SIMPLIFYING THE HDM-4 METHODOLOGY FOR THE CALCULATION OF VEHICLE OPERATING COST

FOR USE IN THE SOUTHERN AFRICAN CONTEXT

A.F. BURGER
G.D. VAN ZYL

V&V CONSULTING ENGINEERS
52 GAZANIA STREET
KENRIDGE EXT 4
BELLVILLE

REPORT NUMBER: VV1/346 v.5

DATE: OCTOBER 2001

Introduction

The calculation of Vehicle Operating Cost (VOC) forms an integral part of any Pavement Management System (PMS). VOC is used in the process of prioritisation of maintenance projects as well as for the identification of economically viable maintenance strategies.

At present V&V's PMS makes use of the TRH22 methodology for the calculation of VOC. However, the TRH22 cost factors are updated infrequently resulting in questionable results for the PMS manager.

Another methodology that may be used for the calculation of VOC is the CB-Roads methodology. This system of equations is based on the HDM-3 methodology and is considered to be outdated.

It is for these reasons that it was decided to update the VOC calculations in the V&V PMS to the new HDM-4 methodology to bring it in line with world trends.

This report documents the procedure for the calculation of VOC based on the HDM-4 methodology. In the first part the VOC calculations are described. Certain modifications have been made to allow for Southern African conditions and are also documented. In the second part of the report the procedure followed for the calculation of the Internal Rate of Return (IRR) is documented.

This report is intended to be used in the process of updating the existing procedures for the calculation of VOC and IRR in the V&V Pavement Management System.

Vehicle Operating Costs – HDM-4 Methodology

“One of the factors influencing the decision to undertake rehabilitation work is the generation of Excess User Costs (EUC) on a road section, owing to poor riding quality. EUC can be defined as the additional Vehicle Operating Cost (VOC) that would not have been experienced on the road if it had had a good riding quality.”

Draft TRH 22, 1994

The **Highway Development and Management** (HDM-4) system has been released recently and it is proposed that PMS systems be updated to do VOC calculations based on HDM-4 methodology.

At present VOC is calculated as (TRH 22):

$$VOC = \sum_{i=1}^{n} A_i \times QI \times No\ of\ Vehicles_i \qquad \textbf{Equation 1}$$

where

- A_i is a cost factor related to vehicle type
- ***QI*** is the pavement roughness in Quarter Car Index

The factor ***A*** is based on the cost of fuel, tyres, depreciation and maintenance and differs for the different vehicle types. These factors are published by the CSIR from time to time. This is the model as proposed by TRH 22. Road roughness is not used directly for the calculation of VOC in this model since the factor A_i is first calculated. This factor is the actual vehicle operating cost before roughness effects are considered.

The CB-Roads methodology differs from the TRH 22 methodology. Five factors are used in CB-Roads. The factors are: Vehicle Capital Cost, Vehicle Maintenance Cost, Fuel Cost, Oil Cost and Tyre Cost. Road roughness is not used as a direct input into the calculation of the different factors. The factors are first calculated and then an adjustment factor related to road roughness is calculated. The different cost factors are then multiplied by the roughness factor and the VOC calculated. The roughness factor has the general form:

$$f_r = \frac{Cost\ factor\ at\ QI\ of\ road}{Cost\ factor\ at\ QI = 40}$$

The CB-Roads user manual refers to work done by Schutte in the calculation of VOC as it is influenced by roughness. The factor f_r as defined above is based on the work done by Schutte. When the VOC's at different QI levels are compared, an exponential relationship is found between the values of VOC at different QI levels. Thus, the adjustment factor has an exponential relation at different QI levels.

The HDM-4 methodology for the calculation of VOC differs significantly from the TRH 22 methodology. HDM-4 calculates VOC based on nine factors. These are:

1. Fuel Consumption*
2. Oil Consumption*
3. Tyre Consumption*
4. Vehicle Service Life* and Vehicle Utilisation [These factors are not costs but are used to calculate costs]
5. Parts Consumption*
6. Labour Hours*
7. Capital Costs: Depreciation* and Interest
8. Crew Hours
9. Overhead

Factors marked with an asterisk (*) are influenced directly by road roughness or are based on a factor that is influenced directly by roughness (e.g. labour hours is a function of parts consumption which is directly related to roughness).

The HDM-4 factors mentioned have roughness as a direct input for cost calculations. It seems that there has been an improvement in the knowledge surrounding VOC and the influence of roughness on VOC. In the past VOC factors were calculated and then adjusted for roughness. Now roughness is used as input for the different VOC factors.

When EUC is considered as an indicator factor for prioritisation of rehabilitation/maintenance work, it makes sense to only use VOC factors directly related to road roughness. Thus, it was decided to only use the HDM factors that are directly related to road roughness (fuel consumption, oil consumption, tyre consumption, service life, parts consumption, labour hours and depreciation). The VOC calculations presented here only use these factors.

The HDM-4 methodology as used here has been simplified further by considering only four vehicle types (in stead of the sixteen used by HDM-4). The vehicle types that are used are the types that are normally counted during a traffic survey. The vehicle types are:

- Light
- Heavy
- Taxi
- Bus

HDM-4 uses vehicle type dependent parameters in the calculation of the VOC factors. These have been simplified/condensed where applicable to reflect the vehicle types used in the modified methodology. Where applicable, the parameters related to vehicle types were based on the values of the following HDM-4 vehicle types:

- Light – HDM-4 type 4: Large Car
- Taxi – HDM-4 type 12: Mini-Bus
- Heavy – HDM-4 type 10: Heavy Truck
- Bus – HDM-4 type 14: Medium Bus

In all cases HDM-4 prescribes that the cost factors be calculated for uphill and downhill sections for a segment. The cost factor for the segment is then calculated by averaging the costs for up- and downhill. Since the topography of a segment should not influence decision-making on an existing network, it is proposed that the cost factors be calculated regardless of whether it is uphill or downhill. In certain cases road curvature is used as an input for calculations – these calculations are also ignored.

In the following sections the calculations of the modified HDM-4 methodology are described.

General Calculations

The following calculations are some general calculations related to the vehicles. These calculations are used further in the calculation of cost factors.

Calculations related to the resistance to motion

Rolling resistance to motion

$$FR = FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2 \right)$$

where

FCLIM a factor related to climatic conditions

the other factors are as defined below and in the tables at the end of the section

$$b11 = CR\_B\_a0 \times WHEEL\_DIA$$

$$b12 = \frac{CR\_B\_a1}{WHEEL\_DIA}$$

$$b13 = \frac{\left(CR\_B\_a2 \times NUM\_WHEELS\right)}{WHEEL\_DIA^2}$$

$$CR2 = Kcr2 \times \left(CR\_CR2\_a0 + CR\_CR2\_a1 \times TD + CR\_CR2\_a2 \times RI \right)$$

where

WHEEL_DIA	wheel diameter
TD	sand patch texture depth (mm)
RI	average riding quality (IRI m/km)

$$FCLIM = 1 + 0.003 \times PCTDS + 0.002 \times PCTDW$$

where

PCTDS	percentage of time travelled on snow covered roads (%) [assume 0%]
PCTDW	percentage of time travelled on wet roads (%) [20% rain days with precipitation >1mm; Weather Bureau Cape Town International Airport]

Thus, FCLIM becomes:

FCLIM = 1.04

In the table below the simplified formulae for the calculation of CR2 for gravel and bituminous paved roads are given.

Vehicle Type	CR2 Bituminous	CR2 Gravel
Light	0.9+0.022*TD+0.022*RI	1+0.075*RI
Taxi	0.9+0.022*TD+0.022*RI	1+0.075*RI
Heavy	0.84+0.03*TD+0.03*RI	1+0.075*RI
Bus	0.84+0.03*TD+0.03*RI	1+0.075*RI

The formula for the calculation of the rolling resistance for each vehicle type simplifies to the following:

Vehicle Type	FR (gravel)	FR (paved)
Light	309.4+23.2*RI	278.5+6.8*TD+6.8*RI
Taxi	395.8+29.69*RI	356.2+8.7*TD+8.7*RI
Heavy	1547.99+116.1*RI	1300.31+46.44*TD+46.44*RI
Bus	780.46+58.53*RI	655.59+23.41*TD+23.41*RI

These formulae are calculated with the assumption that the operating speed of all vehicles is 80 km/h

It can be seen that the rolling resistance to motion is a function of roughness for gravel roads and for paved roads it is a function of the texture depth and roughness.

Note to reader

Since the objective of this discussion is to simplify the HDM-4 methodology, factors that can be assumed to be constant should be ignored. Factors that should not influence decisions should also be ignored. Thus, where appropriate only the rolling resistance to motion should be used as this varies from road to road (roughness and texture depth are inputs – these vary for different roads).

The factors related to the calculation of rolling resistance are listed in the tables below:

Vehicle	WGT_OPER	NUM_WHEELS	WHEEL_DIA	Tyre Type	V
Light	1500	4	0.66	Radial	22.22
Taxi	2500	4	0.7	Radial	22.22
Heavy	13000	10	1.05	Bias-ply	22.22
Bus	6000	6	1.05	Bias-ply	22.22

Vehicle	CR1	CR_B_a0	CR_B_a1	CR_B_a2
Light	1.0	37	0.064	0.012
Taxi	1.0	37	0.064	0.012
Heavy	1.3	37	0.064	0.012
Bus	1.3	37	0.064	0.012

Vehicle	Road Type	Kcr2	CR_CR2_a0	CR_CR2_a1	CR_CR2_a2
Light	Bituminous paved	1	0.9	0.022	0.022
	Gravel	1	1.0	0	0.075
Taxi	Bituminous paved	1	0.9	0.022	0.022
	Gravel	1	1.0	0	0.075
Heavy	Bituminous paved	1	0.84	0.03	0.03
	Gravel	1	1.0	0	0.075
Bus	Bituminous paved	1	0.84	0.03	0.03
	Gravel	1	1.0	0	0.075

Fuel Consumption

The fuel consumption model is based on the ARFCOM mechanistic fuel model. This model predicts that fuel consumption is proportional to the total power requirements of the engine. The total power requirements of the engine are made up of the following components:

- Tractive power – required to overcome forces opposing motion
- Engine drag – required to overcome internal engine drag
- Accessory power – required to run vehicle accessories

Engine drag and accessory power requirements are calculated as one component.

The computational procedure is as follows:

Calculate:

1. Total power requirements of the engine
2. Fuel-to-power efficiency factor
3. Instantaneous fuel consumption
4. Specific fuel consumption over the road section

The annual average fuel consumption over the road section is then calculated for each vehicle type.

As mentioned earlier, uphill and downhill sections will not be considered in the derivation of the formulae and only factors related to road roughness will be considered.

Instantaneous fuel consumption

The instantaneous fuel consumption (IFC) for a vehicle type is given by:

IFC = MAX[IDLE_FUEL, ZETA*PTOT*(1+dFUEL)]

where

IFC	instantaneous fuel consumption [ml/s]
IDLE_FUEL	idle rate of fuel consumption [ml/s]
ZETA	fuel-to-power efficiency factor
PTOT	total power requirement for steady state motion [kW]
dFUEL	additional fuel consumption factor due to vehicle speed-change cycles

Only steady-state motion will be considered in the simplification of the HDM-4 formulae. Thus the factor dFUEL is set to zero. The expression for IFC becomes:

IFC = MAX[IDLE_FUEL, ZETA*PTOT]

<u>Power Requirements</u>

The vehicle power requirements consist of:

- Tractive power
- Engine and accessories power

Tractive Power

The tractive power required is calculated as:

PTR = [(FTR*V)/1000]

where:

PTR	tractive power [kW]
FTR	total resistance to steady state motion [N]
V	speed of vehicle [m/s]

FTR is calculated as:

FTR = FA + FG + FR + FCV

where:

FA	aerodynamic resistance to motion
FG	gradient resistance to motion
FR	rolling resistance to motion
FCV	curvature resistance to motion

Of the factors listed above, only the rolling resistance to motion is influenced directly by road roughness. Thus only FR will be considered, with the expression simplifying to:

FTR = FR

Speed due to roughness effects

Steady state motion was assumed for the derivation of the formulae presented here. The speed that was assumed is 80 km/h (22.22 m/s). However, the speed is influenced by road roughness and the formula used is:

VROUGH = ARVMAX/(VROUGH_a0*RI_{av})

where:

VROUGH	limiting speed due to roughness effects [m/s]
ARVMAX	maximum allowable average rectified velocity of suspension motion of the standard Opala-Maysmater vehicle in response to roughness [mm/s]
VROUGH_a0	regression parameter
RIav	average road roughness [IRI]

The parameters for the different vehicles are:

Vehicle	ARVMAX	VROUGH_a0
Light	203	1.15
Taxi	203	1.15
Heavy	180	1.15
Bus	200	1.15

When these parameters are substituted in the expression for the limiting speed due to roughness, the limiting roughness – the roughness above which the speed of a vehicle will not be constant at 80 km/h – is determined as:

Light, Taxi and Bus:	IRI = 8.0
Heavy:	IRI = 7.0

Thus, the formulae for fuel consumption were derived as steady-state equations below the limiting roughness for the different vehicle. However, for the roughness values above the limiting roughness the fuel consumption was determined at representative roughness values and a regression analysis was performed to determine the fuel consumption equations for the vehicles above the limiting roughness.

