

CONTRACT REPORT

Technical Basis for Estimating the Incremental Cost Impact on Sealed Local Roads from Additional Freight Tasks

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for Western Australian Local Government
Association (WALGA)

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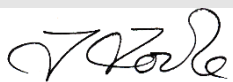
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SUMMARY

A key consideration for Local Governments (LG) in Western Australia is the impact of heavy vehicles on local roads, and the associated cost of road wear. Increasingly over time, there has been greater utilisation of local roads by more significant axle loads. This has had a direct impact on the condition of the roads concerned and, as a consequence, Local Governments are facing significant increases in costs from road wear. In particular, there have been unforeseen increased volumes of heavy and extra-heavy vehicles operated by the freight industry and as a result of resource developments.

The impact of heavy vehicles on shortening road life and increasing maintenance requirements is greater for roads that were not designed and constructed for this intended use, which encompasses many Local Government road networks.

In order to address this challenge, Local Governments have long been seeking mechanisms to quantify the cost of road wear to aid them in effectively negotiating compensation from industry operators. Various methods have been identified previously, and following review of the available methods, a nationally accepted method was chosen. The adopted method captures the performance impacts and full life-cycle costs of maintaining and rehabilitating road infrastructure over an extended period and employs marginal cost principles.

This report provides the technical basis for estimating the incremental cost impact on sealed local roads from additional freight tasks. It also describes a simple catalogue-based approach to determining an applicable estimated cost of road wear to end users which has been published in a stand-alone User Guide by WALGA.

The report details:

- related background and exploratory studies
- the critical variables and models examined in the development of a working model, and the basis for their selection
- the development of a representative road network and a simulation model aimed at producing simple, but sufficiently robust solutions
- the steps involved in generating a catalogue using modelling techniques, including the basis for selection of a suitable analysis tool, and how it was applied to develop the catalogue of charts.

Recommendations are also presented aimed at addressing the needs of unsealed roads and asphalt surfaced pavements, and improving the basis for application across a greater variety of road conditions in WA. This is particularly relevant where conditions differ from the main assumptions used in this study.

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1 INTRODUCTION

1.1 Background

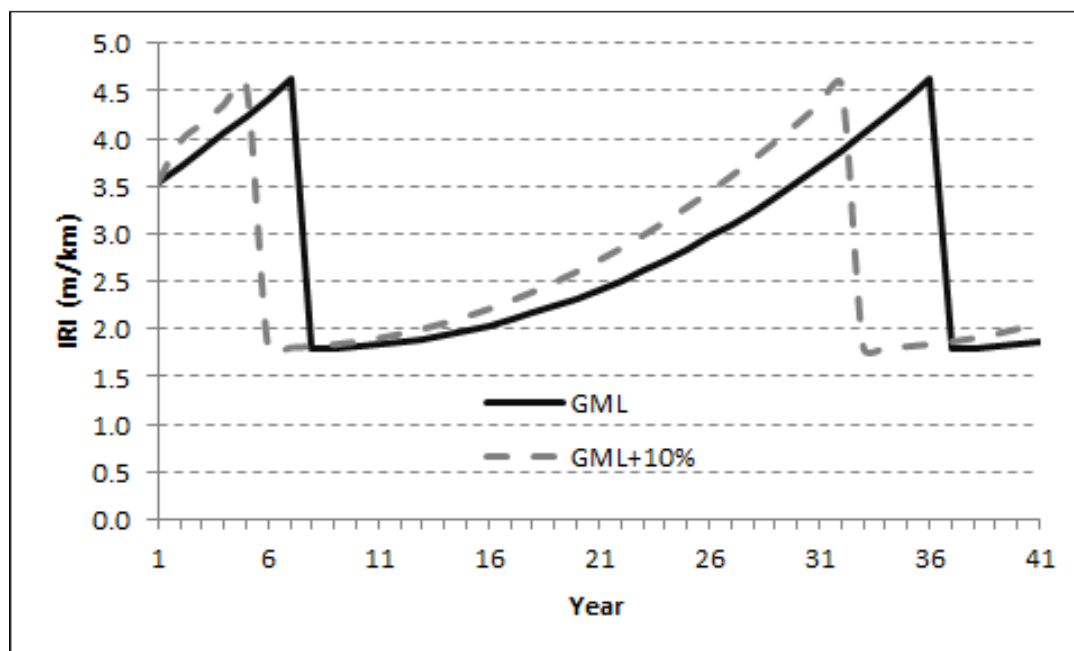
A key consideration for Local Governments (LG) in Western Australia is the impact of heavy vehicles on local roads, and the associated cost of road wear. Increasingly over time, there has been greater utilisation of local roads by more significant axle loads. This has had a direct impact on the condition of the roads concerned, and as a consequence, Local Governments are facing significant increases in costs from road wear. In particular, there have been unforeseen increased volumes of heavy and extra-heavy vehicles operated by the freight industry and as a result of resource developments. The impact of heavy vehicles on shortening road life and increasing maintenance requirements is greater for roads that were not designed and constructed for this intended use, which encompasses many Local Government road networks.

In order to address this challenge, Local Governments have long been seeking mechanisms to quantify the cost of road wear to aid them in effectively negotiating compensation from industry operators. Various methods have been identified by Local Government to evaluate the cost of road wear. These include routine maintenance determination, evidence-based reporting, pavement design approaches, and the evaluation of single marginal costs. However, it is recognised that these methods often require expensive pavement analysis, detailed input data, and involve specialist engineering evaluation and modelling skills, which are not readily available to many Local Governments. Furthermore, they are not consistent with methods developed and adopted nationally to estimate load-related impacts on the cost of maintaining road infrastructure. These latter approaches are based on the use of deterministic pavement performance models which estimate the mean-expected future condition in relation to specific inputs, such as the composition and strength of the road, current and future traffic, climate and the maintenance regime.

The national method is also based on marginal cost principles, this having been widely accepted at an Australian Government, State and Local Government level as a reasonable basis for cost attribution. This is because it aims to capture the performance impacts and full life-cycle costs of maintaining and rehabilitating road infrastructure over an extended period as illustrated in Figure 1.1. This illustration is typical of a long-term policy change such as allowing a change from gross mass limits to higher mass limits or a concessional loading arrangement.

However, the actual loading patterns experienced by Local Government are often concentrated in time and may be an order of magnitude higher than the current rate of loading. This therefore required adaptation of the method so that it was sufficiently flexible to address the variety of circumstances likely to be experienced by local roads.

Figure 1.1: Impact of increasing axle load on rehabilitation intervention timing



Source: Austroads (2012).

1.2 Definition of the Marginal Cost of Road Wear and Influencing Factors

The marginal cost of road wear is defined as the difference in the cost of maintaining a road in a serviceable condition arising from an increase in traffic loading above current or base traffic. Algebraically, it is the rate of change of the cost resulting from the incremental change (increase) in the freight task.

Analysis has shown that the marginal cost is mostly dependent on the magnitude and duration of the additional load, the structural strength of the road and its variation, and the additional cost of road maintenance activities to fulfil performance requirements.

Consequently, a standard marginal cost based on a network average for all roads is inadequate compensation for the majority of Local Government roads that have relatively weak structures in relation to the additional traffic loads they may be subjected to, and in comparison to freeways and highways which are designed, built and maintained to higher standards.

1.3 Development of a Method for use by Local Government

Following initial exploratory work in 2013 and 2014¹, ARRB Group (ARRB) was engaged by WALGA to develop a method to calculate the cost of road wear arising from additional heavy vehicle usage/loading on sealed roads by adapting the national approach (Austroads 2012a). The method was required to be simple in design to enable it to be applied to a range of industry tasks on different classes of Local Government sealed roads by asset management practitioners. A fundamental requirement of the method was that it should allow for the full life cycle costs arising

¹ In 2013, an initial pilot study was conducted to determine the marginal costs for three typical road structures, and to identify the critical factors required for development of a comprehensive catalogue of marginal costs (Hore-Lacy & Burger 2013). Many of the selected parameters were based on previous work undertaken for WALGA as part of the ROMAN II project (ARRB 2012).

from the additional loads to be evaluated, thus providing the LG the possibility of maintaining the road in a serviceable state without detriment to other road users. The model therefore employs the analytical framework adopted in HDM-4, the PIARC/World Road Association supported highway development and management suite of tools and knowledge base (PIARC 2006) and other cost-benefit analysis based tools.

Accounting for the above critical variables, a catalogue of marginal unit cost estimates for typical local roads in Western Australia was developed to inform Local Governments in negotiations with developers, the resource industry and freight operators. The catalogue covers a set of different scenarios based on a hypothetical network representing typical pavement structures and conditions across the state.

The marginal cost for each scenario was modelled using a set of evidence-based deterministic performance models and typical intervention strategies used in road asset management. Therefore, by applying life-cycle cost principles, this approach estimated the agency costs associated with the different loading scenarios modelled. The calculations were performed in the custom software tool, the Freight and Axle Mass Limits Investigation Tool (FAMLIT), developed by ARRB, with the outputs used to compile a catalogue of marginal cost estimates for typical Western Australian Local Government pavements and loading scenarios.

1.4 Purpose and Contents of this Document

This document is the technical basis for the *Estimating the Incremental Cost Impact on Sealed Local Roads from Additional Freight Tasks* (WALGA 2015). The Guide presents a method for estimating the cost of road wear for sprayed seal granular pavements using simple input parameters and local knowledge. The Guide is structured according to a simple stepped process to assist users in selecting the most appropriate combination of parameters, and to determine an applicable road wear cost for additional loading on defined routes. Users of the Guide require a basic understanding of the Western Australian road classification system and the vehicles operating on the network. The Guide can also assist users in the selection of appropriate parameters based on the situation and freight task, and contains a number of worked examples to aid the user in its application.

This document therefore provides a technical summary of the key elements of the developed catalogue, and discusses the critical variables, the assembly of the analysis network and main results of the study which informed its creation. Further information can also be obtained from the Guide, and related technical documents. It is noted that this analysis does not extend to estimating the cost of additional heavy vehicle traffic on unsealed roads, as this was outside the scope of the work performed to date.

Following the Introduction, the report is structured as follows:

- Section 2, *Description of the catalogue of marginal costs and the calculation process*, describes the aims and objectives of the catalogue (and Guide), and summarises the process for calculating the cost of road wear on local roads.
- Section 3, *Development of the catalogue*, summarises the background and exploratory studies that informed the creation of the catalogue, and the main tasks in its completion.
- Section 4, *Critical variables and models*, details the effect of key variables and the basis for selection of the models applied.
- Section 5, *Development of a representative road network and simulation model*, details the definition and population of the network attributes and the components of the process adopted in the network simulation model.

- Section 6, *Generating a catalogue using modelling techniques*, describes the basis for selection of an analysis tool, and how it was applied to develop the required results, including the creation of the catalogue of charts.
- Section 5, *Recommendations*, with these addressing possible widening of the scope of the solutions investigated, and application to other circumstances.

The report is accompanied by Appendix A which contains graphical outputs of marginal costs by cost zone.

2 DESCRIPTION OF THE CATALOGUE OF MARGINAL COSTS AND THE CALCULATION PROCESS

2.1 Aims and Objectives of the Catalogue

The principal aim of providing a catalogue is to provide Local Governments with a simple, robust and transparent means of determining an applicable cost of road wear to end users which represents the costs of additional pavement wear for a wide range of scenarios comprising different loading tasks applied to different parts of the road network.

The objectives the catalogue was designed to support included:

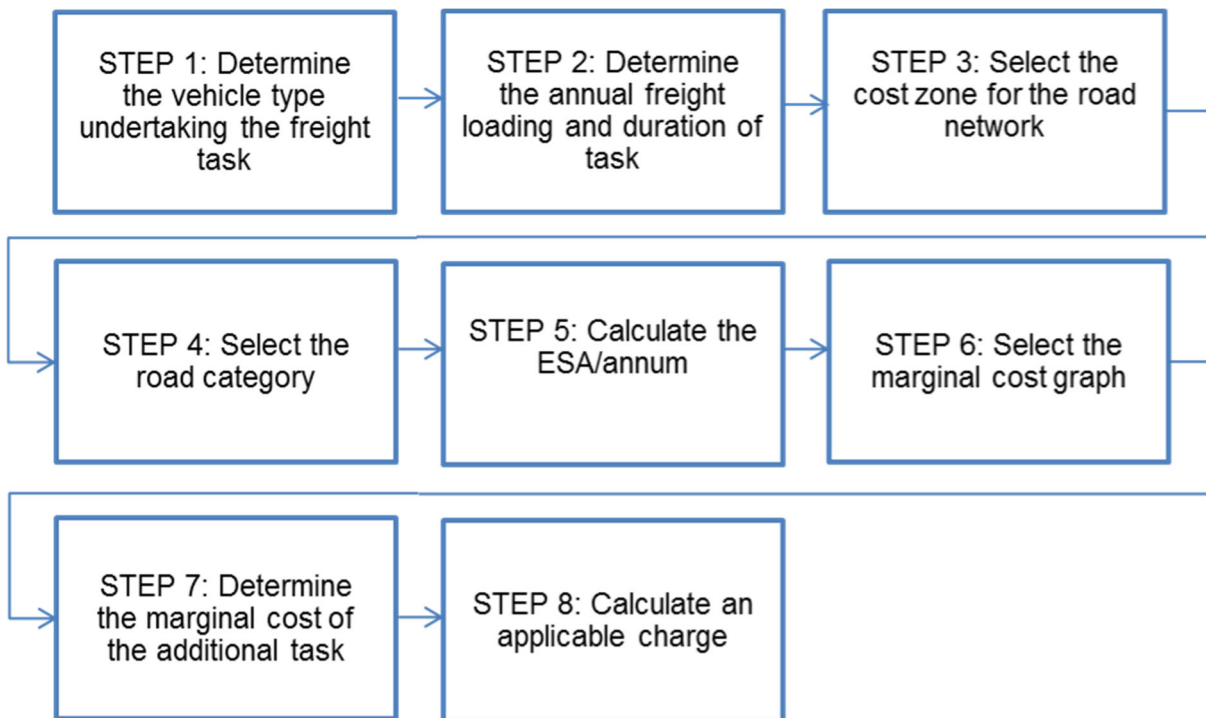
1. Develop a simple, user-friendly methodology for calculating the cost of road wear on sealed local roads using a marginal cost approach.
2. Investigate and develop a set of variables and loadings representative of the range of scenarios likely to be encountered on local roads in WA.
3. Develop a model to calculate the marginal cost of road wear for the range of developed variables and scenarios.
4. Use the model to generate a catalogue of marginal costs representative of the local road scenarios in WA.
5. Incorporate the results into a User Guide to enable easy calculation for the cost of road wear for a range of scenarios.

Underpinning the generation of the catalogue is an analytical framework built into a specific tool, namely FAMLIT (Hassan et al. 2008), which applies life cycle cost principles, with a set of evidence-based performance models, typical intervention strategies, and other input assumptions to inform the generation of marginal costs for the different scenarios represented in the catalogue.

2.2 Process for Calculating the Cost of Road Wear on Local Roads

The process to calculate the cost of road wear is described in detail in the accompanying User Guide (WALGA 2015), which also contains a series of typical worked examples to further assist users. It involves eight simple steps as set out in Figure 2.1.

Figure 2.1: Calculation process to determine the cost of road wear



Source: WALGA (2015).

