A STUDY ON REDUCING PRIMARY TRANSPORT COSTS IN THE SOUTH AFRICAN TIMBER INDUSTRY

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ABSTRACT

Harvesting and transport accounts for up to 70% of the total production cost of roundwood in South Africa. This invokes an interest to improve harvesting systems through the introduction of improved equipment, road networks and more refined operating techniques. A literature review was conducted which investigated the various harvesting systems and equipment with a focus on ground based extraction, as it accounts for 96% of the timber being extracted annually in South Africa. A review of forest roads in South Africa was also conducted and it was concluded that at present there has been little focus on the upgrading and maintenance of forest road networks.

It was concluded that the most significant reduction in transport costs would be achieved by reducing the distances travelled by expensive extended primary transport (R5.83 $t^{-1}.km^{-1}$) and by allowing less expensive secondary terminal transport (R0.4 $t^{-1}.km^{-1}$) to move further into the plantations. This could only be achieved by investing large amounts of capital into the upgrading of forest roads to a standard suitable to service secondary transport vehicles.

A model was developed which was able to determine the tonnage of timber needed to flow over a particular road that will warrant the upgrading cost. The model was applied to two study areas, the first study yielded no results due to the already dense network of B–class roads, possibly excessive. The second study area identified three possible road upgrades to improve the existing transport system. A full costing of the existing and modified transport system was completed and a significant cost saving was shown, not accounting for the road upgrading cost. Capital budgets were used to account for more complex parameters, such as tax and discount rates, previously excluded from the simple model. These were used to determine the economic viability of the upgrades and to evaluate the suitability of the model.

The model proved to be successful and confirmed that forest roads can be optimised accompanied by significant cost savings. The model is generic and simple allowing for easy application to a variety of situations and is also flexible to modifications.

I wish to certify that the work reported in this dissertation is my own unaided work except where specific acknowledgment is made. In addition I wish to declare that this dissertation has not been submitted for a degree in any other university.

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GLOSSARY OF TERMS

(after Stokes *et al.*, 1989)

Bucking – to saw felled trees into shorter lengths.

Butt end – base of a tree, the large end of a log.

Chipping – breaking or cutting trees into small pieces of controlled fibre length.

Choker – short length of flexible wire, rope, or chain used to attach logs to a winch line or directly to a tractor.

Delimbing – removing branches from trees.

Depot – permanent cleared area in a forest where timber is delivered to await final delivery to a processing plant. Most often have a hardened surface to allow all weather loading.

Feller buncher – self-propelled machine designed to fell standing trees and present the timber in bunches on the ground.

Felling – cutting or uprooting standing trees, causing them to fall.

Harvester – self-propelled multifunction machine that can operate as a swath cutter, as well as delimb, debark and buck individual trees.

Highlead – logging-wire rope system that involves yarding in logs or trees by means of a rope passing through a block at the top of the head spar.

Knuckle boom crane – hydraulically operated loading boom of which the mechanical action imitates the human arm.

Landing – temporarily cleared area in the forest to where logs are extracted to for loading onto larger vehicles for delivery to depot or processing plant.

Primary transport – movement of a felled tree from the stump to a landing.

Pulpwood – roundwood used as a source of wood fibre in a pulp mill.

Roundwood – a length of cut tree generally having a round cross-section, such as a log or bolt.

Silviculture – the science and art of cultivating forest crops.

Skyline – cableway stretched between a tower and a spar tree, and used as a track for a skyline carriage.

Tagline – extra length of line at the end of a main line to carry additional chokers.

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1. INTRODUCTION

Background

Forest engineering involving harvesting and transport contributes up to 70% of the total roundwood production cost and is a critical aspect in South African forestry, with potential economic, environmental and social impacts (Grobbelaar, 1999). In South Africa, primary and secondary transport collectively may account for up to 55% of the mill delivered cost of pulpwood (Morkel, 2000).

The cost of transport in forestry is a compound cost, which consists of the road user costs (vehicle operating cost), road construction costs and road maintenance costs. The interactions between these three components need to be understood and considered in an attempt to minimise total transport costs. Forest road networks are therefore, constructed, upgraded and maintained to facilitate the transport of forest products in the most economical manner possible (Morkel, 1994). Due to the extensive variations in the terminology used in South African forestry transport, Ackerman (2001) developed standard terminologies (*cf.* Figure 1.1) which were assumed for this study.

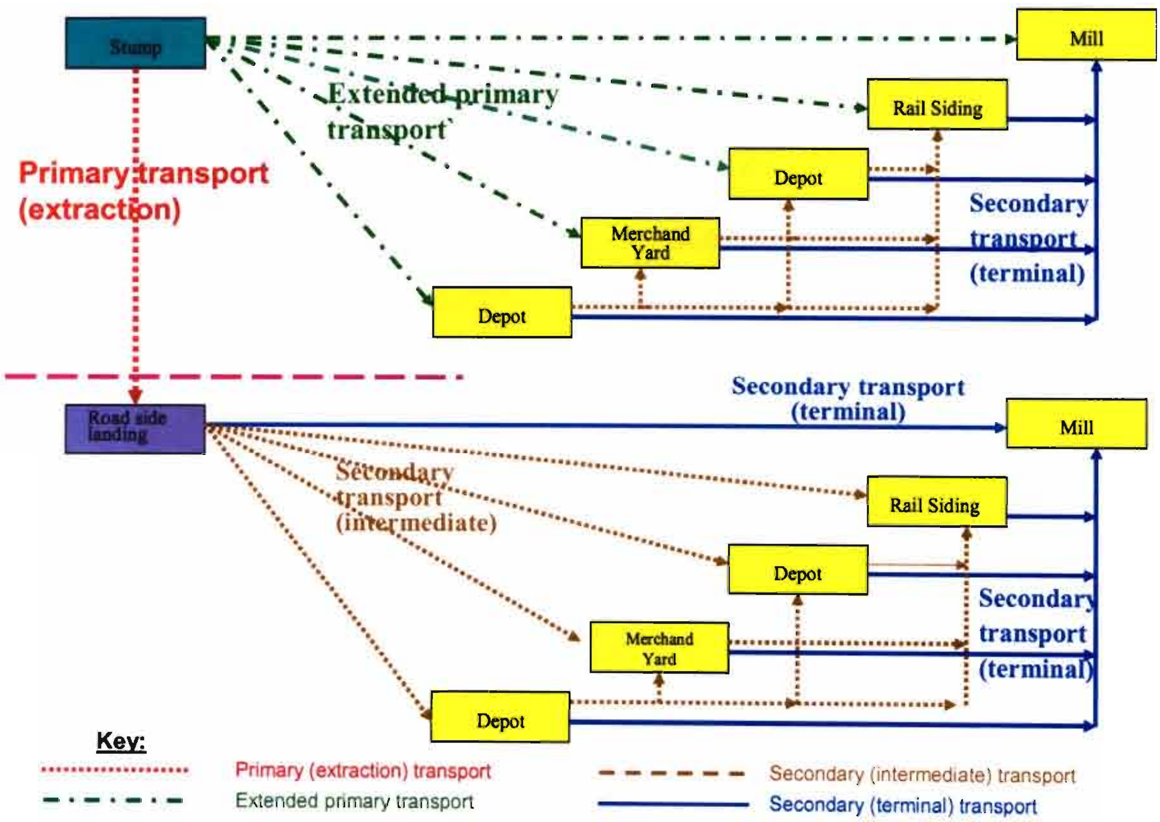


Figure 1.1 Schematic of the phases of wood transport (Ackerman, 2001)

Rationale

One aspect of the value chain is the road infrastructure. A typical timber plantation has a dense network of low cost C–class roads and a sparse network of high cost A or B–class roads which have to satisfy certain design criteria. Over the past two decades forest road infrastructure in South Africa has deteriorated substantially. This can be attributed to roads been capitalised and not reflected against the operational cost of harvesting timber (Morkel, 1994). Furthermore, when budget cuts are required, maintenance budgets are a primary target since the impact is not recognised immediately.

A second aspect of the value chain is the transport system. Vehicles designed for primary transport, transport timber from the stump to some point which is accessible to secondary transport. From this point timber is transported by the secondary transport vehicles along A or B–class roads onto the provincial road network for final delivery to the processing plant. Primary transport in the South African pulpwood industry is commonly performed by vehicles that can incur costs in $R^{-1}.t^{-1}.km^{-1}$ of up to fourteen times higher than that of secondary terminal transport (STT) vehicles, typically a rigid truck with a drawbar trailer (Oberholzer, 2003; personal communication). Although the STT phase is significantly less expensive it has restraints in terms of the terrain and road conditions that can be negotiated, thus only being able to transport timber over an A or B–class road of suitable standard. Therefore, there exists some point where the cost of improving the road network and so allowing STT to gain further access to the plantation will equal to the cost of transporting timber by the expensive primary or extended primary transport (EPT). From this, four main objectives and a number of sub-objectives were set out for this study and are as follows.

Objective one: To review timber extraction in forest harvesting systems to gain an understanding of the equipment and methods used and the influence it has on the South African forestry industry.

Objective two: To conduct a review of forest roads in South Africa. Specific objectives included highlighting important factors concerning forest roads in terms of the design, construction and maintenance and investigating the various road classes in terms of the design vehicles required to traverse them.

Objective three: To develop a simple generic model that will determine the optimal distance to upgrade a road leading into a forest plantation. This will be carried out to minimise the overall cost by making optimum use of the available transport systems. Specific objectives are to:

- develop the model for a single theoretical compartment with a single access road,
- expand the model to account for multiple compartments, with timber entering the proposed road for upgrading, at multiple entry points along its length, and
- to demonstrate the use of the model under theoretical conditions.

Objective four: Apply the model to two case studies to test the functionality and the economic viability of the model. Specific objectives are to:

- select two typical plantations which are representative of the forestry industry,
- determine the current harvesting systems and costs employed in both study areas,
- apply the model to identify possible road upgrades,
- calculate a cost saving between the existing and a modified configuration,
- use a capital budget system to determine the suitability of the model and
- perform a sensitivity analysis on model input variables.

2. A REVIEW OF TIMBER EXTRACTION IN FOREST HARVESTING SYSTEMS

In the early days of forestry the choice of harvesting systems were limited and a one-dimensional approach to its evaluation was sufficient, represented by monetary values only (Hoefle, 1974). Nowadays, the choice has become more difficult with a wide range of equipment and systems available, compounded by international pressures on environmental issues and the concept of sustainable management in forestry through forest certification.

A harvesting system must have the objective of minimising total cost, from felling to processing, as well as being balanced with other objectives, such as environmental and social responsibilities (Brink *et al.*, 1995). It is critical to consider all the operations carried out from the standing tree to the processing plant as a harvesting system. It is ineffective to optimise a single machine or piece of equipment as an improvement in one stage of an operation could have a negative repercussion on other phases within the system (Rönnqvist, 2003). In the past two decades South Africa has had to begin exploring more mechanised systems due to the increase in labour cost and a reduction in labour availability (Brink, 1999). Owing to the high capital investment tied up in the purchase of machines, these systems require full machine utilisation if they are to be cost competitive with less mechanised manual systems.

This review will provide an overview of three harvesting methods and their relevance to the South African forestry industry. Ground based, cable and aerial harvesting systems will be discussed with ground based systems being examined in more detail and emphasis being laid on the three technological levels as set out by Heinrich (1987). The specific details of the equipment used in the extraction phase of ground based harvesting systems are investigated with both a description of the most important features, as well their applications to different operating conditions.

2.1 Harvesting Methods

A harvesting method refers to the form in which wood is delivered to the logging access roads and depends on the amount of processing (e.g. delimbing, bucking, debarking and chipping) which occurs within the compartment (Pulkki, 2002).

Primarily, there are three harvesting methods that are carried out, namely cut to length, tree length and full tree methods. They are individually characterised by the equipment configurations used, as well as the silvicultural systems practised. The choice of harvesting method usually depends on the form of wood the receiving mill requires. Figure 2.1 shows the use of the three different harvesting methods in South Africa. Brink (1999) notes that the cut-to-length method in South Africa has increased overall from 44% of total volume, to 52% from 1987 to 1997.

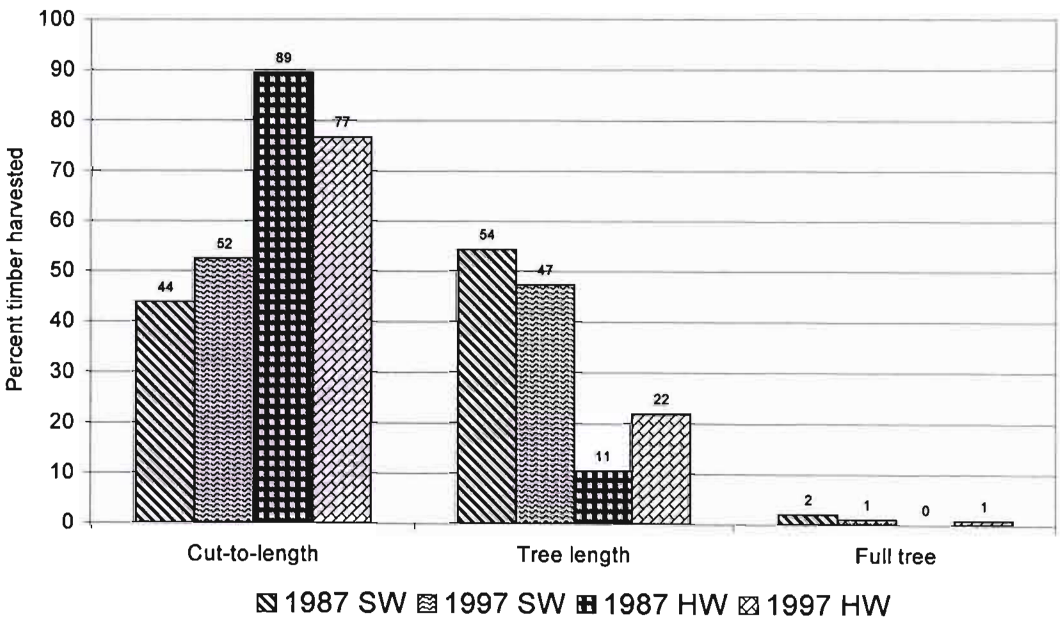


Figure 2.1 Harvesting methods in South Africa (1987 vs 1997); SW = softwood, HW = hardwood (Brink, 1999)

2.1.1 Cut-to-length

Cut-to-length, also commonly known as the shortwood method, refers to trees that are felled (cut-off above the stump with stump height less than one-half butt diameter), delimbed and bucked to various assortments (pulpwood, sawlog, veneer bolt, etc.) directly at the stump area. This method is re-establishing itself in many parts of the world due to its "softer" environmental impact, where it was once deemed an inefficient method of logging (Pulkki, 2002).

Brink (1999) notes that pulp in South Africa is predominantly harvested by the cut-to-length method. Although cut-to-length could remain in the future, harvesting systems will change. The changes will be reflected in terms of harvester heads that will be able to debark quickly and cheaply. The transport dimensions of logs will also increase from the traditional 2.4m logs to predominately 6m logs as both pulp mills and transporters have shown the cost advantages of the extra length (Brink, 1999).

2.1.2 Tree length

The tree length method refers to trees that are felled, delimbed and topped within the compartment. The delimbing and topping can occur either at the stump or at the edge of the compartment. The tree lengths are bucked into log lengths and debarked if necessary at a roadside landing, or can be hauled to the mill by means of tree length hauling. Landings require a greater area than that of the cut-to-length method due to the bucking and debarking that is carried out on the landing (Pulkki, 2002).

The tree length method (where the tree length is delivered to the mill) has significant benefits in terms of the export of chips. There are three chipping plants currently operational in South Africa and because of the significant gains in chip quality from tree lengths, chipping plants will pay a premium for *Eucalyptus* long logs or tree lengths. Tree length chipping will, however, be restricted to plantations harvested closer to the chipping plants due to truck configurations not been able to adequately accommodate such dimensions and therefore not achieving an optimal 42 ton payload (Brink, 1999).

2.1.3 Full tree

The full tree method refers to trees that are felled and transported to roadside intact. They are then either processed at roadside or hauled as full trees to a central processing yard or mill. With the full tree method the residue (limbs, tops and bark) is left at the roadside or yard and needs to be disposed of. It can either be raked into piles and left for natural decomposition or burnt. Another alternative is to spread the residue back over the harvested compartment and thereby utilising the return trip of the skidder or forwarder (Pulkki, 2002).

The full tree method is, however, the most demanding in terms of the size and quality of the landing required and in 1997 only contributed 1% of the total timber harvested in South Africa (Brink, 1998).

2.2 Harvesting Systems

A harvesting system refers to the tools, equipment and machines involved in harvesting an area of timber and delivering that timber to a processing plant. Various components within a harvesting system can be changed without changing the harvesting method (Pulkki, 2002). Ackerman (1998) refers to a harvesting system as a combination of activities in the timber logistic chain, from stump to mill, while making use of appropriate technology in order to meet a customer's objective. Letourneau (1987) describes a harvesting system as a set or arrangement of items related to one another which contribute to an objective that is common to all. Wang *et al.* (1998) notes that the interaction between site and stand conditions, harvesting methods and machine factors must be considered when selecting effective harvesting systems.

In broad terms, harvesting consists of three main phases, viz. cutting trees, carrying out some sort of processing and transporting the timber from one location to another. There are, however, a large number of factors which influence the exact details and sequence of these phases. Due to these operations been conducted sequentially, the output of one phase always becomes the input to the subsequent phase and hence the need for the harvesting of timber to be considered as a system. Harvesting systems are, however, most commonly classified with reference to primary transport and although it is generally the second phase in the sequence, after felling, it is most often the most important due to the limitations it incurs from terrain, weather, slope, soil type and the harvesting method required (MacDonald, 1999).

Primary transport comprises of three components, viz. aerial, cable and ground based systems (*cf.* Figure 2.2). For the purpose of this review the focus will be on ground based systems as this method accounts for 96% of the volume of timber extracted in South Africa annually (Brink, 1998). Although aerial and cable systems are reviewed in the following sections, they are only included so as to appreciate their application under certain conditions.

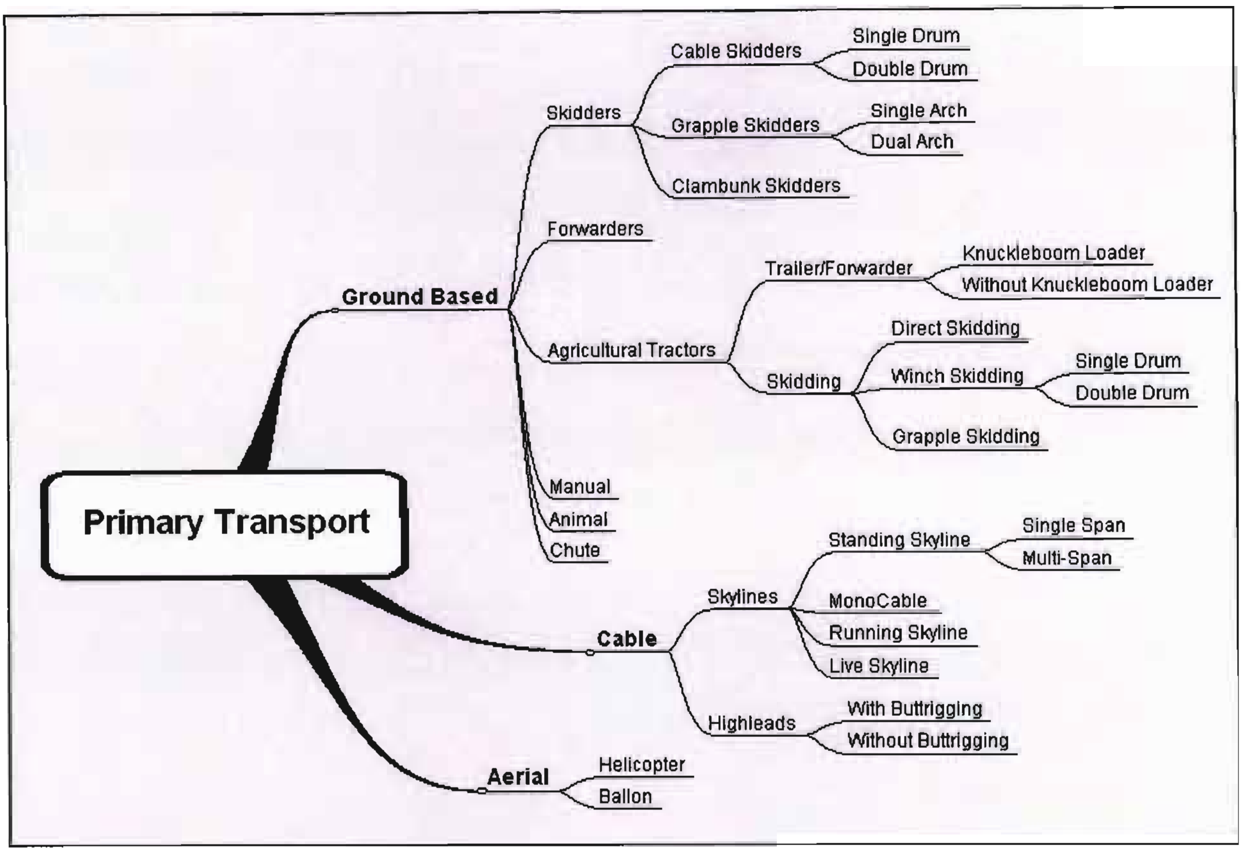


Figure 2.2 A breakdown of the primary transport phase within forest harvesting

2.2.1 Aerial

Aerial systems include both helicopter and balloon logging and are characterised by the ability to lift forest products directly from the felling site to a landing without regard to intervening obstacles (MacDonald, 1999). Helicopters provide operating ranges far greater than those of conventional equipment and an ease of manoeuvrability not obtainable by forwarders or skidders, highlead or skyline, over the widest range of terrain conditions. There are, however, many limitations in terms of the payload capacity and the speed of the aircraft that must be interrelated with the necessary support equipment. Balloon systems combine the lifting capability of the balloon with the characteristics of certain cable systems, as well as extending the reach of traditional cable systems (Conway, 1982).

There are many factors that influence the productivity of aerial systems. A helicopter's maximum flying distance is determined by economics, while the maximum yarding distance in a balloon system is determined by the yarder's cable capacity (MacDonald, 1999). The primary reason for the lack of utilisation of aerial systems internationally, and the non-existence of aerial systems in South Africa, is attributed to the high capital and operating costs (Conway, 1982).

2.2.2 Cable

In cable systems, one or more suspended cables are used to extract timber from the felling site to a landing. The cables are operated by a winching machine (yarder), which can either be placed at the ridge top or at the landing site below (Dykstra and Heinrich, 1996). Figure 2.3 shows a running skyline system with the yarder positioned at the landing site.

Cable systems can be regarded as one of the most versatile extraction systems. Cable systems come at a high capital and a high operational cost as a result of setting up and moving from one harvesting operation to another. This renders cable systems only cost competitive when ground based systems are not possible. Cable systems become most applicable in steep terrain conditions (generally, slope >35%), excessive ground roughness, areas with soft underfoot conditions and environmentally sensitive areas (Oberholzer, 2000).

