CHAPTER 14

VEHICLE OPERATING AND ROAD MAINTENANCE COST MODELS

14.1 Introduction

The second element of a MMS for mine haul roads is based on models of the variation of vehicle operating costs with road roughness. A road roughness progression model was developed in the previous chapter to explain the variation in road roughness or rolling resistance with time or tonnage hauled. This chapter addresses the development of vehicle operating cost prediction models for fuel consumption, tyre cost and vehicle (parts and labour) costs with increased rolling resistance of a haul road. Table 3.14 lists the various model data requirements whilst Figure 2.12 illustrates the concept of vehicle operating cost variation with road roughness. When combined with the road maintenance cost model developed later in the chapter, the optimal maintenance strategy for a specific mine haul road, commensurate with lowest overall vehicle and road maintenance costs may be identified.

14.2 Fuel Consumption Model

The prediction of fuel consumption variation with road roughness is central to any MMS and fuel consumption itself is a significant component of total vehicle operating costs. Fuel consumption of vehicles in the public domain has been shown to vary with vehicle type and speed, road curvature, traffic volume and the grade of the road (Chesher and Harrison, 1987). A description of the analytical approach adopted in determining the contribution of these various factors to haul truck vehicle fuel consumption is described.

14.2.1 Analytical Approach

The analytical approach adopted in the determination of haul truck fuel consumption involved the computer simulation of specific haul trucks to generate a speed model for a range of vehicles commonly used for coal haulage. The speed model formed the basis of the fuel consumption model which was derived from vehicle simulations coupled with vehicle torque/fuel consumption maps. The models developed are finally tested in comparison to mine site vehicle fuel consumption and average journey time data.

The vehicles chosen for the simulation exercises incorporated five rear-dump coal haul trucks typical of the vehicles employed on strip coal mines for coal hauling. Table 14.1 presents a summary of the simulation fleet parameters and Appendix N full vehicle specifications.

Table 14.1 Simulation Vehicle Fleet Specifications

Haul Truck Type	Manufacturer	Fuel and Drive	Engine Type	Engine Torque (kN) @rpm	Tyre Type	Gross Vehicle Mass (GVM) (t)	Unladen Vehicle Mass (UVM) (t)
CAT789	Caterpillar	D TC/DD M	Cat3516	1244 @1900	3600R51	274	120
CAT785	Caterpillar	D TC/DD M	Cat3512	1013 @1900	3000R51	219	95
R170	Euclid	D E	Cummins KTA 50C	1193 @1900	3600R51	274	120
630EH	Dresser-Haulpak	D E	Detroit 16V-149T1B	1342 @1900	3700R57	277	114
CAT793	Caterpillar	D TC/DD M	Cat3516	1487 @1900	4000R57	362	144

Notes

D	Diesel fuel
TC	Torque converter drive up to 7-8km/h
DD	Direct drive with torque converter lock-up above 7-8km/h
M	Mechanical drive
E	Electric drive (electric rear wheel motors)

The vehicle types chosen for the assessment may be classified in terms of gross power (kW) to GVM and UVM ratios from 4,4-4,9 and 11,1-11,8 respectively. Both electric and mechanical drive options have been analysed although the recent trend is to mechanical drive for the larger haul trucks (Caterpillar, 1993). These trucks are referred to in the following analysis with the exception of the R170 which is seen to be similar to the 630EH truck.

The simulation exercises were run on the Komatsu Optimum Fleet Recommendation package (Komatsu, 1994). This simulation package incorporates engine torque/fuel consumption maps for each vehicle and engine combination chosen, together with a vehicle speed/rimpull map and torque/speed ratio map for the particular drive configuration adopted. Vehicle speed limitations on favourable (down) grades are limited by the particular retarder option chosen which is described by a retarder force/speed limit/distance map.

14.2.2 Vehicle Speed Model

As a precursor to the vehicle fuel consumption model, a model was developed to describe the speed variation of haul trucks with total resistance. Total resistance is defined as the sum of rolling and grade resistances as given in Equation [14.1]. Rolling resistance is described as a percentage of vehicle mass as given in Equation [14.2] and grade similarly in terms of percentage meters rise (+) or fall (-) per meter.

$$TR(\%) = GR(\%) + RR(\%) \qquad (14.1)$$

Where

TR = Total rolling resistance (%)
GR(%) = Grade resistance (%)
RR(%) = Rolling resistance (%)

and

$$RR(\%) = \frac{RR.100}{g} \qquad (14.2)$$

where

RR = Rolling resistance (N/kg)

g = acceleration due to gravity, 9,81m/s^2

and

$$GR(\%) = \frac{GR.100}{g} \qquad (14.3)$$

where

GR = Grade resistance (N/kg)

Simulations were conducted with the vehicles given in Table 14.1 for both laden and unladen conditions over a range of favourable and unfavourable grades of road. The simulation model comprised a number of road sections interspersed with shorter acceleration sections such that a constant velocity was attained over alternate road sections. Vehicle speeds were unlimited on both grades. As can be seen from Figures 14.1 and 14.2, two distinct grade/velocity profiles are seen for both favourable and unfavourable grades. For favourable grades with unladen trucks, the vehicle retarder limits the vehicle speed to approximately 55km/h between total resistance values of 0 and -8%. At higher values, vehicle speed is limited by the safe speed of the vehicle in conjunction with retarder performance and thus reduces slightly. A similar effect is seen for laden trucks, the constant speed retarder controlled section being smaller due to increased weight of the truck and its propensity to accelerate down-grade to a speed beyond the limits of vehicle braking.

The profiles of speed against unfavourable grade show similar characteristics, the laden vehicles losing speed more rapidly as the unladen vehicles. In all cases a logit function of the general form given below in Equation [14.4] is used to model the variation in speed for favourable grades laden and unladen (VFL and VFUL respectively) and unfavourable grades laden and unladen (VUFL and VUFUL respectively) with total resistance (TR).

$$V = VMIN + \left[\frac{VMAX - VMIN}{1 + \exp^{(f)}}\right] \qquad (14.4)$$

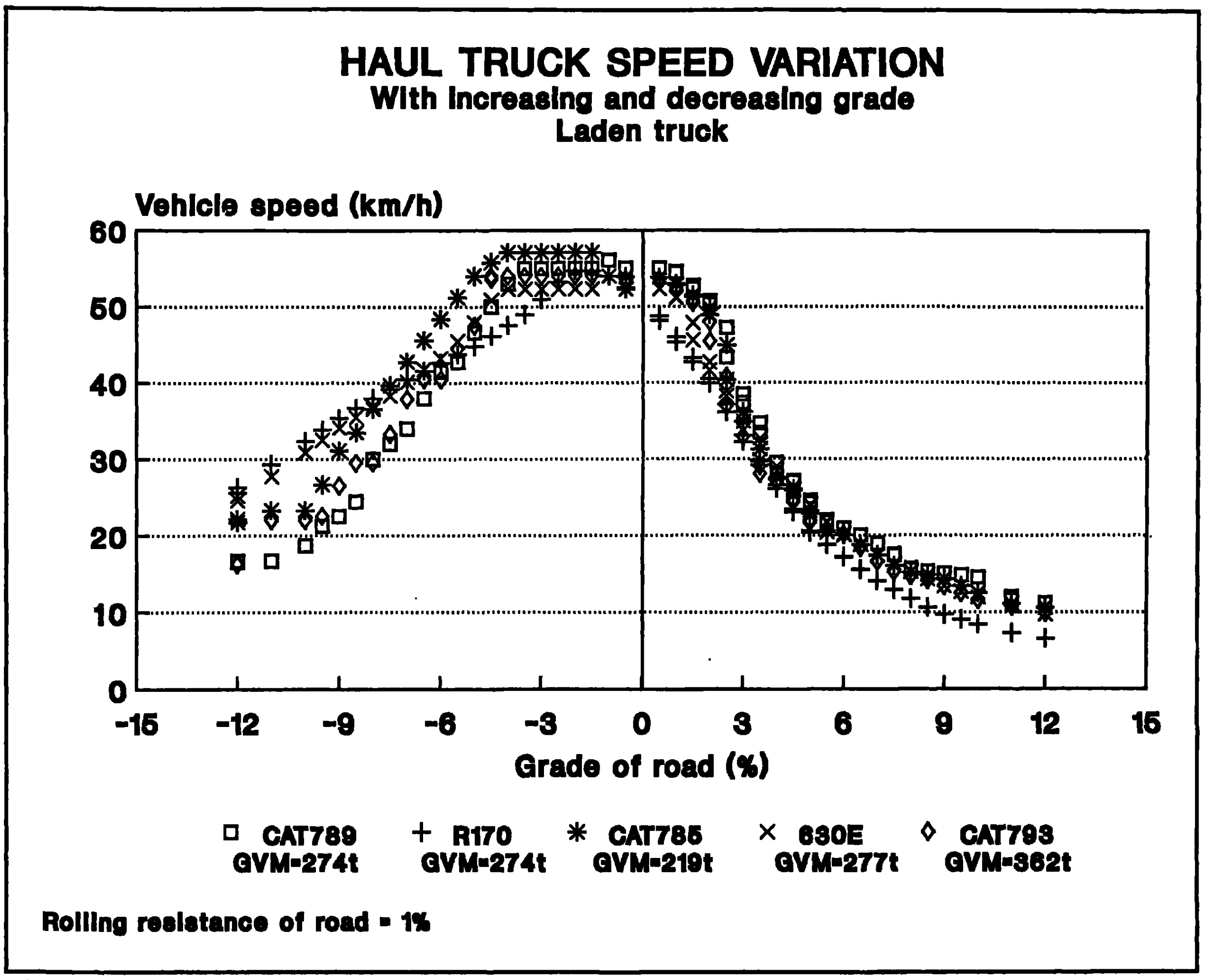


Figure 14.1 Haul truck speed variation for laden simulation fleet.

where

V = Vehicle speed (km/h)
$VMIN$ = Minimum vehicle speed (km/h)
$VMAX$ = Maximum vehicle speed (km/h)
f = Regression function which is linear in total resistance (TR)

The limits of VMIN and VMAX were calculated from inspection of the data combined for all truck types simulated and the following speed models accordingly derived:

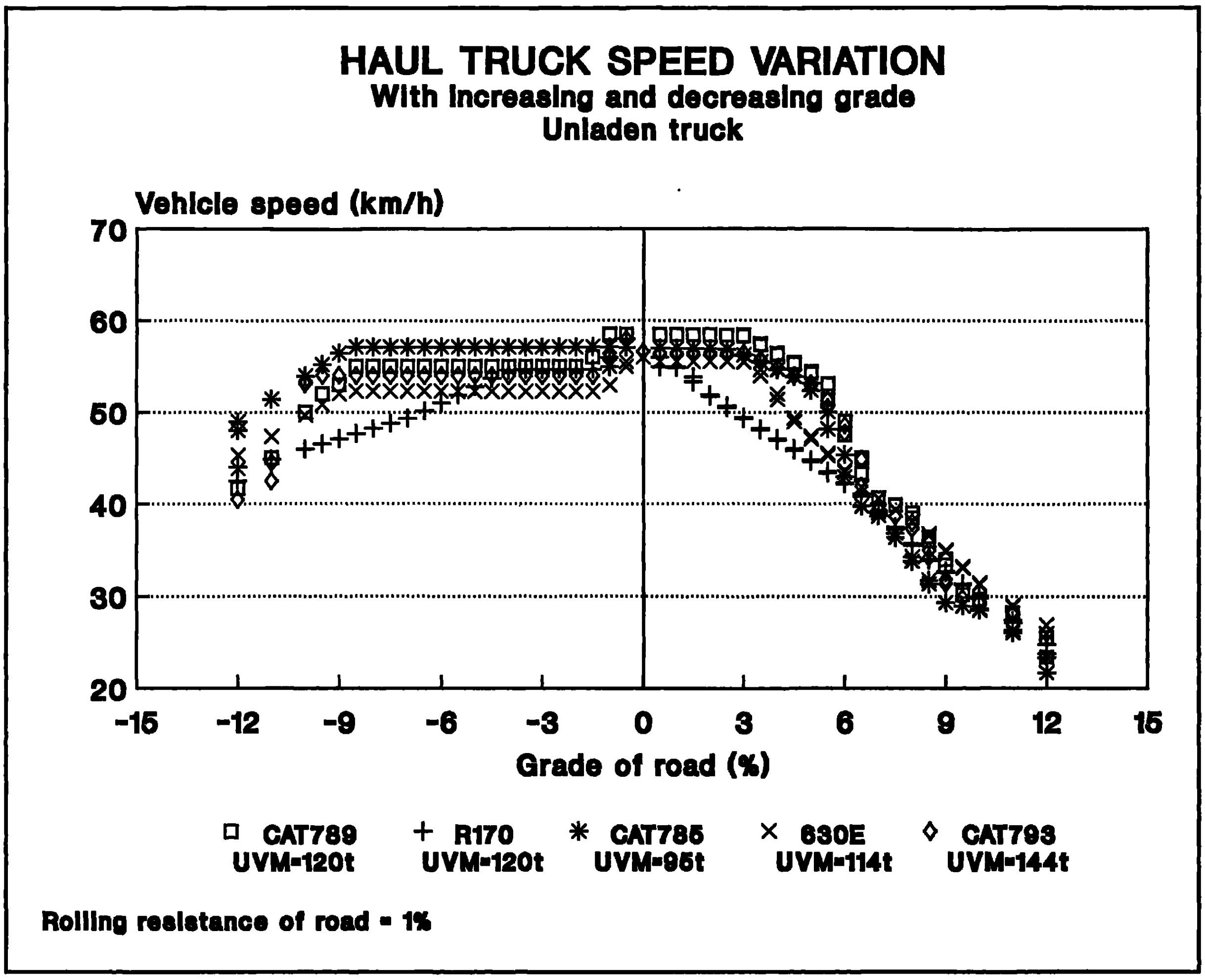


Figure 14.2 Haul truck speed variation for unladen simulation fleet.

$$VFU = 13 + \left[\frac{42}{1+\exp^{\left(\frac{TR+10{,}03}{-0{,}803}\right)}}\right] \tag{14.5}$$

$$VUFU = 22 + \left[\frac{36}{1+\exp^{\left(\frac{TR-6{,}31}{1{,}9}\right)}}\right] \tag{14.6}$$

$$VFL = 5 + \left[\frac{49}{1+\exp^{\left(\frac{TR+9{,}5}{-2{,}4}\right)}}\right] \tag{14.7}$$

$$VUFL = 9 + \left[\frac{55}{1 + \exp^{\left(\frac{TR - 2{,}25}{1{,}75}\right)}} \right] \qquad (14.8)$$

The combined models are shown in Figure 14.3 plotted against total favourable and unfavourable resistance for both unladen and laden trucks. The simulation assumes no traffic interference (from slower moving vehicles) or congestion. The effect of curvature on vehicle speed and total resistance was also investigated by means of specifying the radius of curvature of the sections of haul road comprising the model. For the common limits of haul road geometric design, curvature values of 10° to 90° per 1000m did not reveal any significant decrease in speed. This is due to the much lower super-elevation adopted in the design of mine haul roads, commensurate with the lower vehicle speeds, than those values adopted for the design of public paved and unpaved roads. Some reduction in speed is nevertheless a requirement for safe operation, but this is only applicable for speeds in excess of 48km/h on bends of radii of less than 60m which generally lies outside the range of geometric designs encountered. The effect of air resistance on total resistance, although varying proportionally to the square of the vehicle velocity, was ignored for in this analysis due to the relatively low vehicle speeds and similar frontal areas of the simulation vehicles (Caterpillar, 1993).

14.2.3 Constant Speed Fuel Consumption

The development of a constant speed fuel consumption model utilised the Komatsu OFR simulation program as described previously, in this case using a set course comprising of acceleration and constant speed sections with differing maximum speed limits applied. The course was modelled with various total resistance (TR%) values from -10 to 10%. The dynamic rolling resistance was modelled following Caterpillar (1993) as described in Chapter 13. Figures 14.4 and 14.5 illustrate the variation in fuel consumption with vehicle speed for a laden and unladen Cat 789 vehicle as described in section 14.2.2 running against an (unfavourable) total resistances of 0 and 6%. The curves are broadly similar to those reported for heavy commercial vehicles. Where TR=0%, a slightly increasing rate of fuel

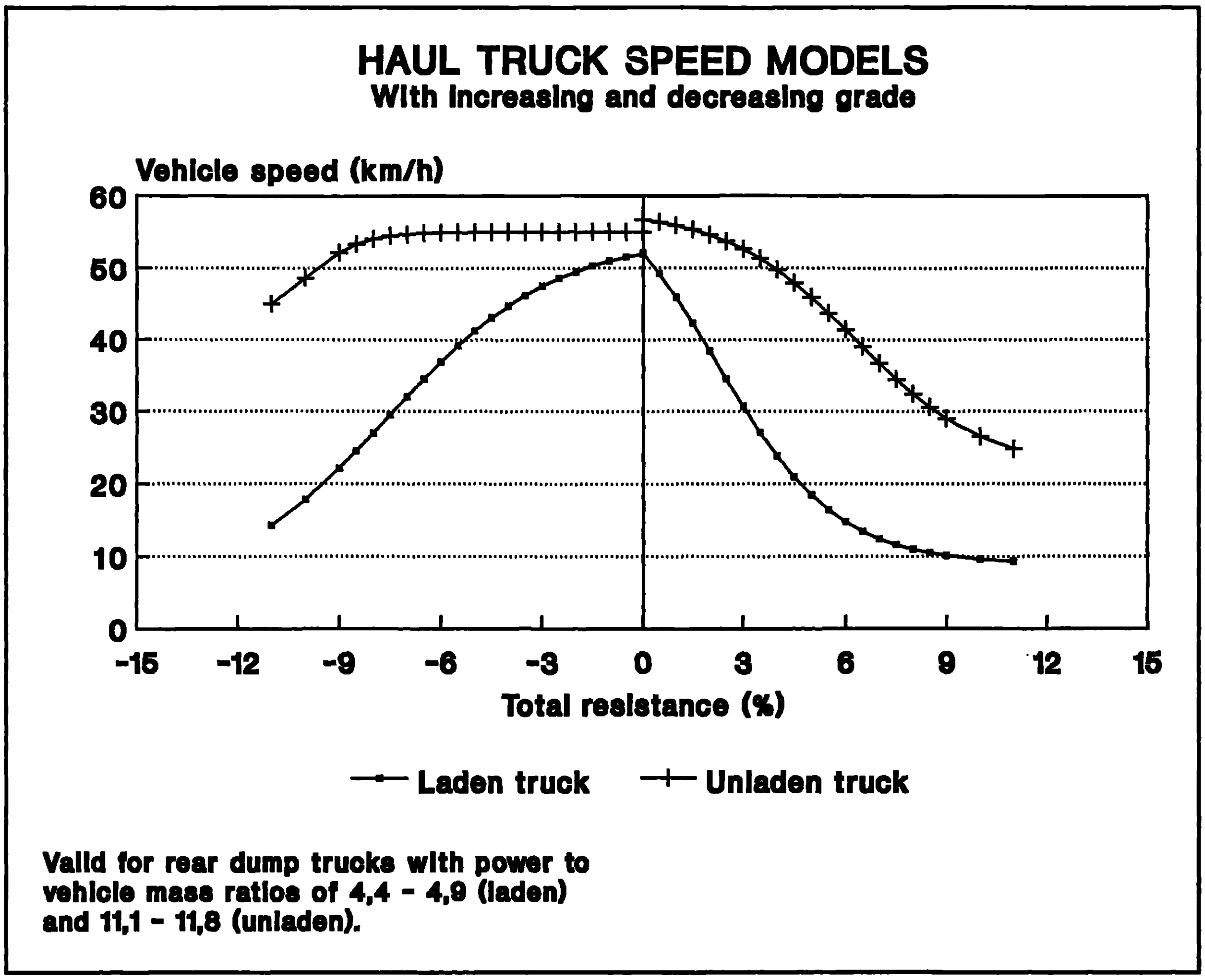


Figure 14.3 Combined speed models for laden and unladen trucks.

consumption with speed is seen due to dynamic rolling resistance effects. At higher levels of total resistance this effect is largely obscured by the approximately linear increase in fuel consumption with speed. A similar effect can be hypothesised from work presented by Chesher and Harrison (1987) in which the rate of fuel consumption increase with speed for heavier vehicles (albeit from various studies) appears less than for light vehicles and motor cars. There is some evidence of increased fuel consumption at low speeds and low total resistance values due to the effect of torque converter drive being engaged at low speeds (7-8km/h). This effect becomes progressively less evident as total resistance increases and as such was ignored in so far as modelling fuel consumption was concerned.