2.2.1 Vehicle Type and Loading (Steps 1 and 2)

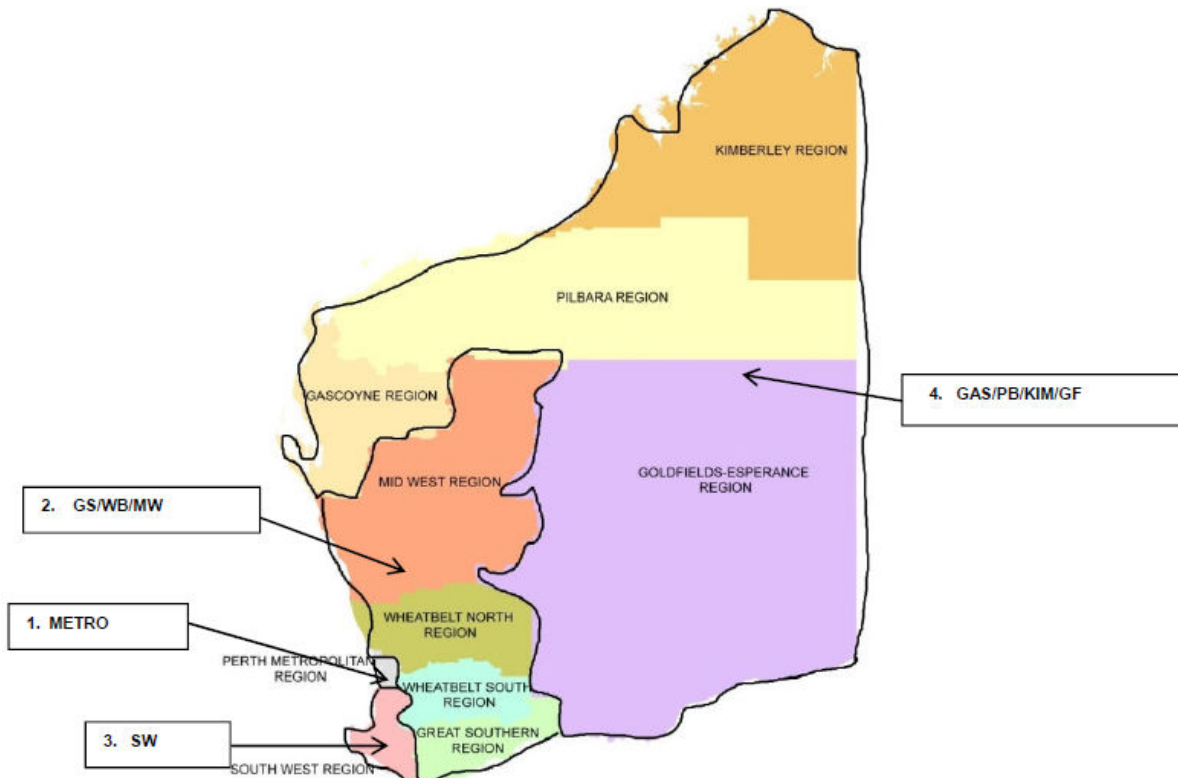
The first step in the method is to obtain information from the industry operator on the type of vehicles to be used, how they will be loaded and the total tonnage of the task. The vehicles may be either carrying the maximum legal load or they may be carrying additional load. A fully loaded vehicle is defined as the maximum legal load so that the vehicle is at the regulation mass limits (RML) as prescribed by Main Roads Western Australia. A concessional load is defined as a vehicle that is loaded with an additional 3.5 t per tri-axle combination or an additional 1.0 t per tandem axle combination in accordance with the Accredited Mass Management Scheme (AMMS) (Peters 2004).

2.2.2 Selecting the Cost Zone (Step 3)

This involves selecting one of the four cost zones (Figure 2.2) surveyed by the Department of Local Government in 2011 and determined to have different unit rates for construction and maintenance. The rates have been escalated to 2015 for use in the analysis tool.

Unit costs (per sq.m.) were supplied for routine maintenance, reseal, overlay and reconstruction activities for each of the four road classes in each cost zone. Costs are highest in Zone 4 and lowest in Zone 3, with the range of costs varying depending on the treatment, with routine maintenance costs showing the highest variation (around 30%) and larger-scale works showing a smaller variation (around 10%).

Figure 2.2: Western Australian cost zones



2.2.3 Selecting the road category (Step 4)

Four road categories are defined, based on the Main Roads classification system and every local road will fall into one of these categories, namely:

- access road
- local distributor
- regional distributor
- district distributor.

Because of the differences in their construction and the standards of maintenance applied, the performance of each road category varies with lower-order roads being particularly at risk from increased loading, and therefore this impacts the marginal cost. Consequently, users need to determine the exact route associated with a particular task and to account for its composition in order to compute a cost estimate.

2.2.4 Calculating the Equivalent Standard Axles (Step 5)

Once the industry task has been identified and the vehicle types, quantity and loading scenarios are known, this information is used to calculate the quantity of equivalent standard axles (ESA) or standard axle repetitions (SAR) that will be generated by the total transport task under consideration.

A standard axle is defined as a single axle with two sets of dual tyres (SADT) carrying a total load of 80 kN (8.2 tonnes). The loading scenarios for other axle configurations resulting in the same

damage as a standard axle have been defined. These loading scenarios are used in the calculation of the total number of ESA per heavy vehicle.

ESA are calculated using the formula outlined in Equation 1:

$$ESA = \left(\frac{\text{Load on Axle Group}}{\text{Standard load}} \right)^m \tag{1}$$

For granular pavements with a thin bituminous surfacing, the damage exponent, m, has been derived from field studies of pavement performance to be equal to 4. Higher exponents are relevant for other types of pavements and failure modes (Austroads 2012a).

The standard load is the load that is equivalent to a single ESA, which is 8.15 tonnes for an SADT. The standard load is different for other axle configurations as shown in Table 2.1.

Table 2.1: Axle group loads that cause the same damage as a standard axle

Axle group type	Standard load (kN)	Standard load (t)
Single axle with single tyres (SAST)	53	5.40
Single axle with dual tyres (SADT)	80	8.15
Tandem axle with single tyres (TAST)	90	9.17
Tandem axle with dual tyres (TADT)	135	13.76
Tri-axle with dual tyres (TRDT)	181	18.45
Quad-axle with dual tyres (QADT)	221	22.53

Source: Austroads (2010).

The total ESA contribution from a specific vehicle configuration also varies based on its payload and how this is distributed, and the characteristics of the pavement. The examples below are for a pocket road train (Figure 2.3) loaded at the regulation mass limit (Table 2.2) and then at the concessional limit (Table 2.3).

Figure 2.3: Prime mover and semi-trailer towing a dog trailer (pocket road train), length 27.5 m



Source: Bondiotti et al. (2014).

A comparison of the total ESA in Table 2.2 and Table 2.3 shows the exponential effect caused by the damage factor in the ESA formula, where an 8.3% increase in load generates a 27.9% increase in ESA.

Table 2.2: ESA calculation for fully loaded pocket road train under RML

Axle group	Mass limit on axle group (t)	Standard Load for axle group (t)	ESA
1: TAST	11.0	9.17	2.07
2: TADT	16.5	13.76	2.07
3: TRDT	20.0	18.45	1.38
4: TADT	16.5	13.76	2.07
5: TRDT	20.0	18.45	1.38
Total	84.0		8.97

Source: Bondiotti et al (2014).

Table 2.3: ESA calculation for a fully loaded pocket road train under AMMS

Axle group	Concessional load limit on axle group (t)	Standard Load for axle group (t)	ESA
1: TAST	11.0	9.17	2.07
2: TADT	16.5	13.76	2.07
3: TRDT	23.5	18.45	2.63
4: TADT	16.5	13.76	2.07
5: TRDT	23.5	18.45	2.63
Total	91.0		11.47

Source: Bondiotti et al (2014).

To assist practitioners in the calculation of the total ESA for a transport task, a series of graphs have been developed for typical heavy vehicles and loading scenarios, including:

- Figure 2.4 which can be used to supply the ESA per payload tonne for different vehicles loaded in accordance with RML or AMMS.
- Figure 2.5 which can be used to calculate the total ESA per payload tonne for different vehicles loaded to different levels – for zero load, 50% of maximum load, maximum RML load and maximum AMMS load.

Figure 2.4: ESA per payload tonne for different vehicle types and loading schemes

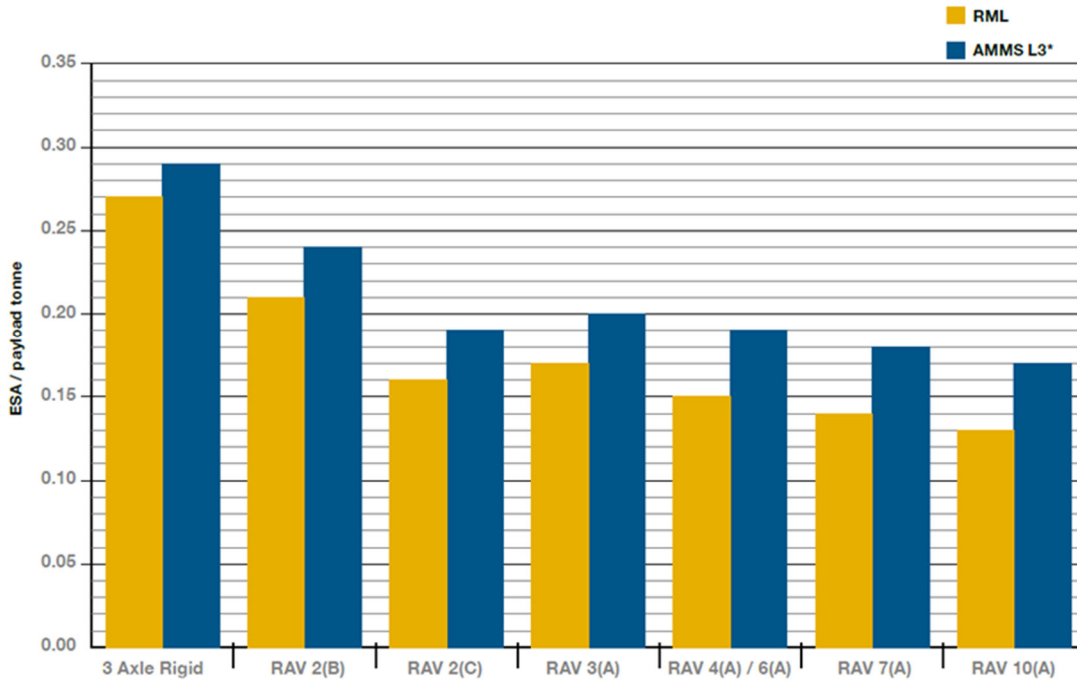
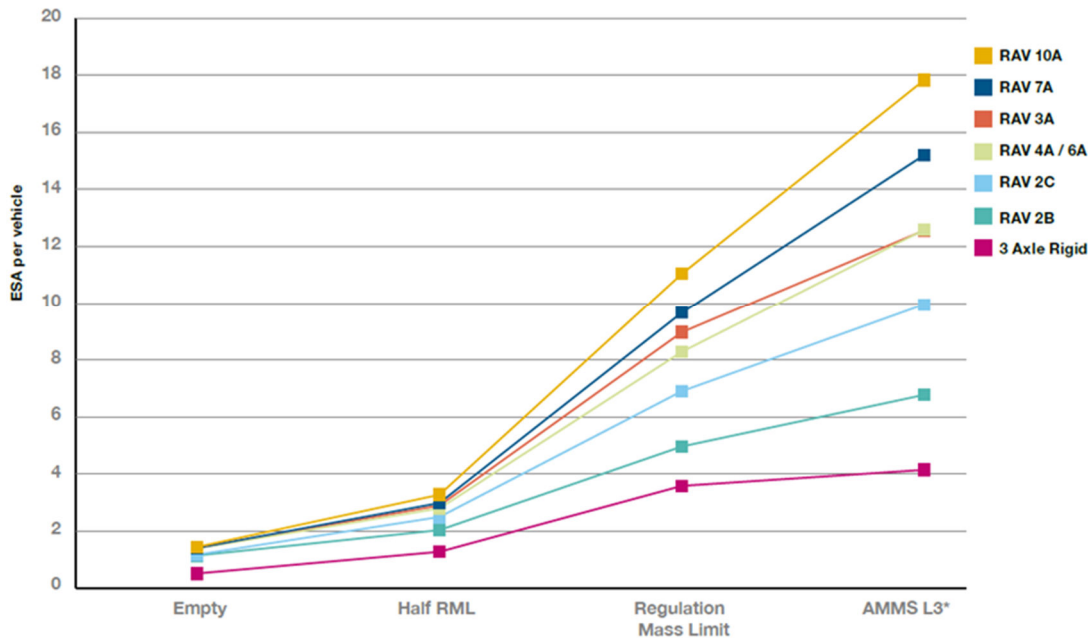


Figure 2.5: ESA per payload tonne



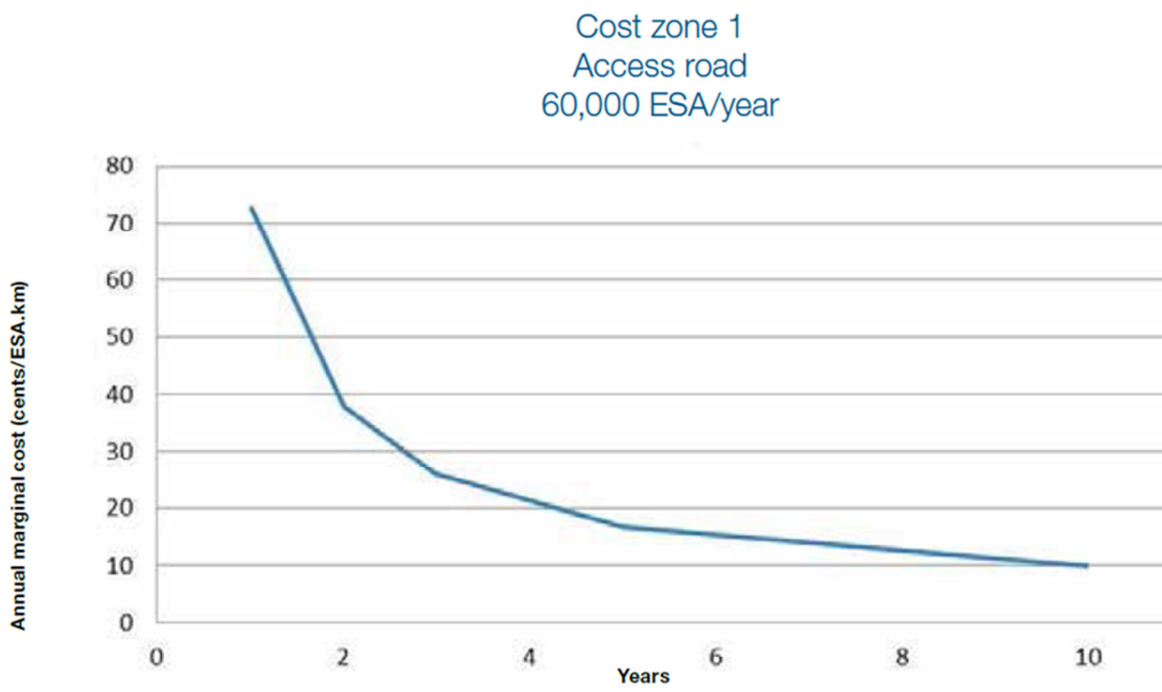
2.2.5 Determining an Appropriate Estimated Cost of Road Wear (Steps 6 to 8)

The final steps comprise:

- Step 6, involving the selection of an appropriate marginal cost from the catalogue of charts. The chart is selected based on the characteristics of the case study, i.e. cost zone, road class, annual loading and loading duration, and specific values are read off (Figure 2.6). A total of 64 output charts are supplied in the User Guide (WALGA 2015) representing four cost zones, four road categories and four loading scenarios. Users must select the chart or charts that are relevant to the scenario that is being assessed.
- Step 7, involving determining the marginal cost of the additional task by reading the annual marginal cost from the chart (e.g. Figure 2.6) based on the duration of loading.
- Step 8, calculating an applicable estimated cost of road wear for each representative road section based on Equation 2, and calculating the total estimated cost as the sum of all sections representing the route.

$$\text{Annual cost} = \text{annual marginal cost} \times \text{ESA per year} \times \text{distance} \quad 2$$

Figure 2.6: Example chart of estimated marginal costs



3 DEVELOPMENT OF THE CATALOGUE

3.1 Background and Exploratory Studies

The development of the catalogue was informed by a series of exploratory studies, these building on previous work in this area and associated studies and knowledge of the performance of road pavements and road management strategies.