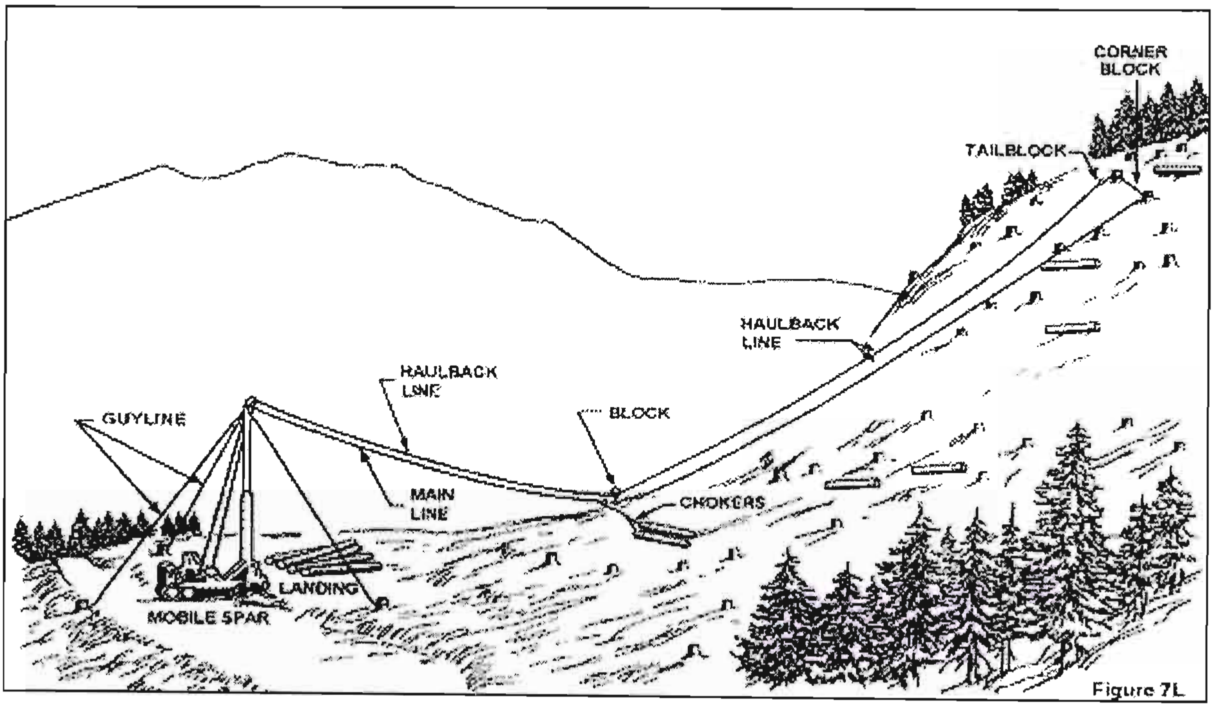


Figure 2.3 A running skyline cable yarding system showing the cable rigging and the yarder positioning (Yee, 2003)

2.2.3 Ground based

Ground based extraction of timber entails the transport of timber across terrain from the felling site to a roadside landing or depot. Due to the wide range of equipment and methods that can be applied to ground based extraction, it is appropriate to subdivide ground based harvesting systems into different technological levels. Heinrich (1987) defines three technological levels, viz. basic technology (manual), intermediate technology (motor-manual) and highly mechanised technology (mechanised). Figure 2.4 shows the dominance of the intermediate technology sector, as well as an 11% increase in the highly mechanised systems from 1989 to 1998 in South Africa.

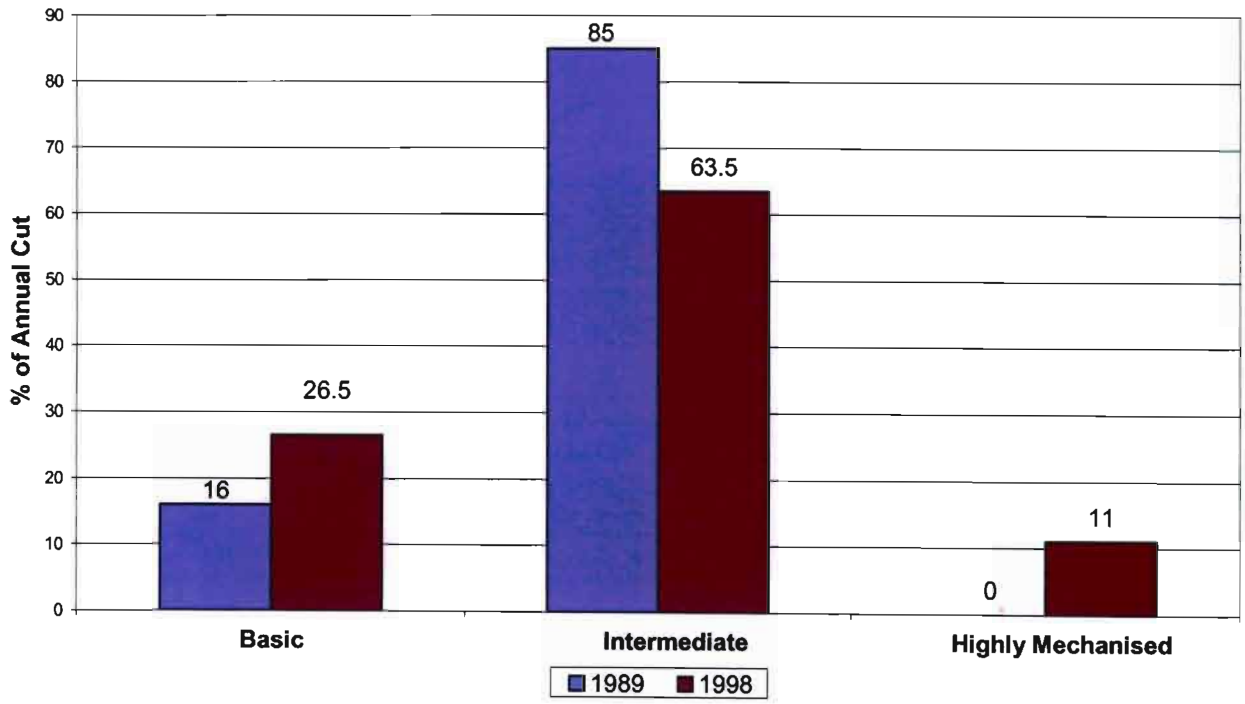


Figure 2.4 A comparison of basic, intermediate and highly mechanised technology in South Africa in 1989 and 1998 (after Brink and Warkotsch, 1989 and Brink, 1998)

2.2.3.1 Basic technology (manual)

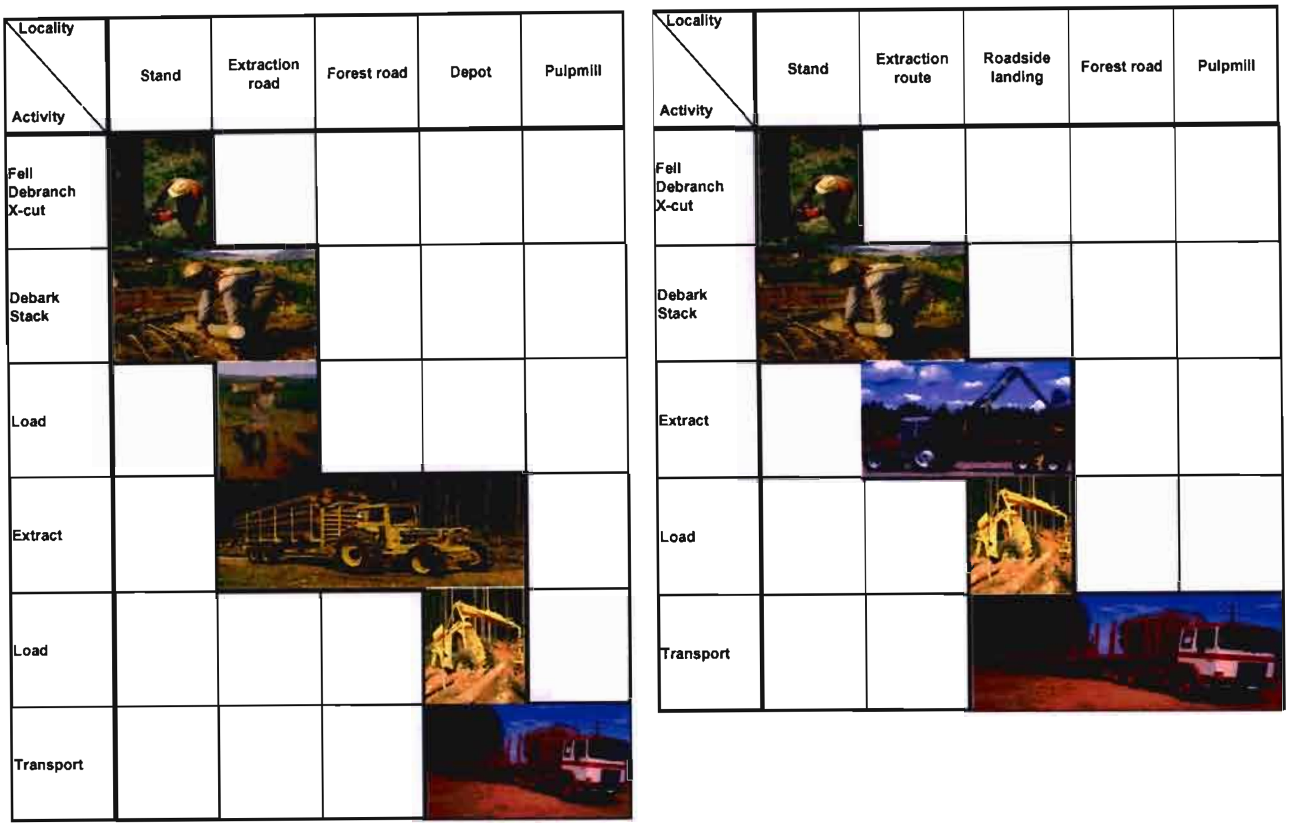
Manual labour dominates in basic technology and includes the use of simple and relatively cheap hand tools and equipment. Under the primary transport heading in Figure 2.2 it includes manual, chute and animal extraction. Most often this technology is aimed at providing tools to reduce the physical stress of manual operations (FAO, 1982; FAO, 1989).

Brink (1999) notes that labour costs have increased significantly over that of machine costs over the in the previous decade, (985% vs. 253%). The redrafting of the Forestry Act and the Employment Equity Act are legislative changes that have increased the cost of labour and so stimulated the future direction of the South African forestry industry to a more mechanised scenario (Brink, 1999).

2.2.3.2 Intermediate technology (motor-manual)

Intermediate technology reduces manual labour and increases productivity through the introduction of machines and equipment (FAO, 1982). This includes chainsaws, agricultural tractors with forestry attachments (skidding winch, skidding grapple and bogie axle trailer), cable skidders and standard cable yarders (Grobbelaar, 2000).

Figure 2.5 shows the sequence of functions performed from the standing tree to the processing plant for two typical intermediate technology systems that are common to South Africa. In the first (a), trees are manually felled, delimbed, processed into log lengths and loaded onto a haulage tractor, which transports the timber to a landing or depot to await final delivery to the processing plant. In the second, (b) an agricultural tractor that has a knuckle boom crane mounted for self loading and off loading is used to extract the timber and so increasing the productivity. There are many variations to the equipment shown and the operating techniques applied to increase productivity specific to site and stand conditions. These variations will be described in Section 2.3 with the emphasis on the extraction phase.



(a) (b)

Figure 2.5 Ground based intermediate technology harvesting systems (after Brink, 2001)

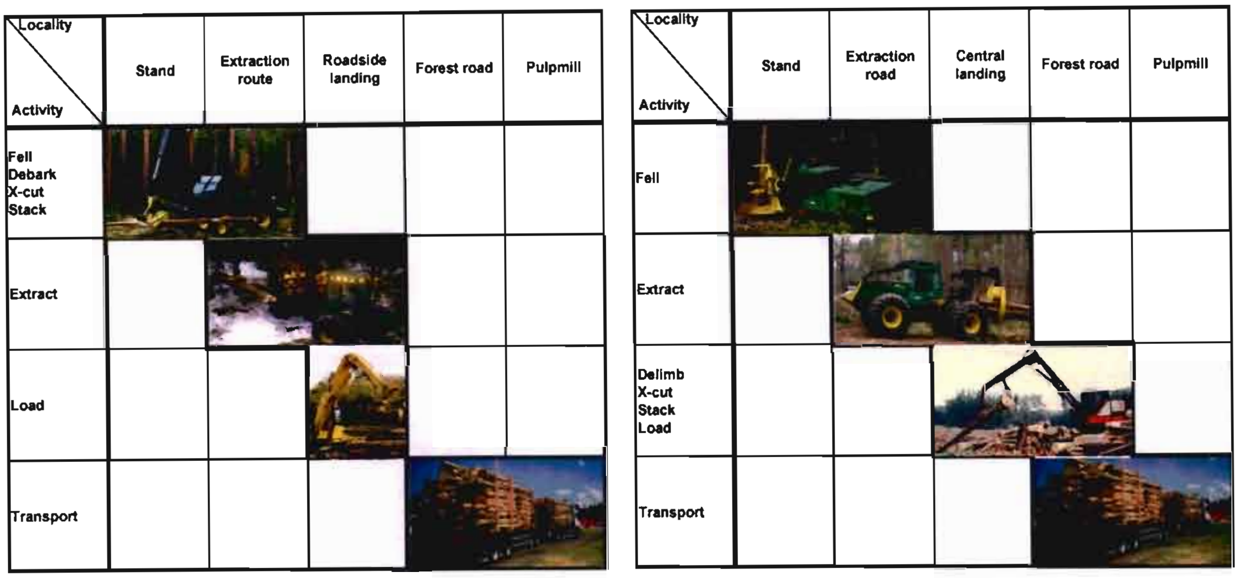
Figure 2.4 indicates that intermediate technology accounted for 63.5% of the volume of timber harvested in 1998 in South Africa. Kellogg (1999) notes that intermediate technology will remain in many future forest operations because of certain social-economic conditions and the inherent advantages of these traditionally used systems.

2.2.3.3 Highly mechanised technology

Highly mechanised technology involves using more powerful, specialised and high production machines (Johansson, 1997). This would include harvesters, feller-bunchers, purpose-built forwarders, grapple skidders and clambunk skidders. This technology requires the machine operator to have a higher level of training and more specialised operating skills.

Technological levels are not entirely dependant on the size of the harvesting operation as a large commercial operation in South Africa can successfully operate at the intermediate technology level. Where as a small scale operation in Scandinavia may use a harvester head attachment on an agricultural tractor and, though not more powerful, is technologically more advanced and therefore falls in the highly mechanised level of technology (Grobbelaar, 2000).

Figure 2.6 shows two highly mechanised systems. In the first (a), timber is felled and processed using a harvester head, log lengths are transported to a landing or depot using a forwarder to await pick-up by secondary terminal transport. In the second (b), a feller bunch fells and bunches full trees, which are then skidded to a landing or depot for processing and final delivery to the processing plant.



(a) (b)

Figure 2.6 Ground based highly mechanised harvesting systems (after Brink, 2001)

Highly mechanised systems have not been used extensively in South Africa as labour has been relatively cheap and plentiful, therefore not warranting the capital cost of such systems. There was, however, an 11% increase in the use of highly mechanised systems from 1989 to 1998 and should continue to increase in years to come (Brink and Warkotsch, 1989; Brink, 1998). This can be ascribed to the increase in labour cost, as well as the decrease in the availability of labour due to the advent of the AIDS pandemic. Though highly mechanised systems require less labour, the machine operators need to be highly skilled. Training therefore plays a critical role as unskilled labour will result low productivities and machines breakages, which in turn will lead to an uneconomical system.

2.3 Ground Based Extraction Methods and Equipment

Extraction is the process of moving trees or logs from the felling site by the most convenient, economical and environmentally acceptable means to a landing were the timber will be processed into logs or consolidated into larger loads for transport to the final processing plant (Dykstra and Heinrich, 1996). The ground based harvesting systems described in the Section 2.2.3 is an overview of how the equipment described in this section contributes to the harvesting system as a whole. This is necessary to consider as the manner in which the timber is presented at the felling site and the means by which it is transported to the landing and off-loaded has consequences in terms of quality of timber and productivity of the operation, in both the preceding and subsequent phases.

Ground based extraction can be divided into two major categories, viz. skidding and forwarding. The skidding process can be carried out by cable skidders, grapple skidders, clambunk skidders and agricultural tractors with various skidding attachments. Skidding is characterised by attaching timber to the extraction unit, lifted at one end, and the timber being dragged along the ground from the stump to the landing site (FESA, 1999). Forwarding is the operation whereby timber is carried from the stump to the landing site by lifting the whole load off the ground, it can be done by means of a purpose built forwarder or a tractor trailer unit (FESA, 1999).

According to FESA (1999), the application of ground based machines are limited by the terrain conditions set out in Table 2.1. The definitions for the specific index values within Table 2.1 are provided in Appendix A.

Table 2.1 Terrain limitations to ground based extraction machines (after FESA, 1999)

CRITERIA	WHEELED SKIDDERS		CLAM BUNK SKIDDER	AGRIC. TRACTOR with Winch or A-Frame	WHEELED FORWARDER		TRACTOR and TRAILER
	Normal Tyres	High Flotation			Normal Tyres	High Flotation	
Slope (%): Up	0 - 20	0 - 20	0 - 25	0 - 10	0 - 30	0 - 30	0 -10
Down	0 - 35	0 - 40	0 - 40	0 - 30	0 - 35	0 - 40	0 - 20
Ground Roughness	1 - 3	1 - 3	1 - 3	1 - 2	1 - 3	1 - 3	1 - 2
Ground Conditions	1 - 3	1 - 4	1 - 3	1 - 2	1 - 3	1 - 4	1 - 2
Extraction Distance (m)	50 - 500	50 - 500	50 - 1000	50 - 300	50 - 1000	50 - 1000	50 - 5000

2.3.1 Skidding

A skidder is a self-propelled machine designed to transport trees or parts of trees by trailing or dragging the timber. This can be done by animals, agricultural tractors or specialised articulated skidders (Stokes *et al.*, 1989). In South Africa, the articulated wheeled skidders play an important role in the movement of timber. They have the advantage over agricultural tractors as they are designed specifically to winch and skid trees from the felling point to a landing. They are also designed in such a way that the centre of gravity is placed well forward, the under carriage is well protected and it has a high power to weight ratio to give efficient performance (de Wet, 2000).

MacDonald (1999) notes that many contractors prefer skidders over forwarders as they are less expensive to purchase and to operate, are versatile and, due to their simplicity, are well understood machines. A skidder, which is intended for fast hauling, is sensitive to adverse slopes (>40%) and broken terrain. This is due to the skidder only being able to handle a reduced load at a longer cycle time in an attempt to skid or winch a load up such grades or over such terrain and so defeats the purpose of the machine (Letourneau, 1987).

De Wet (2000) presents five main factors that influence a skidder's productivity and performance. These are

- skidding distance,
- bunch size (felling operation),
- terrain (travel speed),
- grapple and engine capacity and
- operator decisions.

2.3.1.1 Cable skidders

A cable skidder (*cf.* Figure 2.7) is defined as a self-propelled machine that uses a main winch cable and cable chokers to assemble and hold a load (Stokes *et al.*, 1989). Depending on the size of the skidder it may be fitted with either a single or double drum winch. With a double drum winch each drum is operated separately, hauling in half the load at a time while operating with full power on each cable (Staaf and Wiksten, 1984).

(a) (b)

Figure 2.7 Cable skidder (a) side view of choked logs (b) rear view of butt plate

Skidding by means of a winch has been a common means of extraction in operations where the felling, delimbing and topping has been done manually (Staaf and Wiksten, 1984). This is due to the grapple and clambunk skidders being more suited to the fully mechanised harvesting systems which have the ability of presenting the timber in specific bunch sizes along the skid trail. Cable skidders have the advantage over grapple skidders in terms of accumulating their own load while remaining on designated skid trails and thus reducing intrusion into the compartment (Ackerman, 1998). De Wet (2000) notes that cable skidders are mostly used with larger timber as productivity is severely compromised with smaller timber. This is owing to the time required to hook and unhook chokers, as well as the physical limit to the number of chokers that can be handled simultaneously. Taglines have the ability to alleviate this problem to some extent, as more stems can be attached at a time and so increasing payload. Taglines also enable trees to be choked prior to the skidder's return and thus reducing delay times (de Wet, 2000).

The cable skidder is the least expensive of the three articulated skidders and has the lowest operating cost. It is, however, the most labour intensive and hazardous form of skidding as chokermen are required in the compartment to choke the timber and at least one person is required to dechoke at the landing, unless the operator dismounts to release the load.

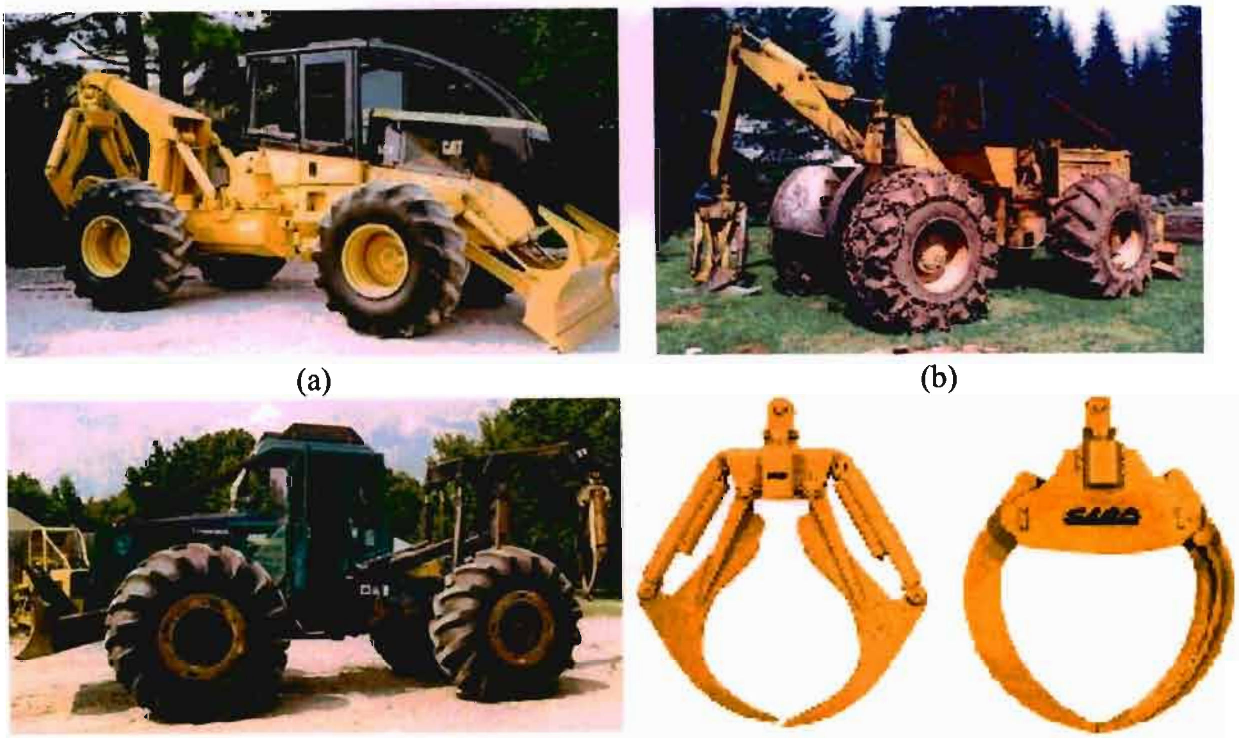
2.3.1.2 Grapple skidders

A grapple skidder is defined as a self-propelled machine that uses a grapple or bottom-opening jaws to assemble and hold a load (Stokes *et al.*, 1989). Three different types of grapple skidders are shown in Figure 2.8. The different configurations of grapple skidders are single arch, dual arch and swing boom, which allow the skidder to operate under varying terrain conditions, as the grapple is able to operate within the varying degrees of freedom listed below.

- Single arch - up/down motion only
- Dual arch - up/down and reach capabilities
- Swing boom - up/down, reach and left/right capabilities

The dual arch system allows for a certain amount of reach for the grapple and so enhancing its capability in rougher terrain. Similarly, the swing boom grapple skidder works effectively in steeper terrain where the skidder is unable to back into the butt ends of the timber as it can make use of its slewing capabilities to retrieve the timber.

The grapple size and type is of highest importance to the effective operation of a grapple skidder. The grapple should be correctly sized to coincide with the bunch size placed in the compartment by the feller buncher (de Wet, 2000). Two types of grapples are shown in Figure 2.8, viz. the sorting grapple and the bunching grapple. The sorting grapple operates with a scissor-like action and is ideal for handling mixed sized logs and gathering individual large diameter logs (Deckard, 2002). A bunching grapple has a wide concave shaped head and full curvature tongs which are designed to gather and securely hold a large number of small diameter logs and prebunched stems (Deckard, 2002).



(a) (b) (c) (d) (e)

Figure 2.8 Grapple skidders (a) single arch (b) swing boom (c) dual arch (d) sorting grapple (e) bunching grapple

Due to a grapple skidder's inability to accumulate optimum loads within an acceptable time frame, they are generally combined with feller bunchers, which assist in the bunching of timber for the skidder to pick-up. Generally, the smaller the timber being harvested the greater the need for the timber to be bunched into bunches corresponding to the grapple size (Ackerman, 1998).

2.3.1.3 Clambunk skidders

A clambunk skidder (*cf.* Figure 2.9) is defined as an articulated rubber-tyred or tracked vehicle for transporting full trees by supporting the butt ends clear off the ground in a top opening log bunk or inverted grapple. They are equipped with a grapple loader for self loading (Kellogg *et al.*, 1993). Clambunk skidders are similar to grapple skidders in that no chokemen or cables are required. It makes use of a knuckle boom crane, which is able to retrieve and load the clambunk with timber. It operates best when the trees are neatly bunched at a low angle close to the skid trails with the butt ends forward (de Wet, 2000).

