MODIFIED SIMPLIFICATION OF HDM-4 METHODOLOGY FOR THE CALCULATION OF VEHICLE OPERATING COST TO INCORPORATE TERRAIN AND EXPANDED TO ALL VEHICLE TYPES FOR USE IN THE WESTERN CAPE CONTEXT

by
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Thesis presented in fulfilment of the requirements for the degree of Master of Science in the Faculty of Engineering at Stellenbosch University

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March 2015

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ABSTRACT

INTRODUCTION

The Western Cape Government (WCG) uses Vehicle Operating Cost (VOC) as part of their Road Management System since 1992. VOC is used in the process of prioritisation of maintenance projects as well as for the identification of economically viable maintenance strategies and is thus an integral part of the system.

In 2001 changes to the VOC calculation methodology in the system to Highway Development and Management (HDM-4) system methodology occurred. The reasons were twofold – to bring the calculation method in line with world trends and due to lack of updated cost factors used in the previous methodology.

In October 2001 a model was implemented with riding quality (IRI) as independent variable. This model was partly based on regression table data. As no geometric/topography data, defined as Terrain data, was available at this stage, Terrain was ignored. In 2006 WCG Systems were updated with Global Positioning System (GPS) data and a process to classify or categorise Terrain was initiated, thus providing the opportunity to include Terrain. As part of the redevelopment to include Terrain, it was decided to re-evaluate the vehicle fleet.

METHODOLOGY

Various alternative methods to develop the Modified Simplification equations were available and evaluated, e.g. regression or direct mathematical substitution. HDM-4

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requires the input of Vehicle Type dependent cost parameters that is based on real vehicles. The WCG required that changes to these dependent parameters is feasible, so that they can be updated periodically. A set of equations therefore needed to be developed, allowing the input of Vehicle Type dependent parameters and the subsequent calculation of VOC with riding quality (IRI) as independent variable. This renders the use of regression analysis untenable.

Composition of the vehicle fleet on each road section is required to utilise HDM-4 for analyses. In order to simplify calculations, different traffic strata was defined, i.e. Business, Commuter, Rural and General. In the evaluation of the Vehicle it is this strata and data from permanent counting stations that is used to compile a Vehicle fleet.

MODEL DEVELOPMENT

The Modified Simplification to include Terrain results in 48 combinations of Vehicle Type, Surface Type and Terrain Type for the basic equation of VOC.

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

TC_{av} -Tyre Cost	$PARTSCOST$ -Parts Cost	$LABOURCOST$ - Labour Cost
$DEPCST_{av}$ - Depreciation Cost	$FuelCost_{av}$ -Fuel Cost	$OilCost_{av}$ - Oil Cost

The variables in VOC are defined by a couple of equations. For explanatory purposes a numeric example is presented.

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CONCLUSION AND RECOMMENDATION

The implementation of this Modified Simplification has assisted not only the WCG, but also other entities, that also use the VOC (published annually) based on these principles. Interested parties have the option to include Terrain in their implementation. Caution should be taken when using the Modified Simplification, as it is important that the principles used to simplify HDM-4 apply to the implementation and the business rules of the Management system of the user.

The current development will not require a redevelopment due to any vehicle fleet change in future as the decision to simplify all defined Vehicle Types in HDM-4 allows the new fleet to be updated.

Recommendation for further research and development include:

- Standalone function that is already considered by the WCG
- Investigating Published Vehicle data
- Economic vehicle data for use in specific applications

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OPSOMMING

INLEIDING

Sedert 1992 gebruik die Wes-Kaapse Regering (WCG) voertuiggebruikskoste (VOC) as deel van hul Plaveisel Bestuurstelsels. VOC word gebruik in die proses van prioritisering van die instandhoudingprojekte sowel as vir die identifisering van ekonomies-vatbare instandhouding-strategieë en is dus 'n integrale deel van die stelsel.

In 2001 is daar besluit om oor te skakel na die berekeningsmetode van Highway Development and Management (HDM-4). Die redes was tweeledig – om die berekeningsmetode in lyn met die wêreld tendense te bring; en as gevolg van 'n gebrek aan opgedateerde koste-faktore in die voorheen-gebruikte metode.

In Oktober 2001 is 'n VOC-model, met rygehalte (IRI) as onafhanklike veranderlike geïmplementeer. Hierdie model was gedeeltelik gebaseer op regressie tabel data. Aangesien daar geen geometriese/topografiese data (gedefiniëer as terreindata) beskikbaar was nie, is die terrein geïgnoreer. In 2006 is WCG Stelsels opgedateer met Globale Positionering Stelsel (GPS) data en 'n proses om terrein te klassifiseer is van stapel gestuur. Deur die verandering in beskikbare data, is die geleentheid om terrein in te sluit in die VOC model geskep. As deel van die insluiting van herontwikkeling om terrein in te sluit, is daar besluit om die voertuigvloot te her-evalueer.

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METODOLOGIE

Verskeie alternatiewe metodes om die Gewysigde Vereenvoudiging-vergelykings te ontwikkel was beskikbaar en is geëvalueer, bv. regressie of direkte wiskundige vervanging en vereenvoudiging. HDM-4 se voertuigafhanklike koste-parameters is op werklike voertuie gebaseer. Die WCG het vereis dat hierdie afhanklike parameters veranderbaar moet wees, sodat hulle dit van tyd tot tyd kan opdateer. Dit was dus nodig om 'n stel vergelykings te ontwikkel met die tipe voertuigkoste-afhanklike parameters as insette. Verder moes alle vergelykings weer in terme van rygehalte wees. Dit maak die gebruik van regressie-analise ononderhoubaar.

Samestelling van die voertuigvloot op elke padseksie is 'n vereiste om HDM-4 aan te wend vir ontledingsdoeleindes. Ten einde berekeninge te vereenvoudig is verskillende verkeerstrata gedefinieer, naamlik Besigheid, Pendel, Landelik en Algemeen. In die evaluering van die Voertuig is dit hierdie strata en data uit permanente telstasies wat gebruik word om 'n voertuigvloot saam te stel.

MODELONTWIKKELING

Die Gemodifiseerde Vereenvoudiging, insluitend terrein, het 48 kombinasies van tipe voertuig, oppervlak en terrein vir die basiese vergelyking van VOC:

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

TC_{av} - Bandkoste; $PARTSCOST$ - Onderdele-koste; $LABOURCOST$ - Arbeidskoste; $FuelCost_{av}$ - Brandstofkoste; $DEPCST_{av}$ - Waardeverminderingskoste; $OilCost_{av}$ - Oliekoste

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Die veranderlikes in VOC word gedefinieer deur 'n paar vergelykings. Vir verduidelikende doeleindes word 'n numeriese voorbeeld ingesluit.

GEVOLGTREKKING EN AANBEVELING

Die implementering van hierdie Gewysigde Vereenvoudiging het nie net die WCG nie, maar ook ander entiteite wat ook die VOC (jaarliks gepubliseer) gebruik, bygestaan. Belangstellendes het die opsie om die terrein in hul implementering in te sluit. Dit is belangrik om ag te slaan op die beginsels wat gebruik is om HDM-4 te vereenvoudig tesame met die besigheidsreëls van die Gewysigde Vereenvoudiging, indien dit gebruik word.

Die huidige model vereis nie 'n herontwikkeling as gevolg van enige voertuigvloot verandering in die toekoms nie. As gevolg van die besluit om alle gedefinieerde tipes voertuig te vereenvoudig, kan die voertuigvloot keuse net in die stelsel opgedateer word.

Aanbeveling vir verdere navorsing en ontwikkeling sluit in:

- Alleenstaande funksie wat reeds deur die WCG beskou word
- Ondersoek Gepubliseerde Voertuig data
- Gebruik van Ekonomiese voertuigdata vir sekere toepassings

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DEDICATION

This thesis is dedicated to the eight people who inspired me to build a greater tomorrow for our Province, our Country and the Industry we work in, with whose support, encouragement and dedication to my career has been unfailing and beyond the call of duty.

- My Role Model and Dearest Friend, Riaan Burger, without your significant contribution this would not be possible.
- My Mentor in the Public Sector, Andre van der Gryp, I hope to make you proud.
- My Private Sector Mentor, Gerrie van Zyl, you inspired me to appreciate the many facets of any answer.
- My Aunt, Suzette van Zyl, you've showed me that women can achieve more.
- My Parents, Thys and Marieta Kemp, who understand the meaning of beyond the call of duty.
- My Daughter, Marsun Suzette Hofmeyr, you are an angel from above.
- My Husband, Jan Hendrik Hofmeyr, your patience and support are my backbone.

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ACKNOWLEDGEMENTS

The advice and assistance of the following people are acknowledged with my sincerest gratitude:

Riaan Burger – Study Leader
Andre van der Gryp – System Manager for Western Cape Government
Gerrie van Zyl – Asset Management Specialist for the Western Cape Government
Prof Kim Jenkins – Supervisor
Chantal Rudman – Colleague
Japie van Niekerk – Technician Mott MacDonald PDNA
Gerhard Fourie – SANRAL, erstwhile director of PD Naidoo and Associates (now Mott McDonald PDNA)
Lenn Fourie – Chief Director, Road Network Branch Western Cape Government
Llewellyn Truter – Chief Engineer Materials, Western Cape Government
Dru Martheze– Chief Engineer Strategic Planning, Western Cape Government
Mervyn Henderson – Specialist Engineer, Western Cape Government
Ileen Wolmarans – Aurecon, South Africa
Hendrik and Marsheille Hofmeyr – Retired Research Team
Karen Muller – Programmer for the Western Cape Government
Trevor Wood – Programmer for Western Cape Government
Johan Gilmer – SNA Director
Fatgie Moos – Mott MacDonald PDNA Director
Prof Fred Hugo – Undergraduate Mentor

This thesis would not have been possible without the financial assistance of the Road Network Branch of the Western Cape Government.

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1. INTRODUCTION

The calculation of Vehicle Operating Cost (VOC) forms an integral part of any Pavement Management System. VOC is used in the process of initial identification of maintenance projects as well as for the identification of economically viable maintenance strategies. This is also applicable to the Western Cape Government (WCG) Road Network Branch Management System, Department of Transport and Public Works (DTPW).

1.1 BACKGROUND

Western Cape Government have been operating their Surface Road Management System (called PMS) from 1980 and the Unsurfaced Roads Management System (called GRMS) from 1988. In terms of South African publications, VOC was used from 1992 and was calculated by using Technical Recommendations for Highways Draft TRH 22 (TRH 22) methodology (1994). As TRH 22 uses cost factors in calculating the VOC, the accuracy of the VOC became questionable as updates of the cost factors became more infrequent.

It was for this reason that it was decided to update the VOC calculations in the Road Network Branch Management Systems to the new Highway Development and Management (HDM-4) system methodology to bring it in line with world trends.

The first attempt was implemented in October 2001 (later referred to as 2001 Simplification) by using a regression and tables developed by Burger and Van Zyl (2001). Furthermore, during the 2001 Simplification, geometric/topography data was

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ignored and it was accepted that all roads in the WCG network were Flat. Part of this process was also to identify a Vehicle fleet in terms of the HDM-4 definitions. After careful consideration the Vehicle Types for the fleet were correlated with vehicle classes as counted in network counts of the WCG DTPW. A fleet with four vehicles was identified.

In 2006 the Road Network Management Systems of the WCG DTPW was updated with Global Positioning Systems (GPS) and a process to classify or categorise each road section in terms of Terrain was initiated.

1.2 MOTIVATION FOR RESEARCH

The classification for Terrain, in terms of each section on the WCG DTPW, started to become a reality and it was due to this information, now freely available, that it was decided to initiate this research (later referred to as Modified Simplification) by modifying the 2001 Simplification to include Terrain.

As part of the research it was also later decided that a review of the vehicle fleet of the WCG DTPW would be desirable.

1.3 OBJECTIVE OF RESEARCH

The objective of this research is to:

1. Include Terrain into a Modified Simplification based on the principles of the 2001 Simplification, keeping all cost parameters independent. (combinations

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of Vehicle Type, Surface Type and Terrain Type for the basic equation of VOC)

2. To expand this Simplification for all Vehicle Types defined in HDM-4
3. To re-evaluate the Vehicle fleet used by the WCG and to document business processes on how to implement this fleet
4. To manage and document the implementation process of all the above into the Management Systems of the WCG

1.4 SCOPE OF RESEARCH

This research would use the procedure for the calculation of VOC based on the HDM-4 methodology and incorporate Terrain as defined by the WCG DTPW.

The Modified Simplification is a simplification and therefore its use is limited. It should be used for identification and not for prioritisation, for network analysis and not for project analysis. The incorporation of Terrain can also not be used to motivate geometric improvements as the simplification is done on a macro level information. Such a geometric improvement requires micro level data. Based on this, the Modified Simplification can make general simplifications for Western Cape circumstances.

Based on the changes of the composition of Vehicle Types in South Africa the full HDM-4 vehicle fleet would be considered in contrast to that of the 2001 Simplification. It is for this reason that Vehicle Type dependent cost parameters that

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are required inputs by HDM-4 (the values of which are based on real vehicles), allow for changes in final simplified equations.

This requirement gives other users of the Simplification the opportunity to input their own applicable parameter values in their own currency, and based on their markets.

The Simplification will therefore focus on VOC in relation to Road Roughness and not on cost explicitly.

Before implementation into the PMS and GRMS of DTPW the fleet required for WCG use would be reviewed and a procedure for the update of parameters would then be documented. At any stage this fleet could be further developed should it become necessary.

The scope of the research was limited to usage by the WCG DTPW, and decisions were made based on their preferences, current systems and resources.

1.5 ORGANISATION OF THESIS

The history of VOC, as well as the Vehicle Fleets Classifications and how they are used in the Road Network Branch Management system of WCG DTPW, are discussed in **Section 2**. **Section 3** explains the Methodology of the Model Development and implementation. The detail Model Development and calculations of Modified Simplification to include Terrain are explained in **Section 4**. **Section 5** shows an example of one of the 48 combinations of Vehicle Type, Surface Type and Terrain Type mathematical substitution and simplification. The implementation

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process, including the review of the Vehicle fleet, is presented in **Section 6**. Conclusions and recommendations for future research are reviewed in **Section 7**.

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2. LITERATURE STUDY

2.1 INTRODUCTION

As explained in the Background (**Section 1.1**), the WCG used the TRH 22 VOC calculation model prior to 2001, as this was a recommended historical South African VOC model. For the purpose of the literature study some of the South African historical models are discussed. The HDM-4 model is subsequently discussed as it is a prerequisite of the research to use HDM-4 Principles. HDM-4 was reviewed with other models, they are not discussed as the use of HDM-4 was considered correct as:

- Many other models are also based on the HDM-4 Principles, a good example being the Road Economic Decision Model (Archondo-Callao, R., Jun 2004) developed by the World Bank.
- Similar to the World Bank, many well-respected organisations also use HDM-4 or HDM-4 Principles. Some closer to home include:
    - SANRAL (South African National Road Agency Limited) (Riaan Burger, Project Engineer for SANRAL Western Cape, personal communication)
    - Namibian Road Agency (Gerrie van Zyl, specialist advisor for Namibian Roads Agency, personal communication)
    - Deighton Agent for Africa, Aurecon (Ileen Wolmarans, Analyst for Aecom, personal communication)

Figure 1 is a visual representation of the process followed during the literature study.

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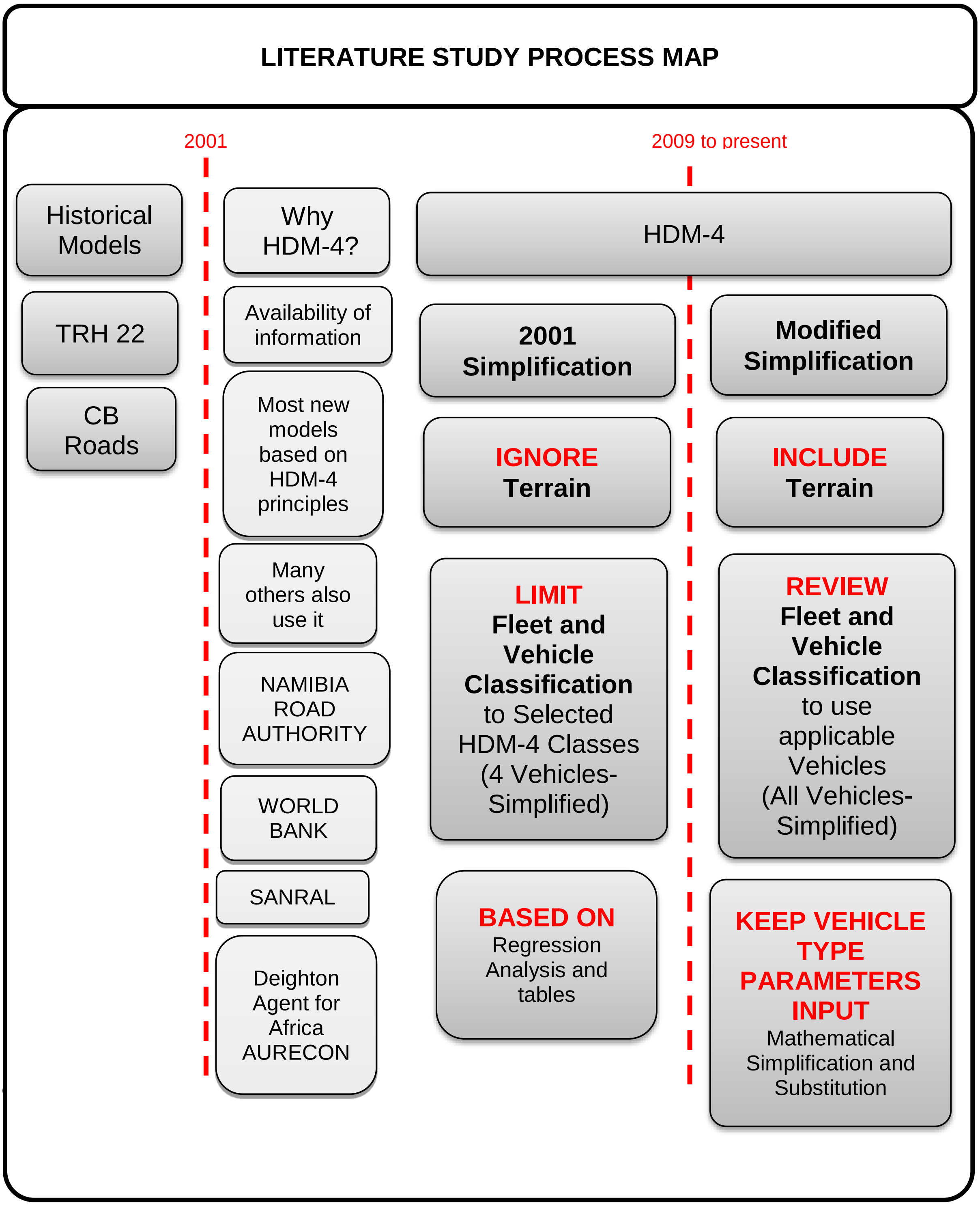

Figure 1 : Literature study map

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2.2 HISTORICAL SOUTH AFRICAN MODELS FOR CALCULATION OF VOC

There are two historical South African models, the one published in the Technical Recommendations for Highways Draft TRH 22, and the other a VOC Model used by Cost Benefit Roads (CB-Roads).

2.2.1 Technical Recommendations for Highways Draft TRH 22

TRH 22 calculated VOC as follows:

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

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. The intention was that factor *A* and others should be published by the CSIR from time to time. At the time of the 2001 Simplification this has not materialized. 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.

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According to the TRH 22 the generation of Excess User Costs (EUC) due to poor riding quality is an influencing factor in decisions regarding rehabilitation. EUC is the difference, in VOC, between a good and poor riding quality road section. The latter will have additional cost.

2.2.2 CB-Roads

The CB-Roads methodology (Jordaan and Joubert, 1994) differs from that of TRH 22. 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 for 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 multiplied by the roughness factor and the VOC calculated. The roughness factor has the general form:

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

Where:

$$\text{Cost } factor\ at\ QI = 40$$

The CB-Roads User Manual (Jordaan and Joubert, 1994) refers to work done by Schutte (1983) in the calculation of VOC as it is influenced by roughness. The factor f_r as defined above is also based on Schutte (1983). When the VOCs are compared at different QI levels, an exponential relationship is found between the values of VOC. Thus, the adjustment factor has an exponential relation at different QI levels.

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2.3 HDM-4 METHODOLOGY FOR CALCULATION OF VOC

The HDM-4 version 2 system has been available since 2001; Burger and Van Zyl (2001) proposed that the Road Network Management Branch systems be updated to do VOC calculations based on HDM-4 methodology.

The HDM-4 methodology for the calculation of VOC differs significantly from the TRH 22 methodology. HDM-4 calculates VOC based on nine factors. (http://www.hdmglobal.com, 2007).

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. Overheads

   *Factors 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).

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2.4 TERRAIN AS PART OF A VOC MODEL

As indicated, commencement of this research was based on the availability of GPS information and new technology that allowed the WCG DTPW to classify Terrain for each road section. HDM-4 includes Terrain in their methodology.

It is however noted that Burger et al. (2003) argues that geometry in calculation of VOC on a well-established network should be excluded from maintenance strategies.

2.5 FLEET AND VEHICLE CLASSIFICATION

Several classification systems are used universally to categorise the vehicle fleet on a road network.

For various reasons a number of different classifications are used within the WCG DTPW road management systems, for example (**Figure 2**):

- Traffic is classed into four types for the hand counts done annually for the Traffic Counting System
- Permanent counting stations (operated by Mikros) yield two traffic classes
- For the HDM-4 implementation, HDM-4 identifies 16 different Vehicle Types
- Selected HDM-4 Classes for VOC 2001 implementation

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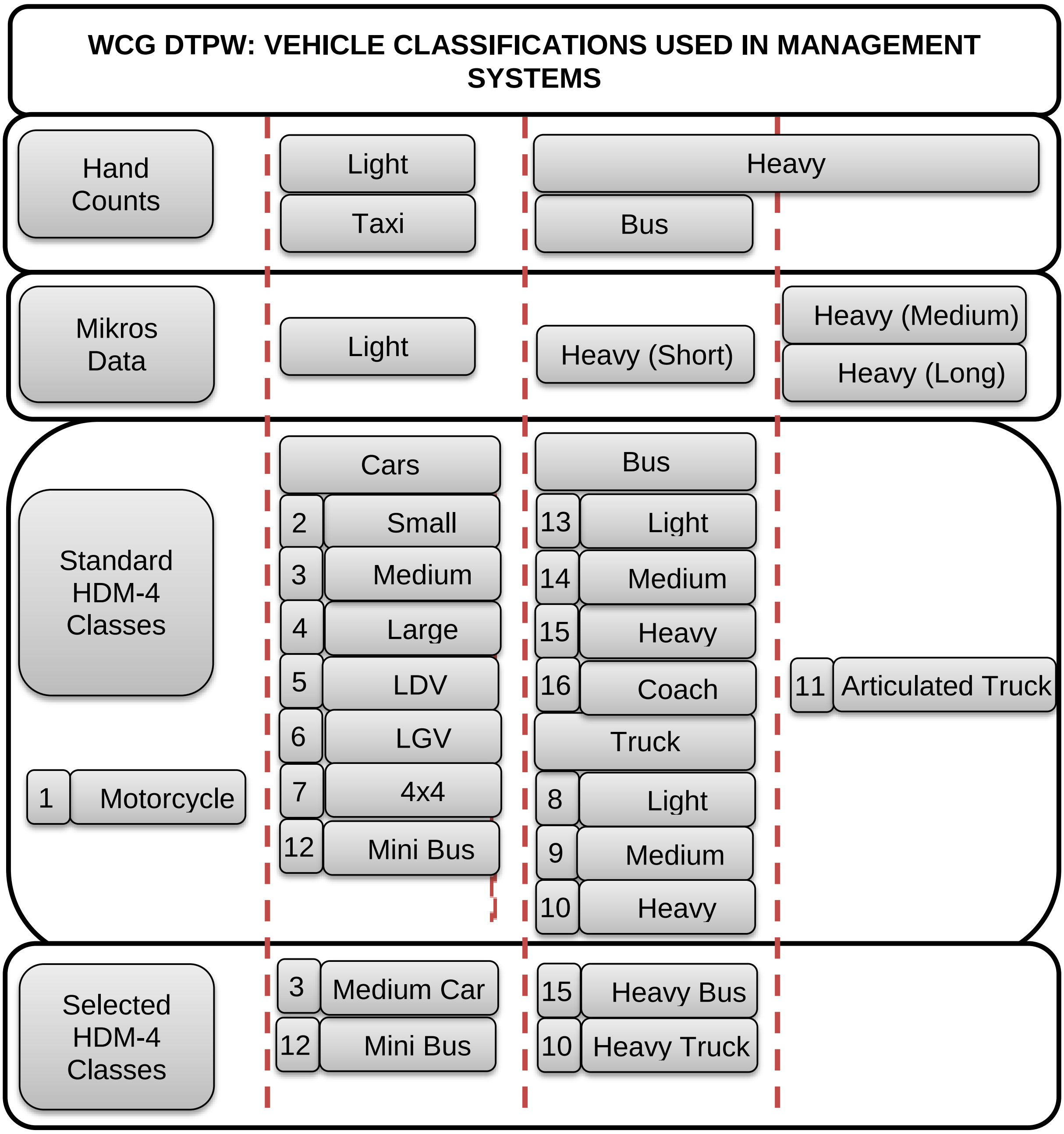

Figure 2 : Vehicle Classification

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2.6 SUMMARY

Multiple methods of calculating VOC exist and even though some have been used for many years, it is accepted that the HDM-4 method is the most applicable for the implementation in the WCG Pavement management system:

- Understanding the previous historical models allows for the focus of how different VOC is in terms of HDM-4.
- The 9 factors identified in the HDM-4 methodology will therefore be the foundation of this research.
- Even though HDM-4 includes Terrain as required by the WCG, it is not suggested in a simplified form by some experts.

Various vehicle fleets are defined and when working with HDM-4 this includes 16 Vehicles; it is therefore a good principle to have all the vehicles as defined in HDM-4 part of the Modified Simplification.

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3. METHODOLOGY

3.1 ORIGINAL SIMPLIFICATION

HDM-4 uses roughness as a direct input for vehicle operating 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-4 factors that are directly related to road roughness, *viz*. fuel consumption, oil consumption, tyre consumption, service life, parts consumption, labour hours and depreciation. The VOC calculations presented here only use these factors.

The 2001 Simplification is based on a vehicle operating speed of 80 km/h, where achievable. This speed was selected as the VOC is calculated in terms of Roughness (IRI) and IRI is calculated from a profile measured at a constant speed of 80 km/h. The operating speed of vehicles is, however, influenced by roughness and the VOC formulae have been adjusted accordingly.

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3.2 MODIFIED SIMPLIFICATION

In the Modified Simplification certain Terrain Types are identified:

- Flat
- Rolling
- Mountainous

The Terrain Types have been included in the Modified Simplification. Taking all the above into account it is possible to use alternative methods to develop the Modified Simplification equations, e.g. regression or direct mathematical substitution. HDM-4 requires the input of Vehicle Type dependent parameters, the values of which are based on real vehicles. This renders the use of regression analysis untenable, as it is a requirement that VOC equations allow for changes in the vehicle dependent parameters. Thus, the set of equations that were developed allows the input of Vehicle Type dependent parameters and the subsequent calculation of VOC with Road Roughness IRI as independent variable.

3.3 VEHICLE FLEET

Vehicle operating cost is calculated for each pre-defined road segment on the road network managed by WCG DTPW and is mainly a function of the roughness and Terrain Type of the road, the traffic volume and composition of the vehicle fleet. The VOC's may then further be utilised to evaluate the impact of alternative maintenance

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strategies and to determine the appropriate remedial measures, timing thereof and budget requirements.

In order to utilise HDM-4 for analyses, the traffic volume and vehicle fleet composition must be known for each pre-defined road segment. In order to simplify calculations different traffic strata have been defined, i.e. Business, Commuter, Rural and General. Every traffic link in the WCG DTPW network is assigned a stratum based on the manual counts at nodes associated with the traffic link. If it is not possible to determine the appropriate stratum from the manual counts (e.g. very low traffic), the “General” stratum is assigned to that link.

Traffic compositions may be determined based on both manual counts and permanent counting data. As the manual counts do not differentiate between the heavy Vehicle Types, the data from the permanent stations may be used for this purpose. The information from permanent traffic stations will be evaluated and a Vehicle Set will be determined. This concept is further developed in **Section 6.1**.

3.4 SYSTEM IMPLEMENTATION

As all the information obtained from the Modified Simplification (**Section 4**) is to be incorporated into the WCG DTPW PMS; it is important to report all data in a format that can easily be programmed by developers.

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It is therefore also important to create an audit system so that when programming has been completed, the system can be easily checked. This will be done by programming the results in a Microsoft Excel format.

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4. MODEL DEVELOPMENT: CALCULATIONS OF MODIFIED HDM-4 SIMPLIFICATION TO INCLUDE TERRAIN

The mathematical simplification of the HDM-4 equations (obtained from Volume 4, from the Highway Development and Management Series (2006)) used in the calculation for VOC is not shown for each Vehicle Type, Surface Type and Terrain Type in the model development. The applicable results and principles are ~~is~~ shown as there are 48 combinations of the Vehicle Type, Surface Type and Terrain. An partial example of the simplification for one of the 48 combinations is provided in **Section 5**.

4.1 MODEL DEVELOPMENT FLOW

The VOC model is developed using the seven factors that are influenced by Road Roughness (**Figure 3**). Each factor is independently influenced by several variables and/or co-factors, some of which are repeated in the VOC factors, and others that are unique. One of the variables influencing multiple VOC factors is total resistance to motion or any of its components:

- Aerodynamic resistance to motion
- Rolling resistance to motion
- Gradient resistance to motion
- Curvature resistance to motion

For this reason these variables are simplified separately (see **Section 4.2**) before each of the VOC factors are calculated.

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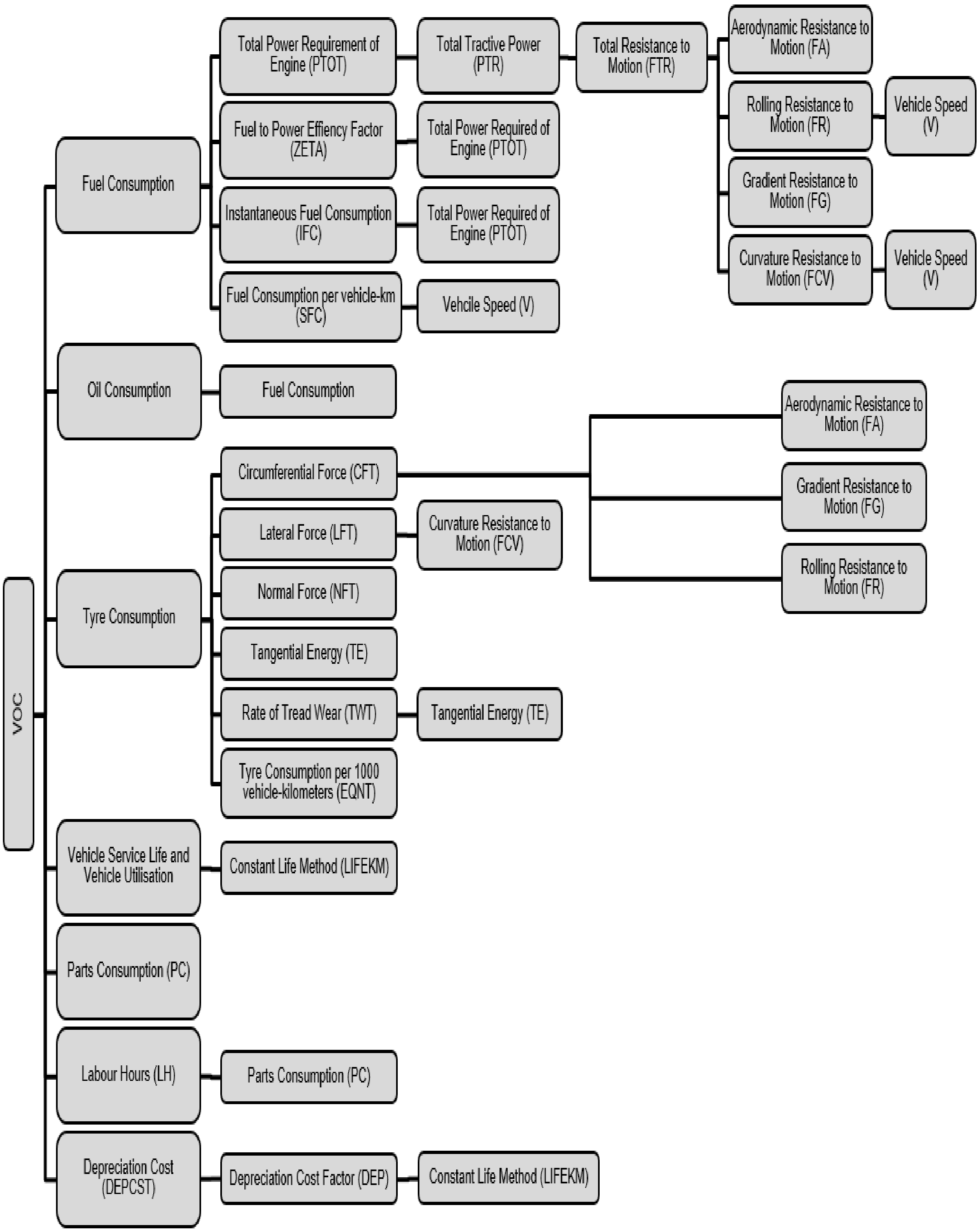

Figure 3 : Comprehensive model development flow

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4.2 RESISTANCE TO MOTION

The total resistance to motion of a vehicle is presented by the following equations:

FTR is calculated as:

$$FTR = FA + FG + FR + FCV$$

where

FTR	total resistance to steady state motion [N]
FA	aerodynamic resistance to motion [N]
FR	rolling resistance to motion [N]
FG	gradient resistance to motion [N]
FCV	curvature resistance to motion [N]

4.2.1 Aerodynamic resistance to motion

The aerodynamic resistance to motion of a vehicle is presented by the following equation;

$$FA = 0.5 \times RH0 \times CGMult \times CD \times AF \times V^2$$

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where

RH0 mass density of air [kg/m^3]

$$RH0 = 1.225\left(1 - 2.26 \times ALT \times 10^{-5}\right)^{4.255}$$

where

ALT road altitude, defined as the evaluation of the road section above mean sea level [m]

CGMult CD multiplier

CD aerodynamic drag coefficient

AF projected frontal area of the vehicle [m^2]

V speed of vehicle type during traffic flow period [m/s]

As per the 2001 Simplification, a constant vehicle operating speed of 80 km/h was selected, when not influenced by roughness. If influenced by roughness:

V the vehicle speed with limiting speed due to roughness [m/s]

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$$VROUGH = \frac{ARVMAX}{VROUGH\ a0 \times RI_{av}}$$

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
RI_{av}	average road roughness [IRI], same as RI previously defined [m/km]

Parameters for the different vehicles are presented in **Appendix A**.