The primary work which inspired this study was undertaken by Austroads and the National Transport Commission, which was used to inform deliberations on heavy vehicle road pricing reform in Australia (Austroads 2012b). This led to the development of an operational tool for use by Austroads members (Austroads 2014) building on the earlier work by Michel and Toole (2005) and by Hassan et al. (2008). Exploratory studies of the application of marginal costs have also been performed in Queensland as part of a network wide (Hore-Lacy et al. 2012; Toole & Sen 2014), and this provided further insight on the key determinants of the marginal cost of road wear and the variation in input data and range of costs.

Whereas the above studies explored and applied methodologies to estimate the marginal cost of road wear, analysis was only possible because of the availability of evidence-based road performance models and associated data. This includes those available from the Australia-wide Austroads Long Term Pavement Performance (LTPP) studies (Austroads 2010a; Austroads 2010b), the Australian Local Government sponsored Local Roads Deterioration Study (LRDS) (Martin et al. 2013), the Austroads-funded Accelerated Loading Facility (ALF) studies, and studies of the performance of sprayed (bituminous) seals (Martin et al. 2004; Oliver 2006). The LTPP, LRDS and ALF studies have been shown to be particularly important because they have produced models which are sensitive to pavement loading and the timing of maintenance and/or pavement rehabilitation and strengthening, and are therefore of high relevance to the subject of this report.

The exploratory studies funded by WALGA which defined the final basis for the catalogue included the following:

1. An initial investigation of the estimated marginal cost of road wear of three different local road types, where simple road designs were investigated using typical input parameters corresponding to assumed traffic load levels and a simple linear load-wear-cost (LWC) relationship was fitted to determine the marginal cost. Five different scenarios were also included to better understand the effect of climate, pavement strength and pavement age on the marginal cost of road wear.

The resulting annual marginal costs varied in magnitude by up to five times, with the arterial road having the lowest marginal cost and the access road the highest. The results were reasonably consistent with other recent analyses showing an overall trend towards a higher marginal cost on weaker roads and in wetter climates.

However, the results were significantly different to those listed in Austroads (2012b) primarily as a result of the different input values for pavement strength. This highlighted the need to better inform model assumptions and the definition of typical pavement characteristics and loading, and that the following improvements should be pursued in developing a working model:

- (a) Include more representative roads in the study and base inputs on real road data with revised pavement strength assumptions which recognise the mean and distribution of the initial strength of in-service pavements. Data for this purpose could be sourced from the LRDS database for Western Australia, or other monitoring studies.

- (b) Employ the published Western Australia LRDS road deterioration and works effects models which are now available, and which show significant traffic and time-based impacts on strength deterioration. Coupled with reasonable initial strength values, and typical values for surface age and distress, the resulting outputs should be representative of the range of conditions in Western Australia.
 - (c) Implement a number of more detailed changes to supplement the main proposed changes, as follows:
 - ◆ Carry out a sensitivity analysis to investigate how the marginal cost is affected by changes in unit rates, pavement age, climate, calibration coefficients.
 - ◆ Conduct analysis using a greater ESA range, noting that additional traffic imposed by the resource industry and developers can lead to a significant increase in ESA above standard levels by some 15 to 20 times, with this applied over different time durations as a step change, as opposed to a less abrupt change typical of changes in policy, e.g. a move from RML to AAMS.
2. In further investigations to establish a working model, the following changes and recommendations were made:
- (a) applying real-life loading scenarios, covering duration and intensity, and ensuring they are realistic in relation to the road category, by:
 - ◆ specifying a number of loading scenarios to be run, i.e. 0.2, 0.4, 0.6 and 0.8 x10⁶ additional loading, or as a proportionate increase above the (annual) design capacity
 - ◆ varying the duration of the additional loading from a single period to a number of different time periods, e.g. for 1, 3, 5, and 10 years
 - ◆ varying the loading across the road types, i.e. applying a smaller additional loading to access roads compared to local distributors and so on.
 - (b) adopting initial in-service pavement strength values for each road category based on a relationship derived from the Austroads LTTP database, and employing a strength distribution function based on observations from the LRDS in Western Australia
 - (c) adopting the LRDS road deterioration models for strength deterioration, and roughness, rutting and cracking progression, with further adaptation where reseal frequencies are extended beyond the estimated 'oxidation age'
 - (d) other items addressed in finalising a working model included:
 - ◆ assessment of the impact of the climate on the resulting outcomes would not be included as part of the analysis design matrix, but climate zone and related variables would be retained as part of the overall model inputs. This is because total infrastructure costs are impacted by climate, but the effect on marginal costs is relatively minor
 - ◆ normal traffic growth would be applied to 'base' or existing traffic to ensure a realistic comparison, and therefore determination of the marginal cost resulting from additional loading.

3.2 Main Tasks in Completing the Catalogue

Having reviewed and agreed on a basis for developing a catalogue, the tasks needed to be completed to finalise the catalogue included:

1. Completing the review of critical variables and models to be applied in the working model

2. Defining a representative network for analysis, and the components of a simulation model which is responsive to additional loading and incorporates full life-cycle costing including road performance, treatment selection and works effects models, and tracks treatment costs and traffic loading
3. Identify and adapt a suitable modelling and reporting tool to support the creation of the analysis networks and case studies, and produce the required analysis results.

These tasks are described in the following sections.

4 CRITICAL VARIABLES AND MODELS

It is recognised that there are a range of factors which influence the cost of road wear. As part of the methodology developed in this study, a series of different data parameters and road deterioration and works effects models were required. These formed the building blocks of the overall model.

It is useful to consider the inputs to the model in a hierarchical form, beginning with the overarching scenario-specific attributes and then the more detailed inputs employed in the modelling process. Comments on their significance are also added.

4.1 Scenario-specific Attributes

These comprise attributes which define the component parts of a particular scenario or a particular case study as required by the User Guide and described in Section 2.2 and include:

- **Cost zone and treatment costs**, which as illustrated earlier are based on 4 separate zones with different costs for each maintenance works type, with the range of unit costs (between regions) illustrated in Table 4.1.

The relative treatments costs vary by a factor of approximately 20 comparing routine maintenance and reseal (resurfacing), a factor of 5 between resurfacing and overlay (or rehabilitation), and a factor of up to 1.3 between overlay and reconstruction. Prolonging the period until a reseal or rehabilitation is needed will limit costs by a significant amount, however this will invariably shorten where significant additional loading is applied.

- **Road category**, comprising 4 types, with these deemed to have been built and maintained to different standards and to possess different design traffic carrying capacity (Table 4.2). The design capacity is shown to vary by 100 fold.

Annual additional loading (in ESA/year) and the duration of the additional loading (in years), where the significance of additional loading and duration as a percentage of initial design loading is illustrated in

- Table 4.3. The relative loading is shown to vary between approximately 1% of the design loading for a district distributor receiving the maximum additional loading over a one-year period, to 5000%, i.e. 50 times the design loading for an access road where the maximum additional loading scenario is applied for a 10-year period. The latter corresponds to reducing the actual life of an existing access road to one year or less. It is clear therefore that the ability of a lower-order road to support significant additional traffic is likely only to be possible if significant investment is made to extend its life through reconstruction or rehabilitation. On the other hand, higher-order roads could require considerably less additional expenditure and therefore additional use would potentially generate lower marginal costs.

Table 4.1: Range of unit costs

Road category	Routine maintenance (\$/sq.m.)	Reseal (\$/sq.m.)	Overlay (\$/cu.m.)	Reconstruction (\$/sq.m.)
Access road	0.27–0.34	5.90–7.50	290.00–470.00	32.00–53.00
Local distributor	0.27–0.41	6.20–8.80	330.00–480.00	39.00–55.00
Regional distributor	0.32–0.45	6.40–8.80	350.00–490.00	44.00–61.00
District distributor	0.40–0.49	6.40–8.80	450.00–530.00	60.00–70.00

Table 4.2: Design traffic loading of different road categories

Road category	Design traffic (ESA x 10 ⁶)	Adopted design traffic (ESA x 10 ⁶)
Access road	< 0.08	0.04
Local distributor	0.08–0.4	0.2
Regional distributor	0.4–2.0	1.2
District distributor	2.0–6.0	4.0

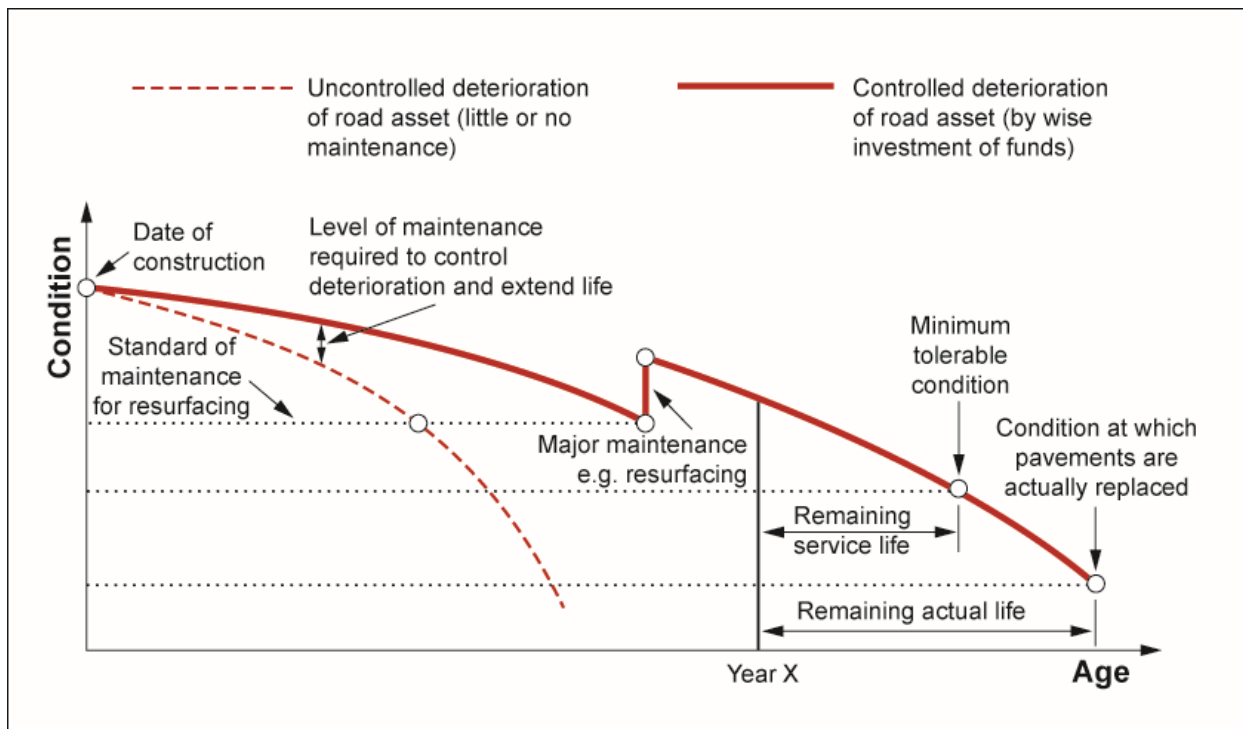
Table 4.3: Additional loading as percentage of design loading for different loading durations

Additional loading per year (ESA x 10 ⁶ /year)	Access road		Local distributor		Regional distributor		District distributor	
	1 year	10 years	1 year	10 years	1 year	10 years	1 year	10 years
0.02	50%	500%	10%	100%	2%	17%	1%	5%
0.06	150%	1500%	30%	300%	5%	50%	2%	15%
0.1	250%	2500%	50%	500%	8%	83%	3%	25%
0.2	500%	5000%	100%	1000%	17%	167%	5%	50%

4.2 Life-cycle Performance Models and Associated Variables

The analysis methodology is based on predicting the future condition trends and response to road maintenance and renewal works of typical road sections under different traffic levels, and current and additional loading. This is illustrated in Figure 4.1, where the effects of low levels of maintenance and more appropriate and timely interventions are illustrated.

Figure 4.1: Typical road condition deterioration with time



Source: After SADC (2003).

The following comments also apply:

1. the rate of deterioration (i.e. the slope of the condition trend) may also be as a result of:
 - (a) inadequate strength for the freight task, including as a result of additional loading, bringing forward the timing of any maintenance
 - (b) lower design standards, such as those appropriate and economic for lower-volume roads
2. the standard of maintenance (or intervention level) and the improvement (commonly referred to as the works effect) resulting from maintenance may also vary depending on:
 - (a) the type of treatment, with a greater improvement from more expensive treatments such as rehabilitation or reconstruction
 - (b) the road category, with higher-order roads and those carrying higher traffic deserving an earlier intervention
 - (c) the availability of adequate funding, with the funding gap likely to be greater due to unforeseen or unplanned, heavier road use.

It was important therefore to address such issues by reviewing and adopting suitable models and standards, and ensuring data was available to inform the overall process. To aid this, an elaboration of the above factors and critical variables follows.