The roughness values that were used for the regression analysis were:

Light, Taxi and Bus:	IRI = 8.0, 10.0 and 12.0
Heavy:	IRI = 7.0, 8.0, 10.0 and 12.0

The results of the regression analysis are given in Appendix C.

The formula for the rolling resistance to motion is:

$$FR = FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2 \right)$$

with all parameters as defined earlier.

Engine and accessories power

The total power required to overcome engine drag and for running vehicle accessories, is calculated as a function of engine speed and vehicle speed as follows:

PENGACCS = Kpea*PRAT*{PACCS_a1+[(PACCS_a0 - PACCS_a1)*(RPM - RPM_IDLE)]/(RPM100 – RPM_IDLE)

where:

PENGACCS	engine and accessories power [kW]
Kpea	calibration factor (default = 1.0)
PRAT	maximum rated engine power [kW]
RPM	engine speed at operating speed [rev/min]
RPM_IDLE	idle engine speed [rev/min]
RPM100	engine speed at 100 km/h [rev/min]
PACCS_a0	ratio of engine and accessory drag to rated engine power when travelling at 100 km/h
PACCS_a1	a model parameter

PACCS_a1 is calculated as follows:

$$a = ZETAB*EHP*Kpea^2*PRAT*(100-PCTPENG)/100$$
$$b = ZETAB*Kpea*PRAT$$
$$c = -IDLE\_FUEL$$

and

$$PACCS\_a1 = [-b + \sqrt{(b^2 - 4*a*c)}]/(2*a)$$

where:

ZETAB	base fuel-to-power efficiency factor [ml/kW/s]
EHP	decrease in engine efficiency when producing higher power
PCTPENG	percentage of the total engine and accessories power produced from the engine (default = 80)

The parameters for the different vehicles are listed in the table below.

Vehicle	RPM_a0	RPM_a1	RPM_a2	RPM_a3	RPM_IDLE	IDLE_FUEL	ZETAB	EHP	PRAT	EDT	PACCS_a0	PCTPENG
Light	1709	7.16	2.25	42	800	0.48	0.067	0.25	90	0.9	0.2	80
Taxi	2490	-30.4	2.25	34	800	0.48	0.067	0.25	60	0.9	0.2	80
Heavy	1167	-24	2.25	22	500	1.12	0.056	0.1	280	0.86	0.2	80
Bus	1214	-24	2.25	22	500	0.37	0.057	0.1	100	0.86	0.2	80

The parameters RPM100 and RPM are calculated from:

Light and Taxi:

$$RPM100 = RPM\_a0 + RPM\_a1*27.8 + RPM\_a2*27.82$$
$$RPM = RPM\_a0 + RPM\_a1*V + RPM\_a2*V^2$$

Heavy and Bus:

$$RPM100 = (RPM\_a0 + RPM\_a1*RPM\_a3 + RPM\_a2*RPM\_a3^2)*27.8/RPM\_a3$$
$$RPM = RPM\_a0 + RPM\_a1*V + RPM\_a2*V^2$$

where:

V vehicle operating speed

Total power requirement

The total power requirement is calculated as:

PTOT = (PTR/EDT + PENGACCS)

where:

PTOT	total power requirement for steady-state motion [kW]
PTR	total tractive power [kW]
EDT	drivetrain efficiency
PENGACCS	total engine and accessories power [kW]

Efficiency factor

The fuel to power efficiency factor ZETA relates the instantaneous fuel consumption to the total power requirement of the engine as follows:

ZETA = ZETAB*[1 + EHP*(PTOT – PCTPENG*PENGACCS/100)/PRAT]

with all parameters as defined earlier.

Fuel consumption per vehicle-km

The specific fuel consumption (ml) per vehicle-km on the road is calculated as:

SFC = 1000*IFC/V

where:

SFC	specific fuel consumption [ml/km]
IFC	instantaneous fuel consumption [ml/s]
V	vehicle operating speed [m/s]

The fuel consumption of the vehicle is then:

$$FC = \frac{SFC}{1000} \quad \text{[l/veh-km]}$$

or

$$FC = \frac{IFC}{V} \quad \text{[l/veh-km]}$$ **Equation 2**

The resulting equations when all calculations are done for the vehicles are:

Table 1: Fuel consumption on unpaved roads below limiting roughness.

IRI	Vehicle	FC – Unpaved
≤ 8	Light	$74.08E-3+1.895E-3\times RI_{av}+2.739E-6\times RI_{av}^{2}$
≤ 8	Taxi	$66.07E-3+2.498E-3\times RI_{av}+6.747E-6\times RI_{av}^{2}$
≤ 7	Heavy	$0.221+7.936E-3\times RI_{av}+8.101E-6\times RI_{av}^{2}$
≤ 8	Bus	$0.097+4.112E-3\times RI_{av}+5.864E-6\times RI_{av}^{2}$

Table 2: Fuel consumption on unpaved roads above limiting roughness.

IRI	Vehicle	FC – Unpaved
> 8	Light	$0.0613\times e^{0.047\times RI_{av}}$
> 8	Taxi	$0.0581\times e^{0.0495\times RI_{av}}$
> 7	Heavy	$0.2009\times e^{0.0455\times RI_{av}}$
> 8	Bus	$0.0983\times e^{0.0352\times RI_{av}}$

Table 3: Fuel consumption on paved roads below limiting roughness.

IRI	Vehicle	FC – Paved
≤ 8	Light	$0.072+553.55E-6\times RI_{av}+236.4E-9\times RI_{av}^{2}$
≤ 8	Taxi	$0.063+729.1E-6\times RI_{av}+577.86E-9\times RI_{av}^{2}$
≤ 7	Heavy	$0.207+3.159E-3\times RI_{av}+1.294E-6\times RI_{av}^{2}$
≤ 8	Bus	$0.09+1.638E-3\times RI_{av}+938.9E-9\times RI_{av}^{2}$

Table 4: Fuel consumption on paved roads above limiting roughness.

IRI	Vehicle	FC – Paved
> 8	Light	$0.0535\times e^{0.0447\times RI_{av}}$
> 8	Taxi	$0.0478\times e^{0.0462\times RI_{av}}$
> 7	Heavy	$0.1693\times e^{0.0425\times RI_{av}}$
> 8	Bus	$0.0822\times e^{0.0279\times RI_{av}}$

Cost of Fuel

$$FuelCost_{av} = \sum_{k=1}^{4} FC_k \times AADT_k \times TypeCost_k$$ **Equation 3**

where

$FuelCost_{av}$	average cost of fuel for an AADT [R/veh-km]
FC_k	fuel consumption for vehicle type k
TypeCost	the cost of a litre fuel for the type of fuel (e.g. petrol/diesel)
$AADT_k$	the annual average vehicles for vehicle type k

Oil Consumption

Oil consumption is modelled in two components: oil loss due to contamination and oil loss due to operation. The equation is:

$$OIL = OILCONT + OILOPER \times FC \qquad \textbf{Equation 4}$$

where:

OIL	oil consumption [l/veh-km]
OILCONT	oil loss due to contamination [l/veh-km]
OILOPER	oil loss due to operation [l/veh-km]
FC	fuel consumption [l/veh-km]

The loss due to contamination is determined as:

OILCONT = OILCAP/DISTCHNG

where:

OILCAP	engine oil capacity [litre]
DISTCHNG	distance between oil changes [km]

The parameters for the vehicles are:

Vehicle	DISTCHNG	OILCAP	OILCONT	OILOPER
Light	10 000	4	0.0004	0.0000028
Taxi	7 500	5	0.000667	0.0000028
Heavy	10 000	31	0.0031	0.0000021
Bus	8 000	14	0.00175	0.0000021

The equations for OIL for the vehicles become:

Vehicle	OIL
Light	0.0004 + 0.0000028*FC
Taxi	0.000667 + 0.0000028*FC
Heavy	0.0031 + 0.0000021*FC
Bus	0.00175 + 0.0000021*FC

These equations can be simplified further as shown in the tables below.

Table 5: Oil consumption on unpaved roads below limiting roughness.

IRI	Vehicle	OIL – Unpaved
≤ 8	Light	$0.0004 + 0.0000028 \times (74.08E-3 + 1.895E-3 \times RI_{av} + 2.739E-6 \times RI_{av}^2)$
≤ 8	Taxi	$0.000667 + 0.0000028 \times (66.07E-3 + 2.498E-3 \times RI_{av} + 6.747E-6 \times RI_{av}^2)$
≤ 7	Heavy	$0.0031 + 0.0000021 \times (0.221 + 7.936E-3 \times RI_{av} + 8.101E-6 \times RI_{av}^2)$
≤ 8	Bus	$0.00175 + 0.0000021 \times (0.097 + 4.112E-3 \times RI_{av} + 5.864E-6 \times RI_{av}^2)$

Table 6: Oil consumption on unpaved roads above limiting roughness.

IRI	Vehicle	OIL – Unpaved
> 8	Light	$0.0004 + 0.0000028 \times (0.0613 \times e^{0.047 \times RI_{av}})$
> 8	Taxi	$0.000667 + 0.0000028 \times (0.0581 \times e^{0.0495 \times RI_{av}})$
> 7	Heavy	$0.0031 + 0.0000021 \times (0.2009 \times e^{0.0455 \times RI_{av}})$
> 8	Bus	$0.00175 + 0.0000021 \times (0.0983 \times e^{0.0352 \times RI_{av}})$

Table 7: Oil consumption on paved roads below limiting roughness.

IRI	Vehicle	OIL – Paved
≤ 8	Light	$0.0004 + 0.0000028 \times (0.072 + 553.55E-6 \times RI_{av} + 236.4E-9 \times RI_{av}^2)$
≤ 8	Taxi	$0.000667 + 0.0000028 \times (0.063 + 729.1E-6 \times RI_{av} + 577.86E-9 \times RI_{av}^2)$
≤ 7	Heavy	$0.0031 + 0.0000021 \times (0.207 + 3.159E-3 \times RI_{av} + 1.294E-6 \times RI_{av}^2)$
≤ 8	Bus	$0.00175 + 0.0000021 \times (0.09 + 1.638E-3 \times RI_{av} + 938.9E-9 \times RI_{av}^2)$

Table 8: Oil consumption on paved roads above limiting roughness.

IRI	Vehicle	OIL – Paved
> 8	Light	$0.0004 + 0.0000028 \times (0.0535 \times e^{0.0447 \times RI_{av}})$
> 8	Taxi	$0.000667 + 0.0000028 \times (0.0478 \times e^{0.0462 \times RI_{av}})$
> 7	Heavy	$0.0031 + 0.0000021 \times (0.1693 \times e^{0.0425 \times RI_{av}})$
> 8	Bus	$0.00175 + 0.0000021 \times (0.0822 * e^{0.0279 \times RI_{av}})$

Cost of Oil

$$OilCost_{av} = \sum_{k=1}^{4} OIL_k \times AADT_k \times Oilprice_k \qquad \textbf{Equation 5}$$

where

$OilCost_{av}$	average cost of oil for an AADT [R/veh-km]
OIL_k	oil consumption for vehicle type k
Oilprice	the cost of a litre oil for the type of vehicle
$AADT_k$	the annual average vehicles for vehicle type k

Tyre Consumption

This section describes the calculations used for the estimation of tyre consumption for the different vehicle types.

$$EQNT = \frac{1 + 0.01 \times RREC \times NR}{DISTOT} + 0.0027 \qquad \textbf{Equation 6}$$

where

EQNT	number of equivalent new tyres per 1000 vehicle-km for each wheel
RREC	retread cost as a percentage of new tyre cost (default = 15)
NR	number of retreads per tyre carcass
DISTOT	total distance travelled by the tyre (1000's km)

Number of retreads per tyre:

$$NR = MAX\left[0, NR0 \times \exp\left(-0.03224 \times RI_{\text{mod}}\right) - 1\right]$$

where

NR0	base number of recaps [default = 1.3]
RI_{mod}	modified value of the average road roughness (IRI m/km)

Thus, the equation for the number of retreads becomes:

$$NR = MAX\left[0,\ 1.3 \times \exp\left(-0.03224 \times RI_{\text{mod}}\right) - 1\right]$$

For RI_{mod} = 7, NR is calculated as 0.04 and for RI_{mod} = 4, NR is calculated as 0.14. This implies an increase in the total distance travelled by a tyre of 4 % and 14 % for the respective values of roughness. Thus, it is concluded that the factor ***NR*** can be ignored.

Total distance travelled by the tyre:

$$DISTOT = (1 + NR) \times \frac{VOL}{TWT}$$

where

VOL	volume of wearable rubber (dm^3)
TWT	rate of tread wear (dm^3/1000 veh-km)

When the previous paragraph is kept in mind, the equation for the total distance travelled simplifies to:

$$DISTOT = \frac{VOL}{TWT}$$

Rate of tread wear:

$$TWT = C0tc + Ctcte \times TE$$

where

TE tangential energy of each tyre (J-m)
C0tc constant term of the tyre tread wear model (dm^3)
Ctcte wear coefficient of the tyre tread wear model (dm^3/J-m)

When the calculation is done for each vehicle type, the formula becomes:

Vehicle	TWT
Light	0.02616+3.466E-8*FR^2
Taxi	0.024+1.906E-8*FR^2
Heavy	0.03529+2.156E-9*FR^2
Bus	0.03088+5.908E-9*FR^2

The values for the tyre parameters are listed in the table below.