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 – may be determined. In contrast to the 2001 Simplification, two sets of formulae were derived (the 2001 Simplification used a regression formula for VOC above limiting roughness). This consists of a set for steady-state equations below the limiting roughness for the different vehicles, and a set for the roughness values above the limiting roughness for different vehicles.

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Aerodynamic resistance to motion is ignored by the WCG due to the information not being readily available in the required format. The applied principle is that height above mean sea level should not influence decisions at network level (Burger and Van Zyl, 2001). Alternatively, the principle of applying an average to the model was also considered. If this is done, Aerodynamic resistance to motion becomes a constant for each vehicle type. The WCG decided that, in terms of Cost Benefit ratio's, such a constant would not have a significant impact on an identification function that the VOC is used for. Therefore, the decision remained to ignore Aerodynamic resistance in terms of the Modified Simplification.

The above was tested by conducting a sensitivity analysis of the impact of Aerodynamic resistance (**Appendix C**).

Aerodynamic for resistance to motion (**Table 2**) is calculated at different Constant Vehicle speeds and at different heights (**Table 1**).

Table 1: Western Cape Government Network Height above mean sea level

Description	ALT (m)
Minimum Height in the WCG Network	0
Median Height in the WCG Network	251.2
Average Height in the WCG Network	392
Maximum Height in the WCG Network	1696.7

Table 2: Results for Aerodynamic Resistance to Motion

Vehicle Type	**Vehicle Speed**	**FA (ALT=0)**	**FA (ALT=251.2)**	**FA ALT=(392)**	**FA ALT=(1696.7)**
Large Car	80 km/h	299.444	292.283	288.318	253.549
	120 km/h	673.750	657.636	648.716	570.486
Articulated Truck	40 km/h	664.222	648.336	639.542	562.419
	80 km/h	2656.889	2593.344	2558.170	2249.674

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From the above table it can be seen that there is an 18% difference between the Highest and Lowest Point for Aerodynamic Resistance to motion. The effect on Fuel consumption of ignoring Aerodynamic Resistance to motion (as preferred by the WCG) is further discussed in **Section 6.6.4**. In terms of the Modified Simplification the preference of the WCG will be followed.

4.2.2 Rolling resistance to motion

The rolling resistance to motion (FR) per vehicle-km on the road is calculated as:

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

where

FCLIM a factor related to climatic conditions

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

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 >1 mm) (Weather

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Bureau, Cape Town International Airport, personal communication)

Thus, FCLIM becomes: 1.04

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

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

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

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

where

CR2	pavement dependent coefficient of rolling resistance [includes IRI, TDI]
CR1	tyre factor [type dependent: bias-ply or radial]
RI	average roughness [IRI, m/km]
WHEEL_DIA	wheel diameter [m]

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TD	sand patch texture depth [mm]. For the purpose of this simplification, texture depth for surfaced roads equals 1 mm
b11 to b13	model parameters
NUM_WHEELS	number of wheels per vehicle
V	as defined in **Section 4.2.1**

Parameters for the different vehicles are presented in **Appendix A**.

In the simplified formulae for the calculation of rolling resistance for each Vehicle Type in each Terrain Type, it can be seen that the gradient resistance to motion is a function of roughness for gravel roads and for surfaced roads. In the case of surfaced roads texture depth also influences rolling resistance to motion. For the sake of simplification a typical texture depth was chosen (1 mm) and substituted in the equations where applicable.

4.2.3 Gradient resistance to motion

The gradient resistance to motion (FG) per vehicle-km on the road is calculated as:

$$FG = WGT\_OPER \times g \times GR$$

where

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WGT_OPER	vehicle operating weight [kg]
g	acceleration due to gravity [9.81 m/s^2]
GR	average gradient of the road section [as a fraction]
where	$GR = \frac{RF}{1000}$ (uphill) and $GR = -\frac{RF}{1000}$ (downhill)

where RF is rise and fall [m/km]

The parameters used for Terrain Types and different vehicles are presented in **Appendix A**.

In the simplified formulae for the calculation of gradient resistance for each Vehicle Type and Terrain Type combination, it can be seen that the gradient resistance to motion is a constant value for each of these combinations. The only impact deviation is uphill and downhill. The WCG have implemented a conservative approach by always only considering the uphill component, and assuming all vehicles drive in the uphill direction.

The above was tested by doing a sensitivity analysis of the impact of Gradient resistance to motion (**Appendix D**) on fuel in various scenarios with a 50:50 directional split in uphill/downhill traffic. The effect on Fuel consumption of ignoring downhill traffic as preferred by the WCG, is further discussed in **Section 6.6.5** In terms of the Modified Simplification the preference of the WCG will be followed.

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4.2.4 Curvature resistance to motion

The curvature resistance to motion (FCV) per vehicle-km on the road is calculated as:

$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times \mathrm{e}\right)^2}{NUM\_WHEEL \times CS \times 1000}\right]$$

where

CS cornering stiffness of tyres

$$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS}\right)^2\right]$$

Kcs Tyre stiffness factor

CS_a0 to CS_a2 model parameters

e super elevation of the road section [as a fraction]

R average radius of curvature of the road section [m]

where

$$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C\right)}$$

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and C is average horizontal degree of curvature of the road section [deg/km]

All the other parameters are as previously defined.

The parameters used for Terrain Types and different vehicles are presented in **Appendix A**.

Similar to rolling resistance in motion, the curvature resistance in motion is a function of the vehicle speed with limiting speed due to roughness effects. Two sets of formulae were derived from this: A set for steady-state equations below the limiting roughness for the different vehicles, and a set for the roughness values above the limiting roughness for different vehicles.

4.3 FUEL CONSUMPTION

The fuel consumption model is based on the Australian Road Fuel Consumption Model (ARFCOM), which is a 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.

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A breakdown of the computational procedure is presented (**Figure 4**) as an extract of the comprehensive model map (**Figure 3**).

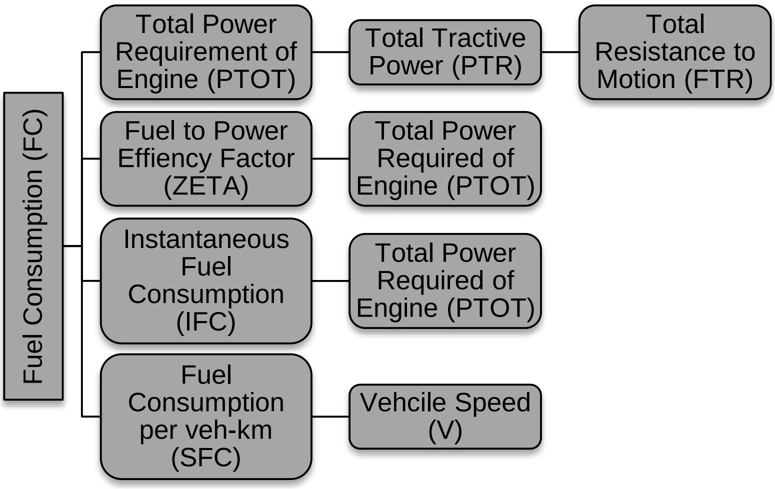

Figure 4 : Fuel Consumption computation procedure

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.

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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 taken into account.

4.3.1 Total power requirements of the engine

The total power requirement for steady-state motion (PTOT) is calculated as:

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS\right)$$

where

PTR	total tractive power [kW]
EDT	drivetrain efficiency
PENGACCS	engine and accessories power [kW]

where the tractive power required (PTR) is calculated as:

$$PTR = \frac{FTR \times V}{1000}$$ with factors as previously defined

Engine and accessory power required is calculated as:

$$PENGACCS = Kpea \times PRAT\left[PACCS\_a1 + \frac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)}\right]$$

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Kpea calibration factor (default = 1.0)

PRAT maximum rated engine power [kW]

RPM engine speed at operating speed [rev/min] calculated by:

$$RPM = RPM\_a0 + RPM\_a1 \times SP + RPM\_a2 \times SP^2 + RPM\_a3 \times SP^3$$

where SP is converted from m/s to km/h

$$SP = \max\left(20, 3.6 \times V\right)$$

As it can be assumed that IRI has a maximum value of 18, it has been confirmed that 3.6V, even at a vehicle speed with limiting speed due to roughness, will always be the maximum value, therefore:

$$\begin{aligned} RPM &= RPM\_a0 + RPM\_a1 \times 3.6 \times V \\ &\quad + RPM\_a2 \times \left(3.6 \times V\right)^2 + RPM\_a3 \times \left(3.6 \times V\right)^3 \end{aligned}$$

RPM_IDLE idle engine speed [rev/min]

RPM100 engine speed at 100 km/h [rev/min] calculated by:

$$RPM100 = RPM\_a0 + RPM\_a1 \times 100 + RPM\_a2 \times 100^2 + RPM\_a3 \times 100^3$$

PACCS_a0 ratio of engine and accessory drag to rated engine power when travelling at 100 km/h

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PACCS_a1 a model parameter calculated by:

$$PACCS\_a1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

where

$$a = ZETAB \times EHP \times Kpea^2 \times PRAT \times \frac{(100 - PCTPENG)}{100}$$

$$b = ZETAB \times Kpea \times PRAT$$

$$c = -IDLE\_FUEL$$

where

IDLE_FUEL idle rate of fuel consumption [ml/s]

ZETAB base fuel-to-power efficiency factor [ml/kW/s]

with all parameters as defined earlier.

It can be seen that the total power required to overcome engine drag and operating vehicle accessories, is calculated as a function of engine speed and vehicle speed. Due to this, two sets of formulae were derived, i.e. a set for steady-state equations below the limiting roughness for the different vehicles, and a set for the roughness

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values above the limiting roughness for different vehicles. It is also noted that RPM and RPM 100 when calculated in isolation for Vehicle Type 1 gives improbable negative values that have been reported to HDMGlobal. When used in the global VOC these results provide expected results.

4.3.2 Fuel to power efficiency factor

The fuel to power efficiency factor ZETA is given by:

$$ZETA = ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100} \right)}{PRAT} \right]$$

where

EHP	decrease in engine efficiency when producing higher power
PCTPENG	percentage of the total engine and accessories power produced from the engine (default = 80)

with all parameters as defined earlier.

4.3.3 Instantaneous fuel consumption

The instantaneous fuel consumption (IFC) for a Vehicle Type is represented by:

$$IFC = max[IDLE\_FUEL, ZETA \times PTOT \times (1 + dFUEL)]$$

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where

dFUEL additional fuel consumption factor due to vehicle speed change cycles with all parameters as defined earlier

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:

$$IFC = max[IDLE\_FUEL, ZETA \times PTOT]$$

4.3.4 Fuel consumption per vehicle-km

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

$$SFC = 1000 \times \frac{IFC}{V}$$

where

SFC specific fuel consumption [ml/km] with all parameters as defined earlier

The fuel consumption of the vehicle is then:

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

$$FC_K = IF(RI < LimitingRoughness, FC_{BELOW(K)}, FC_{ABOVE(K)})$$

$$FC_{BELOW(K)} = FC1 * RI^2 + FC2 * RI + FC3$$

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$$FC_{ABOVE(K)} = FC4 * RI + FC5 + \frac{FC6}{RI} + \frac{FC7}{RI^2} + \frac{FC8}{RI^3} + \frac{FC9}{RI^4} + \frac{FC10}{RI^5} + \frac{FC11}{RI^6} + \frac{FC12}{RI^7} + \frac{FC13}{RI^9}$$

Resulting variables for the calculations conducted on all combinations are presented in **Appendix B**.

4.4 COST OF FUEL

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

where

$FuelCost_{av}$	average cost of fuel for an AADT [R/veh-km]
FC_k	fuel consumption for vehicle type k [l/1000 veh-km]
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

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4.5 OIL CONSUMPTION

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

$$OIL = OILCONT + OILOPER \times FC$$

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:

$$OILCONT = \frac{OILCAP}{DISTCHNG}$$

where

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

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Using the parameters for all the vehicles listed in **Appendix A,** as well as fuel cost equations in **Section 4.3**, equations can be derived for OIL cost in terms of Roughness.

4.6 COST OF OIL

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

where

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

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4.7 TYRE CONSUMPTION

This section describes the calculations used for the estimation of Tyre Consumption (**Figure 5**) for the different Vehicle Types. The rate of tyre consumption is expressed in terms of the number of equivalent new tyres consumed per 100 vehicles for each wheel.

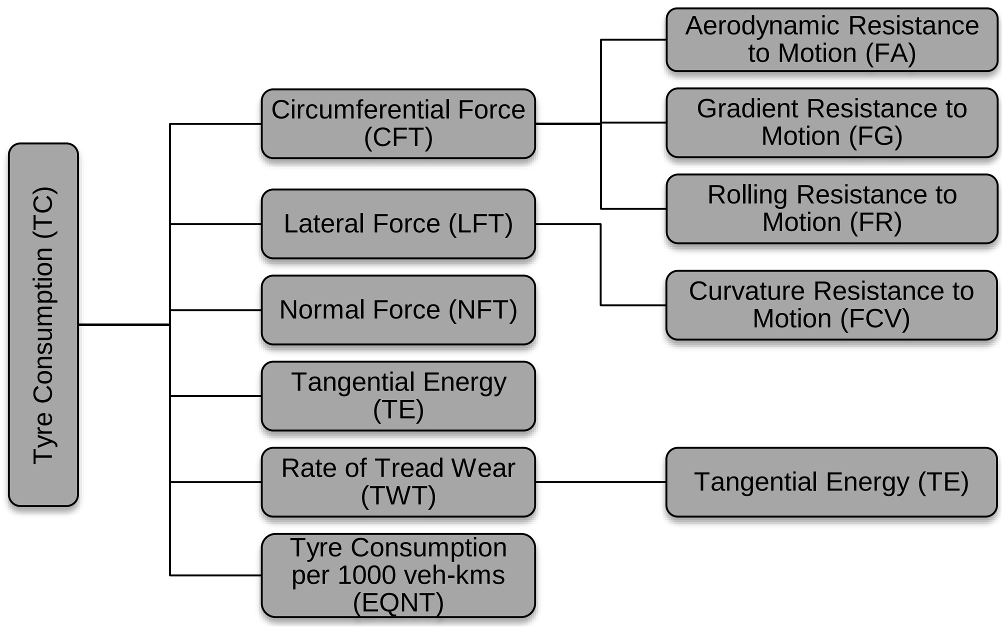

Figure 5: Tyre Consumption computation procedure

The procedure for calculation per Vehicle Type is as follows:

1. Calculate the circumferential, lateral and normal forces acting on the tyre
2. Calculate the tyre energy
3. Calculate the tyre consumption per 1000 vehicle-km
4. The annual average tyre consumption is then calculated

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4.7.1 Circumferential force:

The circumferential force on tyre (CFT) is calculated as:

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

where

CTCON incremental change of tyre consumption related to additional fuel with all parameters as defined earlier

4.7.2 Lateral force:

The lateral force on tyre (LFT) is calculated as:

$$LFT = \frac{FCV_{kp}}{NUM\_WHEELS}$$

with all parameters as defined earlier.

4.7.3 Normal force:

The Normal force on tyre (NFT) is calculated as:

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

with all parameters as defined earlier.

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4.7.4 Tangential energy is calculated as:

The Tangential energy (TE) 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]
NFT	normal force acting on a tyre [N]

4.7.5 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]

4.7.6 Tyre Consumption per 1000 vehicle-kilometers

$$EQNT = \frac{1 + 0.01 \times RREC \times NR}{DISTOT} + 0.0027$$

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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]

where number of retreads (NR) 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 [m/km]

and where total distance travelled (DISTOT) by the tyre:

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

where

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VOL	volume of wearable rubber [dm^3]
TWT	rate of tread wear [dm^3/1000 veh-km]
NR	number of retreads per tyre carcass

In the 2001 Simplification it was found that for IRI=4 and IRI=7, NR is calculated as 0.04 and 0.14 respectively. Therefore, the total distance travelled per tyre increases for the respective values of roughness, concluding that NR can be ignored. In this simplification a further analysis was conducted, that confirmed that NR could be ignored.

4.7.7 Tyre consumption

The tyre consumption (TC) is calculated as:

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

and

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

where

MODFAC	tyre life modification factor
VEHFAC	vehicle type modification factor

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TYPEFAC tyre type modification factor

CONGFAC congestion effects modification factor (for free-flow = 1)

The MODFAC becomes:

$$MODFAC = VEHFAC \times TYPEFAC$$

In the case of unsurfaced 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 unsurfaced roads. For this reason it was decided to use a TYPEFAC value of 1.0 for radial tyres on unsurfaced roads (**Table 3**).

Table 3: HDM-4 wheel type data

Wheel Type	TYPEFAC		
	Surfaced Roads	Unsurfaced Roads	
		$IRI \leq 6$	$IRI > 6$
Bias	1.0	1.0	1.0
Radial	1.25	1.2	1.0

4.7.8 The Annual Average Tyre Consumption is:

The equation for the calculation of tyre consumption becomes:

$$TC_{avk} = TC_k \times AADT_k$$

where

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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

4.8 COST OF TYRES

The cost of tyres is:

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

where

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

Where the above results in a generic equation after substitution

$$TC_K = IF(RI < LimitingRoughness, TC_{BELOW(K)}, TC_{ABOVE(K)}) * \left(\frac{(1 + 0.15 * \mathrm{NR})}{(1 + \mathrm{NR})} \right)$$

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

$$TC_{BELOW(K)} = TC1 * RI^2 + TC2 * RI + TC3$$

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$$TC_{ABOVE(K)} = TC4 * RI^2 + TC5 * RI + TC6 + \frac{TC7}{RI} + \frac{TC8}{RI^2} + \frac{TC9}{RI^3} + \frac{TC10}{RI^4} + \frac{TC11}{RI^6} + \frac{TC12}{RI^8}$$

Resulting variables for the calculations conducted on all combinations are presented in **Appendix B**.

4.9 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.

4.9.1 Constant Life Method

$$LIFEKM = LIFEKM0 = AKM0 \times LIFE0$$

where

LIFEKM	predicted optimal lifetime in kilometers [km]
LIFEKM0	baseline average vehicle service life in kilometers [km]
AKM0	baseline average number of kilometers driven per vehicle per year [km]
LIFE0	baseline average vehicle service life [years]

Using the parameters for all the vehicles in **Appendix A**.

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4.9.2 Adjusted 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:

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

or

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

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4.10 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 kilometers 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

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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:

$$PC = CKM^{KP} \times \left(a0 + a1 \times RI_{adj}\right)$$

The values of the parameters are presented in **Appendix A**.

4.11 PARTS COST

4.11.1 Annual Average Parts Consumption

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

$$PC_{avk} = AADT_k \times PC_k$$

where

$AADT_k$	AADT of vehicle type k
PC_k	the parts consumption of vehicle type k

Thus, the cost of parts is:

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$$PARTSCOST = \sum_{k=1}^{4} PC_{avk} \times VEHCOST_k$$

where

PARTSCOST	cost of parts (R per 1000 veh-km)
$VEHCOST_k$	the average cost of a new vehicle of type k

Resulting in generic Equations of

$$PARTSCOST = \sum_{k=1}^{4} PC_{avk} \times VEHCOST_k$$

$$PC_{avk} = AADT_k \times PC_k$$
$$PC_K = IF(RI < \text{Roughness Adjustment Point}, PC_{BELOW(K)}, PC_{ABOVE(K)})$$

Point where RI=RI0 is defined Roughness Adjustment Point

$$PC_{BELOW(K)} = PC1 + PC2 * RI^{PC3}$$

$$PC_{ABOVE(K)} = PC4 * RI + PC5$$

Resulting variables for the calculations conducted on all combinations are presented in **Appendix B**.

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4.12 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 vehicle-kms 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)

Applying the calibration factors to the formula result in the following equation:

$$LH = a0 \times PC^{a1}$$

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The values of the parameters for each vehicle are presented in **Appendix A**. Resulting variables for the calculations conducted on all combinations are presented in **Appendix B**.

4.13 LABOUR COST

4.13.1 Annual Average Labour Hours

The annual average labour hours are calculated as shown below.

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

where

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

$$LABOURCOST = WAGECOST \times LH_{av}$$

where

LABOURCOST	cost of maintenance labour [R per 1000 vehicle-kms]
WAGECOST	the rate of labour wages

Resulting in generic Equations of

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$$LABOURCOST = WAGECOST \times LH_{av}$$

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

$$LH = LH1 \times PC^{LH2}$$

Resulting variables for the calculations conducted on all combinations are presented in **Appendix B**.

4.14 DEPRECIATION COST

The cost of depreciation is calculated with the following formula:

$$DEPCST = DEP \times NVPLT$$

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:

$$NVPLT = NVP - NUM\_WHEELS \times NTP$$

where

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NVP average new (or replacement) vehicle price

NTP average new tyre price

4.14.1 Depreciation Cost Factor

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

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

where

RVPLTPCT residual vehicle price less tyres as a percentage of new price [%]

LIFEKM predicted optimal vehicle service life [km]

4.14.2 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]

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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).

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

4.15 ANNUAL AVERAGE DEPRECIATION COST

The average annual depreciation cost is calculated as:

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

where

DEPCSTav depreciation cost [R per 1000 veh-km]

$AADT_k$ AADT of vehicle type k

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$DEPCST_k$ depreciation cost of vehicle type k

Resulting in generic Equations of

$$DEPCST = DEP \times NVPLT$$

$$NVPLT = NVP - NUM\_WHEELS \times NTP$$

$$DEP = DEP1 + DEP2 * MAX(0, RI - 5)$$

Resulting variables for the calculations conducted on all combinations are presented in **Appendix B**.

4.16 VEHICLE OPERATING COST

From the previous sections it becomes clear that the VOC for a road segment with an AADT is calculated as:

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

where each is defined by (variables available in **Appendix B**):

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

$$FC_K = IF(RI < LimitingRoughness, FC_{BELOW(K)}, FC_{ABOVE(K)})$$

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$$FC_{BELOW(K)} = FC1 * RI^2 + FC2 * RI + FC3$$

$$FC_{ABOVE(K)} = FC4 * RI + FC5 + \frac{FC6}{RI} + \frac{FC7}{RI^2} + \frac{FC8}{RI^3} + \frac{FC9}{RI^4} + \frac{FC10}{RI^5} + \frac{FC11}{RI^6} + \frac{FC12}{RI^7} + \frac{FC13}{RI^9}$$

$$OilCost_{av} = \sum_{k=1}^{4} OIL_K \times AADT_K \times Oilprice_K$$

$$OIL_K = OIL1 + OIL2 \times FC$$

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

$$TC_{avk} = TC_k \times AADT_k$$

$$TC_K = IF(RI < LimitingRoughness, TC_{BELOW(K)}, TC_{ABOVE(K)}) * \left(\frac{(1 + 0.15 * \mathrm{NR})}{(1 + \mathrm{NR})} \right)$$

$$NR = MAX\left[0, 1.3 \times \exp\left(-0.03224 \times RI\right) - 1\right]$$

$$TC_{BELOW(K)} = TC1 * RI^2 + TC2 * RI + TC3$$

$$TC_{ABOVE(K)} = TC4 * RI^2 + TC5 * RI + TC6 + \frac{TC7}{RI} + \frac{TC8}{RI^2} + \frac{TC9}{RI^3} + \frac{TC10}{RI^4} + \frac{TC11}{RI^6} + \frac{TC12}{RI^8}$$

$$PARTSCOST = \sum_{k=1}^{4} PC_{avk} \times VEHCOST_k$$

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$$PC_{avk} = AADT_k \times PC_k$$

$$PC_K = IF(RI < \text{Roughness Adjustment Point}, PC_{BELOW(K)}, PC_{ABOVE(K)})$$

Point where RI=RI0 is defined Roughness Adjustment Point

$$PC_{BELOW(K)} = PC1 + PC2 * RI^{PC3}$$

$$PC_{ABOVE(K)} = PC4 * RI + PC5$$

$$LABOURCOST = WAGECOST \times LH_{av}$$

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

$$LH = LH1 \times PC^{LH2}$$

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

$$DEPCST = DEP \times NVPLT$$

$$NVPLT = NVP - NUM\_WHEELS \times NTP$$

$$DEP = DEP1 + DEP2 * MAX(0, RI - 5)$$

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5. MODEL DEVELOPMENT: EXAMPLE

In this chapter the mathematical simplification is discussed, as explained in **Section 4** for one of the 48 combinations of Vehicle Type, Surface Type and Terrain Type. See **Appendix B** for equation variables for all combinations.

As indicated previously, it was a requirement that VOC equations allow for changes in the vehicle dependent parameters. Therefore, the set of equations that were developed allows the input of Vehicle Type dependent parameters and the subsequent calculation of VOC with Road Roughness IRI as independent variable.

For the purpose of the example VOC is not calculated and only the equations up to the step before calculating of cost of each component, are shown. This is due to the Vehicle Type dependent parameters being unknown.

The example used is for a Vehicle Type “1” (motorcycle), Surface Type Paved and Terrain Type Flat. All values are shown rounded, although full values have been used in actual calculations – this has the effect that values might differ slightly if calculated by hand following the examples below. Where needed, necessary references have been noted, but no explanation as to actual calculations are included (see **Section 4**), as this is intended to be an example only.

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5.1 RESISTANCE TO MOTION

$$FTR = FA + FG + FR + FCV$$

A schematic representation of the computational procedure is shown in **Figure 6**.

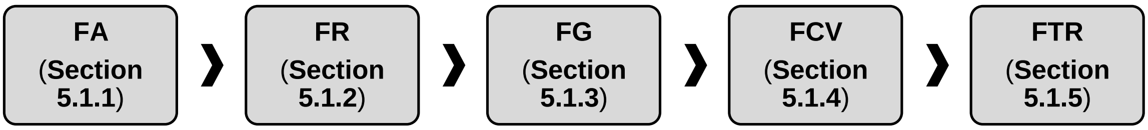

Figure 6 : Calculation process for Resistance to Motion

Final substitution of variables into the above equation is presented in **Section 5.1.5**.

5.1.1 Aerodynamic resistance to motion

$$FA = 0$$

5.1.2 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:

$$\begin{aligned} FCLIM &= 1 + 0.003 \times PCTDS + 0.002 \times PCTDW \\ &= 1 + 0.003 \times 0 + 0.002 \times 20 \\ &= 1 + 0 + 0.04 \\ &= 1.04 \end{aligned}$$

and (**Appendix A**, Tables E2.4 and E2.2)

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$$
\begin{aligned}
b11 &= CR\_B\_a0 \times WHEEL\_DIA \\
&= 37 \times 0.55 \\
&= 20.35
\end{aligned}
$$

$$
\begin{aligned}
b12 &= \frac{CR\_B\_a1}{WHEEL\_DIA} \\
&= \frac{0.064}{0.55} \\
&= 0.116
\end{aligned}
$$

$$
\begin{aligned}
b13 &= \frac{\left(CR\_B\_a2 \times NUM\_WHEELS\right)}{WHEEL\_DIA^2} \\
&= \frac{\left(0.012 \times 2\right)}{0.55^2} \\
&= 0.079
\end{aligned}
$$

Split FR into separate parts:

$$
\begin{aligned}
FR &= FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2\right) \\
&= FCLIM \times CR2 \times \left(term1 + term2 \times V^2\right)
\end{aligned}
$$

where:

$$
\begin{aligned}
term1 &= b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER \\
&= 20.35 \times 2 + 1.3 \times 0.116 \times 200 \\
&= 70.955
\end{aligned}
$$

$$
\begin{aligned}
term2 &= CR1 \times b13 \\
&= 1.3 \times 0.079 \\
&= 0.103
\end{aligned}
$$

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Split $CR2$ into separate parts:

$$\begin{aligned} CR2 &= Kcr2 \times \left(CR\_CR2\_a0 + CR\_CR2\_a1 \times TD + CR\_CR2\_a2 \times RI \right) \\ &= Kcr2 \times CR\_CR2\_a0 + Kcr2 \times CR\_CR2\_a1 \times TD \\ &\quad + Kcr2 \times CR\_CR2\_a2 \times RI \\ &= term3 + term4 \times RI \end{aligned}$$

(**Appendix A**, Table E2.3)

$$\begin{aligned} term3 &= Kcr2 \times CR\_CR2\_a0 + Kcr2 \times CR\_CR2\_a1 \times TD \\ &= 1 \times 0.9 + 1 \times 0.022 \times 1 \\ &= 0.922 \end{aligned}$$

$$\begin{aligned} term4 &= Kcr2 \times CR\_CR2\_a2 \\ &= 1 \times 0.022 \\ &= 0.022 \end{aligned}$$

thus,

$$\begin{aligned} CR2 &= Kcr2 \times \left(CR\_CR2\_a0 + CR\_CR2\_a1 \times TD + CR\_CR2\_a2 \times RI \right) \\ &= term3 + term4 \times RI \\ &= 0.922 + 0.022RI \end{aligned}$$

and:

$$\begin{aligned} FR &= FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2 \right) \\ &= 1.04 \times CR2 \times \left(term1 + term2 \times V^2 \right) \\ &= 1.04 \times \left(0.922 + 0.022RI \right) \times \left(70.955 + 0.103V^2 \right) \\ &= \left(0.959 + 0.023RI \right) \times \left(70.955 + 0.103V^2 \right) \end{aligned}$$

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For vehicle speed not limited due to roughness:

$$V = 80\text{km/h} = 22.222\text{m/s} \qquad V^2 = 22.222^2 = 493.827$$

$$\begin{aligned} FR &= FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2\right) \\ &= \left(0.959 + 0.023RI\right) \times \left(70.955 + 0.103V^2\right) \\ &= \left(0.959 + 0.023RI\right) \times \left(70.955 + 0.103 \times 22.222^2\right) \\ &= 2.789RI + 116.876 \end{aligned}$$

For vehicle speed with limiting speed due to roughness (**Appendix A**, Table E2.5):

$$\begin{aligned} V &= VROUGH \\ &= \frac{ARVMAX}{VROUGHa0 \times RI_{av}} \\ &= \frac{ARVMAX}{VROUGHa0} \times \frac{1}{RI} \\ &= \frac{203}{1.15} \times \frac{1}{RI} \end{aligned}$$

$$\begin{aligned} V^2 &= \left(\frac{203}{1.15} \times \frac{1}{RI_{av}}\right)^2 \\ &= \left(\frac{203}{1.15}\right)^2 \times \left(\frac{1}{RI}\right)^2 \\ &= 31159.924 \times \left(\frac{1}{RI}\right)^2 \\ &= \frac{31159.924}{RI^2} \end{aligned}$$

$$\begin{aligned} FR &= FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2\right) \\ &= \left(0.959 + 0.023RI\right) \times \left(70.955 + 0.103 \times \left(\frac{203}{1.15} \times \frac{1}{RI}\right)^2\right) \\ &= \left(0.959 + 0.023RI\right) \times \left(70.955 + 0.103 \times \frac{31159.924}{RI^2}\right) \\ &= \left(0.959 + 0.023RI\right) \times \left(70.955 + 3213.850\frac{1}{RI^2}\right) \\ &= 1.623RI + 73.533\frac{1}{RI} + 3081.697\frac{1}{RI^2} + 68.037 \end{aligned}$$

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5.1.3 Gradient resistance to motion

$$FG = WGT\_OPER \times g \times GR$$

where:

$$\begin{aligned} FG &= WGT\_OPER \times g \times GR \\ &= WGT\_OPER \times g \times \frac{RF}{1000} \\ &= WGT\_OPER \times 9.81 \times \frac{RF}{1000} \end{aligned}$$

Using $RF = 10$ (**Appendix A**):

$$\begin{aligned} FG &= WGT\_OPER \times g \times GR \\ &= WGT\_OPER \times g \times \frac{RF}{1000} \\ &= 200 \times 9.81 \times \frac{10}{1000} \\ &= 19.74 \end{aligned}$$

5.1.4 Curvature resistance to motion

$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEEL \times CS \times 1000}\right]$$

where (**Appendix A**, Table E2.7)

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$$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS} \right)^2 \right]$$
$$= 1 \times \left[30 + \frac{0 \times 200}{2} + 0 \times \left(\frac{200}{2} \right)^2 \right]$$
$$= 30$$

Using $e = 2.5/100$ (**Appendix A**):

$$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C \right)}$$

Using $C = 15$ (**Appendix A**):

$$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C \right)}$$
$$= \frac{180000}{\pi \times max(5.730, 15)}$$
$$= \frac{180000}{\pi \times 15}$$
$$= 3819.719$$

thus:

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$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEELS \times CS \times 1000}\right]$$

$$= max\left[0, \frac{\left(\frac{200 \times V^2}{3819.719} - 200 \times 9.81 \times \left(\frac{2.5}{100}\right)\right)^2}{2 \times 30 \times 1000}\right]$$

$$= max\left[0, \frac{\left(0.052 \times V^2 - 49.050\right)^2}{60000}\right]$$

For vehicle speed not limited due to roughness:

$$V^2 = 493.827$$

thus

$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEELS \times CS \times 1000}\right]$$

$$= max\left[0, \frac{\left(0.052 \times 493.827 - 49.050\right)^2}{60000}\right]$$

$$= max\left[0, 0.009\right]$$

$$= 0.009$$

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For vehicle speed with limiting speed due to roughness:

$$V^2 = \frac{31159.924}{RI^2}$$

thus:

$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEELS \times CS \times 1000}\right]$$

$$= max\left[0, \frac{\left(0.052 \times \frac{31159.924}{RI^2} - 49.050\right)^2}{60000}\right]$$

$$= max\left[0, 44.365\frac{1}{RI^4} - 2.668\frac{1}{RI^2} + 0.040\right]$$

$$= 44.365\frac{1}{RI^4} - 2.668\frac{1}{RI^2} + 0.040$$

Refer to **Section 3.2.1**. As IRI has a Maximum value 18, the above will be true for all Vehicle Types.

