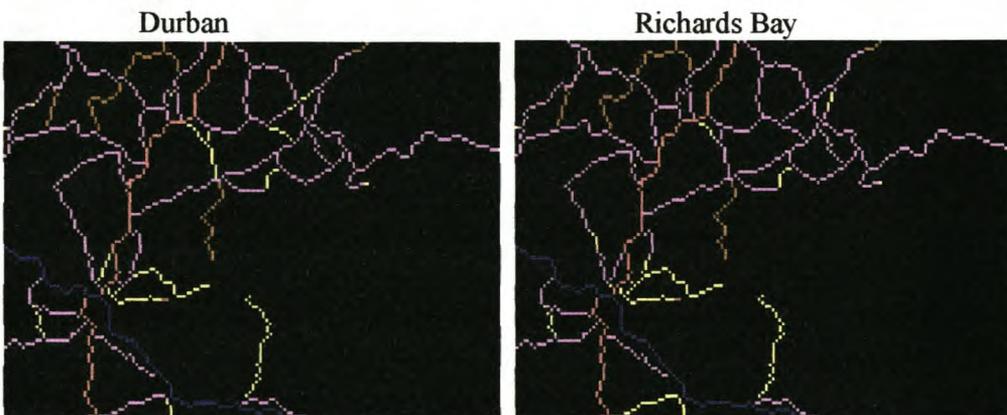
**Figure 41: Area 4, provincial roads carrying 60-100% of the available volume**