Figure 2.9 Clambunk skidders showing the inverted grapple and the knuckle boom crane

Clambunk skidders are designed for the transport of trees, butt ends first, over long distances. Due to their high volume capabilities, they are particularly suited to extracting large trees where the terrain is easy and the ground has a good carrying capacity (Staaf and Wiksten, 1984).

2.3.1.4 Skidding with agricultural tractors

Using specialised logging attachments on modified agricultural tractors for the skidding of timber is limited to firewood harvesting, thinning operations and small scale clearfelling operations (de Wet, 2000). Modifications to the standard agricultural tractor need to be made for forest operations. These include a belly pan to protect the underside and reduce the number of hang ups on stumps and rocks, roll bars, radiator protection, counter weights and 10-12 ply forestry tyres (Shaffer, 1998).

There are two main attachments that can be used for skidding purposes, viz. the grapple and the skidding winch, as shown in Figure 2.10. The skidding grapple has similar features to the grapple skidder described previously. There is no requirement for the driver to dismount the tractor or other workers to choke the timber. The tractor needs to be backed up to the timber within range of the grapple. Therefore, the terrain needs to be relatively uniform and favourable for its successful operation. The skidding winch, with a single or double drum, has the advantage of winching logs out of problem areas, which may otherwise be inaccessible. The skidding winch is more suited to rougher, broken terrain than the grapple attachment, because it has the ability to release the load when difficulties are encountered and re-winch once the obstacle has been cleared (Makkonen, 1989).

(a) (b)

Figure 2.10 Skidding attachments for agricultural tractors (a) grapple (b) winch

An agricultural tractor logging system, with its relatively low capital investment and operating cost, may be an effective way for private land-owners to extract small volumes of timber annually as a profitable enterprise, as opposed to outsourcing to larger contractors.

2.3.2 Forwarding

Dykstra and Heinrich (1996) refer to forwarding as a load of logs being carried completely off the ground, either within the frame of the machine or on a trailer. Forwarding is only possible with a cut-to-length harvesting method, which requires that felling, delimbing, measuring, bucking into segments and perhaps bunching are done at the stump. The timber is then loaded and extracted in 3-6m lengths depending on the bunk configuration (Sever, 1987).

Forwarding is less sensitive to extraction distance compared to ground skidding. This allows the economical extraction distance by forwarding to be two to four times that of ground skidding, therefore allowing the density of haul roads within the forest to be reduced (Dykstra and Heinrich, 1996). Furthermore, the construction of landings is often unnecessary if the forwarding equipment is fitted with a knuckle boom loader since it has the ability to deck the logs alongside the haul road for later collection by the secondary terminal transport (Dykstra and Heinrich, 1996).

Forwarding can be done by means of tractors equipped with trailers and grapple loaders. This type of equipment may be more economical than the purpose built articulated wheeled forwarders on small-scale operations in good terrain conditions (Makkonen, 1989). The articulated wheeled forwarder, however, has the ability to operate on rougher and steeper slopes, travel at higher speeds, carry larger loads and can be equipped with larger and faster loaders. Thus, making articulated wheeled forwarders more suited to large-volume contracts operating in moderate to difficult terrain conditions (Makkonen, 1989).

2.3.2.1 Articulated forwarders

Most often referred to as a forwarder, articulated forwarders are highly specialised machines used with the cut-to-length method and working in tandem primarily with harvesters and less frequently with manual felling operations (MacDonald, 1999). They have the ability to attain a full load with every cycle and, due to a larger load extracted per cycle compared to grapple and cable skidders. Extraction costs are reasonably insensitive to increased lead distances up to approximately 1km. Forwarders productivity therefore becomes more sensitive to travel time rather than load accumulation, as is the case when operating over shorter lead distances (Ackerman, 1998). However, correct pre-bunching of timber is necessary if optimum forwarder productivity is to be achieved, especially in small-sized timber (Sever, 1987). If small-sized timber is not pre-bunched, the grapple volume is not fully utilised with each movement, resulting in an increased loading time.

Figure 2.11 shows two typical forwarders. They are constructed on an articulated chassis with two, three, or four axles fitted with large rubber tyres. Bogie axles are common as they provide lower ground pressures than single axles. Forwarders with bogies can also be operated faster in rough terrain, since bogie axles reduce the vertical lift of the machine to one half the height of the obstacle being crossed. In addition there is a 40% reduction in the shocks transmitted to the forwarder (Makkonen, 1989).

Figure 2.11 An eight and six wheel drive forwarder each with a mounted knuckle boom crane for self loading and off loading

Features such as articulated steering, hydraulic-mechanical transmission, front and rear bogie axles, hydraulic loader with long reach, and ergonomically designed safety cabin, in which all the operator functions are easy to perform, has led to the modern forwarder being a highly specialised and productive machine (Mikkonen, 1984). The features mentioned, however, come at a high capital cost and require a high level of maintenance.

With advanced equipment, such as forwarders, being fully imported to South Africa there are delays incurred in attaining parts and services as well as a high cost in training employees to be mechanically competent on such advanced equipment. These factors have a large influence on the low number of forwarders operated in the South African forest industry. Brink (1999), however, notes that in the future there will be a high-availability of such machines as global machine suppliers maintain an interest in the South African market accompanied by technology transfer. The minimum paid to manual labour will result in labour also not competing favourably with the high productivity of these advanced machines (Brink, 1999).

2.3.2.2 Tractor and trailer as a forwarder

The tractor trailer combinations (*cf.* Figure 2.12) are relatively low-capital alternatives to the purpose-built forwarders for forwarding log-length wood (Wilhoit and Rummer, 1999). The modern agricultural tractor has evolved extensively with more powerful turbocharged engines, four wheel drive, power shift transmission and a safe comfortable cabin environment as common specifications. However, they are primarily designed to be used in agricultural fields as apposed to a harsh forest environment. Their application is therefore limited to good terrain and under favourable conditions, if high productivity is to be maintained (Mikkonen, 1984).

Figure 2.12 Tractor trailer combinations used for forwarding (a) Agricultural tractor with bogie axle trailer and knuckle boom loader (b) Haulage tractor and trailer

Tractor trailer combinations are used extensively in large *Eucalyptus* harvesting operations in South Africa and extract 18% of the total volume of timber annually (Brink, 1998 and de Wet, 2000). The high utilisation of this system can be attributed to the high cost of imported purpose built forestry equipment, as well as the acceptability and availability of this intermediate technology. It is common practise for large companies to award harvesting contracts on an annual basis which restricts a contractor's ability to commit to the large capital investment of dedicated forestry equipment. There is a large second-hand tractor market in South Africa, which enables a contractor to renew his equipment at regular intervals and, should his contract be terminated, the contractor would not be left with a large capital investment.

Tractor operators are relatively common throughout the agricultural industry in South Africa and little investment is needed on the side of the contractor in terms of operator training. Due to the high incidence of AIDS in South Africa, contractors are reluctant to spend large sums of money on training operators who may only work for one or two years. These factors, coupled with the high cost of imported equipment as a result of unfavourable exchange rates, encourage the use of tractor trailer combinations over purpose-built forwarders.

2.4 Conclusion

Forest harvesting and transport plays a critical role in the production of timber products, and requires a clear understanding of the processes involved in getting timber from a standing tree to some processing plant where a merchantable product is produced. Harvesting methods distinguish the amount of processing that occurs within the compartment. The cut-to-length method contributes the largest portion of the timber extracted in South Africa and will do so in the future, even though the harvesting systems may change. The cut-to-length method has the advantage of being "softer" on the environment, compared to tree length and full tree methods, as well as producing timber that is cleaner and of a higher quality.

Harvesting systems can be divided into three categories, viz. ground based, cable and aerial systems. More often than not, as a result of cable and aerial systems having high capital and operating costs, they only become cost effective where ground based systems are not possible. Ground based systems are limited primarily by slope. Generally slopes greater than 35% prohibit the use of ground based systems and with the majority of the forested areas in South Africa being accessible to ground based systems, it accounted for 96% of South Africa's timber extracted in 1998, with no significant changes anticipated in subsequent years.

The primary transport or extraction phase, though generally the second phase after felling, is the most important. The limitations primary transport incurs from terrain, weather, slope, soil type and harvesting method required will ultimately dictate the types of equipment to be used and the operating techniques applied in the larger harvesting system. With the focus on ground based extraction equipment, timber can either be skidded or forwarded from stump to a roadside landing or depot.

Skidders are well understood and simple machines with a relatively low capital cost. The load is dragged with butt ends first, which are suspended either by a cable, grapple or clambunk. Skidders operate well under short lead distances, but have a reputation of disturbing the soil and damaging the environment. However, if operated under strict guidelines, skidders make cost effective means of extraction. Skidding by means of agricultural tractors has been applied successfully in many countries where small areas of forest are privately owned and which requires a small volume of timber to be extracted annually. Their application in South Africa is minimal due to a few large forest companies owning a majority of land under timber production. In South Africa, harvesting is normally outsourced to large contractors who make use of equipment with higher capacities.

Forwarders have the ability to carry their load free of the ground and thus reducing the environmental impact of the harvesting operation. Dedicated forwarders are advanced machines associated with a high capital cost and with difficulties in attaining parts and services in South Africa. Skilled operators are also required to operate the machines at an optimum level. An alternative that is common in South Africa, is the use of tractor trailer combinations as a means of forwarding. They comprise of modified agricultural and haulage tractors with trailers that are constructed from standard components and therefore come at a relatively low cost and with a high availability of parts and services. Forwarding equipment can be operated over longer lead distances, compared to skidders and may result in a reduction in the density of the road network. It is also a more efficient means of extracting timber as a full load is guaranteed every trip. Forwarding by both forwarders and tractor trailer combinations contribute to the largest portion of timber extracted in South Africa since it is most applicable to the cut-to-length method that is a well established practice.

3. A REVIEW OF FOREST ROADS IN SOUTH AFRICA

Plantations in South Africa have a reasonably well developed road network (Warkotsch, 1988). However, while road densities are relatively high when compared to international road densities, the standards in South Africa are in many cases, low (Warkotsch, 1988). With more than 98% of the road network unsealed, significant expenditure in terms of road maintenance and increased vehicle operating costs are incurred. As the percentage of unsealed roads is unlikely to decrease, techniques for improving road networks are becoming increasingly important (Forestry SA, 2004). Forest roads need to be designed to meet management objectives and optimise the harvesting and transportation system while minimising environmental impacts (Slate, 2004).

Over the past two decades the South African forestry industry road infrastructure has been subjected to a substantial deterioration. This is primarily due to the fact that roads are capitalised and not reflected against the operational cost of harvesting timber (Morkel, 1994). Morkel (1994) also notes that this accounting procedure effectively renders forest roads valueless to the operational forester, and so encourages the neglect of existing roads and the construction of unnecessary roads.

3.1 Forest Road Classification and Standards

Forest roads throughout the world are classified in many different ways. Some are classified in terms of the physical road attributes and others in terms of the usage of roads or the level of service they provide. A common road classification system throughout the forest industry would be ideal, however, differences in definitions and categories exist between the various forest companies.

A classification is a description of the function a road must perform or the level of service it must provide and a class is the notation given to a classification (Morkel, 1994). According to Slate (2004), road design will vary for different road standards and classes which are often based on either a design speed or a design vehicle.

A design speed is the maximum safe speed a vehicle can maintain over a segment of road where the physical design features of the road govern the speed, rather than the operational capabilities of the vehicle (AASHTO, 1990).

A design vehicle is a vehicle which determines the minimum design standard for a particular road specification, such as formation width, carriageway, minimum horizontal curve, shortest vertical curve, maximum grade, etc. (Kramer, 1993). The design vehicle is the largest, heaviest vehicle that is required to travel over a particular road (Kramer, 1993). Design factors that need to be accounted for when considering a particular design vehicle are wheel width, wheelbase, gross vehicle mass, axle loadings and overhanging components. For example, a road designed to a minimum standard for use by an agricultural tractor with a 5 ton trailer could not be traversed by a rigid type truck and trailer with a 56 ton gross mass, however, the converse is true. Table 3.1 gives the design vehicles and the road design standards required for particular road classes.

Table 3.1 Guideline to road classes, design vehicles, road specifications and accessibility (adapted from Hendriksa, 2003 and Koetze, 2003; personal communication)

Class	Design Vehicle	Roads Dimensions	Accessibility
A	Rigid Type Truck with Drawbar Trailer Attached (On Road Only)	9m Formation 7m Carriageway Two Lane	All Weather
B	Rigid Type Truck with Drawbar Trailer Attached (On Road Only)	7m Formation 4.5m Carriageway Single Lane	Weather Restricted
C	Agricultural or Haulage Tractor Trailer Combination, Articulated Timber Truck (Off-Road Capabilities)	No Formation < 4m Single Lane	Weather Restricted

3.2 Forest Road Design and Construction

To optimise transport and harvesting system productivity, while simultaneously ensuring operator safety, forest roads have to be correctly designed (Slate, 2004). In the South African Forest Road Handbook, Slate (2004) describes the complex forest road design process and notes that any design should be performed by a competent engineer. This review focuses on the dimensions and specifications of forest roads in terms of design speeds and the intended design vehicle traversing the road (*cf.* Table 3.1). It includes typical cross-sections, wearing course thickness and horizontal and vertical alignments.

3.2.1 Forest road cross-sections

The road cross-section used is dependant on the required drainage, soil stability, slope and expected volume of traffic on the road (Radnor, 1998). Figure 3.1 gives four commonly used cross-sections, which can be used in combination as terrain changes and drainage requirements vary.

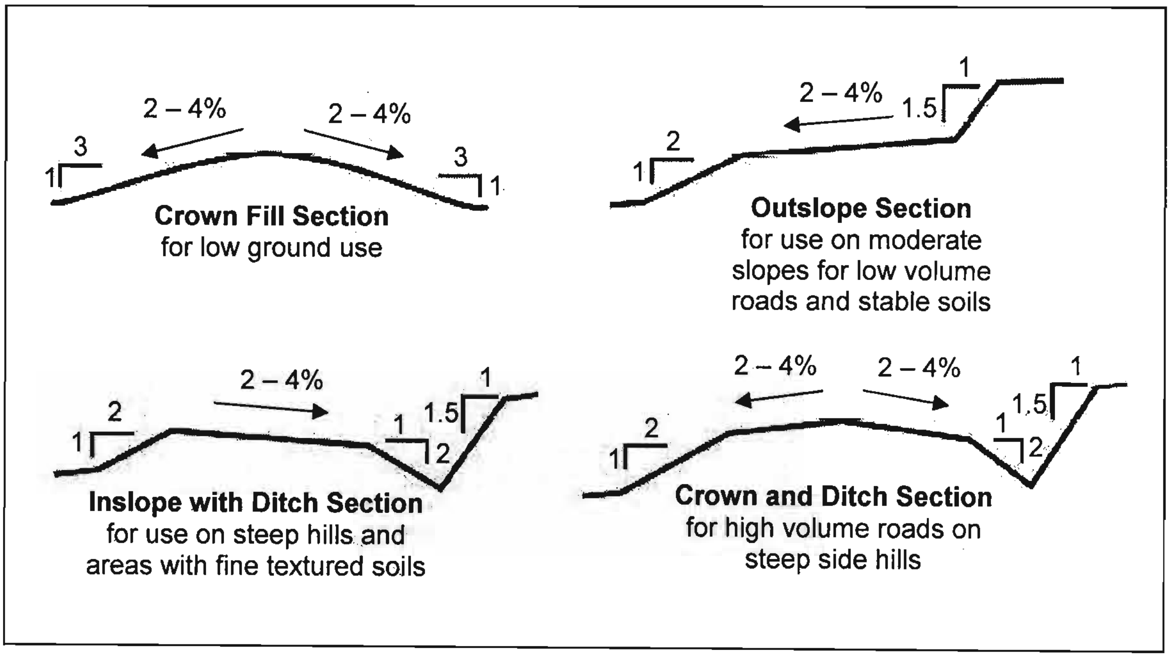


Figure 3.1 Forest road cross-sections dependant on drainage needs, soil stability, slope, and expected traffic volume. Arrows indicate percent slope and direction of surface water flow (Adapted from Anon, 2002)

The subgrade plays a critical role in the drainage and performance of the final road surface (ODF, 2000). In the case of a road having a wearing course applied, viz. A and B–class roads, the subgrade should be shaped (crowned, insloped or outsloped) to the correct dimensions and compacted at the correct moisture content prior to the application of the wearing course. This allowing an even layer of surfacing material to be applied (ODF, 2000).

3.2.2 Wearing course thickness

Applying a wearing course to a road's running surface performs two main functions (ODF, 2000). First, the wearing course allows the vehicle's tyre loads to be spread over a larger area of the subgrade and so helping to prevent rutting and subgrade failure. Secondly, a compacted gravel surface forms an impervious layer, thus serving to move water away from the subgrade. On roads that are to be used during wet weather a wearing course also improves traction and improves the road's resistance to erosion.

In South Africa, a road will generally only be surfaced if required to service secondary terminal transport (road haulage vehicle with no off-road capabilities). It is therefore assumed that the design vehicle for a surfaced road, A or B–class, is a rigid type truck with a drawbar trailer with an allowable gross mass of 56 tons. Figure 3.2 illustrates the suggested minimum requirements of a B–class road to service such a vehicle.

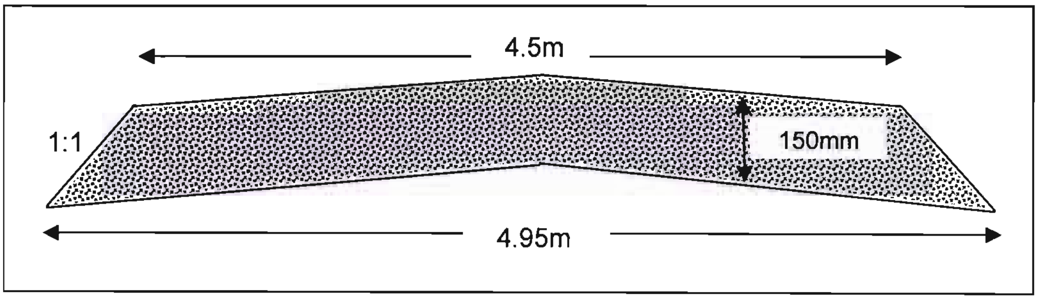


Figure 3.2 Running surface cross-section of a B–class forest road in South Africa, including specifications (Adapted from Hendriksa, 2003, Koetze, 2003 and Slate, 2003; personal communication)

The compacted depth of gravel is given as 150mm, assuming a 30% compaction of the wearing course the loose measure of material required per meter length of road is 0.9 m^3 and when compacted, 0.7 m^3.

It must be noted that thickness of the wearing course is not only dependant on the vehicle traversing the road, but also the strength and stability of the subgrade and the quality of the surfacing material. Each situation should be individually analysed and the minimum requirements determined.

3.2.3 Horizontal and vertical alignment

Horizontal alignment should be consistent with no sudden changes for which the road user may need to compensate. Slate (2004) notes that the road users safety outweighs the absolute design speed standard. As the vehicle speed increases, a greater curve radius is required for the vehicle to negotiate the road (see Table 3.2). Superelavation is not required on the majority of forest roads, as design speeds are usually low enough for it to be excluded (Slate, 2004).

Table 3.2 Minimum horizontal curve radius for a given vehicle speed (Slate, 2004)

Vehicle Speed ($km.h^{-1}$)	Curve Radius (m)
10	10
20	15
30	35
40	65
50	100

When a vehicle with a trailer, such as a timber truck, negotiates a horizontal curve a certain amount of off-tracking occurs. Off-tracking is the deviation of the path of each intermediate axle from that of the leading one (Manesis *et al*, 2002). Kramer (1993) notes that a vehicle's off-tracking is a function of a vehicle's geometry, curve radius and curve deflection angle. A vehicle's wheelbase, axle widths, steering cramp angle and vehicle overhang will all affect its off-tracking (Kramer, 1993). Table 3.3 serves as a guideline in determining the curve widening requirements. The curve widening is added to the inside of the curve as adding to the outside effectively changes to the curve's radius thus requiring a recalculation of the required curve widening (Slate, 2004).

Table 3.3 Guideline of curve widening requirements (Slate, 2004)

Curve Radius (m)	Curve Widening (m)
15 - 18	2.8
19 - 24	2.1
25 - 31	1.6
32 - 37	1.2
38 - 45	1.0

An adverse gradient influences truck speeds, with speed generally being reduced when a gradient exceeds 3% (Slate, 2004). Slate (2004) notes that while a road design should try to minimise the affect of gradient on the travel time, a road must still be constructed to meet management objectives. Table 3.4 gives recommended maximum gradients for different design speeds and horizontal radii.

Table 3.4 Recommended maximum gradients for given design speeds and horizontal curve radii (Slate, 2004)

Parameter		Maximum Gradient (%)		
		Flat	Rolling	Mountainous
Design Speed ($km.h^{-1}$)	40	7	8	9
	60	6	7	8
	80	5	6	7
	100	4	5	6
Horizontal radius (m)	15 - 25	10	8	7
	26 - 40	10	9	8
	41 - 60	11	11	10
	>60	12	11	11

3.3 Forest Road Maintenance

Maintenance of forest roads in South Africa has been largely neglected. This can be primarily attributed to the lack of awareness of the importance of maintaining forest roads and the financial implications to transport operations and forest management (Ackerman and Strydom, 2000). With a lack of maintenance, forest roads deteriorate rapidly and become inaccessible to rigid type trucks with drawbar trailers which are used for secondary terminal transport (STT). This necessitates the use of expensive off-road vehicles to transport timber to the few remaining roads which are accessible to secondary terminal transport (Morkel, 1999).

The objective of forest road maintenance is to maintain the road and structures to the original intended design standard. Of equal importance is limiting the use of a road to its specified design standard, thereby avoiding unnecessary maintenance problems (ODF, 2000). A fully functional drainage system must be maintained while minimising soil disturbance during maintenance activities (ODF, 2000).

According to Ackerman and Strydom (2000), maintenance can be subdivided into the following categories:

- Roadside maintenance
- Drainage maintenance
- Surface maintenance

3.3.1 Roadside maintenance

Roadside is the area adjacent to the edge of the shoulder or pavement and may in certain situations extend well past the nearest tree line into the adjacent compartment (Ackerman and Strydom, 2000). For safety reasons and fire protection, bush should be cleared and grass cut adjacent to the road. The clearing of vegetation should only be to the extent required to keep the road dry, maintain the required sight distance and for fire protection (Paige-Green, 1990). Excessive removal of vegetation will induce erosion. Erosion from cut and fill slopes should be repaired and further erosion prevented by the establishment of vegetation by grass seeding, planting and sodding. Further establishment of vegetation in open areas between road edges and the tree line is mandatory (Wise, 1997).

3.3.2 Drainage maintenance

Drainage can be considered as one of the most important elements to the successful design and serviceability of forest roads. According to Morkel (1994) there are three aspects to drainage of forest roads that need to be catered for:

- Ensuring that the road is not inundated by water by raising it above the surrounding ground, thus preventing the road from becoming a water channel.
- Keeping water off the road by having a compacted surface, camber and constructed catchwater or interceptor drains above cut slopes.
- Removing the water away from the road by constructing effective side and mitre drains.

A definite crown must be maintained at all times to obtain adequate runoff without causing erosion. All longitudinal gradients or cambers greater than 5% are prone to erosion (Ackerman and Strydom, 2000). Drain maintenance is required to maintain the flow capability required to remove surface runoff (ODF, 2000). Drains need to be maintained in such a way that there is no standing water and no erosion, further, drains are to be constructed wherever water accumulates (Morkel, 1994). Ackerman and Strydom (2000) notes that excessive silting indicates inadequate water flow while signs of erosion indicate excessive velocities. Specific attention should be paid to the clearing of debris from drains after harvesting operations have been performed.

3.3.3 Surface maintenance

The objective of surface maintenance is to maintain a smooth, stable running surface and to retain the original surface drainage while preserving the wearing course material. Dust control is also a form of surface maintenance, as dust has a significant environmental, social and economic impact. A poor road surface is directly related to higher machine costs due to slower travel speeds and increased vehicle wear. Forestry SA (2004) presents the routine maintenance of an unsealed road, which comprises of four levels of increasing work, as:

- grader blading (light blading)
- spot regravelling (reconditioning)
- reworking and compaction (rehabilitation or heavy blading), and
- regravelling

During the dry season, corrugations and ravelling occur, whilst during the wet season potholes are the primary problem (Forestry SA, 2004). During dry weather the smoothness of the road should be maintained by removing corrugations and ruts by grader blading. In wet weather, however, grader blading should focus on restoring the shape of the road as the material will be able to re-compact under the moist conditions.