5.1.5 Final Substitution: Resistance to motion

$$FTR = FA + FG + FR + FCV$$

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For vehicle speed not limited due to roughness:

$$
\begin{aligned}
FTR &= FA + FG + FR + FCV \\
&= 0 + 19.74 + (2.789RI + 116.876) + 0.009 \\
&= 136.625 + 2.789RI
\end{aligned}
$$

For vehicle speed with limiting speed due to roughness:

$$
\begin{aligned}
FTR &= FA + FG + FR + FCV \\
&= 0 + 19.74 + \left(1.623RI + 73.533\frac{1}{RI} + 3081.697\frac{1}{RI^2} + 68.037\right) + \left(44.365\frac{1}{RI^4} - 2.668\frac{1}{RI^2} + 0.040\right) \\
&= 1.623RI + 73.533\frac{1}{RI} + 3079.029\frac{1}{RI^2} + 44.365\frac{1}{RI^4} + 87.697
\end{aligned}
$$

5.2 FUEL CONSUMPTION

$$FC = \frac{SFC}{1000}$$

with:

$$SFC = 1000 \times \frac{IFC}{V}$$

thus:

$$FC = \frac{IFC}{V}$$

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and:

$$IFC = max\left[IDLE\_FUEL, ZETA \times PTOT \times \left(1 + dFUEL\right)\right]$$

A schematic representation of the computational procedure is shown in **Figure 7**.

Figure 7 : Calculation process for Fuel Consumption

Final substitution of variables into the above equation is presented in **Section 5.2.4**.

5.2.1 Total power requirements of the engine

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS\right)$$

where:

$$PTR = \frac{FTR \times V}{1000}$$

For vehicle speed not limited due to roughness:

$$\begin{aligned} PTR &= \frac{FTR \times V}{1000} \\ &= \frac{\left(136.407 + 2.786RI\right) \times 22.222}{1000} \\ &= 0.062RI + 3.033 \end{aligned}$$

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For vehicle speed with limiting speed due to roughness:

$$PTR = \frac{FTR \times V}{1000}$$
$$= \frac{\left(1.623RI + 73.533\frac{1}{RI} + 3079.029\frac{1}{RI^2} + 44.365\frac{1}{RI^4} + 87.697\right) \times \left(\frac{203}{1.15} \times \frac{1}{RI}\right)}{1000}$$
$$= 15.480\frac{1}{RI} + 12.980\frac{1}{RI^2} + 543.516\frac{1}{RI^3} + 7.831\frac{1}{RI^5} + 0.287$$

and (**Appendix A**, Table E2.8):

$$PENGACCS = Kpea \times PRAT \times \left[PACCS\_a1 + \frac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \right]$$

with:

$$PACCS\_a1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

$$a = ZETAB \times EHP \times Kpea^2 \times PRAT \times \frac{(100 - PCTPENG)}{100}$$
$$= 0.067 \times 0.25 \times 1^2 \times 15 \times \frac{(100 - 80)}{100}$$
$$= 0.050$$

$$b = ZETAB \times Kpea \times PRAT$$
$$= 0.067 \times 1 \times 15$$
$$= 1.005$$

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$$c = -IDLE\_FUEL$$
$$= -0.12$$

thus:

$$PACCS\_a1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$
$$= \frac{-1.005 + \sqrt{1.005^2 - 4 \times 0.050 \times (-0.120)}}{2 \times 0.050}$$
$$= 0.119$$

and

$$RPM = RPM\_a0 + RPM\_a1 \times 3.6V + RPM\_a2 \times (3.6V)^2 + RPM\_a3 \times (3.6V)^3$$
$$= -0.0026 \times (3.6V)^3 - 4.6723 \times (3.6V)^2 + 298.86 \times 3.6V - 162$$

For vehicle speed not limited due to roughness:

$V = 22.222$ and $3.6V = 80$,

thus:

$$RPM = RPM\_a0 + RPM\_a1 \times 3.6V + RPM\_a2 \times (3.6V)^2 + RPM\_a3 \times (3.6V)^3$$
$$= -0.0026 \times (3.6V)^3 - 4.6723 \times (3.6V)^2 + 298.86 \times 3.6V - 162$$
$$= -0.0026 \times 80^3 - 4.6723 \times 80^2 + 298.86 \times 80 - 162$$
$$= -7487.120$$

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For vehicle speed with limiting speed due to roughness:

$$V=\frac{203}{1.15}\times\frac{1}{RI} \quad \text{and} \quad \begin{aligned} 3.6V &= 3.6\times\frac{203}{1.15}\times\frac{1}{RI} \\ &= 635.478\frac{1}{RI} \end{aligned}$$

thus:

$$\begin{aligned} RPM &= RPM\_a0 + RPM\_a1\times 3.6\times V + RPM\_a2\times(3.6\times V)^2 + RPM\_a3\times(3.6\times V)^3 \\ &= -0.0026\times(3.6V)^3 - 4.6723\times(3.6V)^2 + 298.86\times 3.6V - 162 \\ &= -0.0026\times\left(635.478\frac{1}{RI}\right)^3 - 4.6723\times\left(635.478\frac{1}{RI}\right)^2 + \left(298.86\times 635.478\frac{1}{RI}\right) - 162 \\ &= 189919.033\frac{1}{RI} - 1886827.151\frac{1}{RI^2} - 667229.813\frac{1}{RI^3} - 162 \end{aligned}$$

and:

$$\begin{aligned} RPM100 &= RPM\_a0 + RPM\_a1\times 100 + RPM\_a2\times(100)^2 + RPM\_a3\times(100)^3 \\ &= (-162) + (298.86\times 100) + (-4.6723\times 100^2) + (-0.0026\times 100^3) \\ &= -162 + 29886 - 46723 - 2600 \\ &= -19599 \end{aligned}$$

Due to the doubtful negative result refer to **Section 4.3.1**. RPM and RPM 100 is also calculated for Vehicle Type 2.

For vehicle speed not limited due to roughness:

$$\begin{aligned} V &= 80\text{km/h} \\ &= 22.222\text{m/s} \end{aligned}$$

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For Vehicle Type 2 the vehicle speed with limiting speed due to roughness (**Appendix A**, Table E2.5):

$$
\begin{aligned}
V &= VROUGH \\
&= \frac{ARVMAX}{VROUGHa0 \times RI_{av}} \\
&= \frac{ARVMAX}{VROUGHa0} \times \frac{1}{RI} \\
&= \frac{203}{1.15} \times \frac{1}{RI}
\end{aligned}
$$

thus:

$$
\begin{aligned}
RPM &= RPM\_a0 + RPM\_a1 \times 3.6V + RPM\_a2 \times (3.6V)^2 + RPM\_a3 \times (3.6V)^3 \\
&= -0.0003 \times (3.6V)^3 + 0.2228 \times (3.6V)^2 - 12.311 \times 3.6V + 1910
\end{aligned}
$$

For vehicle speed not limited due to roughness:

$V = 22.222$ and $3.6V = 80$

thus:

$$
\begin{aligned}
RPM &= RPM\_a0 + RPM\_a1 \times 3.6V + RPM\_a2 \times (3.6V)^2 + RPM\_a3 \times (3.6V)^3 \\
&= -0.0003 \times (3.6V)^3 + 0.2228 \times (3.6V)^2 - 12.311 \times 3.6V + 1910 \\
&= -0.0003 \times 80^3 + 0.2228 \times 80^2 - 12.311 \times 80 + 1910 \\
&= 2197.440
\end{aligned}
$$

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For vehicle speed with limiting speed due to roughness:

$$V=\frac{203}{1.15}\times\frac{1}{RI} \quad \text{and} \quad \begin{aligned} 3.6V &= 3.6\times\frac{203}{1.15}\times\frac{1}{RI} \\ &= 635.478\frac{1}{RI} \end{aligned}$$

thus:

$$\begin{aligned} RPM &= RPM\_a0 + RPM\_a1\times 3.6V + RPM\_a2\times(3.6V)^2 + RPM\_a3\times(3.6V)^3 \\ &= -0.0003\times(3.6V)^3 + 0.2228\times(3.6V)^2 - 12.311\times 3.6V + 1910 \\ &= -0.0003\times\left(635.478\frac{1}{RI}\right)^3 + 0.2228\times\left(635.478\frac{1}{RI}\right)^2 - 12.311\times\left(635.478\frac{1}{RI}\right) + 1910 \\ &= -7823.373\frac{1}{RI} + 89973.908\frac{1}{RI^2} - 76988.055\frac{1}{RI^3} + 1910 \end{aligned}$$

and:

$$\begin{aligned} RPM100 &= RPM\_a0 + RPM\_a1\times 100 + RPM\_a2\times(100)^2 + RPM\_a3\times(100)^3 \\ &= 1910 - 12.311\times 100 + 0.2228\times 100^2 - 0.0003\times 100^3 \\ &= 1910 - 1231.1 + 2228 - 300 \\ &= 2606.900 \end{aligned}$$

Back to the example of Vehicle Type 1:

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Split $PENGACCS$ into separate parts:

$$PENGACCS = Kpea \times PRAT \left[\begin{array}{l} PACCS\_a1 \\ + \dfrac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \end{array} \right]$$

$$\begin{aligned} &= Kpea \times PRAT \times PACCS\_a1 \\ &+ Kpea \times PRAT \times \frac{(PACS\_a0 - PACCS\_a1)}{(RPM100 - RPM\_IDLE)} \times (-RPM\_IDLE) \\ &+ Kpea \times PRAT \times \frac{(PACS\_a0 - PACCS\_a1)}{(RPM100 - RPM\_IDLE)} \times RPM \end{aligned}$$

$$= term5 + term6 + term7 \times RPM$$

with:

$$\begin{aligned} term5 &= Kpea \times PRAT \times PACCS\_a1 \\ &= 1 \times 15 \times 0.119 \\ &= 1.780 \end{aligned}$$

$$\begin{aligned} term6 &= Kpea \times PRAT \times \frac{(PACS\_a0 - PACCS\_a1)}{(RPM100 - RPM\_IDLE)} \times (-RPM\_IDLE) \\ &= 1 \times 15 \times \frac{(0.200 - 0.119)}{(-19599 - 800)} \times (-800) \\ &= 0.048 \end{aligned}$$

$$\begin{aligned} term7 &= Kpea \times PRAT \times \frac{(PACS\_a0 - PACCS\_a1)}{(RPM100 - RPM\_IDLE)} \\ &= 1 \times 15 \times \frac{(0.200 - 0.119)}{(-19599 - 800)} \\ &= -5.978 \times 10^{-5} \end{aligned}$$

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thus:

$$PENGACCS = Kpea \times PRAT \left[\begin{array}{l} PACCS\_a1 \\ + \dfrac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \end{array} \right]$$

$$\begin{aligned} &= term5 + term6 + term7 \times RPM \\ &= 1.780 + 0.048 + \left(-5.978 \times 10^{-5}\right) \times RPM \\ &= 1.828 + \left(-5.978 \times 10^{-5}\right) \times RPM \end{aligned}$$

For vehicle speed not limited due to roughness:

$$PENGACCS = Kpea \times PRAT \left[\begin{array}{l} PACCS\_a1 \\ + \dfrac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \end{array} \right]$$

$$\begin{aligned} &= 1.828 + \left(-5.978 \times 10^{-5}\right) \times RPM \\ &= 1.828 + \left(-5.978 \times 10^{-5}\right) \times (-7487.12) \\ &= 2.276 \end{aligned}$$

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For vehicle speed with limiting speed due to roughness:

$$PENGACCS = Kpea \times PRAT \left[PACCS\_a1 + \frac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \right]$$

$$= 1.828 + \left(-5.978 \times 10^{-5}\right) \times RPM$$

$$= 1.828 + \left(-5.978 \times 10^{-5}\right) \times \left(189919.033\frac{1}{RI} - 1886827.151\frac{1}{RI^2} - 667229.813\frac{1}{RI^3} - 162 \right)$$

$$= -11.354\frac{1}{RI} + 112.801\frac{1}{RI^2} + 39.889\frac{1}{RI^3} + 1.838$$

The result of combining the above:

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS \right)$$

For vehicle speed not limited due to roughness:

$$PTOT = \frac{PTR}{EDT} + PENGACCS$$

$$= \frac{(0.062RI + 3.033)}{0.950} + 2.276$$

$$= 0.065RI + 5.469$$

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For vehicle speed with limiting speed due to roughness:

$$PTOT = \frac{PTR}{EDT} + PENGACCS$$
$$= \frac{\left(15.480\frac{1}{RI} + 12.980\frac{1}{RI^2} + 543.516\frac{1}{RI^3} + 7.831\frac{1}{RI^5} + 0.287\right)}{0.950}$$
$$+ \left(-11.354\frac{1}{RI} + 112.801\frac{1}{RI^2} + 39.889\frac{1}{RI^3} + 1.838\right)$$
$$= 4.941\frac{1}{RI} + 126.464\frac{1}{RI^2} + 612.011\frac{1}{RI^3} + 8.244\frac{1}{RI^5} + 2.140$$

5.2.2 Fuel to power efficiency factor

$$ZETA = ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100}\right)}{PRAT}\right]$$

Split $ZETA$ into separate parts:

$$ZETA = ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100}\right)}{PRAT}\right]$$
$$= ZETAB + \frac{ZETAB \times EHP}{PRAT} \times PTOT - \frac{ZETAB \times EHP \times PCTPENG}{PRAT \times 100} \times PENGACCS$$
$$= ZETAB + term8 - term9 \times PENGACCS$$

with:

$$term8 = \frac{ZETAB \times EHP}{PRAT} \times PTOT$$

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$$term9 = \frac{ZETAB \times EHP \times PCTPENG}{PRAT \times 100}$$

For vehicle speed not limited due to roughness:

$$\begin{aligned} term8 &= \frac{ZETAB \times EHP}{PRAT} \times PTOT \\ &= \frac{0.067 \times 0.250}{15} \times (0.065RI + 5.469) \\ &= (7.285 \times 10^{-5})RI + 0.006 \end{aligned}$$

$$\begin{aligned} term9 &= \frac{ZETAB \times EHP \times PCTPENG}{PRAT \times 100} \\ &= \frac{0.067 \times 0.250 \times 80}{15 \times 100} \\ &= 8.933 \times 10^{-4} \end{aligned}$$

and:

$$\begin{aligned} ZETA &= ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100} \right)}{PRAT} \right] \\ &= ZETAB + term8 - term9 \times PENGACCS \\ &= 0.067 + \left((7.285 \times 10^{-5})RI + 0.006 \right) - (8.933 \times 10^{-4}) \times 2.276 \\ &= (7.285 \times 10^{-5})RI + 0.071 \end{aligned}$$

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For vehicle speed with limiting speed due to roughness:

$$term8 = \frac{ZETAB \times EHP}{PRAT} \times PTOT$$
$$= \frac{0.067 \times 0.250}{15} \times \left(4.941 \frac{1}{RI} + 126.464 \frac{1}{RI^2} + 612.011 \frac{1}{RI^3} + 8.244 \frac{1}{RI^5} + 2.140 \right)$$
$$= 0.006 \frac{1}{RI} + 0.141 \frac{1}{RI^2} + 0.683 \frac{1}{RI^3} + 0.009 \frac{1}{RI^5} + 0.002$$

$$term9 = \frac{ZETAB \times EHP \times PCTPENG}{PRAT \times 100}$$
$$= \frac{0.067 \times 0.250 \times 80}{15 \times 100}$$
$$= 8.933 \times 10^{-4}$$

and:

$$ZETA = ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100} \right)}{PRAT} \right]$$
$$= ZETAB + term8 - term9 \times PENGACCS$$
$$= 0.067 + \left(0.006 \frac{1}{RI} + 0.141 \frac{1}{RI^2} + 0.683 \frac{1}{RI^3} + 0.009 \frac{1}{RI^5} + 0.002 \right)$$
$$- \left(8.933 \times 10^{-4} \right) \times \left(-11.354 \frac{1}{RI} + 112.801 \frac{1}{RI^2} + 39.889 \frac{1}{RI^3} + 1.838 \right)$$
$$= 0.016 \frac{1}{RI} + 0.040 \frac{1}{RI^2} + 0.683 \frac{1}{RI^3} + 0.009 \frac{1}{RI^5} + 0.068$$

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5.2.3 Instantaneous fuel consumption

$$IFC = max\left[IDLE\_FUEL, ZETA \times PTOT \times \left(1 + dFUEL\right)\right]$$

(**Appendix A**, Table E2.8)

$$\begin{aligned} IFC &= max\left[IDLE\_FUEL, ZETA \times PTOT \times \left(1 + dFUEL\right)\right] \\ &= max\left[0.120, ZETA \times PTOT \times \left(1 + 0\right)\right] \end{aligned}$$

For vehicle speed not limited due to roughness:

$$\begin{aligned} IFC &= max\left[IDLE\_FUEL, ZETA \times PTOT \times \left(1 + dFUEL\right)\right] \\ &= max\left[0.120, \left(\left(7.285 \times 10^{-5}\right) RI + 0.071\right) \times \left(0.065 RI + 5.469\right) \times \left(1 + 0\right)\right] \\ &= max\left[0.120, \left(4.752 \times 10^{-6}\right) RI^{2} + \left(5.035 \times 10^{-3}\right) RI + 0.388\right] \\ &= \left(4.752 \times 10^{-6}\right) RI^{2} + \left(5.035 \times 10^{-3}\right) RI + 0.388 \end{aligned}$$

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For vehicle speed with limiting speed due to roughness:

$$IFC = max\left[IDLE\_FUEL, ZETA \times PTOT \times (1 + dFUEL)\right]$$
$$= max\left[0.120, ZETA \times PTOT \times (1+0)\right]$$
$$= max\left[\begin{array}{l} 0.120, \left(0.016\frac{1}{RI} + 0.040\frac{1}{RI^2} + 0.683\frac{1}{RI^3} + 0.009\frac{1}{RI^5} + 0.068\right) \\ \times\left(4.941\frac{1}{RI} + 126.464\frac{1}{RI^2} + 612.011\frac{1}{RI^3} + 8.244\frac{1}{RI^5} + 2.140\right)\end{array}\right]$$

$$= max\left[\begin{array}{l} 0.120, 0.368\frac{1}{RI} + 8.732\frac{1}{RI^2} + 45.105\frac{1}{RI^3} + 18.077\frac{1}{RI^4} + 111.761\frac{1}{RI^5} \\ +418.430\frac{1}{RI^6} + 1.498\frac{1}{RI^7} + 11.267\frac{1}{RI^8} + 0.076\frac{1}{RI^{10}} + 0.145\end{array}\right]$$

$$= 0.368\frac{1}{RI} + 8.732\frac{1}{RI^2} + 45.105\frac{1}{RI^3} + 18.077\frac{1}{RI^4} + 111.761\frac{1}{RI^5}$$
$$+418.430\frac{1}{RI^6} + 1.498\frac{1}{RI^7} + 11.267\frac{1}{RI^8} + 0.076\frac{1}{RI^{10}} + 0.145$$

5.2.4 Fuel consumption per vehicle-km

$$FC = \frac{IFC}{V}$$

For vehicle speed not limited due to roughness:

$$FC = \frac{IFC}{V}$$
$$= \frac{1}{22.222} \times \left(\left(4.752\times10^{-6}\right)RI^2 + \left(5.035\times10^{-3}\right)RI + 0.388\right)$$
$$= \left(2.138\times10^{-7}\right)RI^2 + \left(2.266\times10^{-4}\right)RI + \left(1.749\times10^{-2}\right)$$

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For vehicle speed with limiting speed due to roughness:

$$FC = \frac{IFC}{V}$$

$$= \frac{\left(0.368\frac{1}{RI} + 8.732\frac{1}{RI^2} + 45.105\frac{1}{RI^3} + 18.077\frac{1}{RI^4} + 111.761\frac{1}{RI^5} + 418.430\frac{1}{RI^6} + 1.498\frac{1}{RI^7} + 11.267\frac{1}{RI^8} + 0.076\frac{1}{RI^{10}} + 0.145\right)}{\left(\frac{203}{1.15} \times \frac{1}{RI}\right)}$$

$$= \left(8.212\times10^{-4}\right)RI + \left(4.964\times10^{-2}\right)\frac{1}{RI1} + 0.256\frac{1}{RI^2} + 0.102\frac{1}{RI^3} + 0.633\frac{1}{RI^4} + 2.370\frac{1}{RI^5} + \left(8.484\times10^{-3}\right)\frac{1}{RI^6} + \left(6.383\times10^{-2}\right)\frac{1}{RI^7} + \left(4.299\times10^{-4}\right)\frac{1}{RI^9} + \left(2.086\times10^{-3}\right)$$

5.3 OIL CONSUMPTION

$$OIL = OILCONT + OILOPER \times FC$$

Where (**Appendix A**, Table E2.9):

$$OILCONT = \frac{OILCAP}{DISTCHNG} = \frac{2}{5000} = \left(4\times10^{-4}\right)$$

thus:

$$OIL = OILCONT + OILOPER \times FC = \left(4\times10^{-4}\right) + 0.0014 \times FC$$

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For vehicle speed not limited due to roughness:

$$\begin{aligned} OIL &= OILCONT + OILOPER \times FC \\ &= \left(4\times10^{-4}\right) + 0.0014 \times FC \\ &= \left(4\times10^{-4}\right) + \left(\left(2.993\times10^{-10}\right)RI^2 + \left(3.172\times10^{-7}\right)RI + \left(2.449\times10^{-5}\right)\right) \\ &= \left(2.993\times10^{-10}\right)RI^2 + \left(3.172\times10^{-7}\right)RI + \left(4.245\times10^{-4}\right) \end{aligned}$$

For vehicle speed with limiting speed due to roughness:

$$\begin{aligned} OIL &= OILCONT + OILOPER \times FC \\ &= \left(4\times10^{-4}\right) + 0.0014 \times FC \\ &= \left(4\times10^{-4}\right) + 0.0014 \times \left(\begin{aligned} &\left(8.212\times10^{-4}\right)RI + \left(4.964\times10^{-2}\right)\frac{1}{RI1} + 0.256\frac{1}{RI^2} \\ &+0.102\frac{1}{RI^3} + 0.633\frac{1}{RI^4} + 2.370\frac{1}{RI^5} \\ &+\left(8.484\times10^{-3}\right)\frac{1}{RI^6} + \left(6.383\times10^{-2}\right)\frac{1}{RI^7} \\ &+\left(4.299\times10^{-4}\right)\frac{1}{RI^9} + \left(2.086\times10^{-3}\right) \end{aligned}\right) \end{aligned}$$

$$\begin{aligned} &= \left(1.150\times10^{-6}\right)RI + \left(6.925\times10^{-5}\right)\frac{1}{RI1} + \left(3.577\times10^{-4}\right)\frac{1}{RI^2} \\ &+\left(1.434\times10^{-4}\right)\frac{1}{RI^3} + \left(8.864\times10^{-4}\right)\frac{1}{RI^4} + \left(3.319\times10^{-3}\right)\frac{1}{RI^5} \\ &+\left(1.188\times10^{-5}\right)\frac{1}{RI^6} + \left(8.936\times10^{-5}\right)\frac{1}{RI^7} + \left(6.108\times10^{-7}\right)\frac{1}{RI^9} \\ &+\left(4.029\times10^{-4}\right) \end{aligned}$$

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5.4 TYRE CONSUMPTION

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

A schematic representation of the computational procedure is shown in **Figure 8**.

Figure 8 : Calculation process for Tyre Consumption

Final substitution of variables into the above equation is presented in **Section 5.6.7**.

5.4.1 Circumferential force:

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

As previously indicated, $dFUEL = 0$ and $FA = 0$, thus:

$$CFT = \frac{FG + FR}{NUM\_WHEELS}$$
$$= \frac{19.74 + FR}{2}$$

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For vehicle speed not limited due to roughness:

$$\begin{aligned} CFT &= \frac{FG + FR}{NUM\_WHEELS} \\ &= \frac{19.74 + (2.789RI + 116.876)}{2} \\ &= 1.394RI + 68.248 \end{aligned}$$

For vehicle speed with limiting speed due to roughness (**Appendix A**, Table E2.5):

$$\begin{aligned} CFT &= \frac{FG + FR}{NUM\_WHEELS} \\ &= \frac{19.74 + \left(1.623RI + 73.533\frac{1}{RI} + 3081.697\frac{1}{RI^2} + 68.037\right)}{2} \\ &= 0.812RI + 36.766\frac{1}{RI} + 1540.848\frac{1}{RI^2} + 43.828 \end{aligned}$$

5.4.2 Lateral force:

$$\begin{aligned} LFT &= \frac{FCV}{NUM\_WHEELS} \\ &= \frac{FCV}{2} \end{aligned}$$

For vehicle speed not limited due to roughness:

$$\begin{aligned} LFT &= \frac{FCV}{2} \\ &= \frac{0.009}{2} \\ &= 0.0045 \end{aligned}$$

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For vehicle speed with limiting speed due to roughness:

$$LFT = \frac{FCV}{NUM\_WHEELS}$$
$$= \frac{\left(44.365\frac{1}{RI^4} - 2.668\frac{1}{RI^2} + 0.040\right)}{2}$$
$$= 22.182\frac{1}{RI^4} - 1.334\frac{1}{RI^2} + 0.020$$

5.4.3 Normal force:

(**Appendix A**, Table E2.1)

$$NFT = \frac{WGT\_OPER \times g}{NUM\_WHEELS}$$
$$= \frac{200 \times 9.81}{2}$$
$$= 981$$

5.4.4 Tangential energy is calculated as:

$$TE = \frac{\left(CFT^2 + LFT^2\right)}{NFT}$$
$$= \frac{\left(CFT^2 + LFT^2\right)}{981}$$

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For vehicle speed not limited due to roughness:

$$
\begin{aligned}
TE &= \frac{\left(CFT^2 + LFT^2\right)}{NFT} \\
&= \frac{\left(\left(1.394RI + 68.248\right)^2 + 0.0045^2\right)}{981} \\
&= \frac{\left(1.943RI^2 + 190.275RI + 4657.790\right) + 2.025\times10^{-5}}{981} \\
&= \left(1.981\times10^{-3}\right)RI^2 + 0.194RI + 4.748
\end{aligned}
$$

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For vehicle speed with limiting speed due to roughness:

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

$$= \frac{\left(\left(0.812RI + 36.766\frac{1}{RI} + 1540.848\frac{1}{RI^2} + 43.828\right)^2 + \left(22.182\frac{1}{RI^4} - 1.334\frac{1}{RI^2} + 0.020\right)^2\right)}{981}$$

$$= \frac{\left(\begin{array}{l}\left(\begin{array}{l}0.659RI^2 + 71.177RI + 5725.097\frac{1}{RI} + 136416.311\frac{1}{RI^2} \\ +113301.635\frac{1}{RI^3} + 2374212.559\frac{1}{RI^4} + 1980.602\end{array}\right) \\ + \left(\begin{array}{l}-0.053\frac{1}{RI^2} + 2.667\frac{1}{RI^4} - 59.182\frac{1}{RI^6} + 492.041\frac{1}{RI^8} \\ +0.0004\end{array}\right)\end{array}\right)}{981}$$

$$= \frac{\left(\begin{array}{l}0.659RI^2 + 71.177RI + 5725.097\frac{1}{RI} + 136416.258\frac{1}{RI^2} \\ +113301.635\frac{1}{RI^3} + 2374215.226\frac{1}{RI^4} - 59.182\frac{1}{RI^6} \\ +492.041\frac{1}{RI^8} + 1980.602\end{array}\right)}{981}$$

$$= \left(6.718\times10^{-4}\right)RI^2 + 0.073RI + 5.834\frac{1}{RI} + 139.058\frac{1}{RI^2}$$
$$+115.496\frac{1}{RI^3} + 2420.199\frac{1}{RI^4} - 0.060\frac{1}{RI^6} + 0.502\frac{1}{RI^8}$$
$$+2.019$$

5.4.5 Rate of tread wear

(**Appendix A**, Table E2.1):

$$TWT = C0tc + Ctcte \times TE$$
$$= 0.006 + 0.005 \times TE$$

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For vehicle speed not limited due to roughness:

$$
\begin{aligned}
TWT &= C0tc + Ctcte \times TE \\
&= 0.006 + 0.005 \times \left(\left(1.981 \times 10^{-3}\right) RI^2 + 0.194 RI + 4.748 \right) \\
&= \left(9.905 \times 10^{-6}\right) RI^2 + \left(0.097 \times 10^{-2}\right) RI + 0.030
\end{aligned}
$$

For vehicle speed with limiting speed due to roughness:

$$
\begin{aligned}
TWT &= C0tc + Ctcte \times TE \\
&= 0.006 + 0.005 \times \left(\begin{array}{l} \left(6.718 \times 10^{-4}\right) RI^2 + 0.073 RI + 5.834 \frac{1}{RI} \\ +139.058 \frac{1}{RI^2} + 115.496 \frac{1}{RI^3} + 2420.199 \frac{1}{RI^4} \\ -0.060 \frac{1}{RI^6} + 0.502 \frac{1}{RI^8} + 2.019 \end{array} \right) \\
&= \left(3.358 \times 10^{-6}\right) RI^2 + \left(3.630 \times 10^{-4}\right) RI + 0.029 \frac{1}{RI} + 0.695 \frac{1}{RI^2} \\
&\quad +0.577 \frac{1}{RI^3} + 12.101 \frac{1}{RI^4} - 0.0003 \frac{1}{RI^6} + \left(2.508 \times 10^{-3}\right) \frac{1}{RI^8} + 0.016
\end{aligned}
$$

5.4.6 Tyre Consumption per 1000 vehicle-kms

$$
EQNT = \frac{1 + 0.01 \times RREC \times NR}{DISTOT} + 0.0027
$$

for which we need:

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

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

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thus (**Appendix A**, Table E2.10

$$
\begin{aligned}
EQNT &= \frac{1+0.01\times RREC\times NR}{DISTOT}+0.0027\\
&= \frac{1+0.01\times 15\times NR}{\left((1+NR)\times\dfrac{VOL}{TWT}\right)}+0.0027\\
&= \frac{(1+0.15NR)}{(1+NR)}\times\frac{TWT}{(0.35)}+0.0027
\end{aligned}
$$

For simplification, defining $term9=\dfrac{(1+0.15NR)}{(1+NR)}$

$$
\begin{aligned}
EQNT &= \frac{1+0.01\times RREC\times NR}{DISTOT}+0.0027\\
&= term9\times\frac{TWT}{0.35}+0.0027
\end{aligned}
$$

5.4.7 Tyre consumption

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

and (**Appendix A**, Tables E2.11 and E2.12)

$$
\begin{aligned}
MODFAC &= VEHFAC\times TYPEFAC\times CONGFAC\\
&= 2\times 1\times 1\\
&= 2
\end{aligned}
$$

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thus

$$
\begin{aligned}
TC &= \frac{EQNT \times NUM\_WHEELS}{MODFAC} \\
&= \frac{\left(term9 \times \frac{TWT}{0.35} + 0.0027 \right) \times 2}{2} \\
&= term9 \times \frac{TWT}{0.35} + 0.0027
\end{aligned}
$$

Please note that this will not be the case for vehicles with more than 2 wheels.