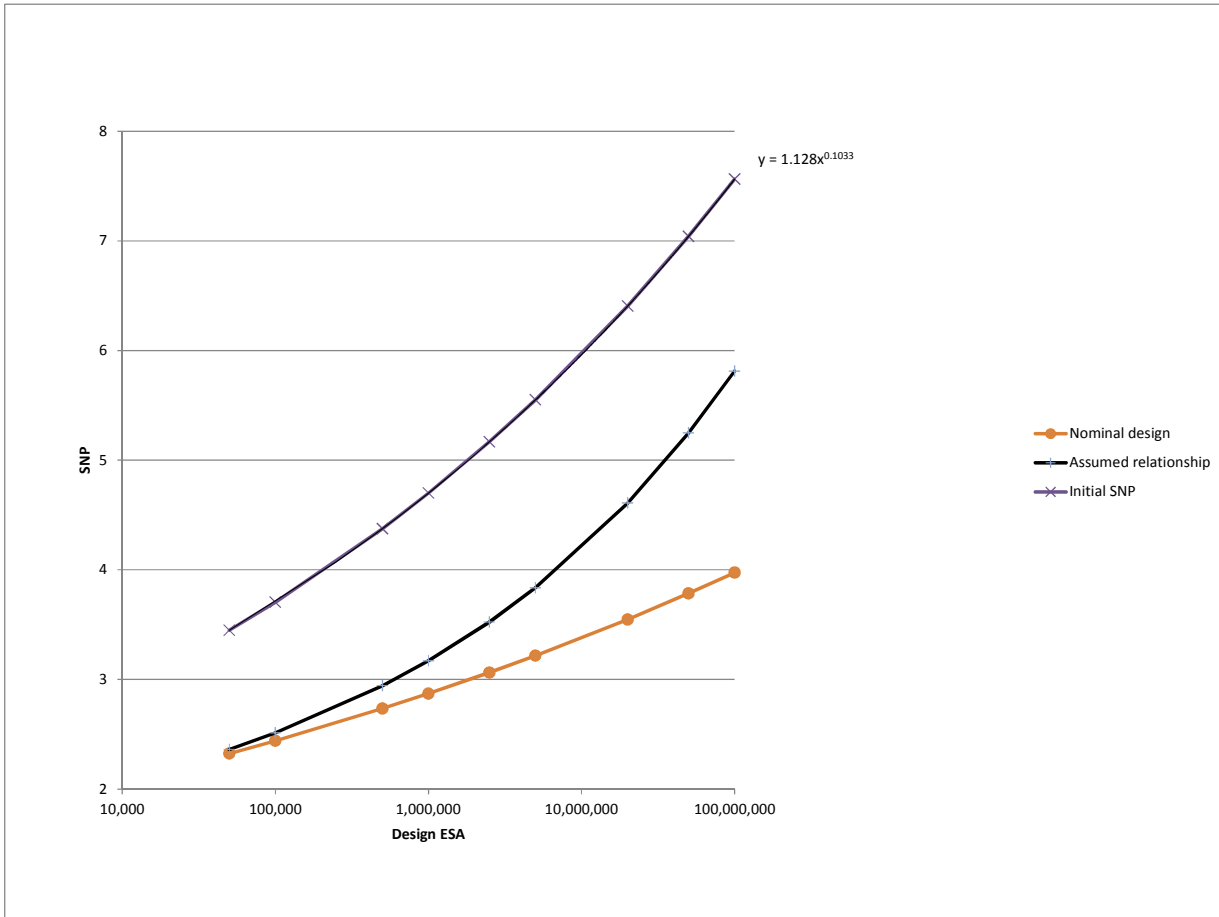
4.3 Pavement Structural Strength

Relevant parameters and models considered included the following:

1. **Initial strength**, where this is represented by the modified structural number (SNC) (Hodges et al. 1975), often referred to interchangeably as the adjusted structural number (SNP)

(Morosiuk et al. 2004), with a requirement for a higher value to support greater traffic loading. SNC estimates were based on a relationship between the 20-year design traffic (in ESA) and SNC established from LTPP studies of in-service roads (Figure 4.2) (Toole & Roper 2013), with these identified as the most suitable based on available evidence. This provided a means of populating the initial strength values for each road category.

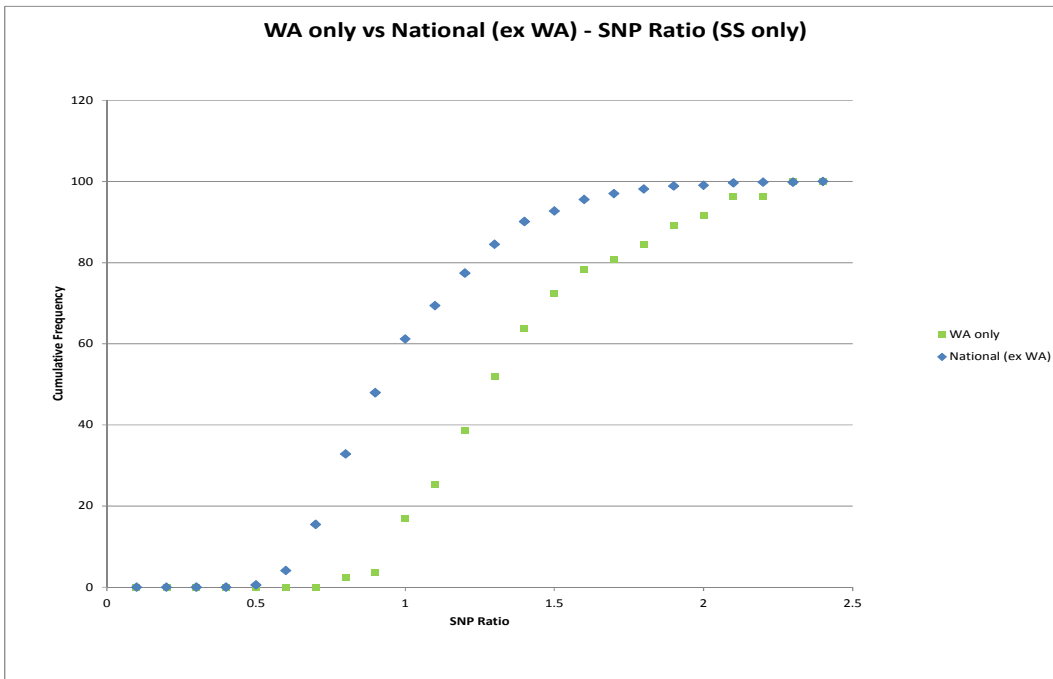
Figure 4.2: LTPP derived strength-capacity relationship and strength ratio distribution



2. **Strength variation**, being the distribution of strength (or scatter) observed between nominally homogenous sections, and represented by the proportion which are weak, moderate or strong relative to the estimated value. The SNC ratio, defined as the ratio between the estimated mean value and measured in situ values, was used to represent this property.

Evidence was available from the LTPP and from the LRDS to define a distribution; in the latter case for both the full national dataset and for WA specific sites. The LRDS WA distribution was selected as it displayed higher strengths consistent with local experience. For practical application, following a detailed data review it was determined that three strength categories should be adopted corresponding to weak (< 0.65 times initial SNC), moderate (0.65–1.35 times initial SNC) and strong (>1.35 times initial SNC), with corresponding proportions of 0%, 45% and 55%. These proportions differ from those of the full national dataset (Figure 4.3), the values for which were approximately 10%, 80% and 10%.

Figure 4.3: LRDS derived strength ratio distribution

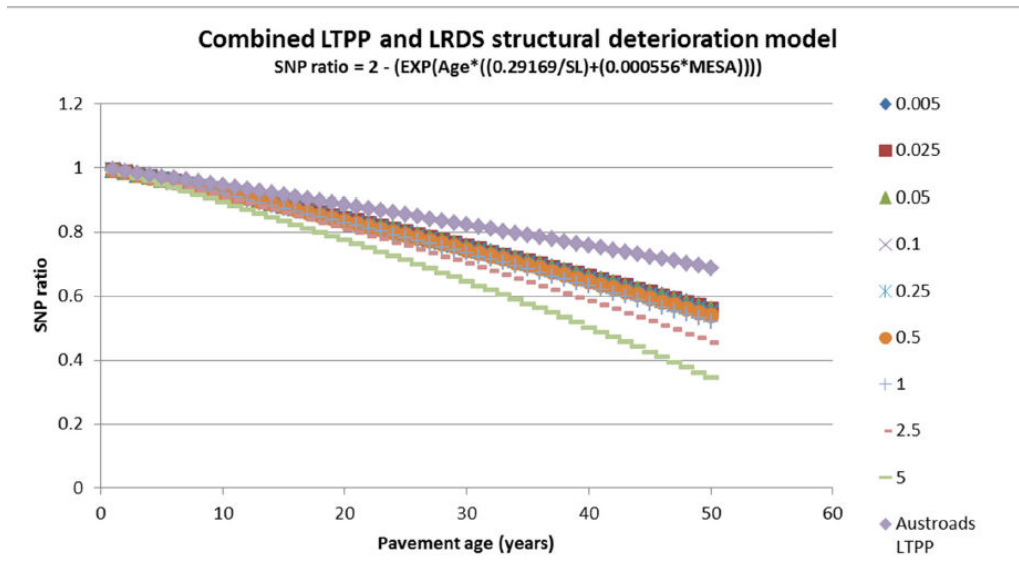


The chosen relationship and distribution were deemed to better represent actual conditions than a previously assumed single relationship based on Roberts et al. (2003) used in the Austroads/NTC studies and the initial exploratory studies, and a nominal design relationship derived from the Austroads pavement design chart for granular pavements with a thin flexible surfacing (Austroads 2012a), both of which were deemed too conservative. This is because they represent design relationships which aim to ensure a low rate of failure, whereas asset management aims to model observed behaviour and should represent the actual variation in strength.

3. **Strength deterioration**, where the initial SNC is reduced over time. Various relationships exist from the LTPP and LRDS studies, with the former representing arterial roads subject to design, whereas the latter represents both designed roads and those which have evolved, e.g. from earth and gravel roads.

Whereas the LTPP relationship was a function of climate, as defined by the Thornthwaite Moisture Index (TMI) (Thornthwaite 1948) and pavement age, the LRDS relationship was a function of traffic loading (in $ESA \times 10^6$) and pavement age. Upon review, neither relationship was deemed suitable because design techniques usually account for climate \-related and other moisture effects, and the impact of traffic loading on strength deterioration was judged excessive. Therefore a relationship (Figure 4.4) based on the combined LTPP and LRDS datasets was derived which was judged to be suited for this study.

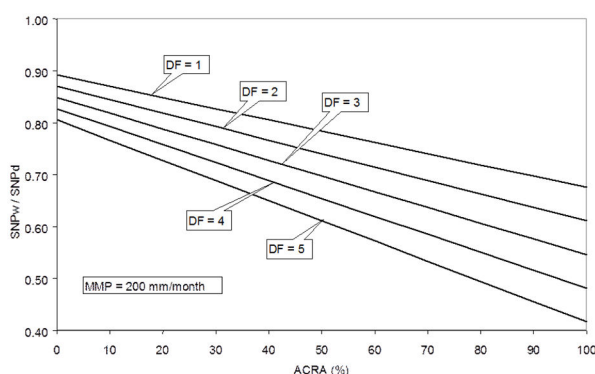
Figure 4.4: Adopted strength deterioration relationship



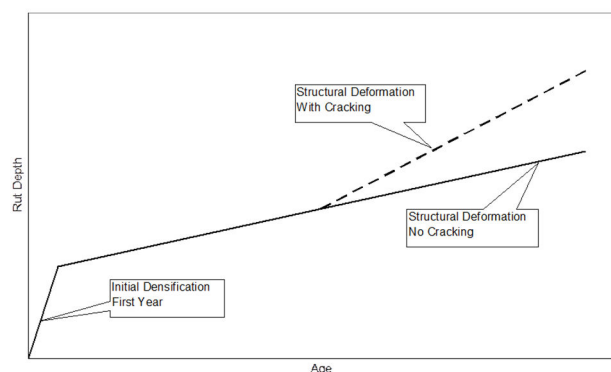
As an example of the possible effect of additional loading, a sustained additional loading of 10 times a current loading of only 0.005 MESA per year would cause a doubling in the rate of strength loss. However, to ensure unreasonable estimates of strength loss (potentially to zero) are not predicted, a maximum loss of 65%, or a minimum SNP ratio of 0.35 is recommended and was applied in the analysis.

- Structural and condition interaction**, where neither of the models account for a change in pavement condition, e.g. the initiation and progression of cracking, or other factors such as the type and condition of drainage facilities. The impact of both of these factors is illustrated in Figure 4.5, where Figure 4.5a) illustrates the interaction of drainage factor, area of cracking and rainfall, and Figure 4.5b) illustrates the potential for a change in rate of rutting following the onset of cracking. With significant constraints on local government budgets being increasingly common, some account for such factors was judged appropriate.

Figure 4.5: Illustration of interaction effects on pavement strength and rate of rutting



(a) Variation of adjusted structural number (SNP) due to drainage and surface cracking



(b) Phases of rut development

Source: Morosiuk et al. (2004).

4.4 Road Condition Deterioration

Models for rutting, cracking and roughness were chosen to determine the combined effects of traffic and the environment on road condition. Whereas roughness (or ride quality) deterioration represents an overall performance measure, being an accumulation of contributions from many components including environment-induced changes, rutting and cracking and other distress types such as ravelling and potholing are primary types of distress to which maintenance activities are directed. As severity and extent increases, overall performance deteriorates further triggering a more significant response.

For this study, the LRDS models were adopted being of the 'deterministic' type, since they are composed of the variables understood or assumed to influence pavement performance. They are also referred to as structured mechanistic-empirical models because they are calibrated, using regression analyses, by observational data (Austroads 2009)². The models must adhere to known boundary conditions and physical limits, and the models can incorporate interactive forms of distress near the end of pavement life, such as the interaction of rutting with cracking, when these interactions are well understood. They are amongst the most popular and widely applied models, the most widely known being the HDM-type (Paterson 1987; Mororsiuk et al. 2004), which are based on significant field studies. However, for practical application they need careful calibration and adaptation, and like many complex models they should be used with a degree of pragmatism.

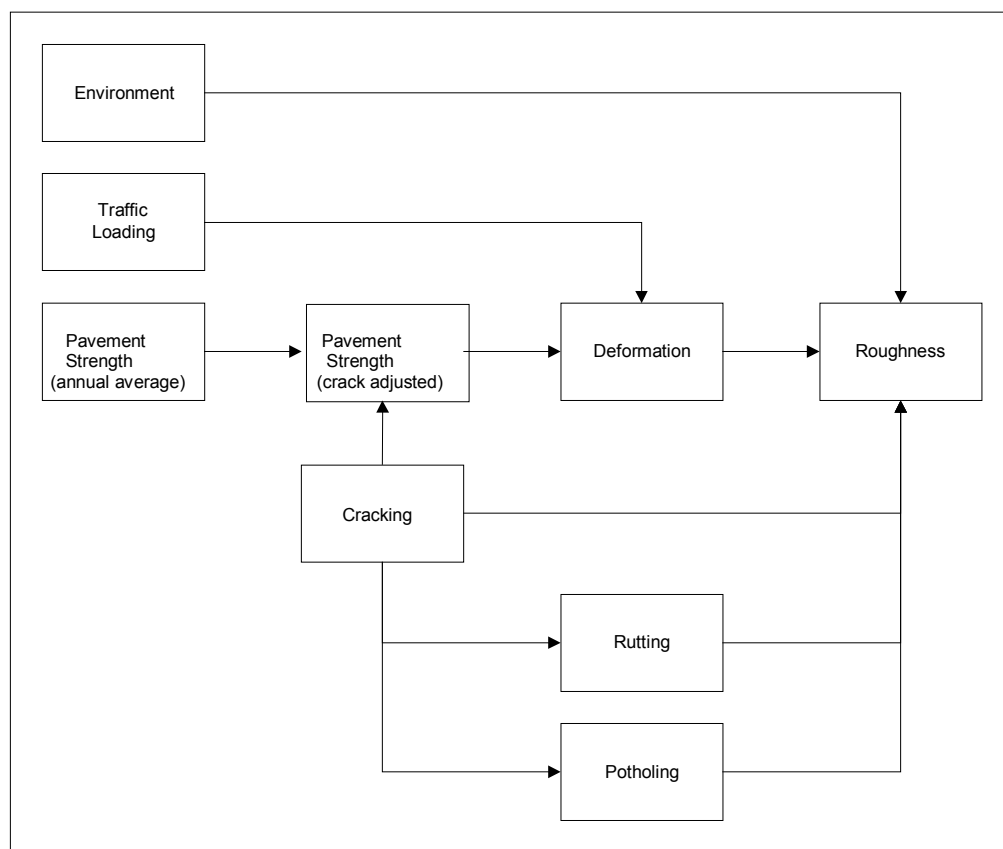
Separate relationships exist from various sources for the prediction of individual distresses, e.g. cracking and rutting, and the accumulation of surface disintegration and road roughness. Models exist which represent the different phases of deterioration, for example:

- initiation and progression of all cracking and wide cracking
- initiation of potholing from cracking or ravelling
- initial densification, structural rut depth progression, plastic deformation and acceleration of rutting from cracking, including impacts of rainfall and changes in structural strength.

The models are also referred to as incremental, and recursive, as they predict annual changes and allow interaction between variables, as illustrated in Figure 4.6.