Vehicle	RI_{mod}	NR0	C0tc	Ctcte	VOL (dm^3)
Light	RI_{av}	1.3	0.02616	0.00204	1.4
Taxi	RI_{av}	1.3	0.024	0.00187	1.6
Heavy	Min[7, RI_{av}]	1.3	0.03529	0.00275	8.0
Bus	Min[7, RI_{av}]	1.3	0.03088	0.00207	6.0

Tangential energy is calculated as:

$$TE = \frac{\left(CFT^2 + LFT^2\right)}{NFT}$$

where

CFT circumferential force acting on a tyre (N)
LFT lateral force acting on a tyre (N) [IGNORED: Geometry dependent]
NFT normal force acting on a tyre (N)

Thus the equation becomes:

$$TE = \frac{CFT^2}{NFT}$$

The tangential energy (TE) for the different vehicles is as follows (note that TE is dependent on road type – see the formulae for calculation of FR):

Vehicle	TE
Light	1.699E-5*FR^2
Taxi	1.019E-5*FR^2
Heavy	7.841E-7*FR^2
Bus	2.854E-6*FR^2

Circumferential force:

$$CFT = \frac{(1 + CTCON \times dFUEL)(FA + FG + FR)}{NUM\_WHEELS}$$

where

CTCON	incremental change of tyre consumption related to additional fuel
dFUEL	additional fuel consumption factor due to speed change effects (= 0 for steady state motion)
FA	aerodynamic resistance to motion [IGNORED: assumed constant]
FG	gradient resistance to motion [IGNORED: Geometry dependent]
FR	rolling resistance to motion

Thus the equation becomes:

$$CFT = \frac{FR}{NUM\_WHEELS}$$

The rolling resistance (FR) is a function of the road type and the formulae for the calculation of FR are as listed previously.

Normal force:

$$NFT = \frac{WGT\_OPER \times g}{NUM\_WHEELS}$$

where

WGT_OPER	operating weight of the vehicle (kg)
g	gravitational constant (9.81 m/s^2)

Tyre Consumption per 1000 veh-km

When all the simplifications are considered, the equation for EQNT becomes:

$$EQNT = \frac{1.15}{DISTOT} + 0.0027$$ **Equation 7**

The value of DISTOT is calculated for each vehicle and pavement type as follows:

	DISTOT (gravel)
Light	$\frac{1.4}{0.02616 + 3.466E{-}8 \times (309.4 + 23.2 \times RI_{av})^2}$
Taxi	$\frac{1.6}{0.024 + 1.906E{-}8 \times (395.8 + 29.69 \times RI_{av})^2}$
Heavy	$\frac{8.0}{0.03529 + 2.156E{-}9 \times (1547.99 + 116.1 \times RI_{av})^2}$
Bus	$\frac{6.0}{0.03088 + 5.908E{-}9 \times (780.46 + 58.53 \times RI_{av})^2}$

The equation for the calculation of DISTOT of the paved roads needs the texture depth as an input. When the value of TD is varied between 0.5 mm and 1.5mm in 0.5 mm intervals, the resulting DISTOT varies with approximately 0.3 % for the different vehicles. Thus, it was decided to set the value of TD to 1 mm. The resulting equations are listed in the table below.

	DISTOT (paved)
Light	$\dfrac{1.4}{0.02616+3.466E{-}8\times(285.3+6.8\times RI_{av})^2}$
Taxi	$\dfrac{1.6}{0.024+1.906E{-}8\times(364.9+8.7\times RI_{av})^2}$
Heavy	$\dfrac{8.0}{0.03529+2.156E{-}9\times(1346.75+46.44\times RI_{av})^2}$
Bus	$\dfrac{6.0}{0.03088+5.908E{-}9\times(679+23.41\times RI_{av})^2}$

The tyre consumption is calculated as:

$$TC = \frac{EQNT \times NUM\_WHEELS}{MODFAC}$$ **Equation 8**

and

$$MODFAC = VEHFAC \times TYPEFAC \times CONGFAC$$

where

- MODFAC tyre life modification factor
- VEHFAC vehicle type modification factor
- TYPEFAC tyre type modification factor
- CONGFAC congestion effects modification factor (for free-flow: = 1)

The MODFAC becomes:

$$MODFAC = VEHFAC \times TYPEFAC$$

Wheel Type	TYPEFAC		
	Paved Roads	Unpaved Roads	
		$IRI \le 6$	$IRI > 6$
Bias	1.0	1.0	1.0
Radial	1.25	1.2	1.0

In the case of unpaved roads, a target roughness value is assigned to a road and the blading frequency is determined to keep the roughness at that value. This roughness value is usually QI = 70, which is equal to an IRI value of 5.7. Thus, the target value is close to the inflection point for the TYPEFAC for radial tyres on unpaved roads. For this reason it was decided to use a TYPEFAC value of 1.0 for radial tyres on unpaved roads.

VEHFAC	
Light	2.0
Taxi	2.0
Heavy	1.0
Bus	1.0

Using these constants the MODFAC for the different vehicle types and road conditions become:

Vehicle	MODFAC	
	Paved	Unpaved
Light	2.5	2.0
Taxi	2.5	2.0
Heavy	1.0	1.0
Bus	1.0	1.0

The equation for the calculation of tyre consumption becomes:

Table 9: Tyre cost factor for unpaved roads.

	TC (unpaved roads)
Light	$4.298E-2 + 5.694E-8x(309.4 + 23.2xRI_{av})^2 + 5.4E-3$
Taxi	$3.45E-2 + 2.74E-8x(395.8 + 29.69xRI_{av})^2 + 5.4E-3$
Heavy	$5.073E-2 + 3.099E-9x(1547.99 + 116.1xRI_{av})^2 + 2.7E-2$
Bus	$3.557E-2 + 6.804E-9x(780.46 + 58.53xRI_{av})^2 + 1.62E-2$

Table 10: Tyre cost factor for paved roads.

	TC (paved roads)
Light	$3.438E-2 + 4.555E-8x(285.3 + 6.8xRI_{av})^2 + 4.32E-3$
Taxi	$2.76E-2 + 2.192E-8x(364.9+ 8.7xRI_{av})^2 + 4.32E-3$
Heavy	$5.073E-2 + 3.099E-9x(1346.75 + 46.44xRI_{av})^2 + 2.7E-2$
Bus	$3.557E-2 + 6.804E-9x(679 + 23.41xRI_{av})^2 + 1.62E-2$

The Annual Average Tyre Consumption is:

$$TC_{avk} = TC_k \times AADT_k$$ **Equation 9**

where

TC_{avk}	average annual tyre consumption of vehicle type k
TC_k	tyre consumption by vehicle type k (per 1000 veh-km)
$AADT_k$	AADT of vehicle type k

The cost of tyres is:

$$TC_{av} = \sum_{k=1}^{4} TC_{avk} \times TYRECOST_k$$ **Equation 10**

where

TC_{av}	tyre cost (R per 1000 veh-km)
$TYRECOST_k$	average cost of a new tyre for vehicle type k

Service Life

The calculation of the service life of a vehicle is based on the optimal vehicle life method. The service life is needed for the calculation of the parts consumption and depreciation cost factors.

Optimal Life Method

$$LIFEKM = \frac{LIFEKM0 \times LIFEKMPCT}{100}$$ **Equation 11**

where

LIFEKM	predicted optimal lifetime in kilometres (km)
LIFEKM0	baseline average vehicle service life in kilometres (km)
LIFEKMPCT	optimal lifetime kilometres as a percentage of baseline vehicle service life (%)

$$LIFEKM0 = AKM0 \times LIFE0$$

where

AKM0	baseline average number of kilometres driven per vehicle per year (km)
LIFE0	baseline average vehicle service life (years)

$$LIFEKMPCT = \frac{100}{1 + \exp\left(a0 \times RI_{adj}^{\ a1}\right)}$$

where

RI_{adj}	adjusted road roughness (IRI m/km)
a0	-65.8553
a1	-1.9194

Vehicle	AKM0	LIFE0	LIFEKM0
Light	30 000	8	240 000
Taxi	30 000	8	240 000
Heavy	86 000	14	1 204 000
Bus	70 000	7	490 000

Adjusting the Road Roughness

$$RI_{adj} = MAX\left[RI_{av}, MIN\left(RI0, RIMIN + a2 \times RI^{a3}\right)\right]$$

$$RI0 = RIMIN + RI\_SHAPE$$

$$a2 = \frac{RI\_SHAPE}{RI0^{\frac{RI0}{RI\_SHAPE}}}$$

$$a3 = \frac{RI0}{RI\_SHAPE}$$

where

RI_{av}	average roughness of the road (IRI m/km)
RIMIN	minimum roughness to be used (default = 3.6 [corresponds to QI =40])
RI_SHAPE	shape factor (default = 0.25)

This equation simplifies to the following equalities:

$$RI_{adj} = 3.6 + 2.409E\text{–}10 \times RI_{av}^{15.4} \quad for\ RI_{av} \leq 3.85$$

or

$$RI_{adj} = RI_{av} \quad for\ RI_{av} > 3.85$$

The equalities can be further simplified to obtain the following values for RI_{adj}:

	RI_{av} ≤ 3.85	**RI_{av} >3.85**
RI_{adj}	3.6	RI_{av}

It can be assumed that the road roughness will very rarely be below IRI = 3.85 (QI = 44). Thus, it can be assumed that the adjusted roughness (RI_{adj}) is equal to the average roughness ($RI_{adj} = RI_{av}$).

The equation for LIFEKMPCT then becomes:

$$LIFEKMPCT = \frac{100}{1 + \exp\left(a0 \times RI_{av}^{a1}\right)}$$ **Equation 12**

Parts Consumption

The parts consumption model considers vehicle age, roughness and speed-change cycles. For steady state free-flow conditions it is not necessary to consider speed-change cycles.

The parts consumption cost factor is expressed as a fraction of the replacement vehicle price.

$$PC = K0pc \times \left[CKM^{KP} \times \left(a0 + a1 \times RI_{adj} \right) + K1pc \right] \times \left[1 + CPCON \times dFUEL \right]$$

where

PC	parts consumption per 1000 veh-km, expressed as a fraction of the average new (or replacement) vehicle price, NVP
CKM	average cumulative number of kilometres driven per vehicle type (km)
KP	age exponent in parts consumption model
RIadj	adjusted road roughness (IRI m/km)
CPCON	incremental change factor due to speed change cycle effects
dFUEL	additional fuel consumption due to speed change cycles
a0	constant term model parameter
a1	roughness dependent model parameter
K0pc	parts consumption rotational calibration factor (default = 1)
K1pc	parts consumption translational calibration factor (default = 0)

The last term of the equation falls away for steady state motion. Thus, the equation becomes:

$$PC = CKM^{KP} \times \left(a0 + a1 \times RI_{av} \right)$$ **Equation 13**

As explained in the previous section, the adjusted roughness (RI_{adj}) can be assumed to be equal to the average roughness (RI_{av}).

The values of the parameters are given in the table below.

Vehicle	CKM	KP	a0	A1
Light	120 000	0.308	36.94E-6	6.2E-6
Taxi	120 000	0.308	36.76E-6	6.2E-6
Heavy	602 000	0.371	11.58E-6	2.96E-6
Bus	245 000	0.483	0.57E-6	0.49E-6

Using the constants given in the table above, the equation for PC becomes:

Table 11: Parts consumption cost factor.

Vehicle	PC
Light	$1.355E\text{-}3 + 2.274E\text{-}4xRI_{av}$
Taxi	$1.348E\text{-}3 + 2.274E\text{-}4xRI_{av}$
Heavy	$1.614E\text{-}3 + 4.126E\text{-}4xRI_{av}$
Bus	$2.285E\text{-}4 + 1.964E\text{-}4xRI_{av}$

The vehicle age is given in terms of the cumulative number of kilometres driven, CKM. The values of CKM as given above is based on the following formula

$$CKM = 0.5 \times LIFEKM$$

where

LIFEKM the predicted optimal vehicle service life (km)

Annual Average Parts Consumption

The annual average parts consumption is calculated as a fraction of the new vehicle price per 1000 veh-km.

$$PC_{avk} = AADT_k \times PC_k \qquad \textbf{Equation 14}$$

where

$AADT_k$ AADT of vehicle type k

PC_k the parts consumption of vehicle type k

Thus, the cost of parts is:

$$PARTSCOST = \sum_{k=1}^{4} PC_{avk} \times VEHCOST_k \qquad \textbf{Equation 15}$$

where

PARTSCOST cost of parts (R per 1000 veh-km)

$VEHCOST_k$ the average cost of a new vehicle of type k

Labour Hours

Maintenance labour hours are calculated as a function of the parts consumption. Labour wage rates are applied to the predicted number of labour hours to obtain labour costs. The formula for calculation of the labour hours is:

$$LH = K0lh \times \left(a0 \times PC^{a1}\right) + K1lh$$

where

LH	number of labour hours per 1000 veh-km
PC	parts consumption per 1000 veh-km expressed as a fraction of average new vehicle price
a0	constant term of maintenance labour model
a1	parts exponent of maintenance labour model
K0lh	rotational calibration factor (default = 1)
K1lh	translational calibration factor (default = 0)

When the calibration factors are applied to the formula it leads to the following equation:

$$LH = a0 \times PC^{a1}$$ **Equation 16**

The values of the parameters used are given in the table below.