Evaluating $term9$:

$$
\begin{aligned}
term9 &= \frac{(1 + 0.15NR)}{(1 + NR)} \\
&= 1
\end{aligned}
$$

As per the 2001 Simplification, NR can be ignored.

For vehicle speed not limited due to roughness:

$$
\begin{aligned}
TC &= \frac{EQNT \times NUM\_WHEELS}{MODFAC} \\
&= term9 \times \frac{TWT}{0.35} + 0.0027 \\
&= 1 \times \frac{\left(\left(9.905 \times 10^{-6}\right) RI^2 + \left(0.097 \times 10^{-2}\right) RI + 0.030 \right)}{0.35} + 0.0027 \\
&= \left(0.283 \times 10^{-4}\right) RI^2 + \left(2.772 \times 10^{-3}\right) RI + 0.086
\end{aligned}
$$

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For vehicle speed with limiting speed due to roughness:

$$TC = \frac{EQNT \times NUM\_WHEELS}{MODFAC}$$
$$= term9 \times \frac{TWT}{0.35} + 0.0027$$
$$= 1 \times \frac{\left(\begin{array}{l} \left(3.358\times10^{-6}\right)RI^2 + \left(3.630\times10^{-4}\right)RI + 0.029\frac{1}{RI} \\ +0.695\frac{1}{RI^2} + 0.577\frac{1}{RI^3} + 12.101\frac{1}{RI^4} - 0.0003\frac{1}{RI^6} \\ +\left(2.508\times10^{-3}\right)\frac{1}{RI^8} + 0.016 \end{array} \right)}{0.35} + 0.0027$$
$$= \left(9.595\times10^{-6}\right)RI^2 + \left(1.036\times10^{-3}\right)RI + \left(8.336\times10^{-2}\right)\frac{1}{RI}$$
$$+1.987\frac{1}{RI^2} + 1.650\frac{1}{RI^3} + 34.573\frac{1}{RI^4} - \left(8.617\times10^{-4}\right)\frac{1}{RI^6}$$
$$+\left(7.166\times10^{-3}\right)\frac{1}{RI^8} + \left(4.710\times10^{-2}\right)$$

5.5 SERVICE LIFE

5.5.1 Constant Life Method

$$LIFEKM = LIFEKM0$$
$$= AKM0 \times LIFE0$$

thus (**Appendix A**, Table E2.3):

$$LIFEKM = AKM0 \times LIFE0$$
$$= 10000 \times 10$$
$$= 100000$$

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5.5.2 Adjusted Road Roughness

$$RI_{adj} = 3.6 + 2.409 \times 10^{-10} \times RI^{15.4} \text{ for } RI \leq 3.85$$

$$RI_{adj} = RI \text{ for } RI > 3.85$$

5.6 PARTS CONSUMPTION

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

However $K0pc = 1$, $K1pc = 0$ and $dFUEL = 0$.

thus:

$$\begin{aligned} PC &= K0pc \times \left[CKM^{KP} \times \left(a0 + a1 \times RI_{adj} \right) + K1pc \right] \times \left[1 + CPCON \times dFUEL \right] \\ &= 1 \times \left[CKM^{KP} \times \left(a0 + a1 \times RI_{adj} \right) + 0 \right] \times \left[1 + CPCON \times 0 \right] \\ &= CKM^{KP} \times \left(a0 + a1 \times RI_{adj} \right) \end{aligned}$$

now (**Appendix A**, Tables E2.13 and E2.14):

$$\begin{aligned} PC &= CKM^{KP} \times \left(a0 + a1 \times RI_{adj} \right) \\ &= 50000^{0.308} \times \left(\left(9.23 \times 10^{-6} \right) + \left(6.20 \times 10^{-6} \right) RI_{adj} \right) \\ &= 28.008 \times \left(\left(9.23 \times 10^{-6} \right) + \left(6.20 \times 10^{-6} \right) RI_{adj} \right) \\ &= 1.736 \times 10^{-4} RI_{adj} + 2.585 \times 10^{-4} \end{aligned}$$

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But:

$$RI_{adj} = 3.6 + 2.409 \times 10^{-10} \times RI^{15.4} \text{ for } RI \leq 3.85$$

$$RI_{adj} = RI \text{ for } RI > 3.85$$

For $RI \leq 3.85$:

$$\begin{aligned} PC &= CKM^{KP} \times \left(a0 + a1 \times RI_{adj}\right) \\ &= 1.736 \times 10^{-4} RI_{adj} + 2.585 \times 10^{-4} \\ &= 1.736 \times 10^{-4} \left(3.6 + 2.409 \times 10^{-10} \times RI^{15.4}\right) + 2.585 \times 10^{-4} \\ &= \left(4.183 \times 10^{-14}\right) RI^{15.4} + \left(8.837 \times 10^{-4}\right) \end{aligned}$$

For $RI > 3.85$:

$$\begin{aligned} PC &= CKM^{KP} \times \left(a0 + a1 \times RI_{adj}\right) \\ &= 1.736 \times 10^{-4} RI_{adj} + 2.585 \times 10^{-4} \\ &= \left(1.736 \times 10^{-4}\right) RI + \left(2.585 \times 10^{-4}\right) \end{aligned}$$

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5.7 LABOUR HOURS

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

However $K0lh = 1$ and $K1lh = 0$, thus:

$$\begin{aligned} LH &= K0lh \times \left(a0 \times PC^{a1}\right) + K1lh \\ &= 1 \times \left(a0 \times PC^{a1}\right) + 0 \\ &= a0 \times PC^{a1} \end{aligned}$$

Now (**Appendix A**, Tables E2.13 and E2.14):

$$\begin{aligned} LH &= a0 \times PC^{a1} \\ &= 77.14 \times PC^{0.547} \end{aligned}$$

For $RI \leq 3.85$:

$$\begin{aligned} LH &= a0 \times PC^{a1} \\ &= 77.14 \times PC^{0.547} \\ &= 77.14 \times \left(\left(4.183 \times 10^{-14}\right) RI^{15.4} + \left(8.837 \times 10^{-4}\right)\right)^{0.547} \end{aligned}$$

For $RI > 3.85$:

$$\begin{aligned} LH &= a0 \times PC^{a1} \\ &= 77.14 \times PC^{0.547} \\ &= 77.14 \times \left(\left(1.736 \times 10^{-4}\right) RI + \left(2.585 \times 10^{-4}\right)\right)^{0.547} \end{aligned}$$

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5.8 DEPRECIATION COST FACTOR

5.8.1 Residual Vehicle Value

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

5.8.2 Depreciation Cost Factor

$$DEP = \frac{1000 \times \left(1 - 0.001 \times RVPLTPCT\right)}{LIFEKM}$$

thus:

$$\begin{aligned} DEP &= \frac{1000 \times \left(1 - 0.001 \times RVPLTPCT\right)}{LIFEKM} \\ &= \frac{1000 \times \left(1 - 0.001 \times \left(15 - MAX\left[0, \left(RI - 5\right)\right]\right)\right)}{100000} \\ &= \frac{1 - 0.001 \times \left(15 - MAX\left[0, \left(RI - 5\right)\right]\right)}{100} \\ &= \left(9.85 \times 10^{-3}\right) - 0.00001 MAX\left[0, \left(RI - 5\right)\right] \end{aligned}$$

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6. IMPLEMENTATION

On completion of the Modified Simplification two aspects were major factors in implementation (**Figure 9**). The first aspect was to identify which vehicle fleet would be used for the WCG System and included costing and the process to cost an identified fleet. The second aspect was Informatics, including programming, validation and system implementation.

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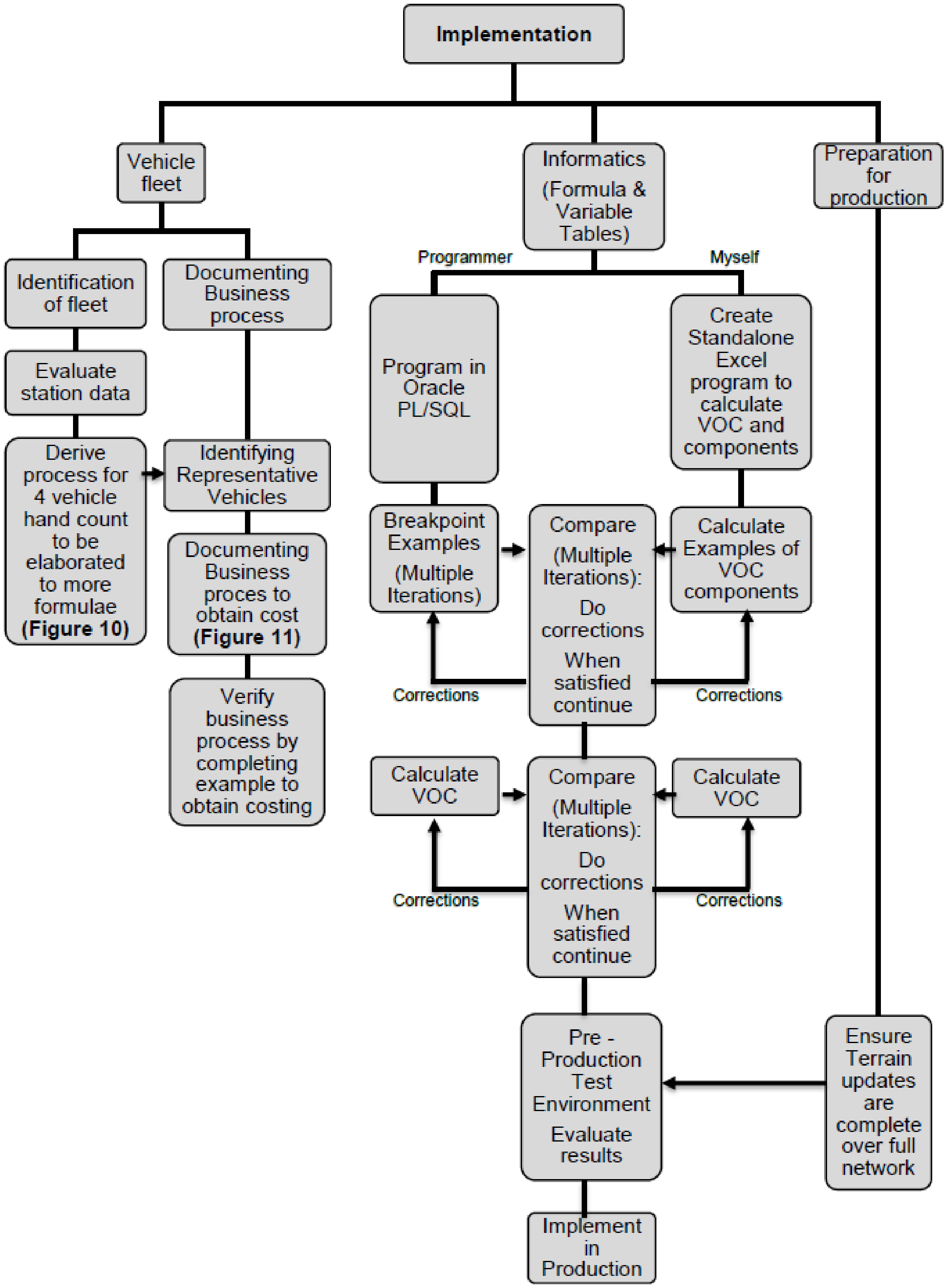

Figure 9 : Implementation flow

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6.1 VEHICLE FLEET

Traffic composition may be determined based on both manual counts and permanent counting data. As the manual counts do not differentiate between the heavy Vehicle Types, the data from the permanent stations (**Table 4**) may be used for this purpose.

Table 4: Heavy vehicle composition as obtained from permanent counting data in Western Cape (Mikros data)

Stratum		Short	Medium	Long
Business	High	66.2	21.3	12.6
	Medium	58.9	25.0	16.1
	Low	50.0	24.9	25.1
Commuter	High	65.4	28.8	5.8
	Medium	77.2	17.6	5.1
	Low	70.4	17.1	12.5
Rural	High	30.4	18.1	51.5
	Medium	46.2	23.3	30.6
	Low	33.7	19.3	47.0
General	High	36.0	39.8	24.2
Average		53.4	23.5	23.1

It becomes apparent from the above data (**Table 4**), why the HDM-4 vehicle fleet was increased from four to five vehicles. The initial simplified VOC model and HDM-4 Vehicle Fleet utilised in workspaces[1] made use of a HDM-4 Type 10 Heavy Vehicle (Rigid Body Heavy Truck). However, it is clear that articulated trucks contribute significantly to the "heavy" count on WCG DTPW traffic links. Therefore,

[1] A workspace is the term used in the HDM-4 software to refer to a unique setup that is used on an analysis of road infrastructure projects. The WCG DTPW provides a workspace to service providers for analysis of road maintenance (periodic and rehabilitation) project options.

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the decision was made to include this Vehicle Type in the simplified VOC model and the HDM-4 Workspace Vehicle Fleet (Burger and van der Gryp, 2008).

The notations “Short”, “Medium” and “Long” refer to the number of axles assigned to a heavy vehicle that pass over the counting loops. The number of axles of short vehicles (2 & 3) indicate that these are generally rigid body trucks, while the medium and long vehicles generally refer to articulated trucks (4 and more axles).

6.2 UTILISING TRAFFIC DATA IN SIMPLIFIED VOC MODEL

The suggested approach to the utilisation of traffic distribution data in the simplified VOC model is as follows (**Figure 10**):

- For each road segment determine the traffic distribution with the Traffic Counting System:
  - Data obtained from the traffic link that is linked to that segment.
- For each discrete length of road the vehicle operating cost may be calculated for each Vehicle Type based on the riding quality and Terrain data for that section of road.
- The VOC calculated in the previous step is multiplied by the number of each Vehicle Type in the fleet and also the length of road section to obtain VOC for road section.
  - The “split” between Type 10 (Heavy Truck) and Type 11 (Articulated Truck) is taken as 40:60 on surface roads and 50:50 on unsurfaced roads.

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- Thus, the VOC for these vehicles is calculated by applying the applicable split to the Heavy count applicable to the road section.
- For reporting, only "Heavy" is reported and this again is the sum of the VOC for Type 10 and Type 11 vehicles.

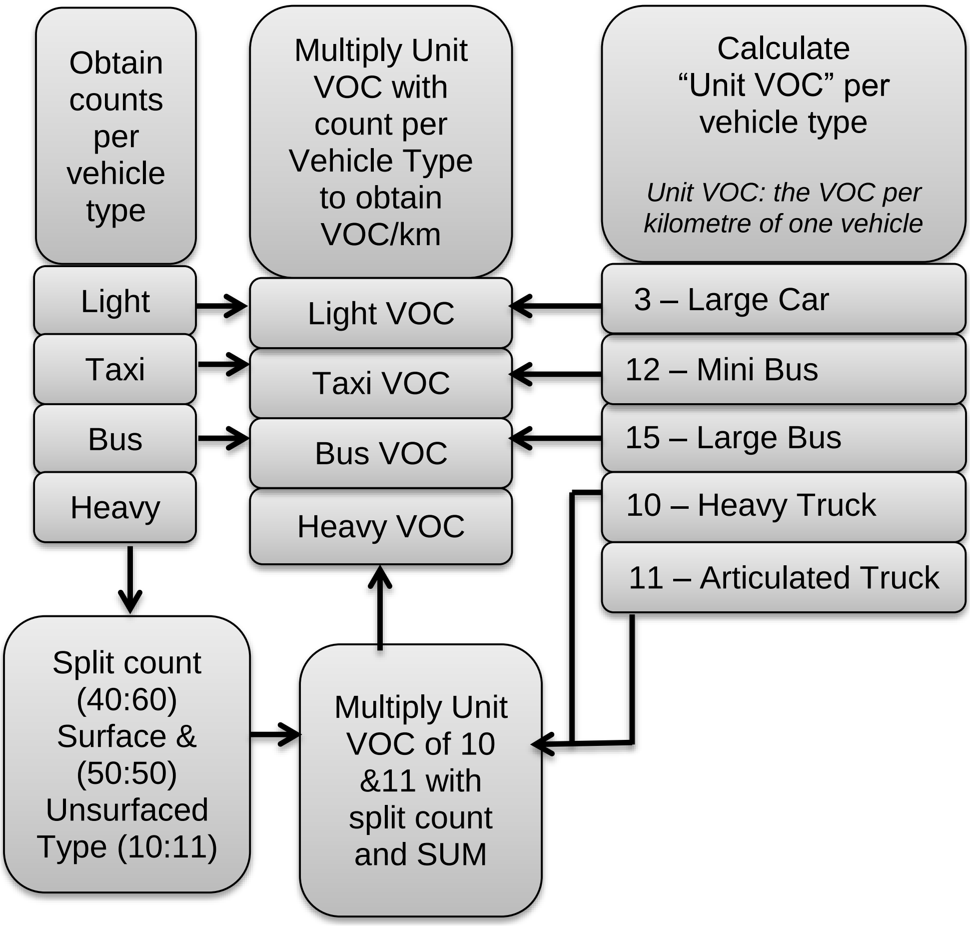

Figure 10 : Data flow for the calculation of VOC

6.3 VEHICLE FLEET COST DATA

This section describes the procedure to be followed in order to obtain/update vehicle cost data annually for the Vehicle Operating Cost model.

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6.3.1 Business decisions in terms of cost data

In terms of the Department the cost data is used in both HDM-4 analyses, *viz*. in the Vehicle Fleet of the workspace, as well as with the simplified VOC model implemented in the relevant management systems. Therefore, it is very important that the data is easily obtainable and that the department is not dependent on others to investigate or publish the information. Economic cost cannot be calculated directly in many instances. In these cases a factor is used that would apply throughout the analysis and would thus not have a major effect on a network analysis result.

6.3.2 Representative Vehicles

The cost data is required for the vehicle fleet reported in **Table 5** (also refer to **Figure 9**). A representative vehicle is chosen for each of the vehicles in **Table** 5**5**. Note that the information in the third column is only an example. Vehicle manufacturers change/update their product ranges on a regular basis and representative vehicles should be identified based on the characteristics required, e.g. the representative light vehicle may be chosen as a “Ford Focus 1.6i Standard”.

Table 5: Vehicle fleet and descriptions

Name	HDM-4 Type	Description/Example
Light	Type 3 – Medium Car	Sedan 1 600 – 2 500 cc e.g. Toyota Corolla 1600 Std
Taxi	Type 12 – Mini Bus	Mini Bus, e.g. Toyota Quantum 14 Seater
Bus	Type 15 – Heavy Bus	e.g. MAN 65 Seater Explorer
Heavy Truck	Type 10 – Heavy Truck	1:2 axle configuration e.g. MAN 26:360
Articulated Truck	Type 11 – Articulated Truck	1:2:2 axle configuration e.g. MAN Truck Tractor 26:480

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6.3.3 Vehicle Characteristics requiring Cost Data

The vehicles listed in **Table 5** have the characteristics listed in **Table 6**. Cost data is obtained based on these characteristics.

Table 6: Vehicle characteristics requiring Cost Data

	Light	**Taxi**	**Bus**	**Heavy Truck**	**Articulated Truck**
New Vehicle Price	List Price	List Price	List Price	List Price	List Price
No. of Wheels	4	4	6	10	18
Wheel Size	14 inch	14 inch	22 inch	22 inch	22 inch
Tyre Size (Alternative size)	175/65R14	195R14 (Bakkie tyres)	385/65R22.5 (12R22.5x16)	385/65R22.5 (12R22.5x16)	385/65R22.5 (12R22.5x16)
Fuel Type	Petrol	Petrol	Diesel	Diesel	Diesel
Oil Type	20W50	20W50	18W40	18W40	18W40
Labour Rate	Mechanic	Mechanic	Mechanic	Mechanic	Mechanic

6.3.4 Procedure for obtaining Cost Data

The procedure to obtain cost data is as follows (also refer to **Figure 11**):

1. A representative vehicle is selected for each of the fleet vehicles.
   a. Ideally, this would be based on an analysis of the eNATIS database. The registration of each Vehicle Type for the previous year will be obtained and the median vehicle chosen as the representative vehicle.
   b. However, the above is cumbersome. As an alternative, the prerogative of choosing a representative vehicle is left to the person updating the

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cost data. The only requirement is that the vehicle should comply with the general description in **Table 5**.

2. The list price for the vehicle is obtained from the manufacturer.
3. Obtain three quotes for a set of tyres of the required size.
    a. The quotes are to be from reputable tyre suppliers.
4. The fuel price is considered to be the price that comes into effect on the first Wednesday of April every year.
    a. The fuel price is obtained on this date as it is the first change in fuel price after the start of the new financial year.
5. Obtain three quotes for oil of the required type.
    a. The oil prices should be obtained from reputable suppliers for 5 litre containers.
    b. Divide each quoted price by 5 to obtain the price per litre of oil.
6. Obtain three quotes for the hourly rate of a technician (mechanic) from reputable service centres for service and/or repairs to the representative vehicles.

Cost data may be obtained from a number of centres (towns) in the Western Cape in order to reflect average prices in the province, e.g. Cape Town, George/Oudtshoorn, Beaufort-West and Vredendal.

The cells shaded blue in **Table 7** should be filled in and the averages calculated (cells shaded green) for the required cost data items.

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Table 7: Cost Data table for calculation of Cost Data items

Name	Light	Taxi	Bus	Heavy	Articulated Heavy
HDM-4 Type	Type 3	Type 12	Type 15	Type 10	Type 11
Description	Medium Car	Mini Bus	Heavy Bus	Heavy Truck	Articulated Truck
Example	Toyota Corolla 1600	Toyota Quantum	MAN 65 Seater Explorer	MAN 26:360	MAN Truck Tractor 26:480
List price					
Wheels	4 wheels – 14 inch	4 wheels – 14 inch	6 wheels – 22 inch	10 wheels – 22 inch	18 wheels – 22 inch
Wheel size	175/65R14	195R14	385/65R22.5	385/65R22.5	385/65R22.5
Alternative size		Bakkie tyres	12R22.5x16	12R22.5x16	12R22.5x16
Quote 1					
Quote 2					
Quote 3					
Average					
Fuel Type*	Petrol	Petrol	Diesel	Diesel	Diesel
Price/litre					
Oil Type**	20W50	20W50	18W40	18W40	18W40
Quote 1					
Quote 2					
Quote 3					
Average					
Labour Rate***					
Quote 1					
Quote 2					
Quote 3					
Average					

*Fuel Price per Fuel Type, obtained on first Wednesday of April.
Price obtained per 5 litre container and **price per litre entered in table.
***Hourly rate of qualified technician (mechanic) from reputable service centre for service/repairs.

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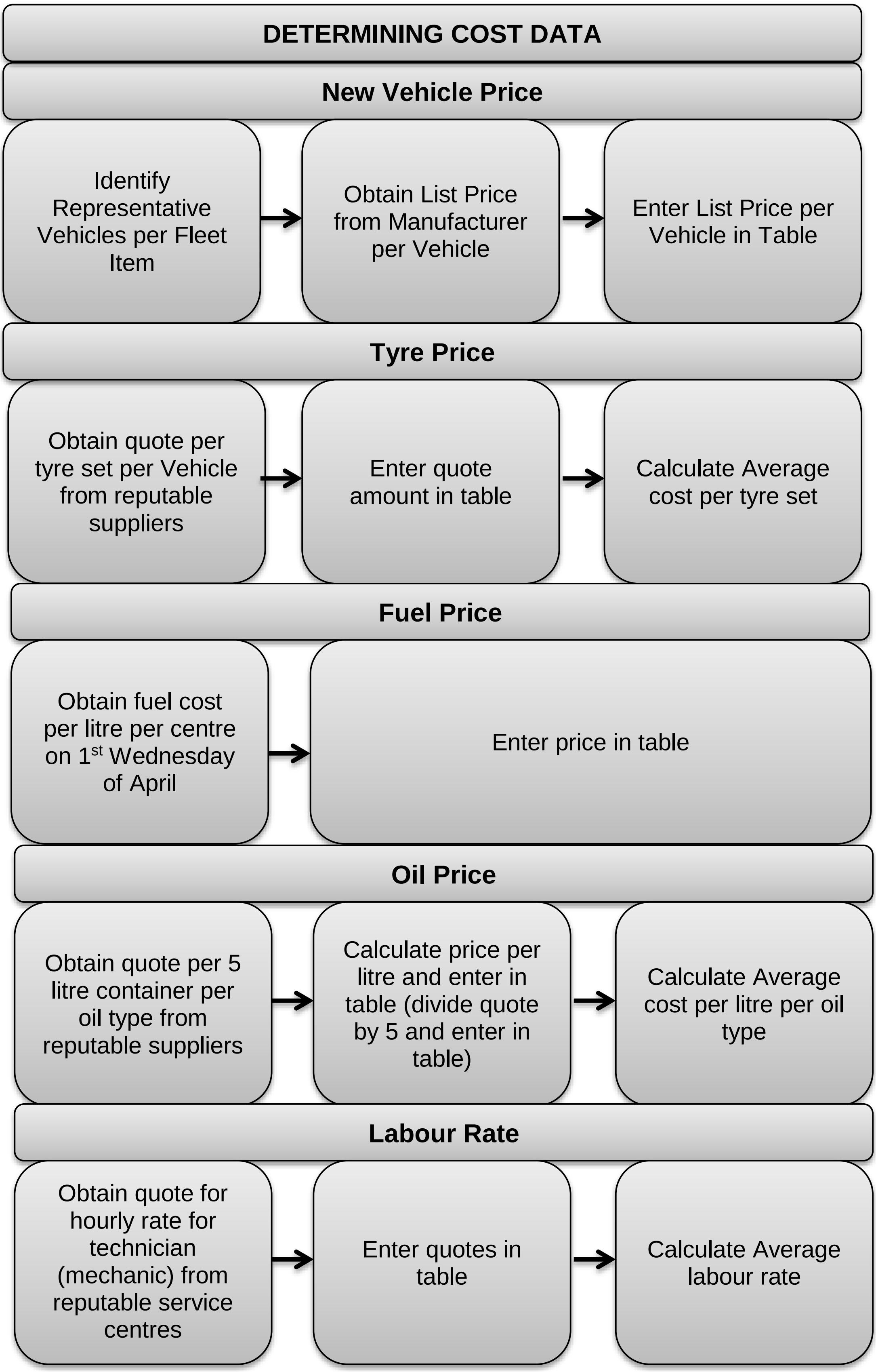

Figure 11 : Flow Chart for determining Cost Data

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6.3.5 Procedure for obtaining Cost Data – Example

In July 2009 cost data was obtained for the first time and the procedure to obtain cost data is as follows (also refer to **Figure 11**):

1. A representative vehicle is selected for each of the fleet vehicles.
    a. Ideally, this would be based on an analysis of the eNATIS database. The registration of each Vehicle Type for the previous year will be obtained and the median vehicle chosen as the representative vehicle.
    b. However, the above is cumbersome. As an alternative, the prerogative of choosing a representative vehicle is left to the person updating the cost data. The only requirement is that the vehicle should comply with the general description in **Table 5**.

Table 8: Representive vehicles chosen

Vehicle Number	Reference vehicle
3	Toyota Corolla 1600 Standard
10	MAN 26:300
11	MAN Truck tractor 26:480
12	Toyota Sivulake
15	MAN65 seater Explorer

2. The list price for the vehicle is obtained from the manufacturer.

   The List Price was obtained at MAN & Market Toyota

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MAN
MAN Truck & Bus Centre – Cape Town
Falcon Close; Okavango Park, 7561
Brackenfell
Telephone no. : +27 (21)9802720

TOYOTA
Market Toyota Cavendish
15 Dreyer Street, Claremont,
Cape Town
Telephone no. : +27 (21) 673 5000

Table 9: Vehicle prices obtained

Vehicle Type	Reference vehicle	Vehicle Price
3	Toyota Corolla 1600 Standard	R 187,500.00
10	MAN 26:300	R 1,225,000.00
11	MAN Truck tractor 26:480	R 1,350,000.00
12	Toyota Sivulake	R 256,800.00
15	MAN65 seater Explorer	R 1,545,000.00

3. Obtain three quotes for a set of tyres of the required size.
    a. The quotes are to be from reputable tyre suppliers.

Tyre Prices was obtained from

Tiger Wheel & Tyre
A Division of TiAuto (Pty) Ltd
33 Bree Street Cape Town
Tel: 021 425 4683
Fax: 021 425 1133
Email: ct@twt.to

The Tyre Guys
N1 City Cape Town
Tel:021-595 2713
Fax:021595 2719
Email:
tyreguys@telkom.net

West Coast Tyres
4 Montague Drive, Montague Gardens
Tel:021 551 2416:

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Table 10: Tyre prices obtained

Vehicle Type	Reference vehicle	TWT	Tyre Guys	West Coast	AVERAGE (per set)
3	Toyota Corolla 1600 Standard	R 1,948.00	R 2,040.00	R 2,066.67	R 2,018.22
10	MAN 26:300	R 27,000.00	R 27,300.00	R 33,060.00	R 29,120.00
11	MAN Truck tractor 26:480	R 81,000.00	R 81,900.00	R 110,940.00	R 91,280.00
12	Toyota Sivulake	R 3,030.00	R 2,820.00	R 7,360.00	R 4,403.33
15	MAN65 Seater Explorer	R 45,000.00	R 45,500.00	R 48,600.00	R 46,366.67

4. The fuel price is taken as the price that comes into effect on the first Wednesday of April every year.
    a. The fuel price is obtained on this date as it is the first change in fuel price after the start of the new financial year.

Petrol price on the first Wednesday of April 2009 was R7.14. The diesel price was obtained by averaging three different service stations prices for April.

Table 11: Diesel prices obtained

Boston Station	Welgemoed Station	Sun Bell Station	Average
R6.98	R7.07	R6.71	R6.92

5. Obtain three quotes for oil of the required type.

Chevron South Africa (Pty) Ltd	ENGEN	BP	Shell
TEL: 021 522 7560	TEL: 021 511 1961	TEL: 011 488 5141	TEL: 021 408 4911

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a. The oil prices should be obtained from reputable suppliers for 5 litre containers.

b. Divide each quoted price by 5 to obtain the price per litre of oil.

Table 12: Oil prices obtained

Oil Type	Engen per 20l 4 x 5 l per box	Chevron per 20l 4 x 5 l per box	BP per 20l 4 x 5 l per box	Average per l
20W50	R 551.53	R 442.32	R 565.90	R 26.00
18W40	R 600.78	R 608.76	R 689.96	R 31.66

6. Obtain three quotes for the hourly rate of a technician (mechanic) from reputable service centres for service and/or repairs to the representative vehicles.

MAN
MAN Truck & Bus Centre – Cape Town
Falcon Close; Okavango Park, 7561
Brackenfell
Telephone no. : +27 (21) 980 2720

Table 13: Truck and bus prices obtained

Vehicle Number	Reference vehicle	Wage Price
10	MAN 26:300	R 433.20
11	MAN Truck tractor 26:480	R 433.20
15	MAN65 Seater Explorer	R 433.20

TOYOTA	Barlow Stellenbosch	Barlow Armstrong (Ford)
Market Toyota Cavendisch		N1 City
TEL:	TEL:	TEL:
+27 (21) 673 5000	+27 (21) 887 1345	+27 (21) 595 63215

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Table 14: Car and taxi prices obtained

Vehicle Number	Reference vehicle	Barlow Armstrong (Ford)	Market Toyota	Barlow Toyota	AVERAGE
3	Toyota Corolla 1600 Standard	R 427.50	R 410.40	R 438.90	R 425.60
12	Toyota Sivulake	R 427.50	R 410.40	R 438.90	R 425.60

The above data was used to populate **Table 6** to create **Table 15** below.