Figure 14.6 illustrates the fuel consumption/speed relationship for the same laden vehicle running with favourable total resistance values from -10 to -2%. At speeds in excess of 10 km/h, fuel is consumed at an approximately constant rate, varying between 7-9ml/s. If the

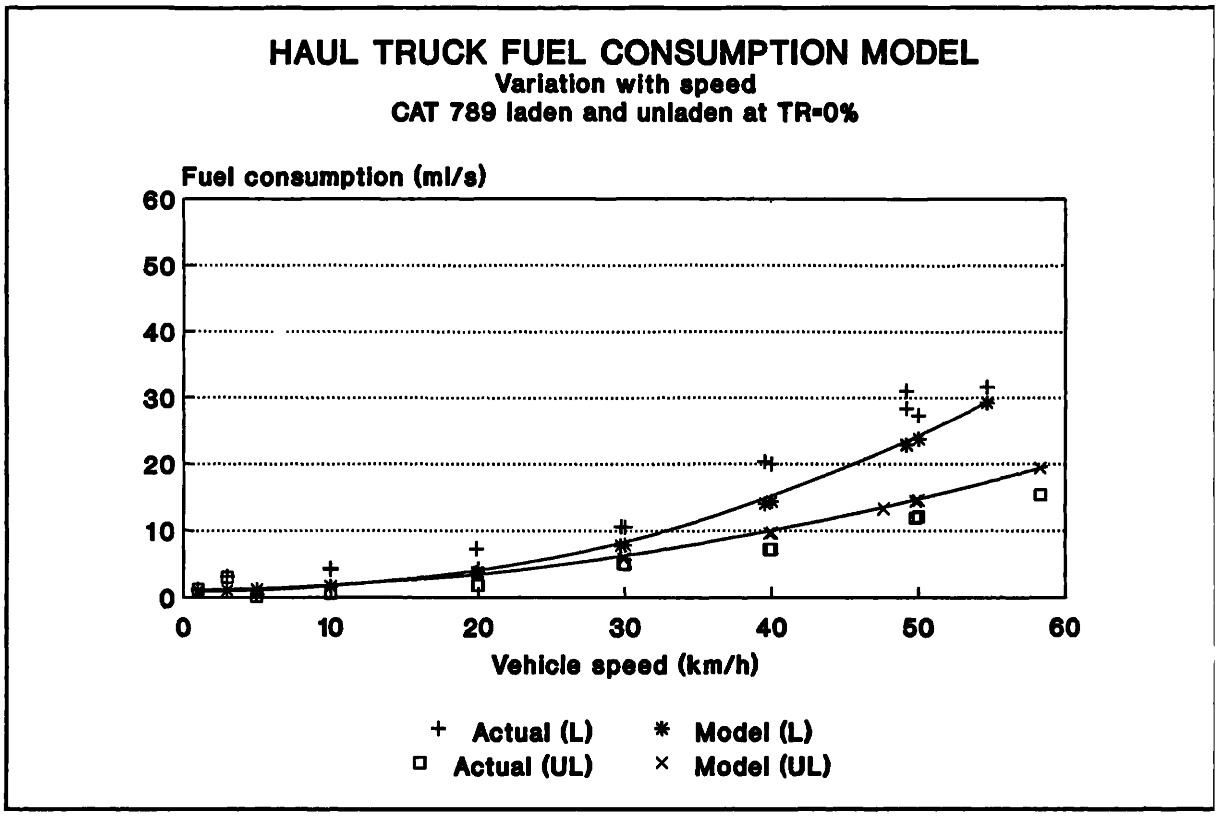


Figure 14.4 Haul truck fuel consumption variation with speed for TR=0%

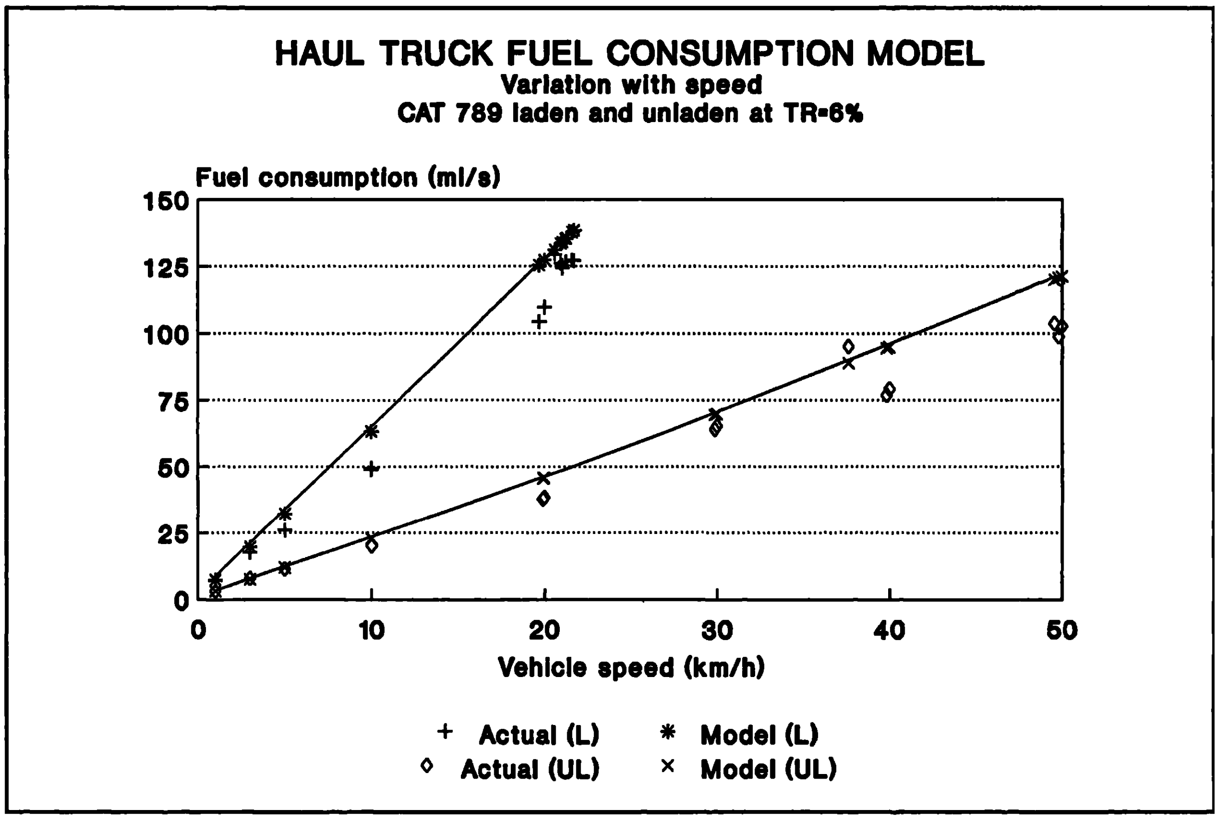


Figure 14.5 Haul truck fuel consumption variation with speed for TR=6%

same data is analysed in terms of consumption variation with total resistance as shown in Figure 14.7, it is seen that consumption remains approximately constant over the range of 0 to -9% (equivalent to 0 to -6% grade if an upper limit of 3% rolling resistance is assumed). From the summary of mine haul road geometric parameters presented in Appendix O it is seen that the majority of roads do not exceed a favourable grade of 2% whilst the much shorter ramp sections do not generally exceed 5%. It is thus feasible to adopt a model in which fuel consumption remains fixed irrespective of the favourable total resistance value. Although this will incur at worst a 20% over-estimation in fuel consumption at total favourable resistance values in excess of 10%, the limited incidence and length of these sections on mine haul roads validates the approximation.

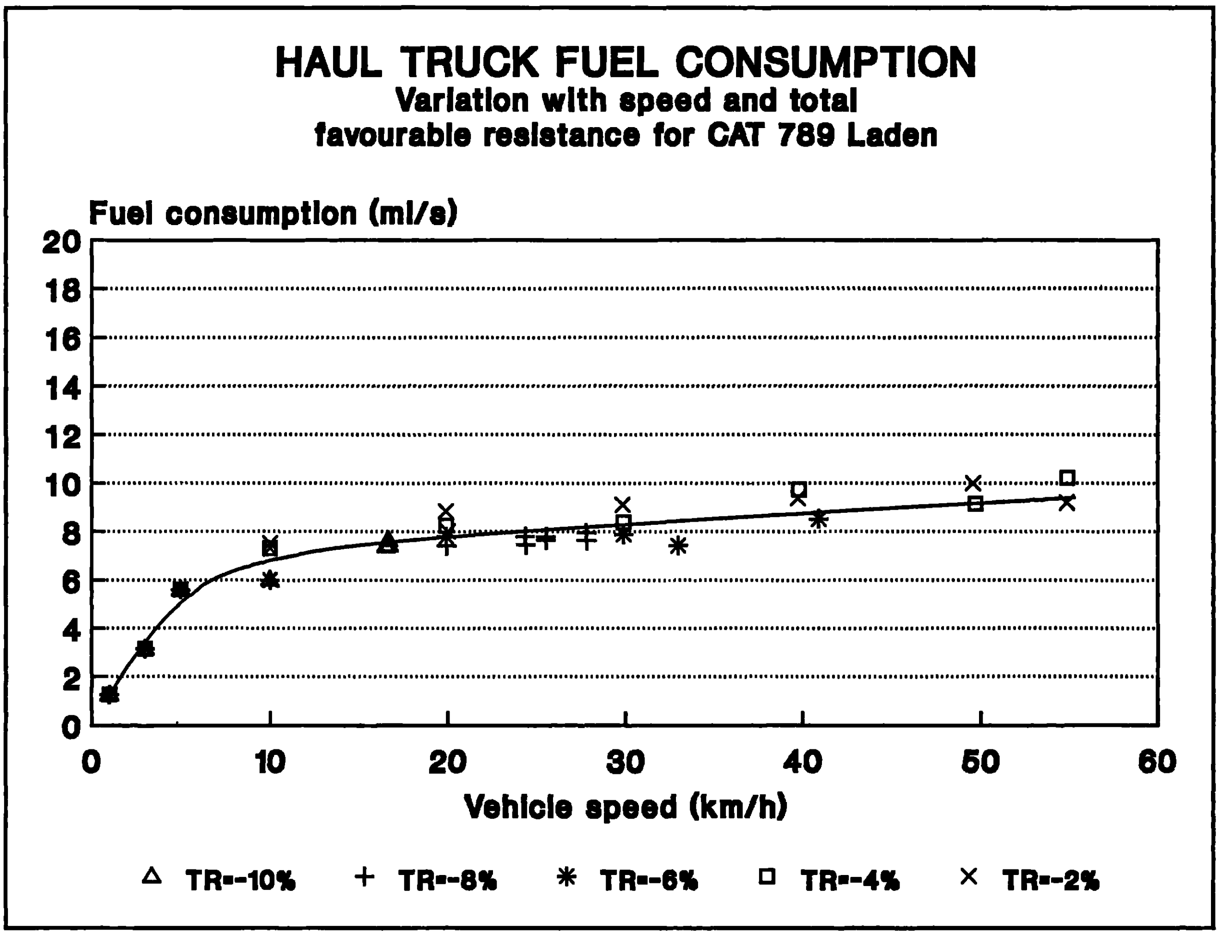


Figure 14.6 Haul truck fuel consumption variation with speed and favourable total resistance.

For sections of haul road in which a favourable total resistance exists (ie. GR+RR<0%), the associated fuel consumption (FCF) and vehicle speed will be limited by the retarder

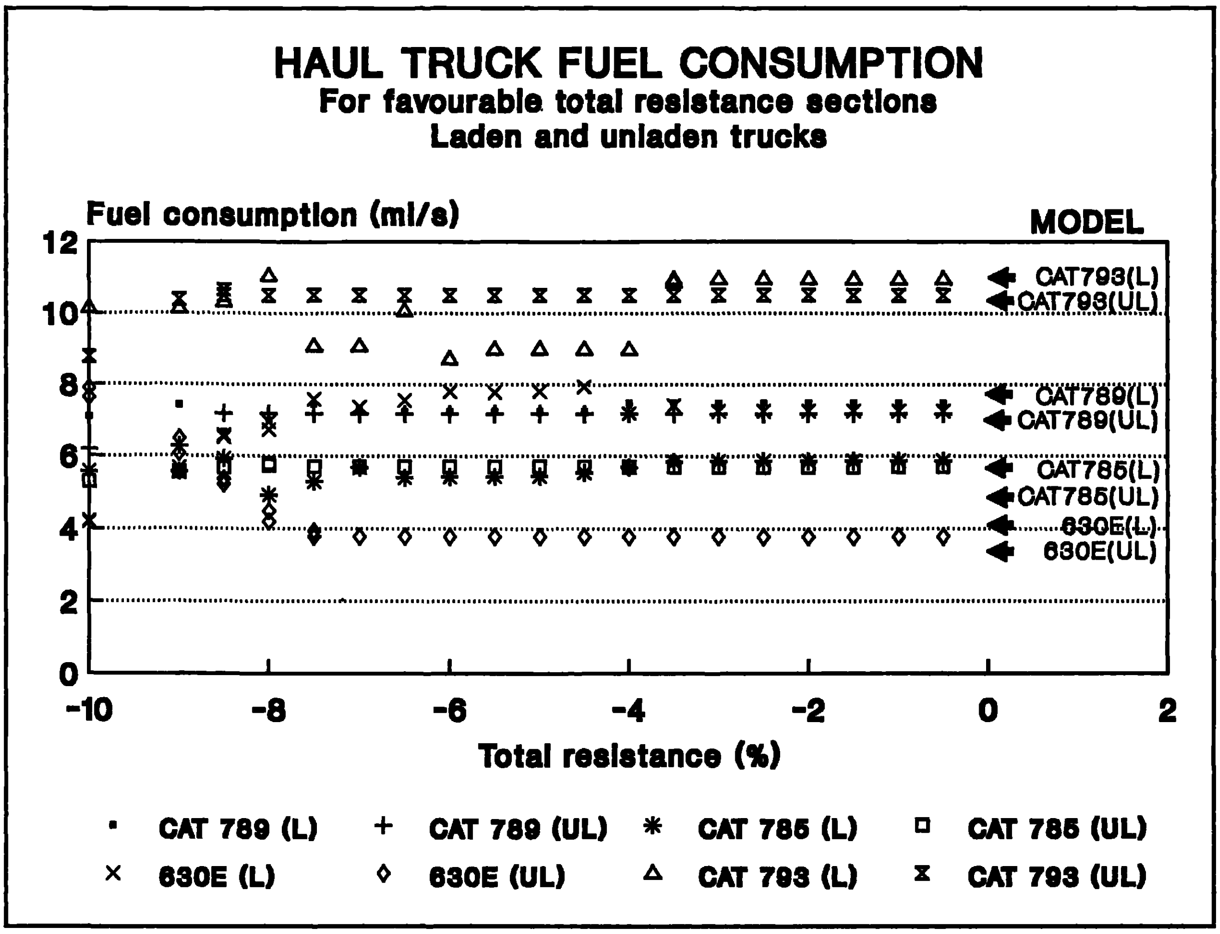


Figure 14.7 Haul truck simulation fleet fuel consumption variation with favourable total resistance.

performance and the effect of total resistance is largely obscured, whilst for sections of road where unfavourable total resistance exists, fuel consumption (FCU) increases with resistance and speed. Thus two models for fuel consumption are required to fully evaluate a particular haul.

The model derived for fuel consumption where total resistance is unfavourable is given below in Equation 14.9.

$$FCU = 1{,}02 + (UVM.V(296.TRU + 4{,}5.V) + L.GVM.V(246.TRU + 0{,}027.V^2)).10^{-5} \qquad 14.9$$

Where

FCU = Fuel consumption (ml/s) for unfavourable total resistance

GVM = Gross Vehicle Mass (t)

UVM = Unladen Vehicle Mass (t)

V = Speed of truck ($VUFL$ or $VUFUL$) (km/h)

TRU = Total resistance (unfavourable, $\geq 0\%$)

L = Truck loading

1 for laden trucks

0 for unladen trucks

The model has an R-squared value of 64%, a standard error of 39,2 and an F value of 295 which is significant at better than the 0,001% level for a sample size of 665. Full statistics are given in Table 14.2 from which it is seen that the both the intercept and vehicle mass/speed coefficients do not figure significantly in the model but are a requirement to simulate idling fuel consumption (at V=0) and fuel consumption when TRU=0. Typical model results are illustrated in Figures 14.4 and 14.5 for the Caterpillar 789 truck.

The model developed for fuel consumption on favourable total resistance sections is given in Equation 14.10.

$$FCF = -3{,}575 + UVM(0{,}092 - 0{,}016.DV) + 0{,}0017L.GVM \tag{14.10}$$

Where

FCF = Fuel consumption (ml/s) for favourable total resistance

DV = Drive type;

1 for electric drive

0 for mechanical drive

The model has an R-squared value of 81% and an F value of 394 which is significant at better than the 0,001% level for a sample size of 271. Full statistics are given in Table 14.2. The drive type indicator is included to accommodate the lower fuel consumption associated with unladen electric drive trucks. Fuel consumption model data points derived according to this model are shown superimposed on Figure 14.7.

Table 14.2 Statistics of Fuel Consumption Models.

STATISTICS OF MODEL ESTIMATION FOR FCU AND FCF								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
1 FCU	Intercept	2,32469	-0,82	0,4	-	-	-	-
	UVM.TRU.V	0,00017	16,54	0	9750	10532	0	44386
	L.GVM.V.TRU	0,00012	20,45	0	9207	14132	0	46553
	L.GVM.V^3	2,88E-7	0,94	0,34	2,16E6	6,8E6	0	5,5E7
	UVM.V^2	22,0E-6	2,02	0,04	70445	96550	95	457733
2 FCF	Intercept	0,38307	-9,33	0	-	-	-	-
	DR.UVM	0,00127	-12,59	0	28,3	49,3	0	114
	L.GVM	0,0004	4,18	0	-	-	-	-
	UVM	0,00324	28,4	0	-	-	-	-
INFERENCE SPACE LIMITS FOR INDEPENDENT VARIABLES USED IN MODEL (1) AND (2)								
TRU					5,13	3,46	0	10
UVM					118,7	19,36	95	144
V					23,29	17,15	2,0	58,47
GVM					281,96	54,92	213	362

14.2.4 Verification of Models

The models developed in the previous sections were combined to determine the fuel consumption over a particular mine haul road and then compared to actual fuel consumption from mine records. Limited data is available specifiying total fleet fuel costs or fuel consumption per operating hour which has to be split according to vehicle type and factorised according to operation efficiency (loader and tip delays, queing, etc.) which precludes meaningful comparison with such data. In the absence of operational data, a validation was carried out against the original simulation program, using data from Kromdraai Colliery with which to compare the results. Using the Kromdraai data, the typical fuel consumption of a laden and unladen truck over the route and back is determined. The model derived fuel consumption was based on the same route geometric parameters given in Appendix O and a section average rolling resistance value derived from the models presented in Chapter 13 in conjunction with wearing course material property data presented in Table 3.10. Two rolling resistance values were adopted representing maintenance intervals of 1 and 7 days.

Table 14.3 summarises the results of the validation exercise from which it is seen that the model derived fuel consumption is in broad agreement with the simulation consumptions. An indication of haul truck speeds are also given which, although no comparative mine data is available, appear realistic and compare well with simulation data. The model illustrates the typical increases in travel time and fuel consumption associated with small (2-3%) increases in rolling resistance associated with the particular haul road geometries, wearing course materials, haul truck and traffic volumes modelled. Fuel costs are seen to increase from R12,83/km to R13,13/km for the Kromdraai model, given a fuel price of R1,68 per litre. Although the model appears to overestimate fuel costs by 22% (using an average cost calculated from the 1- and 7-day models), this discrepancy can, in part, be ascribed to the equivocal assumptions necessary in determining the actual mine fuel cost figure.

14.3 Tyre Cost Model

Numerous tyre cost models exist from studies conducted in Brazil, India, the Caribbean and Kenya, as summarised by Chesher and Harrison (1987). Whilst these relate in part to heavy trucks, these are more typical of vehicles operated on public roads and as such are limited to a GVM of 11-50t and tyre sizes up to 1100x22. Tyre costs are related to tyre wear which involves both abrasive wear of the tyre tread and weakening of the tyre carcass. The option of retreading is not pursued in the case of large mine haul trucks due to the high operating temperature and stresses generated within the tyre. In general terms the cost of tyre wear can be stated as;

$$CTW = \frac{CN}{DISTOT} \tag{14.11}$$

Table 14.3 Results of Model Verification Exercise

Haul road section	1-day model				7-day model			
	Speed (km/h)		Fuel consumption per section (l)		Speed (km/h)		Fuel consumption per section (l)	
	Model	Simulation	Model	Simulation	Model	Simulation	Model	Simulation
KROMDRAAI HR1	27,8	32	43,0	39,0	27,4	31	43,7	40,2
Main (L)	46,8	46	4,4	6,8	46,1	46	4,8	7,5
Ramp-Tip (L)	10,9	8	5,8	3,8	10,8	8	6,0	3,8
Ramp-tip (UL)	20⁽¹⁾	19	0,2	0,4	20⁽¹⁾	19	0,2	0,4
Main (UL)	49,5	47	5,6	6,4	49,1	47	5,7	6,2
HR1 (UL)	55,4	53	9,1	15,2	55,3	53	9,3	15,3
TOTAL			68,1	71,6			69,7	73,4
FUEL COST (R/km)			12,83	13,49			13,13	13,83

NOTES
(1) Assumed speed limit on descent of ramp
L Laden truck
UL Unladen truck
Fuel Price = R1,68/litre

where

CTW = Cost of tyre wear (R/km)
CN = Cost of new tyre (R)
DISTOT = Total distance travelled (km)

In the analysis of tyre costs for large haul trucks a number of problems exist relating to the quality of available data. Since only four mine sites were available, any model of cost variation with road roughness or other geometric parameters will not be particularly robust. In the determination of average haul road roughness over the assessment period a two-fold approach was adopted in which the validity of using IRI roughness values from a single assessment of each road section (as described in Chapter 13.3) was tested against the range of IRI roughness values established from the road roughness progression models presented in Chapter 13.5 and the range of maintenance intervals recorded in Chapter 9 and Appendix F. Table 14.4 summarises the results of the assessment from which it seen that the IRI measurements derived from the single assessment generally fall within the range of expected values. It thus appears reasonable to use these values to generate an average IRI roughness for each mine haul road network, weighted according to individual section length and traffic over the analysis period.

The range of roughness defect scores encountered over the period of assessment for each mine site, as is reflected in Table 14.4, is not large. Whilst individual road sections do exhibit large individual ranges, it is not possible to ascribe a particular truck a specific route, hence the effects of roughness tend to be averaged out.