Should excessive defects appear in the road surface, such as rutting or structural failure of the wearing course, from either a lack of maintenance or extreme weather conditions, then reworking and compaction may need to be carried out. The existing gravel should be reworked, oversized material broken down or removed, additional fines or gravel and moisture added and the surface reshaped and compacted (Wise, 1990).

Surfacing materials gradually break down or are lost to the side of the road after prolonged use and maintenance (ODF, 2000). Steep and curved road segments are particularly susceptible to loss of the wearing course. Once the stage is reached where the road standard can no longer be maintained due to the loss of material, surfacing material should be added to restore the original design standard of the road (ODF, 2000).

3.4 Conclusion

Forest roads play an integral part in the success of any forest plantation. The layout and conditions of forest road networks have a direct effect on vehicle operating costs, environmental impacts, security of timber supply and fire protection. Ackerman (2000) confirmed that the conditions of forest road networks in South Africa are poor and declining. This is a result of both a lack of forest road network upgrading and maintenance due to insufficient funding.

Morkel (1999) notes that the cost of constructing and maintaining forest roads is usually capitalised (adds value to the land). Therefore, capital expenditure approval is required, in order to construct new roads or upgrade existing roads. This may be difficult to justify and could be a lengthy process. It is therefore often easier to convert to vehicles with off-road capabilities, to transport timber to the few roads that are accessible to on road vehicles.

The South African forest industry thus needs to focus its efforts on improving forest road networks. Once it is realised that an improved road network impacts significantly on the profit margins of forest companies and private growers alike, then the literature reviewed in this section can be implemented.

The main factors that influence the safe serviceability of a road is dependant primarily on the characteristics of the design vehicle. It must, however, be emphasised that there are a number of other critical components such as environmental and management issues that need to be considered. In the following chapter a method for improving road networks is developed and is used in the first step of implementing a more efficient transport system.

4. THE DEVELOPMENT OF AN OPTIMUM ROAD UPGRADING MODEL

It has been pointed out that the forester, harvesting contractor and haulier require a simple generic model that will determine the optimal distance to upgrade a road leading into a forest plantation. With the eventual implementation of these upgraded roads, a significant cost saving can be achieved. The following model was derived from first principles and is therefore generic and applicable to most situations, given that minor changes and modifications may need to be implemented to cope with site specific conditions.

4.1 Model Description

Large differences in costs exist between the secondary terminal transport (STT) and both extended primary transport (EPT) and secondary intermediate transport (SIT) phases. The latter are normally substantially more expensive. This is mainly attributed to the small payloads which are transported by vehicles with high operating costs. The model developed in this study calculates a breakeven point between the combined cost of STT and road upgrade cost and the cost of EPT. The model is first derived for a single theoretical large compartment and then for multiple compartments with entry points over the length of the proposed upgraded road. Finally, the model is also adapted for harvesting systems where double handling is unavoidable, such as skidding and cable operations.

The following variables were considered during the model development process.

- Distance from the edge of the compartment to depot or landing (*ep* in km)
- Yield in compartment *i* (y_i in t)
- Cost of EPT or SIT (R_{ept} or R_{sit} in $R.t^{-1}.km^{-1}$)
- Cost of STT (R_{sit} in $R.t^{-1}.km^{-1}$)
- Road upgrade cost (*uc* in $R.km^{-1}$)
- Cost of double handling (*LC* in $R.t^{-1}$)

In practice, STT is charged at a constant $R.t^{-1}.km^{-1}$ rate as the vehicle is transporting timber over long distances, generally in excess of 50km, and so the majority of the vehicle life is spent travelling and a small percent of its life loading and off loading. In contrast, the EPT and SIT is charged at varying $R.t^{-1}.km^{-1}$ rates, dependant on the lead distance travelled. As the distances travelled are relatively short, generally less than 10km, a large portion of the machines life is spent loading and off loading. It can therefore be assumed that the longer the lead distance, the larger the portion of the machine life is spent moving timber rather than idling while loading and off-loading (*cf.* Figure 4.1). This is the reason for a lower $R.t^{-1}.km^{-1}$ rate being charge for the longer lead distance.

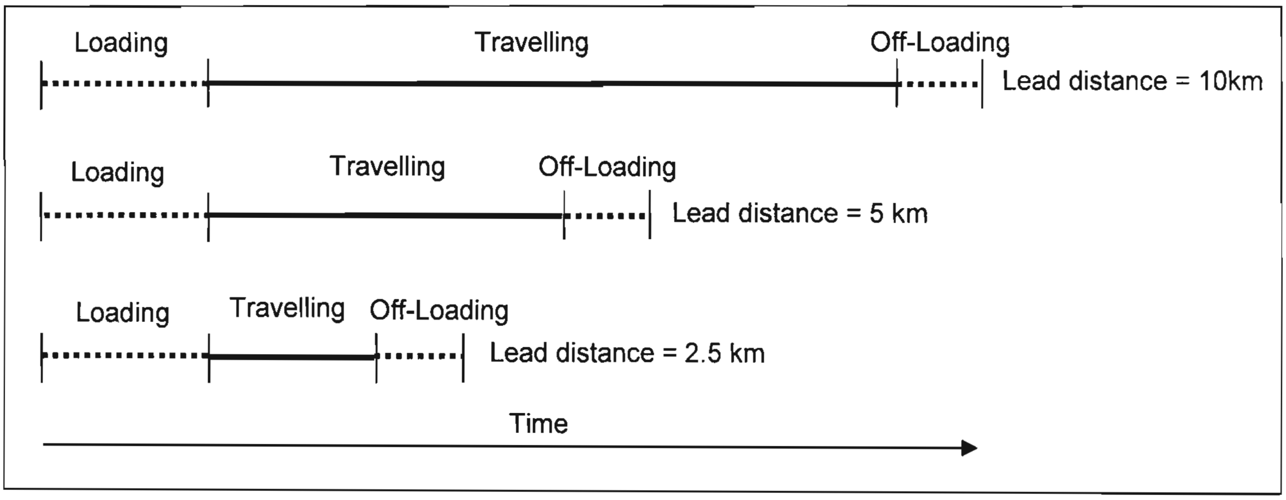


Figure 4.1 Breakdown of machine life into loading, travelling and off-loading over various lead distances against time. Loading and off-loading remain constant, while the travelling time varies for different lead distances

There are certain phases within the harvesting system excluded due to their occurrence irrespective whether the road is upgraded or not, therefore do not affect the optimisation. These include:

- felling and processing
- loading at stump
- transloading at depot, and
- secondary terminal transport from some reference point beyond the plantation to the mill

By excluding these phases, the cost of the EPT or SIT vehicle, while loading and off loading, can be neglected in the model derivation. A classical machine costing (see Appendix B) shows that the operating cost of a vehicle travelling is expressed in terms of $R.t^{-1}.km^{-1}$, while time spent loading and off loading is expressed in $R.t^{-1}$. The non-linear rate originates when loading rates of the vehicles ($R.t^{-1}$) are converted to travelling rates

($R.t^{-1}.km^{-1}$) over various lead distances for contractor quoting purposes. It is therefore more correct to use fixed rates (e.g. $R.t^{-1}.km^{-1}$) for STT, EPT and SIT in the development of an optimum road upgrading model.

Repairs and maintenance where excluded from the optimum road upgrading model. It was assumed that the repair and maintenance costs on a C – class road would be equal to, if not greater than that on a B – class road carrying the same volume of timber. This been attributed to a C – class road not having an adequate formation or drainage and as no wearing course is applied frequent blading is require if travel speeds are to be maintained (Pike, 2004).

4.2 Derivation of a Single Compartment Model with no Double Handling

The first step in deriving an optimum road upgrading model was to assume a single theoretical compartment with a single access road, which is currently C–class and has the opportunity to be upgraded to B-class (see Figure 4.1). The access road should only be upgraded if the costs incurred (i.e. upgrading cost) can be recovered by cost savings in EPT. There are two factors to be considered, the first being the tonnage of timber that needs to be extracted from the compartment to warrant a road upgrade. Secondly, the distance to where the road should be upgraded, whether it be to the edge of the compartment, remain at the existing depot or some point between the two. At this stage it is assumed that the same vehicle moves the timber from the stump past the edge of the compartment to the existing depot in Figure 4.2.

The total cost function is described in Equation 4.1. The equation consists of three main components. First, the cost of moving timber by means of EPT from the edge of compartment to a road that has been upgraded to B–class. Secondly, the cost of moving timber by means of STT from the end of the upgraded road to the existing A or B–class road. Thirdly, the cost to upgrade the existing C–class road to B–class some distance from the existing depot (*cf.* Figure 4.2).

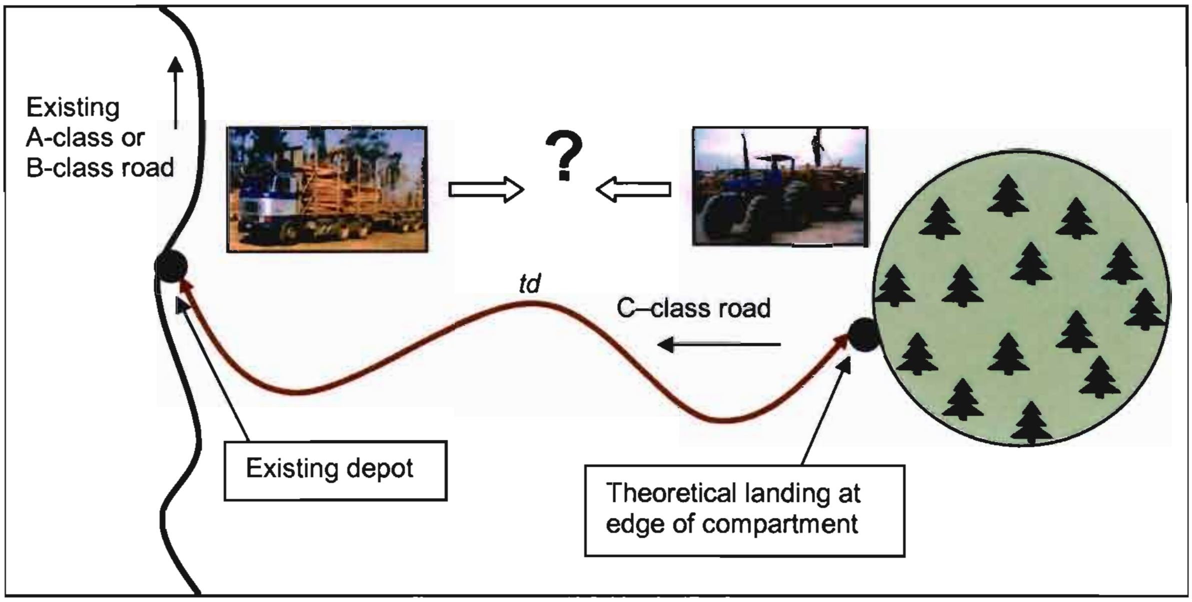


Figure 4.2 Schematic of the road upgrading and transport problem for a single compartment, where *td* is the total distance from the edge of compartment to the existing depot

$$TC = r_{ept}.y.ep + r_{stt}.y.(td - ep) + uc(td - ep) \tag{4.1}$$

where

TC	=	Total transport and road upgrading cost (Rands)
r_{ept}	=	Rate of EPT ($R.t^{-1}.km^{-1}$)
r_{stt}	=	Rate of STT ($R.t^{-1}.km^{-1}$)
y	=	Yield from compartment (t)
ep	=	Distance of EPT from edge of compartment to the end of the upgraded road (km)
td	=	Total distance from the existing B-class road to the compartment (km)
uc	=	Road upgrade cost ($R.km^{-1}$)

To optimise Equation 4.1, *TC* was differentiated with respect to distance *ep*.

$$\frac{dTC}{dep} = r_{ept}.y - r_{stt}.y - uc \tag{4.2}$$

Equation 4.3 was obtained after equating Equation 4.2 to zero to minimise the *TC* function.

$$y = \frac{uc}{r_{ept} - r_{stt}} \tag{4.3}$$

According to Equation 4.3, a threshold tonnage exists that needs to be transported over the road for a particular set of inputs to warrant the upgrading cost from a C-class to B-class road. It should be noted that the threshold tonnage is not dependant on the length of road (*td*), but rather the upgrade cost (*uc*), rate of EPT (r_{ept}) and the rate of STT (r_{stt}). From this it can be concluded that the road should either be upgraded all the way to the edge of compartment or it should not be upgraded at all. There is consequently no optimum point somewhere between the existing depot and the edge of the compartment.

Based on this conclusion it can be assumed that the breakeven point for upgrading or not upgrading will be the point where, *TC* for an upgraded road equals *TC* for a non-upgraded road. The following set of equations (from Equation 4.1) can therefore be assumed:

$$TC_{ep=0} = r_{stt}.y.td + uc.td \qquad (4.4)$$

and

$$TC_{ep=td} = r_{ept}.y.td \qquad (4.5)$$

Therefore, the breakeven point is where

$$TC_{ep=td} = TC_{ep=0} \qquad (4.6)$$

4.3 Derivation of a Single Compartment Model with Double Handling

Cable yarding and skidding operations are often not able to skid timber past the edge of the compartment. In this case, should the road not be upgraded to the compartment, the timber would be loaded onto alternate transportation in order to take the timber to the depot (SIT) (Morkel, 1999). This operation incurs additional transloading costs (*LC* in $R.t^{-1}$), that occurs at the edge of the compartment.

The extra transloading cost consists of two components (both expressed in $R.t^{-1}$): The cost of the haulage vehicle idling during loading and the actual cost of either an independent or integrated loader to load the timber (*cf.* Figure 4.3).

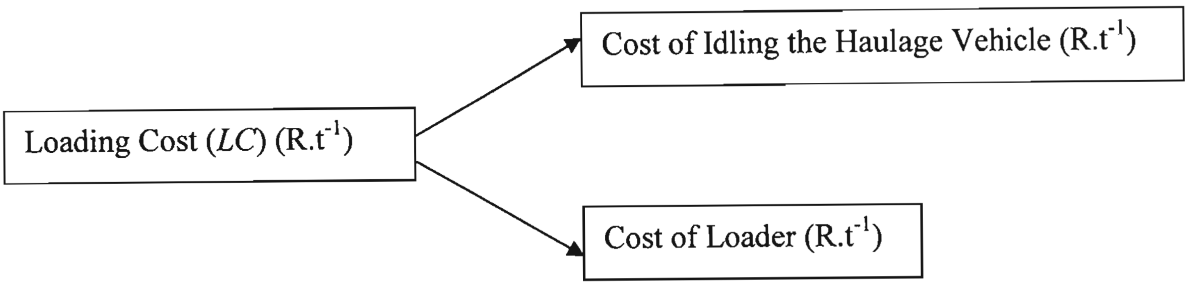


Figure 4.3 Breakdown of loading costs

The model, which accounts for cable and skidding operations, was derived from Equation 4.6. In this model the extra transloading cost was included when the road was not upgraded to the compartment. It was therefore concluded that

$$TC_{ep=0} = r_{stt}.y.td + uc.td \tag{4.7}$$

and

$$TC_{ep=td} = r_{sit}.y.td + LC.y \tag{4.8}$$

Equation 4.9 can be obtained by equating Equations 4.7 and 4.8.

$$y = \frac{uc.td}{LC + r_{sit}.td - r_{stt}.td} \tag{4.9}$$

From Equation 4.9 it can be seen that the threshold tonnage is no longer independent of the distance to the compartment (*td*). Therefore, the threshold tonnage will change as the distance between the existing A or B–class road and the compartment is varied (*cf.* Figure 4.4). Due to the loading rate being in the denominator the threshold tonnage is reduced with higher loading costs (*LC*) and so will encourage the further upgrading of the roads.

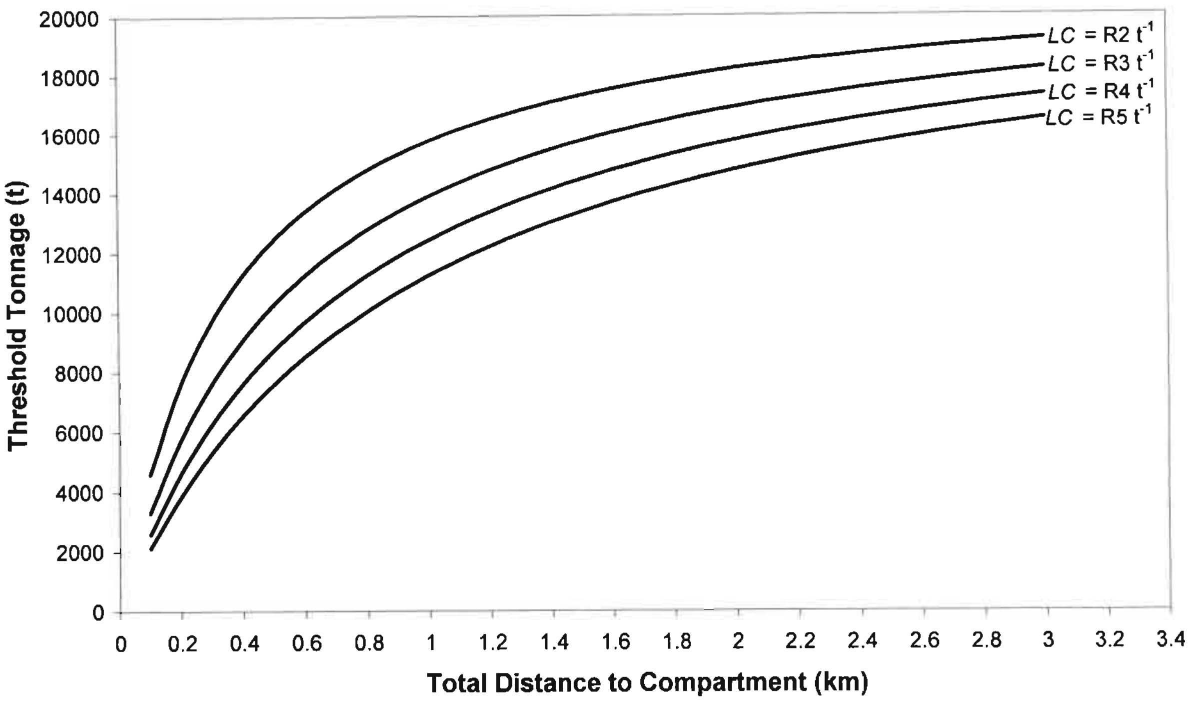


Figure 4.4 Threshold tonnage plotted against the distance to the compartment. Different curves (*LC*) reflect various transloading rates

4.4 Derivation of a Multiple Compartment Model with no Double Handling

Although the single compartment model clearly defined and illustrated the problem, it was oversimplifying the general problem in commercial conditions. The next step was to expand the model to a multiple compartment scenario that accounts for timber entering the proposed road for upgrading, at multiple entry points along its length. A case study of a *Eucalyptus* plantation in the KwaZulu-Natal Midlands (Figure 4.3) was used to derive and demonstrate this model. The model was derived once again for a single vehicle extracting the timber from the stump and along the road, as well as for cable and skidding operations which incur an extra transloading cost at the edge of the compartment (*cf.* Section 4.5).

The model was derived under the same assumptions as stated in 4.2. A vehicle moves the timber from the stump past the edge of the compartment to the upgraded road (EPT) and the cost of moving timber within the compartment was excluded. It was assumed that as the road was upgraded past a compartment, timber would get loaded at a roadside landing, therefore resulting in zero EPT.

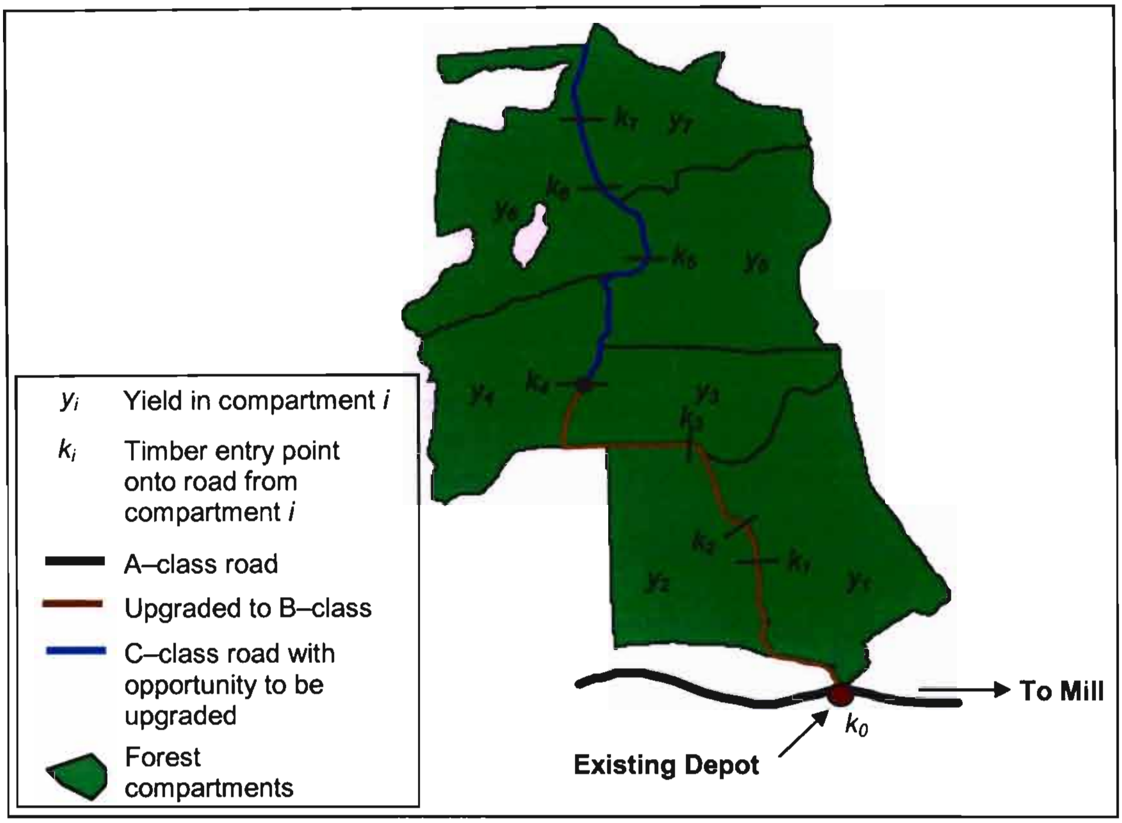


Figure 4.5 A map of forest compartments and roads used to describe the multiple compartment model

The total cost function for the multiple compartment model is described in Equation 4.10. This function calculates total cost as a function of EPT, STT costs and the cost of upgrading the road some distance into the plantation.

$$TC = \sum_{i=1}^{n} \left[r_{ept} . y_i . ep . w_i . s_i \right] + \sum_{i=1}^{n} \left[r_{stt} . y_i \left((td - ep) . s_i + x_i (1 - s_i) \right) \right] + \left[uc(td - ep) \right] \qquad (4.10)$$

where $s_i = \dfrac{1}{2} + \dfrac{\left| ep - (td - x_i) \right|}{2(ep - (td - x_i))}$ and $w_i = \dfrac{ep - (td - x_i)}{ep}$

td	=	Distance from existing upgraded road or depot to furthest entry point, k_7 in Figure 4.5 (km)
x_i	=	Distance to k_i from the current upgraded road or depot (km)
ep	=	Distance from k_n back to the proposed upgraded road (km)
y_i	=	Yield in compartment i (t)
s_i	=	Boolean variable (0 or 1), to include or exclude compartments as the road is upgraded to various distances

w_i	=	Weighting to determine distance travelled by EPT (0 to 1)
n	=	Total number of compartments

Each of the seven compartments in Figure 4.5 is assumed to have a single entry point into the proposed road upgrade, k_1 to k_7, and therefore yield y_i will enter the road at point k_i. According to Section 4.2, it will be viable for the road upgrade to be extended to the next entry point, k_{i+1} or remain at k_i, since there exists no optimum point between the two. For the road upgrade remaining at the existing depot, k_0, all timber will be transported by EPT from all entry points back to k_0 and then transloaded onto STT for delivery to the mill.