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Table 15: Cost Data table populated with JULY 2009 data

Name	Light	Taxi	Bus	Heavy	Articulated Heavy
HDM-4 Type	Type 3	Type 12	Type 15	Type 10	Type 11
Description	Medium Car	Mini Bus	Heavy Bus	Heavy Truck	Articulated Truck
Example	Toyota Corolla 1600	Toyota Quantum	MAN 65 seater Explorer	MAN 26:360	MAN Truck Tractor 26:480
List price	R 187,500.00	R 256,800.00	R 1,545,000.00	R 1,225,000.00	R 1,350,000.00
Wheels	4 wheels – 14 inch	4 wheels – 14 inch	6 wheels – 22 inch	10 wheels – 22 inch	18 wheels – 22 inch
Wheel size	175/65R14	195R14	385/65R22.5	385/65R22.5	385/65R22.5
Alternative size		Bakkie tyres	12R22.5x16	12R22.5x16	12R22.5x16
Quote 1	R487.00	R757.50	R4,500.00	R4,500.00	R4,500.00
Quote 2	R510.00	R705.00	R4,550.00	R4,550.00	R4,550.00
Quote 3	R516.67	R1,840.00	R4,860.00	R5,510.00	R6,163.33
Average	R504.56	R1,100.83	R4,636.67	R4,853.33	R5,071.11
Fuel Type*	Petrol	Petrol	Diesel	Diesel	Diesel
Price/litre					
Oil Type**	20W50	20W50	18W40	18W40	18W40
Quote 1	R 27.58	R 27.58	R 30.04	R 30.04	R 30.04
Quote 2	R 22.12	R 22.12	R 30.44	R 30.44	R 30.44
Quote 3	R 28.29	R 28.29	R 34.50	R 34.50	R 34.50
Average	R 26.00	R 26.00	R 31.66	R 31.66	R 31.66
Labour Rate***					
Quote 1	R 427.50	R 427.50	R 433.20	R 433.20	R 433.20
Quote 2	R 410.40	R 410.40			
Quote 3	R 438.90	R 438.90			
Average	R 425.60	R 425.60	R 433.20	R 433.20	R 433.20

*Fuel Price per Fuel Type, obtained on first Wednesday of April.
Price obtained per 5 litre container and **price per litre entered in table.
***Hourly rate of qualified technician (mechanic) from reputable service centre for service/repairs.

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6.4 PROGRAMMING

The VOC for a road segment with an AADT is calculated as explained in the previous chapter. After full substitution and simplification each formula changes to an extensive formula as seen previously. As the programmer requires a simple programming solution, the formula was simplified and all variables tabled so that it could easily be uploaded and thus decrease the possibility for error. See **Appendix B** for Variable Summary.

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

where

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

$$FC_K = IF(RI < LimitingRoughness, FC_{BELOW(K)}, FC_{ABOVE(K)})$$

$$FC_{BELOW(K)} = FC1 * RI^2 + FC2 * RI + FC3$$

$$FC_{ABOVE(K)} = FC4 * RI + FC5 + \frac{FC6}{RI} + \frac{FC7}{RI^2} + \frac{FC8}{RI^3} + \frac{FC9}{RI^4} + \frac{FC10}{RI^5} + \frac{FC11}{RI^6} + \frac{FC12}{RI^7} + \frac{FC13}{RI^9}$$

$$OilCost_{av} = \sum_{k=1}^{4} OIL_K \times AADT_K \times Oilprice_K$$

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$$OIL_K = OIL1 + OIL2 \times FC$$

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

$$TC_{avk} = TC_k \times AADT_k$$

$$TC_K = IF(RI < LimitingRoughness, TC_{BELOW(K)}, TC_{ABOVE(K)}) * \left(\frac{(1 + 0.15 * \mathrm{NR})}{(1 + \mathrm{NR})} \right)$$

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

$$TC_{BELOW(K)} = TC1 * RI^2 + TC2 * RI + TC3$$

$$TC_{ABOVE(K)} = TC4 * RI^2 + TC5 * RI + TC6 + \frac{TC7}{RI} + \frac{TC8}{RI^2} + \frac{TC9}{RI^3} + \frac{TC10}{RI^4} + \frac{TC11}{RI^6} + \frac{TC12}{RI^8}$$

$$PARTSCOST = \sum_{k=1}^{4} PC_{avk} \times VEHCOST_k$$

$$PC_{avk} = AADT_k \times PC_k$$

$$PC_K = IF(RI < \text{Roughness Adjustment Point}, PC_{BELOW(K)}, PC_{ABOVE(K)})$$

Point where RI=RI0 is defined Roughness Adjustment Point

$$PC_{BELOW(K)} = PC1 + PC2 * RI^{PC3}$$

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$$PC_{ABOVE(K)} = PC4 * RI + PC5$$

$$LABOURCOST = WAGECOST \times LH_{av}$$

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

$$LH = LH1 \times PC^{LH2}$$

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

$$DEPCST = DEP \times NVPLT$$

$$NVPLT = NVP - NUM\_WHEELS \times NTP$$

$$DEP = DEP1 + DEP2 * MAX(0, RI - 5)$$

6.5 VALIDATION

Validation of the new changes that programming of the Modified VOC Simplification added to the WCG System, included various steps:

1. A standalone programme was created in Microsoft Excel.
2. The new module for VOC was programmed in Oracle PL/SQL (Procedural Language/Structured Query Language) as well as html and JavaScript.

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3. Exercises and examples for validation of the new module and the Excel programme were conducted to ensure that the results were correct and that no mistakes were made in programming. This is done by including breakpoints in the programming and to calculate components of the VOC formula to compare with components calculated in excel. Similarly examples for VOC was also compared. This is an iterative process than includes finding mistakes, correcting them and then repeating the process until satisfied.
4. Ensuring that the Terrain updates of the network were completed.
5. Testing the incorporation of the new module into the greater pavement management system.
6. Business processes were confirmed to ensure how and when the VOC would be updated and be available for service providers and other interested parties, including Deighton Agent for Africa, Aurecon and the Road Authority of Namibia, among others. This is due to the fact that the 2001 Simplifications VOC results were known to be used by other interested parties. Current yearly updated VOC can be found on the RNIS website. (https://rnis.pgwc.gov.za, under General Reports, VOC report).

6.6 LESSONS LEARNED FROM WCG IMPLEMENTATION OF THE VOC

Information collected from the WCG implementation of the simplified VOC system include aspects of practical value, as well as lessons in terms of opinions that may differ from the Department. These opinions were collected from personal

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communication with various entities that have implemented the Modified Simplification and use the annual data published by the WCG.

6.6.1 Practical Lessons

The practical experience gained demonstrated differences in the theoretical approach of engineers and programmers. It also focusses requirement of the engineers to collaborate with the programmer during the development process.

6.6.2 Changes to a Pavement Management System.

During the validation process many tests were conducted to enable comparison with previous calculations. Flat Terrain results compares relatively closely with the 2001 Simplification results. This is an added benefit to non WCG users as it still allows the choice to include Terrain, as Flat Terrain results could be seen as an option that excludes the Terrain and geometry.

It subsequently became apparent that reports such as the biennial Preservation Report and others, may give a distorted picture when compared to previous reports. Changes were therefore noted for public knowledge.

6.6.3 Vehicle cost data

During the establishment of business processes a departmental decision was made that vehicle expenditure by the WCG would be a financial and not an economic cost. During the implementation process it was concluded that it might be beneficial to have both options available.

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In some strategic and planning operations it is considered appropriate that decisions should be based exclusively on economic principles as it is the department's responsibility to use the most economical option. This has been recognized as a further development to be introduced at a later stage.

Additionally, many associations and companies publish prices for different vehicles on an annual basis and that it could be considered to obtain data from such sources. However, it is difficult to envisage if this will be sustainable and is not currently being considered by the department.

6.6.4 Decisions taken in terms of Aerodynamic Resistance to Motion.

As in the 2001 Simplification system, it was WCG preference to ignore Aerodynamic resistance to motion and is therefore applied to the Modified Simplification.

The effect of this decision is evaluated in a sensitivity analysis where the Fuel consumption calculated by:

- Comparing Fuel consumption incorporating Aerodynamic resistance to motion at more than two Constant speeds,
- Modified Simplification vs Fuel Consumption incorporating Aerodynamic resistance to motion.

For the purpose of the sensitivity Aerodynamic, resistance to motion is calculated at the average height above sea level of the WCG network, 392 m, with IRI=4 (**Appendix C**).

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From the results (**Table 16**) it is clear that a change in speed has a significant impact on fuel consumption, should the Aerodynamic resistance to motion be incorporated in the analysis. For a Large Car the impact of increasing constant speed to 120 km/h, is an increase in fuel consumption of 36,13% and 52,69%, for Flat and Mountainous respectively. Decreasing the speed of an Articulated Truck to 40 km/h decreases the fuel consumption by 8,83% and 20,95%, for Flat and Mountainous respectively.

Table 16: Gradient resistance to motion at various speeds, Sensitivity results

Vehicle Type	**Terrain**	**V (km/h)**	**FC**
Large Car	Flat	80	0.107
		120	0.146
	Mountainous	80	0.135
		120	0.207
Articulated Truck	Flat	40	0.658
		80	0.721
	Mountainous	40	1.042
		80	1.319

When comparing the Modified Simplification Fuel consumption with Fuel consumption incorporating Aerodynamic resistance, at IRI=4, at 80 km/h the result is an increase in fuel consumption between 18%-35% (**Table 17**).

Table 17: Aerodynamic resistance to motion, Sensitivity results

Vehicle Type	**Terrain**	**Modified FC**	**Sensitivity FC**
Large Car	Flat	0.083	0.107
	Mountainous	0.110	0.135
Articulated Truck	Flat	0.534	0.721
	Mountainous	1.110	1.319

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When considering the increase that Aerodynamic resistance to motion has on fuel consumption, it is important that, should the Modified Simplification not only be used for project identification in terms of a cost benefit ratio, it not be disregarded.

6.6.5 Decisions taken in terms of Gradient Resistance to Motion.

It is the preference of the WCG to consider all traffic to be traveling in an uphill direction and it is therefore applied in the Modified Simplification.

The effect of this decision is evaluated in a sensitivity analysis where the Fuel consumption, calculated by comparing the Modified Simplification vs Fuel Consumption, incorporates a 50:50 directional split in traffic.

For the purpose of the sensitivity the Fuel Consumption is incorporated at IRI=4 and IRI=7 (**Appendix C**)

When comparing the Modified Simplification Fuel consumption with Fuel consumption incorporating Gradient resistance to motion on a 50:50 split, at IRI=4 and IRI=7, at 80 km/h the result shows a decrease in fuel consumption of 1%-30% for the Large car and 30%-62% for the Articulated Truck (**Table 18**).

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Table 18: Gradient resistance to motion, Sensitivity result

Vehicle Type	Terrain	IRI	V (km/h)	Modified FC	FC Sensitivity
Large Car	Flat	4	80	0.083	0.082
		7	80	0.084	0.073
	Mountainous	4	80	0.111	0.074
		7	80	0.113	0.076
Articulated Truck	Flat	4	80	0.534	0.337
		7	71.553	0.555	0.363
	Mountainous	4	80	1.143	0.471
		7	71.553	1.166	0.435

When considering the large decrease in fuel consumption, it is clear that the conservative approach of the WCG is extremely conservative.

6.6.6 Decisions taken in terms of constant speed.

In the 2001 Simplification system it was decided to standardise vehicle speed at a constant 80 km/h. Furthermore, acceleration and deceleration was ignored due to the rural characteristic of the network. In the implementation of the simplified VOC it has come apparent that, should the assessment of municipal areas be included in our expanded evaluations in future, this decision would influence results.

It is, however, not the core business of the WCG Transport department to review municipal areas and it will consequently not be considered at present.

6.6.7 Modified Simplification application that can be used as a standalone function.

Organizations that co-operate with the WCG or follow the progress of the Road Network Branch Management Systems, would benefit from a standalone system for

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calculating VOC. The availability of the Modified Simplification for terrain for bigger vehicle fleets would allow potential users to calculate a VOC for their specific situation. This would include analysis of larger vehicle fleets than those used in the network analysis and enable amendment to calculation of costs for different vehicles.

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7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

7.1.1 General Modification

Various factors, including keeping abreast with new technology development, led to a decision by the WCG DTPW to update the 2001 Simplification with Terrain and a review of the vehicle fleets used in the WCG DTPW Road Network Management Systems.

The sound principles that were developed in the widely accepted 2001 Simplification provided the foundation for this study.

The implementation of this Modified Simplification over the last 5 years have assisted not only the WCG DTPW, but various entities, including Government Departments, that also use the VOC (published annually) based on these principles. Interested parties have the option to include Terrain in their implementation of Terrain by using all three Terrain Types or Flat only, as an added benefit. Caution should be taken when using the Modified Simplification, as it is important that the principles used to simplify HDM-4, apply to this implementation and the business standards of the Management system of the user, *inter alia*:

- ignoring aerodynamic resistance to motion
- assuming 100% traffic flow in the uphill direction for gradient resistance to motion

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- weather (rainfall and snow covered roads)
- typical texture depth, and
- rural characteristics of the network that allows the use of example free-flow, constant speed of 80 km/h for network analysis

The negative result for RPM for Vehicle Type 1 Motorcycle is questionable and HDMGlobal has been contacted in this regard. Currently this Vehicle Type has not been used in one of the Management Systems using the Modified Simplification. When the negative result is reviewed in isolation, it is incorrect. However, the negative result are acceptable when used as part of the greater calculation of VOC.

7.1.2 Implementation

In future, should the department reconsider the fleet, the process to change the vehicle fleet will not require a redevelopment as the Modified Simplification was adapted to include all Vehicle Types defined by HDM-4. Should a standalone application be developed, this may assist in case studies to see if any change to the fleet would have value on network level.

7.2 RECOMMENDATIONS FOR FUTHER DEVELOPMENT AND RESEARCH

7.2.1 Standalone function

The first development being considered by the WCG DTPW, is a standalone function that will assist the department in case studies and on project level implementations. Other users that accept the principles of the Modified Simplification will be allowed to

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use their own Vehicle cost data (in local currency) where it may differ from the WCG DTPW.

7.2.2 Investigating Published Vehicle cost data

As more than a decade has passed after the 2001 Simplification, it may be useful to review the availability of published data in terms of Vehicle cost data. Such Vehicle cost data may be useful for comparisons, case studies and in a future standalone function.

7.2.3 Economic Vehicle Data

This is an area that has been identified for more research, should the Modified Simplification be used on strategic and planning operations. The first phase may include identifying factors only that may be applied to the Financial Vehicle Data. This aspect falls outside the scope of this research.

7.2.4 Incorporating Aerodynamic resistance to motion

A study on how to incorporate aerodynamic resistance to motion, may be of great value to the WCG. This could include road specific height information, but preferable more information on the speed on each road.

7.2.5 Gradient resistance to motion incorporation

Further investigations on how to incorporate the direction split of vehicles in terms of gradient resistance to motion, may also be of great benefit to the WCG, and is definitely a more accurate approach.

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APPENDIX A: HDM-4 PARAMETER VALUES FOR VEHICLES AND TERRAIN

The tables below are extracts from HDM-4 Volume 4 – Analytical Framework & Model Description: Part E

Table E2.1 Default representative vehicle classes and basic characteristics

Vehicle Number	Type	Description	Abbreviation	Fuel type	Number of axels	Number of wheels	Aerodynamic drag Coeff	Projected frontal area (m^2)	Tare weight (t)	Operating weight (t)
1	**Motorcycle**	Motorcycle or scooter	MC	P	2	2	0.70	0.8	0.1	0.2
2	**Small car**	Small passenger cars	PC-S	P	2	4	0.40	1.8	0.8	1
3	**Medium car**	Medium passenger cars	PC-M	P	2	4	0.42	1.9	1	1.2
4	**Large Car**	Large passenger cars	PC-L	P	2	4	0.45	2	1.2	1.4
5	**Light delivery vehicle**	Panel van, utility or pickup truck	LDV	P	2	4	0.50	2	1.3	1.5
6	**Light goods vehicle**	Very light truck for carrying goods (4 tyres)	LGV	P	2	4	0.50	2.8	0.9	1.5
7	**Four wheel drive**	Landrover / Jeep type vehicles	4WD	P	2	4	0.55	2.8	1.5	1.8
8	**Light truck**	Small two-axle rigid truck (approx. <3.5t)	LT	D	2	4	0.60	4	1.8	2
9	**Medium truck**	Medium two-axle rigid truck (approx. >3.5t)	MT	D	2	6	0.70	5	4.5	7.5
10	**Heavy truck**	Multi-axle rigid truck	HT	D	3	10	0.80	8.5	9	13
11	**Articulated truck**	Articulated truck or truck with drawbar trailer	AT	D	5	18	0.50	9	11	28
12	**Mini Bus**	Small bus based on panel van chassis (usually 4 tyres)	MNB	P	2	4	0.50	2.9	1.1	1.5
13	**Light Bus**	Light bus (approx. <3.5t)	LB	D	2	4	0.50	4	1.75	2.5
14	**Medium Bus**	Medium bus (3.5 – 8.0 t)	MB	D	2	6	0.55	5	4.5	6
15	**Heavy Bus**	Multi-axle or large two-axle bus	HB	D	3	10	0.65	6.5	8	10
16	**Coach**	Large bus designed for long distance travel	COACH	D	3	10	0.65	6.5	10	15

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Table E2.2 Default steady-state speed model parameters

Vehicle Number	Type	Model Parameters		VDRIVE	VBRAKE			
		Speed_sigma	Speed_Beta	PDRIVE (kW)	Pbrake (kW)	CGR_a0	CGR_a1	CGR_a2
1	Motorcycle	0	0.151	12	5	94.9	0.85	2.80
2	Small car	0	0.151	26	20	94.9	0.85	2.80
3	Medium car	0	0.151	33	20	94.9	0.85	2.80
4	Large Car	0	0.151	36	20	94.9	0.85	2.80
5	Light delivery vehicle	0	0.151	40	25	94.9	0.85	2.80
6	Light goods vehicle	0	0.151	40	20	94.9	0.85	2.80
7	Four wheel drive	0	0.151	45	25	94.9	0.85	2.80
8	Light truck	0	0.191	50	45	94.9	0.85	2.80
9	Medium truck	0	0.164	87	70	94.9	0.85	2.80
10	Heavy truck	0	0.110	227	255	94.9	0.85	2.80
11	Articulated truck	0	0.110	227	255	94.9	0.85	2.80
12	Mini Bus	0	0.151	40	26	94.9	0.85	2.80
13	Light Bus	0	0.191	50	45	94.9	0.85	2.80
14	Medium Bus	0	0.191	65	70	94.9	0.85	2.80
15	Heavy Bus	0	0.110	120	120	94.9	0.85	2.80
16	Coach	0	0.110	180	180	94.9	0.85	2.80

Table E2.3 Rolling resistance model parameters

Surface class	Surface Type	WGT_OPER<=2500 kg				WGT_OPER >2500 kg			
		CR_CR2_a0	CR_CR2_a1	CR_CR2_a2	Kcr2	CR_CR2_a0	CR_CR2_a1	CR_CR2_a2	Kcr2
Bituminous	AM or ST	0.90	0.022	0.022	1	0.84	0.03	0.03	1
Unsealed	GR	1.00	0.00	0.075	1	1.00	0.00	0.075	1

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Table E2.4 Parameters for calculating aerodynamic, rolling and inertial resistance															
Vehicle Number	Type	Aerodynamic resistance parameters			Rolling resistance parameters							Inertial Resistance Parameters			
		CD multiplier	Aero. Drag Coeff	Projected frontal Area (m2)	Number of wheels	Wheel diameter (m)	Type of tyre	CR1 pg E2-11	Tyre parameters			EMRAT_a0	EMRAT_a1	EMRAT_a2	
		CDMULT	CD	AF	NUM WHEELS	WHEEL_DIA	TYRE_TYPE		CR_B_a0	CR_B_a1	CR_B_a2				
1	Motorcycle	1.10	0.70	0.8	2	0.55	Bias	1.3	37	0.064	0.012	1.10	0	0	
2	Small car	1.10	0.40	1.8	4	0.60	Radial	1	37	0.064	0.012	1.14	1.010	399.0	
3	Medium car	1.10	0.42	1.9	4	0.60	Radial	1	37	0.064	0.012	1.05	0.213	1260.7	
4	Large Car	1.10	0.45	2	4	0.66	Radial	1	37	0.064	0.012	1.05	0.213	1260.7	
5	Light delivery vehicle	1.11	0.50	2.8	4	0.70	Radial	1	37	0.064	0.012	1.10	0.891	244.2	
6	Light goods vehicle	1.11	0.50	2.8	4	0.70	Bias	1.3	37	0.064	0.012	1.10	0.891	244.2	
7	Four wheel drive	1.11	0.50	2.8	4	0.70	Bias	1.3	37	0.064	0.012	1.10	0.891	244.2	
8	Light truck	1.13	0.55	4	4	0.80	Bias	1.3	37	0.064	0.012	1.04	0.830	12.4	
9	Medium truck	1.13	0.60	5	6	1.05	Bias	1.3	37	0.064	0.012	1.04	0.830	12.4	
10	Heavy truck	1.14	0.70	8.5	10	1.05	Bias	1.3	37	0.064	0.012	1.07	1.910	10.1	
11	Articulated truck	1.22	0.80	9	18	1.05	Bias	1.3	37	0.064	0.012	1.07	1.910	10.1	
12	Mini Bus	1.11	0.50	2.9	4	0.70	Radial	1	37	0.064	0.012	1.10	0.891	244.2	
13	Light Bus	1.13	0.50	4	4	0.80	Bias	1.3	37	0.064	0.012	1.10	0.891	244.2	
14	Medium Bus	1.14	0.55	5	6	1.05	Bias	1.3	37	0.064	0.012	1.04	0.830	12.4	
15	Heavy Bus	1.14	0.65	6.5	10	1.05	Bias	1.3	37	0.064	0.012	1.04	0.830	12.4	
16	Coach	1.14	0.65	6.5	10	1.05	Bias	1.3	37	0.064	0.012	1.04	0.830	12.4	

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Vehicle Number	Type	Table 2.5 Default model parameters for VCURVE AND VROUGH				Table E2.6 Default model parameters for VDESIR					
		VCURVE		VROUGH		Desired speed (Bituminous surface roads)					
		VCURVE_a0	VCURVE_a1	ARVMAX (mm/s)	VROUGH_a0	VDES2 (m/s)	VDES_a0	VDES_a1	VDES_a2	CW1	CW2
1	Motorcycle	3.9	0.34	203	1.15	40.0	0.0020	2.9	0.75	4	6.8
2	Small car	3.9	0.34	203	1.15	40.1	0.0020	2.9	0.75	4	6.8
3	Medium car	3.9	0.34	203	1.15	34.8	0.0020	2.9	0.75	4	6.8
4	Large Car	3.9	0.34	203	1.15	34.4	0.0020	2.9	0.75	4	6.8
5	Light delivery vehicle	3.9	0.34	203	1.15	42.0	0.0020	2.9	0.75	4	6.8
6	Light goods vehicle	3.9	0.34	200	1.15	40.0	0.0020	2.9	0.75	4	6.8
7	Four wheel drive	3.9	0.34	200	1.15	39.2	0.0020	2.9	0.75	4	6.8
8	Light truck	4.8	0.29	200	1.15	35.6	0.0028	0.7	0.75	4	6.8
9	Medium truck	4.8	0.29	200	1.15	29.3	0.0028	0.7	0.75	4	6.8
10	Heavy truck	4.6	0.28	180	1.15	24.6	0.0033	0.7	0.75	4	6.8
11	Articulated truck	4.2	0.27	160	1.15	29.1	0.0039	0.7	0.75	4	6.8
12	Mini Bus	3.9	0.34	203	1.15	46.1	0.0020	0.6	0.75	4	6.8
13	Light Bus	4.8	0.29	200	1.15	34.4	0.0028	0.6	0.75	4	6.8
14	Medium Bus	4.8	0.29	200	1.15	39.4	0.0028	0.6	0.75	4	6.8
15	Heavy Bus	4.6	0.28	180	1.15	24.8	0.0033	0.6	0.75	4	6.8
16	Coach	4.6	0.28	180	1.15	24.5	0.0033	0.6	0.75	4	6.8

Table E2.7 Cornering stiffness model parameters				
Coefficient	WGT_OPER <=2500 kg		WGT_OPER >=2500 kg	
	Bias	Radial	Bias	Radial
CS_a0	30	43	8.8	0
CS_a1	0	0	0.088	0.0913
CS_a2	0	0	-0.0000225	-0.0000114
Kcs	1	1	1	1

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Table E2.8 Default fuel model parameters

Vehicle Number	Type	Engine speed model parameters				Idle engine speed	Idle fuel rate	Base fuel efficiency	Decrease in efficiency	Rated engine power	Efficiency of the drivetrain	Engine and Accessories power	
		RPM_a0	RPM_a1	RPM_a2	RPM_a3	RPM_IDLE	IDLE_FUEL	ZETAB	EHP	PRAT	EDT	PACCS_a0	PCTENG
		RPM	RPM/(km/h)	RPM/(km/h)2	RPM/(km/h)	RPM	ml/s	ml/kW/s		kW			
1	Motorcycle	-162	298.86	-4.6723	-0.0026	800	0.12	0.067	0.25	15	0.95	0.20	80
2	Small car	1910	-12.311	0.2228	-0.0003	800	0.25	0.067	0.25	60	0.90	0.20	80
3	Medium car	1910	-12.311	0.2228	-0.0003	800	0.36	0.067	0.25	70	0.90	0.20	80
4	Large Car	1910	-12.311	0.2228	-0.0003	800	0.48	0.067	0.25	90	0.90	0.20	80
5	Light delivery vehicle	1910	-12.311	0.2228	-0.0003	800	0.48	0.067	0.25	60	0.90	0.20	80
6	Light goods vehicle	2035	-20.036	0.3560	-0.0009	800	0.37	0.067	0.25	55	0.90	0.20	80
7	Four wheel drive	2035	-20.036	0.3560	-0.0009	800	0.48	0.057	0.10	60	0.90	0.20	80
8	Light truck	2035	-20.036	0.3560	-0.0009	500	0.37	0.057	0.10	75	0.86	0.20	80
9	Medium truck	1926	-32.352	0.7403	-0.0027	500	0.37	0.057	0.10	100	0.86	0.20	80
10	Heavy truck	1905	-12.988	0.2494	-0.0004	500	1.12	0.056	0.10	280	0.86	0.20	80
11	Articulated truck	1900	-10.178	0.1521	0.00004	500	1.12	0.055	0.10	300	0.86	0.20	80
12	Mini Bus	1910	-12.311	0.2228	-0.0003	800	0.48	0.067	0.25	60	0.90	0.20	80
13	Light Bus	2035	-20.036	0.3560	-0.0009	500	0.37	0.057	0.10	75	0.86	0.20	80
14	Medium Bus	1926	-32.352	0.7403	-0.0027	500	0.37	0.057	0.10	100	0.86	0.20	80
15	Heavy Bus	1926	-32.352	0.7403	-0.0027	500	1.12	0.057	0.10	130	0.86	0.20	80
16	Coach	1926	-32.352	0.7403	-0.0027	500	1.12	0.057	0.10	150	0.86	0.20	80

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		Table E2.9 Default oil consumption model values			Table E2.10 Default tyre consumption model values				Table E2.11 Roughness effects &	
Vehicle Number	**Type**	**Distance between oil changes (km)**	**Engine oil capacity (l)**	**Oil loss due to operation OILOPER**	**NRO**	**Cotc**	**Ctcte**	**VOL (dm^3)**	**Adjusted roughness (RI_{mod})**	**VEH FAC**
1	**Motorcycle**	5000	2.00	0.0014	1.30	0.00639	0.005	0.35	**RI_{av}**	2
2	**Passenger car**	10000	4.00	0.0028	1.30	0.02616	0.00204	1.40	**RI_{av}**	2.0
3	**Passenger car**	10000	4.00	0.0028	1.30	0.02616	0.00204	1.40	**RI_{av}**	2.0
4	**Passenger car**	10000	4.00	0.0028	1.30	0.02616	0.00204	1.40	**RI_{av}**	2.0
5	**Light goods and delivery vehicles, Mini Bus 4WD**	7500	5.00	0.0028	1.30	0.02400	0.00187	1.60	**RI_{av}**	2.0
6	**Light goods and delivery vehicles, Mini Bus 4WD**	7500	5.00	0.0028	1.30	0.02400	0.00187	1.60	**RI_{av}**	2.0
7	**Light goods and delivery vehicles, Mini Bus 4WD**	7500	5.00	0.0028	1.30	0.02400	0.00187	1.60	**RI_{av}**	2.0
8	**Light and medium truck**	9000	14.00	0.0021	1.30	0.02400	0.00187	1.60	**RI_{av}**	2.0
9	**Light and medium truck**	9000	14.00	0.0021	1.30	0.02585	0.00201	6.00	**7**	1.0
10	**Heavy and articulated truck**	10000	31.00	0.0021	1.30	0.03529	0.00275	8.00	**Min (7,RI_{av})**	1.0
11	**Heavy and articulated truck**	10000	31.00	0.0021	1.30	0.03988	0.00311	8.00	**Min (7,RI_{av})**	1.0
12	**Light goods and delivery vehicles, Mini Bus 4WD**	7500	5.00	0.0028	1.30	0.02400	0.00187	1.60	**RI_{av}**	2.0
13	**Light and Medium Bus**	8000	14.00	0.0021	1.30	0.02173	0.00169	1.60	**RI_{av}**	2.0
14	**Light and Medium Bus**	8000	14.00	0.0021	1.30	0.02663	0.00207	6.00	**7**	1.0
15	**Heavy Bus and coach**	8000	20.00	0.0021	1.30	0.03088	0.00241	8.00	**Min (7,RI_{av})**	1.0
16	**Heavy Bus and coach**	8000	20.00	0.0021	1.30	0.03088	0.00241	8.00	**Min (7,RI_{av})**	1.0

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Table E2.12 Tyre type modification factor (TYPEFAC)			
Tyre type	**Surfaced roads**	**Unsurfaced roads**	
		IRI<6 m/km	**IRI>6 m/km**
Bias	1.00	1.00	1.00
Radial	1.25	1.20	1.00

		Table E2.13 Default vehicle Utilisation model values			**Table E2.14 Proposed default parts consumption model values**				**Table E2.15 Proposed default labour hours model parameter values**	
Vehicle Number	**Type**	**AKMO (km/year)**	**LIFEO (years)**	**HRWKO (h/year)**	**CKM**	**KP**	**a0 x 10^{-6}**	**a1 x 10^{-6}**	**a0**	**a1**
1	**Motorcycle**	10000	10	400	50 000	0.308	9.23	6.20	77.14	0.547
2	**Small car**	23000	10	550	115 000	0.308	36.94	6.20	77.14	0.547
3	**Medium car**	23000	10	550	115 000	0.308	36.94	6.20	77.14	0.547
4	**Large Car**	23000	10	550	115 000	0.308	36.94	6.20	77.14	0.547
5	**Light delivery vehicle**	30000	8	1300	120 000	0.308	36.94	6.20	77.14	0.547
6	**Light goods vehicle**	30000	8	130	120 000	0.308	36.94	6.20	77.14	0.547
7	**Four wheel drive**	30000	8	1300	120 000	0.371	7.29	2.96	77.14	0.547
8	**Light truck**	30000	8	1300	120 000	0.371	7.29	2.96	242.03	0.519
9	**Medium truck**	40000	12	1200	240 000	0.371	11.58	2.96	242.03	0.519
10	**Heavy truck**	86000	14	2050	602 000	0.371	11.58	2.96	301.46	0.519
11	**Articulated truck**	86000	14	2050	602 000	0.371	13.58	2.96	301.46	0.519
12	**Mini Bus**	30000	8	750	120 000	0.308	36.76	6.20	77.14	0.547
13	**Light Bus**	34000	8	850	136 000	0.371	10.14	1.97	242.03	0.519
14	**Medium Bus**	70000	7	1750	245 000	0.483	0.57	0.49	293.44	0.517
15	**Heavy Bus**	70000	12	1750	420 000	0.483	0.65	0.46	293.44	0.517
16	**Coach**	70000	12	1750	420 000	0.483	0.64	0.46	293.44	0.517

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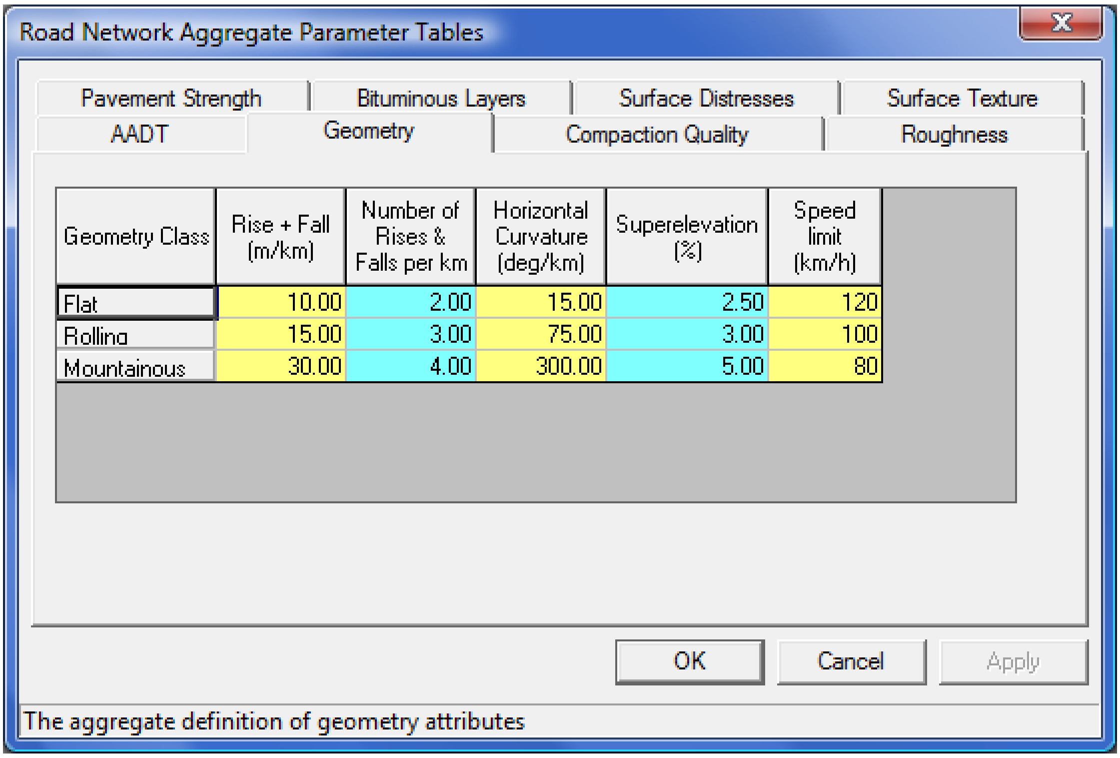
WCG Aggregate Geometry data used as classification of Terrain*