Table 12: Labour hours calculation factors.

Vehicle	a0	a1	LH
Light	77.14	0.547	$77.14x(1.355E\text{-}3 + 2.274E\text{-}4xRI_{av})^{0.547}$
Taxi	77.14	0.547	$77.14x(1.348E\text{-}3 + 2.274E\text{-}4xRI_{av})^{0.547}$
Heavy	301.46	0.519	$301.46x(1.614E\text{-}3 + 4.126E\text{-}4xRI_{av})^{0.519}$
Bus	293.44	0.519	$293.44x(2.285E\text{-}4 + 1.964E\text{-}4xRI_{av})^{0.519}$

Annual Average Labour Hours

The annual average labour hours are calculated as shown below.

$$LH_{av} = \sum_{k=1}^{4} LH_k \times AADT_k$$ **Equation 17**

where

$AADT_k$	AADT of vehicle type k
LH_k	labour hours per 1000 veh-km for vehicle type k

Labour cost is calculated as follows:

$$LABOURCOST = WAGECOST \times LH_{av}$$ **Equation 18**

where

LABOURCOST	cost of maintenance labour (R per 1000 veh-km)
WAGECOST	the rate of labour wages

Depreciation Cost

The cost of depreciation is calculated through the following formula:

$$DEPCST = DEP \times NVPLT$$ **Equation 19**

where

DEPCST	depreciation cost (R per 1000 veh-km)
DEP	depreciation cost factor per 1000 veh-km
NVPLT	average new (or replacement) vehicle price less tyres

NVPLT is calculated as follows:

$$NVPLT = NVP - NUM\_WHEELS \times NTP$$ **Equation 20**

where

NVP	average new (or replacement) vehicle price
NTP	average new tyre price

Depreciation Cost Factor

The calculation of the depreciation cost factor based on the optimal life method is shown below.

$$DEP = \frac{1000 \times (1 - 0.001 \times RVPLTPCT)}{LIFEKM}$$ **Equation 21**

where

RVPLTPCT	residual vehicle price less tyres as a percentage of new price(%)
LIFEKM	predicted optimal vehicle service life (km)

Residual Vehicle Value

The residual vehicle value is calculated as:

$$RVPLTPCT = MAX\left[a2\,, a3 - MAX\left(0, \left(RI_{av} - a4\right)\right)\right]$$

where

RVPLTPCT	residual vehicle price less tyres at the end of its service life (%)
RI_{av}	average road roughness (IRI m/km)

a2	minimum residual value of the vehicle (default = 2) (%)
a3	maximum residual value of the vehicle (default = 15) (%)
a4	average road roughness, IRI, below which the maximum residual value arises (default = 5)

Thus, RVPLTPCT becomes:

$$RVPLTPCT = MAX\left[2\ ,15 - MAX\left(0,\left(RI_{av} - 5\right)\right)\right]$$

It can be assumed that the average roughness of a road will never exceed IRI = 18 (QI = 242). Thus the equation simplifies to:

$$RVPLTPCT = 15 - MAX\left[0,\left(RI_{av} - 5\right)\right]$$

This equation simplifies to the following equalities:

$$RVPLTPCT = 20 - RI_{av} \qquad for \quad RI_{av} > 5$$

$$RVPLTPCT = 15 \qquad for \quad RI_{av} \leq 5$$

When the two scenario's ($RI_{av}>5$ and $RI_{av}\leq5$) are used to calculate the depreciation factor, DEP, it is seen that the value of the roughness does not influence the factor. Therefore it was decided to only use the equation for the case when $RI_{av}>5$.

The depreciation cost factor for each of the vehicle types becomes:

Table 13: Depreciation cost factors.

Vehicle	DEP
Light	$\dfrac{980 + RI_{av}}{\left[\dfrac{240000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$
Taxi	$\dfrac{980 + RI_{av}}{\left[\dfrac{240000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$
Heavy	$\dfrac{980 + RI_{av}}{\left[\dfrac{1204000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$
Bus	$\dfrac{980 + RI_{av}}{\left[\dfrac{490000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$

Annual Average Depreciation Cost

The average annual depreciation cost is calculated as:

$$DEPCST_{av} = \sum_{k=1}^{4} AADT_k \times DEPCST_k$$ **Equation 22**

where

DEPCSTav	depreciation cost (R per 1000 veh-km)
$AADT_k$	AADT of vehicle type k
$DEPCST_k$	depreciation cost of vehicle type k

Vehicle Operating Cost

The VOC for a road segment with an AADT is calculated as:

$$VOC = \left(TC_{av} + PARTSCOST + LABOURCOST + DEPCST_{av}\right) \times \frac{Length \quad of\ road\ segment}{1000}$$
$$+ (FuelCost_{av} + OilCost_{av}) \times Length \quad of\ road\ segment$$

where

$$FuelCost_{av} = \sum_{k=1}^{4} FC_k \times AADT_k \times TypeCost_k \qquad \text{(p. 15)}$$

$$FC = \frac{IFC}{V} \qquad \text{(p. 13)}$$

$$OilCost_{av} = \sum_{k=1}^{4} OIL_k \times AADT_k \times Oilprice_k \qquad \text{(p. 18)}$$

$$OIL = OILCONT + OILOPER \times FC \qquad \text{(p. 16)}$$

$$TC_{av} = \sum_{k=1}^{4} TC_{avk} \times TYRECOST_k \qquad \text{(p. 25)}$$

$$TC_{avk} = TC_k \times AADT_k \qquad \text{(p. 24)}$$

$$TC = \frac{EQNT \times NUM\_WHEELS}{MODFAC} \qquad \text{(p. 23)}$$

$$PARTSCOST = \sum_{k=1}^{4} PC_{avk} \times VEHCOST_k \qquad \text{(p. 29)}$$

$$PC_{avk} = AADT_k \times PC_k \qquad \text{(p. 29)}$$

$$PC = CKM^{KP} \times \left(a0 + a1 \times RI_{av}\right) \qquad \text{(p. 28)}$$

$$LABOURCOST = WAGECOST \times LH_{av} \qquad \text{(p. 31)}$$

$$LH_{av} = \sum_{k=1}^{4} LH_k \times AADT_k \qquad \text{(p. 30)}$$

$$LH = a0 \times PC^{a1}$$ (p. 30)

$$DEPCST_{av} = \sum_{k=1}^{4} AADT_k \times DEPCST_k$$ (p. 34)

$$DEPCST = DEP \times NVPLT$$ (p. 32)

$$NVPLT = NVP - NUM\_WHEELS \times NTP$$ (p. 32)

$$DEP = \frac{1000 \times (1 - 0.001 \times RVPLTPCT)}{LIFEKM}$$ (p. 32)

Table 1: Fuel consumption on unpaved roads below limiting roughness. (p. 14)

IRI	Vehicle	FC – Unpaved
≤ 8	Light	$74.08E-3 + 1.895E-3 \times RI_{av} + 2.739E-6 \times RI_{av}^2$
≤ 8	Taxi	$66.07E-3 + 2.498E-3 \times RI_{av} + 6.747E-6 \times RI_{av}^2$
≤ 7	Heavy	$0.221 + 7.936E-3 \times RI_{av} + 8.101E-6 \times RI_{av}^2$
≤ 8	Bus	$0.097 + 4.112E-3 \times RI_{av} + 5.864E-6 \times RI_{av}^2$

Table 2: Fuel consumption on unpaved roads above limiting roughness. (p. 14)

IRI	Vehicle	FC – Unpaved
> 8	Light	$0.0613 \times e^{0.047 \times RI_{av}}$
> 8	Taxi	$0.0581 \times e^{0.0495 \times RI_{av}}$
> 7	Heavy	$0.2009 \times e^{0.0455 \times RI_{av}}$
> 8	Bus	$0.0983 \times e^{0.0352 \times RI_{av}}$

Table 3: Fuel consumption on paved roads below limiting roughness. (p. 14)

IRI	Vehicle	FC – Paved
≤ 8	Light	$0.072 + 553.55E-6 \times RI_{av} + 236.4E-9 \times RI_{av}^2$
≤ 8	Taxi	$0.063 + 729.1E-6 \times RI_{av} + 577.86E-9 \times RI_{av}^2$
≤ 7	Heavy	$0.207 + 3.159E-3 \times RI_{av} + 1.294E-6 \times RI_{av}^2$
≤ 8	Bus	$0.09 + 1.638E-3 \times RI_{av} + 938.9E-9 \times RI_{av}^2$

Table 4: Fuel consumption on paved roads above limiting roughness. (p. 14)

IRI	Vehicle	FC – Paved
> 8	Light	$0.0535 \times e^{0.0447 \times RI_{av}}$
> 8	Taxi	$0.0478 \times e^{0.0462 \times RI_{av}}$
> 7	Heavy	$0.1693 \times e^{0.0425 \times RI_{av}}$
> 8	Bus	$0.0822 \times e^{0.0279 \times RI_{av}}$

Table 5: Oil consumption on unpaved roads below limiting roughness. (p. 17)

IRI	Vehicle	OIL – Unpaved
≤ 8	Light	$0.0004 + 0.0000028 \times (74.08E - 3 + 1.895E - 3 \times RI_{av} + 2.739E - 6 \times RI_{av}^{2})$
≤ 8	Taxi	$0.000667 + 0.0000028 \times (66.07E - 3 + 2.498E - 3 \times RI_{av} + 6.747E - 6 \times RI_{av}^{2})$
≤ 7	Heavy	$0.0031 + 0.0000021 \times (0.221 + 7.936E - 3 \times RI_{av} + 8.101E - 6 \times RI_{av}^{2})$
≤ 8	Bus	$0.00175 + 0.0000021 \times (0.097 + 4.112E - 3 \times RI_{av} + 5.864E - 6 \times RI_{av}^{2})$

Table 6: Oil consumption on unpaved roads above limiting roughness. (p. 17)

IRI	Vehicle	OIL – Unpaved
> 8	Light	$0.0004 + 0.0000028 \times (0.0613 \times e^{0.047 \times RI_{av}})$
> 8	Taxi	$0.000667 + 0.0000028 \times (0.0581 \times e^{0.0495 \times RI_{av}})$
> 7	Heavy	$0.0031 + 0.0000021 \times (0.2009 \times e^{0.0455 \times RI_{av}})$
> 8	Bus	$0.00175 + 0.0000021 \times (0.0983 \times e^{0.0352 \times RI_{av}})$

Table 7: Oil consumption on paved roads below limiting roughness. (p. 17)

IRI	Vehicle	OIL – Paved
≤ 8	Light	$0.0004 + 0.0000028 \times (0.072 + 553.55E - 6 \times RI_{av} + 236.4E - 9 \times RI_{av}^{2})$
≤ 8	Taxi	$0.000667 + 0.0000028 \times (0.063 + 729.1E - 6 \times RI_{av} + 577.86E - 9 \times RI_{av}^{2})$
≤ 7	Heavy	$0.0031 + 0.0000021 \times (0.207 + 3.159E - 3 \times RI_{av} + 1.294E - 6 \times RI_{av}^{2})$
≤ 8	Bus	$0.00175 + 0.0000021 \times (0.09 + 1.638E - 3 \times RI_{av} + 938.9E - 9 \times RI_{av}^{2})$

Table 8: Oil consumption on paved roads above limiting roughness. (p. 17)

IRI	Vehicle	OIL – Paved
> 8	Light	$0.0004 + 0.0000028 \times (0.0535 \times e^{0.0447 \times RI_{av}})$
> 8	Taxi	$0.000667 + 0.0000028 \times (0.0478 \times e^{0.0462 \times RI_{av}})$
> 7	Heavy	$0.0031 + 0.0000021 \times (0.1693 \times e^{0.0425 \times RI_{av}})$
> 8	Bus	$0.00175 + 0.0000021 \times (0.0822 * e^{0.0279 \times RI_{av}})$

Table 9: Tyre cost factor for unpaved roads. (p. 24)

	TC (unpaved roads)
Light	$4.298E{-2} + 5.694E{-8}x(309.4 + 23.2xRI_{av})^2 + 5.4E{-3}$
Taxi	$3.45E{-2} + 2.74E{-8}x(395.8 + 29.69xRI_{av})^2 + 5.4E{-3}$
Heavy	$5.073E{-2} + 3.099E{-9}x(1547.99 + 116.1xRI_{av})^2 + 2.7E{-2}$
Bus	$3.557E{-2} + 6.804E{-9}x(780.46 + 58.53xRI_{av})^2 + 1.62E{-2}$

Table 10: Tyre cost factor for paved roads. (p. 24)

	TC (paved roads)
Light	$3.438E{-2} + 4.555E{-8}x(285.3 + 6.8xRI_{av})^2 + 4.32E{-3}$
Taxi	$2.76E{-2} + 2.192E{-8}x(364.9+ 8.7xRI_{av})^2 + 4.32E{-3}$
Heavy	$5.073E{-2} + 3.099E{-9}x(1346.75 + 46.44xRI_{av})^2 + 2.7E{-2}$
Bus	$3.557E{-2} + 6.804E{-9}x(679 + 23.41xRI_{av})^2 + 1.62E{-2}$