Should the model indicate that the road can be upgraded up to entry point k_4, for example, (as depicted by the brown line in Figure 4.5) then all timber that enters the road ahead of k_4 (k_5 to k_7) would be transported to k_4 by means of EPT and then transloaded onto STT for final delivery to the mill. Also, for timber entering at points which now exist before k_4 (k_1 to k_4), the timber is loaded directly onto STT at the edge of compartment and delivered to the mill, whilst incurring a zero EPT cost. Equation 4.10 represents this procedure by using the boolean variable (s_i) to either include or exclude the EPT phase as the road is upgraded to different entry points along the road. The weighting (w_i) is used to determine the distance to be travelled by the EPT back to the upgraded road. To calculate where TC is a minimum, the derivative is required, however due to the function being discontinuous at certain points, obtaining the derivative was not possible. It is shown however, that once a road is upgraded to a certain point, the decision to upgrade further is based on the tonnage ahead of the upgraded road and therefore the same methodology as in Section 4.2 exists. The decision to upgrade is only dependant on the compartments ahead of the existing upgraded road. Therefore, Equation 4.3 still applies for the multiple compartment model and is expressed in terms of the threshold tonnage (TT in t, Equation 4.11).

$$TT = \frac{uc}{r_{ept} - r_{stt}} \tag{4.11}$$

Therefore, the optimum upgrade distance is the point k_i, under the conditions that I is where

$$\sum_{i=(j+1)}^{n} y_i < TT \leq \sum_{i=j}^{n} y_i \tag{4.12}$$

If by upgrading the road to the next compartment reduces the tons of timber ahead of the proposed road upgrade to a value less than the threshold tonnage (*TT*), then the road should not be upgraded any further. In contrast, if upgrading the road to the next compartment still exceeds the tonnage ahead of the proposed road upgrade to a value below *TT*, then the road upgrade should be extended until Equation 4.12 is satisfied.

4.5 Derivation of a Multiple Compartment Model with Double Handling

It can be shown in a similar fashion to Equations 4.11 and 4.12 that Equation 4.9 applies to both a single and multiple compartment scenarios. The threshold tonnage function for the multiple compartment model with double handling is described in Equation 4.13.

$$TT = \frac{uc.d}{LC + r_{sit}.d - r_{stt}.d} \tag{4.13}$$

TT	=	Threshold tonnage for next compartment ahead of the upgraded road (t)
d	=	Distance from the end of the upgraded road to the next compartment (km)

It is required that the threshold tonnage is recalculated as the road is upgraded to each consecutive compartment. The distance (*d*) will be unique, depending on the distance to the next compartment from the existing upgraded road. For example in Figure 4.5 the distance (*d*) would be the distance between k_4 and k_5. If the threshold tonnage is less than the sum of tonnages y_5, y_6 and y_7, then the road should be upgraded to entry point k_5 and the threshold tonnage recalculated using the distance to the subsequent compartment (k_5 to k_6).

4.6 Model Demonstration

To demonstrate the use of the model under theoretical conditions a more complex set of compartments is used. The purpose of the demonstration is to test the functionality of the model and to quantify the cost saving that can be recognised in an ideal situation. Figure 4.6 shows the layout of the compartments, and roads which have the opportunity to be upgraded to allow for STT to gain further access into the plantation. The combination of eighteen compartments gives a total area of 400 ha with a 5.1 km stretch of C–class road that has the opportunity to be upgraded to B–class. For the purpose of this demonstration it is assumed that no double-handling exists.

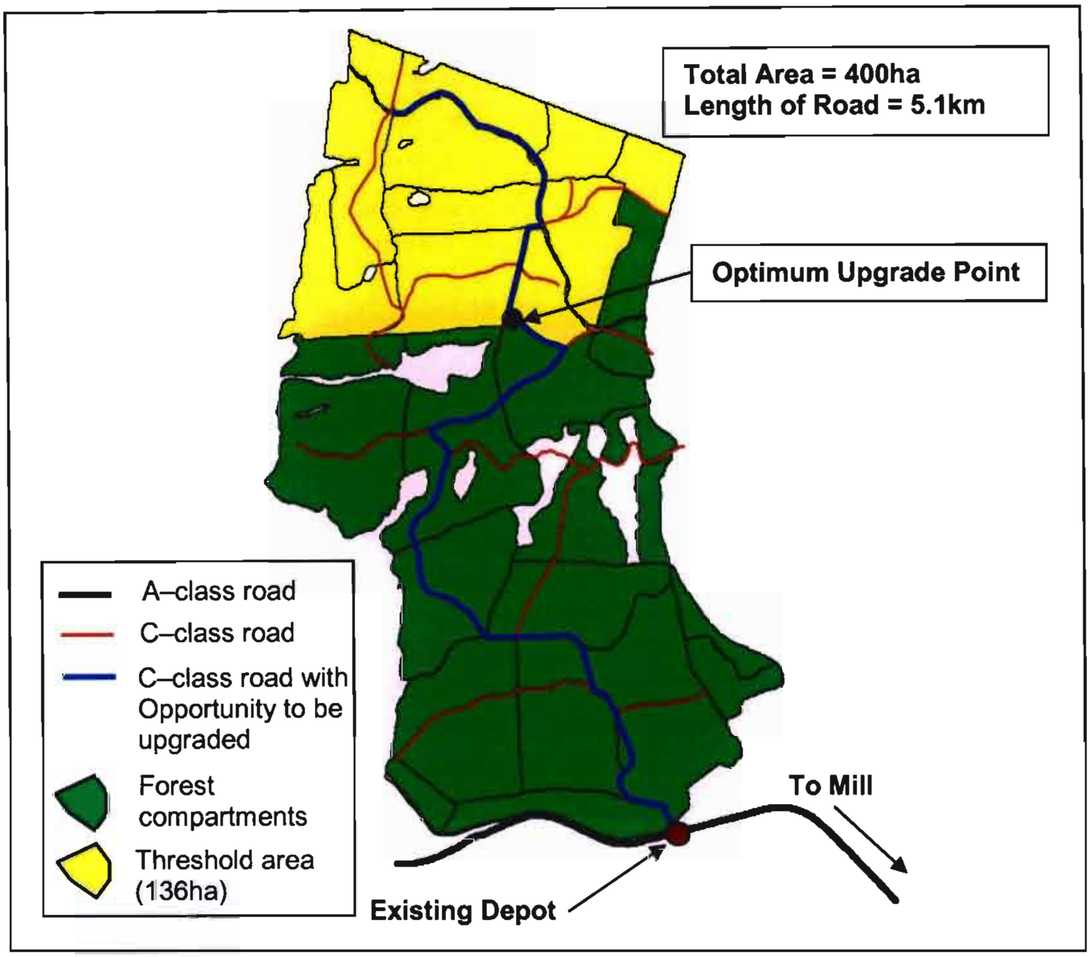


Figure 4.6 Forest compartments and roads used in the demonstration of the multiple compartment model

Total cost (*cf.* Equation 4.10) was calculated for the full volume of timber being extracted from the study area in Figure 4.6. By using real inputs for costs, yields and distances the point of minimum cost is calculated and so the optimum road upgrade distance determined. The inputs listed in Table 4.1 were used to calculate *TC* (Hendriksa, 2003 and Koetze, 2003; personal communication).

Table 4.1 Inputs used to demonstrate the use of the model under theoretical conditions

Variable	Value	Units
r_{ept}	5.83	$R.t^{-1}.km^{-1}$
r_{stt}	0.4	$R.t^{-1}.km^{-1}$
y_i	165	$t.ha^{-1}$
td	5.1	km
uc	117 000	$R.km^{-1}$
x_i	see Appendix C	km

Appendix C contains output from Excel spreadsheets used to calculate the cost of transporting timber from each of the eighteen compartments while upgrading the road from 0 km to the total distance of 5.1 km in 100 m intervals. Total cost is plotted against the upgrade distance (*cf.* Figure 4.7).

The *TC* curve indicates a minimum cost when the road is upgraded to a distance of 3.9 km (*cf.* Figure 4.6). A 43% cost saving in the transport phase between the edge of compartment and the existing depot is shown if the road is upgraded to this point. This emphasises the significant cost saving that can be achieved from the optimum upgrading of forest roads in a theoretical situation. A second method for obtaining the optimum upgrade distance is shown after manipulating Equation 4.11 by making the rate of EPT equal to the rate of STT plus the road upgrade cost divided by the threshold tonnage (*cf.* Equation 4.14).

$$r_{ept} = r_{stt} + \frac{uc}{TT} \qquad (4.14)$$

It was concluded that due to the assumptions made in the derivation of the optimum road upgrading model, that linear rates for EPT (r_{ept}) and STT (r_{stt}) are to be used. In Equation 4.14 the upgrade cost (uc) is divided by the threshold tonnage (TT) which now creates a non-linear relationship dependant on the threshold tonnage. In Figure 4.7 it can be seen that combined rate of STT and upgrade cost divided by the tons of timber flowing over the road increases rapidly towards the end of the road as there are less tons to contribute to the upgrading cost. Figure 4.7 shows that the intersection of these two curves coincides with the minimum of the *TC* curve. Thus confirming the assumptions made in deriving Equation 4.11.

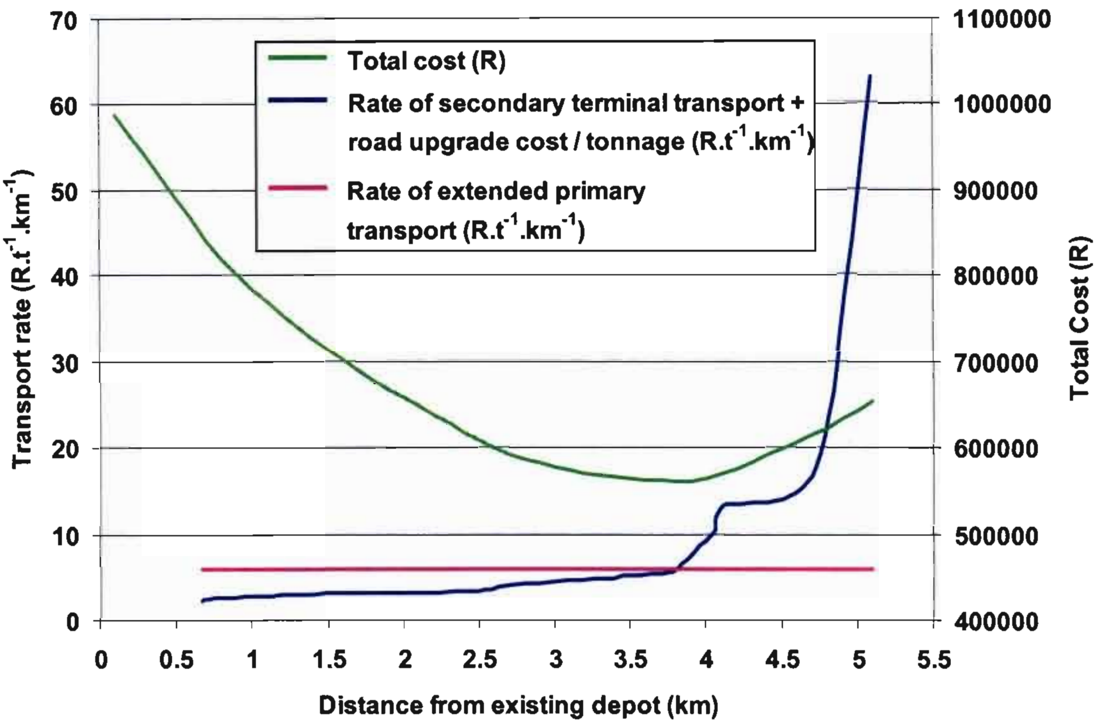


Figure 4.7 Graph showing the total cost curve of moving all timber at varying upgrade distances. The interception of the extended primary transport rate with a combination of secondary terminal transport and road upgrade rate indicating the optimum upgrade distance is also shown

The threshold tonnage (*TT*) is calculated using Equation 4.11 (*cf.* Equation 4.15). By assuming an average annual yield (y_i) of 165 $t.ha^{-1}$, the threshold area equates to 130.6 ha. The area beyond the optimum upgrade distance of 3.9km, in Figure 4.5, is 136 ha. This confirms that a threshold tonnage (*TT*) can be calculated by inputting three variables into Equation 4.11, thereby the ability to determine the optimum road upgrade distance.

$$TT = \frac{uc}{r_{ept} - r_{stt}} = \frac{117000}{5.83 - 0.40} = 21547t \qquad (4.15)$$

4.7 Conclusion

The model derived in this chapter enables the calculation of a threshold tonnage, which is the tonnage required to pass over a road under a set of inputs, to warrant an upgrading. The model reduces to the simple question: Is the tonnage ahead of the existing upgraded road larger than the threshold tonnage? It was also shown that the road will never be upgraded to some point between the timber entry points of two compartments, but rather to the next compartment. An adjusted model was described that took into account the extra transloading cost incurred at the edge of the compartment in cable and skidding operations. In this scenario a new threshold tonnage needed to be calculated as the upgraded road reached each subsequent compartment.

5. MODEL APPLICATION IN TWO CASE STUDIES

It was concluded in the previous chapter that under theoretical conditions significant cost savings could be realised through the upgrading of forest roads. This chapter serves to evaluate the functionality of the model and the economic viability of the results obtained by applying the model to two study areas. Possible road upgrades were assessed by using the model and companying cost savings between the existing and the modified configurations. A capital budget was used to reconfirm the economic viability of the road upgrade.

5.1 A Description of the Study Areas and Assumptions

The model was applied to two typical plantations in the KwaZulu-Natal (KZN) Midlands where the majority of the timber grown is *Eucalyptus* pulpwood (Brink, 1998). Results from these case studies may be applicable to larger areas and should compliment previous studies performed in the area (Ackerman, 2003; personal communication). In both areas, the majority of timber was transported by means of either Extended Primary Transport (EPT) or Secondary Intermediate Transport (SIT) to a network of depots situated on either A or B–class roads. Both areas have high road densities and are typical of commercial plantations in South Africa.

The aim of this chapter was to test the model in real world situations. Specific objectives were as follows.

Objective one: To demonstrate the application of the model by recommending certain road upgrades in the study areas.

Objective two: To calculate the increased economic benefit once the particular road upgrades have been identified. This excludes capital investment expenditure.

Objective three: To use a capital budget to determine the number of years for the capital investment in the road upgrade to break even, therefore pointing out the economic viability of the particular road upgrade.

Objective four: To perform a sensitivity analysis. First, on the threshold tonnage which is influenced by the three variables entered into the model. Secondly, for the number of years to breakeven, as influenced by the economic parameters entered into the capital budget.

5.1.1 Study Area A

Study Area A (*cf.* Figure 5.1) is situated near the town of Richmond in the KZN Midlands. The estate is planted to hardwood (*Eucalyptus*) and sugarcane. Table 5.1 summarises the areas for the estate. The largest portion of the estate is planted to *Eucalyptus* and will be the area of focus used to demonstrate the application of the optimum road upgrading model. Protected areas consist of riparian and special management zones, which are not planted to timber due to best management practice policies.

Table 5.1 Breakdown of agricultural and silvicultural areas for Study Area A near Richmond, KwaZulu-Natal

Surface Cover	Area (ha)
Sugarcane	70
Hardwood (*Eucalyptus*)	1606
Protected Areas	406
Total Area	**2082**

Eucalyptus in Study Area A is used for producing pulp and is harvested on a 11 year rotation, from planting or coppice, with a mean annual yield estimated at $165t.ha^{-1}$. Depicted on the map (*cf.* Figure 5.1) are the existing roads and depots, while the compartments are subdivided according to which depot the timber will be delivered. For example, all timber in the yellow area will be delivered to Depot 1 when harvested. These distributions were established during consultation with the harvesting contractor and harvesting forester in the study area. The map shows a high density of roads with a large number of B–class roads and depots existent throughout the plantation.

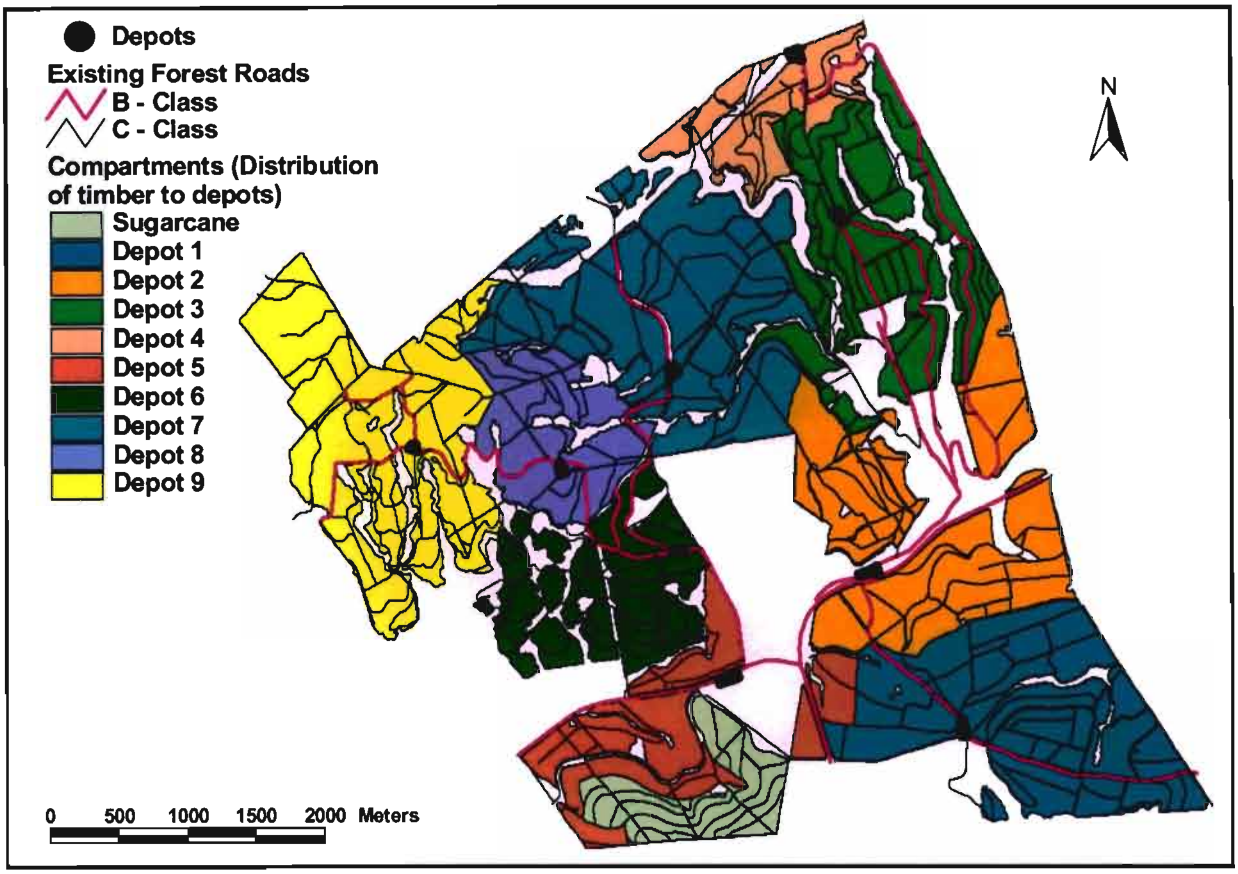


Figure 5.1 Map of Study Area A near Richmond, KwaZulu-Natal. Compartments are subdivided according to the depot to which timber is delivered. Existing roads, depots and rivers are also depicted

5.1.2 Study Area B

Study Area B (*cf.* Figure 5.2) is situated near the town of Highflats in the KZN Midlands. The surface cover consists of hardwood (*Eucalyptus*), which is used for the production of pulp and protected areas as summarised in Table 5.2.

Table 5.2 Breakdown of agricultural and silvicultural areas for Study Area B near Highflats, KwaZulu-Natal

Surface Cover	Area (ha)
Hardwood (*Eucalyptus*)	2079
Protected Areas	287
Total Area	**2366**

Eucalyptus pulpwood in Study Area B is harvested on a 14 year rotation from planting or coppice and the mean annual yield is estimated at 150 $t.ha^{-1}$. Figure 5.2 depicts the various land covers and features that are of importance to the model in a similar fashion to Figure 5.1. The map shows a high density of C–class roads, while A and B–class roads are generally restricted to the outer boundaries of the plantation.

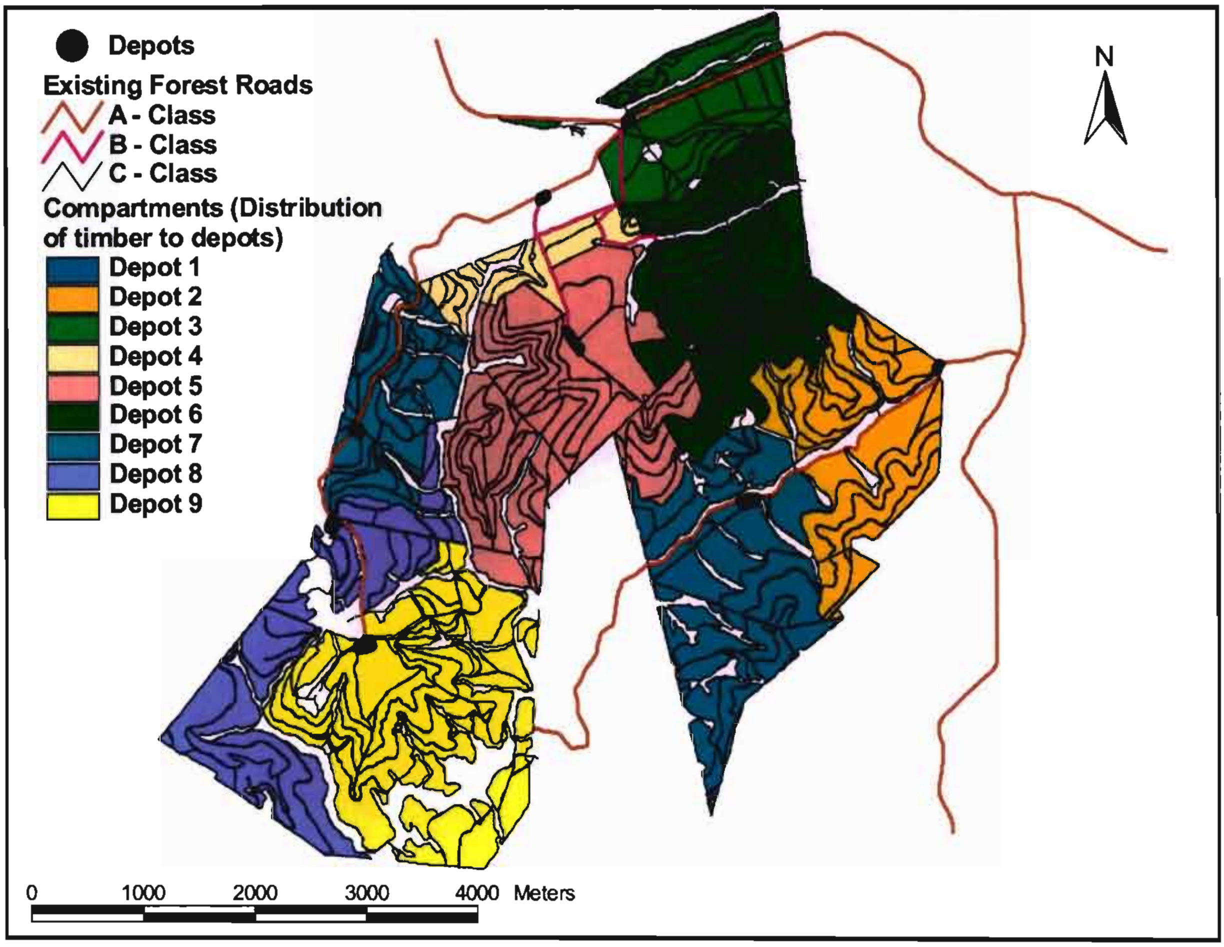


Figure 5.2 Map of Study area B near Highflats, KwaZulu-Natal. Compartments are subdivided according to the depot to which timber is delivered. Existing roads, depots and rivers are also depicted

5.2 The Current Harvesting System and Costs

Currently on both estates contractors perform all harvesting and transport operations. The timber is felled, debarked, crosscut and then stacked manually into five ton bundles on the extraction routes within the compartment. An agricultural tractor with a self loading cantilever trailer is used for the EPT phase (*cf.* Figure 5.3). The bundles are choked with chains and loaded onto the trailer using a cantilever system. The timber is off loaded at the depot by lowering the deck of the trailer and releasing the chains (Ackerman, 2001). Secondary terminal transport then moves the timber from the network of depots past the plantation exit point to the processing plant.

Figure 5.3 Agricultural tractor trailer combinations used for the extended primary transport phase in the two study areas.
(Study Area A) Ford 8030 with 5 ton bundle trailer (left)
(Study Area B) John Deere 6320 with 5 ton bundle trailer (right)

Three wheel log loaders (*cf.* Figure 5.4) are used at depots to index and stack timber to await pick up by the STT vehicle. The three wheel log loader is also used to load the STT, which consists of a rigid type truck with a drawbar trailer attached (*cf.* Figure 5.5). This truck configuration has the ability to transport 40 tons of timber from the plantation to the processing plant situated 107 km from Study Area A and 95 km from Study Area B, respectively.