Geometry Class	Rise + Fall (m/km)	Number of Rises & Falls per km	Horizontal Curvature (deg/km)	Superelevation (%)	Speed limit (km/h)
Flat	10.00	2.00	15.00	2.50	120
Rolling	15.00	3.00	75.00	3.00	100
Mountainous	30.00	4.00	300.00	5.00	80

*Note that classification of Terrain is a business decision made by the Western Cape Government and is predefined

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APPENDIX B: VARIABLES FOR NEW SIMPLIFIED HDM-4 VOC

Fuel Consumption Variables for vehicle types 1 to 8 on Surfaced Roads on Flat Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	**7.951**	**7.951**	**7.951**	**7.951**	**7.951**	**7.834**	**7.834**	**7.834**
FC1	**2.138E-07**	**2.738E-07**	**2.745E-07**	**2.215E-07**	**3.351E-07**	**5.199E-07**	**1.975E-07**	**1.677E-07**
FC2	**2.266E-04**	**4.996E-04**	**5.393E-04**	**5.435E-04**	**5.623E-04**	**6.814E-04**	**5.882E-04**	**6.018E-04**
FC3	**1.749E-02**	**5.899E-02**	**6.805E-02**	**8.050E-02**	**6.785E-02**	**6.893E-02**	**6.457E-02**	**7.252E-02**
FC4	**8.212E-04**	**3.732E-03**	**4.484E-03**	**5.718E-03**	**4.326E-03**	**4.061E-03**	**4.029E-03**	**4.599E-03**
FC5	**2.086E-03**	**9.553E-03**	**1.226E-02**	**1.147E-02**	**2.308E-02**	**2.021E-02**	**2.493E-02**	**1.856E-02**
FC6	**4.946E-02**	**1.692E-01**	**1.768E-01**	**2.175E-01**	**1.066E-01**	**1.740E-01**	**9.773E-02**	**1.862E-01**
FC7	**2.555E-01**	**2.225E-01**	**2.173E-01**	**1.230E-01**	**1.893E-01**	**1.023E-01**	**1.198E-01**	**-7.940E-02**
FC8	**1.024E-01**	**1.237E-01**	**1.178E-01**	**9.279E-02**	**1.043E-01**	**9.316E-02**	**3.874E-02**	**9.410E-03**
FC9	**6.331E-01**	**4.201E-01**	**3.790E-01**	**2.084E-01**	**2.654E-01**	**1.790E-01**	**1.742E-01**	**4.903E-02**
FC10	**2.370E+00**	**3.442E-01**	**2.791E-01**	**5.879E-02**	**2.678E-01**	**6.620E-02**	**8.196E-02**	**7.021E-02**
FC11	**8.484E-03**	**6.704E-02**	**8.615E-02**	**1.118E-01**	**9.047E-02**	**2.177E-01**	**6.631E-02**	**1.253E-01**
FC12	**6.383E-02**	**1.156E-01**	**1.372E-01**	**6.680E-02**	**2.160E-01**	**7.434E-02**	**1.141E-01**	**-1.157E-01**
FC13	**4.299E-04**	**9.974E-03**	**1.773E-02**	**2.554E-02**	**5.049E-02**	**9.897E-02**	**6.402E-02**	**7.806E-02**

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Fuel Consumption Variables for vehicle types 9 to 16 on Surfaced Roads on Flat Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	**7.834**	**7.051**	**6.267**	**7.951**	**7.834**	**7.834**	**7.051**	**7.051**
FC1	**1.260E-06**	**1.296E-06**	**4.968E-06**	**3.351E-07**	**4.044E-07**	**9.389E-07**	**2.006E-06**	**3.015E-06**
FC2	**1.975E-03**	**3.234E-03**	**6.777E-03**	**5.623E-04**	**9.392E-04**	**1.685E-03**	**2.862E-03**	**3.829E-03**
FC3	**1.501E-01**	**3.019E-01**	**5.069E-01**	**6.785E-02**	**7.787E-02**	**1.316E-01**	**2.121E-01**	**2.816E-01**
FC4	**6.066E-03**	**1.837E-02**	**2.536E-02**	**4.326E-03**	**4.894E-03**	**5.814E-03**	**1.082E-02**	**1.238E-02**
FC5	**7.005E-02**	**1.282E-01**	**3.149E-01**	**2.308E-02**	**2.403E-02**	**5.251E-02**	**1.257E-01**	**1.750E-01**
FC6	**4.740E-01**	**4.953E-01**	**4.089E-01**	**1.066E-01**	**1.893E-01**	**4.661E-01**	**2.338E-01**	**3.777E-01**
FC7	**-7.661E-01**	**-1.748E-01**	**3.663E-01**	**1.893E-01**	**-9.028E-02**	**-7.847E-01**	**-1.494E-01**	**-3.618E-01**
FC8	**-3.062E-01**	**-2.538E-02**	**1.547E-01**	**1.043E-01**	**2.784E-03**	**-2.108E-01**	**-9.433E-02**	**-2.723E-01**
FC9	**-9.974E-01**	**3.987E-01**	**8.891E-01**	**2.654E-01**	**1.138E-01**	**-1.118E+00**	**2.713E-01**	**3.673E-01**
FC10	**2.641E+00**	**2.156E-01**	**4.780E-01**	**2.678E-01**	**1.087E-01**	**2.499E+00**	**2.907E-01**	**8.609E-01**
FC11	**7.727E-01**	**3.028E-01**	**2.573E-01**	**9.047E-02**	**1.986E-01**	**5.567E-01**	**1.875E-01**	**4.777E-01**
FC12	**-2.528E+00**	**-2.713E-01**	**3.305E-01**	**2.160E-01**	**-2.078E-01**	**-1.805E+00**	**-3.253E-01**	**-1.187E+00**
FC13	**6.619E-01**	**2.820E-01**	**5.183E-01**	**5.049E-02**	**1.906E-01**	**3.436E-01**	**2.844E-01**	**8.473E-01**

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Fuel Consumption Variables for vehicle types 1 to 8 on Surfaced Roads on Rolling Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
FC1	2.138E-07	2.738E-07	2.745E-07	2.215E-07	3.351E-07	5.199E-07	1.975E-07	1.677E-07
FC2	2.281E-04	5.041E-04	5.444E-04	5.482E-04	5.700E-04	6.913E-04	5.923E-04	6.058E-04
FC3	1.830E-02	6.319E-02	7.310E-02	8.635E-02	7.433E-02	7.551E-02	7.076E-02	7.969E-02
FC4	8.337E-04	3.732E-03	4.484E-03	5.718E-03	4.326E-03	4.061E-03	4.029E-03	4.599E-03
FC5	3.571E-03	1.360E-02	1.714E-02	1.716E-02	2.923E-02	2.634E-02	3.098E-02	2.528E-02
FC6	5.060E-02	1.705E-01	1.785E-01	2.191E-01	1.101E-01	1.777E-01	9.954E-02	1.877E-01
FC7	2.826E-01	2.166E-01	2.056E-01	1.048E-01	1.642E-01	8.589E-02	8.765E-02	-1.174E-01
FC8	1.423E-01	1.331E-01	1.244E-01	8.986E-02	1.020E-01	7.780E-02	3.301E-02	-6.837E-03
FC9	7.913E-01	1.494E+00	1.932E+00	2.322E+00	2.728E+00	2.445E+00	2.918E+00	3.414E+00
FC10	2.871E+00	7.100E-01	8.358E-01	7.276E-01	1.770E+00	1.618E+00	9.686E-01	9.554E-01
FC11	2.384E-01	2.402E+00	3.087E+00	4.007E+00	3.242E+00	5.444E+00	1.658E+00	3.132E+00
FC12	1.927E+00	3.815E+00	4.334E+00	1.557E+00	6.086E+00	3.257E-01	1.860E+00	-4.100E+00
FC13	3.279E-01	1.281E+01	2.276E+01	3.280E+01	6.483E+01	6.186E+01	4.001E+01	4.879E+01

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Fuel Consumption Variables for vehicle types 9 to 16 on Surfaced Roads on Rolling Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
FC1	1.260E-06	1.296E-06	4.968E-06	3.351E-07	4.044E-07	9.389E-07	2.006E-06	3.015E-06
FC2	2.013E-03	3.273E-03	6.939E-03	5.700E-04	9.470E-04	1.710E-03	2.917E-03	3.925E-03
FC3	1.798E-01	3.513E-01	6.186E-01	7.433E-02	8.697E-02	1.546E-01	2.514E-01	3.439E-01
FC4	6.066E-03	1.837E-02	2.536E-02	4.326E-03	4.894E-03	5.814E-03	1.082E-02	1.238E-02
FC5	9.646E-02	1.731E-01	4.117E-01	2.923E-02	3.247E-02	7.334E-02	1.607E-01	2.288E-01
FC6	4.886E-01	5.097E-01	4.673E-01	1.101E-01	1.916E-01	4.752E-01	2.545E-01	4.167E-01
FC7	-1.189E+00	-8.173E-01	-9.503E-01	1.642E-01	-1.515E-01	-1.046E+00	-5.332E-01	-1.240E+00
FC8	-7.392E-01	-2.893E-01	-7.233E-01	1.020E-01	-2.572E-02	-4.670E-01	-3.896E-01	-1.112E+00
FC9	3.109E+01	3.812E+01	6.102E+01	2.728E+00	5.383E+00	1.935E+01	2.313E+01	5.179E+01
FC10	2.650E+01	1.480E+01	4.274E+01	1.770E+00	1.803E+00	1.477E+01	1.625E+01	4.661E+01
FC11	5.386E+01	2.150E+01	1.956E+01	3.242E+00	4.966E+00	3.447E+01	1.161E+01	3.590E+01
FC12	-2.661E+02	-6.834E+01	-1.065E+02	6.086E+00	-8.147E+00	-1.483E+02	-5.748E+01	-2.551E+02
FC13	3.216E+03	1.421E+03	2.997E+03	6.483E+01	1.191E+02	1.317E+03	1.090E+03	4.784E+03

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Fuel Consumption Variables for vehicle types 1 to 8 on Surfaced Roads on Mountainous Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	**7.951**	**7.951**	**7.951**	**7.951**	**7.951**	**7.834**	**7.834**	**7.834**
FC1	**2.138E-07**	**2.738E-07**	**2.745E-07**	**2.215E-07**	**3.351E-07**	**5.199E-07**	**1.975E-07**	**1.677E-07**
FC2	**2.330E-04**	**5.199E-04**	**5.624E-04**	**5.653E-04**	**5.979E-04**	**7.310E-04**	**6.095E-04**	**6.229E-04**
FC3	**2.097E-02**	**7.788E-02**	**9.122E-02**	**1.078E-01**	**9.868E-02**	**1.026E-01**	**9.700E-02**	**1.110E-01**
FC4	**8.337E-04**	**3.732E-03**	**4.484E-03**	**5.718E-03**	**4.326E-03**	**4.061E-03**	**4.029E-03**	**4.599E-03**
FC5	**5.981E-03**	**2.571E-02**	**3.170E-02**	**3.415E-02**	**4.758E-02**	**4.483E-02**	**4.928E-02**	**4.560E-02**
FC6	**5.185E-02**	**1.765E-01**	**1.859E-01**	**2.265E-01**	**1.250E-01**	**1.936E-01**	**1.072E-01**	**1.943E-01**
FC7	**2.815E-01**	**1.824E-01**	**1.468E-01**	**1.800E-02**	**5.156E-02**	**-7.744E-02**	**-1.444E-01**	**-3.982E-01**
FC8	**1.890E-01**	**1.369E-01**	**1.084E-01**	**3.800E-02**	**1.092E-02**	**-1.353E-01**	**-7.780E-02**	**-1.507E-01**
FC9	**2.130E+00**	**1.291E+01**	**1.841E+01**	**2.475E+01**	**2.874E+01**	**3.844E+01**	**4.596E+01**	**5.634E+01**
FC10	**3.565E+00**	**7.921E+00**	**1.159E+01**	**1.353E+01**	**2.848E+01**	**4.136E+01**	**2.344E+01**	**2.363E+01**
FC11	**3.815E+00**	**2.682E+01**	**3.446E+01**	**4.473E+01**	**3.619E+01**	**8.710E+01**	**2.652E+01**	**5.012E+01**
FC12	**2.998E+01**	**2.752E+01**	**2.161E+01**	**-2.120E+01**	**-8.326E+00**	**-1.616E+02**	**-7.810E+01**	**-1.971E+02**
FC13	**8.393E+01**	**1.596E+03**	**2.836E+03**	**4.087E+03**	**8.079E+03**	**1.584E+04**	**1.024E+04**	**1.249E+04**

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Fuel Consumption Variables for vehicle types 9 to 16 on Surfaced Roads on Mountainous Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	**7.834**	**7.051**	**6.267**	**7.951**	**7.834**	**7.834**	**7.051**	**7.051**
FC1	**1.260E-06**	**1.296E-06**	**4.968E-06**	**3.351E-07**	**4.044E-07**	**9.389E-07**	**2.006E-06**	**3.015E-06**
FC2	**2.158E-03**	**3.425E-03**	**7.571E-03**	**5.979E-04**	**9.829E-04**	**1.808E-03**	**3.125E-03**	**4.302E-03**
FC3	**2.995E-01**	**5.470E-01**	**1.080E+00**	**9.868E-02**	**1.298E-01**	**2.457E-01**	**4.078E-01**	**6.008E-01**
FC4	**6.066E-03**	**1.837E-02**	**2.536E-02**	**4.326E-03**	**4.894E-03**	**5.814E-03**	**1.082E-02**	**1.238E-02**
FC5	**1.715E-01**	**3.006E-01**	**6.822E-01**	**4.758E-02**	**5.804E-02**	**1.334E-01**	**2.615E-01**	**3.794E-01**
FC6	**5.522E-01**	**5.713E-01**	**7.098E-01**	**1.250E-01**	**2.018E-01**	**5.157E-01**	**3.413E-01**	**5.791E-01**
FC7	**-1.757E+00**	**-1.702E+00**	**-2.563E+00**	**5.156E-02**	**-5.965E-01**	**-1.484E+00**	**-1.211E+00**	**-2.316E+00**
FC8	**-2.072E+00**	**-1.093E+00**	**-3.081E+00**	**1.092E-02**	**-2.958E-01**	**-1.339E+00**	**-1.410E+00**	**-3.417E+00**
FC9	**1.879E+02**	**2.167E+02**	**3.219E+02**	**2.874E+01**	**8.826E+01**	**1.347E+02**	**1.507E+02**	**2.790E+02**
FC10	**2.160E+02**	**1.350E+02**	**3.650E+02**	**2.848E+01**	**4.584E+01**	**1.252E+02**	**1.643E+02**	**3.869E+02**
FC11	**3.091E+02**	**1.211E+02**	**1.029E+02**	**3.619E+01**	**7.945E+01**	**2.227E+02**	**7.499E+01**	**1.911E+02**
FC12	**-2.290E+03**	**-7.813E+02**	**-1.433E+03**	**-8.326E+00**	**-4.515E+02**	**-1.386E+03**	**-8.088E+02**	**-2.496E+03**
FC13	**1.059E+05**	**4.512E+04**	**8.293E+04**	**8.079E+03**	**3.049E+04**	**5.498E+04**	**4.551E+04**	**1.356E+05**

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Fuel Consumption Variables for vehicle types 1 to 8 on Unsurfaced Roads on Flat Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
FC1	2.485E-06	3.182E-06	3.191E-06	2.574E-06	3.895E-06	6.042E-06	2.295E-06	1.949E-06
FC2	7.776E-04	1.710E-03	1.845E-03	1.858E-03	1.925E-03	2.335E-03	2.010E-03	2.056E-03
FC3	1.830E-02	6.076E-02	6.996E-02	8.243E-02	6.985E-02	7.135E-02	6.666E-02	7.465E-02
FC4	1.157E-03	4.623E-03	5.473E-03	6.780E-03	5.433E-03	5.363E-03	5.226E-03	5.826E-03
FC5	3.364E-03	1.114E-02	1.403E-02	1.330E-02	2.529E-02	2.285E-02	2.702E-02	2.061E-02
FC6	6.614E-02	1.905E-01	1.982E-01	2.356E-01	1.230E-01	1.959E-01	1.135E-01	1.988E-01
FC7	3.171E-01	2.626E-01	2.572E-01	1.541E-01	2.231E-01	1.442E-01	1.477E-01	-6.014E-02
FC8	1.904E-01	1.805E-01	1.695E-01	1.300E-01	1.396E-01	1.521E-01	5.591E-02	2.152E-02
FC9	1.097E+00	5.578E-01	4.970E-01	2.717E-01	3.400E-01	2.624E-01	2.051E-01	5.711E-02
FC10	3.330E+00	4.532E-01	3.697E-01	8.805E-02	3.356E-01	9.679E-02	1.071E-01	5.998E-02
FC11	1.373E-02	7.885E-02	1.007E-01	1.246E-01	1.100E-01	2.535E-01	8.237E-02	1.374E-01
FC12	8.357E-02	1.330E-01	1.586E-01	8.557E-02	2.447E-01	1.269E-01	1.377E-01	-9.778E-02
FC13	5.246E-04	9.974E-03	1.773E-02	2.554E-02	5.049E-02	9.897E-02	6.402E-02	7.806E-02

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Fuel Consumption Variables for vehicle types 9 to 16 on Unsurfaced Roads on Flat Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	**7.834**	**7.051**	**6.267**	**7.951**	**7.834**	**7.834**	**7.051**	**7.051**
FC1	**7.874E-06**	**8.100E-06**	**3.105E-05**	**3.895E-06**	**2.528E-06**	**5.868E-06**	**1.254E-05**	**1.884E-05**
FC2	**4.966E-03**	**8.112E-03**	**1.705E-02**	**1.925E-03**	**2.357E-03**	**4.232E-03**	**7.199E-03**	**9.637E-03**
FC3	**1.586E-01**	**3.159E-01**	**5.364E-01**	**6.985E-02**	**8.195E-02**	**1.389E-01**	**2.246E-01**	**2.983E-01**
FC4	**8.720E-03**	**2.281E-02**	**3.442E-02**	**5.433E-03**	**6.104E-03**	**8.081E-03**	**1.463E-02**	**1.747E-02**
FC5	**7.903E-02**	**1.423E-01**	**3.460E-01**	**2.529E-02**	**2.783E-02**	**5.995E-02**	**1.388E-01**	**1.931E-01**
FC6	**4.903E-01**	**5.124E-01**	**4.414E-01**	**1.230E-01**	**2.007E-01**	**4.806E-01**	**2.529E-01**	**4.020E-01**
FC7	**-7.395E-01**	**-1.351E-01**	**4.314E-01**	**2.231E-01**	**-5.847E-02**	**-7.587E-01**	**-1.084E-01**	**-3.202E-01**
FC8	**-3.207E-01**	**-1.623E-02**	**1.953E-01**	**1.396E-01**	**1.535E-02**	**-2.218E-01**	**-7.984E-02**	**-2.672E-01**
FC9	**-9.940E-01**	**4.159E-01**	**9.219E-01**	**3.400E-01**	**1.333E-01**	**-1.117E+00**	**2.847E-01**	**3.838E-01**
FC10	**2.539E+00**	**2.142E-01**	**5.309E-01**	**3.356E-01**	**9.216E-02**	**2.390E+00**	**2.816E-01**	**8.437E-01**
FC11	**7.954E-01**	**3.140E-01**	**2.768E-01**	**1.100E-01**	**2.147E-01**	**5.730E-01**	**2.041E-01**	**5.045E-01**
FC12	**-2.462E+00**	**-2.389E-01**	**3.869E-01**	**2.447E-01**	**-1.613E-01**	**-1.758E+00**	**-2.771E-01**	**-1.109E+00**
FC13	**6.619E-01**	**2.820E-01**	**5.183E-01**	**5.049E-02**	**1.906E-01**	**3.436E-01**	**2.844E-01**	**8.473E-01**

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Fuel Consumption Variables for vehicle types 1 to 8 on Unsurfaced Roads on Rolling Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
FC1	2.485E-06	3.182E-06	3.191E-06	2.574E-06	3.895E-06	6.042E-06	2.295E-06	1.949E-06
FC2	7.827E-04	1.725E-03	1.863E-03	1.874E-03	1.951E-03	2.369E-03	2.024E-03	2.069E-03
FC3	1.911E-02	6.498E-02	7.503E-02	8.830E-02	7.636E-02	7.797E-02	7.286E-02	8.184E-02
FC4	1.157E-03	4.623E-03	5.473E-03	6.780E-03	5.433E-03	5.363E-03	5.226E-03	5.826E-03
FC5	4.187E-03	1.526E-02	1.898E-02	1.907E-02	3.157E-02	2.914E-02	3.315E-02	2.739E-02
FC6	6.648E-02	1.920E-01	2.000E-01	2.373E-01	1.268E-01	1.999E-01	1.154E-01	2.004E-01
FC7	3.190E-01	2.579E-01	2.467E-01	1.367E-01	1.989E-01	1.292E-01	1.159E-01	-9.798E-02
FC8	2.084E-01	1.917E-01	1.779E-01	1.282E-01	1.387E-01	1.388E-01	5.081E-02	5.508E-03
FC9	1.182E+00	1.645E+00	2.070E+00	2.410E+00	2.848E+00	2.580E+00	2.975E+00	3.451E+00
FC10	3.345E+00	8.396E-01	9.556E-01	7.928E-01	1.904E+00	1.725E+00	1.033E+00	9.871E-01
FC11	3.431E-01	2.825E+00	3.609E+00	4.464E+00	3.941E+00	6.337E+00	2.059E+00	3.436E+00
FC12	2.081E+00	4.438E+00	5.103E+00	2.230E+00	7.115E+00	1.641E+00	2.451E+00	-3.654E+00
FC13	3.279E-01	1.281E+01	2.276E+01	3.280E+01	6.483E+01	6.186E+01	4.001E+01	4.879E+01

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Fuel Consumption Variables for vehicle types 9 to 16 on Unsurfaced Roads on Rolling Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	**7.834**	**7.051**	**6.267**	**7.951**	**7.834**	**7.834**	**7.051**	**7.051**
FC1	**7.874E-06**	**8.100E-06**	**3.105E-05**	**3.895E-06**	**2.528E-06**	**5.868E-06**	**1.254E-05**	**1.884E-05**
FC2	**5.060E-03**	**8.211E-03**	**1.746E-02**	**1.951E-03**	**2.376E-03**	**4.296E-03**	**7.335E-03**	**9.879E-03**
FC3	**1.886E-01**	**3.655E-01**	**6.488E-01**	**7.636E-02**	**9.108E-02**	**1.621E-01**	**2.641E-01**	**3.610E-01**
FC4	**8.720E-03**	**2.281E-02**	**3.442E-02**	**5.433E-03**	**6.104E-03**	**8.081E-03**	**1.463E-02**	**1.747E-02**
FC5	**1.058E-01**	**1.876E-01**	**4.442E-01**	**3.157E-02**	**3.634E-02**	**8.105E-02**	**1.743E-01**	**2.477E-01**
FC6	**5.061E-01**	**5.278E-01**	**5.038E-01**	**1.268E-01**	**2.032E-01**	**4.905E-01**	**2.751E-01**	**4.438E-01**
FC7	**-1.168E+00**	**-7.823E-01**	**-9.021E-01**	**1.989E-01**	**-1.198E-01**	**-1.023E+00**	**-4.967E-01**	**-1.212E+00**
FC8	**-7.707E-01**	**-2.937E-01**	**-7.316E-01**	**1.387E-01**	**-1.323E-02**	**-4.863E-01**	**-3.881E-01**	**-1.147E+00**
FC9	**3.157E+01**	**3.844E+01**	**6.189E+01**	**2.848E+00**	**5.448E+00**	**1.961E+01**	**2.347E+01**	**5.267E+01**
FC10	**2.778E+01**	**1.569E+01**	**4.520E+01**	**1.904E+00**	**1.915E+00**	**1.541E+01**	**1.719E+01**	**4.910E+01**
FC11	**5.544E+01**	**2.229E+01**	**2.104E+01**	**3.941E+00**	**5.368E+00**	**3.548E+01**	**1.264E+01**	**3.791E+01**
FC12	**-2.615E+02**	**-6.605E+01**	**-1.022E+02**	**7.115E+00**	**-6.984E+00**	**-1.454E+02**	**-5.450E+01**	**-2.493E+02**
FC13	**3.216E+03**	**1.421E+03**	**2.997E+03**	**6.483E+01**	**1.191E+02**	**1.317E+03**	**1.090E+03**	**4.784E+03**

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Fuel Consumption Variables for vehicle types 1 to 8 on Unsurfaced Roads on Mountainous Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	**7.951**	**7.951**	**7.951**	**7.951**	**7.951**	**7.834**	**7.834**	**7.834**
FC1	**2.485E-06**	**3.182E-06**	**3.191E-06**	**2.574E-06**	**3.895E-06**	**6.042E-06**	**2.295E-06**	**1.949E-06**
FC2	**7.996E-04**	**1.779E-03**	**1.924E-03**	**1.933E-03**	**2.046E-03**	**2.505E-03**	**2.083E-03**	**2.128E-03**
FC3	**2.179E-02**	**7.973E-02**	**9.322E-02**	**1.098E-01**	**1.008E-01**	**1.052E-01**	**9.916E-02**	**1.132E-01**
FC4	**1.157E-03**	**4.623E-03**	**5.473E-03**	**6.780E-03**	**5.433E-03**	**5.363E-03**	**5.226E-03**	**5.826E-03**
FC5	**6.659E-03**	**2.758E-02**	**3.379E-02**	**3.630E-02**	**5.032E-02**	**4.813E-02**	**5.166E-02**	**4.791E-02**
FC6	**6.781E-02**	**1.983E-01**	**2.078E-01**	**2.449E-01**	**1.422E-01**	**2.165E-01**	**1.234E-01**	**2.072E-01**
FC7	**3.206E-01**	**2.272E-01**	**1.911E-01**	**5.179E-02**	**8.835E-02**	**-3.283E-02**	**-1.163E-01**	**-3.799E-01**
FC8	**2.591E-01**	**2.006E-01**	**1.667E-01**	**7.905E-02**	**5.072E-02**	**-7.238E-02**	**-6.034E-02**	**-1.399E-01**
FC9	**2.547E+00**	**1.324E+01**	**1.880E+01**	**2.513E+01**	**2.938E+01**	**3.948E+01**	**4.649E+01**	**5.686E+01**
FC10	**4.078E+00**	**8.316E+00**	**1.207E+01**	**1.403E+01**	**2.938E+01**	**4.280E+01**	**2.418E+01**	**2.437E+01**
FC11	**5.490E+00**	**3.154E+01**	**4.029E+01**	**4.983E+01**	**4.400E+01**	**1.014E+02**	**3.295E+01**	**5.497E+01**
FC12	**3.245E+01**	**3.447E+01**	**3.019E+01**	**-1.369E+01**	**3.164E+00**	**-1.405E+02**	**-6.865E+01**	**-1.900E+02**
FC13	**8.393E+01**	**1.596E+03**	**2.836E+03**	**4.087E+03**	**8.079E+03**	**1.584E+04**	**1.024E+04**	**1.249E+04**

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Fuel Consumption Variables for vehicle types 9 to 16 on Unsurfaced Roads on Mountainous Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	**7.834**	**7.051**	**6.267**	**7.951**	**7.834**	**7.834**	**7.051**	**7.051**
FC1	**7.874E-06**	**8.100E-06**	**3.105E-05**	**3.895E-06**	**2.528E-06**	**5.868E-06**	**1.254E-05**	**1.884E-05**
FC2	**5.421E-03**	**8.589E-03**	**1.903E-02**	**2.046E-03**	**2.466E-03**	**4.539E-03**	**7.855E-03**	**1.082E-02**
FC3	**3.089E-01**	**5.618E-01**	**1.113E+00**	**1.008E-01**	**1.340E-01**	**2.536E-01**	**4.214E-01**	**6.195E-01**
FC4	**8.720E-03**	**2.281E-02**	**3.442E-02**	**5.433E-03**	**6.104E-03**	**8.081E-03**	**1.463E-02**	**1.747E-02**
FC5	**1.820E-01**	**3.162E-01**	**7.185E-01**	**5.032E-02**	**6.215E-02**	**1.419E-01**	**2.766E-01**	**4.009E-01**
FC6	**5.730E-01**	**5.925E-01**	**7.575E-01**	**1.422E-01**	**2.141E-01**	**5.332E-01**	**3.663E-01**	**6.137E-01**
FC7	**-1.743E+00**	**-1.673E+00**	**-2.533E+00**	**8.835E-02**	**-5.672E-01**	**-1.465E+00**	**-1.181E+00**	**-2.303E+00**
FC8	**-2.124E+00**	**-1.113E+00**	**-3.141E+00**	**5.072E-02**	**-2.905E-01**	**-1.370E+00**	**-1.427E+00**	**-3.495E+00**
FC9	**1.907E+02**	**2.185E+02**	**3.265E+02**	**2.938E+01**	**8.907E+01**	**1.365E+02**	**1.529E+02**	**2.838E+02**
FC10	**2.241E+02**	**1.402E+02**	**3.782E+02**	**2.938E+01**	**4.809E+01**	**1.302E+02**	**1.707E+02**	**4.007E+02**
FC11	**3.181E+02**	**1.256E+02**	**1.107E+02**	**4.400E+01**	**8.589E+01**	**2.292E+02**	**8.166E+01**	**2.018E+02**
FC12	**-2.264E+03**	**-7.684E+02**	**-1.410E+03**	**3.164E+00**	**-4.328E+02**	**-1.367E+03**	**-7.896E+02**	**-2.465E+03**
FC13	**1.059E+05**	**4.512E+04**	**8.293E+04**	**8.079E+03**	**3.049E+04**	**5.498E+04**	**4.551E+04**	**1.356E+05**

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Tyre Consumption Variables for vehicle types 1 to 8 on Surfaces Roads on Flat Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
TC1	2.831E-05	2.655E-06	2.588E-06	2.301E-06	1.738E-06	2.471E-06	2.507E-06	2.187E-06
TC2	2.772E-03	3.096E-04	3.112E-04	2.888E-04	2.230E-04	2.993E-04	3.119E-04	2.835E-04
TC3	8.609E-02	4.640E-02	4.672E-02	4.644E-02	3.715E-02	3.906E-02	3.970E-02	3.919E-02
TC4	9.595E-06	1.485E-06	1.523E-06	1.513E-06	1.205E-06	1.652E-06	1.747E-06	1.661E-06
TC5	1.036E-03	1.897E-04	1.999E-04	2.047E-04	1.654E-04	2.138E-04	2.313E-04	2.265E-04
TC6	4.710E-02	4.349E-02	4.399E-02	4.434E-02	3.570E-02	3.697E-02	3.770E-02	3.775E-02
TC7	8.336E-02	6.678E-03	6.277E-03	4.876E-03	3.377E-03	4.814E-03	4.582E-03	3.304E-03
TC8	1.987E+00	1.696E-01	1.611E-01	1.265E-01	8.806E-02	1.228E-01	1.178E-01	8.589E-02
TC9	1.650E+00	5.625E-02	4.688E-02	2.744E-02	1.624E-02	2.585E-02	2.154E-02	1.137E-02
TC10	3.457E+01	1.179E+00	9.824E-01	5.752E-01	3.404E-01	5.420E-01	4.520E-01	2.389E-01
TC11	-8.617E-04	-1.337E-03	-2.310E-03	-3.669E-03	-3.619E-03	-6.800E-03	-1.175E-02	-1.612E-02
TC12	7.166E-03	1.112E-02	1.921E-02	3.051E-02	3.010E-02	5.489E-02	9.484E-02	1.301E-01

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Tyre Consumption Variables for vehicle types 9 to 16 on Surfaced Roads on Flat Terrain