² Austroads (2009) contains further information on the various types of performance models and the development and application of these world-wide and in Australia.

Figure 4.6: Dependence of roughness development on model parameters in HDM-III and HDM-4



Source: Morosiuk et al. (2004).

The roughness progression models include contributions from primary surface distresses and overall structural-traffic balance and age-environment contributions, based on broad climate categories considering moisture-temperature differences and evapo-transpiration potential. This offers the potential for investigating the consequences of different combinations of input conditions, and their impact on future condition.

The specific LRDS models employed (Martin et al. 2013) which are based on the same principles are summarised below showing the variety of factors included, all of which are statistically significant based on Australian evidence:

1. **Pavement rut depth**, R_i , as described by Equation 3, consists of two components: (i) the initial rutting, R_o , which normally occurs during the initial densification period of one year after the pavement construction or rehabilitation; and, (ii) the cumulative rutting deterioration, Δrut described by Equation 4, which develops following initial densification to be the remaining part of the observed total rut depth.

$$R_i = R_o + \Delta rut_i \tag{3}$$

where

R_i = observed rut depth (mm) at time i

R_o = initial densification rutting (mm) value at the end of year 1

$$K_{rid} \times [51740 \times (MESA \times 10^6)^{(0.09 + 0.0384 \times 6.5 \times SNC_0^{-1.6})} \times SNC_0^{-0.502} \times COMP^{-2.3}] \quad (3a)$$

- Δr_{uti} = cumulative change in rut depth since initial densification (mm) at time i
- MESA = million ESA/lane/year
- COMP = relative compaction value (100% assumed)
- K_{rid} = calibration factor for initial densification (= 1.0 default for single seals and asphalt)
- SNC_0 = initial modified structural number

$$\Delta r_{uti} = k_r \times 4.003 \times [0.0035 \times AGE_i + 0.18 \times (100 + TMI)/100 + EXP (5.853 \times MESA - 0.418 \times SNC_i)] \quad 4$$

where

- k_r = local calibration factor for rutting (default = 1.0)
- TMI = Thornthwaite Moisture Index (incorporates temperature and rainfall impacts)
- SNC_i = modified structural number at time i

and all other variables are as defined previously

2. **Cracking deterioration**, where due to high variability in the data collected under the local roads deterioration study, an existing cracking deterioration model form formulated for an independent data set consisting of long-term data collected from various highways in Australia was adopted. Equation 5 was therefore developed and found to be the most suitable cumulative cracking deterioration model for the full range of cracking, with the initiation of cracking, and seal life, assumed to be based on the ARRB binder oxidation model (Oliver 2006).

$$\Delta cr_x = 100 - 200 \times [1 + EXP (k_c \times (Sage / ((200 - TMI) / 25))^{0.649})]^{-1} \quad 5$$

where

- Δcr_x = cumulative total cracking as a percentage of observed lane area (%)
- k_c = local calibration factor for cracking (default = 1.0)
- Sage = elapsed time after crack initiation (years)
age of seal – seal life (estimate)
- seal life = $[(0.158 \times T_{min} - 0.107 \times R + 0.84) / (0.0498 \times T_{ave} - 0.0216 \times D - 0.000381 \times S^2)]^2$

- T_{ave} = the average temperature of the site (°C)
($T_{max} + T_{min}$)/2
- T_{min} = the yearly mean of the daily minimum air temperature (°C)
- T_{max} = the yearly mean of the daily maximum air temperature (°C)
- R = risk factor associated with delaying resealing (range of 1 to 10; used $R = 10$ for high risk)
- D = the ARRB durability test result (= 10 days)
- S = nominal seal size (mm)

and all other variables are as defined previously

3. **Roughness deterioration** was modelled using measured data in terms of the International Roughness Index (IRI, m/km). The total roughness, IRI_i , at any time, is defined by Equation 6.

$$IRI_i = IRI_o + \Delta IRI_i \tag{6}$$

where

- IRI_o = initial roughness (m/km) at pavement age, $AGE_i = 0$
- ΔIRI_i = cumulative roughness at pavement age, $AGE_i = i$

and all other variables are as defined previously

The cumulative roughness deterioration model, ΔIRI_i , is shown by Equation 7 to predict cumulative roughness deterioration with a full set of contributing component variables for traffic, rutting, cracking and climatic effects:

$$\Delta IRI_i = k_{iri} \times [1.393 \times IRI_{env} + 0.09 \times \Delta rut_i + 0.029 \times \Delta crx] \tag{7}$$

where

- k_{iri} = local calibration factor for roughness (default = 1.0)
- ΔIRI_i = cumulative increase in overall roughness since the initial roughness, IRI_o
- IRI_{env} = roughness due to climatic effects (= $m \times IRI_o \times AGE_i$)
- Δrut_i = cumulative increase in rutting, see Equation 4
- Δcrx = cumulative increase in cracking, see Equation 5

Finally, for actual application an annual incremental form of the deterioration models for the rutting and roughness models needed to be used and adapted into the analysis framework where the annual traffic loading, MESA, is not a constant in these particular models. In

principle the annual incremental model form needs to be capable of predicting the pavement distress in any given year, as this is the founding principle of the life-cycle modelling approach applied.

4.5 Effect of Delaying Reseal Timing

Actual performance evidence on the effect of delaying reseal timing is scarce, although a number of studies have produced or calibrated crack initiation and progression relationships. This is believed to be because of the historical focus on preserving sprayed seal granular pavements by timely resealing, and hence limiting the likelihood of accelerated deterioration.

However, experimental evidence exists from the Austroads Accelerated Load Facility (ALF) studies where such pavements have been tested under conditions where cracks have been induced and water applied (Martin et al. 2004). The results of these studies suggest that the incremental rate of rutting and the incremental rate of roughness progression under wet and cracked conditions is some 2.06 times and 1.96 times that of an uncracked surface tested under dry conditions. Whilst the relative performance factor (RPF) may be overstated for in-service roads, and drier climates, and could be proportioned by the area of cracking and/or length of wet and dry seasons, it is suggested that the above factors are simply applied to the predicted annual incremental change in rutting and roughness condition predicted by the LRDS deterioration model in circumstances where cracking has initiated on the pavement surface. This in the view of the authors is a pragmatic approach as a basis for an upper-bound estimate of pavement condition, based on the view that greater complexity is unjustified without field evidence.

In addition, it is suggested that the maximum reseal frequency should be limited to 1.3 times the estimated oxidation-based life (Oliver 2006), or 30% all cracking on the pavement segment. Beyond this point rapid deterioration is likely, and few authorities ever risk managing assets under such conditions due to the uncertainty in behaviour and potential for complete pavement failure.

4.6 Maintenance Standards

4.6.1 Defining the Intervention Types

The maintenance standards were set to represent the target intervention levels and responses that a typical WA Local Government road agency may aim to achieve. The maintenance standards in FAMLIT were specified by road type, and include the following types of treatments:

- routine maintenance: regular pothole patching, crack sealing, etc.
- reseal: single seal
- rehabilitation: 100 mm overlay + single seal
- reconstruction: to existing/required standards.

As outlined in Table 4.4, there are three pavement treatment types that are defined and applied within the analysis:

- Resurface (or resealing) – involves performing works to maintain the surface integrity of the pavement and waterproofing it so that water ingress into the pavement is minimised and hence the pavement's base and subgrade are not compromised.
- Overlay (or rehabilitation) – involves the removal of the pavement's top course through milling. The top course is then replaced with a new overlay (asphalt or granular) to a specified thickness, and in turn extends the overall life of the pavement.

- Reconstruction – involves removal of the existing pavement and replacing it with a new pavement of the same type, designed for the nominated traffic and growth rates.

For clarity, routine maintenance is applied in the modelling framework and costs are determined as a function of loading on each road section.

4.6.2 Defining the Intervention Criteria

The maintenance standards comprise specific treatment types and trigger points (or intervention levels) at which they are applied. For the latter it is customary (and economic) to intervene at different measurable condition states based on road importance and traffic use, with this supporting different levels of service (LOS) based on traffic demand/usage. It is also both good engineering and economic practice to employ different treatments, and for the range of their application to coincide with specific trigger types and absolute levels of distress.

The above principles are reflected in the applied triggers and boundary limits for major treatments in Table 4.4.

Table 4.4: Applied triggers and boundary limits for each of the treatments

Road Category	Resurface			Overlay (varying thickness mm)						Reconstruction				
	IRI minimum	IRI limit	Max int. (years)	IRI trigger	SL trigger	IRI limit	IRI reset	Min int. (years)	Max int. (years)	IRI trigger	SL trigger	IRI reset	Min int. (years)	Max int. (years)
District distributor	1.8	4.5	12	4.5	3	6.5	1.8	2	100	6.5	5	1.6	2	100
Regional distributor	1.8	4.5	12	4.5	3	6.5	1.8	2	100	6.5	5	1.6	2	100
Local distributor	2	5.5	17	5.5	3	8	2	2	100	8	5	1.8	2	100
Access road	2.2	6.1	17	6.1	3	8	2.2	2	100	8	5	1.8	2	100

The treatments take place in response to:

1. A change in roughness (represented by IRI) where:
 - (a) IRIMinimum is the post-construction IRI for a new pavement
 - (b) IRILimit is the maximum IRI for this treatment, with no overlap between treatment types
 - (c) IRIReset is the post-overlay or reconstruction IRI which depends on the treatment applied, and represents the effect of works.
2. Application of minimum or maximum interval (years), where:
 - (a) Max Int (years) is the maximum time between successive treatments of a given type, noting the hierarchical rules that a reconstruction would reset the age of an overlay and surfacing, and an overlay would reset the age of a surfacing
 - (b) Min Int (years) is the minimum time between successive treatments.
3. Use of a structural life trigger, where:
 - (a) SLTrigger is the minimum remaining structural life (in years) below which an overlay or reconstruction is triggered.
4. Other works-related rules and models included:
 - (a) Reduction in pavement life, where the maximum structural life is reduced where a significant increase in loading occurs, based on Equation 8.

$$\text{Annual reduction in SL (years) in year}_i = \frac{\text{actual MESA in year}_i}{\text{original design MESA}} \quad 8$$

As an example of the use of Equation 8, a five-fold increase in MESA in a single year would reduce pavement life by five years. Whilst severe, if a 50-year service life is used, then it is considered pragmatic and would complement the functional triggers.

- (b) Overlay thickness auto-calculation, where the overlay thickness can either be user defined or calculated. A procedure for overlay thickness auto-calculation has been adopted from PLATO (Roberts et al. 2003). Costing rather than modelling routine maintenance, with the expectation that normal maintenance standards, in terms of defined hazards and defects, and response times, would be adhered to.

5 DEVELOPING THE ANALYSIS NETWORK AND SIMULATION MODEL

5.1 General

Having established the basis for performance modelling and treatments, the next stage comprised developing an analysis network and simulation model, and involved:

1. Creation of a representative road network. This required consideration of a broad range of pavement assets likely to be subjected to additional loadings, with these reflecting the principal attributes described earlier.
2. Collation and review of data from various sources and assessment of their suitability to the analysis, with this including treatment cost information, vehicle fleet information, and loading scenarios.
3. Definition of a network simulation model to facilitate the construction of a catalogue of applicable marginal costs for a specific loading scenario and duration.

5.2 Development of a Representative Road Network

Creation and population of a representative network involved first acknowledging that by adopting a catalogue-based approach it would be ‘synthetic’, i.e. an appropriate representation of WA Local Government road networks rather than a network comprising location-specific physical sections. However, it had to be defined based on the variation in the characteristics of physical sections in order to produce realistic results.

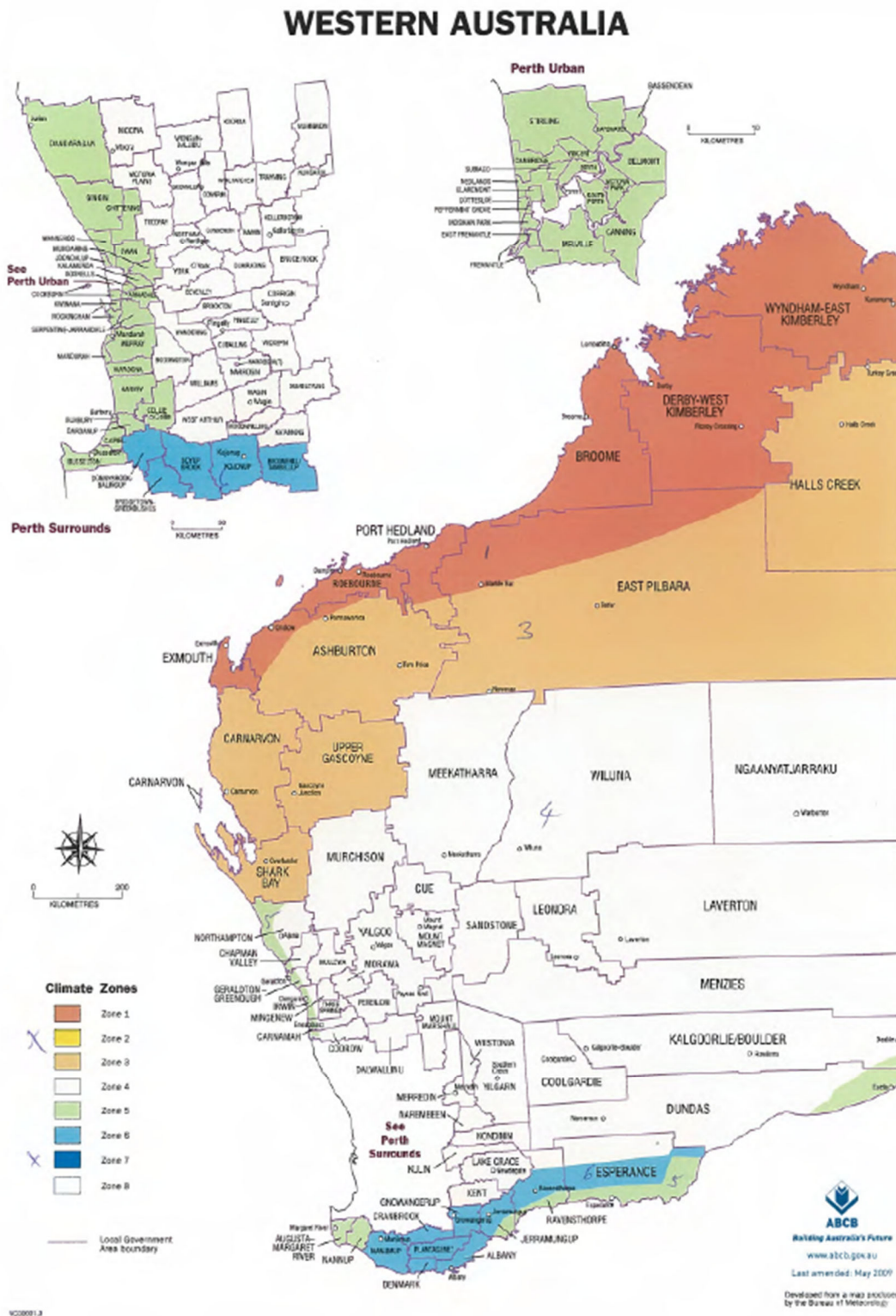
To address this, a broader set of attributes in addition to the set of four primary attributes identified as the basis for catalogues needed to be identified as shown in Table 5.1.