**Figure 42: Area 4, provincial roads carrying 40-100% of the available volume**

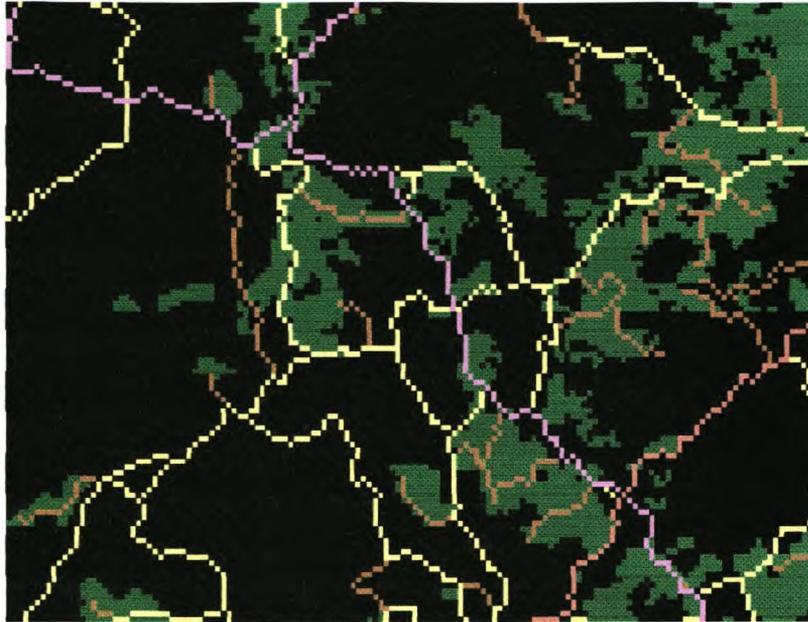


**Figure 43: Area 4, provincial roads carrying 20-100% of the available volume**

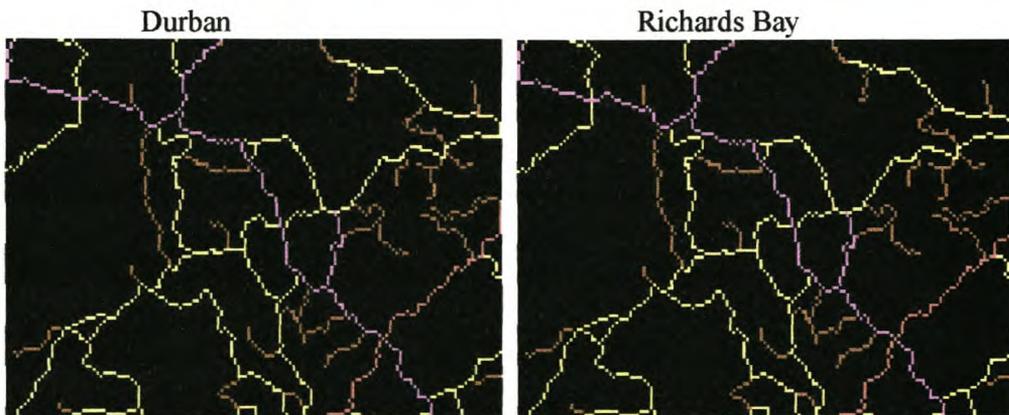


**Figure 44: Area 4, all provincial roads used**

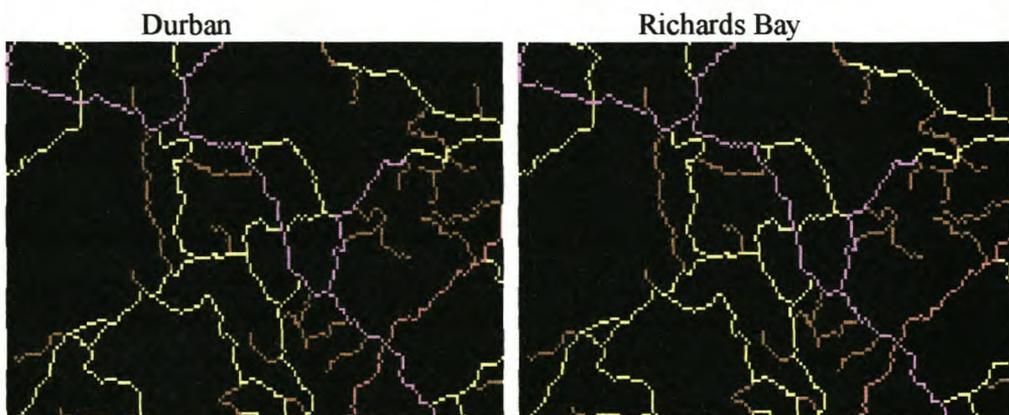
**Area 5**



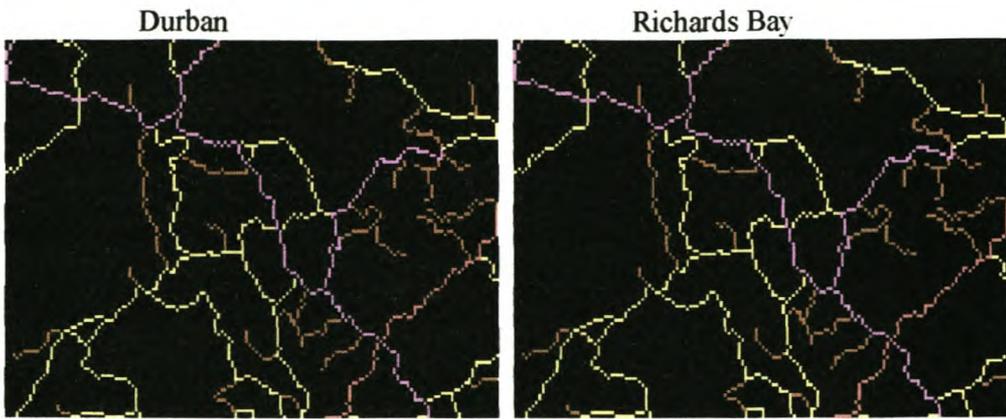
**Figure 45: Area 5, all roads and forest**