Figure 5.4 Bell three wheel log loader used for indexing, stacking and loading onto secondary terminal transport in the two study areas

Figure 5.5 Rigid type truck with drawbar trailer used for secondary terminal transport in the two study areas

5.2.1 Machine and road upgrading costs

All machine costs used in this study are contractor rates, which is the cost incurred by the forestry company. Machine utilisation plays a critical role in machine costs. Higher machine utilisation spreads overhead costs, which implies lower rates for timber transportation, loading and off loading. For this study it was assumed that with any change in the system due to the upgrading of roads, contractors will adjust their operation accordingly, implying full utilisation of all machines and rendering machine costs equivalently, irrespective of road upgrades.

A number of variables which were highlighted in Chapter 3 determine both the construction and upgrading costs of forest roads. Of concern to this study is the upgrading from a C–class to a STT vehicle accessible B-class road. Table 5.3 summarises machine costs, road upgrading cost, rotation lengths and average annual yield that were obtained during consultation with local contractors and harvesting foresters at the two study areas.

Table 5.3 Machine costs, road upgrading cost, length of rotation, and average annual yields assumed for the two study areas

Variable	Description	Value
R_{stt}	Rate of secondary terminal transport	R0.40 $t^{-1}.km^{-1}$
R_{ept}	Rate of extended primary transport	R5.83 $t^{-1}.km^{-1}$
uc	Road upgrading cost from C-class to B-class	R117 000 km^{-1}
y_A	Mean annual yield for Study area A	165 $t.ha^{-1}$
y_B	Mean Annual yield for Study area B	150 $t.ha^{-1}$
R_A	Length of one rotation for Study area A	11 yrs
R_B	Length of one rotation for Study area B	14 yrs

Secondary terminal transport vehicles have a low power to weight ratio and relatively higher travelling speeds, compared to vehicle configurations used for EPT and SIT. The STT is therefore normally cheaper in $R.t^{-1}.km^{-1}$ terms. Extended primary transport and SIT can cost up to 14 times higher, in $R.t^{-1}.km^{-1}$ terms, than that of STT. In the case of EPT, the high operating cost can be attributed to the four wheel drive vehicles with off road capabilities transporting small payloads of approximately five tons.

The road upgrading cost in Table 5.3 is the combined cost to (1) form and compact the road to the correct specifications and (2) transport the rock material (wearing course) from the quarry site to the road being upgraded. The forming and compaction cost is based on an $R.km^{-1}$ rate and is dependant on the terrain, slope, underlying material and soil type. The transport cost of rock material is expressed in terms of $R.m^{-3}$ and is dependant on the lead distance from the quarry site to the road. A generic cost of R117 000 km^{-1} was used for both plantations based on information obtained from the forestry companies involved.

The mean annual yield and rotation length of the two study areas were obtained from local foresters. The yield obtained from a plantation over a particular rotation is site specific and predominately determined by climatic and soil characteristics.

During the model derivation (*cf.* Section 4.3), harvesting systems that make use of skidding and cable operations were included (*cf.* Equation 4.9). It was concluded that with such systems, an additional loading cost would be incurred should the road not be upgraded to the edge of the compartment. This is due to the cost of either an integrated or an independent loader (*cf.* Figure 5.4) and the cost of the haulage vehicle while being loaded.

Adverse terrain conditions, however, do not impede the use of tractor trailer combinations in either of the two study areas, therefore extra transloading costs were not considered

5.2.2 Harvesting schedule

A harvesting schedule plays a critical role when determining the future operational plan of an area. It determines when compartments are to be harvested and planted. The harvesting schedule is important because a road may be constructed or upgraded in year 0, while the timber that justifies the payment of the road may only be harvested later. This makes the number of years until each compartment is harvested of critical importance. An abbreviated example of a harvesting schedule assumed for Study Area B is given in Table 5.4.

Table 5.4 An example of a harvesting schedule for Study Area B near Highflats, KwaZulu-Natal

Comapartment No.	Area (ha)	Plant Date	Current Date	Current age of Crop	Years to Harvest
A 1	41.55	1995/08	2004/01	8.4	6
A 2	22.05	1999/03	2004/01	4.8	9
A 3	38.64	1997/10	2004/01	6.3	8
A 4	13.42	1997/11	2004/01	6.2	8
A 5	26.82	1995/08	2004/01	8.4	6
A 6	13.20	1996/06	2004/01	7.6	6
A 7	37.87	1990/09	2004/01	13.3	1
"	"	"	"	"	"
"	"	"	"	"	"
C 4	32.74	1995/09	2004/01	8.3	6
C 5	13.13	1998/04	2004/01	5.8	8
C 6	40.93	1998/02	2004/01	5.9	8
C 7	41.92	1999/03	2004/01	4.8	9

5.3 Application of the Model to the Study Areas

The application of the model followed a stepwise approach. The layout of the existing configuration was identified in terms of roads, depots and the distribution of timber being delivered to the various depots (*cf.* Figure 5.1 and Figure 5.2). By applying the model a threshold tonnage and in turn a threshold area for the two study areas was calculated. Areas further away from their delivery depots that exceeded the threshold were identified and possible routes for upgraded roads to gain access to these areas were identified.

The threshold tonnage was obtained using Equation 4.11 and the input data summarised in Table 5.3. This equated to 21 547 t of timber, which implies threshold areas of 130.6 ha and 143.6 ha for Study Areas A and B, respectively.

5.3.1 Study Area A

For Study Area A there were no areas away from the existing depots or A and B–class roads which exceeded the threshold area of 130.6 ha. This is attributed to the already dense network of depots and B–class roads. The existing configuration allows sufficient access of STT to the plantation for an efficient and cost effective transport system to be implemented. Currently all timber is transported to depots even if the STT vehicle has the ability to be loaded at roadside. In almost all cases in South Africa, transport contractors responsible for STT collect timber at depots independently of the harvesting contractor, who is responsible for the EPT and SIT phases (Morkel, 1999). This leaves each contractor to optimise their operation, while losing sight of optimising total delivered costs. Morkel (1999) notes that this inadequacy came about during the industry's focus on the improvement of longhaul or STT operations in 1993/94, which were warranted at the time. Morkel (1999) describes the possibility of implementing seconded stump-to-mill contracts as a solution to this problem. It involves the use of STT vehicles exclusively by the harvesting contractor, yet managed by a professional haulier since payment will then be on a mill delivered basis, there will be an improved focus on total delivered cost. Should such a situation be implemented a significant cost saving would be recognised with the existing road network. The current model should also be expanded to identify roads that could potentially be decommissioned in order to save on maintenance costs and increase production area.

5.3.2 Study Area B

Figure 5.6 shows the threshold areas for Study Area B (dark green compartments). The upgraded roads that are required for STT to gain access to the threshold areas need to be continued from either an existing depot or an A or B–class road. The criteria for an upgraded road which provides safe access to STT vehicles, is set out in Chapter 3 and is to be followed at all times. The sink indicated on the map is the point beyond which all transport costs could be assumed similar, irrespective of upgraded roads or not.

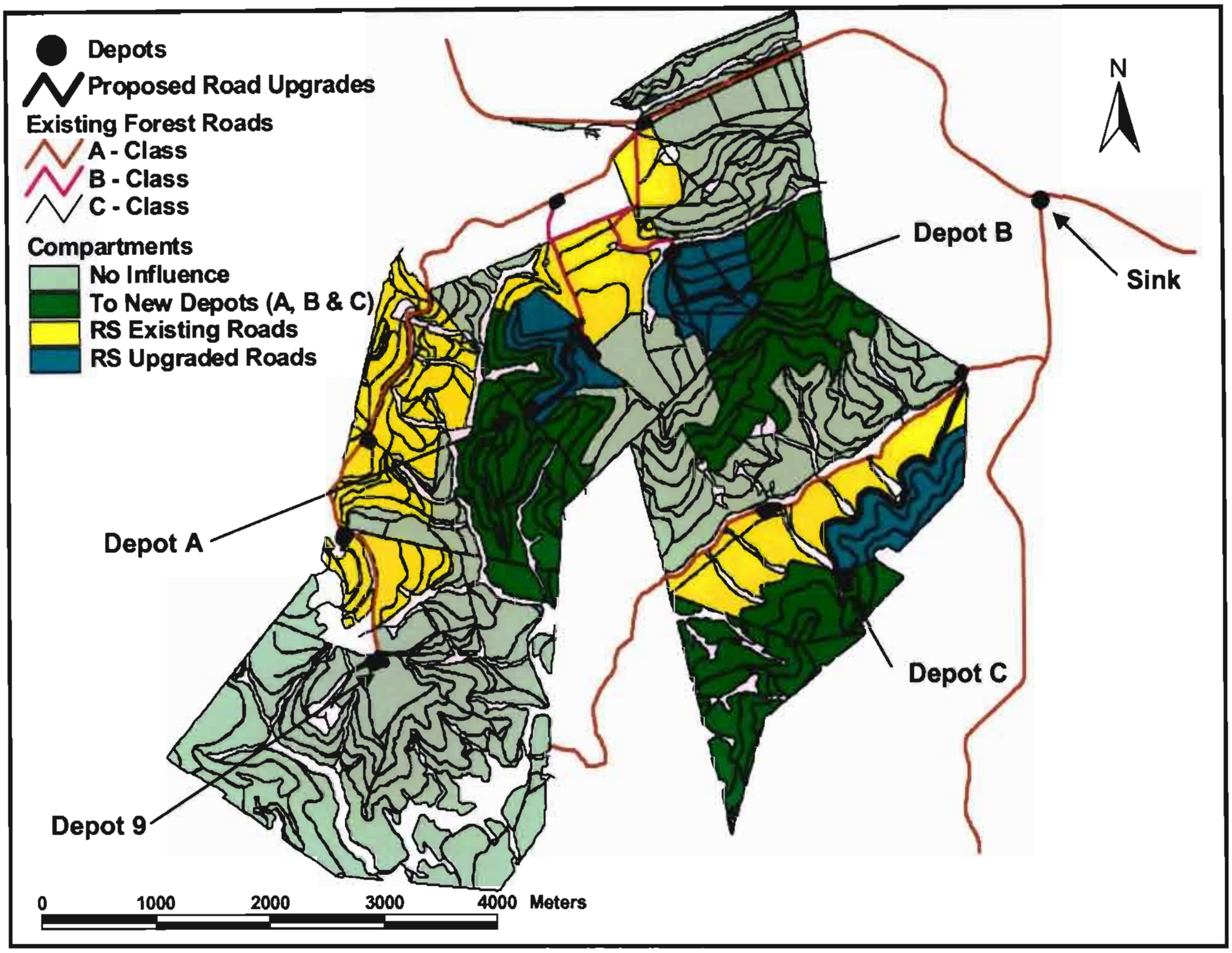


Figure 5.6 Threshold areas and upgraded roads for Study Area B near Highflats, KwaZulu-Natal. Compartments are divided into those that are influenced by the road upgrades, those that can be loaded at roadside (RS) of existing roads and those that are not influenced by the upgrade. New depots and their access roads are shown (marked A, B and C)

Three possible road upgrades are shown in black in Figure 5.6. Compartments where roadside loading could be made possible due to the upgraded roads and thus incurring no EPT cost are represented by the light blue areas. The estimated tonnage of timber that could be transported over the upgraded roads and the tonnage which will have the opportunity to be loaded at roadside are given in Table 5.5.

Table 5.5 The tonnage of timber that could be transported over the three road upgrades in a single rotation. The tonnage of timber which now has the opportunity to be loaded at roadside due to the upgraded roads is also given

Road Upgrade	Estimated Tonnage of Timber Transported Over Upgraded Road	Estimated Tonnage of Timber with Opportunity to be loaded at Roadside
Depot A	24705	6900
Depot B	23595	9420
Depot C	23295	8730

A fourth road upgrade would be expected to extend into the supply area of Depot 9 (*cf.* Figure 5.6) as this area substantially exceeds the threshold area of 143.6 ha. However, due to the majority of the area being subjected to an average slope of 35% or more, safe access by means of STT would come at an upgrade rate exceeding that assumed for this study. The distances and cost of upgrading roads to the new Depots A, B and C are supplied in Table 5.6.

Table 5.6 Road upgrade distances and costs for Study Area B near Highflats, KwaZulu-Natal

Depot	Road Upgrade Length (km)	Cost of Upgrade (R)
A	1.12	130 572
B	0.88	103 428
C	2.89	337 779

5.4 Economics of Study Area B

Three road upgrades have been identified for Study Area B in the previous section (*cf.* Table 5.6). During the application of the model, described in the previous section, it was assumed that the full volume of timber would be extracted simultaneously and not according to a harvesting schedule. Tax and discount rates are economic criteria that were therefore not incorporated into the model. It is hence important that a detailed economic analysis of the three road upgrades is conducted. This will reconfirm whether the road upgrades are economically viable. It will also show how suitable the simplified model performs against a more detailed economic assessment.

The economic analysis consists of calculating the change in transport costs between the existing and modified configuration, which estimates the extra revenue generated from the road upgrade (the cost saving). Capital budgets are used to account for the cost saving, capital investment, tax and discount rates and in turn calculate the number of years for the investment to breakeven for the three road upgrades (Barry *et al*, 1995).

5.4.1 Influence of road upgrades on travel distances and cost saving

To determine whether the implementation of the road upgrades in Table 5.6 will create a more cost effective transport system, a comparison in cost between the existing and the modified configuration needs to be made. Only the compartments that are affected by the road upgrades need to be considered, while those not affected are excluded from the economic analysis (*cf.* Figure 5.6).

The cost of timber being transported in the existing configuration is calculated by using the EPT rate to transport timber from within each compartment to the nearest depot (*cf.* Figure 5.2). The cost of STT from the sink to the processing plant is excluded as all timber transported over the same route with the same vehicle irrespective of the road upgrades. The STT rate is used to calculate the cost of transporting timber from the depot to the plantation sink (*cf.* Figure 5.6). For both EPT and STT (when loaded at roadside), a compartment's entry point to a road was assumed to be the point on a road situated closest to the compartment's centroid (A, B or C–class for EPT, only A or B–class for STT).

The modified configuration transports timber to new Depots A, B and C, at the end of the three upgraded roads by EPT and then STT transport moves timber to the plantation sink. Where possible, STT is loaded at roadside and moved directly to the plantation sink.

The distances travelled by the EPT and STT for the existing and modified configuration for Depots A, B and C are summarised in Table 5.7. With the upgraded roads in place a significant reduction in the distance travelled by the expensive EPT is shown. Road upgrades to Depots A, B and C saw a 53%, 32% and 39% reduction in the distance travelled by EPT, respectively. The distance travelled by the STT showed an increase, yet due to the distance from the sink to the processing plant being in excess of 100 km the increased distance travelled amounts to less than 1% in all three road upgrades.

Table 5.7 Compartments and areas in Study Area B near Highflats, KwaZulu-Natal, affected by the road upgrades to Depots A, B and C, respectively. Distances travelled by extended primary transport and secondary terminal transport for the existing and modified configuration are given

Compartment No.	Area (ha)	Extended Primary Transport (km)		Secondary Terminal Transport (km)	
		Existing Configuration	Modified Configuration	Existing Configuration	Modified Configuration
ROAD UPGRADE TO DEPOT A					
A 1	30.0	0.97	0.00	6.96	7.03
A 2	16.0	0.67	0.00	6.96	7.03
A 3	15.7	1.50	1.02	6.96	7.78
A 4	6.6	1.61	0.28	6.96	7.78
A 5	31.1	2.52	1.16	6.96	7.78
A 6	19.4	2.30	0.96	6.96	7.78
A 7	19.0	2.34	1.07	6.96	7.78
A 8	5.8	2.90	1.64	6.96	7.78
A 9	27.9	2.17	1.76	6.96	7.78
A 10	15.6	2.90	1.55	6.96	7.78
A 11	23.6	2.15	1.03	5.52	7.78
Average Distance (km)		2.00	0.95	6.83	7.64
ROAD UPGRADE TO DEPOT B					
B 1	29.3	0.42	0.00	6.24	6.98
B 2	20.0	0.83	0.00	6.24	6.95
B 3	13.5	0.39	0.00	6.24	6.60
B 4	37.9	1.68	0.63	6.24	7.13
B 5	14.6	1.15	0.76	6.24	7.13
B 6	37.7	2.01	0.64	6.24	7.13
B 7	29.0	2.21	1.99	6.24	7.13
B 8	10.2	2.23	2.01	6.24	7.13
B 9	11.1	2.41	2.26	6.24	7.13
B 10	16.8	2.87	2.68	6.24	7.13
Average Distance (km)		1.62	1.10	6.24	7.04
ROAD UPGRADE TO DEPOT C					
C 1	58.2	1.69	0.00	4.85	4.05
C 2	40.2	2.13	0.81	4.85	5.11
C 3	14.2	2.08	1.96	4.85	5.11
C 4	22.0	2.56	2.12	4.85	5.11
C 5	38.3	2.30	1.02	4.85	5.11
C 6	21.5	3.59	3.07	4.85	5.11
C 7	19.2	1.73	0.88	4.85	5.11
Average Distance (km)		2.30	1.41	4.85	4.96

The subsequent EPT and STT costs are calculated in Table 5.8, by assuming the economic values supplied in Table 5.3 and applying the distances travelled given in Table 5.7. Compartments that show a zero EPT cost for the modified configuration indicate roadside loading, while the remaining compartments are delivered to Depots A, B and C.

All compartments demonstrated a cost saving due to the reduced distance travelled by the expensive EPT. The total cost saving for the road upgrades to Depots A, B and C for a single rotation is estimated at R177 256, R115 913 and R210 240, respectively.

Table 5.8 Cost of extended primary transport and secondary terminal transport in Study Area B near Highflats, KwaZulu-Natal, for the compartments affected by the road upgrades to Depots A, B and C, respectively. Cost for the existing and modified configuration and the cost saving for each compartment is given

Compartment No.	Extended Primary Transport (R)		Secondary Terminal Transport (R)		Cost Saving (R)
	Existing Configuration	Modified Configuration	Existing Configuration	Modified Configuration	
ROAD UPGRADE TO DEPOT A					
A 1	25516.26	0.00	12504.65	12637.66	25383.26
A 2	9316.31	0.00	6687.07	6761.08	9242.30
A 3	20642.24	13940.03	6555.58	7326.38	5931.40
A 4	9242.67	1622.93	2747.04	3070.04	7296.74
A 5	68466.51	31595.74	12978.84	14504.88	35344.72
A 6	38921.31	16280.81	8095.03	9046.83	21688.69
A 7	38908.65	17815.81	7940.16	8873.76	20159.25
A 8	14681.17	8301.79	2414.77	2698.70	6095.45
A 9	52928.51	42938.77	11658.54	13029.35	8618.93
A 10	39529.61	21164.39	6517.60	7283.93	17598.89
A 11	44328.94	21246.54	7818.01	11003.80	19896.61
				Total Cost Saving (R)	177256.23
ROAD UPGRADE TO DEPOT B					
B 1	10671.60	0.00	10963.46	12261.03	9374.03
B 2	14580.78	0.00	7507.79	8355.48	13733.09
B 3	4586.40	0.00	5064.01	5355.98	4294.43
B 4	55671.68	20831.34	14187.99	16194.40	32833.93
B 5	14724.18	9718.22	5470.87	6244.53	4232.30
B 6	66152.65	21072.56	14127.67	16125.55	43082.22
B 7	56173.32	50540.76	10869.43	12406.54	4095.45
B 8	19878.84	17945.30	3817.21	4357.02	1393.72
B 9	23338.95	21857.27	4148.76	4735.46	894.98
B 10	42247.72	39377.23	6306.32	7198.13	1978.68
				Total Cost Saving (R)	115912.84
ROAD UPGRADE TO DEPOT C					
C 1	86228.94	0.00	16958.91	14138.83	89049.02
C 2	74970.48	28504.95	11703.11	12330.10	45838.53
C 3	25731.36	24209.02	4121.07	4341.86	1301.56
C 4	49097.55	40642.40	6398.39	6741.18	8112.36
C 5	77106.22	34102.10	11143.17	11740.16	42407.12
C 6	67557.77	57745.54	6258.91	6594.24	9476.91
C 7	29061.15	14706.86	5590.07	5889.56	14054.81
				Total Cost Saving (R)	210240.31

5.4.2 Capital budgets

A significant cost saving for the modified configuration was shown in the previous section. The capital budget system (Barry *et al.*, 1995) is a technique of accounting for investments made and cost savings achieved over a number of years. Depreciation of capital, discount rates and tax rates are accounted for in a capital budget. A capital investment depreciates over a set period of time, dependant on the asset purchased. The discount rate comprises of an opportunity cost and risk, where the opportunity cost is the rate of return that could be achieved if that money was invested elsewhere and an element of risk is included to account for fluctuations of interest rates in the future. All values are expressed in real terms. Therefore, all cost savings are calculated using present input costs and so removes the need to account for inflation. Cost saving and investment values that occur in the future are discounted back to present values (*PV*) by applying Equation 5.2. Table 5.9 summarises the economic parameters that were assumed for the capital budget for Study Area B.

$$PV = FV(1+i)^{-n} \tag{5.2}$$

where, FV is the future value, n the number of years being discounted back and i the discount rate.

Table 5.9 Economic parameters used as inputs to capital budgets for three road upgrades in Study Area B near Highflats, KwaZulu-Natal.

Variable	Value
Depreciation of Capital	
Year 1	50%
Year 2	30%
Year 3	20%
Discount Rate	
Opportunity Cost	5%
Risk	2%
Tax on Revenue	40%

Tables 5.10, 5.11 and 5.13 summarise the capital budgets for the three proposed road upgrades in Study Area B for timber being extracted according to the harvesting schedule. The investment in the road is made in year 0, while the cost savings reflected in the previous section are entered into the year during which the compartment is due to be

harvested. Not all years are reflected, since some years had no timber harvested, therefore not affecting the capital budget.

For the road upgrades to Depot A and B, it is shown that the investment in road upgrade is paid off in fourteen years, one rotation. For the upgrade to Depot B, the first compartment to be harvested is only in year four, consequently the investment in the upgrade was made in this year and the capital budget was carried through to year eighteen, equivalent to a single rotation. This shows that the simple model has performed well for road upgrades to Depot A and B against the detailed economic analysis as one rotation is equivalent to the full volume of timber being extracted once. Calculated at the bottom of Tables 5.10, 5.11 and 5.12 is the percentage of the investment returned in different years for upgrades to depots A, B and C, respectively. In Table 5.10 a large number of compartments are harvested in year one and accounts for 61% of the investment returned. While, in Table 5.11 the investment is paid back relatively consistently over the fourteen year period.

Table 5.12 contains the capital budget for the road upgrade to Depot C. After fourteen years only 67% of the investment was paid off. On further investigation after a second rotation only 75% of the investment in the road upgrade was returned. The model did not perform well for the road upgrade to Depot C due to certain terrain restraints that were incurred. The excessive slope in the area did not allow for the road to be extended from Depot 2 (*cf.* Figure 5.2), as required by the model. By upgrading the road from Depot 1 in order to access the threshold area (*cf.* Figure 5.6) a substantially longer upgrade distance and in turn a much larger investment was incurred. The upgrade to Depot C was fundamentally incorrect, but was included in this discussion to point out possible shortcomings of the model. The model was developed in context that a single road should be considered for upgrading and not to consider alternate routes, as performed in the case of Depot C.