Table 5.1: Additional network attributes

Attribute	Classes	Variables
Climate	5 climate zones, representing North West (1), Gascoyne / East Pilbara (3), Central (4), West Coast (5) and South West (6) (see Figure 5.1)	Thornthwaite Moisture Index Mean monthly rainfall Mean, maximum and average annual air temperature
Pavement type	1 type, Sprayed seal granular pavement (GN)	Represented by surface type and base type, SNC, last treatment age
Initial strength category	3 categories, weak, moderate and strong	Modified structural number (SNC) with values based on initial SNC and design ESA relationship, and strength distribution proportions
Road condition	3 categories, good, fair and poor	Roughness (in IRI), with corresponding values of 2, 4 and 6 IRI
Pavement history	Assigned against road condition categories	Reseal age (yrs), rehabilitation age (yrs) reconstruction age (yrs), with corresponding values of 5, 10 and 10 for reseal age, and 5, 25 and 45 for rehabilitation and reconstruction age

In addition, a number of general characteristics needed to be defined to complete the network, as shown in Table 5.2.

Figure 5.1: Climate zone map for Australian Building Codes Board



Source: Based on Australia Building Codes Board 2009, Western Australia climate zone map.

Table 5.2: General default characteristics

Parameter	Default value applied
Road length (km)	1
Road (lane) width (m)	3.5
Pavement type	GN
Nominal chip size (mm)	10
Road geometry	Flat and straight
Pavement service life (years)	50
Parameter	Default value applied

5.3 Collation and Review of Additional Input Data

The additional input data required included:

- Vehicle fleet data, where one common heavy vehicle was selected to simplify the modelling yet ensure that the design loading was achieved within the specified service life. An R11 (Austroads Class 3) two-axle rigid vehicle was used, and was assigned the volume required to accumulate the design loading over 50 years for the relevant road type. This was purely for convenience as the marginal cost is related to ESA and not individual vehicle numbers.
- Equivalent daily traffic volumes of 18, 55, 90 and 180 vehicles per lane for the four road categories.
- Equivalent representative heavy vehicle volumes of 1, 4, 23 and 75 for the four road categories.

5.4 Definition of a Network Simulation Model

To facilitate the construction of a catalogue of applicable marginal costs for a specific cost zone, road category, and loading scenario and duration, a network simulation model was required comprising the following components:

1. **Definition of analysis sections and traffic**, where if all cases were tested 15,120 analysis records would be required, including for base traffic and additional traffic. This was rationalised to 1,008 records on the basis of findings from exploratory studies that a) climate did not significantly affect marginal costs; b) the distribution of WA LG strength values (being predominantly moderate and strong) also did not significantly affect marginal costs. Consequently, a single representative climate (Central) and a single representative strength category (moderate) was chosen. This resulted in the following attributes and their combinations representing the analysis network:
 - cost zones (4)
 - road categories (4)
 - current loading level (1)
 - additional loading levels (4)
 - additional loading durations (5)
 - road condition states (3)
 - strength categories (1)
 - climate (1)

2. **Application of the road performance models**, which predict future conditions year by year based on the specified input data (1) representing the main data attributes, including changes in the freight task.
3. **Triggering of treatment interventions and associated costs**, which are applied yearly for major works as intervention criteria are exceeded with a stream of (undiscounted) costs generated for the full analysis period.
4. **Road network resets**, which resets pavement condition, strength and age attributes, and initiates a new deterioration and treatment cycle (steps 2 and 3).

The above cycle needed to be completed for all analysis records, including for the base traffic case, i.e. existing traffic with no additional freight task, and for a number of calculated values to be tracked year-by-year, including:

- annual ESA
- strength
- roughness
- time since reseal
- time since overlay
- time since reconstruction
- routine maintenance cost
- reseal cost
- overlay thickness
- overlay cost
- reconstruction cost.

The year-by-year values need to be available for reporting, to review and assess results, and as the input to the determination of the marginal cost of each scenario, where the latter is determined based on Equation 9.

$$MC \text{ per ESA.km} = (\text{discounted } RAC_{alt} - RAC_{base}) / (\text{discounted } ESA_{alt} - ESA_{base}) \quad 9$$

where

- MC per ESA. km = marginal cost estimated per ESA kilometre
- discounted RAC_{alt} = discounted road agency costs for the alternative case
- discounted RAC_{base} = discounted road agency costs for the base case
- discounted ESA_{alt} = discounted cumulative ESA loading for the alternative case
- discounted ESA_{base} = discounted cumulative ESA loading for the base case

6 GENERATING A CATALOGUE USING MODELLING TECHNIQUES

6.1 General

Having established the basis for performance modelling and treatments, completion and operation of a working model involved the following further steps to generate a catalogue of solutions:

1. Selection and development of a working tool capable of producing the required analysis outputs.
2. Development of the catalogue of marginal cost charts to facilitate estimation of an applicable cost of road wear to operators requesting permission for additional freight loading on the network.

These steps were fundamental in generating a catalogue appropriate for the calculation of marginal costs. Additionally, the development of a catalogue which supports the objectives of this project is dependent on the model selected. Further details are described below.

6.2 Selection and Development of a Working Tool

In order to execute the analysis, a modelling and reporting tool needed to be selected.

For this purpose, rather than build a new tool, the Freight and Axle Mass Limits Investigation Tool (FAMLIT) was identified as the most appropriate tool, having been originally built by ARRB (Michel & Toole 2005) to evaluate the impact of different freight tasks on behalf of the Department of State Growth (formerly the Department of Infrastructure, Energy and Resources (DIER) Tasmania.

Since then, FAMLIT was subject to further development under Austroads project AT1165 (Hassan et al. 2008) and was the subject of further work undertaken for Austroads/NTC to inform national deliberations on the marginal cost of road wear (Austroads 2012b). This work also produced an alternative version of FAMLIT which was issued for application by state road authorities (Austroads 2014), but with a focus on its use as a basis for evaluating policy changes resulting from the introduction of high productivity vehicles.

Exploratory studies of the application of marginal costs have also been performed in Queensland in network-wide studies (Hore-Lacy et al. 2012; Toole & Sen 2014) which have helped inform this study and the selection of which version of FAMLIT was to be applied.

FAMLIT is designed to support road asset managers in the following tasks:

- assessing the financial and economic impacts associated with changes in the heavy vehicle fleet, and either changes in the transport task caused by additional road use or incremental increases in mass limits
- assessing variations in road agency costs under different loading scenarios for different pavement types, with different structural capacities and conditions in different environments
- assessing the capacity of each link in the network to support a change in axle mass or the freight task, or those most at risk
- setting of different axle mass limits to be applied to each link in the network
- assessing the economic impacts and possible efficiency gains from transport modal shifts.

Two versions of FAMLIT exist as a result of the above studies, namely:

- Version 1, which is a development of the original tool (Michel & Toole 2005; Hassan et al. 2008) and incorporates a simple user interface. This shields the user from the detailed tables and software code. The tool evaluates the overall impact of a change in the freight task, whether short-term or long-term, and produces a series of direct outputs. These outputs show projected impacts on the network, road agency costs, and the marginal unit road wear costs for each section-alternative and change in freight task investigated.
- Version 2 is more open in structure and is intended to generate outputs that can be used to derive statistical relationships between the equivalent uniform annualised cost (EUAC) and the change in the freight task (Austroads 2014).

Version 1 was selected for this study because of its ability to:

- configure the analysis inputs at a user interface level
- consider network or route-based outputs, as well as section-level outputs
- access direct calculations of the marginal costs.

6.3 Application of FAMLIT

6.3.1 General

To undertake a FAMLIT analysis to generate results and inform the creation of the catalogue requires an understanding of the following:

1. FAMLIT base and alternative analysis structure, where these need to be established adequately to differentiate between the cost implications associated with the additional loading only and not as a consequence of a variable level of service.
2. FAMLIT data input required, with this being compiled in the FAMLIT data preparation tool, with section characteristics populated for all relevant attributes.
3. FAMLIT maintenance treatment selection logic, where application of these treatments will result in different performance and cost outcomes for the different analyses being undertaken.
4. FAMLIT output records, where key section attributes and year-by-year output values for the base and alternative cases respectively are available.
5. Reporting of selected results, including purpose-built graphs to illustrate section level outputs, such as condition, strength and agency cost trends.
6. Compilation of results from multiple sections and scenarios as input to developing the graphical outputs required for the catalogue of marginal costs.

Examples of these are presented below.

6.3.2 FAMLIT Base and Alternative Analysis Structure

FAMLIT allows users to undertake an assessment of the cost implications from two perspectives, where these are associated with either:

- changes in the traffic loading (difference between a base and the alternative traffic), or
- changes in the level of service the agency is delivering (difference between the base and the alternative maintenance standards/interventions).

The tool has the ability to undertake assessment of two maintenance alternative scenarios, in addition to the base case (base fleet). The two alternative scenarios have the same fleet (alternative fleet) and growth rates but vary in maintenance standards. For the purposes of the development of the catalogue, the maintenance standards were kept constant and only the difference in traffic level was applied between the base and the alternative scenario.

6.3.3 FAMLIT Input Records

Section-level inputs comprising road referencing details and general characteristics are shown in Figure 6.1 for a sample of the overall matrix. The corresponding pavement characterisation and condition information is shown in Figure 6.2.

The strength characteristics in Figure 6.2 have been separated into the component parts of the overall initial pavement strength (SNC) based on the Hodges et al. (1975) relationship which separates the pavement layer component (SN) and the subgrade component (SN_{sg}).

Figure 6.1: Road referencing and characterisation matrix defined for moderate strength pavements

Road Referencing and Characterisation																			
Unique Sequential ID (1, 2, 3...)	Road Number	Road Name	Link No	Link Name	Cway	KmPost From	Offset From	KmPos tTo	Offset To	Start Chain	End Chain	Road Length (km)	Road Width (incl. Shoulders) (m)	Road Category	Pavement Type	Nominal seal size (mm) for Chip Sealed roads	Road Geometry	Pavement Service Life (Years)	Thornthwaite
1		Access Road-Central : Moderate SN _Good Cond				Moderate SN		Good Cond				1	3.5	Access Road GN	GN	10	Flat and Straight	50	
2		Access Road-Central : Moderate SN _Fair Cond				Moderate SN		Fair Cond				1	3.5	Access Road GN	GN	10	Flat and Straight	50	
3		Access Road-Central : Moderate SN _Poor Cond				Moderate SN		Poor Cond				1	3.5	Access Road GN	GN	10	Flat and Straight	50	
4		Local Distributor-Central : Moderate SN _Good Cond				Moderate SN		Good Cond				1	3.5	Local Distrib GN	GN	10	Flat and Straight	50	
5		Local Distributor-Central : Moderate SN _Fair Cond				Moderate SN		Fair Cond				1	3.5	Local Distrib GN	GN	10	Flat and Straight	50	
6		Local Distributor-Central : Moderate SN _Poor Cond				Moderate SN		Poor Cond				1	3.5	Local Distrib GN	GN	10	Flat and Straight	50	
7		Regional Distributor-Central : Moderate SN _Good Cond				Moderate SN		Good Cond				1	3.5	Regional Dist GN	GN	10	Flat and Straight	50	
8		Regional Distributor-Central : Moderate SN _Fair Cond				Moderate SN		Fair Cond				1	3.5	Regional Dist GN	GN	10	Flat and Straight	50	
9		Regional Distributor-Central : Moderate SN _Poor Cond				Moderate SN		Poor Cond				1	3.5	Regional Dist GN	GN	10	Flat and Straight	50	
10		District Distributor-Central : Moderate SN _Good Cond				Moderate SN		Good Cond				1	3.5	District Dist GN	GN	10	Flat and Straight	50	
11		District Distributor-Central : Moderate SN _Fair Cond				Moderate SN		Fair Cond				1	3.5	District Dist GN	GN	10	Flat and Straight	50	
12		District Distributor-Central : Moderate SN _Poor Cond				Moderate SN		Poor Cond				1	3.5	District Dist GN	GN	10	Flat and Straight	50	

Figure 6.2: Pavement characterisation and performance

Road Referencing and Characterisation			Pavement Characterisation & Performance											
Unique Sequential ID (1, 2, 3...)	Road Number	Road Name	Deflection D0 (microns)	SN	CBR	Surface Thickness (THsf)	base Thickness (THbs)	Subbase Thickness (THsb)	Subgrade Thickness (THsg)	Surface Coefficient (MCsf)	Base Coefficient (MCbs)	Subbase Coefficient (MCsb)	subgrade Coefficient (MCsg)	Roughness m/km
1		Access Road-Central : Moderate SN_Good Cond		2.141	10									2
2		Access Road-Central : Moderate SN_Fair Cond		2.141	10									4
3		Access Road-Central : Moderate SN_Poor Cond		2.141	10									6
4		Local Distributor-Central : Moderate SN_Good Cond		2.75	10									2
5		Local Distributor-Central : Moderate SN_Fair Cond		2.75	10									4
6		Local Distributor-Central : Moderate SN_Poor Cond		2.75	10									6
7		Regional Distributor-Central : Moderate SN_Good Cond		3.559	10									2
8		Regional Distributor-Central : Moderate SN_Fair Cond		3.559	10									4
9		Regional Distributor-Central : Moderate SN_Poor Cond		3.559	10									6
10		District Distributor-Central : Moderate SN_Good Cond		4.194	10									2
11		District Distributor-Central : Moderate SN_Fair Cond		4.194	10									4
12		District Distributor-Central : Moderate SN_Poor Cond		4.194	10									6

6.3.4 FAMLIT Maintenance Treatment Selection Logic

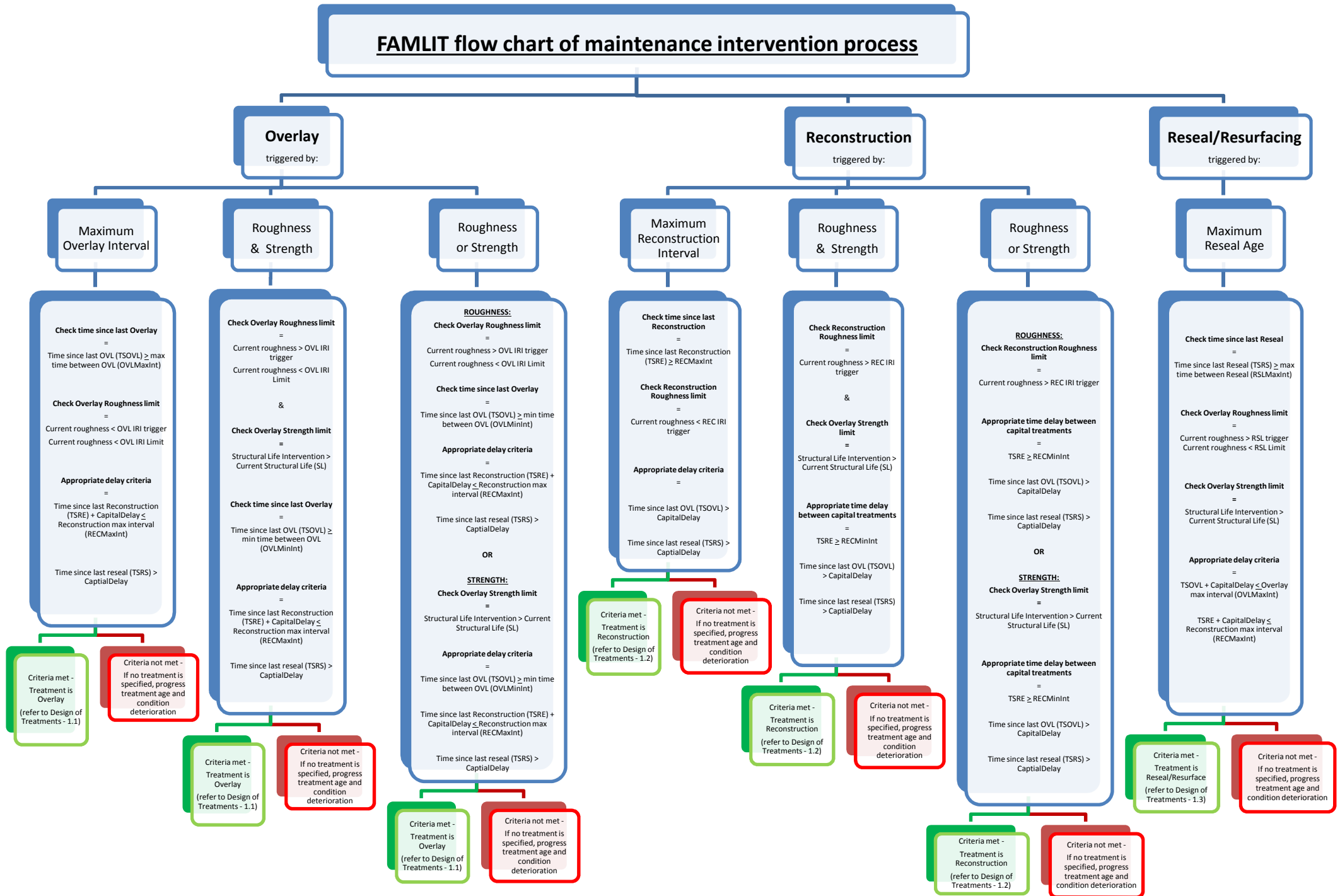
FAMLIT applies a life-cycle costing approach that draws on the input data and the maintenance standards established by road type, as depicted in Table 4.4, to undertake analysis of maintenance needs for the two defined scenarios. The maintenance treatments (outlined previously in Section 4.6) adopted in FAMLIT are as follows:

- Periodic maintenance (resurfacing) is based on scheduled resealing/resurfacing and is triggered by a user-defined maximum surface life. Other relevant rules include:
 - a user-defined minimum and maximum roughness level
 - the works effects as a result of this treatment include
 - ◆ the age of the seal is reset when the treatment is applied
 - ◆ for asphalt surfacings, the user has the option of resetting the roughness level after works to simulate the effects of plane/mill and replace works in urban areas. In FAMLIT, the benefit from resurfacing is assumed to be half that of a full overlay. The reduction in roughness is therefore half the difference between current roughness and the nominated overlay reset value (see Austroads 2007).
- Rehabilitation (overlay, granular or asphalt) is triggered by overlay age or roughness and/or structural life. The treatment is triggered through the following:
 - the maximum interval between overlay treatments is user-defined
 - the roughness intervention level (roughness trigger) is user-defined and varies by road category or traffic level
 - the structural life trigger (SLT, years) is the time between when the pavement is due for rehabilitation and when it will require full reconstruction, i.e. to subgrade level, if rehabilitation is not carried out; typically 3–5 years. To check whether the threshold is met or not, the remaining structural life of a pavement is calculated annually to take account of the changes in traffic/growth over time. The process involves the following
 - ◆ the structural life is determined from the reduction in life as outlined in Section 4.6.2
 - ◆ rehabilitation is triggered when the current remaining structural life is equal to or lower than the user-defined minimum life for rehabilitation
 - resets for roughness, overlay design life and design growth rate, and minimum and maximum intervals between overlay treatments are user-defined
 - the age of the overlay is reset when the treatment is applied. Application of an overlay does not reset the pavement construction age used in determining the annual roughness
 - other input parameters include overlay unit costs (\$/m³), material coefficients, minimum and maximum thicknesses
 - ◆ costs of the surfacing/seal layers should be included in the overlay unit costs.
- Reconstruction treatments are triggered by roughness and/or structural life or age (max Recon structural life, years), and include:
 - minimum interval between construction treatments and maximum reconstruction structural life are user-defined
 - unit costs (\$/m²) are used to indicate typical treatments used by the agency

- resets of pavement age, roughness and structural life (i.e. new design life). The latter two are user-defined and depend on the type of treatment applied.

A flow chart of the maintenance intervention and treatment selection process as applied in FAMLIT has been developed and is presented in Figure 6.3 to assist with understanding the logic outlined in the above sections.

Figure 6.3: Flow chart of FAMLIT maintenance and treatment selection logic



6.3.5 *FAMLIT output records*

Example output records with key section attributes and year-by-year output values are illustrated in the examples provided in Figure 6.4 and Figure 6.5 for the base and alternative cases respectively.

These figures provide the basis to estimate the marginal costs associated with the specified additional loading scenario. The following is noted:

1. The additional traffic loading is applied in the first four years in the alternative case relative to the loading in the base case.
2. Different treatment requirements are selected for each of the defined road sections within each scenario, i.e. for the base case, one section requires a reconstruction treatment in year 1 to accommodate existing traffic and a reseal treatment is required on another section in the first 10 years. In the alternative case a reconstruction treatment is triggered in year 1 for all sections, with this designed to cope with the significant additional traffic loading, in this case the annual loading has increased from approximately 1 000 ESA per year to more 269 000 ESA per year.
3. As a consequence of the triggered treatments, significant improvements in pavement condition are also evident where reconstruction has been triggered with this most evident in the alternative case for roughness (large reduction) and strength (large increase).
4. The costs of the different treatments within the individual cases and between the cases are also shown, with notable differences evident as a result of treatments.

Figure 6.4: Calculated parameters for each individual road section as modelled within FAMLIT over the analysis period for the base case

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
	Show Main Menu		Road	Seal	Dirac	Road																								
	P.S	ID	Pave Ty	Cl	et	waif	Zone	Size (mi)	Sl	Service	Design	R	AA	Sp	§	V	E	Leng	Widd	Tracking	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
2	1	Access R	SS	Access	Flat and Straight	South West	10	4.55	50	2.00	1	1.00	5	5	5	1	3.5	Pavement Type	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
3	1																		Annual SAR	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
4	1																		Strength	4.42	4.39	4.36	4.33	4.30	4.28	4.25	4.22	4.19	4.16	
5	1																		Roughness	2.18	2.23	2.28	2.33	2.38	2.48	2.58	2.68	2.79	2.89	
6	1																		RUC	224	224	225	226	226	227	229	230	231	233	
7	1																		TSRS	6	7	8	9	10	11	12	13	14	15	
8	1																		TSOVL	6	7	8	9	10	11	12	13	14	15	
9	1																		TSRE	6	7	8	9	10	11	12	13	14	15	
10	1																		Routine Cost	3	3	3	3	3	3	3	3	3	3	
11	1																		Reseal Cost	0	0	0	0	0	0	0	0	0	0	
12	1																		Overlay Thickness	0	0	0	0	0	0	0	0	0	0	
13	1																		Overlay Cost	0	0	0	0	0	0	0	0	0	0	
14	1																		Reconstruction Cost	0	0	0	0	0	0	0	0	0	0	
15	2	Access R	SS	Access	Flat and Straight	South West	10.0	4.6	50	4.0	1	1.00	10	25	25	1	3.5	Pavement Type	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
16	2																		Annual SAR	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
17	2																		Strength	3.84	3.80	3.77	3.74	3.71	3.68	3.65	3.62	3.58	3.55	
18	2																		Roughness	4.78	4.88	4.98	5.08	5.19	5.29	5.40	5.50	5.55	5.60	
19	2																		RUC	257	258	260	261	262	263	265	266	267	267	
20	2																		TSRS	11	12	13	14	15	16	17	1	2	3	
21	2																		TSOVL	26	27	28	29	30	31	32	33	34	35	
22	2																		TSRE	26	27	28	29	30	31	32	33	34	35	
23	2																		Routine Cost	3	3	3	3	3	3	3	3	3	3	
24	2																		Reseal Cost	0	0	0	0	0	0	0	22400	0	0	
25	2																		Overlay Thickness	0	0	0	0	0	0	0	0	0	0	
26	2																		Overlay Cost	0	0	0	0	0	0	0	0	0	0	
27	2																		Reconstruction Cost	0	0	0	0	0	0	0	0	0	0	
28	3	Access R	SS	Access	Flat and Straight	South West	10	4.55	50	6.00	1	1.00	10	45	45	1	3.5	Pavement Type	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
29	3																		Annual SAR	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
30	3																		Strength	4.56	4.54	4.51	4.48	4.45	4.43	4.40	4.37	4.34	4.32	
31	3																		Roughness	1.80	1.97	2.02	2.07	2.12	2.17	2.22	2.27	2.32	2.37	
32	3																		RUC	219	221	222	222	223	224	224	225	225	226	
33	3																		TSRS	1	2	3	4	5	6	7	8	9	10	
34	3																		TSOVL	1	2	3	4	5	6	7	8	9	10	
35	3																		TSRE	1	2	3	4	5	6	7	8	9	10	
36	3																		Routine Cost	0	3	3	3	3	3	3	3	3	3	
37	3																		Reseal Cost	0	0	0	0	0	0	0	0	0	0	
38	3																		Overlay Thickness	0	0	0	0	0	0	0	0	0	0	
39	3																		Overlay Cost	0	0	0	0	0	0	0	0	0	0	
40	3																		Reconstruction Cost	131275	0	0	0	0	0	0	0	0	0	

Figure 6.5: Calculated parameters for each individual road section as modelled within FAMLIT over the analysis period for the alternative case

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	
	Section	Ty	Ca	Road Geome	Thornth	Climate	Seal Size (m)	S	Service Life	Design Grov	R	AAD T	Dirction	TSRS	TSO	TSRE	Road Leng	Road Wid	Tracking	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025		
1	1	Access Ro	SS	Access f	Flat and Straight	South Wes	10	4.55	50		2.00	1	1.00	5	5	5	1.000	3.5	Pavement Type	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	
2	1																			Annual SAR	0.269	0.269	0.269	0.269	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
3	1																			Strength	8.30	8.25	8.20	8.15	8.10	8.05	8.00	7.95	7.90	7.85	7.80	
4	1																			Roughness	1.80	1.97	2.02	2.07	2.12	2.17	2.22	2.27	2.32	2.37	2.47	
5	1																			RUC	71,696	72,408	72,619	72,830	223	224	225	225	225	226	227	
6	1																			TSRS	1	2	3	4	5	6	7	8	9	10	11	
7	1																			TSOVL	1	2	3	4	5	6	7	8	9	10	11	
8	1																			TSRE	1	2	3	4	5	6	7	8	9	10	11	
9	1																			Routine Cost	0	832	832	832	3	3	3	3	3	3	3	
10	1																			Reseal Cost	0	0	0	0	0	0	0	0	0	0	0	
11	1																			Overlay Thickness	0	0	0	0	0	0	0	0	0	0	0	
12	1																			Overlay Cost	0	0	0	0	0	0	0	0	0	0	0	
13	1																			Reconstruction Cost	397978	0	0	0	0	0	0	0	0	0	0	
14	1																															
15	2	Access Ro	SS	Access f	Flat and Straight	South Wes	10.0	4.6	50		4.0	1	1.00	10	25	25	1.000	3.5	Pavement Type	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	
16	2																			Annual SAR	0.269	0.269	0.269	0.269	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
17	2																			Strength	8.30	8.25	8.20	8.15	8.10	8.05	8.00	7.95	7.90	7.85	7.80	
18	2																			Roughness	1.80	1.97	2.02	2.07	2.12	2.17	2.22	2.27	2.32	2.37	2.47	
19	2																			RUC	71,696	72,408	72,619	72,830	223	224	224	225	225	226	227	
20	2																			TSRS	1	2	3	4	5	6	7	8	9	10	11	
21	2																			TSOVL	1	2	3	4	5	6	7	8	9	10	11	
22	2																			TSRE	1	2	3	4	5	6	7	8	9	10	11	
23	2																			Routine Cost	0	832	832	832	3	3	3	3	3	3	3	
24	2																			Reseal Cost	0	0	0	0	0	0	0	0	0	0	0	
25	2																			Overlay Thickness	0	0	0	0	0	0	0	0	0	0	0	
26	2																			Overlay Cost	0	0	0	0	0	0	0	0	0	0	0	
27	2																			Reconstruction Cost	397978	0	0	0	0	0	0	0	0	0	0	
28	3	Access Ro	SS	Access f	Flat and Straight	South Wes	10	4.55	50		6.00	1	1.00	10	45	45	1.000	3.5	Pavement Type	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	
29	3																			Annual SAR	0.269	0.269	0.269	0.269	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
30	3																			Strength	8.30	8.25	8.20	8.15	8.10	8.05	8.00	7.95	7.90	7.85	7.80	
31	3																			Roughness	1.80	1.97	2.02	2.07	2.12	2.17	2.22	2.27	2.32	2.37	2.47	
32	3																			RUC	71,696	72,408	72,619	72,830	223	224	224	225	225	226	227	
33	3																			TSRS	1	2	3	4	5	6	7	8	9	10	11	
34	3																			TSOVL	1	2	3	4	5	6	7	8	9	10	11	
35	3																			TSRE	1	2	3	4	5	6	7	8	9	10	11	
36	3																			Routine Cost	0	832	832	832	3	3	3	3	3	3	3	
37	3																			Reseal Cost	0	0	0	0	0	0	0	0	0	0	0	
38	3																			Overlay Thickness	0	0	0	0	0	0	0	0	0	0	0	
39	3																			Overlay Cost	0	0	0	0	0	0	0	0	0	0	0	
40	3																			Reconstruction Cost	397978	0	0	0	0	0	0	0	0	0	0	

6.3.6 Section-level Graphical Results

A selection of section-level results is presented in purpose-built graphs to illustrate condition, strength and agency cost trends. For the loading scenario applied, the responsiveness is very apparent, including:

1. the calculated roughness profile for a selected section under the base and alternative case (Figure 6.6)
2. the calculated strength profile for a selected section under the base and alternative case (Figure 6.7)
3. the network agency costs for a selected section under the base and alternative case (Figure 6.8).

The inspection and illustration of individual record outputs was an important step in validating the reasonableness of the key building blocks of the chosen modelling framework.