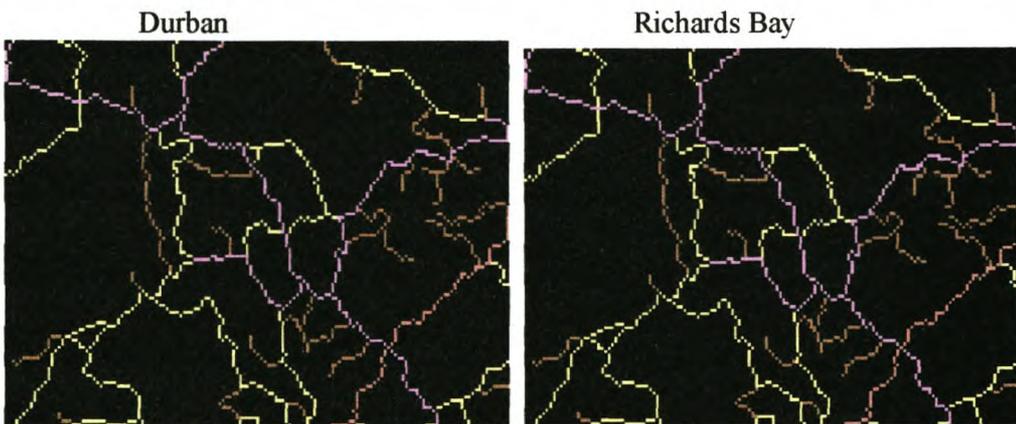
**Figure 46: Area 5, provincial roads carrying 80-100% of available volume**



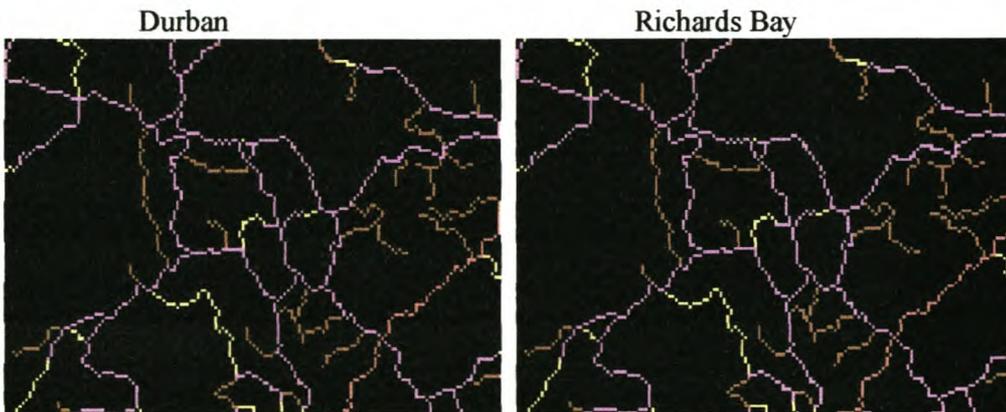
**Figure 47: Area 5, provincial roads carrying 60-100% of the available volume**