Other limitations exist with regard to damage attributable to loading or dumping areas as opposed to the road itself, Ingle (1991) reporting that up to 70% of tyre damage may occur in loading or dumping areas. This would obscure any road roughness effect on tyre costs. Limited information from Kriel Colliery on tyre consumption highlights this problem, revealing that 60% of the tyres consumed during the assessment period failed due to puncture, ply separation or side-wall damage. Of those tyres which were scrapped as a result of tread wear only, the tyre life varied between 4700 and 5200 hours, equivalent to approximately 37 600 and 41 600km. Other factors which preclude reliable analysis include

Table 14.4 Comparative Assessment of Mine Haul Road Section and Overall IRI

Mine haul road section	Modelled IRI(1) for minimum and maximum maintenance interval (m/km)			Measured IRI(2) (m/km)	Weighted IRI of mine road network(3) (m/km)
	Min	Max	Average		
KRIEL					5,21
MAIN (Site 3)	4,79	5,29	5,04	4,94	
MAIN (Site 2)	4,78	5,4	5,09	4,81	
RAMP 7				4,87	
RAMP 6	4,59	5,08	4,84	5,92	
RAMP 8/11				6,06	
KROMDRAAI					4,49
MAIN and TIP	4,65	5,37	5,01	4,8	
HR1	4,49	4,86	4,68	3,92	
HR2	4,91	5,24	5,08	4,91	
NEW VAAL					4,30
RAMP-TIP				4,09	
MAIN				4,43	
RAMP 0-2	5,14	6,39	5,77	5,33	
RAMP 2-3				4,89	
RAMP 3-4	4,88	5,63	5,25	5,13	
RAMP 4-6/7				4,63	
RAMP 6/7-9	4,98	5,28	5,13	4,73	
KLEINKOPJE					5,22
MAIN-TIP				7,17	
5W-MAIN	4,63	5,05	4,84	4,76	
R13/14-MAIN				5,71	
2A9-MAIN				4,24	
2A8-MAIN	4,58	5,0	4,79	4,76	
2A7-MAIN				4,81	
3A-TIP				4,96	

Notes

1. Following models presented in Chapter 13.5 and maintenance interval data in Appendix F.
2. Following data in Appendix K corresponding to the test sections modelled in (1) above.
3. Weighted according to section length and traffic volume (ramp sections included but not tabulated)

matching changeouts of tyres to provide a vehicle with a set of tyres of a similar condition, usually involving movement of these tyres between front and rear axles of different machines.

Similar data limitations are seen when haul route geometric parameters are considered. Both the Brazilian and Indian models for tyre costs included expressions for rise and fall and road curvature. Whilst averaging techniques could be applied to generate a typical haul truck route, it would be difficult to deduce any significant model effects for curvature due to the similar and limited geometry of the road studied.

In any MMS model it is the rate of increase of a particular cost item with increasing road roughness which is of major concern as opposed to a fixed cost, although the latter is important in assessing the relative contribution of that cost to total costs. Table 14.5 presents a summary of available tyre consumption data on the basis of cost per kilometre and consumption per 1000km. The cost per kilometre was calculated both from annual costs reported by the mine and from tyre unit costs and consumption data. For a 6-wheel rear dump truck using 3600R51 tyres, costs are seen to vary from R5,14 to R7,98/km and consumption from 0,11 to 0,12 tyres/1000km.

In the absence of suitable data, recourse is made to established models to provide a point of departure in estimating the influence of roughness and geometric parameters on tyre costs. Further research is necessary to assess the validity and transferability of the basic model presented here since only the underlying hypotheses of a roughness- and geometric-related tyre cost relationship can be intuitively deduced, the established model parameter ranges, vehicle types, GVM and tyre types bearing no resemblance to mine haul trucks.

The consumption data presented in Table 14.5 is plotted in Figure 14.8 which shows the tyre consumption/surface roughness relationships developed for commercial trucks from the Caribbean, Brazilian (medium truck only), Indian and Kenyan studies. Consumption at low IRI values appears comparable, despite significant vehicle differences. The model adopted for tyre consumption is expressed in Equation 14.12;

Table 14.5 Summary of Tyre Cost and Consumption Data

TYRE COST AND CONSUMPTION DATA SUMMARY
Based on 150-160t capacity rear-dump truck, 6 tyres per vehicle

	Kriel Mine		**Kromdraai Mine**		**Kleinkopje Mine**	
	Vehicle		**Vehicle**		**Vehicle**	
Tyre consumption (tyres/1000km)	R170 BD180⁽³⁾	0,113 0,462	630EH	0,121	CH130⁽⁴⁾	0,075
Tyre cost (R/km)⁽¹⁾	R170 BD180	6,77 11,69	630EH	5,14	CH130	4,04
Tyre cost (R/km)⁽²⁾	R170 BD180	7,45 13,86	630EH	7,98	CH130	3,37

Notes

1. Calculated from annual tyre costs
2. Calculated from consumption and tyre unit costs
3. Consumption and costs based on 10 3000R51 tyres per 180t capacity bottom dump truck
4. Consumption and costs based on 10 2700R49 tyres per 130t capacity bottom dump truck

$$TW = 0{,}06 + 0{,}012.IRI + 0{,}002\,|GR| \tag{14.12}$$

where

TW = Tyre wear (tyres consumed per 1000km)
IRI = Road roughness (m/km)
GR = Positive value of road grade (%)

The model predicts a 29% increase in tyre consumption for a 60% increase in road roughness from IRI=5m/km. This equates to an increase in cost of R2,38/km from a cost of R5,18/km at IRI=5, assuming a new tyre cost of R66 000. The effect of road geometry on tyre consumption is modelled as an increase in consumption with grade of road, a 1% change in grade resulting in a 1,6% increase in tyre consumption at IRI=5. No curvature effects were modelled since this effect is generally assumed to be insignificant for large trucks (Chesher and Harrison, 1987).

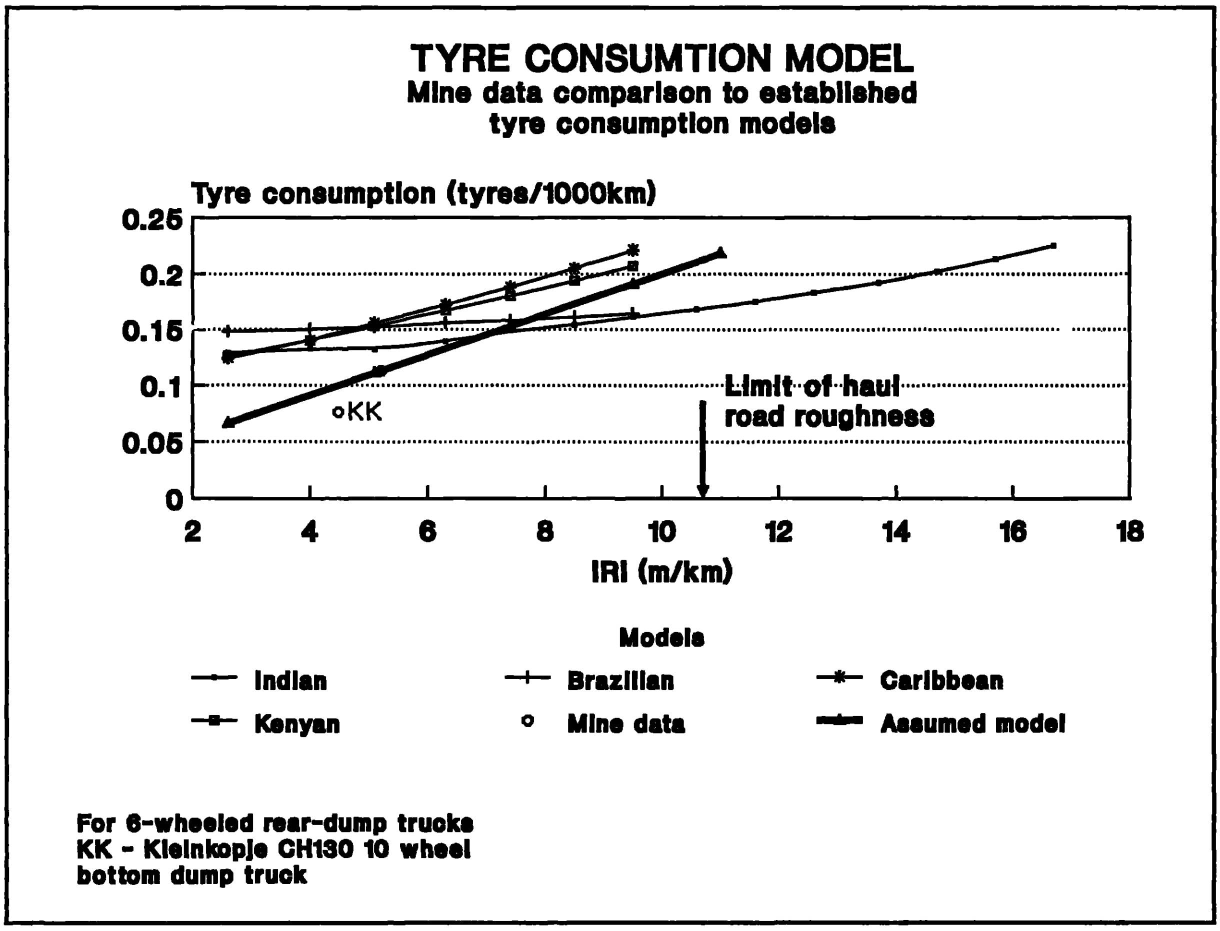


Figure 14.8 Assumed haul truck tyre consumption model in comparison to established models

14.4 Vehicle Maintenance Cost Models

Vehicle maintenance and repair costs comprise both the cost of the parts consumed and the labour hours expended on the repair and maintenance of the vehicle. These costs are related to the type of vehicle, its age, how the vehicle is used and route characteristics. This cost component of the total vehicle operating cost has been shown to be a significant contributor to the benefits from road improvements; up to 80% of the benefits in certain public road projects (International Study of Highway Development and Management Tools, 1995). For the case of haul trucks operating on mine roads similar effects can be hypothesised with reference to the stress sensitivity of large haul trucks as reported variously by Kondo (1984), Deslandes & Marshall (1986) and Taylor & Hurry (1987).

Similar data limitations exist with respect to individual mine parts and labour cost data as explained in Chapter 14.3 with additional complications of costs not being easily ascribed to a particular vehicle type where more than one vehicle type is used for coal hauling and the influence of high cost long-life replacement parts fitted during the period of assessment. The available data does not permit a reliable breakdown of costs on a per vehicle basis and parts consumption history is insufficient to derive suitable weighting coefficients for high cost long-life parts. The analysis, interpretation and transferability of any data generated will be dependant on individual mine maintenance strategies, speeds, loads, driver behaviour, the level of preventative maintenance and the history of the vehicle. It may be anticipated that across mine differences exist in policy and expenditure on maintenance which should ideally be addressed statistically when comparing results.

With these data limitations in mind, recourse was made to established models to provide a suitable point of departure in estimating suitable models for parts and labour costs. Limited data is available with which to corroborate such models but further research is necessary to verify the validity and transferability of the models proposed.

The general form for established models for parts and labour costs are given below in Equation 14.13;

$$\begin{aligned}\text{Parts cost} &= f(IRI,\ vehicle\ age)\\ \text{Labour cost} &= f(parts\ cost,\ IRI)\end{aligned} \tag{14.13}$$

where

Vehicle age = Total vehicle operating hours (h)
IRI = Road roughness (m/km)

The absence of geometric effects is partially explained by Chesher and Harrison (1987) with reference to the aforementioned user-cost studies for commercial heavy vehicles in which speed and load reduction effects were postulated as being the main reason why geometric effects were negligible and poorly determined in these models. In the case of mine haul trucks, load reduction effects are not applicable and the vehicle speed is generally a function of maximum vehicle power and retarder performance as opposed to any driver-applied limit. The majority of haul road networks incorporate unfavourable grade resistance on the laden-haul and, coupled with the greater exploitation of engine capacity on any section of haul irrespective of grade, these effects can be discounted. In addition, with reference to Appendix O it may be seen that the weighted (laden) haul grades are approximately similar for each mine, ranging form 1,1% to 1,91%. With regard to curvature, no effects are predicted for the same reasons as mentioned in Chapter 14.3.

14.4.1 Vehicle Parts Cost

The common practice of road user cost studies has been to express the parts consumption in terms of a standard parts cost. This represents the parts consumption as a fraction of the replacement price of the vehicle as given in Equation 14.14.

$$\text{Standardised parts cost} = \frac{P}{VP} \qquad (14.14)$$

where

P = Parts cost (R/1000km)
VP = Replacement price of vehicle ($Rx10^5$)

The general form of the models presented in the user-cost studies previously discussed incorporate a roughness and multiplicative age effect. A linear increase in standard parts cost for increasing roughness is predicted whilst the contribution of vehicle age to parts cost is predicted at a progressively reducing rate with age. The contribution of grade effects is assumed linear.

The available data from each mine was analysed on a fleet, as opposed to a vehicle basis and whilst the resultant model can be seen as applicable to both rear-and bottom-dump trucks, the limitations of this approach (especially with regard to the different vehicle designs and variations in vehicle drive systems) should be borne in mind. Table 14.6 summarises the available standardised cost parts data from each mine.

Table 14.6 Standardised Haul Truck Parts Costs

	Kriel Colliery	Kriel Colliery$^{(1)}$	Kromdraai Colliery	New Vaal Colliery	Kleinkopje Colliery
Fleet	R170 (5)$^{(E)}$ BD180 (3)$^{(TT)}$	R170 (5)$^{(E)}$	HD630EH (7)$^{(E)}$	R170 (6)$^{(E)}$ HD1600M (5)	CH120 (4)$^{(TT)}$ CH130 (5)$^{(TT)}$
Annual fleet t.km (single trip)	33 496 000	33 496 000	19 266 100	46 376 350	25 481 000
Annual fleet km	408 487	158 160	236 393	301 145	407 696
Annual fleet parts cost (R)	1 106 890	66 134	996 373	7 962 554$^{(1)}$	811 340
Average replacement vehicle cost (Rm)	1,7	1,7	1,83	1,9	2,4
Standardised parts cost	159	247	230	-	80
Average fleet age (hrs)	11 072	11 865	8 745	14 400	4 898

Notes

1.	Based on estimated parts cost for R170 fleet alone
TT	Truck-trailer combination, bottom dumper, mechanical drive
E	Electric drive
(1)	Tyre, parts and labour costs not specified separately

Considerable variation in the standardised parts cost is evident and when assessed in relation to average road roughness as given in Table 14.4, no trend is apparent over the small range of roughness representing each mine haul road. However, using this data as a rough guide, the model illustrated in Figure 14.9 and 14.10 was derived from the form of the established models described previously. The parts cost model is expressed as;

$$\frac{P}{VP} = (4+20.IRI).H^{0,375} \tag{14.15}$$

where

H = Vehicle age (total operating hours) ('1000hrs)

The model predicts a 57% increase in standardised parts cost for a 60% increase in road roughness from IRI=5, given a vehicle age of 5000 hours. If vehicle age is doubled, the standardised parts cost is seen to increase by 29% given a road roughness of IRI=5m/km. In terms of parts cost/km, these roughness and age increase effects represents a cost increase of R1/km from R3,23/km for a truck costing R1,7m. This compares to mine cost data which varies between R2,09 and R4,03/km.

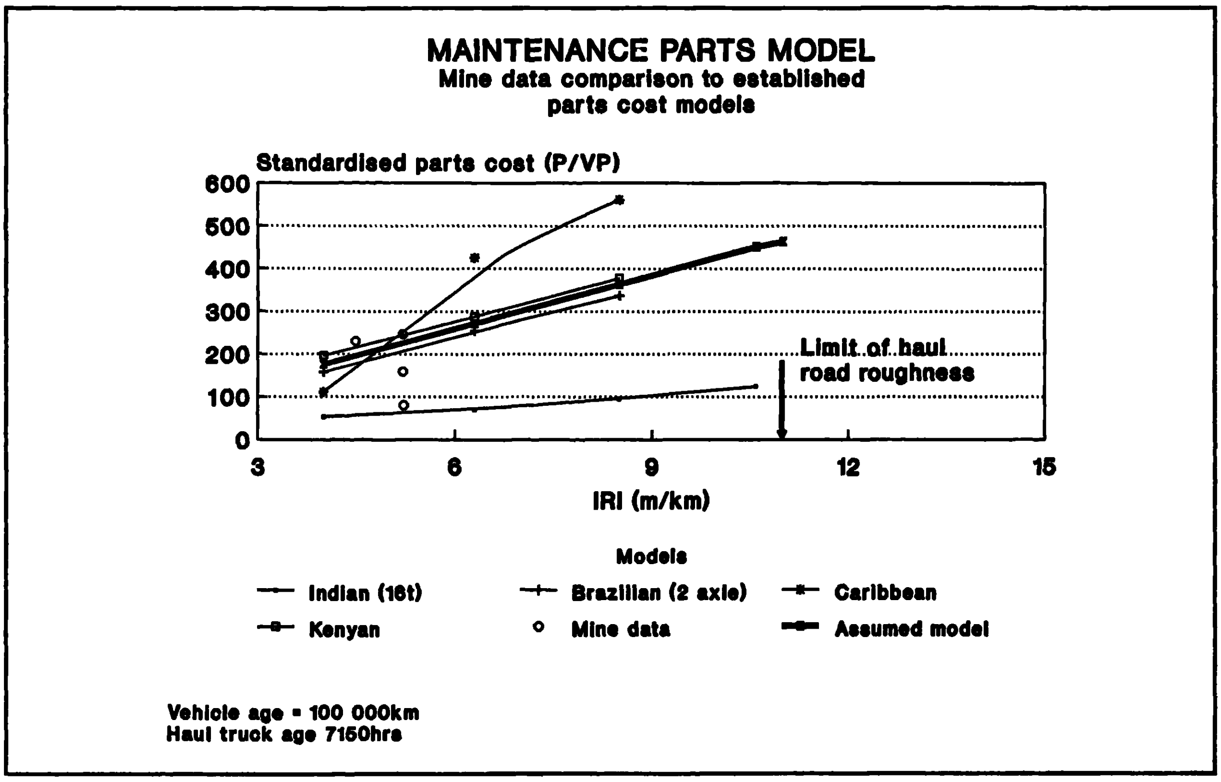


Figure 14.9 Proposed parts cost model for mine haul trucks showing effect of increasing road roughness

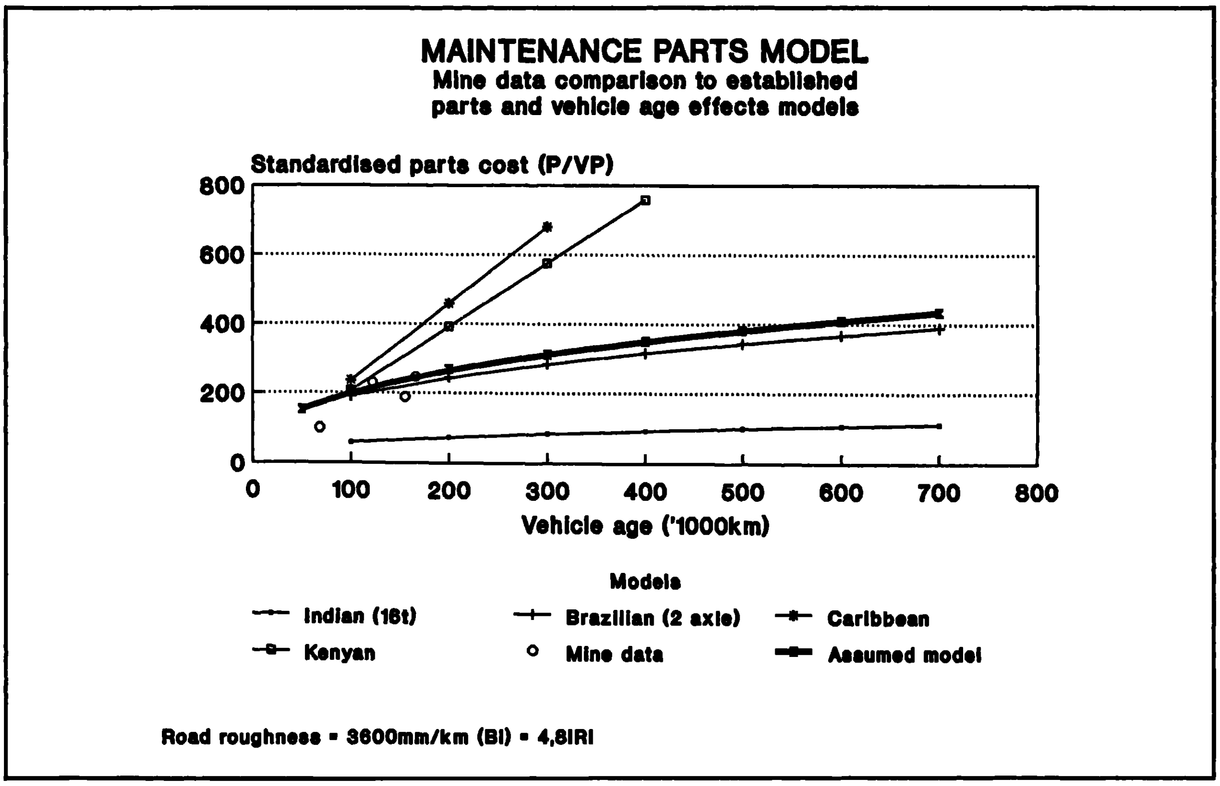


Figure 14.10 Haul truck age effects on parts cost

14.4.2 Vehicle Labour Costs

The approach advocated in the estimation of labour cost involves relating maintenance labour quantity per unit distance to parts consumption per unit distance and highway characteristics as discussed by Chesher and Harrison (1987) with reference to the Brazilian, Indian and Kenyan road-user cost studies. The Caribbean study reports in terms of labour costs and wage rates are not provided with which to compare this data to the other studies. Maintenance labour again proved to be a difficult item on which to obtain usable information as most mines carried out a combination of in-house and contractor repairs and no hourly record was kept of the former in the case of individual vehicles or vehicle types in a mixed fleet. Whilst the absence of an hourly labour rate limits the extent to which established models can be used directly (on a cost basis), a basic model can nevertheless be derived based on the hypothesised interaction of the dependant variables of standardised parts cost and road roughness as given in Equation 14.13.