Table 5.10 Capital budget for road upgrade to Depot A with timber being harvested over 14 years near Highflats, KwaZulu-Natal. Values are expressed in Rands. PV of Δ Net Cash Flow reflects the change in the net cash flow expressed in present value terms

Step	Year	0	1	2	3	5	6	7	14
1	Investment (-ve)	-130572							
2	Depreciation of Capital		-65286	-39172	-26114				
	Transport Cost Saving per Compartment								
	A 1					25383			
	A 2						9242		
	A 3		5931						
	A 4							7297	
	A 5		35345						
	A 6		21689						
	A 7		20159						
	A 8	6095							
	A 9		8619						
	A 10								17599
	A 11					19897			
3	Total Annual Cost Saving (Real)	6095	91743	0	0	45280	9242	7297	17599
4	Change in Taxable Income	6095	26457	-39172	-26114	45280	9242	7297	17599
5	Change in Tax (40%)	2438	10583	-15669	-10446	18112	3697	2919	7040
6	Change in Net Cash Flow	-126915	81160	15669	10446	27168	5545	4378	10559
7	PV of Δ Net Cash Flows (i = 7%)	-126915	75851	13686	8527	19370	3695	2726	4095
8	Accumulative Net Income	-126915	-51064	-37378	-28852	-9481	-5786	-3060	1035
9	Percentage of Investment Returned	3%	61%	71%	78%	93%	96%	98%	101%

Table 5.11 Capital budget for road upgrade to Depot B with timber being harvested over 14 years near Highflats, KwaZulu-Natal. Values are expressed in Rands. PV of Δ Net Cash Flow reflects the change in the net cash flow expressed in present value terms

Step	Year	4	5	6	7	14	18
1	Investment (-ve)	-103428					
2	Depreciation of Capital		-51714	-31028	-20686		
	Transport Cost Saving per Compartment						
	B 1			9374			
	B 2			13733			
	B 3						4294
	B 4	32834					32834
	B 5			4232			
	B 6				43082		
	B 7			4095			
	B 8				1394		
	B 9				895		
	B 10					1979	
3	Total Annual Cost Saving (Real)	32834	0	31435	45371	1979	37128
4	Change in Taxable Income	32834	-51714	406	24685	1979	37128
5	Change in Tax (40%)	13134	-20686	163	9874	791	14851
6	Change in Net Cash Flow	-83728	20686	31272	35497	1187	22277
7	PV of Δ Net Cash Flows (i = 7%)	-63875	14749	20838	22106	460	6591
8	Accumulation of Net Income	-63875	-49127	-28289	-6183	-5723	868
9	Percentage of Investment Returned	38%	53%	73%	94%	94%	101%

Table 5.12 Capital budget for road upgrade to Depot C with timber being harvested over 14 years near Highflats, KwaZulu-Natal. Values are expressed in Rands. PV of Δ Net Cash Flow reflects the change in the net cash flow expressed in present value terms

Step	Year	0	1	2	3	5	13	14
1	Investment (-ve)	-337779						
2	Depreciation of Capital		-168890	-101334	-67556			
	Transport Cost Saving per Compartment							
	C 1					89049		
	C 2						45839	
	C 3							1302
	C 4	8112						8112
	C 5	42407						42407
	C 6	9477						9477
	C 7					14055		
3	Total Annual Cost Saving (Real)	59996	0	0	0	103104	45839	61298
4	Change in Taxable Income	59996	-168890	-101334	-67556	103104	45839	61298
5	Change in Tax (40%)	23999	-67556	-40533	-27022	41242	18335	24519
6	Change in Net Cash Flow	-301781	67556	40533	27022	61862	27503	36779
7	PV of Δ Net Cash Flows (i = 7%)	-301781	63136	35404	22058	44107	11413	14263
8	Accumulative Net Income	-301781	-238645	-203241	-181183	-137076	-125663	-111400
9	Percentage of Investment Returned	11%	29%	40%	46%	59%	63%	67%

The three capital budgets demonstrated in this section reconfirm the suitability of the model developed in Chapter 3. The demonstration also, however, points to the limitation that the model can not be used to consider alternative routes for extraction.

5.5 Sensitivity Analysis of Model Inputs

It has been shown that the model performs well if applied judiciously. The road upgrades used to demonstrate the application of the optimum road upgrading model used site and time specific inputs. These inputs were related to the particular study area in terms of the harvesting system employed, machine and road upgrade costs. The current economic situation in terms of the tax and discount rate of forestry companies in South Africa also plays a critical role in the use of capital budgets. The above-mentioned may change at any time or from place to place due to a number of factors, such as weather conditions, fuel and machine prices, variations in the exchange rate and adoption of new harvesting technologies. Therefore, a sensitivity analysis was required to gain an understanding of how the output from the model and the results obtained in this study would be affected by changing variables.

Figure 5.7 shows the affect of changes in upgrade cost (*uc*) and the difference in the rate of EPT (R_{ept}) and the rate of STT (R_{stt}) on the threshold tonnage (*TT*) calculated by the model. The upgrade cost plotted on the Y-axis was considered to vary from R50 000 km^{-1} to R200 000 km^{-1}, while the difference in EPT and STT rates was considered to vary from R1 t^{-1}.km^{-1} to R10 t^{-1}.km^{-1}. The isoquant lines represent the model's threshold tonnages, which range from less than 12 500 t to greater than 187 500 t.

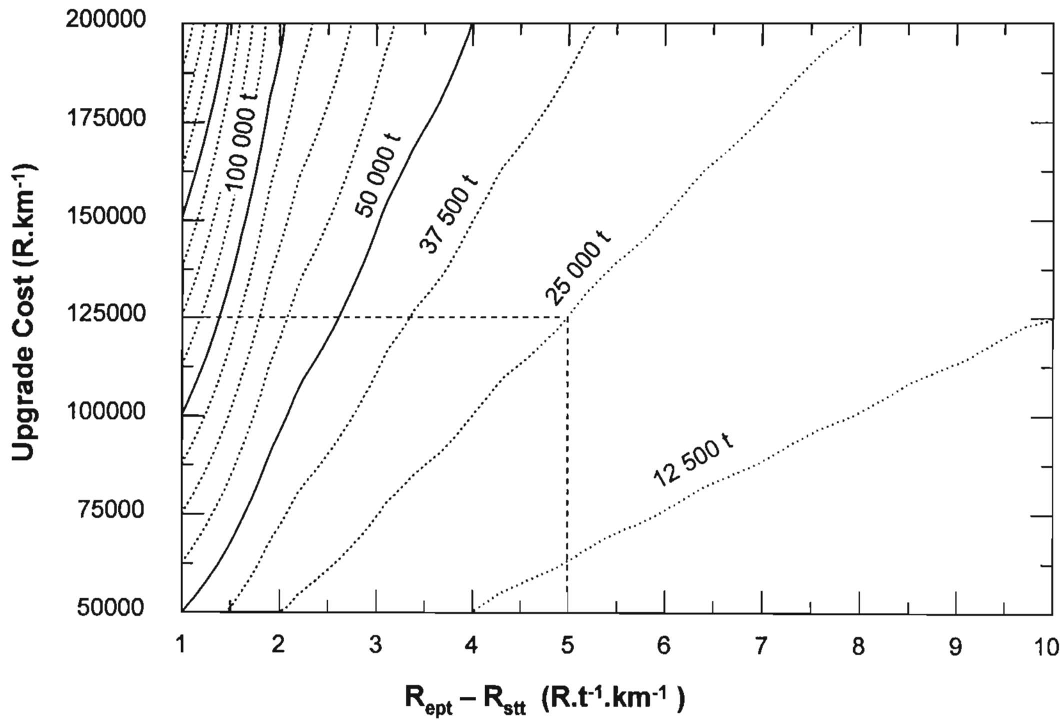


Figure 5.7 Sensitivity of the threshold tonnage to the road upgrade cost and difference in rate of extended primary transport (R_{ept}) and rate of secondary terminal transport (R_{stt}) for the model described in Equation 4.11

To illustrate the use of Figure 5.7 an example is given. Should the upgrade cost be R125 000 km^{-1} and the difference between the EPT and STT rates is R5 t^{-1}.km^{-1} then from the graph it can be shown that the threshold tonnage is 25 000 t (dashed lines). Therefore, if there is an area that has more than 25 000 t away from an A or B–class road, then it would be a viable option to upgrade the road to the threshold area. Figure 5.7 indicates higher threshold tonnage gradients when the difference between EPT and STT rates is low

(< R3 $t^{-1}.km^{-1}$) and significantly lower gradients when there is a large difference in the EPT and STT rates (> R5 $t^{-1}.km^{-1}$).

The other variables that were considered to play an important role in rendering a road upgrade is the tax rate the forestry company is subjected to, as well as the opportunity cost and risk (discount rate) of the money that has been invested. The discount rate and the tax rate affect the number of years that the investment takes to breakeven. Results in Figure 5.8 are based on the specific example for the road upgrade to Depot A in Study Area B (Section 5.3). Plotted on the Y-axis is the discount rate (opportunity cost + risk) ranging from 2% to 15% and on the X-axis, the tax rate ranging from 15% to 65%. It can be seen that with a low tax rate and low discount rate the investment breaks even in fewer years, while the number of years to breakeven increase as either of the two rates increase. The discount rate seems to be the more sensitive variable of the two with relatively small changes altering the number of years to break even, while it takes a substantial change in the tax rate to alter the number of years to breakeven.

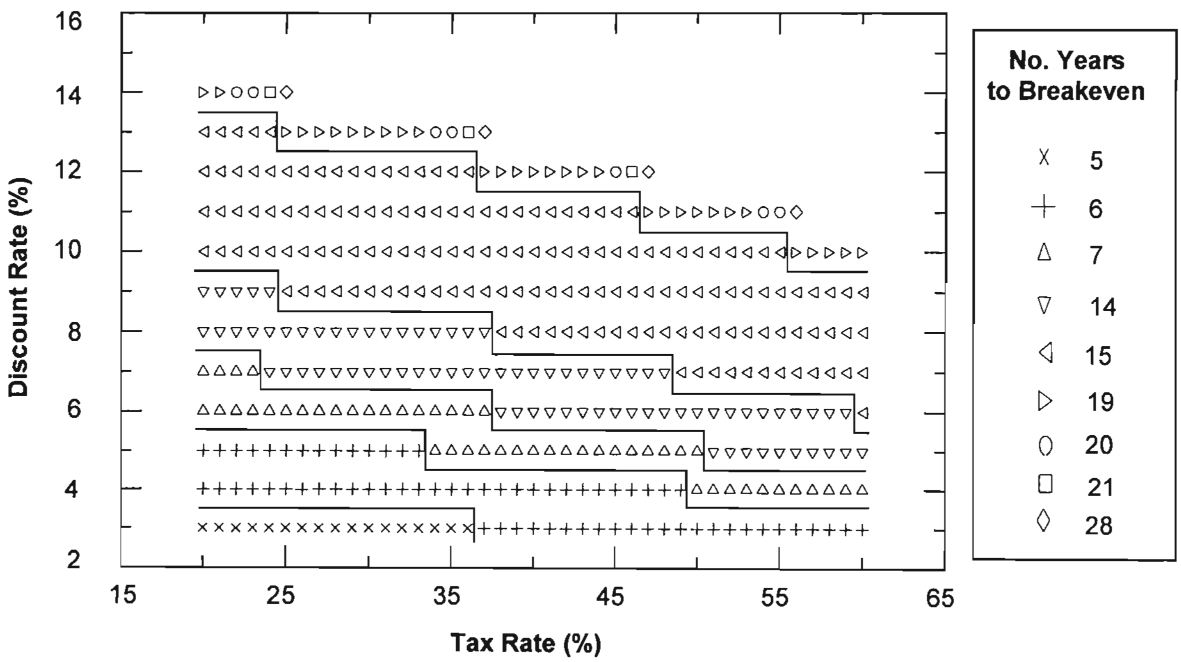


Figure 5.8 Sensitivity of the number of years to breakeven to the discount and tax rates for the road upgrade to Depot A in Study Area B near Highflats, KwaZulu-Natal

5.6 Conclusion

The application of the optimum road upgrading model was demonstrated in this chapter. The model was used to identify the threshold areas and possible road upgrades. While a detailed economic analysis, including a cost saving calculation and a capital budgeting system was used to verify the road upgrades and the applicability of the model to a real world scenario.

It was shown that the model performs well under the correct assumptions and with a simple analysis of the study area. Also by inputting the required variables into the model, threshold areas can be identified with relative ease. The model also helps to establish if the existing road network is satisfactory to implement an efficient transport system. A limitation of the model is that for the road upgrade to be viable the road accessing the threshold area needs to be placed on the general route that the timber would have flowed in the existing configuration.

For the model to be applied to a specific area a few simple inputs are required. These inputs should be common knowledge to both the harvesting forester and contractor. The model results were verified using a capital budgeting technique, which used the cost difference between the modified and existing configuration and accounted for timber being extracted according to the harvesting schedule. Two of the three demonstrated road upgrades gave improved economics. The road upgrade that was shown not to be economically viable, highlighted that the threshold tonnage is the tons of timber that needs to flow over a road to warrant the upgrading of that particular road, and not to determine alternate routes for the road upgrade and the optimum road network. Study Area A did not warrant any road upgrades. Since these two study areas were typical of large forestry areas, it implies that in many cases roads may be sufficient, or even excessive.

As the model was applied to two specific case studies, a sensitivity analysis was included to establish the model's robustness under different economic scenarios. The road upgrade cost would vary substantially in different plantations. Machine costs will vary from year to year, dependant on the country's economic situation, and possible innovations in the harvesting systems.

6. CONCLUSIONS AND RECOMMENDATIONS

A review of timber extraction in forest harvesting systems and a review of forest roads in South Africa was conducted. A large range of equipment is available to foresters for all possible types of timber that need to be harvested and delivered in a particular form. However, a good forest road network forms the basis for an efficient and economical harvesting and transport system to be implemented. Forest road networks in South Africa were noted in the literature to be poor and deteriorating on an annual basis. This neglect of forest road networks has prompted equipment manufacturers to promote more expensive machines with more off road capabilities to cope with the poor road conditions. With the accounting practise that exists within forestry companies, it has become easier to justify the more expensive machine which invariably increases the total delivered cost of timber rather than improving road networks. The cost of this primary transport is also far more costly than the secondary terminal transport.

With this in mind, an optimum road upgrading model was developed to evaluate the improvement that could be made to existing transport systems used in the South African forest industry if the correct roads were upgraded to utilise the secondary transport effectively. The model calculates a threshold tonnage which is required to be transported over a particular road to warrant the upgrading cost from a C–class to B–class road. Taken into consideration is the road upgrade cost, the cost of extended primary or secondary intermediate transport and the cost of secondary terminal transport. Initially, a theoretical set of compartments was used to demonstrate the use of the model. The results showed that a 43% cost saving in the transport from stump to the existing depot could be achieved if the road was upgraded to the threshold area. Though not demonstrated, the model was also developed to account for cable and skidding operations where an extra transloading cost would be incurred at roadside, if the road is not upgraded to the compartment.

The model application in two case studies was described in Chapter 5. In Study Area A, a dense network of B–class roads already existed. Therefore, in applying the model, no threshold areas outside of existing B–class or depots could be identified. This pointed out that the model could possibly be used to identify areas were roads are in excess. In Study Area B three possible road upgrades were identified. They confirmed that the model operates reasonably, and although it doesn't account for interest on capital, tax, opportunity costs and risk, a satisfactory result is achieved if all assumptions are maintained. Two of the three upgrades returned the capital invested in the road upgrade after one rotation (14 years). Therefore in the second rotation, assuming the road is maintained to the original design standard, a significant cost saving in the transport system will be made. The third upgrade investigated was unable to repay the capital investment, even after a second rotation (28 years). In the derivation of the optimum road upgrading model, it was determined that the threshold tonnage is the minimum required tonnage to be transported over a particular road to warrant the upgrading cost. The model did not perform well due to certain terrain constraints which restricted the placement of the road upgrade. This demonstrated the limitation that the model cannot be used to consider alternative routes for extraction.

A sensitivity analysis performed on the model illustrated that the smaller the difference between the primary and secondary transport rates, the more sensitive that model becomes to the upgrading cost. Therefore, the upgrading cost must be accurately calculated when the difference between transport costs are less than approximately R4 $t^{-1}.km^{-1}$. A sensitivity analysis of the capital budget and the effect of tax and discount rates on the number of years to breakeven was performed for one of the successful upgrades. It was shown that the tax rate could be increased from 40% to 48% before the number of years to breakeven becomes more than one rotation (14 years). In South Africa's current economic situation it is likely that the tax rate will decrease over the coming years rather than increase.

Recommendations

Currently in both study areas that were investigated, all timber is delivered to depots. While roadside loading in many cases is limited by terrain, more often it is not implemented due to the primary and secondary transport phases conducted by different companies. By implementing roadside loading, where possible, directly onto the secondary terminal transport, a more cost effective transport system would be possible immediately.

The model does not help to plan new roads, rather focussed on the decision to upgrade existing roads. It is assumed that the network is already optimal in terms of the layout and needs only improvement in the standard of certain roads to allow secondary terminal transport to gain further access to the plantation. The model should be expanded to optimise the road network, in terms of constructing completely new roads, decommissioning unnecessary roads and only then making the decisions to upgrade or not.

With the improved road network the primary transport equipment should be re-evaluated. Due to reduced lead distances, more efficient equipment may be implemented at a reduced rate. With these different rates the model would need to be applied iteratively until the optimum transport system is achieved.

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8. APPENDICES

Appendix A. Index values for different terrain conditions (Erasmus, 1994)

Ground Conditions (trafficability within the stand)	
1	very good
2	good
3	moderate
4	poor
5	very poor

Ground Roughness	
1	smooth
2	slightly uneven
3	uneven
4	rough
5	very rough

Slope Class	Gradient	
	Percent	Designation
1	0 - 11	level
2	12 - 20	gentle
3	21 - 30	moderate
4	31 - 35	steep 1
5	36 - 40	steep 2
6	41 - 50	steep 3
7	> 50	very steep

Appendix B. Classical machine costing

MACHINE DESCRIPTION	Ford 8030 + Self Loading Cantilever Trailer
TIMBER	*Euculyptus* Pulp
LOG LENGTH	2.4 m
FUNCTION	EXTENDED PRIMARY TRANSPORT

1.1 OWNERSHIP COSTS

Machine Price excl Vat		380000	
Less Cost of Tyres		42400	R
Residual Value	20%	76000	R
Paid Hours/Shift		9.20	Hrs
Mach Idle Time/Shift		1.88	Hrs
Machine Availability		85	%
Ave Mach Hrs per Shift		6.22	Hrs
Machine Utilisation		67.6	%
No.Mach Shifts/Day		2	#
Ave Mach Hrs/Day		12.44	Hrs
Avail Working Days/Yr		260	Days
Mach Idle Days/Yr		5	Days
Annual Hours Worked		3173	Hrs
Machine Life Years		3.2	Yrs
Machine Life Hours		10000	Hrs
Interest Rate		15	%
Lic & Ins.% Mach Price		1.5	%
Monthly Installment		R9,673.31	
Annual Installment		R116,079.73	
Annual Cost Lic.& Ins		R5,700.00	
Annual Ownership Cost		R121,779.73	
Ownership Cost / Hour		38.38	R/hr

1.2 OPERATING COSTS

Maint % Cap Cost/10000			60.0	%
Fuel Consumption			10.0	L/hr
Fuel Cost			3.58	R/l
Oil % Fuel Consumption			4.0	%
Oil Cost			8.00	R/l
Tyres	Qty	R/Tyre	Hrs	
Front	2	8000	2000	
Rear	2	4000	2000	
Trailer	2	3000	3000	
Maintenance Cost / Hr			22.80	R/hr
Fuel. Cost / Hr			35.8	R/hr
Oil. Cost / Hr			3.20	R/hr
Tyres. Cost / Hr			14.00	R/hr
Operating Cost / Hour			75.80	R/hr

1.3 LABOUR COSTS

Driver Wage / Shift	60	R
No. Drivers / Shift	1	#
Labour Wage / Shift	31	R
No.Labour / Shift	1	#
Lab. O/Heads. % Wage	5	%
Supervision. % Wage		%
Direct Labour. Cost / Hr	14.63	R/hr
Labour O/Heads Cost / Hr	0.73	R/hr
Supervision Cost / Hr	0	R/hr
Labour Cost / Hour	15.36	R/hr

SUMMARY

OWNERSHIP COST / HOUR	38.38	R/hr
OPERATING COST / HOUR	75.80	R/hr
LABOUR COST / HOUR	15.36	R/hr
TOTAL COST / HOUR	129.53	R/hr
TOTAL COST/DAY	1611.923	

2.0 IDLE TIME ANALYSIS

2.1 Daily Maintenance		
Mins / Shift	30.0	Mins
2.2 REST ALLOWANCE		
% Paid Hours / Shift	5.0	%
Mins per shift	27.6	Mins
2.3 WAITING TIME		
% Paid hours / Shift	10.0	%
Wait time, Mins / Shift	55.2	Mins

WORK STUDY ANALYSIS

3.1 AVERAGE TRUCK LOAD		
Average payload	5.0	Tons
3.2 NON PRODUCTIVE TRAVEL TIME		
Mins / Shift	15.0	Mins
3.3 LOADING TIME		
Enter Rack	1.0	Mins
Load Trailer	12.0	Mins
Exit Rack	1.0	Mins
Loading Time	14.0	Mins

3.4 TRAVELLING SPEEDS		
Ave Speed Loaded	8.0	Km/hr
Ave Speed Empty	10.0	Km/hr
3.5 OFFLOADING TIME		
Enter Landing	1.0	Mins
Offload	3.0	Mins
Exit Landing	1.0	Mins
Offloading Time	5.0	Mins

SYSTEM COST PER TONNE (FORD 8030 5t and TRAILER)

Road Lead Kms	Loads/ Shift	Tons/ hour	Tons/shift 100% avail	Tons p.a 85% avail	Non prod travel time R/ton	Non prod travel time R/t/km	Travel to & from depot Min/load	Travel to & from depot R/ton	Travel to & from depot R/t/km	Loading R/ton	Loading R/t/km	Offloading R/ton	Offloading R/t/km	Total Cost R/ton/km	Total Cost R /Tonne
0.1	21	14.85	105	45517.5	0.31	3.08	1.35	0.58	5.83	6.04	60.45	2.16	21.59	90.95	9.10
0.2	20	14.14	100	43350	0.32	1.62	2.7	1.17	5.83	6.04	30.22	2.16	10.79	48.47	9.69
0.3	18	12.73	90	39015	0.36	1.20	4.05	1.75	5.83	6.04	20.15	2.16	7.20	34.37	10.31
0.4	17	12.02	85	36847.5	0.38	0.95	5.4	2.33	5.83	6.04	15.11	2.16	5.40	27.29	10.92
0.5	16	11.32	80	34680	0.40	0.81	6.75	2.91	5.83	6.04	12.09	2.16	4.32	23.05	11.52
0.6	16	11.32	80	34680	0.40	0.67	8.1	3.50	5.83	6.04	10.07	2.16	3.60	20.18	12.11
0.7	15	10.61	75	32512.5	0.43	0.62	9.45	4.08	5.83	6.04	8.64	2.16	3.08	18.17	12.72
0.8	14	9.90	70	30345	0.46	0.58	10.8	4.66	5.83	6.04	7.56	2.16	2.70	16.66	13.33
0.9	14	9.90	70	30345	0.46	0.51	12.15	5.25	5.83	6.04	6.72	2.16	2.40	15.46	13.91
1	13	9.19	65	28177.5	0.50	0.50	13.5	5.83	5.83	6.04	6.04	2.16	2.16	14.53	14.53
1.1	13	9.19	65	28177.5	0.50	0.45	14.85	6.41	5.83	6.04	5.50	2.16	1.96	13.74	15.11
1.2	12	8.49	60	26010	0.54	0.45	16.2	6.99	5.83	6.04	5.04	2.16	1.80	13.12	15.74
1.3	12	8.49	60	26010	0.54	0.42	17.55	7.58	5.83	6.04	4.65	2.16	1.66	12.55	16.32
1.4	11	7.78	55	23842.5	0.59	0.42	18.9	8.16	5.83	6.04	4.32	2.16	1.54	12.11	16.95
1.5	11	7.78	55	23842.5	0.59	0.39	20.25	8.74	5.83	6.04	4.03	2.16	1.44	11.69	17.54
1.6	10	7.07	50	21675	0.65	0.40	21.6	9.33	5.83	6.04	3.78	2.16	1.35	11.36	18.18
1.7	10	7.07	50	21675	0.65	0.38	22.95	9.91	5.83	6.04	3.56	2.16	1.27	11.04	18.76
1.8	10	7.07	50	21675	0.65	0.36	24.3	10.49	5.83	6.04	3.36	2.16	1.20	10.75	19.34
1.9	10	7.07	50	21675	0.65	0.34	25.65	11.08	5.83	6.04	3.18	2.16	1.14	10.49	19.93
2	9	6.36	45	19507.5	0.72	0.36	27	11.66	5.83	6.04	3.02	2.16	1.08	10.29	20.58
2.1	9	6.36	45	19507.5	0.72	0.34	28.35	12.24	5.83	6.04	2.88	2.16	1.03	10.08	21.16
2.2	9	6.36	45	19507.5	0.72	0.33	29.7	12.82	5.83	6.04	2.75	2.16	0.98	9.89	21.75
2.3	8	5.66	40	17340	0.81	0.35	31.05	13.41	5.83	6.04	2.63	2.16	0.94	9.75	22.42
2.4	8	5.66	40	17340	0.81	0.34	32.4	13.99	5.83	6.04	2.52	2.16	0.90	9.58	23.00
2.5	8	5.66	40	17340	0.81	0.32	33.75	14.57	5.83	6.04	2.42	2.16	0.86	9.43	23.59
2.6	8	5.66	40	17340	0.81	0.31	35.1	15.16	5.83	6.04	2.32	2.16	0.83	9.30	24.17
2.7	8	5.66	40	17340	0.81	0.30	36.45	15.74	5.83	6.04	2.24	2.16	0.80	9.17	24.75
2.8	7	4.95	35	15172.5	0.93	0.33	37.8	16.32	5.83	6.04	2.16	2.16	0.77	9.09	25.45
2.9	7	4.95	35	15172.5	0.93	0.32	39.15	16.90	5.83	6.04	2.08	2.16	0.74	8.98	26.03
3	7	4.95	35	15172.5	0.93	0.31	40.5	17.49	5.83	6.04	2.01	2.16	0.72	8.87	26.62