**Figure 48: Area 5, provincial roads carrying 40-100% of the available volume**

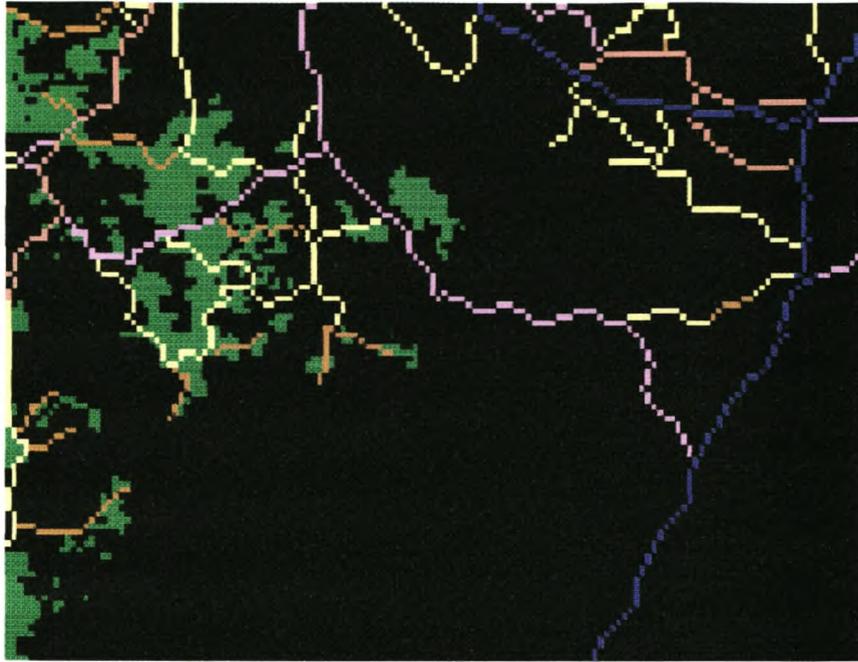


**Figure 49: Area 5, provincial roads carrying 20-100% of the available volume**

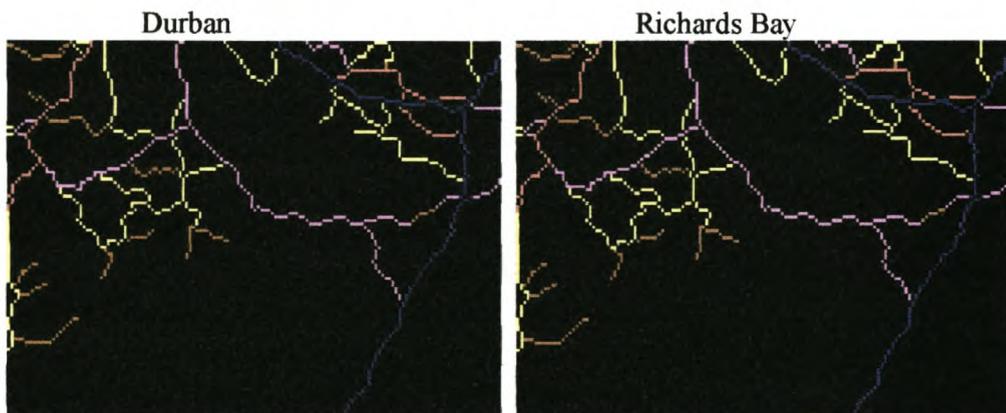


**Figure 50: Area 5, all provincial roads used**

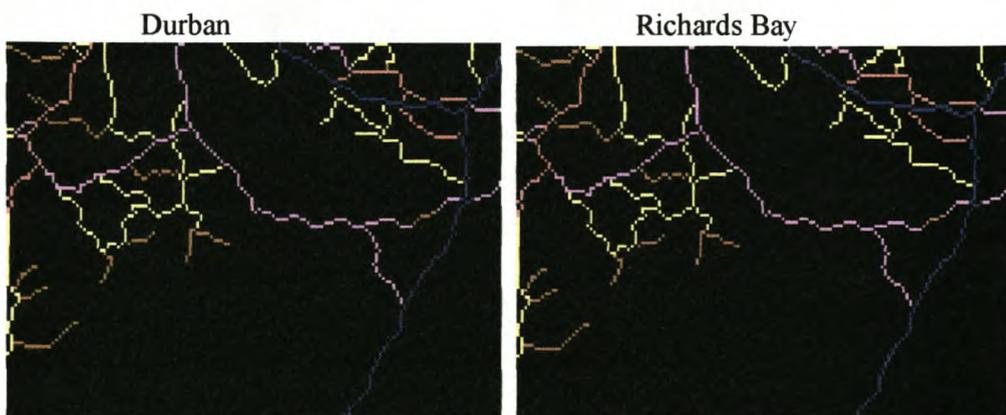
**Area 6**



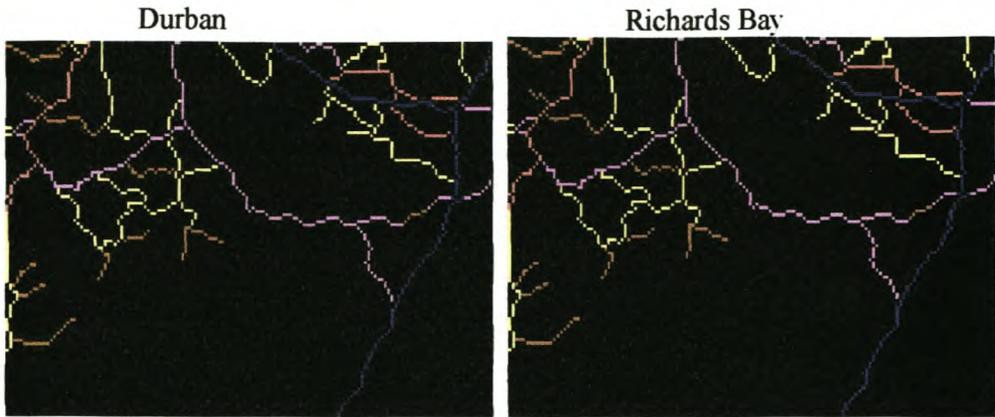
**Figure 51: Area 6, all roads and forest**



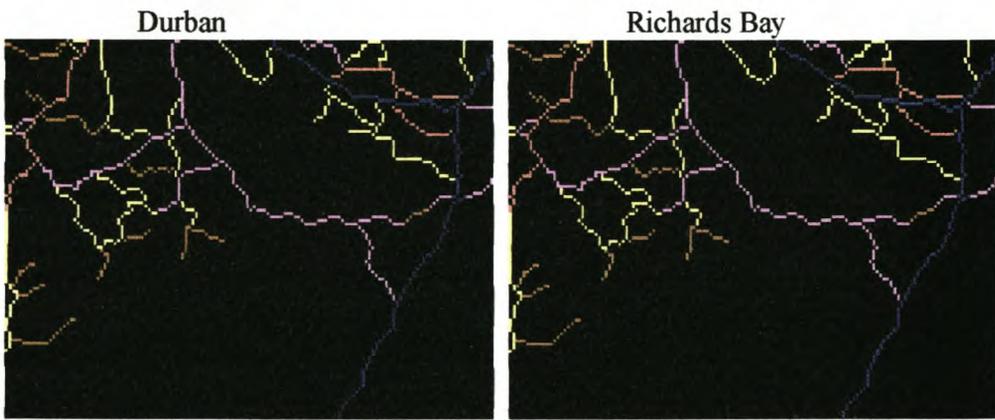