The form of the models adopted in the Indian and Brazilian studies is given below in Equation 14.16.

$$L = a\left[\frac{P}{VP}\right]^{b} \tag{14.16}$$

where

L = Labour hours or cost per 1000km
a,b = Coefficients

The coefficient *b* is reported to be less than unity, varying from 0,47 to 0,65 for buses and trucks. Increases in parts costs are predicted to lead to an increase in labour costs but at a decreasing rate which may reflect the relatively capital intensive nature of major repairs on large haul trucks and their unitised construction. Engines, wheel motors, etc. are often removed as a complete unit to be repaired off-site by contractors, the only labour cost being recorded arising as a result of removal and replacement of items as opposed to their repair. The coefficient *a* is found to be affected by road roughness in some studies, both increasing the labour cost (with fixed parts cost), suggesting that maintenance activities for vehicles on rough roads are relatively more labour intensive, and decreasing the labour cost implying less labour at a given parts cost being applicable for rough roads. In each case only small and poorly determined effects were reported for commercial trucks. In the case of mine haul trucks, due to their unitised construction it may be anticipated that no additional road roughness effect will be present, other than that included in the standardised parts cost appearing as an explanatory variable.

In estimating the form of a model describing haul truck vehicle maintenance costs, limited data from the participating mines provides a starting point. Plotting labour cost (R/1000km) against standardised parts cost, as shown in Figure 14.11 reveals an approximate trend which is described in Equation 14.17.

$$L = 220\left[\frac{P}{VP}\right]^{0{,}45} \qquad (14.17)$$

where

L = Labour cost (R/1000km)

The model approximates the increasingly capital intensive nature of major repairs, albeit at a lower rate of increase than for the Brazilian and Indian models which are illustrated in Figure 14.11, an assumed hourly labour cost being applied only for comparison purposes. To ensure transferability of the model, a labour cost-increase factor should be applied based on the 1994-1995 average hourly labour rate incorporated in these figures.

14.5 Road Maintenance Cost Model

The road maintenance activities of blading and watering were introduced in Chapter 2 as they apply to mine haul roads. Since total costs incorporate both vehicle operating and road maintenance costs elements, as seen in Figure 2.2, it is evident that the minimisation of total costs must incorporate an estimate of road maintenance cost per kilometer. The road maintenance operating cost per kilometer comprises both grader and water car operating costs. Although not contributing directly to a reduction in road roughness, the incorporation

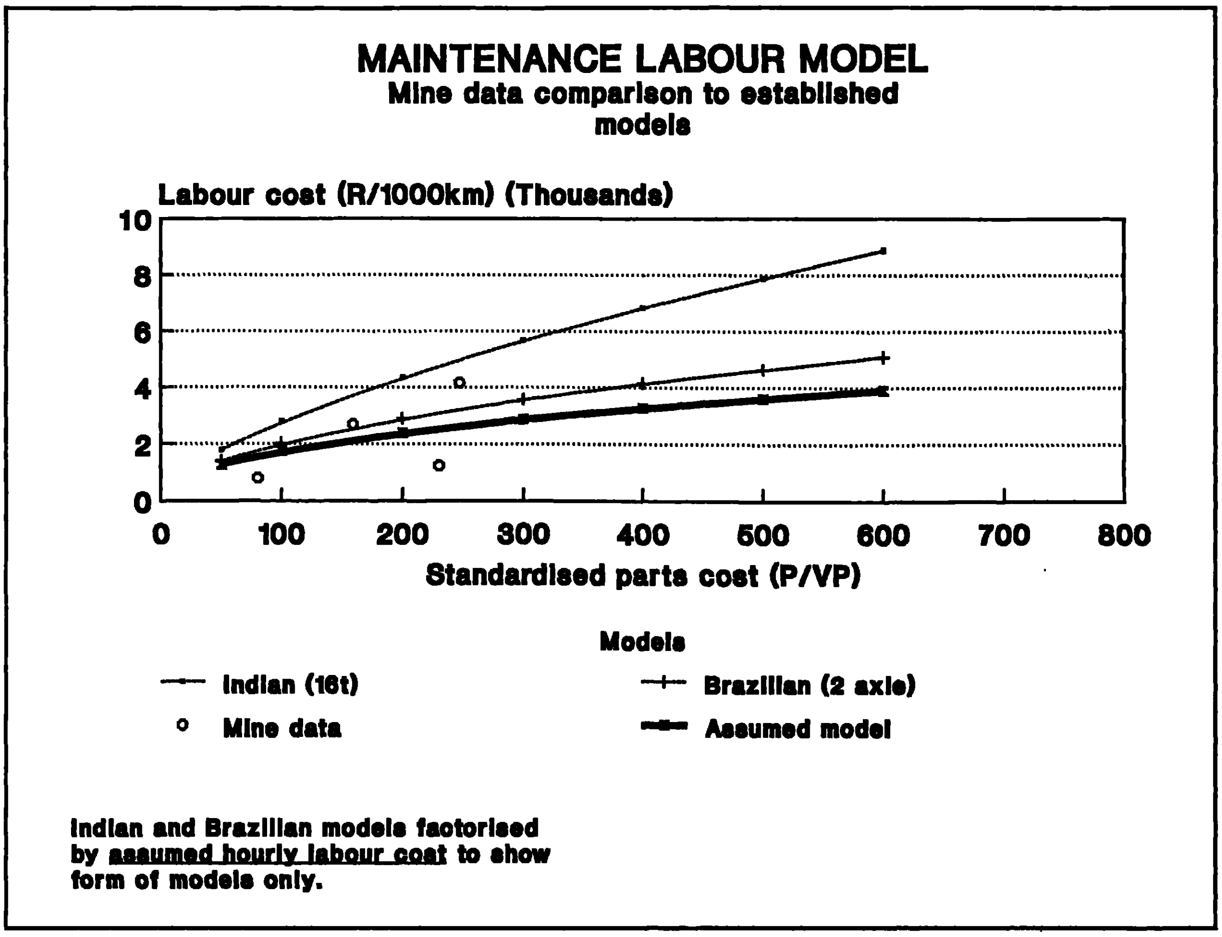


Figure 14.11 Proposed labour cost model variation with standardised parts cost

of the watering costs in the maintenance costs model is intended to reflect (ideal) operating practice in which, immediately after blading, the section of road is watered to reduce dust, erosion and aid recompaction.

Table 14.7 summarises the road maintenance fleet productivities and costs for the 1994/1995 financial year for three participating mines. From observation and discussion with operating personnel at each mine, grader and water-car productivity was theoretically calculated based on a road width of 24m, a blade or spray pass-width of 3 and 12m, maximum vehicle speeds during operation and annual vehicle operating hours. This gave a productivity of 0,75 and 6,25km maintained road per operating hour for each machine respectively. The total number of kilometer-passes per day varied between 23 and 56 depending on the daily operating hours of each grader. Whilst no productivity standards have been published with regard to mine haul road maintenance, a figure of between 8-18km of maintained road per 16 hour day is quoted by mine personnel which is in broad agreement with the theoretically calculated

Table 14.7 Summary of Road Maintenance Costs and Productivities

SUMMARY OF ROAD MAINTENANCE FLEET COSTS AND PRODUCTIVITIES						
	KRIEL		**KROMDRAAI**		**KLEINKOPJE**	
	GRADER	**WATERCAR**	**GRADER**	**WATERCAR**	**GRADER**	**WATERCAR**
Make	CAT 14G	EUCLID W50	CAT 14G	HD465/325	CAT 14G	HD465
Number in use	2	1	3	2	3	2
Annual operating hours (hrs)	5290	2838	6900	3649	3273	3616
Annual operating cost (R)	351520,50	221874,84	428256,00	434362,00	224102,31	269319,68
Operating cost per hour (R)	66,45	78,18	62,07	119,04	68,47	74,48
Production (ROM ton.km/day) (single trip)	119291	119291	68611	68611	90744	90744
Daily cost (R/t.km)	2,95	1,86	6,24	6,33	2,47	2,97
Daily t.km per machine	59645,50	119291,00	22870,33	34304,35	30248,00	45372,00
Road width (m)	24	24	24	24	24	24
Blade or spray width per pass (m)	3	12	3	12	3	12
Time to complete single pass (min)	10,0	4,8	10,0	4,8	10,0	4,8
Productivity (km/op.h)	0,75	6,25	0,75	6,25	0,75	6.25
Productivity (km passes/day)	56,52	126,34	49,15	81,22	23,31	80,48
Annual kilometers	3968	17738	5175	22806	2455	22600
Operating cost of machine (R/km)	88,60	12,51	82,75	19,05	91,29	11,92
TOTAL ROAD MAINTENANCE COST (R/km)	**101,11**		**101,08**		**103,21**	

productivity of 0,75km/hr.

The assumption of a single blade-pass was adopted in this analysis on the basis of observation. However, with reference to the roughness defect descriptions of degree and extent (Tables 13.1 and 13.2) most operators envisaged an increase in the number of blade-passes required to achieve an acceptable finish when the roughness defect score exceeded degree 3 and extent 3. A productivity curve is thus proposed, incorporating this reduction in grader productivity associated with excessively rough roads as shown in Figure 14.12. A similar approach is adopted by Visser (1981) in which road grader productivity is reduced with increasing road roughness.

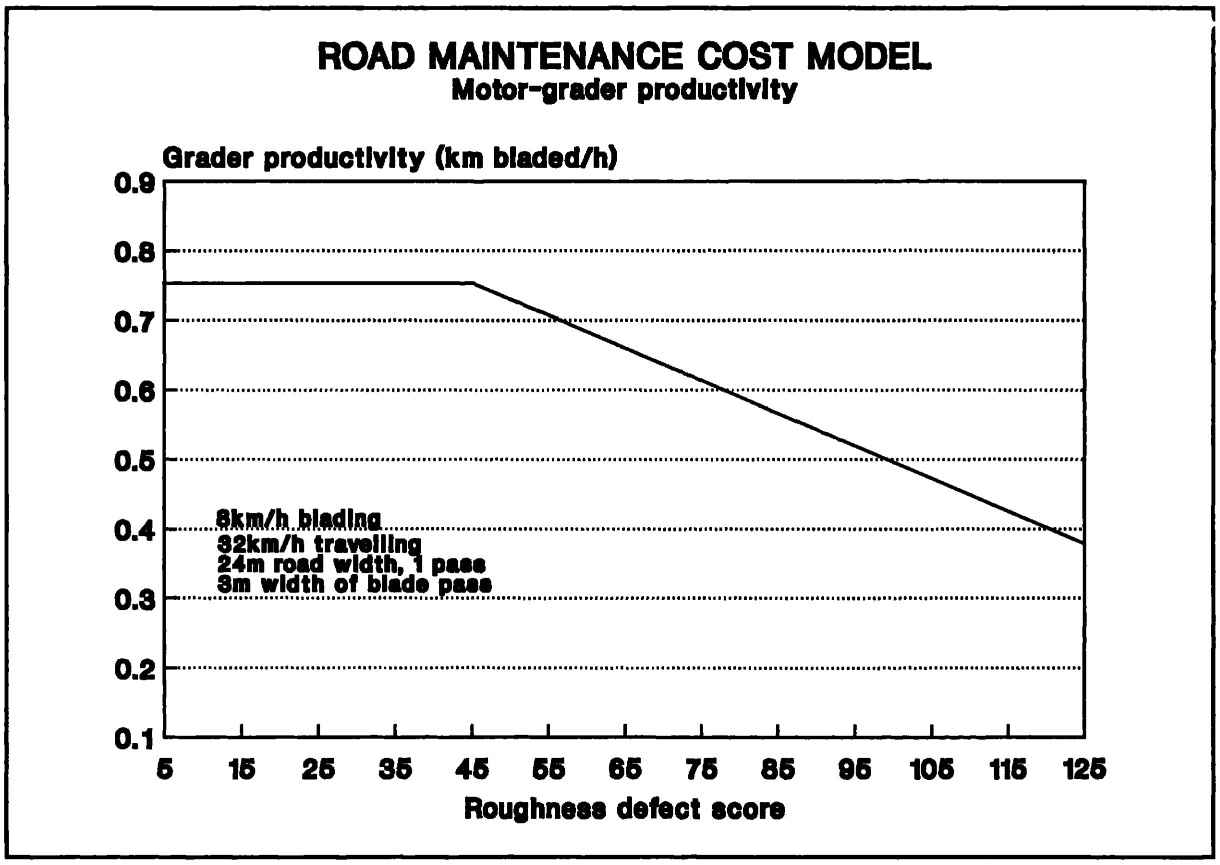


Figure 14.12 Productivity of a motor-grader during routine haul road maintenance operations.

The hourly operating cost for both grader and water car appear similar except for Kromdraai Mine where a smaller (32,5t) water car is used along with a 46,5t, the latter being more typical of the other mines. The fleet size recommendation (Long, 1968) of 1 grader per

45 000 daily ton-kilometer of production cannot be confirmed from this data although it would appear (from a road maintenance point of view) that the Kriel Colliery grader fleet is too small for the daily ton-kilometres produced whilst that of Kromdraai too large. The fleet size recommendations can be more reliably determined from a MMS solution incorporating specific material roughness defect progression models and traffic volumes as described in the following chapter. Nevertheless, the total road maintenance costs appear very similar, ranging from R101,08 to R103,21 per kilometre road maintained. For the purposes of the MMS model, these figures are user-defined, allowing escalation of the maintenance costs if necessary.

The road maintenance cost model is thus constructed from consideration of the average blade width per pass, road width, roughness defect score before blading, motor-grader productivity curve and cost per hour from which the motor-grader cost per kilometre is found. This cost is then combined with the cost per kilometre of the water-car and workshop costs to produce a total cost per kilometre for road maintenance.

14.6 Summary and Conclusions

The development of a mine haul truck vehicle operating cost model comprising the components of fuel, tyre, maintenance parts and maintenance labour was addressed in this chapter, together with a model of road maintenance activities in terms of the cost per kilometre for grader and water car. The combination of the road maintenance and vehicle operating cost models enables the optimal maintenance strategy to be sought based on the minimisation of these costs over a particular haul route.

The fuel consumption model development was based on a haul truck simulation package in which engine torque/fuel consumption maps were used in conjunction with vehicle speed/rimpull and retarder force/speed/distance maps to simulate the operation of a truck over a defined course. A number of rear dump trucks were chosen for simulation, representing typical vehicles operated or likely to be operated by strip coal mines. The similarity in speed versus total resistance performance of these trucks prompted the development of four universal equations by means of which vehicle speed could be predicted for any combination of total resistance and truck loading.

The constant speed fuel consumption model was used as an explanatory variable in the fuel consumption model in which equations were developed for the fuel consumed by trucks on both favourable and unfavourable total resistance segments of a haul route. Fuel consumption was seen to vary with vehicle speed, laden and unladen mass and total resistance for unfavourable resistance sections. For favourable resistance sections, fuel consumption was seen to be approximately constant for a particular truck type between 0 and -9% resistance, the maximum downhill speed of the vehicles being approximately similar and controlled by retarder performance. The fuel consumption model developed thus incorporated only vehicle loading and drive as explanatory variables. The verification of the models to actual mine data proved problematic since no fuel consumption test data was found with which to validate the models. An approximate fuel consumption figure was deduced from mine operating records and vehicle annual ton-kilometres which exhibited broad agreement with the model when applied over a similar haul route. It is recommended however, that on-site fuel consumption tests be conducted with which to rigorously verify the fuel consumption models adopted.

With regard to the tyre, vehicle maintenance parts and maintenance labour models developed, similar data limitations were seen which precluded the development of statistically robust models. The approach advocated involved the analysis of existing models developed for commercial trucks used on public roads. Although the parameter ranges bore little resemblance to those of mine haul trucks, when coupled with a hypothesis of the influence road roughness and geometry on these cost components, a basic model was developed in each case. These models were then compared with the limited mine data available to verify the order of magnitude of the costs modelled and to indicate the likely rate of change of these costs with road roughness. The latter proved particularly problematic due to data characteristic limitations and it is recommended that further research be conducted to assess the validity and transferability of the basic models proposed.

CHAPTER 15

A MAINTENANCE MANAGEMENT SYSTEM PROGRAM FOR MINE HAUL ROADS

15.1 Introduction

The interaction and influences of the various models proposed to represent vehicle operating costs (VOC), road maintenance costs and the progression of road roughness as developed in Chapters 13 and 14 can only be effectively analysed using a systems analysis approach. The conceptual outline of a maintenance management systems (MMS) model was discussed in Chapter 3 and illustrated in Figure 3.12 and this is used as a basis for developing an appropriate model for mine haul roads. Details of program input parameters are given prior to a discussion of the computational phase and an analysis of sample output reports. These reports are evaluated in the light of both established maintenance activities on participating mines and the sensitivity of results to variations in key input parameters.

15.2 The MMS Model

The objective of producing a MMS model for a mine haul road network was to evaluate alternative maintenance strategies within a system of constraints related to total cost and maintenance quantities such that the optimal maintenance policy for the network, commensurate with lowest total costs, could be identified. The basis of the evaluation were road user costs, consisting of haul truck fuel, tyre, parts and labour costs together with road maintenance costs for both the road grader and water-car. Road construction and vehicle depreciation costs were not considered since these will be the same irrespective of the maintenance strategy evaluated.

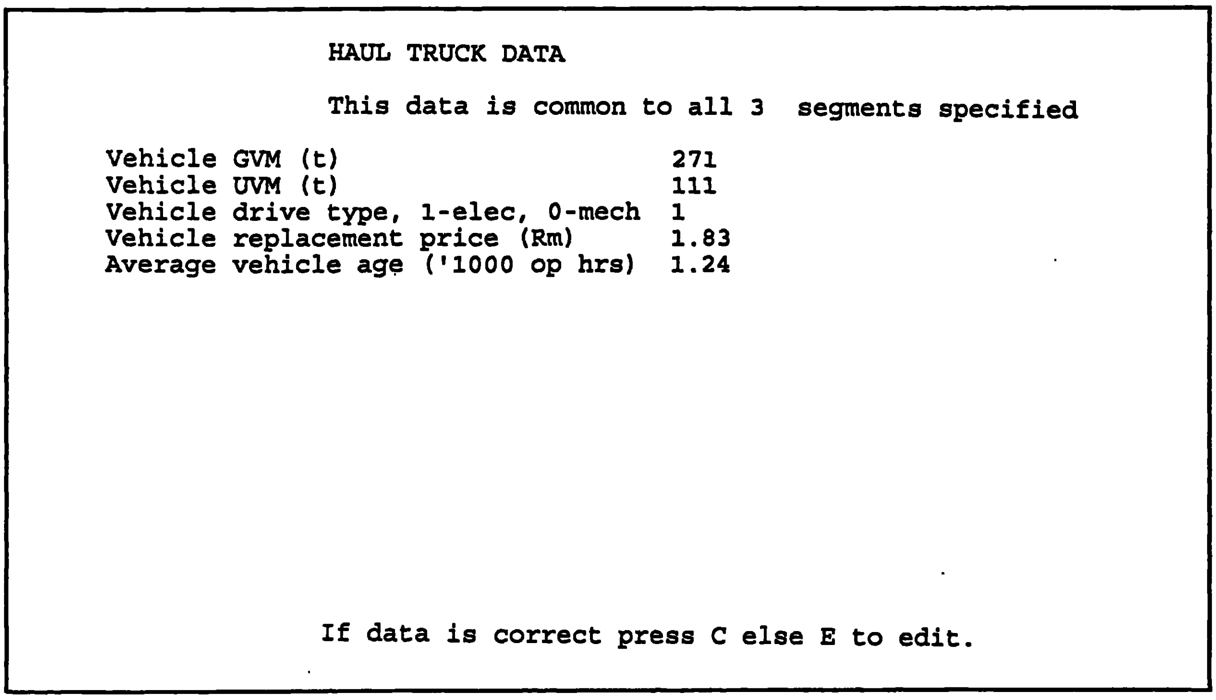
A complete listing of the program is given in Appendix P based on the flow-chart presented in Figure 3.12, repeated for each maintenance strategy evaluated. The program is written in QBasic version 4.5 in a modular self documenting format, readily allowing the modification of the various sub-programs representing each model previously developed. A basic error handler is incorporated to trap common data errors. The program may be split into four operations concerning data input, calculation of the various cost components of total road-user cost, selection of the optimum maintenance strategy and the reporting of the results.

15.2.1 MMS Model Data Input

The input phase of the program is divided into six active input screens, the first being a general introduction to the MMS methodology, specifying program objectives and general data requirements. The following data input screens are given in Tables 15.1 to 15.5 as an aid to clarifying the scope of the MMS program for mine haul roads. The mine haul road network is divided into a number of specific road links corresponding to changes in haul road geometry, wearing course materials or the daily tonnage a particular section carries. The screen shown in Table 15.1 allows the user to specify data relating to the type of haul truck operated common to each segment specified. On completion of data input the option is provided to edit the data if necessary. As discussed in Chapter 14 only rear dump trucks are accommodated in the program. Table 15.2 contains details pertaining to the road maintenance fleet, specifically the number, daily operating hours and hourly operating costs of the road grader and water-car.

The haul road is sub-divided into a number of segments as described previously. Each such link as determined by the user is assigned a segment number and the required segment data, in terms of geometry, tonnage and wearing course material properties is specified as shown in Table 15.3. The input data shown in Table 15.4 is designed to permit unit cost factors to be included in the calculation of costs. An escalation factor for (workshop) labour costs is included since the labour cost model developed in Chapter 14 is based on a per kilometre cost as opposed to labour hours cost thus any escalation in labour rates should be reflected in the labour cost model. Unit prices can also be specified for diesel fuel and haul truck tyres. The VOC component models for tyre, parts and labour can be modified by the user by altering the coefficients of any model. This input is not compulsory and the program would adopt the default values if no changes are made.