Appendix C. Cost of timber transport from eighteen theoretical compartments for model demonstration purposes

Timber Entry Points for Each Compartment	k18	k17	k16	k15	k14	k13	k12	k11	k10	k9	k8	k7	k6	k5	k4	k3	k2	k1
Distance (m)	5090	4719	4113	4062	3999	3826	3771	3482	3331	2976	2625	2490	1707	1310	1066	826	699	659.00
Distance (km)	5.1	4.719	4.113	4.062	3.999	3.826	3.771	3.482	3.331	2.976	2.625	2.49	1.707	1.31	1.066	0.826	0.699	0.659
Hectares	11.33	29.653	14.194	14.594	11.697	34.519	20.825	10	13.528	20.151	29.507	31.347	23.427	22.245	20.176	28.975	10.885	56.58
Tons	1869.5	4892.7	2342.0	2408.0	1930.0	5695.6	3436.1	1650.0	2232.1	3324.9	4868.7	5172.3	3865.5	3670.4	3329.0	4780.9	1796.0	9335.9
Accumulated Tons	1869.5	6762.2	9104.2	11512.2	13442.2	19137.9	22574.0	24224.0	26456.1	29781.0	34649.7	39821.9	43687.4	47357.8	50686.8	55467.7	57263.7	66599.6

Yield for Plantation	165

EPT 18	EPT 17	EPT 16	EPT 15	EPT 14	EPT 13	EPT 12	EPT 11	EPT 10	EPT 9	EPT 8	EPT 7	EPT 6	EPT 5	EPT 4	EPT 3	EPT 2	EPT 1
0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.8	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.62	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.1	0.72	0.11	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.2	0.82	0.21	0.16	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.3	0.92	0.31	0.26	0.20	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.4	1.02	0.41	0.36	0.30	0.13	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.5	1.12	0.51	0.46	0.40	0.23	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.6	1.22	0.61	0.56	0.50	0.33	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.7	1.32	0.71	0.66	0.60	0.43	0.37	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.8	1.42	0.81	0.76	0.70	0.53	0.47	0.18	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.9	1.52	0.91	0.86	0.80	0.63	0.57	0.28	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1.62	1.01	0.96	0.90	0.73	0.67	0.38	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.1	1.72	1.11	1.06	1.00	0.83	0.77	0.48	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.2	1.82	1.21	1.16	1.10	0.93	0.87	0.58	0.43	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.3	1.92	1.31	1.26	1.20	1.03	0.97	0.68	0.53	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.4	2.02	1.41	1.36	1.30	1.13	1.07	0.78	0.63	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.5	2.12	1.51	1.46	1.40	1.23	1.17	0.88	0.73	0.38	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.6	2.22	1.61	1.56	1.50	1.33	1.27	0.98	0.83	0.48	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.7	2.32	1.71	1.66	1.60	1.43	1.37	1.08	0.93	0.58	0.23	0.09	0.00	0.00	0.00	0.00	0.00	0.00
2.8	2.42	1.81	1.76	1.70	1.53	1.47	1.18	1.03	0.68	0.33	0.19	0.00	0.00	0.00	0.00	0.00	0.00
2.9	2.52	1.91	1.86	1.80	1.63	1.57	1.28	1.13	0.78	0.43	0.29	0.00	0.00	0.00	0.00	0.00	0.00
3	2.62	2.01	1.96	1.90	1.73	1.67	1.38	1.23	0.88	0.53	0.39	0.00	0.00	0.00	0.00	0.00	0.00
3.1	2.72	2.11	2.06	2.00	1.83	1.77	1.48	1.33	0.98	0.63	0.49	0.00	0.00	0.00	0.00	0.00	0.00
3.2	2.82	2.21	2.16	2.10	1.93	1.87	1.58	1.43	1.08	0.73	0.59	0.00	0.00	0.00	0.00	0.00	0.00
3.3	2.92	2.31	2.26	2.20	2.03	1.97	1.68	1.53	1.18	0.83	0.69	0.00	0.00	0.00	0.00	0.00	0.00
3.4	3.02	2.41	2.36	2.30	2.13	2.07	1.78	1.63	1.28	0.93	0.79	0.01	0.00	0.00	0.00	0.00	0.00
3.5	3.12	2.51	2.46	2.40	2.23	2.17	1.88	1.73	1.38	1.03	0.89	0.11	0.00	0.00	0.00	0.00	0.00
3.6	3.22	2.61	2.56	2.50	2.33	2.27	1.98	1.83	1.48	1.13	0.99	0.21	0.00	0.00	0.00	0.00	0.00
3.7	3.32	2.71	2.66	2.60	2.43	2.37	2.08	1.93	1.58	1.23	1.09	0.31	0.00	0.00	0.00	0.00	0.00
3.8	3.42	2.81	2.76	2.70	2.53	2.47	2.18	2.03	1.68	1.33	1.19	0.41	0.01	0.00	0.00	0.00	0.00
3.9	3.52	2.91	2.86	2.80	2.63	2.57	2.28	2.13	1.78	1.43	1.29	0.51	0.11	0.00	0.00	0.00	0.00
4	3.62	3.01	2.96	2.90	2.73	2.67	2.38	2.23	1.88	1.53	1.39	0.61	0.21	0.00	0.00	0.00	0.00
4.1	3.72	3.11	3.06	3.00	2.83	2.77	2.48	2.33	1.98	1.63	1.49	0.71	0.31	0.07	0.00	0.00	0.00
4.2	3.82	3.21	3.16	3.10	2.93	2.87	2.58	2.43	2.08	1.73	1.59	0.81	0.41	0.17	0.00	0.00	0.00
4.3	3.92	3.31	3.26	3.20	3.03	2.97	2.68	2.53	2.18	1.83	1.69	0.91	0.51	0.27	0.03	0.00	0.00
4.4	4.02	3.41	3.36	3.30	3.13	3.07	2.78	2.63	2.28	1.93	1.79	1.01	0.61	0.37	0.13	0.00	0.00
4.5	4.12	3.51	3.46	3.40	3.23	3.17	2.88	2.73	2.38	2.03	1.89	1.11	0.71	0.47	0.23	0.10	0.06
4.6	4.22	3.61	3.56	3.50	3.33	3.27	2.98	2.83	2.48	2.13	1.99	1.21	0.81	0.57	0.33	0.20	0.16
4.7	4.32	3.71	3.66	3.60	3.43	3.37	3.08	2.93	2.58	2.23	2.09	1.31	0.91	0.67	0.43	0.30	0.26
4.8	4.42	3.81	3.76	3.70	3.53	3.47	3.18	3.03	2.68	2.33	2.19	1.41	1.01	0.77	0.53	0.40	0.36
4.9	4.52	3.91	3.86	3.80	3.63	3.57	3.28	3.13	2.78	2.43	2.29	1.51	1.11	0.87	0.63	0.50	0.46
5	4.62	4.01	3.96	3.90	3.73	3.67	3.38	3.23	2.88	2.53	2.39	1.61	1.21	0.97	0.73	0.60	0.56
5.1	4.72	4.11	4.06	4.00	3.83	3.77	3.48	3.33	2.98	2.63	2.49	1.71	1.31	1.07	0.83	0.70	0.66

y18	y17	y16	y15	y14	y13	y12	y11	y10	y9	y8	y7	y6	y5	y4	y3	y2	y1	Accumulated yi
1869.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1869.5
1869.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1869.5
1869.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1869.5
1869.45	4892.745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6762.2
1869.45	4892.745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6762.2
1869.45	4892.745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6762.2
1869.45	4892.745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6762.2
1869.45	4892.745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6762.2
1869.45	4892.745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6762.2
1869.45	4892.745	2342.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9104.2
1869.45	4892.745	2342.01	2408.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11512.2
1869.45	4892.745	2342.01	2408.01	1930.005	0	0	0	0	0	0	0	0	0	0	0	0	0	13442.2
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	0	0	0	0	0	0	0	0	0	0	0	0	19137.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	0	0	0	0	0	0	0	0	0	0	0	22574.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	0	0	0	0	0	0	0	0	0	0	0	22574.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	0	0	0	0	0	0	0	0	0	0	0	22574.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	0	0	0	0	0	0	0	0	0	0	24224.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	0	0	0	0	0	0	0	0	0	26456.1
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	0	0	0	0	0	0	0	0	0	26456.1
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	0	0	0	0	0	0	0	0	0	26456.1
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	0	0	0	0	0	0	0	0	0	26456.1
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	0	0	0	0	0	0	0	0	29781.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	0	0	0	0	0	0	0	0	29781.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	0	0	0	0	0	0	0	0	29781.0
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	0	0	0	0	0	0	0	34649.7
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	0	0	0	0	0	0	0	34649.7
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	0	0	0	0	0	0	39821.9
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	0	0	0	0	0	43687.4
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	0	0	0	0	0	43687.4
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	0	0	0	0	0	43687.4
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	0	0	0	0	0	43687.4
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	0	0	0	0	47357.8
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	0	0	0	0	47357.8
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	0	0	0	0	47357.8
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	0	0	0	50686.8
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	0	0	0	50686.8
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	0	0	55467.7
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	0	0	55467.7
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6
1869.45	4892.745	2342.01	2408.01	1930.005	5695.635	3436.125	1650	2232.12	3324.915	4868.655	5172.255	3865.455	3670.425	3329.04	4780.875	1796.025	9335.865	66599.6

Upgrade Rate (R.km-1)	STT Distance (km)	Road Upgrade Cost (R)	STT Rate (R.t-1.km-1)
117000	5.00	585000	0.4
117000	4.90	573300	0.4
117000	4.80	561600	0.4
117000	4.70	549900	0.4
117000	4.60	538200	0.4
117000	4.50	526500	0.4
117000	4.40	514800	0.4
117000	4.30	503100	0.4
117000	4.20	491400	0.4
117000	4.10	479700	0.4
117000	4.00	468000	0.4
117000	3.90	456300	0.4
117000	3.80	444600	0.4
117000	3.70	432900	0.4
117000	3.60	421200	0.4
117000	3.50	409500	0.4
117000	3.40	397800	0.4
117000	3.30	386100	0.4
117000	3.20	374400	0.4
117000	3.10	362700	0.4
117000	3.00	351000	0.4
117000	2.90	339300	0.4
117000	2.80	327600	0.4
117000	2.70	315900	0.4
117000	2.60	304200	0.4
117000	2.50	292500	0.4
117000	2.40	280800	0.4
117000	2.30	269100	0.4
117000	2.20	257400	0.4
117000	2.10	245700	0.4
117000	2.00	234000	0.4
117000	1.90	222300	0.4
117000	1.80	210600	0.4
117000	1.70	198900	0.4
117000	1.60	187200	0.4
117000	1.50	175500	0.4
117000	1.40	163800	0.4
117000	1.30	152100	0.4
117000	1.20	140400	0.4
117000	1.10	128700	0.4
117000	1.00	117000	0.4
117000	0.90	105300	0.4
117000	0.80	93600	0.4
117000	0.70	81900	0.4
117000	0.60	70200	0.4
117000	0.50	58500	0.4
117000	0.40	46800	0.4
117000	0.30	35100	0.4
117000	0.20	23400	0.4
117000	0.10	11700	0.4
117000	0.00	0	0.4

STT Cost 18	STT Cost 17	STT Cost 16	STT Cost 15	STT Cost 14	STT Cost 13	STT Cost 12	STT Cost 11	STT Cost 10	STT Cost 9	STT Cost 8	STT Cost 7	STT Cost 6	STT Cost 5	STT Cost 4	STT Cost 3	STT Cost 2	STT Cost 1	STT Cost (R)	Total STT Cost + Upgrade Cost
3739	9236	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	67746	652746
3664	9236	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	67671	640971
3589	9236	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	67596	629196
3515	9198	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	67484	617384
3440	9003	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	67214	605414
3365	8807	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	66943	593443
3290	8611	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	66673	581473
3215	8416	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	66402	569502
3141	8220	3853	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	66132	557532
3066	8024	3841	3913	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	65849	545549
2991	7828	3747	3853	3087	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	65425	533425
2916	7633	3654	3756	3011	8717	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	64888	521188
2842	7437	3560	3660	2934	8657	5183	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	64291	508891
2767	7241	3466	3564	2856	8430	5085	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	63428	496328
2692	7046	3372	3468	2779	8202	4948	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	62525	483725
2617	6850	3279	3371	2702	7974	4811	2298	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	61622	471122
2542	6654	3185	3275	2625	7746	4673	2244	2974	3958	5112	5152	2639	1923	1420	1580	502	2461	60665	458465
2468	6458	3091	3179	2548	7518	4536	2178	2946	3958	5112	5152	2639	1923	1420	1580	502	2461	59669	445769
2393	6263	2998	3082	2470	7290	4398	2112	2857	3958	5112	5152	2639	1923	1420	1580	502	2461	58610	433010
2318	6067	2904	2986	2393	7063	4261	2046	2768	3958	5112	5152	2639	1923	1420	1580	502	2461	57552	420252
2243	5871	2810	2890	2316	6835	4123	1980	2679	3958	5112	5152	2639	1923	1420	1580	502	2461	56494	407494
2169	5676	2717	2793	2239	6607	3986	1914	2589	3857	5112	5152	2639	1923	1420	1580	502	2461	55334	394634
2094	5480	2623	2697	2162	6379	3848	1848	2500	3724	5112	5152	2639	1923	1420	1580	502	2461	54143	381743
2019	5284	2529	2601	2084	6151	3711	1782	2411	3591	5112	5152	2639	1923	1420	1580	502	2461	52952	368852
1944	5088	2436	2504	2007	5923	3574	1716	2321	3458	5063	5152	2639	1923	1420	1580	502	2461	51712	355912
1869	4893	2342	2408	1930	5696	3436	1650	2232	3325	4869	5152	2639	1923	1420	1580	502	2461	50326	342826
1795	4697	2248	2312	1853	5468	3299	1584	2143	3192	4674	4965	2639	1923	1420	1580	502	2461	48754	329554
1720	4501	2155	2215	1776	5240	3161	1518	2054	3059	4479	4758	2639	1923	1420	1580	502	2461	47161	316261
1645	4306	2061	2119	1698	5012	3024	1452	1964	2926	4284	4552	2639	1923	1420	1580	502	2461	45568	302968
1570	4110	1967	2023	1621	4784	2886	1386	1875	2793	4090	4345	2639	1923	1420	1580	502	2461	43975	289675
1496	3914	1874	1926	1544	4557	2749	1320	1786	2660	3895	4138	2639	1923	1420	1580	502	2461	42382	276382
1421	3718	1780	1830	1467	4329	2611	1254	1696	2527	3700	3931	2639	1923	1420	1580	502	2461	40790	263090
1346	3523	1686	1734	1390	4101	2474	1188	1607	2394	3505	3724	2639	1923	1420	1580	502	2461	39197	249797
1271	3327	1593	1637	1312	3873	2337	1122	1518	2261	3311	3517	2629	1923	1420	1580	502	2461	37593	236493
1196	3131	1499	1541	1235	3645	2199	1056	1429	2128	3116	3310	2474	1923	1420	1580	502	2461	35845	223045
1122	2936	1405	1445	1158	3417	2062	990	1339	1995	2921	3103	2319	1923	1420	1580	502	2461	34098	209598
1047	2740	1312	1348	1081	3190	1924	924	1250	1862	2726	2896	2165	1923	1420	1580	502	2461	32350	196150
972	2544	1218	1252	1004	2962	1787	858	1161	1729	2532	2690	2010	1909	1420	1580	502	2461	30588	182688
897	2349	1124	1156	926	2734	1649	792	1071	1596	2337	2483	1855	1762	1420	1580	502	2461	28694	169094
823	2153	1030	1060	849	2506	1512	726	982	1463	2142	2276	1701	1615	1420	1580	502	2461	26800	155500
748	1957	937	963	772	2278	1374	660	893	1330	1947	2069	1546	1468	1332	1580	502	2461	24817	141817
673	1761	843	867	695	2050	1237	594	804	1197	1753	1862	1392	1321	1198	1580	502	2461	22790	128090
598	1566	749	771	618	1823	1100	528	714	1064	1558	1655	1237	1175	1065	1530	502	2461	20713	114313
523	1370	656	674	540	1595	962	462	625	931	1363	1448	1082	1028	932	1339	502	2461	18494	100394
449	1174	562	578	463	1367	825	396	536	798	1168	1241	928	881	799	1147	431	2241	15984	86184
374	979	468	482	386	1139	687	330	446	665	974	1034	773	734	666	958	359	1867	13320	71820
299	783	375	385	309	911	550	264	357	532	779	828	618	587	533	765	287	1494	10656	57456
224	587	281	289	232	683	412	198	268	399	584	621	464	440	399	574	216	1120	7992	43092
150	391	187	193	154	456	275	132	179	266	389	414	309	294	266	382	144	747	5328	28728
75	196	94	96	77	228	137	66	89	133	195	207	155	147	133	191	72	373	2664	14364
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix C. Cont.

EPT Rate (R.t-1.km-1)	EPT Cost 18	EPT Cost 17	EPT Cost 16	EPT Cost 15	EPT Cost 14	EPT Cost 13	EPT Cost 12	EPT Cost 11	EPT Cost 10	EPT Cost 9	EPT Cost 8	EPT Cost 7	EPT Cost 6	EPT Cost 5	EPT Cost 4	EPT Cost 3	EPT Cost 2	EPT Cost 1	Total EPT Cost (R)
5.83	1090	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1090
5.83	2180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2180
5.83	3270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3270
5.83	4360	542	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4902
5.83	5449	3394	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8844
5.83	6539	6247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12786
5.83	7629	9099	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16729
5.83	8719	11952	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20671
5.83	9809	14804	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24613
5.83	10899	17657	178	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28733
5.83	11989	20509	1543	870	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34911
5.83	13079	23362	2908	2274	1114	0	0	0	0	0	0	0	0	0	0	0	0	0	42737
5.83	14169	26214	4274	3678	2239	863	0	0	0	0	0	0	0	0	0	0	0	0	51437
5.83	15258	29067	5639	5082	3364	4184	1422	0	0	0	0	0	0	0	0	0	0	0	64017
5.83	16348	31919	7004	6486	4490	7504	3426	0	0	0	0	0	0	0	0	0	0	0	77177
5.83	17438	34772	8370	7890	5615	10825	5429	0	0	0	0	0	0	0	0	0	0	0	90338
5.83	18528	37624	9735	9294	6740	14146	7432	789	0	0	0	0	0	0	0	0	0	0	104287
5.83	19618	40477	11101	10697	7865	17466	9435	1751	403	0	0	0	0	0	0	0	0	0	118813
5.83	20708	43329	12466	12101	8990	20787	11439	2713	1705	0	0	0	0	0	0	0	0	0	134237
5.83	21798	46181	13831	13505	10115	24107	13442	3675	3006	0	0	0	0	0	0	0	0	0	149661
5.83	22888	49034	15197	14909	11241	27428	15445	4637	4307	0	0	0	0	0	0	0	0	0	165085
5.83	23978	51886	16562	16313	12366	30748	17448	5599	5609	1473	0	0	0	0	0	0	0	0	181982
5.83	25067	54739	17928	17717	13491	34069	19452	6560	6910	3412	0	0	0	0	0	0	0	0	199345
5.83	26157	57591	19293	19121	14616	37389	21455	7522	8211	5350	0	0	0	0	0	0	0	0	216707
5.83	27247	60444	20658	20525	15741	40710	23458	8484	9513	7288	710	0	0	0	0	0	0	0	234779
5.83	28337	63296	22024	21928	16867	44031	25461	9446	10814	9227	3548	0	0	0	0	0	0	0	254980
5.83	29427	66149	23389	23332	17992	47351	27465	10408	12115	11165	6386	2714	0	0	0	0	0	0	277894
5.83	30517	69001	24755	24736	19117	50672	29468	11370	13417	13104	9225	5729	0	0	0	0	0	0	301110
5.83	31607	71854	26120	26140	20242	53992	31471	12332	14718	15042	12063	8745	0	0	0	0	0	0	324327
5.83	32697	74706	27485	27544	21367	57313	33474	13294	16019	16981	14902	11760	0	0	0	0	0	0	347543
5.83	33787	77559	28851	28948	22493	60633	35478	14256	17321	18919	17740	14776	0	0	0	0	0	0	370759
5.83	34876	80411	30216	30352	23618	63954	37481	15218	18622	20857	20579	17791	0	0	0	0	0	0	393975
5.83	35966	83264	31582	31756	24743	67274	39484	16180	19923	22796	23417	20806	0	0	0	0	0	0	417191
5.83	37056	86116	32947	33159	25868	70595	41488	17142	21225	24734	26255	23822	158	0	0	0	0	0	440565
5.83	38146	88969	34312	34563	26993	73916	43491	18104	22526	26673	29094	26837	2411	0	0	0	0	0	466035
5.83	39236	91821	35678	35967	28119	77236	45494	19066	23827	28611	31932	29853	4665	0	0	0	0	0	491505
5.83	40326	94673	37043	37371	29244	80557	47497	20028	25129	30550	34771	32868	6918	0	0	0	0	0	516975
5.83	41416	97526	38408	38775	30369	83877	49501	20990	26430	32488	37609	35884	9172	214	0	0	0	0	542658
5.83	42506	100378	39774	40179	31494	87198	51504	21952	27731	34426	40448	38899	11426	2354	0	0	0	0	570268
5.83	43596	103231	41139	41583	32619	90518	53507	22914	29033	36365	43286	41914	13679	4494	0	0	0	0	597877
5.83	44685	106083	42505	42986	33745	93839	55510	23876	30334	38303	46124	44930	15933	6634	1281	0	0	0	626768
5.83	45775	108936	43870	44390	34870	97159	57514	24838	31635	40242	48963	47945	18186	8773	3222	0	0	0	656318
5.83	46865	111788	45235	45794	35995	100480	59517	25799	32937	42180	51801	50961	20440	10913	5163	725	0	0	686594
5.83	47955	114641	46601	47198	37120	103801	61520	26761	34238	44119	54640	53976	22693	13053	7103	3512	0	0	718931
5.83	49045	117493	47966	48602	38245	107121	63523	27723	35539	46057	57478	56992	24947	15193	9044	6299	1037	3211	755517
5.83	50135	120346	49332	50006	39371	110442	65527	28685	36841	47995	60317	60007	27200	17333	10985	9086	2084	8654	794344
5.83	51225	123198	50697	51410	40496	113762	67530	29647	38142	49934	63155	63022	29454	19473	12926	11874	3131	14097	833172
5.83	52315	126051	52062	52814	41621	117083	69533	30609	39443	51872	65993	66038	31708	21613	14867	14661	4178	19540	871999
5.83	53405	128903	53428	54217	42746	120403	71536	31571	40745	53811	68832	69053	33961	23752	16808	17448	5225	24982	910827
5.83	54494	131756	54793	55621	43871	123724	73540	32533	42046	55749	71670	72069	36215	25892	18748	20235	6272	30425	949655
5.83	55584	134608	56159	57025	44996	127044	75543	33495	43347	57688	74509	75084	38468	28032	20689	23023	7319	35868	988482

Upgrade Dist From Depot (km)	Total Cost (R)
5.1	653836
5	643151
4.9	632466
4.8	622286
4.7	614257
4.6	606229
4.5	598201
4.4	590173
4.3	582145
4.2	574282
4.1	568336
4	563925
3.9	560328
3.8	560345
3.7	560903
3.6	561460
3.5	562753
3.4	564582
3.3	567248
3.2	569913
3.1	572579
3	576617
2.9	581088
2.8	585559
2.7	590691
2.6	597806
2.5	607448
2.4	617371
2.3	627295
2.2	637218
2.1	647141
2	657065
1.9	666988
1.8	677058
1.7	689080
1.6	701103
1.5	713125
1.4	725346
1.3	739362
1.2	753377
1.1	768585
1	784408
0.9	800906
0.8	819325
0.7	841701
0.6	866164
0.5	890628
0.4	915091
0.3	939555
0.2	964019
0.1	988482