**Figure 52: Area 6, provincial roads carrying 80-100% of available volume**



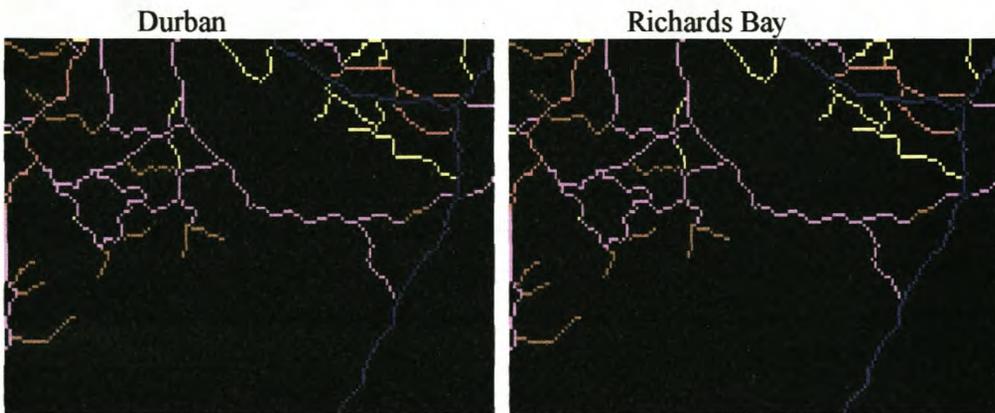
**Figure 53: Area 6, provincial roads carrying 60-100% of the available volume**



**Figure 54: Area 6, provincial roads carrying 40-100% of the available volume**



**Figure 55: Area 6, provincial roads carrying 20-100% of the available volume**



**Figure 56: Area 6, all provincial roads used**

## Appendix C: Road network analysis tool interface