Table 15.1 MMS Program Input - Haul Truck Data



```
                    HAUL TRUCK DATA

                    This data is common to all 3  segments specified

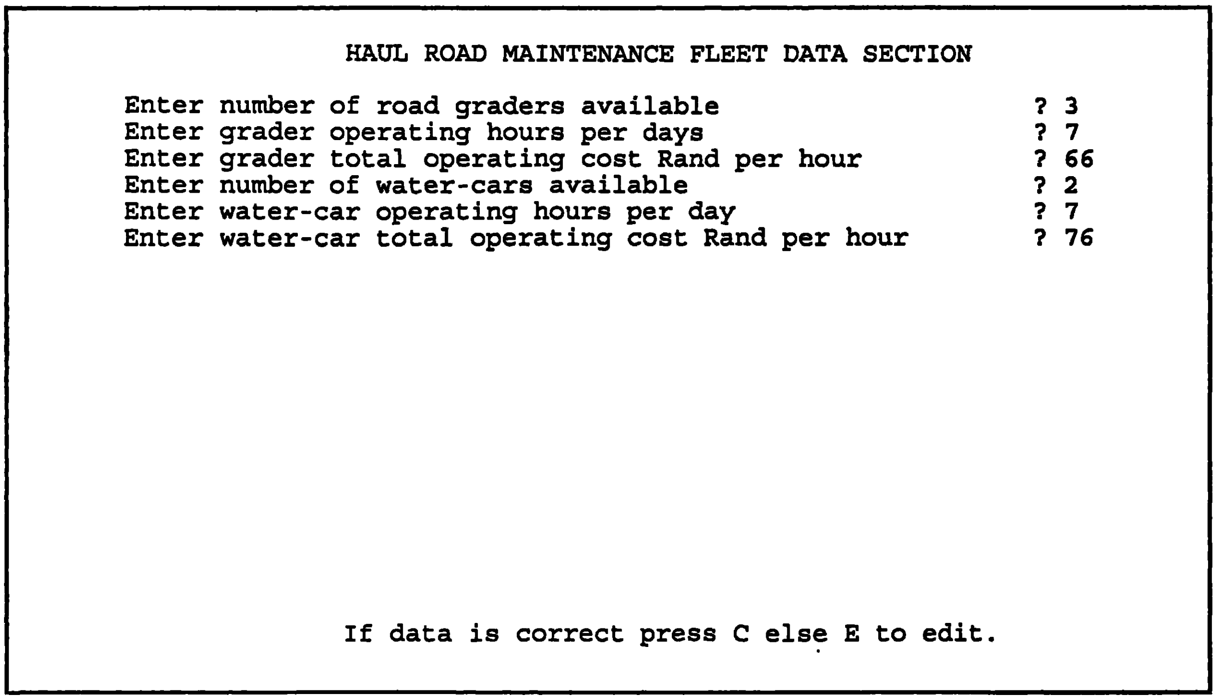
      Vehicle GVM (t)                        271
      Vehicle UVM (t)                        111
      Vehicle drive type, 1-elec, 0-mech     1
      Vehicle replacement price (Rm)         1.83
      Average vehicle age ('1000 op hrs)     1.24






                    If data is correct press C else E to edit.
```

Table 15.2 MMS Program Input - Haul Road Maintenance Fleet



```
                    HAUL ROAD MAINTENANCE FLEET DATA SECTION

       Enter number of road graders available                ? 3
       Enter grader operating hours per days                 ? 7
       Enter grader total operating cost Rand per hour       ? 66
       Enter number of water-cars available                  ? 2
       Enter water-car operating hours per day               ? 7
       Enter water-car total operating cost Rand per hour    ? 76






                    If data is correct press C else E to edit.
```

Table 15.3 MMS Program Input - Haul Road Segments

```
Please input values at prompt for each segment specified previously

                  SEGMENT              1       2        3
Segment name                          HR1     HR2      HR3
Length of segment (km)                0.94    3.24     4.53
Width of road (m)                     24      24       26
Grade of road (%) (uphill positive) -1.7    0.99     0.55
Average segment speed (20-50kph)      40      40       45
Daily tonnage hauled (kt)             15      7.7      7.3

Material properties of section
Material type, 1-mixes, 0-fericrete  0       0        0
California Bearing Ratio (%) CBR      46      50       162
Shrinkage product (SP)                198     196      82
Grading coefficient (GC)              36.3    21.3     30.1
Dust ratio (DR)                       0.6     0.6      0.4
Plasticity index (PI)                 10      8        4



             If data is correct press C else E to edit.
```

Table 15.4 MMS Program Input - Unit Cost Factors

```
UNIT COST FACTORS

Parts and labour costs are based on 1995 prices
Please specify escalation factor? 1

Fuel cost is based on a current diesel price
Please specify diesel price Rand per litre? 1.68

Tyre cost is based on current tyre price
Please specify tyre price (R)? 65000

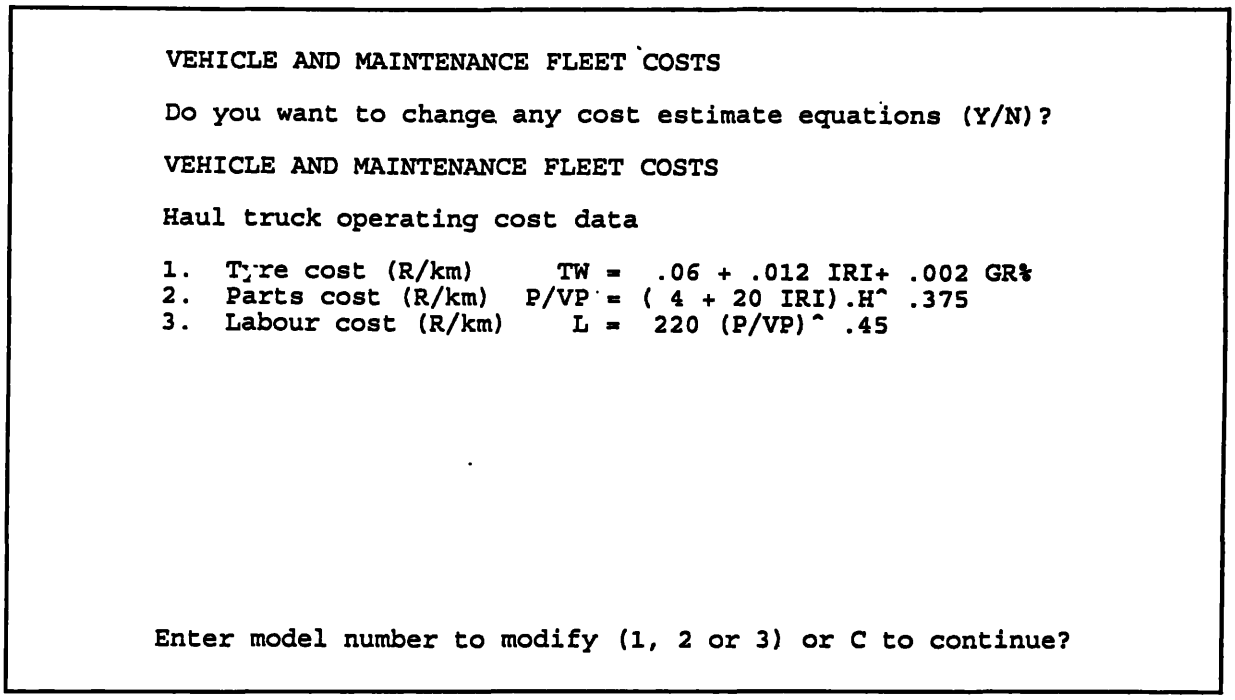






If data is correct press C else E to edit.
```

Table 15.5 MMS Program Input - Haul Truck VOC Model Data



```
VEHICLE AND MAINTENANCE FLEET COSTS

Do you want to change any cost estimate equations (Y/N)?

VEHICLE AND MAINTENANCE FLEET COSTS

Haul truck operating cost data

1.  Tyre cost (R/km)      TW =  .06 + .012 IRI+ .002 GR%
2.  Parts cost (R/km)   P/VP =  ( 4 + 20 IRI).H^ .375
3.  Labour cost (R/km)     L =  220 (P/VP)^ .45




Enter model number to modify (1, 2 or 3) or C to continue?
```

However, as discussed in Chapter 14, characteristic data limitations prevent the development of robust statistical models for these cost components and as such an improved model may be substituted by the user.

15.2.2 Calculation of Total Road-User Costs

In the case of mine haul roads, road-user costs encompass both vehicle operating and road maintenance costs since the agency controlling the haul road network is also affected by user operating costs. A number of sub-programs evaluate the various models which combine to form the total costs for each maintenance strategy evaluated. Initially, a roughness defect score is calculated for a range of maintenance strategies from daily grading (ie. maintenance interval=0 days) to a 20 day grading interval using Equations [13.9], [13.10] and [13.11] for each segment of the network. The roughness defect score is then translated by means of Equations [13.3] and [13.4] into an equivalent rolling resistance. Since it was shown in Chapter 13 that rolling resistance was dependant on vehicle speed and vehicle speed itself is a function of rolling resistance, an initial estimate of vehicle speed over the section is requested from the user (Table 15.3). This estimate of segment speed is associated with a maximum error of 4% over a speed range of 20km/h at roughness defect scores above 30. Actual vehicle speed is then calculated according to Equations [14.5], [14.6], [14.7] and [14.8] depending on the particular segment total resistance and loading of the truck. The calculation of fuel consumption then follows from Equations [14.9] and [14.10]. The cost of fuel consumption is then found for the particular segment at a particular maintenance interval from consideration of tonnage hauled and total laden and unladen distances travelled over the segment.

The VOC components are calculated according to the models presented in Equations [14.12], [14.15] and [14.17] for tyre, parts and labour cost respectively. Costs are calculated for each maintenance interval from consideration of traffic volume (tonnage hauled) and total laden and unladen distances travelled over the segment. Total VOCs are then found from the sum of each of the fuel, tyre, parts and labour costs for each segment as illustrated in Figure 15.1.

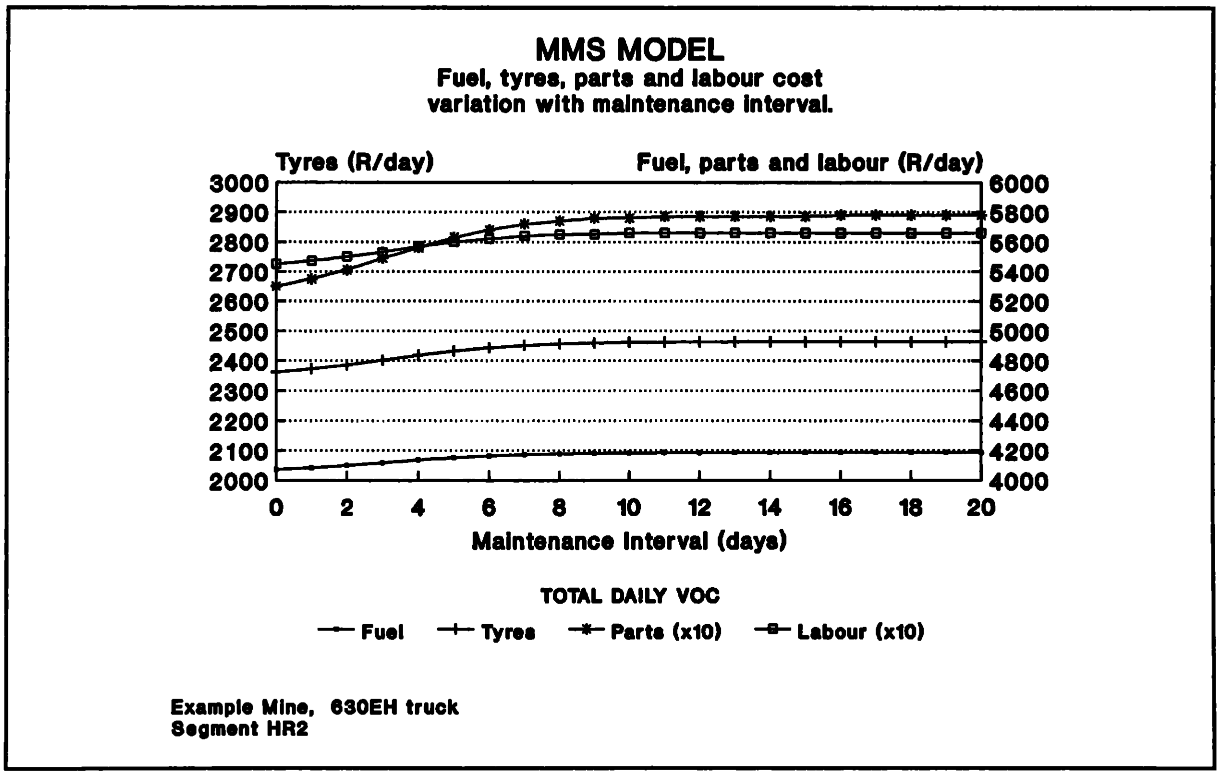


Figure 15.1 Segment VOC Component Variation with Maintenance Interval

The variation in VOC for one particular segment simulation are shown in Figure 15.1. Costs are seen to increase with increasing road roughness arising from the increasing maintenance interval. As predicted by the roughness progression model, the rate of increase reduces with increasing maintenance intervals as the roughness experienced by the vehicle approaches a constant value. The corresponding component costs are summed to give total VOC for each segment under each maintenance interval.

The cost of haul road maintenance is calculated from consideration of the productivity data presented in Chapter 14.5 together with the productivity curve for motor graders presented in Figure 14.12. The daily cost of maintenance is then calculated according to specified hourly operating costs, segment length and width and the roughness defect score relating to the particular maintenance interval. The maintenance cost refers solely to that associated with the particular segment maintenance interval and does not include the cost of additional maintenance activities arising from rain, spillage, spot repairs, etc. Figure 15.2 illustrates the road maintenance cost and total VOC variation with maintenance interval and the resultant total cost profile for one particular segment of network.

15.2.3 Selection of Optimal Maintenance Strategy and Reporting

Each segment comprising the haul road network will have a unique minimum total cost solution dependant on section geometry, traffic volume and wearing course material properties. This is illustrated in Figure 15.3 for a particular network from which it is seen that segment HR1 costs are minimum for a daily maintenance regime, segment HR2 minimum for an interval of two days between maintenance and segment HR3 for an interval of 1 day. Whilst these may represent the optimum maintenance strategy from a minimum total cost point of view, no maintenance equipment fleet productivity constraints have been considered. When maintenance fleet equipment numbers and operating hours are considered, the cost-based optimal strategy may not be attainable with the specified maintenance fleet.

The optimal cost based solution is assessed in terms of required operating hours per day which is dependant on the associated optimal maintenance interval. If available water-car

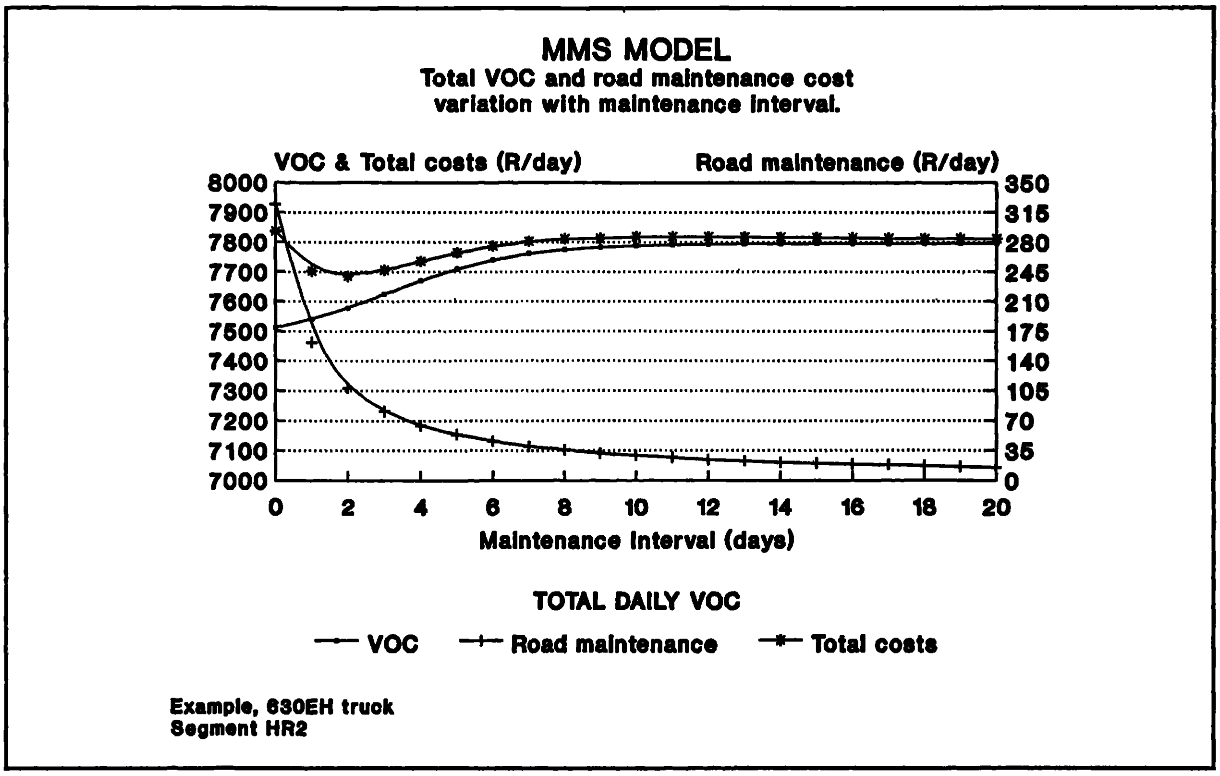


Figure 15.2 Total VOC and Road Maintenance Segment Cost Variation with Maintenance Interval

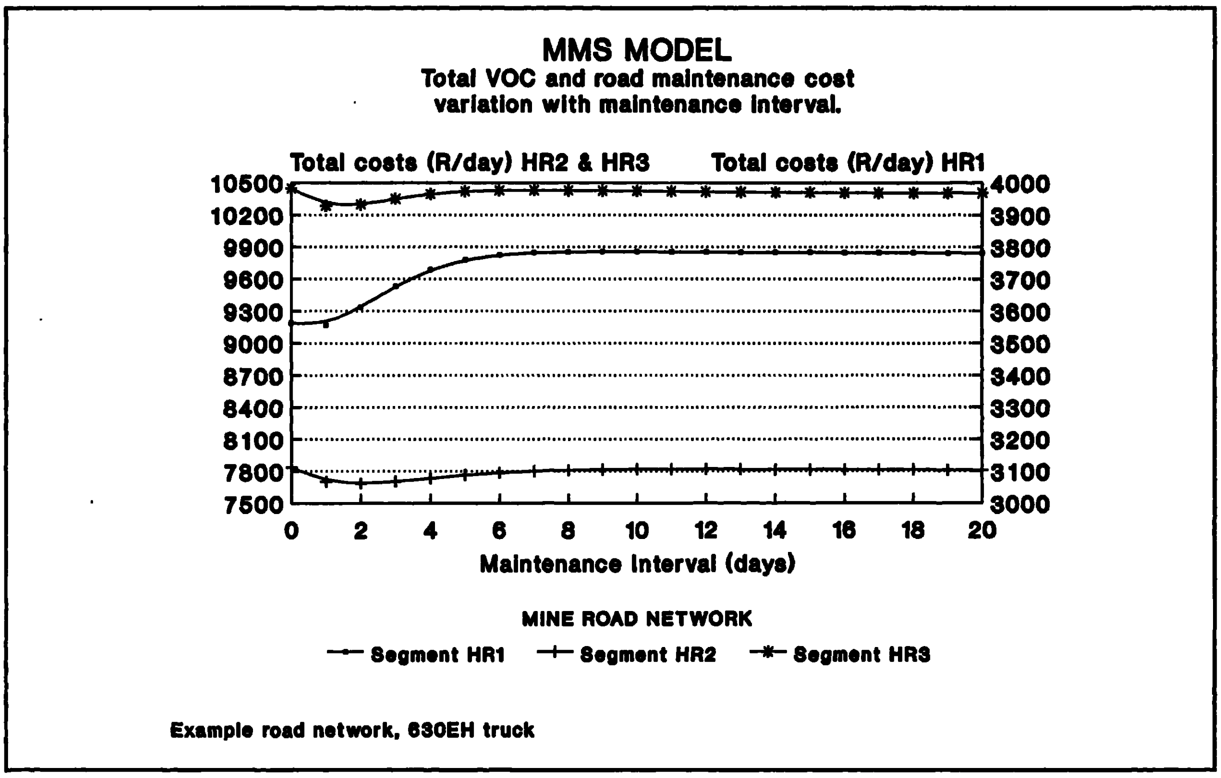
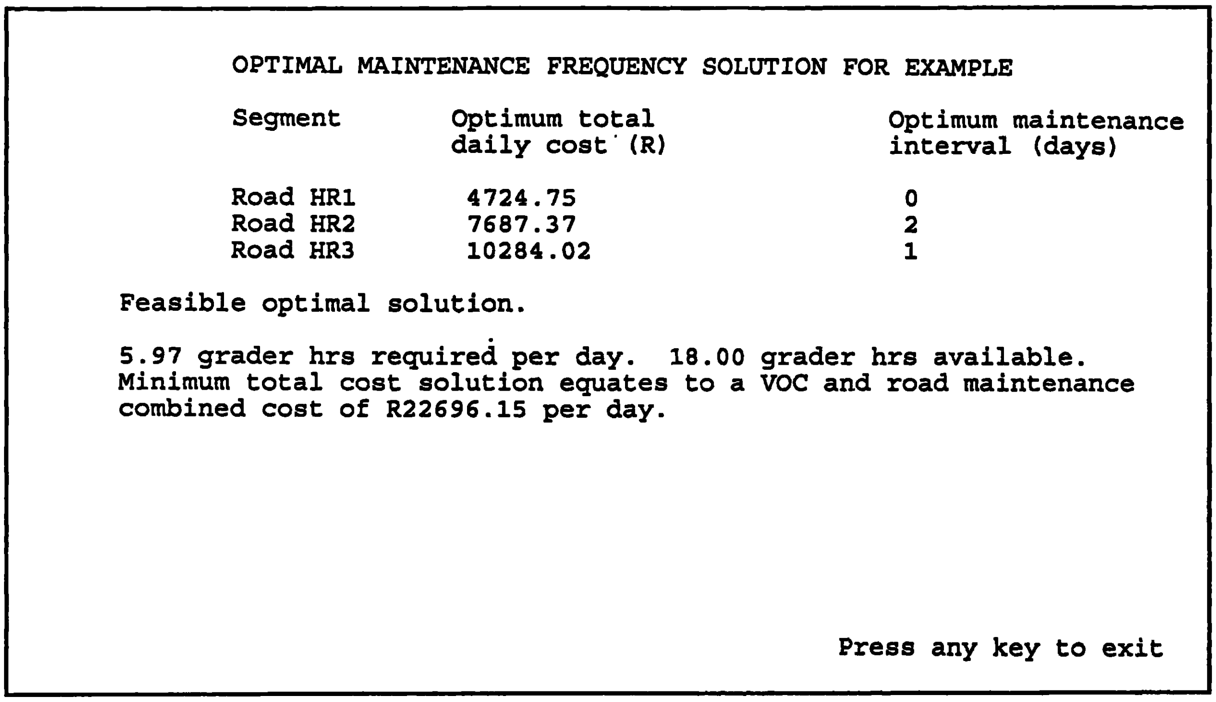


Figure 15.3 Total Segment Cost variation with Maintenance Interval

or grader hours exceeds required maintenance hours then the final solution is reported together with an indication of required grader hours as shown in Table 15.6. Whilst the final solution only utilises 32% of the available grader-hours per day, it indicates the extent to which the road-graders may be used for additional activities without detriment to optimal haul road performance.