Table 11: Parts consumption cost factor. (p. 29)

Vehicle	**PC**
Light	$1.355E{-3} + 2.274E{-4}xRI_{av}$
Taxi	$1.348E{-3} + 2.274E{-4}xRI_{av}$
Heavy	$1.614E{-3} + 4.126E{-4}xRI_{av}$
Bus	$2.285E{-4} + 1.964E{-4}xRI_{av}$

Table 12: Labour hours calculation factors. (p. 30)

Vehicle	**LH**
Light	$77.14x(1.355E{-3} + 2.274E{-4}xRI_{av})^{0.547}$
Taxi	$77.14x(1.348E{-3} + 2.274E{-4}xRI_{av})^{0.547}$
Heavy	$301.46x(1.614E{-3} + 4.126E{-4}xRI_{av})^{0.519}$
Bus	$293.44x(2.285E{-4} + 1.964E{-4}xRI_{av})^{0.519}$

Table 13: Depreciation cost factors. (p. 33)

Vehicle	DEP
Light	$\frac{980 + RI_{av}}{\left[\frac{240000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$
Taxi	$\frac{980 + RI_{av}}{\left[\frac{240000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$
Heavy	$\frac{980 + RI_{av}}{\left[\frac{1204000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$
Bus	$\frac{980 + RI_{av}}{\left[\frac{490000}{1 + \exp\left(-65.8553 \times RI_{av}^{-1.9194}\right)}\right]}$

Economic Evaluation of Projects: Internal Rate of Return (IRR) – HDM-4 Methodology

There are several factors that can be calculated to evaluate the economic viability of different investment options. These are:

- Net Present Value (NPV)
- Internal Rate of Return (IRR)
- Benefit/Cost Ratio (BCR)
- First Year Benefits (FYB)

In order to compare different investment options, it is necessary to calculate the net benefits of implementing one option relative to the other. This is done on a year to year basis for the analysis period considered.

This discussion focuses on the use of the Internal Rate of Return for the determination of economic viability of different maintenance options on a given road segment.

For the calculation of the IRR the following parameters must be defined by the user or modelled from existing data:

- Traffic characteristics: AADT and Traffic Growth Rate (Defined)
- Roughness deterioration with time (Modelled)
- Analysis period (Defined)
- Investment options (Defined)

For the calculation of the IRR different investment options must be defined. Investment options as it is used here refers to the different maintenance options on a road segment. Maintenance options refers to different maintenance strategies that are applicable to the segment over the analysis period.

Maintenance options must include an option to “Do Nothing”. This means that one of the maintenance strategies that must be considered is to leave the road as it is and do nothing to keep it at a certain service level or improve the service level. All other maintenance strategy benefits are then compared relative to the Do Nothing option.

Methodology

The general methodology for the calculation of the IRR is outlined in this section.

1. The cost to the road agency is calculated:

   The cost differences between a pair of investment options, *m* and *n* (n being the base option – usually the do noting option), in a given year are calculated as:

$$\Delta C_{(m-n)} = C_{ms} - C_{ns}$$

   where

   $\Delta C_{(m-n)}$ difference in road administration cost of investment option *m* relative to base option *n*

   C_{js} the total cost to road administration incurred by investment option *j* (j = m or n) for road section *s*.

   The difference in Road Agency Cost (RAC) is:

$$\Delta RAC_{(m-n)} = \Delta C_{m-n}$$

2. The savings in vehicle operating costs are calculated:

$$\Delta VCN_{(m-n)} = VCN_{ns} - VCN_{ms}$$

   with

$$VCN_{ms} = \sum_k AADT_{sk} \times UC_{msk}$$

$$VCN_{ns} = \sum_k AADT_{sk} \times UC_{nsk}$$

   where

   $\Delta VCN_{(m-n)}$ vehicle operating benefits due to normal traffic of investment option *m* relative to base option *n*

   VCN_{js} annual vehicle operating cost due to normal traffic over road section *s* with investment option *j*

   $AADT_{sk}$ the annual average daily traffic on section *s* for vehicle type *k*

   UC_{jsk} annual average operating cost per vehicle-trip over road section *s*, for vehicle type *k* under investment option *j*

Note: the AADT is the AADT from the base year inflated by the traffic growth rate to year *y*

The annual saving in vehicle operating costs is given by:

$$\Delta VOC_{(m-n)} = \Delta VCN_{(m-n)}$$

3. The annual net economic benefits are calculated:

For each pair of investment options, the annual economic benefits of implementing option *m* relative to option *n* in a given year are calculated from the costs to the road administration and road user costs as:

$$NB_{y(m-n)} = \Delta RUC_{y(m-n)} - \Delta RAC_{y(m-n)}$$

where:

$NB_{y(m-n)}$ net economic benefit of investment option *m* relative to base option *n* in year *y*

4. The internal rate of return is calculated:

The formula for the calculation of the IRR is based on the formula for the calculation of Net Present Value (NPV). The IRR is defined as the discount rate at which the NPV is zero. The formula is:

$$\sum_{y=1}^{Y} \frac{NB_{y(m-n)}}{[1+0.01\times r^{o}]^{(y-1)}} = 0$$

where

$NB_{y(m-n)}$ the net economic benefits as defined earlier
r^{o} the IRR

This equation is solved for r^{o} by evaluating the NPV at 5 % intervals of discount rates between -95 and 900 % and determining the zero(es) of the equation by linear interpolation of adjacent discount rates with NPV with opposite signs.

The IRR does not give an indication of the size of costs or benefits of an investment option. The IRR acts as a guide to the profitability of the investment. If the computed IRR is higher than the planning discount rate, then the investment option is economically justified.

APPENDIX A – UNIT PRICES FOR VOC CALCULATIONS

The table below lists the unit prices for the different vehicle types as received from the CSIR: Transportek.

Table 1: Unit prices (market prices) (2000, Rand) and conversion factors (CV)					
Vehicle type	Tyres			New vehicles	
	Unit price (R/set)	CV	Number of tyres per set	Unit Price (R/vehicle)	CV
Cars	1 217	0.874	4	93 430	0.877
Mini-buses	2 226	0.873	4	133 506	0.877
Buses	9 354	0.875	6	565 639	0.877
Bakkies	1 971	0.875	4	89 162	0.877
LGVs	9 354	0.875	6	321 624	0.877
MGVs	20 268	0.840	10	573 238	0.877
HGVs	36 482	0.840	18	827 734	0.877
Note: The conversion factor is needed to convert market prices to shadow prices.					

The table below gives the recommended values to be used.

Vehicle	Tyres (R/set)	New Vehicle Price (R/vehicle)	Wage Rate (R/hour)	TypeCost (R/litre)	Oilprice (R/litre)
Light	1 217	93 430	150	3.64	20.50
Taxi	2 226	133 506	150	3.64	20.50
Bus	9 354	565 639	150	3.50	20.50
Heavy	20 268	573 238	150	3.50	20.50

APPENDIX B – CB-Roads VOC Equations

This appendix contains the formulae used in CB-Roads for the calculation of VOC and is included for information purposes.

CB-Roads calculates the following costs for VOC:

- Vehicle Capital Cost
- Vehicle Maintenance Cost
- Fuel Cost
- Oil Cost
- Tyre Cost

The formulae for these factors are presented in this appendix.

<u>Vehicle Capital Cost</u>

Light Vehicles

The CB-Roads manual refers to work that were done to determine the depreciation of light vehicles. The depreciation is:

[0.34 x 10^{-5}] x [Purchase price less tyres] (R per km travelled)

Heavy Vehicles

The formulae for the depreciation/capital cost of heavy vehicles are:

$$U = s \times t$$

$$E = 0.2$$

$$r = \left(1 + \frac{i}{100}\right)^{\frac{1}{U}} - 1$$

$$K = P^o \times \frac{r \times \left[(1+r)^U - E\right]}{(1+i)^U + 1}$$

where

s	average annual kilometres travelled
t	average service life in years
U	total kilometres in lifespan
E	residual value factor
i	discount rate as a percentage
r	discount rate per kilometre as a factor of 100
P^o	initial cost of vehicle (incl. VAT) less cost of set of tyres

K capital cost (R/km)

Vehicle Maintenance Cost

The formulae for the calculation of Maintenance Cost are:

$$m = \frac{\left(K1 + K2 \times v + \frac{K3}{v} + K4 \times v^2\right)}{K5}$$

$$M^o = m \times A^o$$

where

v	speed in km/h
K1,..., K5	maintenance constants
m	maintenance cost factor per km
A^o	initial cost of vehicle
M^o	maintenance cost in R/km

Fuel Cost

Fuel cost is calculated from the following formulae:

$$F = f + fh$$

where

F	total fuel consumption (l/km)
f	basic fuel consumption on good surface (l/km)
fh	extra fuel consumption on horizontal curves (l/km)

The basic fuel consumption is calculated as:

$$f = \left(Ka + \frac{Kb}{v} + Kc \times v^2 + Kd \times G\right) \times 10^{-3}, \qquad f \geq \frac{Kb}{v} \times 10^{-3}$$

where

v	speed in km/h
G	gradient in m/m

$$Ka = \frac{b \times A \times M}{\mu}$$

Kb idling fuel consumption

$$Kc = \frac{\frac{1}{2} \times b \times p \times Cd \times Af}{\mu \times 3.6 \times 3.6}$$

$$Kd = \frac{b \times M \times g}{\mu}$$

where

b	fuel conversion factor (ml/kJ)
A	rolling resistance coefficient (N/kg)
M	mass (kg)
µ	drive-line efficiency
p	air density (kg/m^3)
Cd	aerodynamic drag coefficient
Af	projected frontal area (m^2)
g	gravitational constant

The extra fuel consumption on horizontal curves is calculated as:

$$fh = \frac{b \times Rc}{\mu} \times 10^{-3}$$

where

b	fuel conversion factor
Rc	total curve resistance
µ	factor depending on vehicle class

$$Rc = Rt + Rac \qquad \textit{for light vehicles}$$

$$Rc = Rah \qquad \textit{for heavy vehicles}$$

where

Rt	additional force on vehicle in direction of travel (N)
Rac	air resistance (N)
Rah	total resistance (N)

$$n = \frac{v^2}{R \times g}$$

where

n	cornering acceleration coeffiecient
R	radius of horizontal curve (m)
v	speed in m/s

$$Rt = n^2 \times M \times g \times (0.067 + 0.057 \times n)$$

M mass of vehicle

$$Rac = \frac{1}{2} \times p \times Cd \times v^2 \times As \times \left(0.067 \times n + 0.57 \times n^2 - l/R\right)$$

p air density
Cd aerodynamic drag coefficient
As projected side area (m^2)
l distance from centre of mass to rear axle (m)

$$Rah = \frac{\pi}{(180 \times w \times c)} \times (M \times g \times n)^2 + 0.1 \times g \times Mt \times \frac{lt}{R}$$

w number of wheels
c cornering stiffness per tyre (N)
Mt mass on tandems (kg)
lt tandem spacing (m)

The fuel cost is calculated by multiplying the total fuel consumption with the cost of fuel to obtain a cost per km.

Oil Costs

Oil costs are calculated with fuel consumption as:

$$C = \frac{A}{100} + \beta \times B$$

where

- C total oil consumption (l/km)
- A oil consumption due to contamination (l/km)
- B fuel consumption (l/km)
- β oil consumption as a factor of fuel consumption

Oil cost is calculated by the multiplication of the oil consumption with the cost of oil to obtain a cost per kilometre.

Tyre Cost

The cost of tyres is calculated as:

$$T = K1 + K2 \times v + K3 \times v^2$$

where

K1, K2, K3	tyre wear factors
v	speed (km/h)
T	tyre consumption in % tread per km

$$C = \frac{T}{100} \times P$$

where

P	cost of a set of tyres
C	tyre cost (R/km)

Effect of Road Roughness

The factors are first calculated and then an adjustment factor related to road roughness is calculated. The different cost factors are then multiplied by the roughness factor and the VOC calculated. The roughness factor has the general form:

$$f_r = \frac{Cost\ \ factor\ at\ QI\ of\ \ road}{Cost\ \ factor\ at\ QI = 40}$$

The CB-Roads user manual refers to work done by Schutte in the calculation of VOC as it is influenced by roughness. The factor f_r as defined above is based on the work done by Schutte.

APPENDIX C – VOC Comparative figures

The simplified HDM-4 formulae presented in this document were compared to the existing PAWC VOC formulae, as well as to the formulae that is proposed for use by Gautrans. The results are shown on the following figures.

On the figures the reader will notice two graphs for the Gautrans formulae (AFRICON graphs). This is because the Gautrans formulae contains a time component in the VOC formulae which was not included in the present study. Thus, the Gautrans graphs were plotted with and without the time component included for a better comparison.

On each figure the dark blue line represents the current PAWC formulae, while the pink line represents the formulae presented in this report. The yellow and light blue lines represent the Gautrans formulae.

The results of the regression analysis for the fuel consumption formulae are also presented in this Appendix.