	Medium Truck	**Heavy Truck**	**Articulated Truck**	**Mini Bus**	**Light Bus**	**Medium Bus**	**Heavy Bus**	**Coach**
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	**7.83**	**7.05**	**6.27**	**7.95**	**7.83**	**7.83**	**7.05**	**7.05**
TC1	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
TC2	3.349E-06	5.813E-06	1.276E-05	1.738E-06	3.814E-06	3.213E-06	4.676E-06	5.405E-06
TC3	3.760E-04	6.564E-04	1.479E-03	2.230E-04	3.618E-04	3.479E-04	5.063E-04	6.231E-04
TC4	3.640E-02	6.264E-02	1.326E-01	3.715E-02	3.574E-02	3.605E-02	5.231E-02	5.656E-02
TC5	3.034E-06	5.280E-06	1.173E-05	1.205E-06	3.002E-06	2.864E-06	4.168E-06	4.957E-06
TC6	3.489E-04	6.105E-04	1.388E-03	1.654E-04	2.988E-04	3.187E-04	4.638E-04	5.839E-04
TC7	3.590E-02	6.179E-02	1.308E-01	3.570E-02	3.465E-02	3.551E-02	5.152E-02	5.582E-02
TC8	1.629E-03	2.240E-03	3.495E-03	3.377E-03	3.685E-03	1.757E-03	2.071E-03	1.915E-03
TC9	3.141E-02	4.326E-02	6.796E-02	8.806E-02	6.768E-02	3.351E-02	3.949E-02	3.720E-02
TC10	1.695E-03	1.829E-03	1.942E-03	1.624E-02	1.057E-02	2.182E-03	2.083E-03	1.389E-03
TC11	2.587E-02	2.809E-02	3.115E-02	3.404E-01	1.546E-01	3.250E-02	3.104E-02	2.203E-02
TC12	-2.786E-02	-2.747E-02	-4.117E-02	-3.619E-03	-2.845E-02	-1.862E-02	-1.440E-02	-3.299E-02

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Tyre Consumption Variables for vehicle types 1 to 8 on Surfaced Roads on Rolling Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
TC1	2.831E-05	2.655E-06	2.588E-06	2.301E-06	1.738E-06	2.471E-06	2.507E-06	2.187E-06
TC2	2.971E-03	3.532E-04	3.583E-04	3.368E-04	2.616E-04	3.454E-04	3.628E-04	3.336E-04
TC3	9.619E-02	4.912E-02	4.977E-02	4.970E-02	3.985E-02	4.207E-02	4.312E-02	4.272E-02
TC4	9.595E-06	1.485E-06	1.523E-06	1.513E-06	1.205E-06	1.652E-06	1.747E-06	1.661E-06
TC5	1.152E-03	2.223E-04	2.361E-04	2.436E-04	1.976E-04	2.515E-04	2.738E-04	2.702E-04
TC6	5.371E-02	4.575E-02	4.658E-02	4.722E-02	3.813E-02	3.962E-02	4.077E-02	4.101E-02
TC7	8.861E-02	7.371E-03	6.970E-03	5.449E-03	3.785E-03	5.329E-03	5.097E-03	3.699E-03
TC8	2.207E+00	1.986E-01	1.901E-01	1.504E-01	1.051E-01	1.443E-01	1.393E-01	1.023E-01
TC9	1.650E+00	5.625E-02	4.688E-02	2.744E-02	1.624E-02	2.585E-02	2.154E-02	1.137E-02
TC10	3.458E+01	1.183E+00	9.900E-01	5.873E-01	3.523E-01	5.531E-01	4.711E-01	2.651E-01
TC11	-1.293E-01	-4.120E-01	-7.119E-01	-1.131E+00	-1.115E+00	-1.020E+00	-1.763E+00	-2.418E+00
TC12	4.478E+00	1.428E+01	2.467E+01	3.917E+01	3.864E+01	3.430E+01	5.928E+01	8.131E+01

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Tyre Consumption Variables for vehicle types 9 to 16 on Surfaced Roads on Rolling Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
TC1	3.349E-06	5.813E-06	1.276E-05	1.738E-06	3.814E-06	3.213E-06	4.676E-06	5.405E-06
TC2	4.668E-04	8.161E-04	1.848E-03	2.616E-04	4.321E-04	4.287E-04	6.239E-04	7.779E-04
TC3	4.212E-02	7.277E-02	1.567E-01	3.985E-02	3.940E-02	4.093E-02	5.942E-02	6.661E-02
TC4	3.034E-06	5.280E-06	1.173E-05	1.205E-06	3.002E-06	2.864E-06	4.168E-06	4.957E-06
TC5	4.354E-04	7.627E-04	1.742E-03	1.976E-04	3.611E-04	3.949E-04	5.747E-04	7.322E-04
TC6	4.149E-02	7.169E-02	1.545E-01	3.813E-02	3.807E-02	4.027E-02	5.844E-02	6.567E-02
TC7	1.897E-03	2.612E-03	4.093E-03	3.785E-03	4.171E-03	2.033E-03	2.397E-03	2.241E-03
TC8	3.742E-02	5.128E-02	7.769E-02	1.051E-01	8.157E-02	4.060E-02	4.785E-02	4.293E-02
TC9	1.695E-03	1.829E-03	1.942E-03	1.624E-02	1.057E-02	2.182E-03	2.083E-03	1.389E-03
TC10	3.868E-01	4.837E-01	1.024E+00	3.523E-01	2.009E-01	2.226E-01	2.126E-01	6.356E-01
TC11	-3.248E+01	-3.321E+01	-5.713E+01	-1.115E+00	-4.268E+00	-1.713E+01	-1.325E+01	-4.471E+01
TC12	1.093E+03	9.047E+02	1.230E+03	3.864E+01	1.435E+02	5.761E+02	3.609E+02	1.218E+03

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Tyre Consumption Variables for vehicle types 1 to 8 on Surfaced Roads on Mountainous Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
TC1	2.831E-05	2.655E-06	2.588E-06	2.301E-06	1.738E-06	2.471E-06	2.507E-06	2.187E-06
TC2	3.568E-03	4.839E-04	4.996E-04	4.808E-04	3.776E-04	4.837E-04	5.154E-04	4.838E-04
TC3	1.307E-01	5.947E-02	6.157E-02	6.262E-02	5.064E-02	5.394E-02	5.695E-02	5.739E-02
TC4	9.595E-06	1.485E-06	1.523E-06	1.513E-06	1.205E-06	1.652E-06	1.747E-06	1.661E-06
TC5	1.500E-03	3.200E-04	3.445E-04	3.603E-04	2.941E-04	3.646E-04	4.012E-04	4.011E-04
TC6	7.775E-02	5.467E-02	5.691E-02	5.886E-02	4.798E-02	5.016E-02	5.307E-02	5.424E-02
TC7	1.044E-01	9.448E-03	9.048E-03	7.166E-03	5.010E-03	6.874E-03	6.642E-03	4.882E-03
TC8	2.867E+00	2.855E-01	2.769E-01	2.219E-01	1.560E-01	2.081E-01	2.024E-01	1.495E-01
TC9	1.650E+00	5.625E-02	4.688E-02	2.744E-02	1.624E-02	2.585E-02	2.154E-02	1.137E-02
TC10	3.464E+01	1.275E+00	1.149E+00	8.397E-01	6.013E-01	1.047E+00	1.325E+00	1.436E+00
TC11	-1.379E+01	-2.139E+01	-3.696E+01	-5.870E+01	-5.791E+01	-1.088E+02	-1.880E+02	-2.579E+02
TC12	1.146E+03	1.779E+03	3.074E+03	4.881E+03	4.815E+03	8.782E+03	1.518E+04	2.082E+04

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Tyre Consumption Variables for vehicle types 9 to 16 on Surfaced Roads on Mountainous Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
TC1	3.349E-06	5.813E-06	1.276E-05	1.738E-06	3.814E-06	3.213E-06	4.676E-06	5.405E-06
TC2	7.394E-04	1.295E-03	2.955E-03	3.776E-04	6.429E-04	6.710E-04	9.766E-04	1.242E-03
TC3	6.776E-02	1.183E-01	2.670E-01	5.064E-02	5.538E-02	6.240E-02	9.066E-02	1.124E-01
TC4	3.034E-06	5.280E-06	1.173E-05	1.205E-06	3.002E-06	2.864E-06	4.168E-06	4.957E-06
TC5	6.949E-04	1.219E-03	2.804E-03	2.941E-04	5.482E-04	6.237E-04	9.077E-04	1.177E-03
TC6	6.565E-02	1.145E-01	2.573E-01	4.798E-02	5.224E-02	6.061E-02	8.804E-02	1.085E-01
TC7	2.703E-03	3.727E-03	5.887E-03	5.010E-03	5.629E-03	2.863E-03	3.374E-03	3.219E-03
TC8	5.829E-02	8.000E-02	1.220E-01	1.560E-01	1.197E-01	6.273E-02	7.394E-02	6.732E-02
TC9	1.695E-03	1.829E-03	1.942E-03	1.624E-02	1.057E-02	2.182E-03	2.083E-03	1.389E-03
TC10	2.095E+00	2.547E+00	4.810E+00	6.013E-01	2.268E+00	1.415E+00	1.352E+00	3.048E+00
TC11	-4.457E+02	-4.395E+02	-6.588E+02	-5.791E+01	-4.552E+02	-2.979E+02	-2.304E+02	-5.278E+02
TC12	3.598E+04	2.873E+04	3.403E+04	4.815E+03	3.674E+04	2.404E+04	1.506E+04	3.451E+04

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Tyre Consumption Variables for vehicle types 1 to 8 on Unsurfaced Roads on Flat Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Type Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
TC1	3.291E-04	3.085E-05	3.008E-05	2.674E-05	2.020E-05	2.872E-05	2.914E-05	2.542E-05
TC2	1.013E-02	1.120E-03	1.123E-03	1.040E-03	8.021E-04	1.080E-03	1.124E-03	1.019E-03
TC3	9.627E-02	4.753E-02	4.786E-02	4.749E-02	3.796E-02	4.016E-02	4.084E-02	4.022E-02
TC4	1.115E-04	1.726E-05	1.770E-05	1.759E-05	1.400E-05	1.920E-05	2.030E-05	1.931E-05
TC5	3.764E-03	6.825E-04	7.184E-04	7.343E-04	5.929E-04	7.689E-04	8.309E-04	8.124E-04
TC6	6.013E-02	4.485E-02	4.534E-02	4.555E-02	3.663E-02	3.822E-02	3.899E-02	3.889E-02
TC7	3.052E-01	2.429E-02	2.281E-02	1.770E-02	1.225E-02	1.750E-02	1.665E-02	1.199E-02
TC8	2.502E+00	2.012E-01	1.900E-01	1.478E-01	1.025E-01	1.437E-01	1.374E-01	9.942E-02
TC9	6.101E+00	2.080E-01	1.733E-01	1.015E-01	6.003E-02	9.559E-02	7.966E-02	4.202E-02
TC10	4.067E+01	1.387E+00	1.156E+00	6.766E-01	4.004E-01	6.376E-01	5.316E-01	2.809E-01
TC11	-8.617E-04	-1.337E-03	-2.310E-03	-3.669E-03	-3.619E-03	-6.800E-03	-1.175E-02	-1.612E-02
TC12	7.166E-03	1.112E-02	1.921E-02	3.051E-02	3.010E-02	5.489E-02	9.484E-02	1.301E-01

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Tyre Consumption Variables for vehicle types 9 to 16 on Unsurfaced Roads on Flat Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
TC1	2.093E-05	3.633E-05	7.977E-05	2.020E-05	2.384E-05	2.008E-05	2.923E-05	3.378E-05
TC2	1.013E-03	1.767E-03	3.973E-03	8.021E-04	9.871E-04	9.394E-04	1.367E-03	1.675E-03
TC3	3.809E-02	6.560E-02	1.392E-01	3.796E-02	3.738E-02	3.762E-02	5.459E-02	5.936E-02
TC4	1.896E-05	3.300E-05	7.332E-05	1.400E-05	1.876E-05	1.790E-05	2.605E-05	3.098E-05
TC5	9.381E-04	1.641E-03	3.725E-03	5.929E-04	8.120E-04	8.587E-04	1.250E-03	1.567E-03
TC6	3.757E-02	6.467E-02	1.373E-01	3.663E-02	3.624E-02	3.706E-02	5.374E-02	5.856E-02
TC7	4.481E-03	6.160E-03	9.596E-03	1.225E-02	1.023E-02	4.842E-03	5.708E-03	5.261E-03
TC8	3.897E-02	5.362E-02	8.402E-02	1.025E-01	8.549E-02	4.171E-02	4.912E-02	4.603E-02
TC9	4.871E-03	5.255E-03	5.581E-03	6.003E-02	3.038E-02	6.270E-03	5.987E-03	3.991E-03
TC10	3.377E-02	3.661E-02	4.020E-02	4.004E-01	2.039E-01	4.267E-02	4.074E-02	2.850E-02
TC11	-2.786E-02	-2.747E-02	-4.117E-02	-3.619E-03	-2.845E-02	-1.862E-02	-1.440E-02	-3.299E-02
TC12	2.249E-01	1.796E-01	2.127E-01	3.010E-02	2.296E-01	1.503E-01	9.414E-02	2.157E-01

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Tyre Consumption Variables for vehicle types 1 to 8 on Unsurfaced Roads on Rolling Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
TC1	3.291E-04	3.085E-05	3.008E-05	2.674E-05	2.020E-05	2.872E-05	2.914E-05	2.542E-05
TC2	1.081E-02	1.268E-03	1.284E-03	1.204E-03	9.339E-04	1.237E-03	1.297E-03	1.190E-03
TC3	1.071E-01	5.040E-02	5.107E-02	5.092E-02	4.080E-02	4.333E-02	4.444E-02	4.393E-02
TC4	1.115E-04	1.726E-05	1.770E-05	1.759E-05	1.400E-05	1.920E-05	2.030E-05	1.931E-05
TC5	4.160E-03	7.936E-04	8.416E-04	8.670E-04	7.026E-04	8.974E-04	9.756E-04	9.611E-04
TC6	6.715E-02	4.723E-02	4.805E-02	4.857E-02	3.917E-02	4.101E-02	4.221E-02	4.231E-02
TC7	3.231E-01	2.665E-02	2.517E-02	1.965E-02	1.364E-02	1.926E-02	1.840E-02	1.334E-02
TC8	2.741E+00	2.327E-01	2.215E-01	1.738E-01	1.210E-01	1.670E-01	1.607E-01	1.172E-01
TC9	6.101E+00	2.080E-01	1.733E-01	1.015E-01	6.003E-02	9.559E-02	7.966E-02	4.202E-02
TC10	4.067E+01	1.391E+00	1.163E+00	6.887E-01	4.123E-01	6.486E-01	5.507E-01	3.071E-01
TC11	-1.293E-01	-4.120E-01	-7.119E-01	-1.131E+00	-1.115E+00	-1.020E+00	-1.763E+00	-2.418E+00
TC12	4.478E+00	1.428E+01	2.467E+01	3.917E+01	3.864E+01	3.430E+01	5.928E+01	8.131E+01

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Tyre Consumption Variables for vehicle types 9 to 16 on Unsurfaced Roads on Rolling Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
TC1	2.093E-05	3.633E-05	7.977E-05	2.020E-05	2.384E-05	2.008E-05	2.923E-05	3.378E-05
TC2	1.240E-03	2.166E-03	4.896E-03	9.339E-04	1.163E-03	1.141E-03	1.661E-03	2.062E-03
TC3	4.421E-02	7.641E-02	1.649E-01	4.080E-02	4.134E-02	4.285E-02	6.221E-02	7.008E-02
TC4	1.896E-05	3.300E-05	7.332E-05	1.400E-05	1.876E-05	1.790E-05	2.605E-05	3.098E-05
TC5	1.154E-03	2.021E-03	4.609E-03	7.026E-04	9.679E-04	1.049E-03	1.527E-03	1.938E-03
TC6	4.354E-02	7.523E-02	1.625E-01	3.917E-02	3.994E-02	4.214E-02	6.114E-02	6.905E-02
TC7	5.152E-03	7.089E-03	1.109E-02	1.364E-02	1.144E-02	5.533E-03	6.523E-03	6.075E-03
TC8	4.615E-02	6.325E-02	9.634E-02	1.210E-01	1.015E-01	5.000E-02	5.888E-02	5.318E-02
TC9	4.871E-03	5.255E-03	5.581E-03	6.003E-02	3.038E-02	6.270E-03	5.987E-03	3.991E-03
TC10	3.947E-01	4.922E-01	1.033E+00	4.123E-01	2.501E-01	2.328E-01	2.223E-01	6.421E-01
TC11	-3.248E+01	-3.321E+01	-5.713E+01	-1.115E+00	-4.268E+00	-1.713E+01	-1.325E+01	-4.471E+01
TC12	1.093E+03	9.047E+02	1.230E+03	3.864E+01	1.435E+02	5.761E+02	3.609E+02	1.218E+03

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Tyre Consumption Variables for vehicle types 1 to 8 on Un-Surfaced Roads on Mountainous Terrain

	Motorcycle	Small Car	Medium Car	Large Car	Light Delivery Vehicle	Light Goods Vehicle	Four Wheel Drive	Light Truck
Vehicle Number	1	2	3	4	5	6	7	8
Limiting Roughness	7.951	7.951	7.951	7.951	7.951	7.834	7.834	7.834
TC1	3.291E-04	3.085E-05	3.008E-05	2.674E-05	2.020E-05	2.872E-05	2.914E-05	2.542E-05
TC2	1.285E-02	1.714E-03	1.766E-03	1.695E-03	1.329E-03	1.709E-03	1.817E-03	1.702E-03
TC3	1.437E-01	6.122E-02	6.337E-02	6.435E-02	5.200E-02	5.569E-02	5.880E-02	5.913E-02
TC4	1.115E-04	1.726E-05	1.770E-05	1.759E-05	1.400E-05	1.920E-05	2.030E-05	1.931E-05
TC5	5.346E-03	1.127E-03	1.211E-03	1.265E-03	1.032E-03	1.283E-03	1.410E-03	1.407E-03
TC6	9.242E-02	5.649E-02	5.877E-02	6.063E-02	4.936E-02	5.196E-02	5.497E-02	5.600E-02
TC7	3.768E-01	3.374E-02	3.225E-02	2.550E-02	1.782E-02	2.452E-02	2.367E-02	1.737E-02
TC8	3.457E+00	3.270E-01	3.156E-01	2.514E-01	1.762E-01	2.363E-01	2.292E-01	1.687E-01
TC9	6.101E+00	2.080E-01	1.733E-01	1.015E-01	6.003E-02	9.559E-02	7.966E-02	4.202E-02
TC10	4.073E+01	1.483E+00	1.322E+00	9.412E-01	6.613E-01	1.143E+00	1.404E+00	1.478E+00
TC11	-1.379E+01	-2.139E+01	-3.696E+01	-5.870E+01	-5.791E+01	-1.088E+02	-1.880E+02	-2.579E+02
TC12	1.146E+03	1.779E+03	3.074E+03	4.881E+03	4.815E+03	8.782E+03	1.518E+04	2.082E+04

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Tyre Consumption Variables for vehicle types 9 to 16 on Unsurfaced Roads on Mountainous Terrain

	Medium Truck	Heavy Truck	Articulated Truck	Mini Bus	Light Bus	Medium Bus	Heavy Bus	Coach
Vehicle Type Number	9	10	11	12	13	14	15	16
Limiting Roughness	7.834	7.051	6.267	7.951	7.834	7.834	7.051	7.051
TC1	2.093E-05	3.633E-05	7.977E-05	2.020E-05	2.384E-05	2.008E-05	2.923E-05	3.378E-05
TC2	1.921E-03	3.363E-03	7.665E-03	1.329E-03	1.690E-03	1.747E-03	2.543E-03	3.223E-03
TC3	7.103E-02	1.240E-01	2.801E-01	5.200E-02	5.824E-02	6.537E-02	9.498E-02	1.179E-01
TC4	1.896E-05	3.300E-05	7.332E-05	1.400E-05	1.876E-05	1.790E-05	2.605E-05	3.098E-05
TC5	1.803E-03	3.162E-03	7.264E-03	1.032E-03	1.436E-03	1.621E-03	2.360E-03	3.050E-03
TC6	6.882E-02	1.200E-01	2.699E-01	4.936E-02	5.492E-02	6.347E-02	9.218E-02	1.138E-01
TC7	7.165E-03	9.878E-03	1.558E-02	1.782E-02	1.509E-02	7.606E-03	8.966E-03	8.519E-03
TC8	7.051E-02	9.680E-02	1.484E-01	1.762E-01	1.459E-01	7.573E-02	8.921E-02	8.181E-02
TC9	4.871E-03	5.255E-03	5.581E-03	6.003E-02	3.038E-02	6.270E-03	5.987E-03	3.991E-03
TC10	2.103E+00	2.556E+00	4.819E+00	6.613E-01	2.317E+00	1.426E+00	1.361E+00	3.054E+00
TC11	-4.457E+02	-4.395E+02	-6.588E+02	-5.791E+01	-4.552E+02	-2.979E+02	-2.304E+02	-5.278E+02
TC12	3.598E+04	2.873E+04	3.403E+04	4.815E+03	3.674E+04	2.404E+04	1.506E+04	3.451E+04

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Oil Consumption, Labour Hours, Depreciation and Parts Consumption Variables for all Terrain Types and Surface Types for Vehicle Types 1 to 8

	Motorcycle	**Small Car**	**Medium Car**	**Large Car**	**Light Delivery Vehicle**	**Light Goods Vehicle**	**Four Wheel Drive**	**Light Truck**
Vehicle Number	1	2	3	4	5	6	7	8
OIL1	4.000E-04	4.000E-04	4.000E-04	4.000E-04	6.667E-04	6.667E-04	6.667E-04	1.556E-03
OIL2	1.400E-03	2.800E-03	2.800E-03	2.800E-03	2.800E-03	2.800E-03	2.800E-03	2.100E-03
LH1	7.714E+01	7.714E+01	7.714E+01	7.714E+01	7.714E+01	7.714E+01	7.714E+01	2.420E+02
LH2	5.470E-01	5.470E-01	5.470E-01	5.470E-01	5.470E-01	5.470E-01	5.470E-01	5.190E-01
DEP1	9.850E-03	4.283E-03	4.283E-03	4.283E-03	4.104E-03	4.104E-03	4.104E-03	4.104E-03
DEP2	1.000E-05	4.348E-06	4.348E-06	4.348E-06	4.167E-06	4.167E-06	4.167E-06	4.167E-06
Roughness adjustment	3.850	3.850	3.850	3.850	3.850	3.850	3.850	3.850
PC1	8.837E-04	2.145E-03	2.145E-03	2.145E-03	2.173E-03	2.173E-03	1.375E-03	1.375E-03
PC2	4.183E-14	5.407E-14	5.407E-14	5.407E-14	5.478E-14	5.478E-14	5.464E-14	5.464E-14
PC3	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01
PC4	1.736E-04	2.244E-04	2.244E-04	2.244E-04	2.274E-04	2.274E-04	2.268E-04	2.268E-04
PC5	2.585E-04	1.337E-03	1.337E-03	1.337E-03	1.355E-03	1.355E-03	5.586E-04	5.586E-04

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Oil Consumption, Labour Hours, Depreciation and Parts Consumption Variables for all Terrain Types and Surface Types for Vehicle Types 9 to 16

	Medium Truck	**Heavy Truck**	**Articulated Truck**	**Mini Bus**	**Light Bus**	**Medium Bus**	**Heavy Bus**	**Coach**
Vehicle Number	9	10	11	12	13	14	15	16
OIL1	1.556E-03	3.100E-03	3.100E-03	6.667E-04	1.750E-03	1.750E-03	2.500E-03	2.500E-03
OIL2	2.100E-03	2.100E-03	2.100E-03	2.800E-03	2.100E-03	2.100E-03	2.100E-03	2.100E-03
LH1	2.420E+02	3.015E+02	3.015E+02	7.714E+01	2.420E+02	2.934E+02	2.934E+02	2.934E+02
LH2	5.190E-01	5.190E-01	5.190E-01	5.470E-01	5.190E-01	5.170E-01	5.170E-01	5.170E-01
DEP1	2.052E-03	8.181E-04	8.181E-04	4.104E-03	3.621E-03	2.010E-03	1.173E-03	1.173E-03
DEP2	2.083E-06	8.306E-07	8.306E-07	4.167E-06	3.676E-06	2.041E-06	1.190E-06	1.190E-06
Roughness adjustment	3.850	3.850	3.850	3.850	3.850	3.850	3.850	3.850
PC1	2.204E-03	3.099E-03	3.378E-03	2.167E-03	1.383E-03	9.356E-04	1.199E-03	1.194E-03
PC2	7.066E-14	9.940E-14	9.940E-14	5.478E-14	3.809E-14	4.732E-14	5.763E-14	5.763E-14
PC3	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01	1.540E+01
PC4	2.933E-04	4.126E-04	4.126E-04	2.274E-04	1.581E-04	1.964E-04	2.392E-04	2.392E-04
PC5	1.148E-03	1.614E-03	1.893E-03	1.348E-03	8.139E-04	2.285E-04	3.380E-04	3.328E-04

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APPENDIX C: SENSITIVITY TO EVALUATE AERODYNAMIC RESISTANCE TO MOTION AT DIFFERENT CONSTANT SPEEDS

For this sensitivity the impact on Fuel Consumption is evaluated in terms of the decision not to incorporate Aerodynamic Resistance to Motion. This is done evaluating the following four scenarios in terms of Fuel Consumption at IRI=4:

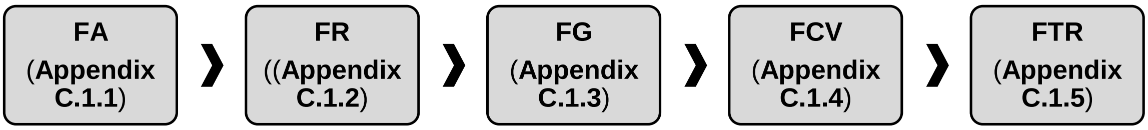
Vehicle Type	Terrain	Vehicle Speed
Large Car	Flat	80 km/h→22.222 m/s
		120 km/h→33.333 m/s
Articulated Truck	Mountainous	40 km/h→11.111 m/s
		80 km/h→22.222 m/s

This is done using the same flow process as **Chapter 5**.

C.1. RESISTANCE TO MOTION

$$FTR = FA + FG + FR + FCV$$

A schematic representation of the computational procedure is shown below.



Final substitution of variables into the above equation is presented in **Section C.1.5**.

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C.1.1. Aerodynamic resistance to motion

$$FA = 0.5 \times RH0 \times CDMult \times CD \times AF \times V^2$$

where:

$$RH0 = 1.225\left(1 - 2.26 \times ALT \times 10^{-5}\right)^{4.255}$$

For the purpose of the sensitivity(example below) the Weighted Average for height above sea level was used, this is calculated by average all height values on the network 1.8 million values over 18000 km, one height every 10m, the result being 392m.

$$\begin{aligned} RH0 &= 1.225\left(1 - 2.26 \times ALT \times 10^{-5}\right)^{4.255} \\ &= 1.225\left(1 - 2.26 \times 392 \times 10^{-5}\right)^{4.255} \\ &= 1.179 \end{aligned}$$

Vehicle speed is taken as constant speed, in all cases it is however required to evaluate if any of these speeds will be limited by roughness. Therefore the limiting roughness for each speed is calculated (**Appendix A**, Table E2.5):

Limiting roughness is calculated by $RI_{av} = \dfrac{ARVMAX}{VROUGHa0 \times V}$

Vehicle Type	Vehicle Speed	Limiting Roughness (IRI)
Large Car	80 km/h→22.222 m/s	7.943
	120 km/h→33.333 m/s	5.296
Articulated Truck	40 km/h→11.111 m/s	12.522
	80 km/h→22.222 m/s	6.261

The result show that limiting roughness for each scenarios is greater than IRI of 4.

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Therefore:

$$FA = 0.5 \times RH0 \times CGMult \times CD \times AF \times V^2$$

Large Car (4)	
80 km/h	**120 km/h**
$FA = 0.5 \times RH0 \times CGMult \times CD \times AF \times V^2$ $= 0.5 \times 1.179 \times 1.1 \times 0.45 \times 2 \times 22.222^2$ $= 288.318$	$FA = 0.5 \times RH0 \times CGMult \times CD \times AF \times V^2$ $= 0.5 \times 1.179 \times 1.1 \times 0.45 \times 2 \times 33.333^2$ $= 648.716$
Articulated Truck (11)	
40 km/h	**80 km/h**
$FA = 0.5 \times RH0 \times CGMult \times CD \times AF \times V^2$ $= 0.5 \times 1.179 \times 1.22 \times 0.8 \times 9 \times 11.111^2$ $= 639.542$	$FA = 0.5 \times RH0 \times CGMult \times CD \times AF \times V^2$ $= 0.5 \times 1.179 \times 1.22 \times 0.8 \times 9 \times 22.222^2$ $= 2558.170$

* FA is not dependent on Terrain

Vehicle Type	Vehicle Speed	FA
Large Car	80 km/h	288.318
	120 km/h	648.716
Articulated Truck	40 km/h	639.542
	80 km/h	2558.170

C.2.1. Rolling resistance to motion

Rolling resistance to motion is not dependant on terrain and therefore only IRI and Vehicle Type is considered:

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

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where:

$$\begin{aligned} FCLIM &= 1 + 0.003 \times PCTDS + 0.002 \times PCTDW \\ &= 1 + 0.003 \times 0 + 0.002 \times 20 \\ &= 1 + 0 + 0.04 \\ &= 1.04 \end{aligned}$$

$FCLIM$ is not dependant on IRI, or Vehicle Type

and (**Appendix A**, Tables E2.4 and E2.2)

Large Car (4)	Articulated Truck (11)
$b11 = CR\_B\_a0 \times WHEEL\_DIA = 37 \times 0.66 = 24.420$ $b12 = \frac{CR\_B\_a1}{WHEEL\_DIA} = \frac{0.064}{0.66} = 0.097$ $b13 = \frac{(CR\_B\_a2 \times NUM\_WHEELS)}{WHEEL\_DIA^2} = \frac{(0.012 \times 4)}{0.660^2} = 0.110$	$b11 = CR\_B\_a0 \times WHEEL\_DIA = 37 \times 1.050 = 38.850$ $b12 = \frac{CR\_B\_a1}{WHEEL\_DIA} = \frac{0.064}{1.050} = 0.061$ $b13 = \frac{(CR\_B\_a2 \times NUM\_WHEELS)}{WHEEL\_DIA^2} = \frac{(0.012 \times 18)}{1.050^2} = 0.196$

Split FR into separate parts:

$$\begin{aligned} FR &= FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2 \right) \\ &= FCLIM \times CR2 \times \left(term1 + term2 \times V^2 \right) \end{aligned}$$

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where:

Large Car (4)	Articulated Truck (11)
$term1 = b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER = 24.420 \times 4 + 1 \times 0.097 \times 1400 = 233.483$ $term2 = CR1 \times b13 = 1 \times 0.110 = 0.110$	$term1 = b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER = 38.85 \times 18 + 1.3 \times 0.061 \times 28000 = 2917.967$ $term2 = CR1 \times b13 = 1.3 \times 0.196 = 0.255$

Split $CR2$ into separate parts:

$$\begin{aligned} CR2 &= Kcr2 \times \left(CR\_CR2\_a0 + CR\_CR2\_a1 \times TD + CR\_CR2\_a2 \times RI \right) \\ &= Kcr2 \times CR\_CR2\_a0 + Kcr2 \times CR\_CR2\_a1 \times TD \\ &\quad + Kcr2 \times CR\_CR2\_a2 \times 4 \\ &= term3 + term4 \times 4 \end{aligned}$$

(**Appendix A**, Table E2.3)

Large Car (4)	Articulated Truck (11)
$term3 = Kcr2 \times CR\_CR2\_a0 + Kcr2 \times CR\_CR2\_a1 \times TD = 1 \times 0.9 + 1 \times 0.022 \times 1 = 0.922$ $term4 = Kcr2 \times CR\_CR2\_a2 = 1 \times 0.022 = 0.022$ $CR2 = term3 + term4 \times 4 = 0.922 + 0.022 \times 4 = 1.010$	$term3 = Kcr2 \times CR\_CR2\_a0 + Kcr2 \times CR\_CR2\_a1 \times TD = 1 \times 0.840 + 1 \times 0.030 \times 1 = 0.870$ $term4 = Kcr2 \times CR\_CR2\_a2 = 1 \times 0.030 = 0.030$ $CR2 = term3 + term4 \times 4 = 0.870 + 0.030 \times 4 = 0.990$

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$$FR = FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2\right)$$
$$= 1.04 \times CR2 \times \left(term1 + term2 \times V^2\right)$$

Large Car (4)	
V = 80 km/h	**V = 120 km/h**
$FR = 1.040 \times CR2 \times (term1 + term2 \times V^2)$ $= 1.040 \times 1.010 \times (233.438 + 0.110 \times 22.22^2)$ $= 302.362$	$FR = 1.040 \times CR2 \times (term1 + term2 \times V^2)$ $= 1.040 \times 1.010 \times (233.438 + 0.110 \times 33.33^2)$ $= 373.810$
Articulated Truck (11)	
V = 40 km/h	**V = 80 km/h**
$FR = 1.04 \times CR2 \times (term1 + term2 \times V^2)$ $= 1.04 \times 0.990 \times (2917.967 + 0.255 \times 11.11^2)$ $= 3036.713$	$FR = 1.04 \times CR2 \times (term1 + term2 \times V^2)$ $= 1.04 \times 0.990 \times (2917.967 + 0.255 \times 22.22^2)$ $= 3133.836$

Vehicle Type	Vehicle Speed	FR
Large Car	80 km/h	302.362
	120 km/h	373.810
Articulated Truck	40 km/h	3036.713
	80 km/h	3133.836

C.1.2. Gradient resistance to motion

$$FG = WGT\_OPER \times g \times GR$$

where:

$$FG = WGT\_OPER \times g \times GR$$
$$= WGT\_OPER \times g \times \frac{RF}{1000}$$
$$= WGT\_OPER \times 9.81 \times \frac{RF}{1000}$$

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(**Appendix A**):

Large Car (4)	
Flat	**Mountainous**
$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 1400 \times 9.81 \times \frac{10}{1000}$ $= 137.34$	$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 1400 \times 9.81 \times \frac{30}{1000}$ $= 412.02$
Articulated Truck (11)	
Flat	**Mountainous**
$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 28000 \times 9.81 \times \frac{10}{1000}$ $= 2746.80$	$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 2800 \times 9.81 \times \frac{30}{1000}$ $= 8240.4$

FG is not dependent on speed.