Table 15.6 Sample Program Report For Feasible Optimal Solution



```
            OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

            Segment        Optimum total               Optimum maintenance
                           daily cost (R)              interval (days)

            Road HR1        4724.75                     0
            Road HR2        7687.37                     2
            Road HR3        10284.02                    1

     Feasible optimal solution.

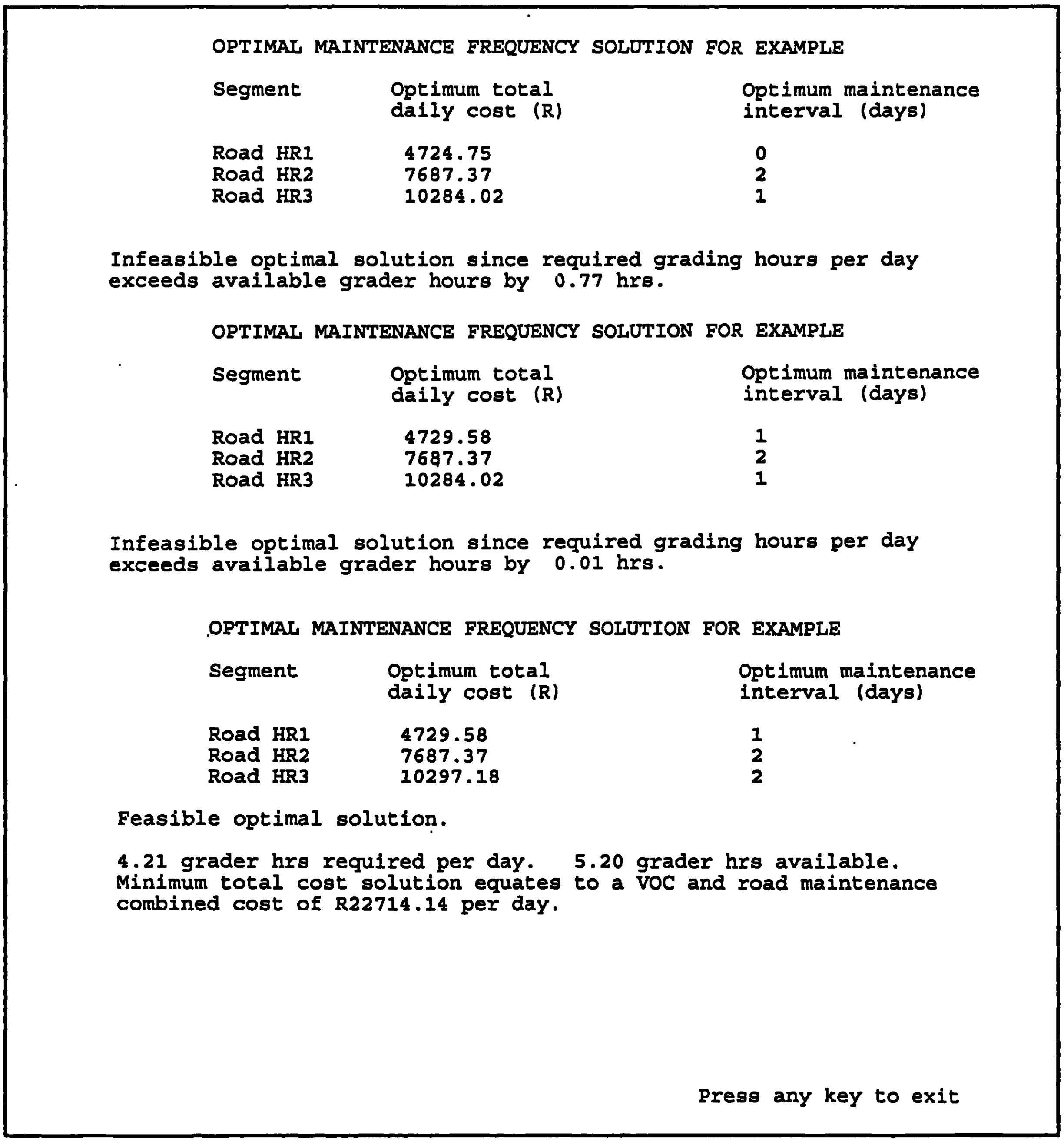
     5.97 grader hrs required per day.  18.00 grader hrs available.
     Minimum total cost solution equates to a VOC and road maintenance
     combined cost of R22696.15 per day.




                                                      Press any key to exit
```

If required maintenance hours as dictated by the optimal maintenance interval for the various haul road segments exceeds available grader hours, an intermediate solution is given indicating the shortfall in grader operating hours associated with the cost-based optimal solution. A feasible solution is then sought from consideration of the rate of increase in total costs with increases in the maintenance interval. The road segment possessing the lowest rate of total cost change for a maintenance interval increase of one day from the optimal is selected and the maintenance interval for this segment extended by one day. The revised grader operating hours per day are recalculated for this new strategy and if less than the available hours a feasible solution is reported. If required grader hours remain in excess of available hours the process is repeated until a feasible solution is found. The cost based approach to identifying a feasible solution does not necessarily mean that segment roughness is minimised since the lowest rate of change of total costs is more likely to be associated with short, low traffic volume segments which contribute only marginally to increases in network total costs. Table 15.7 gives typical program reports from this second stage of optimisation.

Table 15.7 Sample Program Reports for Initially Infeasible Solution



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              OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

              Segment       Optimum total                Optimum maintenance
                            daily cost (R)               interval (days)

              Road HR1       4724.75                      0
              Road HR2       7687.37                      2
              Road HR3       10284.02                     1

        Infeasible optimal solution since required grading hours per day
        exceeds available grader hours by  0.77 hrs.

              OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

              Segment       Optimum total                Optimum maintenance
                            daily cost (R)               interval (days)

              Road HR1       4729.58                      1
              Road HR2       7687.37                      2
              Road HR3       10284.02                     1

        Infeasible optimal solution since required grading hours per day
        exceeds available grader hours by  0.01 hrs.

              OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

              Segment       Optimum total                Optimum maintenance
                            daily cost (R)               interval (days)

              Road HR1       4729.58                      1
              Road HR2       7687.37                      2
              Road HR3       10297.18                     2

        Feasible optimal solution.

        4.21 grader hrs required per day.   5.20 grader hrs available.
        Minimum total cost solution equates to a VOC and road maintenance
        combined cost of R22714.14 per day.




                                                       Press any key to exit
```

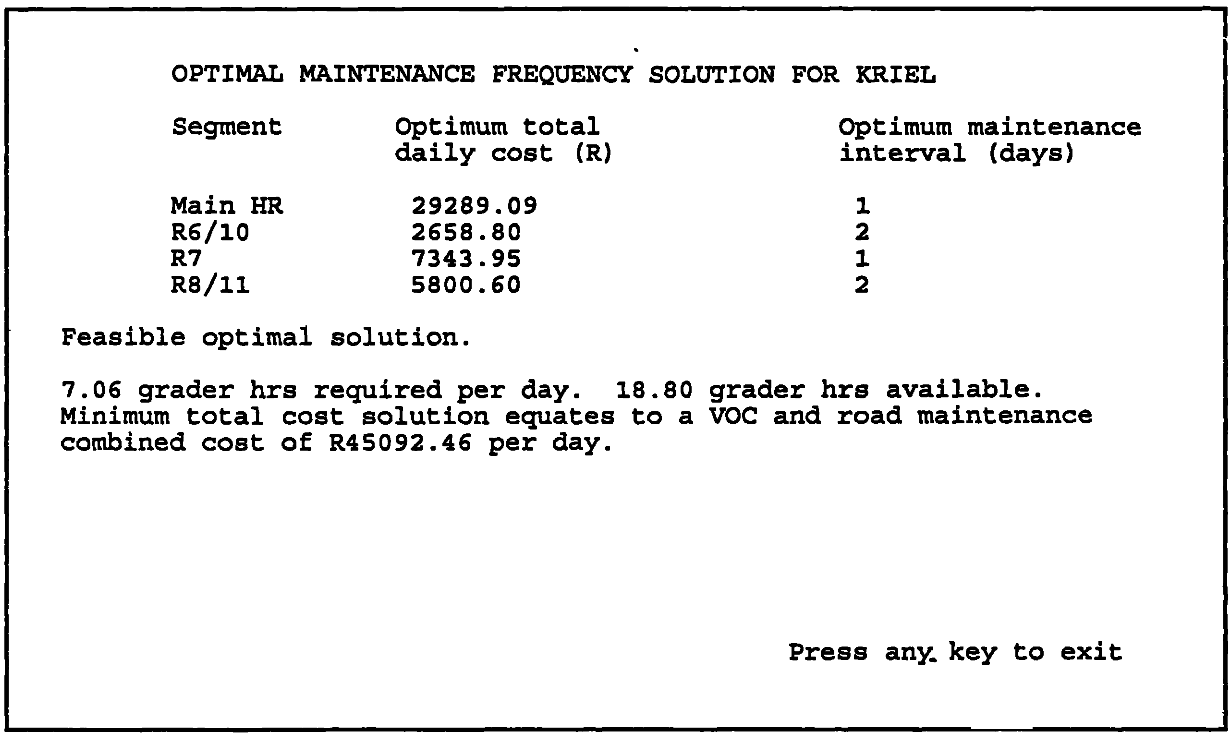
15.3 Comparison of Program Results with Established Maintenance Practices

In order to compare the optimal maintenance strategy determined by the MMS model program with the established maintenance practices on the mines, analyses were undertaken for Kriel, Kromdraai, New Vaal and Kleinkopje Collieries. The data used in each model is given in Appendix P. Since Kriel, Kleinkopje and New Vaal operated mixed fleets, the assumption of a standard (Euclid R170) truck is made in these cases. Material property values are assigned to each section based on the material testing results given in Tables 3.9 to 3.12 and knowledge of the construction of the particular segment. Geometric data and traffic volumes are assigned following data in Appendix O and ramp lengths and grades have been incorporated in segment lengths where applicable.

Results of the analyses are presented in Tables 15.8-15.12 for each mine. For Kriel Colliery it is seen that for the four segments (including ramps) comprising the network, the main and ramp 7 road total costs are optimised with maintenance every other day whilst the remaining roads should be maintained every third day. This policy entails 7,06 grading hours per day which is well within the maximum available hours of 18,8 per day. Current practice at Kriel entails daily blading of the ramp areas and sections of the main haul road. Since the main haul road accounts for 65% of total daily VOC and road maintenance costs it should receive more regular maintenance. This is evident if grader hours are artificially reduced, the resultant optimal solution extending maintenance intervals on all other roads in an attempt to accommodate an optimal solution for the main haul road within the maintenance hours constraint. Total annual vehicle and road maintenance operating costs are estimated by the program at R12,66m whilst those reported by the mine are R16,59m. This difference can be ascribed primarily to the assumption of a single as opposed the mixed haul truck fleet operated at Kriel.

The results of the Kromdraai Colliery assessment (Table 15.9) also indicate a feasible optimal solution within the available grader operating hours constraint and the optimised maintenance intervals are in broad agreement with those applied by the mine, as discussed in Chapter 9.3. Estimated total annual road maintenance and vehicle operating costs of R6,18m are in broad agreement with the mine cost figure of R5,61m, the latter being based on costs assigned to

Table 15.8 Optimum Maintenance Frequency Solution for Kriel Colliery



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          OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR KRIEL

          Segment        Optimum total               Optimum maintenance
                         daily cost (R)              interval (days)

          Main HR         29289.09                    1
          R6/10           2658.80                     2
          R7              7343.95                     1
          R8/11           5800.60                     2

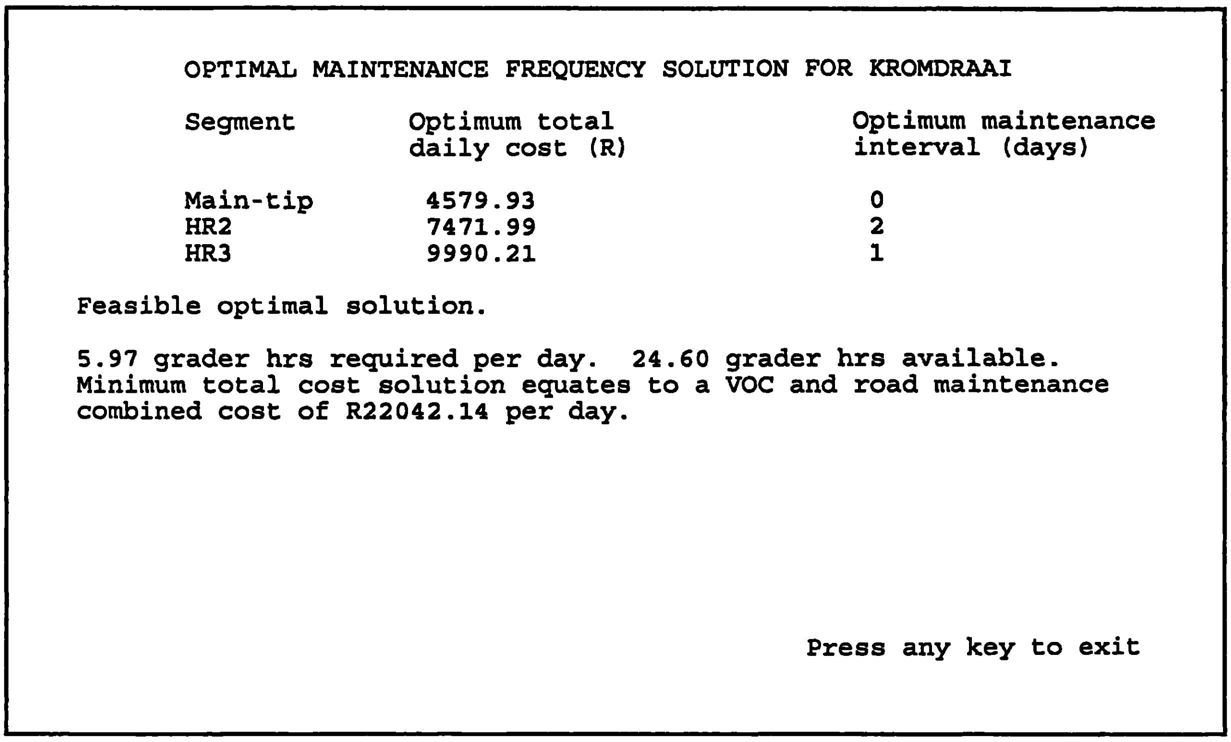
   Feasible optimal solution.

   7.06 grader hrs required per day.  18.80 grader hrs available.
   Minimum total cost solution equates to a VOC and road maintenance
   combined cost of R45092.46 per day.




                                                     Press any key to exit
```

Table 15.9 Optimum Maintenance Frequency Solution for Kromdraai Colliery



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          OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR KROMDRAAI

          Segment        Optimum total               Optimum maintenance
                         daily cost (R)              interval (days)

          Main-tip        4579.93                     0
          HR2             7471.99                     2
          HR3             9990.21                     1

   Feasible optimal solution.

   5.97 grader hrs required per day.  24.60 grader hrs available.
   Minimum total cost solution equates to a VOC and road maintenance
   combined cost of R22042.14 per day.

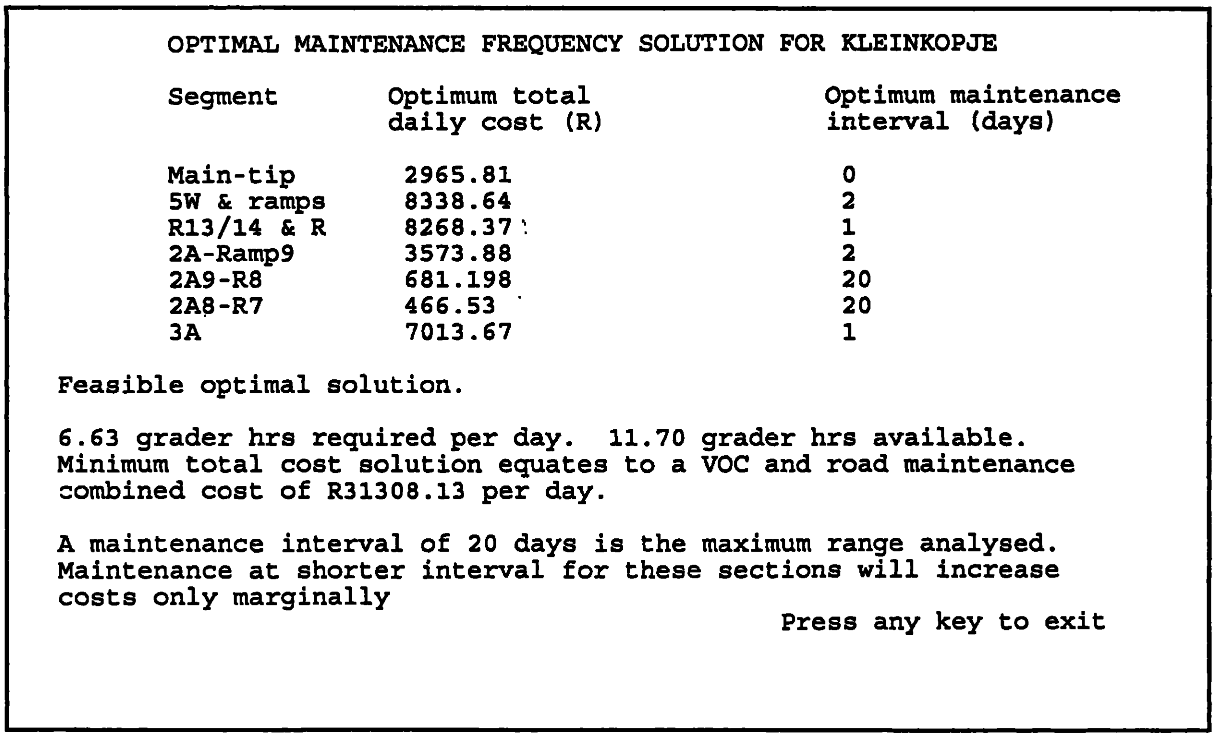



                                                     Press any key to exit
```

a single piece of equipment multiplied by total fleet numbers. Further research into more representative VOC models should reduce this discrepancy.

In the case of the Kleinkopje assessment as shown in Table 15.10, an optimum (maximum) maintenance interval of 20 days is reported for the 2A9-R8 and 2A8-R7 roads. For this type of result, the program will also report the influence of the maximum interval on total costs. Table 15.11 presents the cost reports for daily VOC, daily maintenance cost and unoptimised total daily cost for each segment. With reference to daily VOC, roads 2A9-R8 and 2A8-R7 show relatively low costs and more critically, a low rate of increase in cost as maintenance interval increases. When maintenance costs are added to VOC it is seen that the maintenance interval and associated maintenance costs exert the greatest influence over total costs and that cost is minimum at maximum maintenance interval. If daily tonnage hauled on these segments were to be increased then this result would change, emphasising the inter-relationship between traffic volumes and rate of roughness defect progression. Due to the very different haul truck fleet from that modelled, no cost comparisons are made.

Table 15.10 Optimum Maintenance Frequency Solution for Kleinkopje Colliery



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              OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR KLEINKOPJE

              Segment        Optimum total                Optimum maintenance
                             daily cost (R)               interval (days)

              Main-tip        2965.81                      0
              5W & ramps      8338.64                      2
              R13/14 & R      8268.37                      1
              2A-Ramp9        3573.88                      2
              2A9-R8          681.198                      20
              2A8-R7          466.53                       20
              3A              7013.67                      1

       Feasible optimal solution.

       6.63 grader hrs required per day.  11.70 grader hrs available.
       Minimum total cost solution equates to a VOC and road maintenance
       combined cost of R31308.13 per day.

       A maintenance interval of 20 days is the maximum range analysed.
       Maintenance at shorter interval for these sections will increase
       costs only marginally
                                                Press any key to exit
```

Table 15.11 Segment Cost Reports for Kleinkopje Colliery (R/km)

TOTAL DAILY VOC PER SEGMENT FOR KLEINKOPJE

Days	Main-tip	SW & ramps	R13/14 &	R2A-Ramp9	2A9-R8	2A8-R7	3A
0	2914.31	8137.67	8075.71	3465.30	652.24	446.94	6851.14
1	2940.80	8175.75	8121.56	3479.20	654.99	448.80	6896.74
2	2977.03	8228.41	8184.82	3498.34	658.78	451.36	6959.13
3	3018.26	8287.77	8256.09	3520.19	663.10	454.28	7030.63
4	3056.39	8341.09	8320.17	3540.43	667.06	456.97	7097.65
5	3085.46	8380.07	8367.13	3555.82	670.04	458.98	7149.62
6	3104.54	8404.46	8396.61	3565.88	671.96	460.29	7184.30
7	3115.85	8418.28	8413.37	3571.82	673.09	461.05	7205.20
8	3122.16	8425.67	8422.36	3575.11	673.70	461.46	7217.02
9	3125.56	8429.51	8427.04	3576.87	674.03	461.69	7223.47
10	3127.36	8431.46	8429.43	3577.79	674.20	461.80	7226.92
11	3128.30	8432.45	8430.64	3578.28	674.29	461.86	7228.74
12	3128.79	8432.95	8431.25	3578.53	674.33	461.89	7229.70
13	3129.04	8433.20	8431.56	3578.66	674.36	461.91	7230.20
14	3129.18	8433.32	8431.72	3578.72	674.37	461.92	7230.47
15	3129.24	8433.38	8431.80	3578.76	674.37	461.92	7230.60
16	3129.28	8433.42	8431.84	3578.77	674.38	461.92	7230.68
17	3129.30	8433.43	8431.86	3578.78	674.38	461.92	7230.72
18	3129.31	8433.44	8431.87	3578.79	674.38	461.92	7230.73
19	3129.31	8433.44	8431.87	3578.79	674.38	461.92	7230.74
20	3129.31	8433.45	8431.87	3578.79	674.38	461.92	7230.75