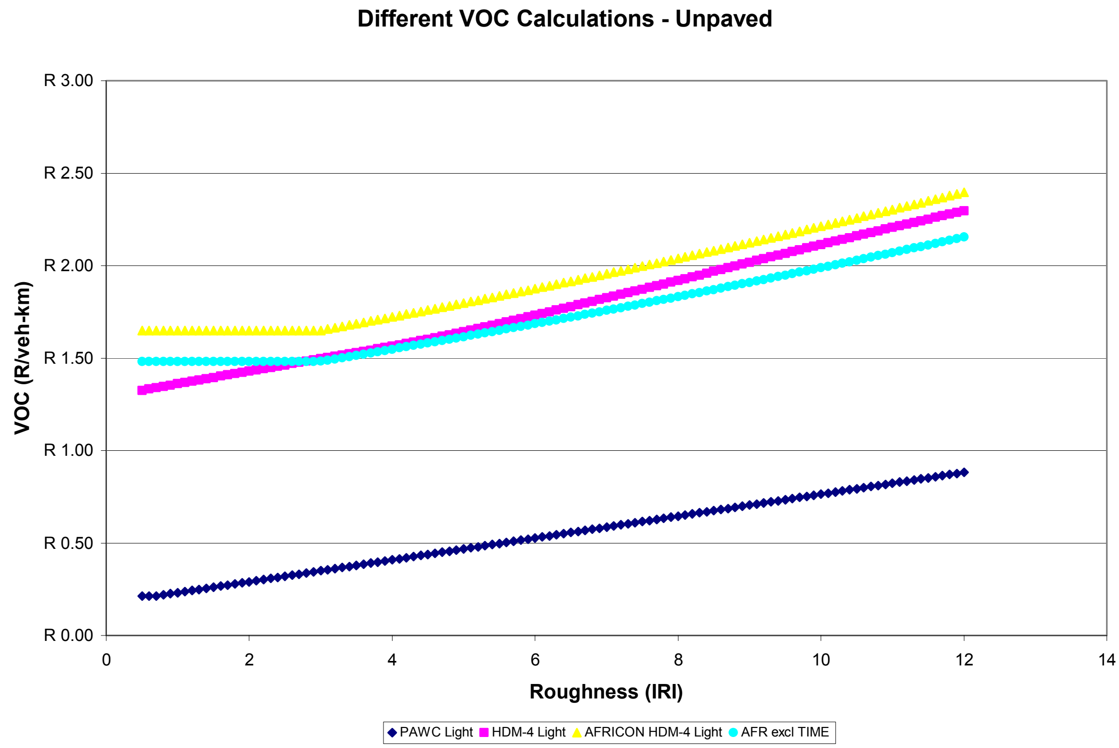


Figure C - 1: VOC formulae for light vehicle – unpaved roads.

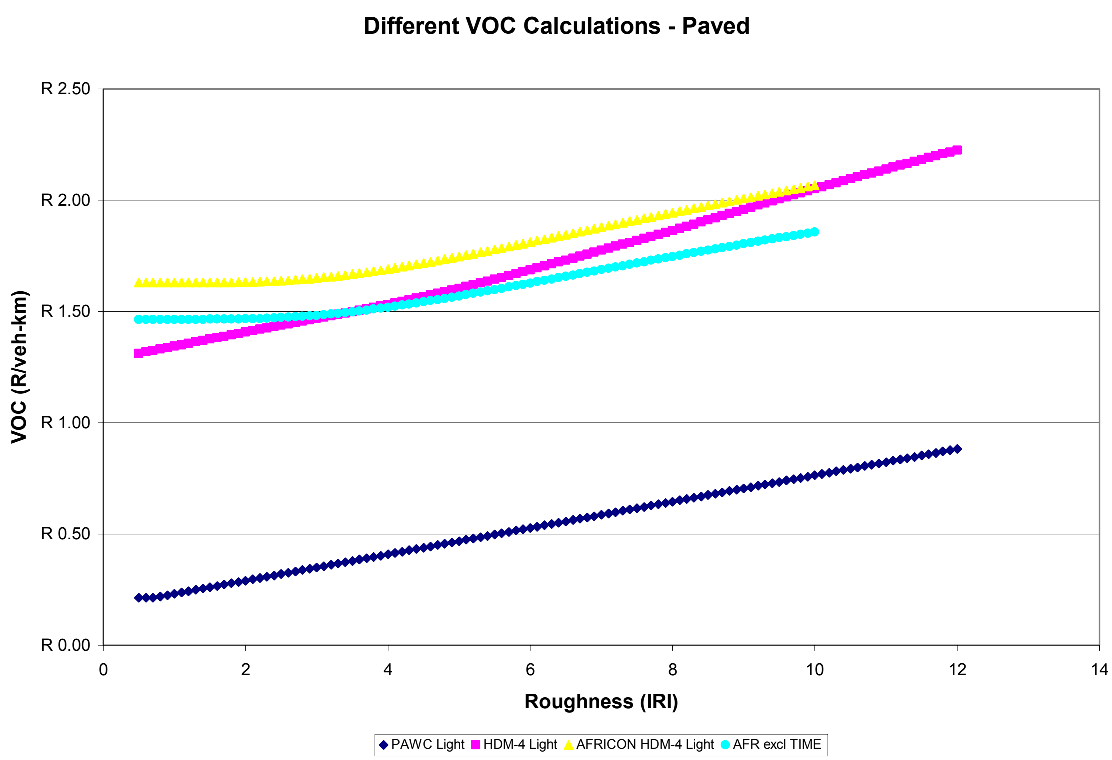


Figure C - 2: VOC formulae for light vehicle – paved roads.

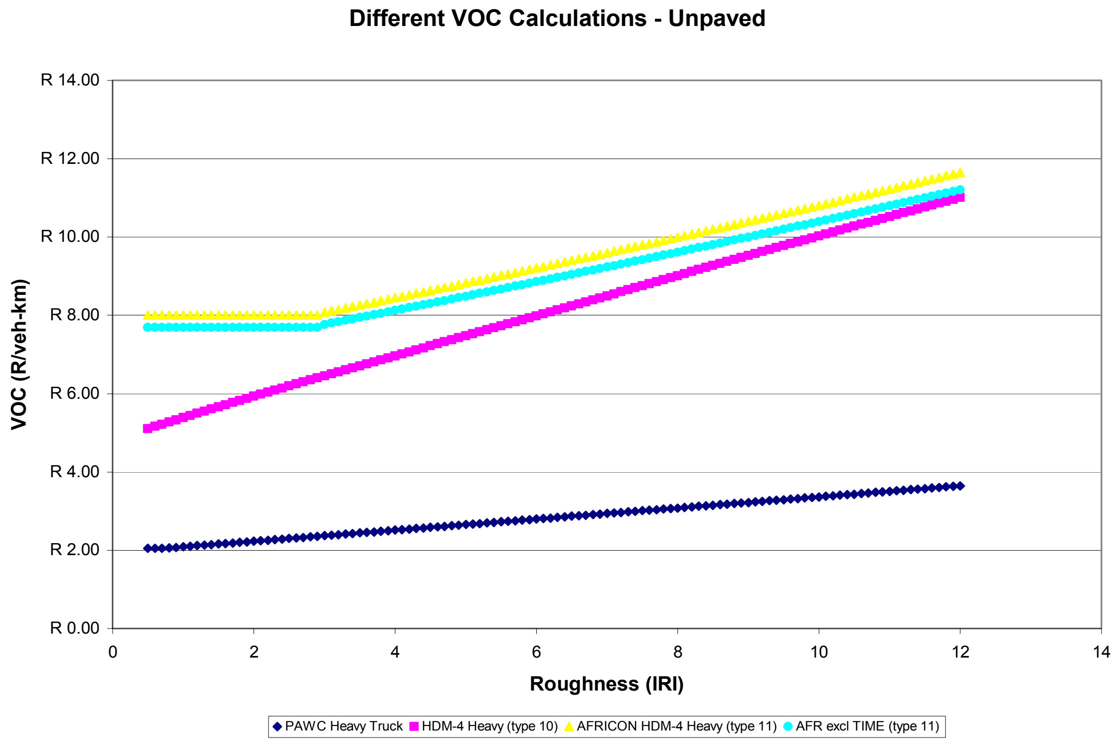


Figure C - 3: VOC formulae for heavy vehicle – unpaved roads.

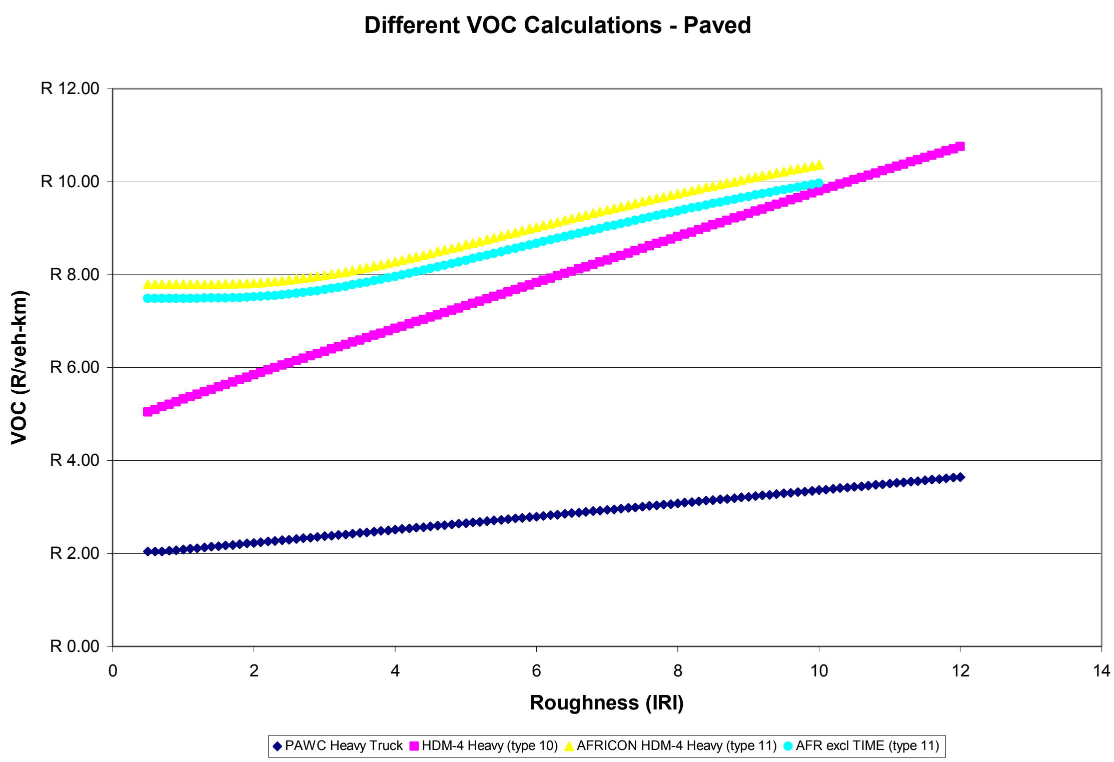


Figure C - 4: VOC formulae for heavy vehicle – paved roads.

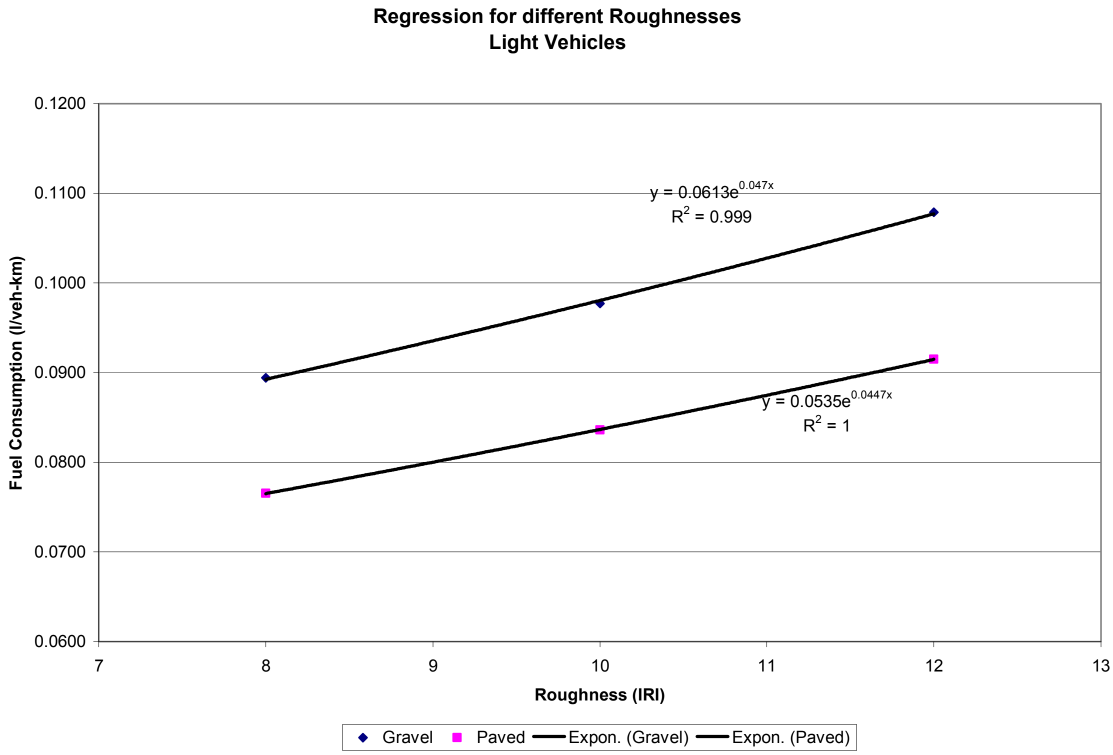


Figure C - 5: Light vehicle regression.