Vehicle Type	Terrain	FG
Large Car	Flat	137.34
	Mountainous	412.02
Articulated Truck	Flat	2746.8
	Mountainous	8240.4

C.1.3. Curvature resistance to motion

$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEEL \times CS \times 1000}\right]$$

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where (**Appendix A**, Table E2.7)

$$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS} \right)^2 \right]$$

Large Car (4)	Articulated Truck (11)
$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS} \right)^2 \right]$ $= 1 \times \left[43 + \frac{0 \times 1400}{4} + 0 \times \left(\frac{1400}{4} \right)^2 \right]$ $= 43$	$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS} \right)^2 \right]$ $= 1 \times \left[8.8 + \frac{0.088 \times 28000}{18} + 0 \times \left(\frac{28000}{18} \right)^2 \right]$ $= 91.244$

$$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C \right)}$$

(**Appendix A**):

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Terrain	e	
Flat	2.5/100	$R=\dfrac{180000}{\pi\times max\left(\dfrac{18}{\pi},C\right)}=\dfrac{180000}{\pi\times max(5.730,15)}=3819.719$
Mountainous	5/100	$R=\dfrac{180000}{\pi\times max\left(\dfrac{18}{\pi},C\right)}=\dfrac{180000}{\pi\times max(5.730,300)}=190.986$

thus:

Large Car (4)
$FCV=max\left[0,\dfrac{\left(\dfrac{WGT\_OPER\times V^2}{R}-WGT\_OPER\times g\times e\right)^2}{NUM\_WHEELS\times CS\times 1000}\right]=max\left[0,\dfrac{\left(\dfrac{1400\times V^2}{R}-1400\times 9.81\times e\right)^2}{4\times 43\times 1000}\right]$
Articulated Truck (11)
$FCV=max\left[0,\dfrac{\left(\dfrac{WGT\_OPER\times V^2}{R}-WGT\_OPER\times g\times e\right)^2}{NUM\_WHEELS\times CS\times 1000}\right]=max\left[0,\dfrac{\left(\dfrac{28000\times V^2}{R}-28000\times 9.81\times e\right)^2}{18\times 91.244\times 1000}\right]$

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Large Car (4)		
V	Flat	Mountainous
80 km/h	$FCV = max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times 22.222^2}{3819.719} - 1400 \times 9.81 \times \left(\frac{2.5}{100}\right)\right)^2}{4 \times 43 \times 1000}\right]$ $= max[0, 0.153]$ $= 0.153$	$FCV = max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times 22.222^2}{190.986} - 1400 \times 9.81 \times \left(\frac{5}{100}\right)\right)^2}{4 \times 43 \times 1000}\right]$ $= max[0, 50.023]$ $= 50.023$
120 km/h	$FCV = max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times 33.333^2}{3819.719} - 1400 \times 9.81 \times \left(\frac{2.5}{100}\right)\right)^2}{4 \times 43 \times 1000}\right]$ $= max[0, 0.024]$ $= 0.024$	$FCV = max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times 33.333^2}{190.986} - 1400 \times 9.81 \times \left(\frac{5}{100}\right)\right)^2}{4 \times 43 \times 1000}\right]$ $= max[0, 323.397]$ $= 323.397$

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Articulated Truck (11)		
V	**Flat**	**Mountainous**
40 km/h	$FCV = max\left[0, \frac{\left(\frac{28000\times V^2}{R} - 28000\times 9.81\times e\right)^2}{18\times 91.244\times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000\times 11.111^2}{3819.719} - 28000\times 9.81\times\left(\frac{2.5}{100}\right)\right)^2}{18\times 91.244\times 1000}\right]$ $= max[0, 21.642]$ $= 21.642$	$FCV = max\left[0, \frac{\left(\frac{28000\times V^2}{R} - 28000\times 9.81\times e\right)^2}{18\times 91.244\times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000\times 11.111^2}{190.986} - 28000\times 9.81\times\left(\frac{5}{100}\right)\right)^2}{18\times 91.244\times 1000}\right]$ $= max[0, 11.605]$ $= 11.605$
80 km/h	$FCV = max\left[0, \frac{\left(\frac{28000\times V^2}{R} - 28000\times 9.81\times e\right)^2}{18\times 91.244\times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000\times 22.222^2}{3819.719} - 28000\times 9.81\times\left(\frac{2.5}{100}\right)\right)^2}{18\times 91.244\times 1000}\right]$ $= max[0, 6.419]$ $= 6.419$	$FCV = max\left[0, \frac{\left(\frac{28000\times V^2}{R} - 28000\times 9.81\times e\right)^2}{18\times 91.244\times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000\times 22.222^2}{190.986} - 28000\times 9.81\times\left(\frac{5}{100}\right)\right)^2}{18\times 91.244\times 1000}\right]$ $= max[0, 2095.448]$ $= 2095.448$

thus

Vehicle Type	Terrain	V (km/h)	FCV
Large Car	Flat	80	0.153
		120	0.024
	Mountainous	80	50.023
		120	323.397
Articulated Truck	Flat	40	21.642
		80	6.419
	Mountainous	40	11.605
		80	2095.448

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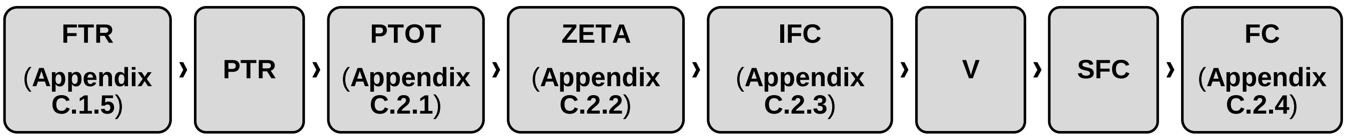
C.1.4. Final Substitution: Resistance to motion

$$FTR = FA + FG + FR + FCV$$

Vehicle Type	Terrain	V (km/h)	FA	FG	FR	FCV	FTR
Large Car	Flat	80	288.318	137.34	302.362	0.153	728.173
		120	648.716	137.34	373.810	0.024	1159.890
	Mountainous	80	288.318	412.02	302.362	50.023	1052.723
		120	648.716	412.02	373.810	323.642	1757.943
Articulated Truck	Flat	40	639.542	2746.8	3036.713	21.642	6444.698
		80	2558.170	2746.8	3133.836	6.419	8445.225
	Mountainous	40	639.542	8240.4	3036.713	11.605	11928.260
		80	2558.170	8240.4	3133.836	2095.448	16027.854

C.2. FUEL CONSUMPTION

A schematic representation of the computational procedure is shown below.



Final substitution of variables into the above equation is presented in **Section C.2.4**.

C.2.1. Total power requirements of the engine

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS\right) \text{ where } \qquad PTR = \frac{FTR \times V}{1000}$$

Vehicle Type	Terrain	V (km/h)	FTR	PTR
Large Car	Flat	80	728.173	16.182
		120	1159.890	39.663
	Mountainous	80	1052.723	23.394
		120	1757.943	58.598
Articulated Truck	Flat	40	6444.698	71.608
		80	8445.225	187.672
	Mountainous	40	11928.260	132.536
		80	16027.854	356.175

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and (**Appendix A**, Table E2.8):

$$PENGACCS = Kpea \times PRAT \times \left[PACCS\_a1 + \frac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \right]$$

and

$$RPM = RPM\_a0 + RPM\_a1 \times 3.6V + RPM\_a2 \times (3.6V)^2 + RPM\_a3 \times (3.6V)^3$$

and:

$$RPM100 = RPM\_a0 + RPM\_a1 \times 100 + RPM\_a2 \times (100)^2 + RPM\_a3 \times (100)^3$$

thus the result of combining the above:

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS \right)$$

Vehicle Type	Terrain	V (km/h)	PTR	RPM	RPM100	PENGACCS	PTOT
Large Car	Flat	80	16.182	2197.440	2606.900	15.538	33.518
		120	39.663	3122.600	2606.900	21.101	64.060
	Mountainous	80	23.394	2197.440	2606.900	15.538	41.531
		120	58.598	3122.600	2606.900	21.101	86.210
Articulated Truck	Flat	40	71.608	1738.800	2443.200	45.622	128.887
		80	187.672	2079.680	2443.200	52.580	270.803
	Mountainous	40	132.536	1738.800	2443.200	45.622	199.734
		80	356.175	2079.680	2443.200	52.580	466.736

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C.2.2. Fuel to power efficiency factor

$$ZETA = ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100} \right)}{PRAT} \right]$$

Vehicle Type	Terrain	V (km/h)	ZETA
Large Car	Flat	80	0.071
		120	0.076
	Mountainous	80	0.072
		120	0.080
Articulated Truck	Flat	40	0.057
		80	0.059
	Mountainous	40	0.058
		80	0.063

C.2.3. Instantaneous fuel consumption

$$IFC = max\left[IDLE\_FUEL, ZETA \times PTOT \times (1 + dFUEL) \right]$$ with dFuel= 1

Vehicle Type	Terrain	V (km/h)	IDLE_FUEL	ZETA	PTOT	IFC
Large Car	Flat	80	0.480	0.071	33.518	2.377
		120	0.480	0.076	64.060	4.854
	Mountainous	80	0.480	0.072	41.531	3.008
		120	0.480	0.080	86.210	6.888
Articulated Truck	Flat	40	1.120	0.057	128.887	7.307
		80	1.120	0.059	270.803	16.030
	Mountainous	40	1.120	0.058	199.734	11.583
		80	1.120	0.063	466.736	29.304

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C.2.4. Fuel consumption per vehicle-km

$$FC = \frac{IFC}{V}$$

Vehicle Type	Terrain	V (km/h)	IFC	FC
Large Car	Flat	80	2.377	0.107
		120	4.854	0.146
	Mountainous	80	3.008	0.135
		120	6.888	0.207
Articulated Truck	Flat	40	7.307	0.658
		80	16.030	0.721
	Mountainous	40	11.583	1.042
		80	29.304	1.319

C.3. Fuel Consumption: Modified Simplification vs Incorporating Aerodynamic

$$FC_{BELOW(K)} = FC1 * RI^2 + FC2 * RI + FC3$$

	Flat		Mountainous	
	Large Car	**Articulated Truck**	**Large Car**	**Articulated Truck**
Vehicle Type Number	4	4	11	11
Limiting Roughness	7.951	6.267	7.951	6.267
FC1	2.215E-07	4.968E-06	2.215E-07	4.968E-06
FC2	5.435E-04	6.777E-03	5.653E-04	7.571E-03
FC3	8.050E-02	5.069E-01	1.078E-01	1.080E+00

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With IRI=4, at 80 km/h

Vehicle Type	Terrain	Modified FC	Sensitivity FC
Large Car	Flat	0.083	0.107
	Mountainous	0.110	0.135
Articulated Truck	Flat	0.534	0.721
	Mountainous	1.110	1.319

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APPENDIX D: SENSITIVITY TO EVALUATE GRADIENT RESISTANCE TO MOTION

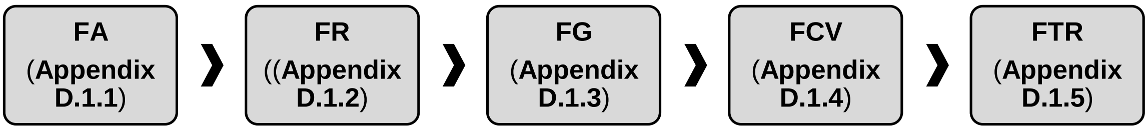
For this sensitivity the impact on Fuel consumption is evaluated in terms of the decision to evaluate all gradient resistance in motion as uphill versus calculating it for a directional split of 50:50. This is done evaluating the following eight scenarios in terms of Fuel Consumption:

Vehicle Type	Terrain	IRI
Large Car	Flat	4
Articulated Truck	Mountainous	7

D.1. RESISTANCE TO MOTION

$$FTR = FA + FG + FR + FCV$$

A schematic representation of the computational procedure is shown below.



Final substitution of variables into the above equation is presented in **Section D.1.5**.

D.1.1. Aerodynamic resistance to motion

The objective of this sensitivity analysis to evaluate the effect of Gradient and therefore Aerodynamic resistance to motion is kept unchanged in comparison to the Modified Simplification. ‘FA=0

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D.1.2. Rolling resistance to motion

Rolling resistance to motion is not dependant on terrain and therefore only IRI and Vehicle Type is considered:

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

where:

$$\begin{aligned} FCLIM &= 1 + 0.003 \times PCTDS + 0.002 \times PCTDW \\ &= 1 + 0.003 \times 0 + 0.002 \times 20 \\ &= 1 + 0 + 0.04 \\ &= 1.04 \end{aligned}$$

FCLIM is not dependant on IRI, or Vehicle Type

and (**Appendix A**, Tables E2.4 and E2.2)

Large Car (4)	Articulated Truck (11)
$b11 = CR\_B\_a0 \times WHEEL\_DIA = 37 \times 0.66 = 24.420$	$b11 = CR\_B\_a0 \times WHEEL\_DIA = 37 \times 1.050 = 38.850$
$b12 = \frac{CR\_B\_a1}{WHEEL\_DIA} = \frac{0.064}{0.66} = 0.097$	$b12 = \frac{CR\_B\_a1}{WHEEL\_DIA} = \frac{0.064}{1.050} = 0.061$
$b13 = \frac{(CR\_B\_a2 \times NUM\_WHEELS)}{WHEEL\_DIA^2} = \frac{(0.012 \times 4)}{0.660^2} = 0.110$	$b13 = \frac{(CR\_B\_a2 \times NUM\_WHEELS)}{WHEEL\_DIA^2} = \frac{(0.012 \times 18)}{1.050^2} = 0.196$

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Split FR into separate parts:

$$FR = FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2\right)$$
$$= FCLIM \times CR2 \times \left(term1 + term2 \times V^2\right)$$

where:

Large Car (4)	Articulated Truck (11)
$term1 = b11 \times NUM\_WHEELS$ $+CR1 \times b12 \times WGT\_OPER$ $= 24.420 \times 4 + 1 \times 0.097 \times 1400$ $= 233.483$	$term1 = b11 \times NUM\_WHEELS$ $+CR1 \times b12 \times WGT\_OPER$ $= 38.85 \times 18 + 1.3 \times 0.061 \times 28000$ $= 2917.967$
$term2 = CR1 \times b13$ $= 1 \times 0.110$ $= 0.110$	$term2 = CR1 \times b13$ $= 1.3 \times 0.196$ $= 0.255$

Split $CR2$ into separate parts:

$$CR2 = Kcr2 \times \left(CR\_CR2\_a0 + CR\_CR2\_a1 \times TD + CR\_CR2\_a2 \times RI\right)$$
$$= Kcr2 \times CR\_CR2\_a0 + Kcr2 \times CR\_CR2\_a1 \times TD$$
$$+Kcr2 \times CR\_CR2\_a2 \times RI$$
$$= term3 + term4 \times RI$$

(**Appendix A**, Table E2.3)

Large Car (4)	Articulated Truck (11)
$term3 = Kcr2 \times CR\_CR2\_a0 + Kcr2$ $\times CR\_CR2\_a1 \times TD$ $= 1 \times 0.9 + 1 \times 0.022 \times 1$ $= 0.922$	$term3 = Kcr2 \times CR\_CR2\_a0 + Kcr2$ $\times CR\_CR2\_a1 \times TD$ $= 1 \times 0.840 + 1 \times 0.030 \times 1$ $= 0.870$
$term4 = Kcr2 \times CR\_CR2\_a2$ $= 1 \times 0.022$ $= 0.022$	$term4 = Kcr2 \times CR\_CR2\_a2$ $= 1 \times 0.030$ $= 0.030$

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Now calculate CR2:

Large Car (4)	
IRI = 4	**IRI = 7**
$CR2 = term3 + term4 \times 4$ $= 0.922 + 0.022 \times 4$ $= 1.010$	$CR2 = term3 + term4 \times 7$ $= 0.870 + 0.022 \times 7$ $= 1.076$
Articulated Truck (11)	
IRI = 4	**IRI = 7**
$CR2 = term3 + term4 \times 4$ $= 0.870 + 0.030 \times 4$ $= 0.990$	$CR2 = term3 + term4 \times 7$ $= 0.870 + 0.030 \times 7$ $= 1.080$

Vehicle speed is taken as constant speed, in all cases it is however required to evaluate if any of these speeds will be limited by roughness.

Therefore the limiting roughness for each speed is calculated (**Appendix A**, Table E2.5):

Limiting roughness is calculated by $RI_{av} = \frac{ARVMAX}{VROUGHa0 \times V}$

Vehicle Type	**Vehicle Speed**	**Limiting Roughness (IRI)**
Large Car	80 km/h→22.222 m/s	7.943
Articulated Truck	80 km/h→22.222 m/s	6.261

From this can be seen that when considering a IRI of 7 Articulated Trucks will be limited in speed and therefore the speed will be reduced.

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Vehicle speed due to Limiting roughness is calculated by

$$V = VROUGH = \frac{ARVMAX}{VROUGHa0 \times RI_{av}} = \frac{160}{1.15 \times 7} = 19.876$$

this equated to **71.553 km/h**

Therefore even though the sensitivity is based on constant speed of 80 km per hour the Articulated Truck speed at **IRI= 7** will be **71.553km/h**

$$FR = FCLIM \times CR2 \times \left(b11 \times NUM\_WHEELS + CR1 \times b12 \times WGT\_OPER + CR1 \times b13 \times V^2\right) = 1.04 \times CR2 \times \left(term1 + term2 \times V^2\right)$$

Large Car (4)	
IRI = 4, V = 80 km/h	**IRI = 7, V = 80 km/h**
$FR = 1.04 \times CR2 \times (term1 + term2 \times V^2) = 1.04 \times 1.010 \times (233.438 + 0.110 \times 22.22^2) = 302.362$	$FR = 1.04 \times CR2 \times (term1 + term2 \times V^2) = 1.04 \times 1.076 \times (233.438 + 0.110 \times 22.22^2) = 322.120$
Articulated Truck (11)	
IRI = 4, V = 80 km/h	**IRI = 7, V = 71.553km/h**
$FR = 1.04 \times CR2 \times (term1 + term2 \times V^2) = 1.04 \times 0.990 \times (2917.967 + 0.255 \times 22.22^2) = 3133.836$	$FR = 1.04 \times CR2 \times (term1 + term2 \times V^2) = 1.04 \times 1.080 \times (2917.967 + 0.255 \times 19.876^2) = 3390.472$

Vehicle Type	IRI	Vehicle Speed (km/h)	FR
Large Car	4	80	302.362
	7	80	322.120
Articulated Truck	4	80	3133.836
	7	71.553	3390.472

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D.1.3. Gradient resistance to motion

$$FG = WGT\_OPER \times g \times GR$$

where:

$$\begin{aligned} FG &= WGT\_OPER \times g \times GR \\ &= WGT\_OPER \times g \times \frac{RF}{1000} \\ &= WGT\_OPER \times 9.81 \times \frac{RF}{1000} \end{aligned}$$

(**Appendix A**):

Large Car (4)	
Flat	**Mountainous**
$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 1400 \times 9.81 \times \frac{10}{1000}$ $= 137.34$	$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 1400 \times 9.81 \times \frac{30}{1000}$ $= 412.02$
Articulated Truck (11)	
Flat	**Mountainous**
$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 28000 \times 9.81 \times \frac{10}{1000}$ $= 2746.80$	$FG = WGT\_OPER \times g \times GR$ $= WGT\_OPER \times g \times \frac{RF}{1000}$ $= 2800 \times 9.81 \times \frac{30}{1000}$ $= 8240.4$

FG is not dependent on speed.

Vehicle Type	Terrain	FG	FG_{uphill}	$FG_{Downhill}$
Large Car	Flat	137.34	68.67	-68.67
	Mountainous	412.02	206.01	-206.01
Articulated Truck	Flat	2746.8	1373.4	-1373.4
	Mountainous	8240.4	4120.2	-4120.2

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D.1.4. Curvature resistance to motion

$$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEEL \times CS \times 1000}\right]$$

where (**Appendix A**, Table E2.7)

$$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS}\right)^2\right]$$

Large Car (4)	Articulated Truck (11)
$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS}\right)^2\right]$ $= 1 \times \left[43 + \frac{0 \times 1400}{4} + 0 \times \left(\frac{1400}{4}\right)^2\right]$ $= 43$	$CS = Kcs \times \left[CS\_a0 + \frac{CS\_a1 \times WGT\_OPER}{NUM\_WHEELS} + CS\_a2 \times \left(\frac{WGT\_OPER}{NUM\_WHEELS}\right)^2\right]$ $= 1 \times \left[8.8 + \frac{0.088 \times 28000}{18} + 0 \times \left(\frac{28000}{18}\right)^2\right]$ $= 91.244$

$$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C\right)}$$

(**Appendix A**):

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Terrain	e	
Flat	2.5/100	$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C\right)} = \frac{180000}{\pi \times max(5.730, 15)} = 3819.719$
Mountainous	5/100	$R = \frac{180000}{\pi \times max\left(\frac{18}{\pi}, C\right)} = \frac{180000}{\pi \times max(5.730, 300)} = 190.986$

thus:

Large Car (4)
$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEELS \times CS \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$
Articulated Truck (11)
$FCV = max\left[0, \frac{\left(\frac{WGT\_OPER \times V^2}{R} - WGT\_OPER \times g \times e\right)^2}{NUM\_WHEELS \times CS \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000 \times V^2}{R} - 28000 \times 9.81 \times e\right)^2}{18 \times 91.244 \times 1000}\right]$

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Large Car (4)		
V	**Flat**	**Mountainous**
80 km/h	$FCV = max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times 22.222^2}{3819.719} - 1400 \times 9.81 \times \left(\frac{2.5}{100}\right)\right)^2}{4 \times 43 \times 1000}\right]$ $= max[0, 0.153]$ $= 0.153$	$FCV = max\left[0, \frac{\left(\frac{1400 \times V^2}{R} - 1400 \times 9.81 \times e\right)^2}{4 \times 43 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{1400 \times 22.222^2}{190.986} - 1400 \times 9.81 \times \left(\frac{5}{100}\right)\right)^2}{4 \times 43 \times 1000}\right]$ $= max[0, 50.023]$ $= 50.023$

Articulated Truck (11)		
V	**Flat**	**Mountainous**
80 km/h	$FCV = max\left[0, \frac{\left(\frac{28000 \times V^2}{R} - 28000 \times 9.81 \times e\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000 \times 22.222^2}{3819.719} - 28000 \times 9.81 \times \left(\frac{2.5}{100}\right)\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max[0, 6.419]$ $= 6.419$	$FCV = max\left[0, \frac{\left(\frac{28000 \times V^2}{R} - 28000 \times 9.81 \times e\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000 \times 22.222^2}{190.986} - 28000 \times 9.81 \times \left(\frac{5}{100}\right)\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max[0, 2095.448]$ $= 2095.448$
71.553 km/h	$FCV = max\left[0, \frac{\left(\frac{28000 \times V^2}{R} - 28000 \times 9.81 \times e\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000 \times 19.876^2}{3819.719} - 28000 \times 9.81 \times \left(\frac{2.5}{100}\right)\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max[0, 9.602]$ $= 9.602$	$FCV = max\left[0, \frac{\left(\frac{28000 \times V^2}{R} - 28000 \times 9.81 \times e\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max\left[0, \frac{\left(\frac{28000 \times 19.876^2}{190.986} - 28000 \times 9.81 \times \left(\frac{5}{100}\right)\right)^2}{18 \times 91.244 \times 1000}\right]$ $= max[0, 1188.580]$ $= 1188.580$

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Thus

Vehicle Type	Terrain	IRI	V (km/h)	FCV
Large Car	Flat	4 & 7	80	0.153
	Mountainous			50.023
Articulated Truck	Flat	4	80	6.419
		7	71.533	9.602
	Mountainous	4	80	2095.448
		7	71.533	1188.580

D.1.5. Final Substitution: Resistance to motion

$FTR = FA + FG + FR + FCV$ with

From all the above FA =0 and

Vehicle Type	Terrain	IRI	V (km/h)	FG_{uphill}	$FG_{Downhill}$	FR up and down	FCV up and down
Large Car	Flat	4	80	137.340	-137.340	302.362	0.153
		7	80	137.340	-137.340	322.120	0.153
	Mountainous	4	80	412.020	-412.020	302.362	50.023
		7	80	412.020	-412.020	322.120	50.023
Articulated Truck	Flat	4	80	2746.800	-2746.800	3133.836	6.419
		7	71.553	2746.800	-2746.800	3390.472	9.602
	Mountainous	4	80	8240.400	-8240.400	3133.836	2095.448
		7	71.553	8240.400	-8240.400	3390.472	1188.580

Vehicle Type	Terrain	IRI	V (km/h)	FTR_{uphill}	$FTR_{Downhill}$
Large Car	Flat	4	80	439.855	165.175
		7	80	322.273	184.933
	Mountainous	4	80	352.384	-59.636
		7	80	372.143	-39.877
Articulated Truck	Flat	4	80	3140.256	393.456
		7	71.553	3400.074	653.274
	Mountainous	4	80	5229.284	-3011.116
		7	71.553	4579.052	-3661.348

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D.2. FUEL CONSUMPTION

Similar to Chapter 5 the calculation process for Fuel Consumption (**Section .2.4**):

FTR (Appendix D.1.5) › **PTR** › **PTOT (Appendix D.2.1)** › **ZETA (Appendix D.2.2)** › **IFC (Appendix D.2.3)** › **V** › **SFC** › **FC (Appendix D.2.4)**

D.2.1. Total power requirements of the engine

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS \right) \quad \text{where} \qquad PTR = \frac{FTR \times V}{1000}$$

Vehicle Type	Terrain	IRI	V (km/h)	FTR_{uphill}	$FTR_{Downhill}$	PTR_{uphill}	$PTR_{Downhill}$
Large Car	Flat	4	80	439.855	165.175	9.775	3.671
		7	80	322.273	184.933	7.162	4.110
	Mountainous	4	80	352.384	-59.636	7.831	-1.325
		7	80	372.143	-39.877	8.270	-0.886
Articulated Truck	Flat	4	80	3140.256	393.456	69.783	8.743
		7	71.553	3400.074	653.274	67.579	12.984
	Mountainous	4	80	5229.284	-3011.116	116.206	-66.914
		7	71.553	4579.052	-3661.348	91.012	-72.772

and (**Appendix A**, Table E2.8):

$$PENGACCS = Kpea \times PRAT \times \left[PACCS\_a1 + \frac{(PACS\_a0 - PACCS\_a1)(RPM - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \right]$$

and

$$RPM = RPM\_a0 + RPM\_a1 \times 3.6V + RPM\_a2 \times (3.6V)^2 + RPM\_a3 \times (3.6V)^3$$

and

$$RPM100 = RPM\_a0 + RPM\_a1 \times 100 + RPM\_a2 \times (100)^2 + RPM\_a3 \times (100)^3$$

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thus the result of combining the above:

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS \right)$$

Vehicle Type	Terrain	IRI	V (km/h)	PTR_{uphill}	$PTR_{Downhill}$	RPM	RPM100
Large Car	Flat	4	80	9.775	3.671	2197.440	2606.900
		7	80	7.162	4.110	2197.440	2606.900
	Mountainous	4	80	7.831	-1.325	2197.440	2606.900
		7	80	8.270	-0.886	2197.440	2606.900
Articulated Truck	Flat	4	80	69.783	8.743	2079.680	2443.200
		7	71.553	67.579	12.984	1965.111	2443.200
	Mountainous	4	80	116.206	-66.914	2079.680	2443.200
		7	71.553	91.012	-72.772	1965.111	2443.200

and

Vehicle Type	Terrain	IRI	V (km/h)	PENGACCS	$PTOT_{uphill}$	$PTOT_{Downhill}$
Large Car	Flat	4	80	15.538	26.399	19.616
		7	80	15.538	23.495	20.104
	Mountainous	4	80	15.538	24.239	14.066
		7	80	15.538	24.727	14.553
Articulated Truck	Flat	4	80	52.580	133.724	62.747
		7	71.553	50.241	128.822	65.339
	Mountainous	4	80	52.580	187.704	-25.227
		7	71.553	50.241	156.070	-34.377

D.2.2. Fuel to power efficiency factor

$$ZETA = ZETAB \times \left[1 + \frac{EHP \times \left(PTOT - \frac{PCTPENG \times PENGACCS}{100} \right)}{PRAT} \right]$$

Vehicle Type	Terrain	IRI	V (km/h)	$ZETA_{uphill}$	$ZETA_{Downhill}$
Large Car	Flat	4	80	0.070	0.068
		7	80	0.069	0.068
	Mountainous	4	80	0.069	0.067
		7	80	0.069	0.067
Articulated Truck	Flat	4	80	0.057	0.055
		7	71.553	0.057	0.055
	Mountainous	4	80	0.058	0.054
		7	71.553	0.057	0.054

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D.2.3. Instantaneous fuel consumption

$IFC = max\left[IDLE\_FUEL, ZETA \times PTOT \times (1 + dFUEL)\right]$ with dFuel= 1

Vehicle Type	Terrain	IRI	V (km/h)	IDLE_FUEL	IFC_{uphill}	$IFC_{Downhill}$
Large Car	Flat	4	80	0.480	1.837	1.804
		7	80	0.480	1.623	1.608
	Mountainous	4	80	0.480	1.677	1.631
		7	80	0.480	1.713	1.666
Articulated Truck	Flat	4	80	1.120	7.580	7.405
		7	71.553	1.120	7.295	7.145
	Mountainous	4	80	1.120	10.825	10.092
		7	71.553	1.120	8.915	8.370

D.2.4. Fuel consumption per vehicle-km

$$FC = \frac{IFC}{V}$$

Vehicle Type	Terrain	IRI	V (km/h)	FC_{uphill}	$FC_{Downhill}$	FC
Large Car	Flat	4	80	0.083	0.081	0.082
		7	80	0.073	0.072	0.073
	Mountainous	4	80	0.075	0.073	0.074
		7	80	0.077	0.075	0.076
Articulated Truck	Flat	4	80	0.341	0.333	0.337
		7	71.553	0.367	0.359	0.363
	Mountainous	4	80	0.487	0.454	0.471
		7	71.553	0.449	0.421	0.435

D.3. Fuel Consumption: Modified Simplification vs Incorporating Aerodynamic

$$FC_{BELOW(K)} = FC1 * RI^2 + FC2 * RI + FC3$$

$$FC_{ABOVE(K)} = FC4 * RI + FC5 + \frac{FC6}{RI} + \frac{FC7}{RI^2} + \frac{FC8}{RI^3} + \frac{FC9}{RI^4} + \frac{FC10}{RI^5} + \frac{FC11}{RI^6} + \frac{FC12}{RI^7} + \frac{FC13}{RI^9}$$

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

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	Flat		**Mountainous**	
	Large Car	Articulated Truck	Large Car	Articulated Truck
Vehicle Type Number	4	11	4	11
Limiting Roughness	7.951	6.267	7.951	6.267
FC1	2.215E-07	4.968E-06	2.215E-07	4.968E-06
FC2	5.435E-04	6.777E-03	5.653E-04	7.571E-03
FC3	8.050E-02	5.069E-01	1.078E-01	1.080E+00
FC4	5.718E-03	2.536E-02	5.718E-03	2.536E-02
FC5	1.147E-02	3.149E-01	3.415E-02	6.822E-01
FC6	2.175E-01	4.089E-01	2.265E-01	7.098E-01
FC7	1.230E-01	3.663E-01	1.800E-02	-2.563E+00
FC8	9.279E-02	1.547E-01	3.800E-02	-3.081E+00
FC9	2.084E-01	8.891E-01	2.475E+01	3.219E+02
FC10	5.879E-02	4.780E-01	1.353E+01	3.650E+02
FC11	1.118E-01	2.573E-01	4.473E+01	1.029E+02
FC12	6.680E-02	3.305E-01	-2.120E+01	-1.433E+03
FC13	2.554E-02	5.183E-01	4.087E+03	8.293E+04

Vehicle Type	**Terrain**	**IRI**	**V (km/h)**	**Modified FC**	**FC Sensitivity**
Large Car	Flat	4	80	0.083	0.082
		7	80	0.084	0.073
	Mountainous	4	80	0.111	0.074
		7	80	0.113	0.076
Articulated Truck	Flat	4	80	0.534	0.337
		7	71.553	0.555	0.363
	Mountainous	4	80	1.143	0.471
		7	71.553	1.166	0.435