TOTAL DAILY MAINTENANCE COST PER SEGMENT FOR KLEINKOPJE

Days	Main-tip	SW & ramps	R13/14 &	R2A-Ramp9	2A9-R8	2A8-R7	3A
0	51.51	330.71	293.62	226.66	143.21	96.84	233.87
1	25.76	165.36	146.81	113.33	71.60	48.42	116.93
2	17.17	110.24	97.87	75.55	47.74	32.28	77.96
3	12.88	82.68	73.41	56.66	35.80	24.21	58.47
4	10.30	66.14	58.72	45.33	28.64	19.37	46.77
5	8.59	55.12	48.94	37.78	23.87	16.14	38.98
6	7.36	47.24	41.95	32.38	20.46	13.83	33.41
7	6.44	41.34	36.70	28.33	17.90	12.11	29.23
8	5.72	36.75	32.62	25.18	15.91	10.76	25.99
9	5.15	33.07	29.36	22.67	14.32	9.68	23.39
10	4.68	30.06	26.69	20.61	13.02	8.80	21.26
11	4.29	27.56	24.47	18.89	11.93	8.07	19.49
12	3.96	25.44	22.59	17.44	11.02	7.45	17.99
13	3.68	23.62	20.97	16.19	10.23	6.92	16.70
14	3.43	22.05	19.57	15.11	9.55	6.46	15.59
15	3.22	20.67	18.35	14.17	8.95	6.05	14.62
16	3.03	19.45	17.27	13.33	8.42	5.70	13.76
17	2.86	18.37	16.31	12.59	7.96	5.38	12.99
18	2.71	17.41	15.45	11.93	7.54	5.10	12.31
19	2.58	16.54	14.68	11.33	7.16	4.84	11.69
20	2.45	15.75	13.98	10.79	6.82	4.61	11.14

UNOPTIMISED TOTAL DAILY COST PER SEGMENT FOR KLEINKOPJE

Days	Main-tip	SW & ramps	R13/14 &	R2A-Ramp9	2A9-R8	2A8-R7	3A
0	2965.82	8468.38	8369.34	3691.95	795.45	543.78	7085.01
1	2966.55	8341.11	8268.37	3592.53	726.59	497.22	7013.67
2	2994.21	8338.64	8282.69	3573.89	706.52	483.64	7037.09
3	3031.14	8370.45	8329.49	3576.86	698.90	478.49	7089.10
4	3066.69	8407.24	8378.90	3585.76	695.70	476.33	7144.42
5	3094.05	8435.18	8416.06	3593.60	693.91	475.12	7188.59
6	3111.90	8451.71	8438.56	3598.26	692.42	474.12	7217.71
7	3122.29	8459.62	8450.07	3600.15	690.99	473.15	7234.43
8	3127.89	8462.42	8454.99	3600.29	689.61	472.22	7243.00
9	3130.71	8462.58	8456.40	3599.53	688.35	471.37	7246.85
10	3132.04	8461.52	8456.12	3598.40	687.22	470.61	7248.18
11	3132.59	8460.01	8455.11	3597.17	686.22	469.93	7248.23
12	3132.75	8458.38	8453.84	3595.96	685.35	469.34	7247.69
13	3132.72	8456.82	8452.54	3594.85	684.58	468.82	7246.91
14	3132.61	8455.37	8451.29	3593.83	683.91	468.37	7246.06
15	3132.46	8454.05	8450.15	3592.92	683.32	467.97	7245.22
16	3132.31	8452.87	8449.11	3592.11	682.80	467.62	7244.43
17	3132.16	8451.80	8448.17	3591.38	682.33	467.30	7243.71
18	3132.02	8450.85	8447.32	3590.72	681.92	467.02	7243.04
19	3131.89	8449.98	8446.55	3590.12	681.54	466.77	7242.44
20	3131.77	8449.19	8445.86	3589.59	681.20	466.53	7241.89

The results of the New Vaal Colliery assessment are given in Table 15.12 from which it is seen that the main haul road segment costs are optimised with daily maintenance. This is due in most part to the high traffic volumes experienced by these sections of road. As traffic volume decreases, the optimal maintenance interval increases on those roads carrying less traffic. This is in broad agreement with the observations made in Chapter 9.3 in which it was seen that the maintenance intervals applied at New Vaal were largely in response to anticipated traffic volumes as available production moved from ramp to ramp. As a result of the traffic volume experienced on the road, a large increase in the roughness defect score is seen which, at high maintenance intervals, reduces grader productivity. This effect is shown in Table 15.13, the upper limit on roughness defect score being 47 for road M-tip-R0.

Table 15.12 Optimum Maintenance Frequency Solution for New Vaal Colliery

```
          OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR NEW VAAL

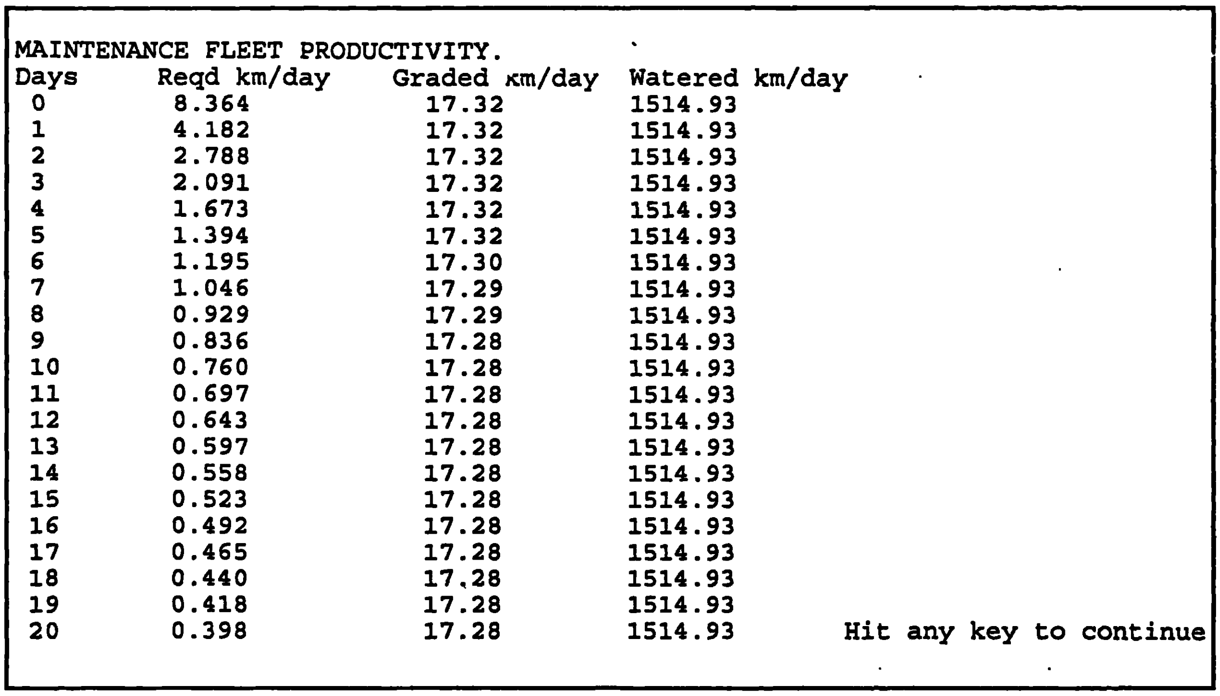
          Segment        Optimum total               Optimum maintenance
                         daily cost (R)              interval (days)

          M-tip-R0        11351.53                    0
          MR0-R2          18667                       0
          MR2-R3          8797.16                     0
          MR3-R4          4077.14                     0
          MR4-R6/7        3795.02                     1
          MR6/7-R9        2317.30                     3
          R0              5314.19                     1
          R2              1999.56                     2
          R3              2710.01                     2
          R4              605.34                      20

   Feasible optimal solution.
   7.11 grader hrs required per day.  23.10 grader hrs available.
   Minimum total cost solution equates to a VOC and road maintenance
   combined cost of R59634.28 per day.
   A maintenance interval of 20 days is the maximum range analysed.
   Maintenance at shorter interval for these sections will increase
   costs only marginally                       Press any key to exit
```

The examples addressed here are based on average annual data supplied by each mine and as such reflect the optimum policy for these particular conditions. Coal production is dynamic in the sense that traffic volumes on various segments of the network change as coal production areas move. Further benefit may be realised when the MMS is applied in