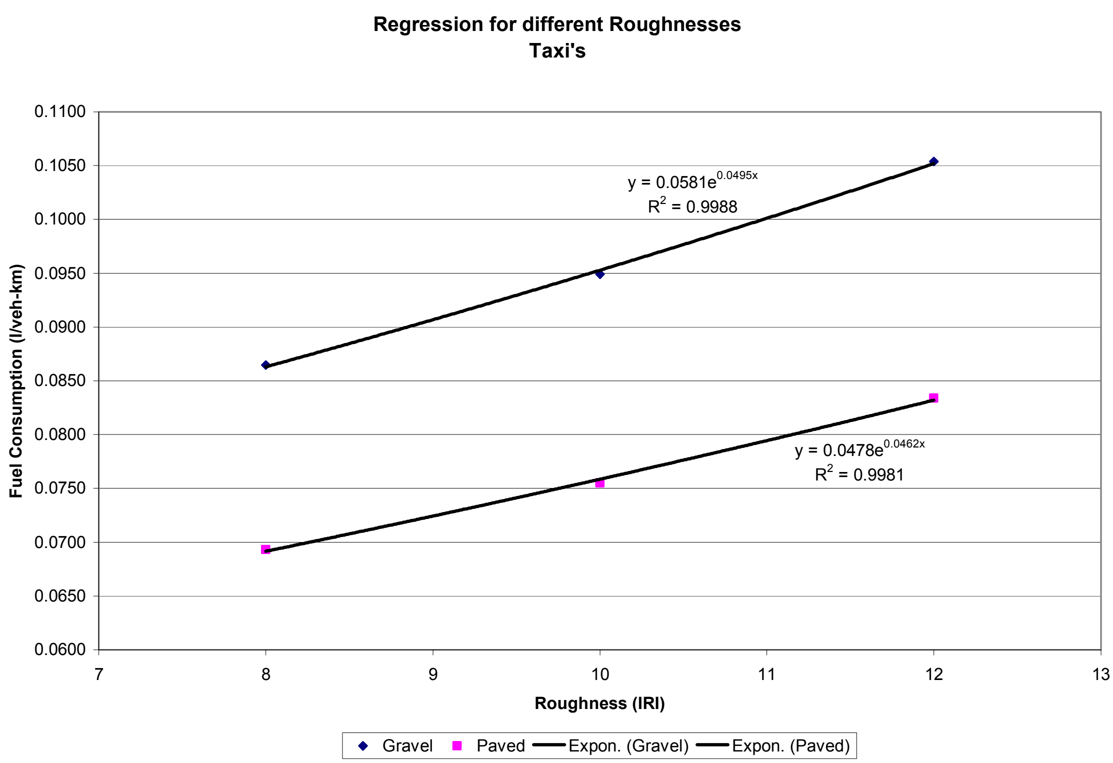


Figure C - 6: Taxi regression.

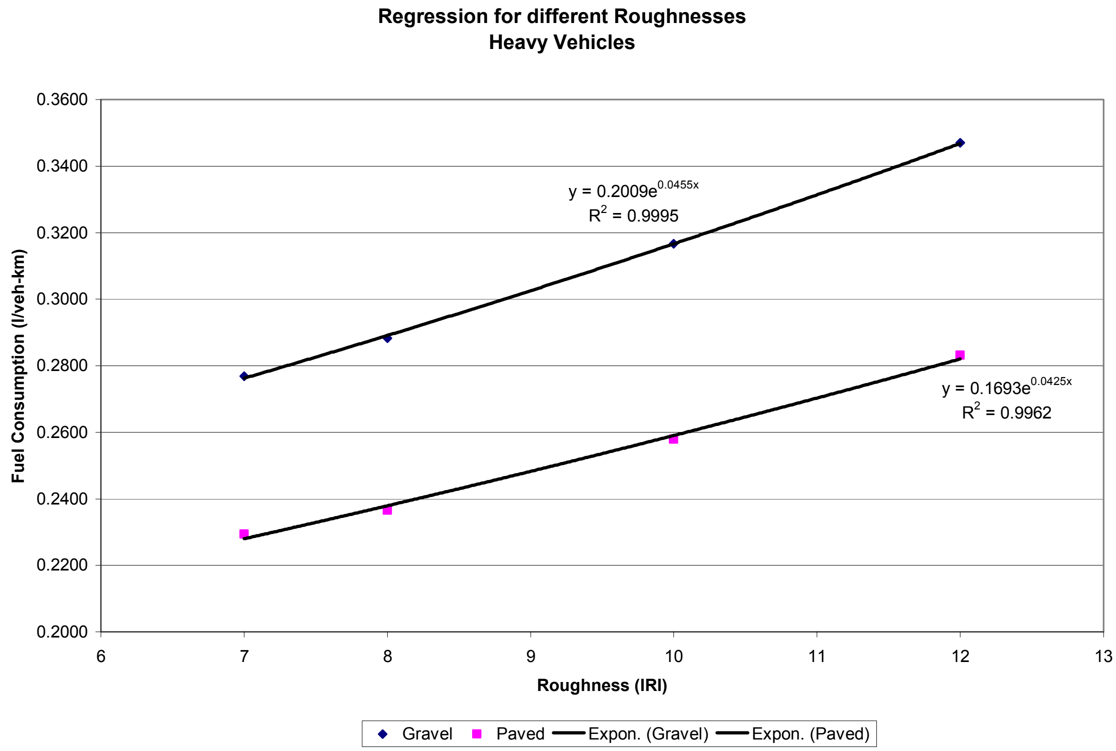


Figure C - 7: Heavy vehicle regression.

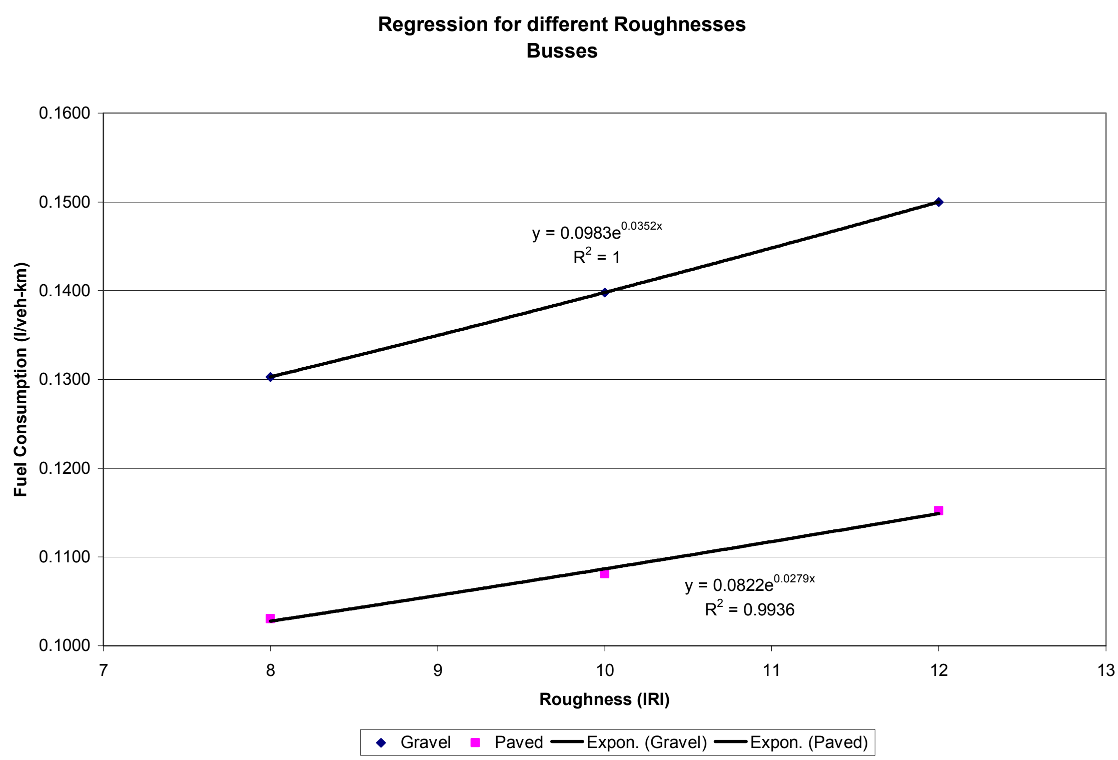


Figure C - 8: Bus regression.

Implementing the HDM-4 methodology for calculation of VOC and IRR in the PAWC GRMS

A.F. BURGER
G.D. VAN ZYL
H.G. FOURIE

V&V CONSULTING ENGINEERS
52 GAZANIA STREET
KENRIDGE EXT 4
BELLVILLE

REPORT NUMBER: VV2/346 v. 2

DATE: JUNE 2001

Introduction

This document outlines the procedure for the calculation of VOC and IRR in the Gravel Road Management System (GRMS). The document describes the procedure that must be followed and gives a graphical representation of the procedure in a flow diagram.

This document should be read together with report VV1/346: *"SIMPLIFYING THE HDM-4 METHODOLOGY FOR THE CALCULATION OF VEHICLE OPERATING COST"*

Procedure

The procedure that must be followed is outlined in this section. The flow diagram at the end of the document must be kept at hand to understand the flow of information between the different modules in the GRMS.

The main inputs needed are:

- Visual Assessment
- Material Properties
- Traffic Data
- DCP Data
- Model Manager Variables

The first four inputs are obtained per 5 km road section for the gravel roads.

The Model Manager Variables includes (specified by the user):

- Analysis Period
- Layer thickness threshold
- Target Roughness Value
- Cost tables (for different maintenance actions)
- Design Period of a sealed road
- Traffic Growth (if not available from Traffic Data)

<u>Remaining Life for Regravelling and Riding Quality Deterioration:</u>

From the Visual Assessment a **Riding Quality** value (QI) is assigned to the RQ class of the road (e.g. very poor, fair, good, etc.). The QI value is converted to an IRI value for use in the VOC calculations.

The **Layer Thickness** (LT) is also obtained from the Visual Assessment data.

The Roughness Value obtained is used, together with the existing **Traffic** on the road, for the modeling of the ***riding quality (RQ) deterioration curve***. This curve is modeled based on the TRH 20 equations and is used as the "Do Nothing" option.

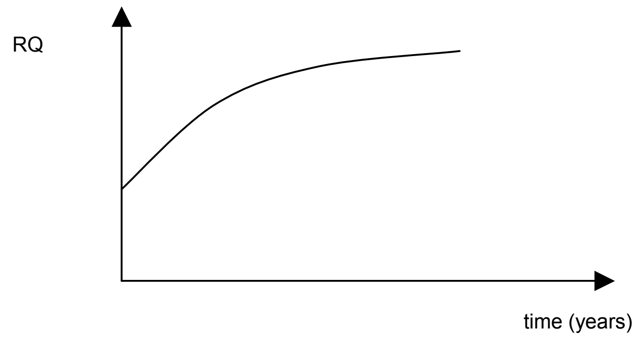


Figure 1: Typical RQ deterioration curve.

The layer thickness (LT) is used together with the **Material Properties**, **Traffic**, and **Layer Thickness Threshold** to obtain the ***remaining life for regravelling*** of the road section through the TRH 20 equations.

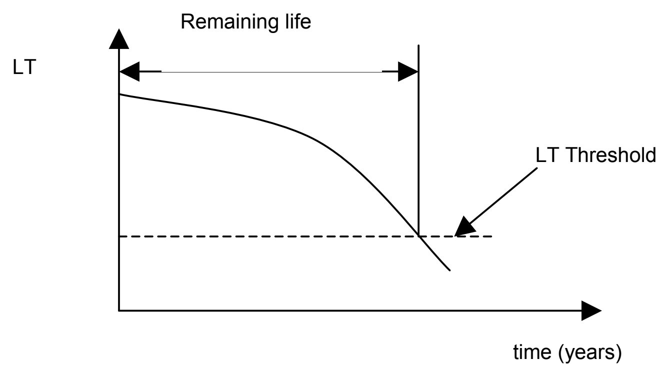


Figure 2: Typical curve for determination of remaining life for regravelling.

The ***VOC per year*** for the Do Nothing option (Option 1) is calculated with the **RQ deterioration curve**, **Traffic** and **Traffic Growth Rate** as inputs. The formulae for the calculation of VOC is used as listed in report VV1/346.

Maintenance Strategies:

The user defines the Maintenance Strategies. Typically these are:

- Blading only Option (Option 2)
- Blading and Regravelling Option (Option 3)
- Seal Option (Option 4)

In this section each of the maintenance options is discussed in more detail.

Option 2:

The **Target Roughness** as defined in the *Model Manager* is used to obtain a suitable ***blading frequency***. The **blading frequency** is used together with the **RQ deterioration equations** to obtain the ***RQ deterioration curve for Option 2***. A typical RQ deterioration curve for option 2 is shown below (Figure 3).

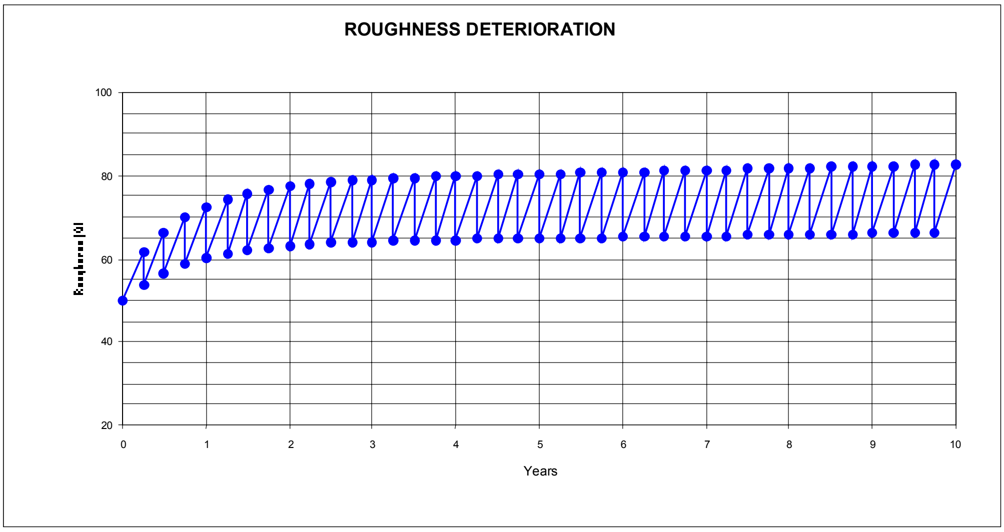


Figure 3: Typical RQ deterioration curve for option 2.

The ***Agency Cost per year*** is calculated from the **RQ deterioration curve** for option 2 and the **Cost Tables** from the *Model Manager.* Typically the agency cost would consist of the blading cost multiplied by the blading frequency per year and any other routine maintenance required.

The ***VOC per year*** is calculated with the **roughness value as an average** (from RQ deterioration curve) for the year under consideration. The **Traffic** and **% traffic growth** are also considered in the calculation of VOC – the traffic at present is inflated with the growth factor to the traffic in the year under consideration.

The ***Net Benefit per year*** is calculated as:

ΔVOC = VOC "Do Nothing" – VOC "Option 2"

ΔAgency Cost = Agency Cost "Option 2" – Agency Cost "Do Nothing"
ΔAgency Cost = Agency Cost "Option 2"

Net Benefit = ΔVOC – ΔAgency Cost

These equations are used per year to calculate the net benefit per year for the option under consideration.

Option 3:

The ***blading frequency*** and ***remaining life for regravel*** is calculated from the input data and user defined variables (Model Manager).

From the data obtained a ***RQ deterioration curve*** is drawn as shown in the figure below (Figure 4).

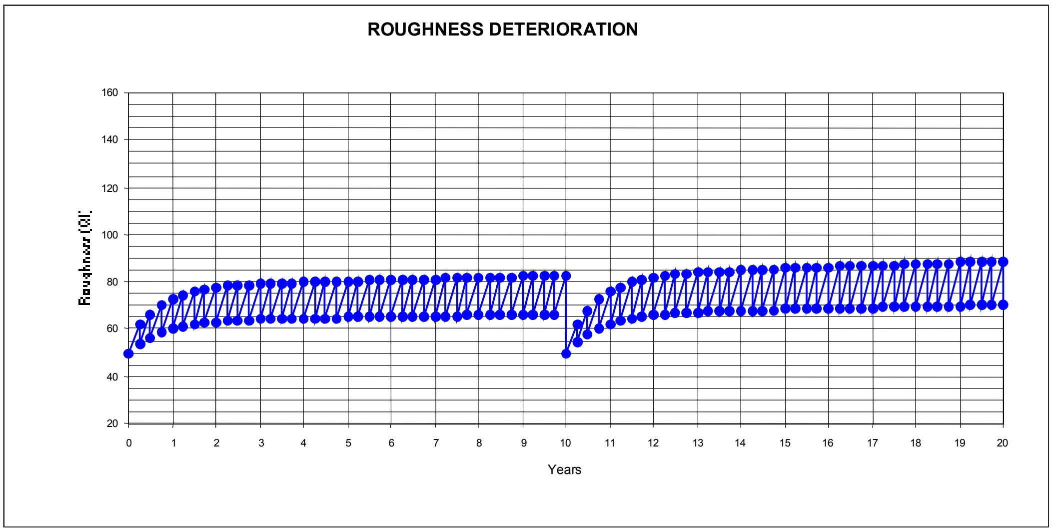


Figure 4: Typical RQ deterioration curve for Option 3.

From the **RQ deterioration curve** and the **Cost Tables** the ***Agency Cost per year*** is calculated for Option 3.

The ***VOC per year*** is calculated with the **roughness value as an average** (from RQ deterioration curve) for the year under consideration. The **Traffic** and

% traffic growth are also considered in the calculation of VOC – the traffic at present is inflated with the growth factor to the traffic in the year under consideration.

The ***Net Benefit per year*** is calculated as:

ΔVOC = VOC "Do Nothing" – VOC "Option 3"

ΔAgency Cost = Agency Cost "Option 3" – Agency Cost "Do Nothing"
ΔAgency Cost = Agency Cost "Option 3"

Net Benefit = ΔVOC – ΔAgency Cost

Option 4:

This option is calculated differently to the other two options.

The seal type and required structure is determined through the following steps: The ***existing strength of the in-situ material*** is calculated from the **DCP data**. This information together with the **design period** is used to calculate the ***design traffic on the road***.

The **design traffic** together with the **drainage conditions** (from Visual Assessment) is used to determine the ***Required Additional Structure***. This information is then used together with the **Cost Tables** to calculate the ***agency cost for Option 4***.

The ***RQ deterioration curve*** is calculated from a **sigmoidal deterioration equation** used for sealed roads (see Figure 5 below). This is then used to calculate the ***VOC per year for Option 4***.

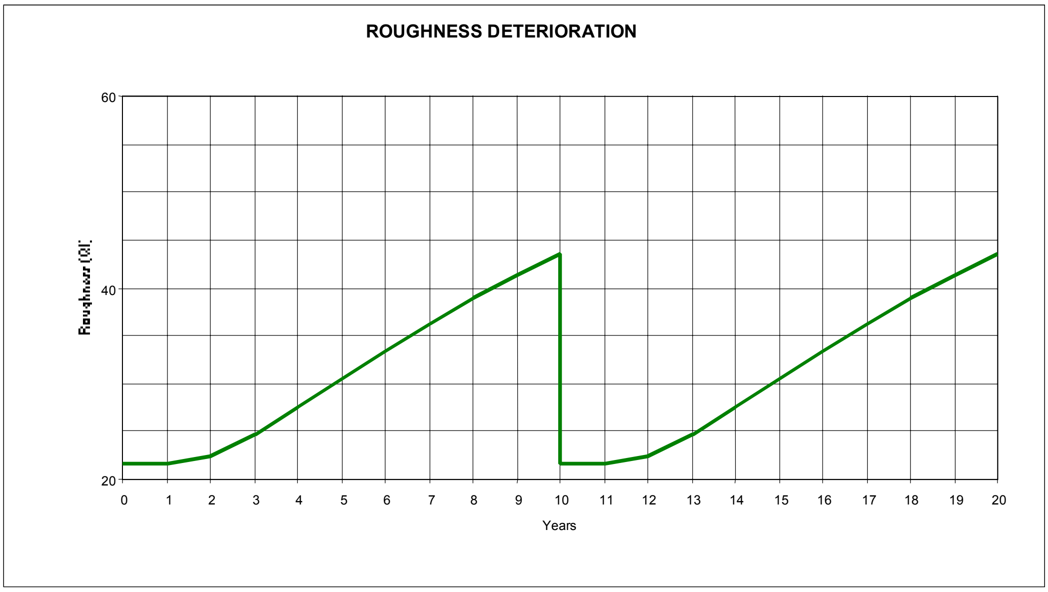


Figure 5: Typical RQ deterioration curve for Option 4.

The ***VOC per year*** is calculated with the **roughness value as an average** (from RQ deterioration curve) for the year under consideration. The **Traffic** and **% traffic growth** are also considered in the calculation of VOC – the traffic at present is inflated with the growth factor to the traffic in the year under consideration.

The ***Net Benefit per year*** is calculated as:

ΔVOC = VOC "Do Nothing" – VOC "Option 4"

ΔAgency Cost = Agency Cost "Option 4" – Agency Cost "Do Nothing"
ΔAgency Cost = Agency Cost "Option 4"

Net Benefit = ΔVOC – ΔAgency Cost

<u>IRR of different Maintenance Strategies:</u>

The procedure as set out in report VV1/346 is followed to determine the IRR for each of the maintenance strategies.

The net benefit per year is calculated as described previously and then used in the calculation of the IRR for each strategy.

Most Cost Effective Maintenance Strategy for each road section:

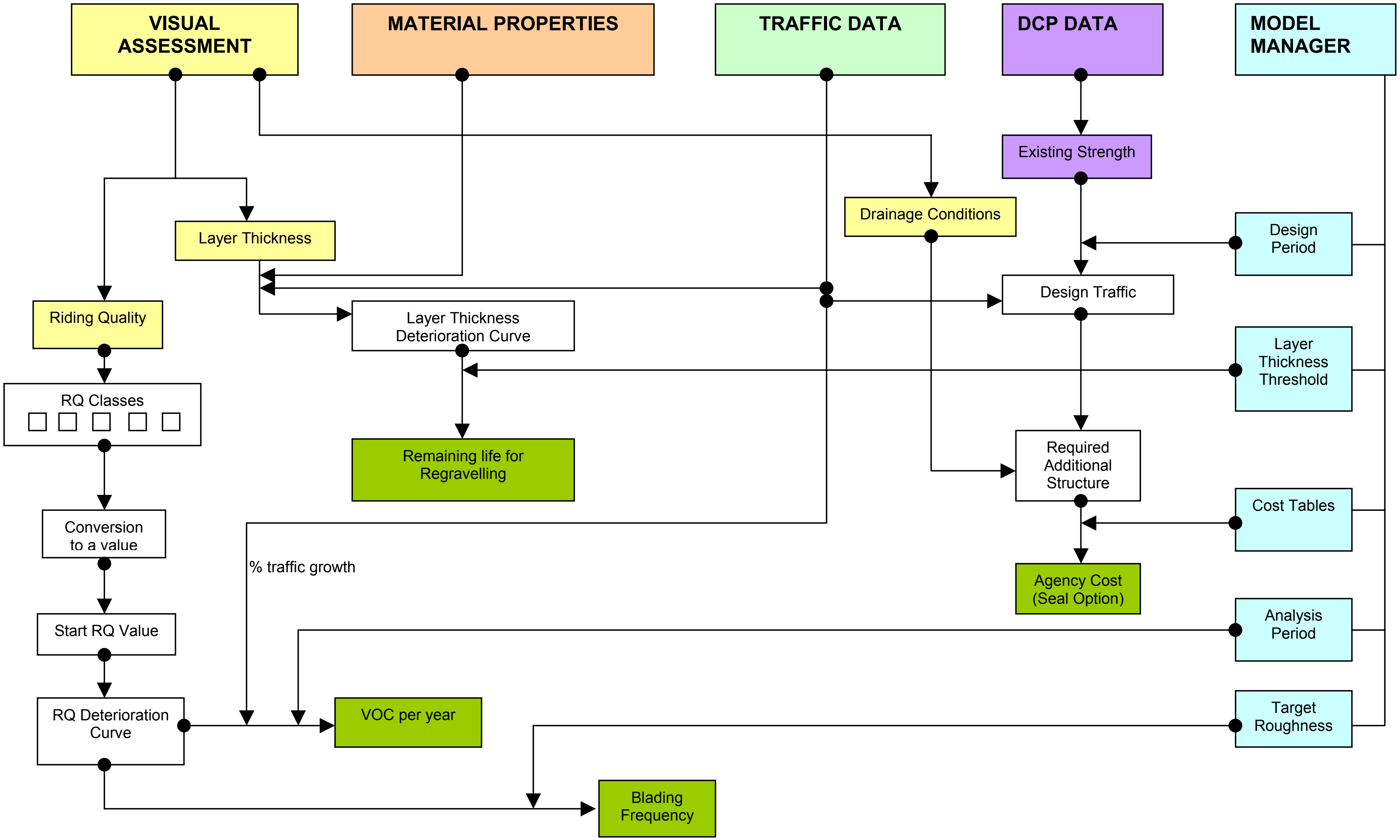
The most cost effective maintenance strategy is determined for each road by comparing the IRR of each maintenance strategy: The maintenance strategy with the highest IRR is the most cost effective.

Seal Priority List:

All roads that show a higher IRR for the seal option (option 4) compared to both options 2 and 3 are placed on a seal priority list.

The seal priorities are determined according to descending IRR (i.e. first road on list has highest IRR, second road on list has second highest IRR, etc.).

FLOW DIAGRAM



Flow Diagram For Different Options