Table 15.13 Maintenance Fleet Productivity, New Vaal Colliery



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MAINTENANCE FLEET PRODUCTIVITY.
Days       Reqd km/day      Graded km/day   Watered km/day
 0          8.364             17.32         1514.93
 1          4.182             17.32         1514.93
 2          2.788             17.32         1514.93
 3          2.091             17.32         1514.93
 4          1.673             17.32         1514.93
 5          1.394             17.32         1514.93
 6          1.195             17.30         1514.93
 7          1.046             17.29         1514.93
 8          0.929             17.29         1514.93
 9          0.836             17.28         1514.93
 10         0.760             17.28         1514.93
 11         0.697             17.28         1514.93
 12         0.643             17.28         1514.93
 13         0.597             17.28         1514.93
 14         0.558             17.28         1514.93
 15         0.523             17.28         1514.93
 16         0.492             17.28         1514.93
 17         0.465             17.28         1514.93
 18         0.440             17.28         1514.93
 19         0.418             17.28         1514.93
 20         0.398             17.28         1514.93       Hit any key to continue
```

conjunction with monthly production planning, so as to identify any changes in the optimal maintenance policy as planned production areas change. Whilst these results generally reflect current maintenance practices on the mines, it is also important to determine the sensitivity of total and segment costs to varying sub-optimal maintenance strategies.

15.4 Sensitivity of Maintenance Strategy to Model Parameters

Total vehicle operating and road maintenance costs have been seen to vary with maintenance interval as discussed in Section 15.3. Whilst the optimum maintenance frequency was identified for each mine haul road segment, no indication was given of the cost trade-offs due to departure from the optimal schedule. An indication of the cost of sub-optimal maintenance intervals on segment and network total costs can be assessed from the program segment cost reports similar to those presented in Table 15.11.

Figure 15.4 illustrates the change in daily operating cost for each segment of the Kromdraai Colliery road. As can be seen, total costs decrease as the optimal intervals are approached for each section of road. In this particular case, the rate of change of costs for both under- and over-maintaining the road are approximately similar, by virtue of the cost of maintenance and segment total VOC's being similar. This situation would change as tonnage hauled varies as depicted in Figure 15.5. In this analysis, a single segment (HR3) of the Kromdraai Colliery road network is subjected to increasing traffic volumes and the maintenance interval and rate of change of total (segment) cost is seen to vary as the VOC component increases with tonnage hauled.

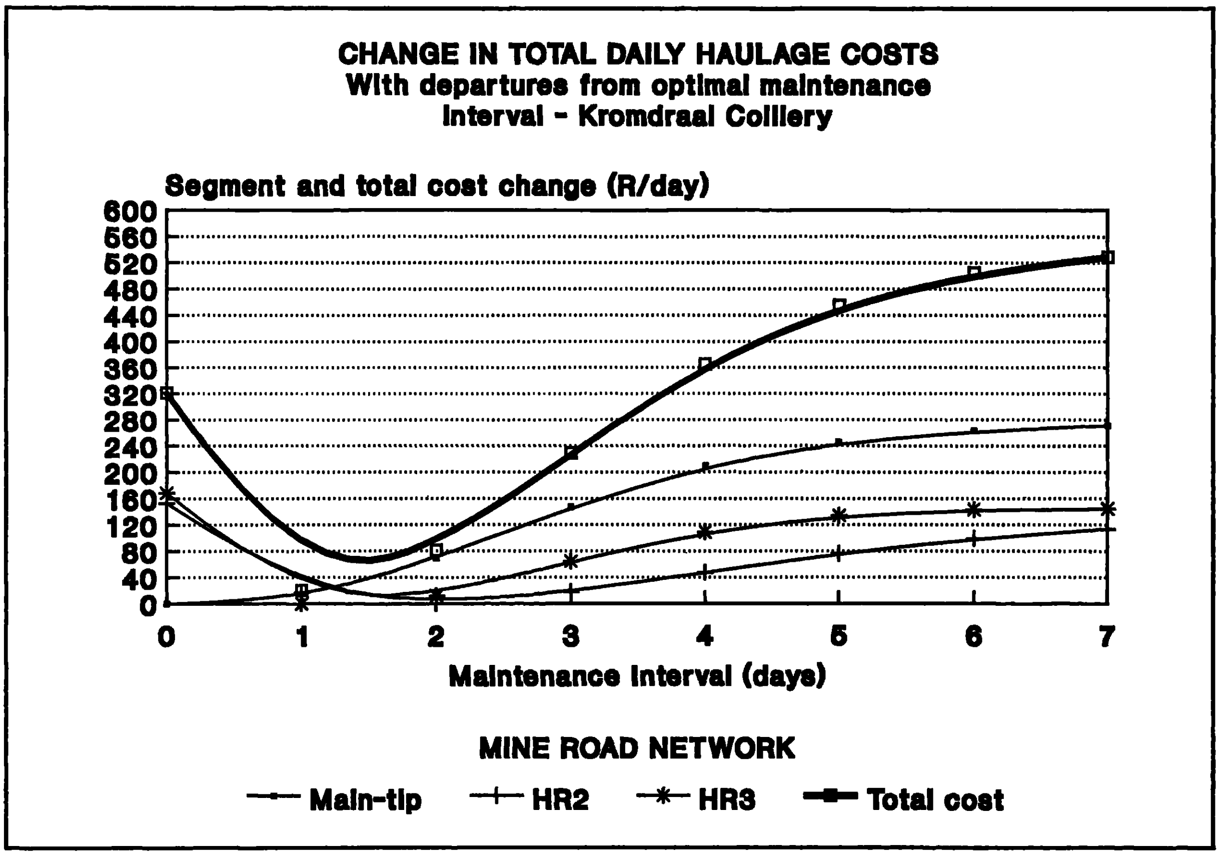

Figure 15.4 Total Daily Haulage Cost Variation with Maintenance Interval - Kromdraai Colliery

Similar effects are seen for Kriel (Figure 15.6) and Kleinkopje (Figure 15.7). In the case of New Vaal Colliery, if sub-optimal maintenance strategies are adopted, total costs are seen only to rise. This is a result of the combination of high tonnages and associated daily maintenance regimes on the heavy traffic sections of road. Full results are given in Table 15.14 for each segment of the New Vaal Colliery haul road network. If maintenance intervals are reduced by a day for those roads with a optimum interval of one day or more, annual total costs are seen to increase by R9 375. However, if an extra day is added to the

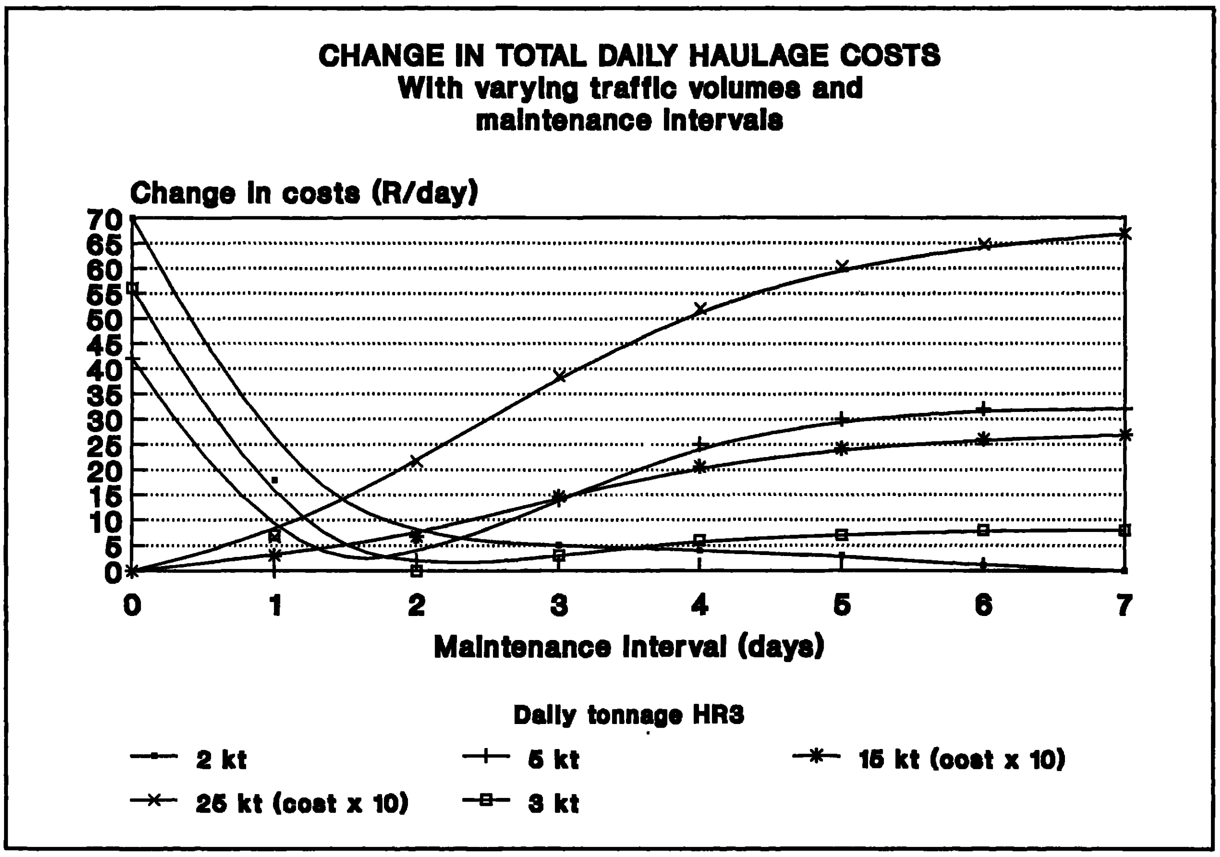

Figure 15.5 Effect of Traffic Volumes on Segment Daily Costs

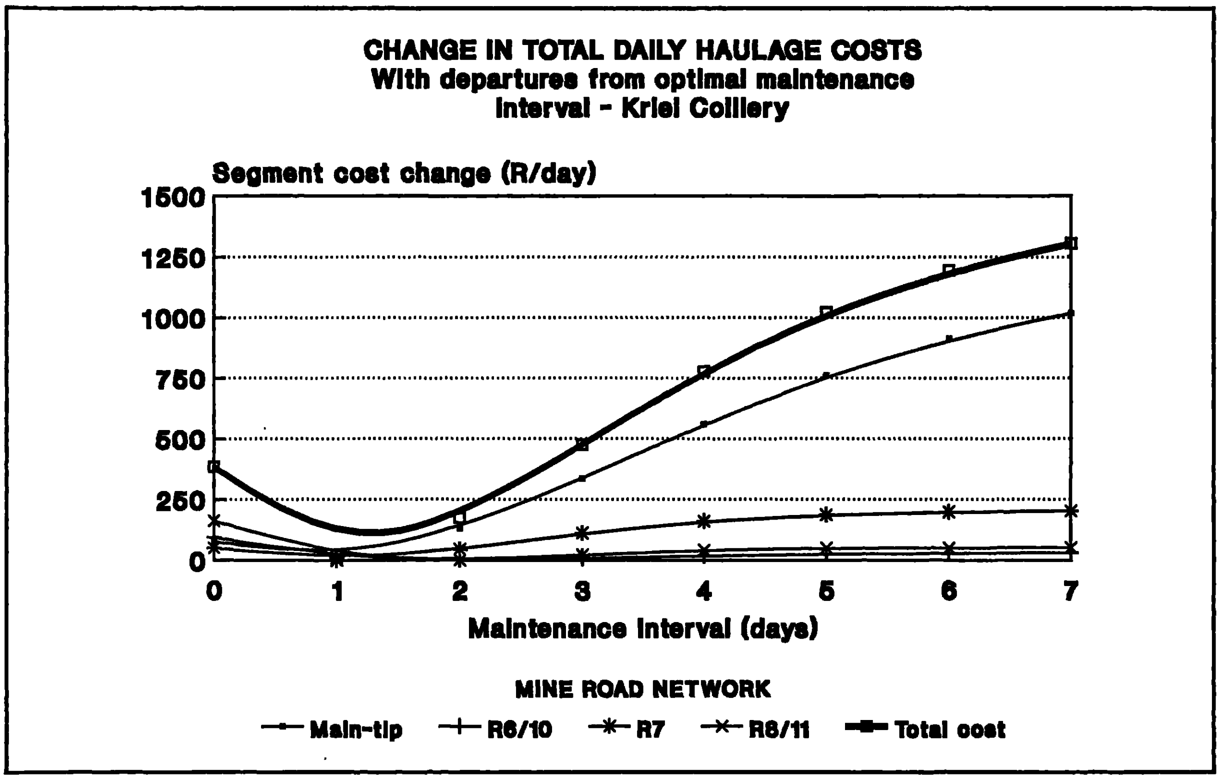

Figure 15.6 Total Daily Haulage Cost Variation with Maintenance Interval - Kriel Colliery

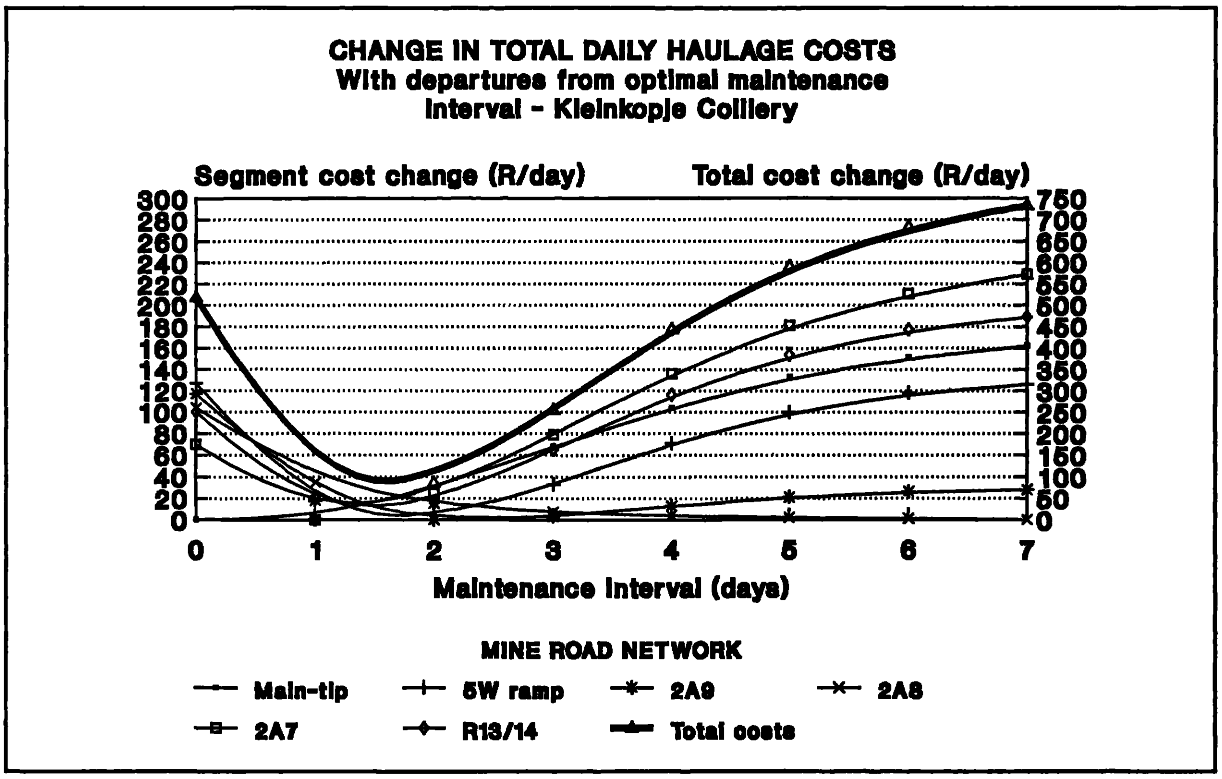

Figure 15.7 Total Daily Haulage Cost Variation with Maintenance Interval - Kleinkopje Colliery

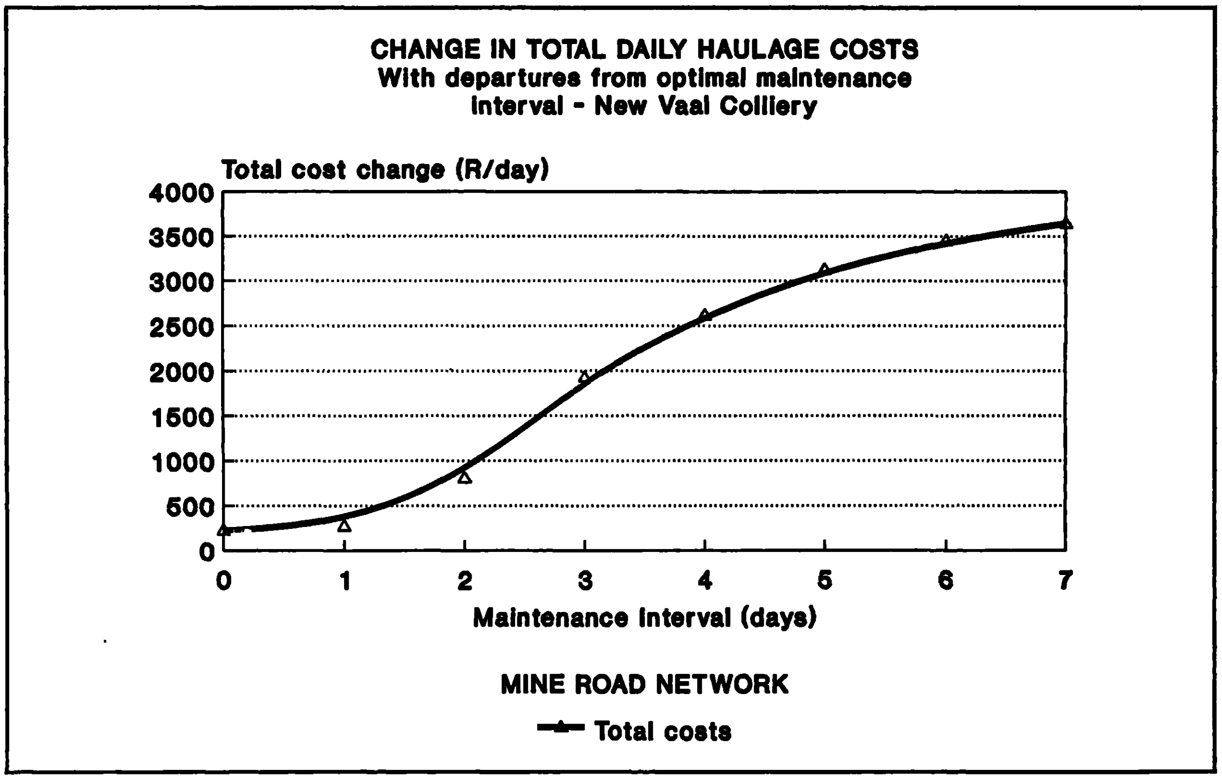

Figure 15.8 Total Daily Haulage Cost Variation with Maintenance Interval - New Vaal Colliery

Table 15.14 Total VOC and Road Maintenance Cost Increases Associated with Sub-optimal Maintenance Intervals - New Vaal Colliery

SEGMENT TOTAL DAILY VOC AND ROAD MAINTENANCE COST VARIATION WITH INCREASING AND DECREASING MAINTENANCE INTERVALS											
Maintenance Interval	HAUL ROAD SEGMENT TOTAL COST (R)										**Annual savings (R)**
	M-tip-R0	**MR0-R2**	**MR2-R3**	**MR3-R4**	**MR4-R6/7**	**MR6/7-R9**	**R0**	**R2**	**R3**	**R4**	
Optimum	11351,53	18667,00	8797,16	4077,14	3795,02	2317,30	5314,19	1999,56	2710,01	605,34	-
+ 1 day	11490,23	18817,77	8841,87	4078,09	3808,12	2320,09	5335,67	2004,21	2719,02	-	108520
+ 2 day	11705,64	19104,70	8956,26	4116,13	3832,42	2323,25	5322,47	2010,40	2723,83	-	312237
- 1 day	-	-	-	-	3815,22	2317,99	5368,24	2000,24	2713,53	0,04	9375

optimal maintenance interval of each segment, annual total VOC and road maintenance costs for the network are seen to increase by R108 520 and for an interval of 2 days beyond optimal, annual costs increase by R312 237. Depending on the specific mine haul route characteristics, the MMS system has the potential to generate significant cost savings.

15.5 Summary and Conclusions

A MMS model program for mine haul roads was developed for the evaluation of alternative maintenance intervals and the associated effect on total operating costs, comprising VOC and road maintenance. Models comprising these cost components, developed in previous chapters, were included in the program to determine road roughness, rolling resistance, vehicle speed, fuel, tyre and parts consumption costs and labour hours. Road maintenance costs and fleet productivity was assessed by means of user specified data in conjunction with a basic grader productivity model. The limitations in the application of these best estimate models should be borne in mind when analysing the results presented by the model.

An evaluation of the total cost variation with maintenance interval enabled the optimum maintenance interval to be determined, both on a minimum total cost basis and in terms of maintenance equipment available operating hours. When analysing the results of individual mine simulations, the actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance intervals on lightly trafficked roads. In all cases, available grader hours was found to be considerably more than the operating hours required for the optimal policy. The total costs predicted by the program were found to be in broad agreement with cost data supplied by the mine, bearing in mind the assumptions necessary in modelling each haul truck fleet and the exclusion of additional road maintenance activities.

From an analysis of the rate of change in VOC and road maintenance costs for individual segments with increases and decreases in the optimal maintenance interval, a sub-optimal maintenance interval incorporating too infrequent maintenance was seen to be associated with excessive costs. The rate of change of costs for both under- and over-maintaining the road were found to be a function of the cost of maintenance and segment total VOC's. Increasing traffic volumes result in more frequent maintenance and the penalties associated with over-maintenance of the road are seen to decrease in significance compared to the rate of increase in costs associated with under-maintenance of the road. It is concluded that the adoption of the MMS model program for mine haul roads has the potential to generate significant cost savings when used dynamically in conjunction with production planning.

CHAPTER 16

CONCLUSIONS AND RECOMMENDATIONS

16.1 Conclusions

The primary objective of the research was the development of a portable and practical haul road design and management technique that encompassed both pavement strength and operating performance considerations. These performance characteristics were subdivided into structural, functional and maintenance design categories. The primary objectives addressed within each design category were;

- The prediction of mine haul road structural performance through the use of analytical models and the recommendation of a formal mechanistic structural design procedure which encompasses typical mine haul road vehicle loads and available construction material properties.
- The development and analysis of material selection guidelines for use in haul road functional design together with recommendation of selected wearing course material parameter ranges to fulfil road-user defined mine haul road functional performance requirements.
- Through an analysis of pavement deterioration rates and maintenance cost/road quality relationships, the development of vehicle operating and pavement performance models for incorporation in a maintenance management system for surface mine haul roads.

16.1.1 Structural Design

The optimal mechanistic structural design of a surface mine haul road embodies the determination of limiting structural design criteria, the recommendation of target effective elastic modulus values for the construction materials available and the placement of those materials such as to optimise their performance both as individual layers and over the entire structure. Structural performance was analysed in terms of minimum wearing course thickness and compaction and the limiting design criteria of vertical strain in the base, sub-base and sub-grade layers. In addition, of the various design options analysed, the inclusion of a rock layer immediately below the wearing course proffered the structure increased resilience to the applied loads without recourse to excessive structural thickness.

The derivation of limiting design criteria for the mechanistic design of surface mine haul roads was based on a structural performance categorisation of mine haul roads. Stresses and strains generated from a multi-layer elastic solution for each road test section were compared with the structural performance categorisation to establish suitable design criteria. Construction material elastic moduli were assessed in terms of both the TRH14 and TRH20 classification and the DCP derived empirical relationship whereby suitable moduli for the various classes of granular materials used in haul road construction were derived.

Two design criteria were proposed with which to assess the structural performance of mine haul roads, namely factor of safety (FOS) for the two uppermost layers and vertical elastic compressive strain for each layer below the top layer. It was found that the vertical strain criterion correlated well with structural performance of the road; those mine sites exhibiting poor performance and an associated excessive maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. It was found that an upper limit of 2000 microstrain should be placed on layer strain values, this value being associated with typical traffic volumes and required degree of structural performance. Strain values exceeding this value have been shown to be associated with unacceptable structural performance. The depth of influence at which load induced stresses are no longer felt was identified at approximately 3000mm pavement depth. With regard to the FOS design criteria for the upper layers, it was concluded that this criteria was not applicable to haul road design. In the absence of any definitive criterion, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality gravel was recommended.

The selection of target effective elastic modulus values for typical construction materials incorporated an analysis of material grading, Atterberg limits, CBR, swelling and field compaction characteristics. This catalogue-type approach assists in the practical application of the method where road building materials, essentially similar to those analysed, are encountered on the mines. A modulus range of 150-200MPa was proposed for G4-G6 gravels when used as a wearing course and 75-100MPa for the same material when used as a base or sub-base layer. Values for the modulus of the in-situ sub-grade material were found to be very much site and material specific and ranged from 17MPa to 388MPa. The use of DCP derived CBR values in conjunction with published data was recommended as the most tractable approach in ascertaining suitable modulus values for this material.

Recommendations regarding the structural design of surface mine haul roads were centred on the inclusion of a dumprock layer within the structure. The optimal location of this layer was found to be immediately below the wearing course layer, thereby reducing deflections in the lower layers to a minimum. Using this approach, a reduced structural thickness was realised without the attendant deformation and reduction in structural performance level that would otherwise be evident without a rock layer. In a comparative study of the hitherto empirical CBR cover curve design methodology for mine haul roads with the new mechanistically designed optimal equivalent, it was found that the proposed optimal design provided an improved structural response to the applied loads in comparison to thicker CBR based design and, in addition, did not contravene any of the proposed limiting design criteria for the particular traffic type, volume and required degree of performance. In terms of construction costs, a 15% cost saving per kilometre was realised over the CBR based design by using the mechanistically derived optimal design.

16.1.2 Functional Design

Functional design aspects refer to the ability of the haul road to perform its function, i.e to provide an economic, safe and vehicle friendly ride. This is dictated to a large degree through the choice, application and maintenance of wearing course materials. The commonality between typical defects reported for unpaved public roads and the functionality requirements for mine haul roads indicated that existing specifications for unpaved public road wearing course construction materials would form a suitable base for the development of specifications for mine haul roads. A qualitative functional performance assessment methodology was developed based on typical haul road wearing course, formation and function defects in order to assess the utility of established performance related wearing course selection guidelines and as a basis for revised functional performance parameter specifications.

From the functionality assessment exercise it was found that the major haul road functional defects encountered were dustiness, loose material, fixed and loose stoniness and crocodile cracking. A statistical analysis of deterioration and maintenance effects associated with these key defects revealed that wearing course material properties, especially grading and plasticity parameters, together with traffic volume, could be used to adequately model the functional performance of these key defects. The high prediction errors associated with the model were ascribed to the variability in both the defined and undefined independent variables which control defect progression rates. However, the applicability of the model is limited by the relatively small inference space of the data and where materials are encountered which differ significantly from those assessed during the test work, judgement and care should be exercised when applying the predicted results. In determining suitable wearing course material selection guidelines this work confirmed the earlier qualitative observations that grading and plasticity parameters would adequately anticipate the functional performance of a wearing course material.

The development of acceptability criteria for haul road functionality fulfilled a deficiency identified in the literature review. In addition to assigning acceptability ranges to each type of defect, the impact and accident potential of each defect was categorised and ranked according to the total impact and accident potential on the components of hauling, namely operation, truck and tyre. It was concluded from the ranking exercise that wet skid resistance, dustiness, erodibility and ravelling and corrugating are critical defects which control the functionality of mine haul roads and that the consequences, in terms of the possible generation of these defects, should therefore be incorporated into any suitable selection criteria established for mine haul road wearing course materials.

The derivation of wearing course material selection guidelines was based on the identification, characterisation and ranking of haul road functional defects. A reference framework was developed within which suitable specifications should fall, based on an assessment of the requirements of good specifications in the light of functional defect ranking and acceptability limits. The TRH20 wearing course material selection guidelines were found to be a suitable source for the specification of mine haul road wearing course material parameter requirements. A revised range of parameters was derived based on the road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects. The specification included the parameters of shrinkage product and grading coefficient and limits of 85-200 and 20-35 respectively were proposed. In addition, from analysis of the range of material property parameters assessed and their association with the functional defects analysed, parameter ranges were additionally specified for density, dust ratio, Atterberg limits, CBR and maximum particle size. By analysing the trends evident in the individual defect rankings, the predictive capability of the specification was enhanced by depicting the variation in functional defects which would arise when departures are made from recommended parameter limits.

16.1.3 Maintenance Design

The maintenance aspect of haul road design cannot be considered separate from the structural and functional design aspects since the two are mutually inclusive. Maintenance design concerns the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs. The proposed mine haul road maintenance management system (MMS) was developed from established MMS applied in the public domain, together with specific modifications which reflect the requirements of mine haul road-users. The road roughness progression model forms the basis of the MMS since roughness is the principal measure of pavement condition that can be directly related to both vehicle operating costs and the frequency of maintenance activities.

A qualitative road roughness evaluation technique was developed as a precursor to the development of a model for roughness progression. Increasing traffic volume, grading coefficient and shrinkage product were all associated with an increasing rate of roughness progression whilst increasing CBR and plasticity index were associated with a decreasing progression. To facilitate portability and comparison of the qualitative assessment technique, expressions were developed to enable direct comparison to be made between roughness defect score and IRI. In addition, rolling resistance was assessed and results compared to established models for light commercial vehicles. The model derived for mine haul road roughness variation with IRI was found to be broadly similar to models developed for paved and unpaved public roads, albeit with a non-linear rate of change of rolling resistance per unit IRI. Based on the tentative similarity between experimentally derived rolling resistance model values for mine haul road roughness and those reported in the literature it was proposed that the models derived to describe rolling resistance variation with road roughness be provisionally adopted in the MMS model. However, to fully characterise the effect of road roughness attributes on ultra-heavy haul trucks it is recommended that an investigation be undertaken specifically using these trucks.

The second element of a MMS for mine haul roads was based on models of the variation of vehicle operating and road maintenance costs with road roughness. The combination of these models enabled the optimal maintenance strategy to be sought based on the minimisation of these costs over a particular haul route. The fuel consumption model development was based on the simulation of typical coal haulage trucks used by the mines. The similarity in speed versus total resistance performance of these trucks prompted the development of four universal equations by means of which vehicle speed could be predicted for any combination of total resistance and truck loading. The constant speed fuel consumption model was used as an explanatory variable in the fuel consumption model in which equations were developed for the fuel consumed by trucks on both favourable and unfavourable total resistance segments of a haul route. The verification of the models to actual mine data proved problematic since no fuel consumption test data was found with which to validate the models. An approximate fuel consumption figure was deduced from mine operating records and vehicle annual ton-kilometres which showed good agreement with the model when applied over a similar haul route. It is recommended however, that on-site fuel consumption tests be conducted with which to rigorously verify the fuel consumption models adopted.

With regard to the tyre, vehicle maintenance parts and maintenance labour models developed, similar data limitations were seen which precluded the development of statistically robust models. Existing models developed for commercial trucks in the public domain were used as a basis for the development of mine haul truck models. Although the parameter ranges bore little resemblance to those of mine haul trucks, when coupled with a hypothesis of the influence road roughness and geometry on these cost components, a basic model was developed in each case. These models were then compared with the limited mine data available to verify the order of magnitude of the costs modelled and, more critically, to indicate the likely rate of change of these costs with road roughness. The latter proved particularly problematic due to data characteristic limitations and it is recommended that further research be conducted to assess the validity and transferability of the basic models proposed.

A MMS model program for mine haul roads was developed for the evaluation of alternative maintenance intervals and the associated effect on total operating costs, comprising vehicle operating and road maintenance cost elements. Road maintenance costs and fleet productivity was assessed by means of user specified data in conjunction with a basic grader productivity model. The limitations inherent in the development and application of these models should be borne in mind when analysing the results presented by the model.

An evaluation of the total cost variation with maintenance interval enabled the optimum maintenance interval to be determined, both on a minimum total cost basis and in terms of maintenance equipment available operating hours. When analysing the results of individual mine simulations, the actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance interval on lightly trafficked roads. From an analysis of the rate of change in vehicle operating and road maintenance costs for individual segments with reductions in the frequency of maintenance beyond the optimal maintenance interval, these sub-optimal maintenance strategies were seen to be associated with excessive expenditure on total road-user costs. It was concluded that the adoption of the MMS model program for mine haul roads has the potential to generate significant cost benefits when used dynamically in conjunction with production planning to optimise mine haul road maintenance activities.

16.2 Recommendations

The development of a portable and practical haul road design and management technique was addressed in this thesis. During its development, assumptions had to be made regarding aspects of structural, functional and maintenance management designs which were beyond the scope or feasibility of this research project. Whilst some hypotheses postulated were in general agreement with the available data, verification in a wider inference space is desirable, as is the development of relationships describing certain mine haul-truck and -road interactions. Specific recommendations are:

- To test the hypothesis that if the optimal mechanistic design for mine haul roads is adopted, the primary mode of road deterioration is related to the functional performance of the wearing course materials.

- To confirm the hypothesis that contact stresses under a ultra-heavy haul truck wheel can be reliably predicted from tyre inflation pressures and the assumption of circular contact areas.

- To determine if the vertical compressive strains recorded in each layer of a haul road designed according to the mechanistic structural methodology correlate with those predicted from a multi-layer elastic solution using the recommended material effective elastic modulus selection parameters and limiting design criteria.

- To perform additional studies to validate and extend the inference sphere of the various models developed to predict individual and combined functional defect progression rates.

- To fully characterise the effect of road roughness attributes on ultra-heavy haul truck rolling resistance.

- To test the validity of the fuel consumption equations developed for mine haul trucks through a combined series of road roughness/rolling resistance and fuel consumption tests on a selection of mine roads.

- To develop rigorous road grader productivity relationships which relate at least to road roughness defect score before blading.

- To develop applicable road-user cost relationships that would eliminate the need to adopt road roughness and cost relationships from other studies in which key parameter ranges are not directly comparable. For reliable application, these relationships should cover the widest range of road roughnesses available and include an appropriately designed data collation exercise for each cost component.

16.3 Implementation

The implementation of the new design and management techniques developed for mine haul roads is desirable in determining the practical advantages and disadvantages of the structural, functional and maintenance management methods proposed. Limited implementation of the structural design recommendations has occurred, but a rigorous evaluation of the method, in which predicted and actual pavement layer vertical compressive strains are assessed, is required for comprehensive verification of the methodology.

The recommended wearing course material selection parameters need to be assessed in practice together with the proposed functionality progression models. The implementation of these selection parameters on a number of operating mines would also permit the verification of the models over a wider inference space and resultant feedback would facilitate adjustments of the models to more reliably accommodate lower quality materials.

The maintenance management system developed for mine haul roads reflects closely the current operating practices on a number of mines. Implementation of the system on operating mines will provide the opportunity to assess the practicality of the optimum maintenance schedules proposed and the applicability of the roughness defect progression models upon which the optimisation of maintenance is based.