Figure 6.6: Calculated roughness profile for a selected section under the base and alternative case

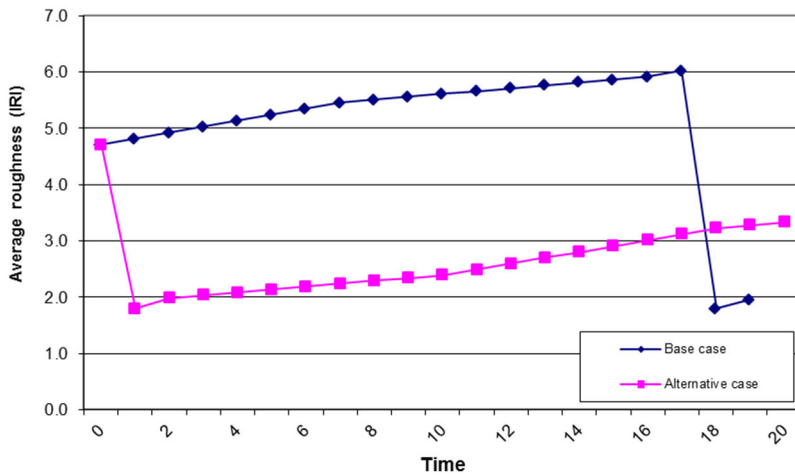


Figure 6.7: Calculated strength profile for a selected section under the base and alternative case

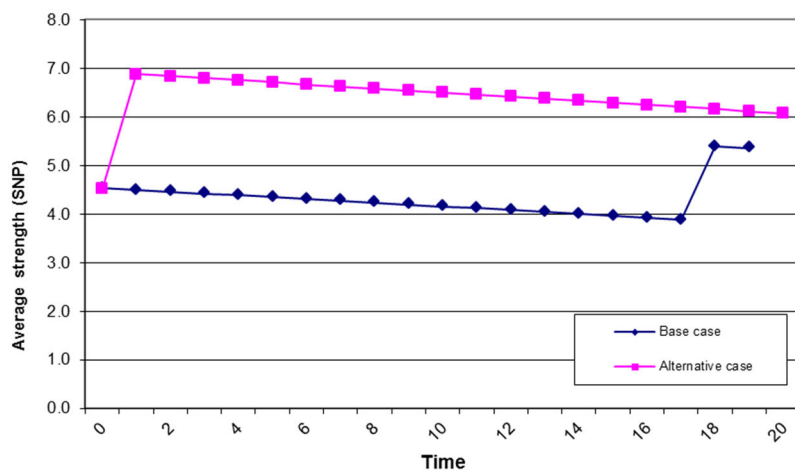
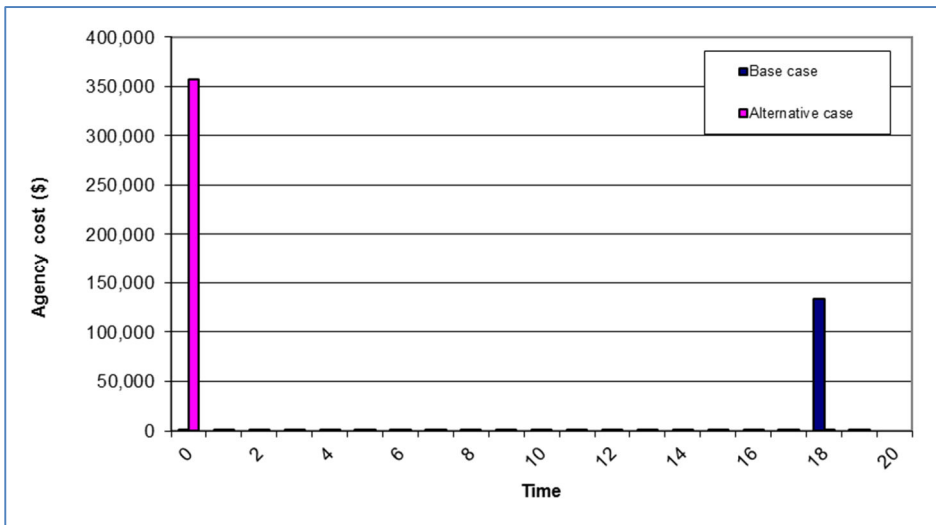


Figure 6.8: Calculated agency costs for both the base and alternative cases



6.3.7 Developing Marginal Costs from the FAMLIT Outputs

Marginal road wear costs are associated with the difference in expenditure required to maintain a pavement under a different loading scenario. In the analyses undertaken and outlined above, the difference in cost can be determined by comparing maintenance costs when a base traffic loading is increased to a substantially higher, and heavier traffic loading (the alternative case).

Furthermore, the time-based distribution of the additional loading can also be determined, with this represented by the difference between the base traffic volume and associated loading that would consume the structural capacity of the selected pavement structures over a 50-year period, i.e. the pavement’s service life, and the alternative case.

To illustrate how the marginal cost is calculated within FAMLIT, an example of the modelled traffic volumes and cumulative cost profiles is presented in Figure 6.9 and Figure 6.10 for an example scenario. In Figure 6.9 the variation in the traffic volume as a result of an additional loading period over the first 10 years of the analysis is shown, after which the traffic volume is modelled to return to the same value as in the base case.

In response to the additional traffic loading requirements shown, the cumulative cost profiles in Figure 6.10 show a greater cost required in the alternative case compared with the base case. The higher costs in the alternative case relative to the base case are due to the higher maintenance needs to deliver the same level of service under the higher loading case relative to the normal loading under the base.

With the modelled year-by-year traffic and cost streams determined, these then need to be discounted as input to Equation 7 to determine the marginal unit cost per ESA. The discounting process simply brings the two modelled streams into present day values and then the ratio of the difference between the two cases facilitates the marginal cost estimate.

Figure 6.9: Traffic volume profiles for the base and alternative cases for a single scenario

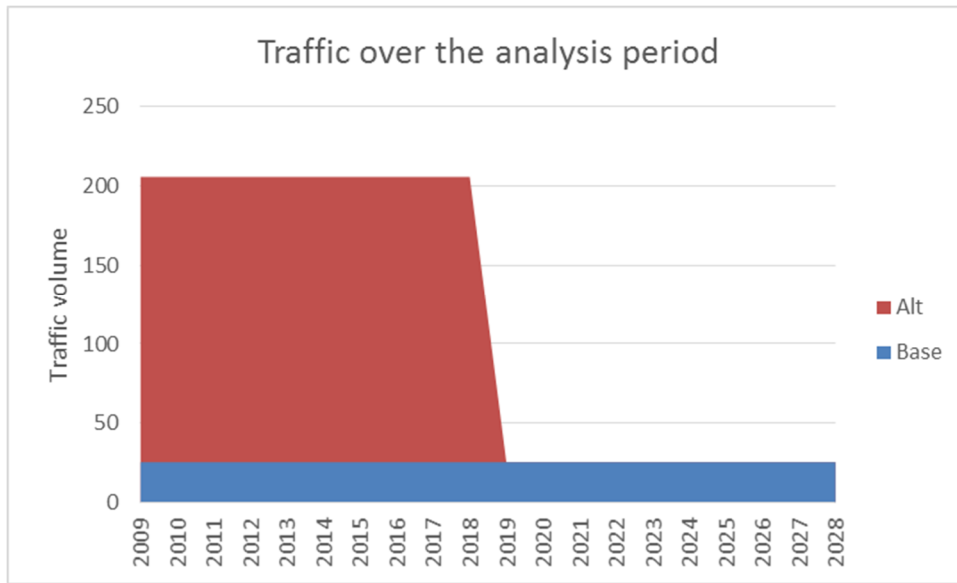
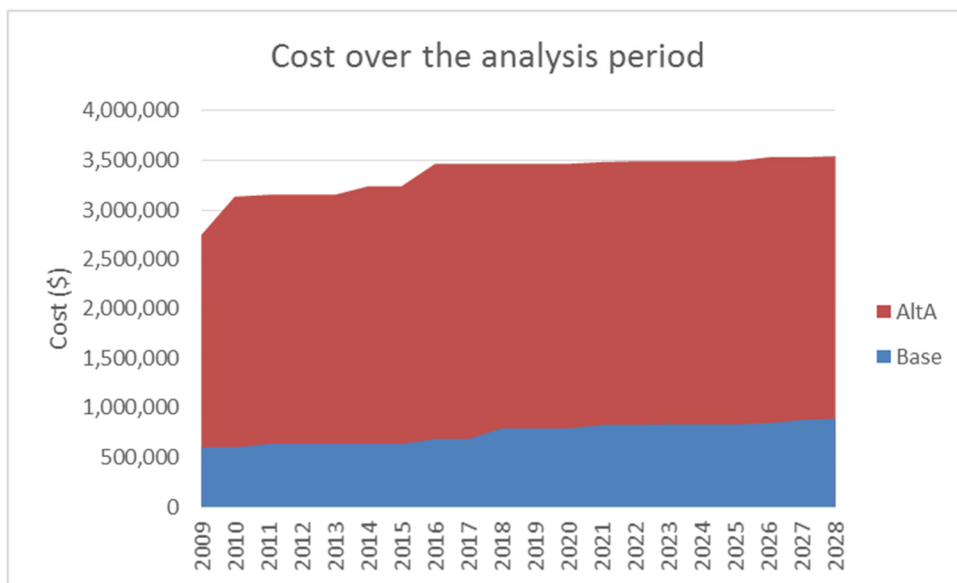


Figure 6.10: Modelled cumulative agency costs for the base and alternative cases for a single scenario



6.4 Generation of the Marginal Cost Charts

The final stage in the determination of the catalogue was to complete the analysis and extract results from each of the FAMLIT runs and store these in a specifically developed FAMLIT marginal cost summary spreadsheet to facilitate the marginal cost reporting requirements of the study.

In so doing, each scenario was represented by combining the results obtained from each representative road network, comprising the matrix of sections with variable surface condition and age states. This ensured that the range of estimated costs matched what would be typically expected on a network of variable initial condition and performance.

This resulted in sufficient analysis results to populate 64 charts comprising a mix of four cost zones, four road classifications and four loading scenarios, with each graph constructed using results representing five loading durations. From these, users can select the chart or charts that are relevant to their specific road network or route to derive an applicable estimated cost of road wear.

As an example of the results, Figure 6.11 presents the summarised data for the estimated annual marginal costs for district distributors located in a single cost zone (1) under the four levels of additional loading. These have all been presented on the one chart to facilitate comparison, whereas the individual charts for each loading scenario are applied in the User Guide. In this example, the trend in marginal costs against increased loading and load duration is clearly illustrated.

In a further example, Figure 6.12 illustrates the summarised data for the total costs estimated for a particular road class and loading scenario, as evaluated for the different cost zones. In this case, the access road for a loading scenario of 200 000 additional ESA has been employed.

Figure 6.11: Annual marginal costs for district distributors in cost zone 1 for the different loading scenarios

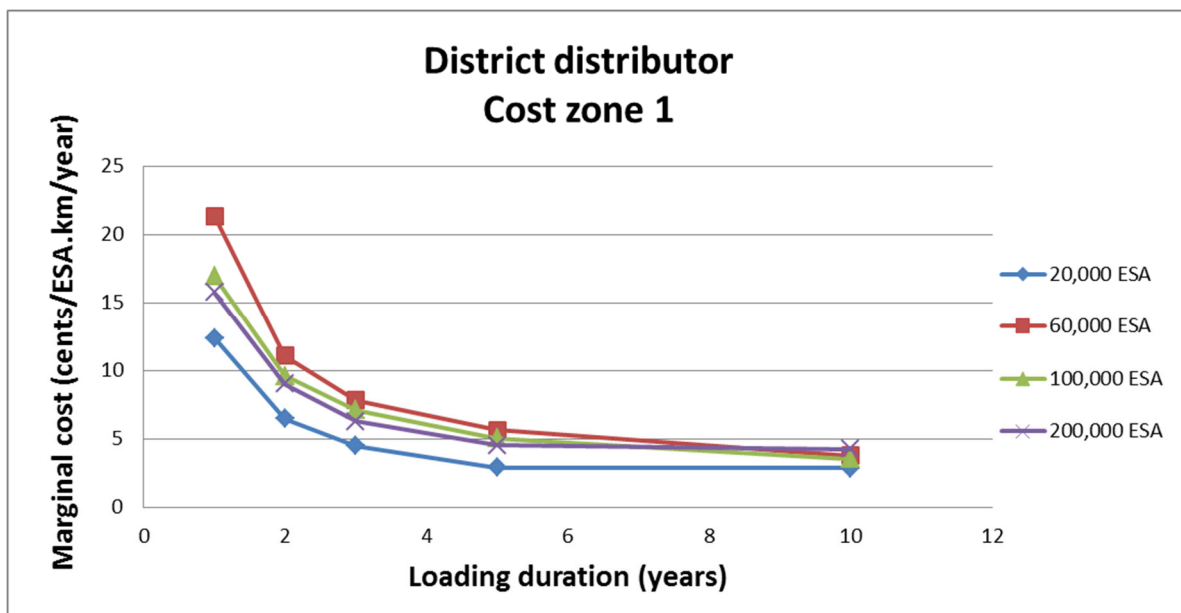
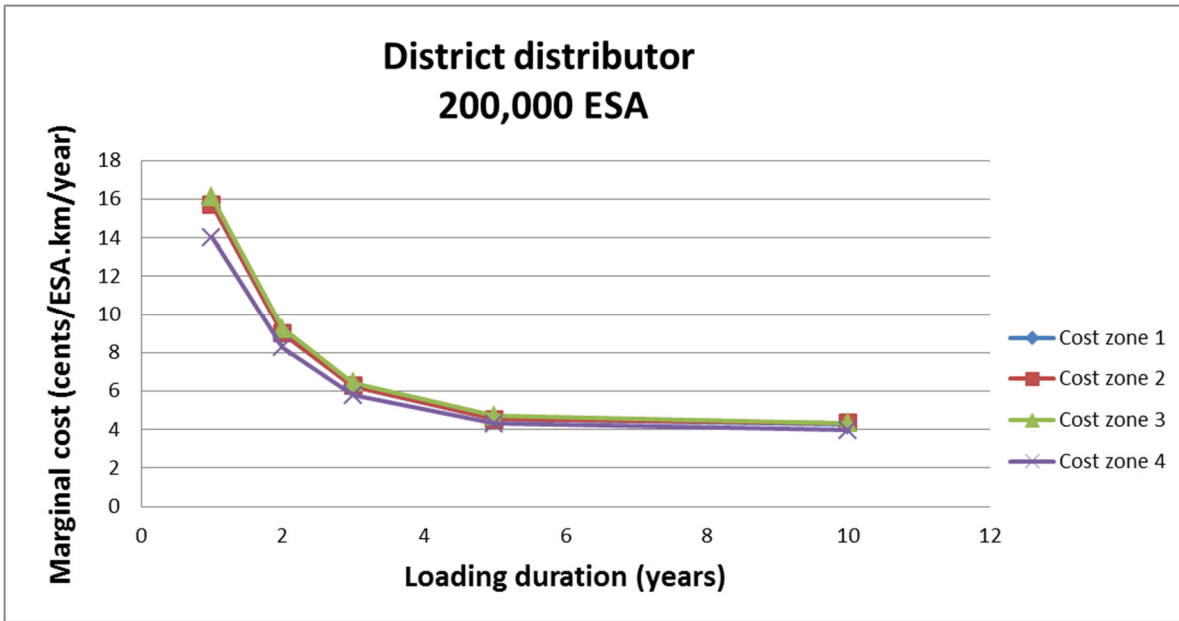


Figure 6.12: Cost zone comparison for marginal costs for a district distributor road per kilometre of road in the different cost zones



7 RECOMMENDATIONS

Recommendations for further development of this work include:

1. Extension of the scope of application to include unsealed roads and asphalt surfaced pavements, noting the following considerations:
 - (a) Unsealed roads comprise a large proportion of the LG network and are routinely subject to use by freight vehicles with significant damage often resulting. Pilot studies of applying marginal cost principles have been undertaken in other jurisdictions, and performance models are available from LRDS and international studies and would provide an appropriate starting point.
 - (b) Asphalt surfaced roads are common in LG urban and sub-urban areas and often carry heavy loads, during the development of sub-divisions and as access roads. They are also susceptible to fatigue, and shear failure under high stresses and temperatures. Design solutions and costs also differ, with a need for sufficient support and high stability mixes to prevent premature failure.
2. Consideration of circumstances where general assumptions are likely to differ significantly from local conditions, including:
 - (a) Road sections and regions with high water-tables or subject to inundation, sensitive soils, and those where pavement standards are known to be particularly low.
 - (b) Circumstances of extreme loading which are beyond the scope of the current catalogue, and its technical basis.
3. Perform a project-level assessment and user survey to assess model-generated costs with actual costs.

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APPENDIX A SUMMARY COST ZONE OUTPUTS

Appendix A provides the generated charts for the road class and cost zone combinations for the three result types. These include the raw estimated marginal costs reported per year of loading, the factored-up marginal costs for the specified loading duration, and the total costs factored up to report the cost in dollars per kilometre.

A.1 Marginal Cost (Cents/ESA.km/year)

Figure A 1: Marginal cost chart for district distributors in cost zone 1

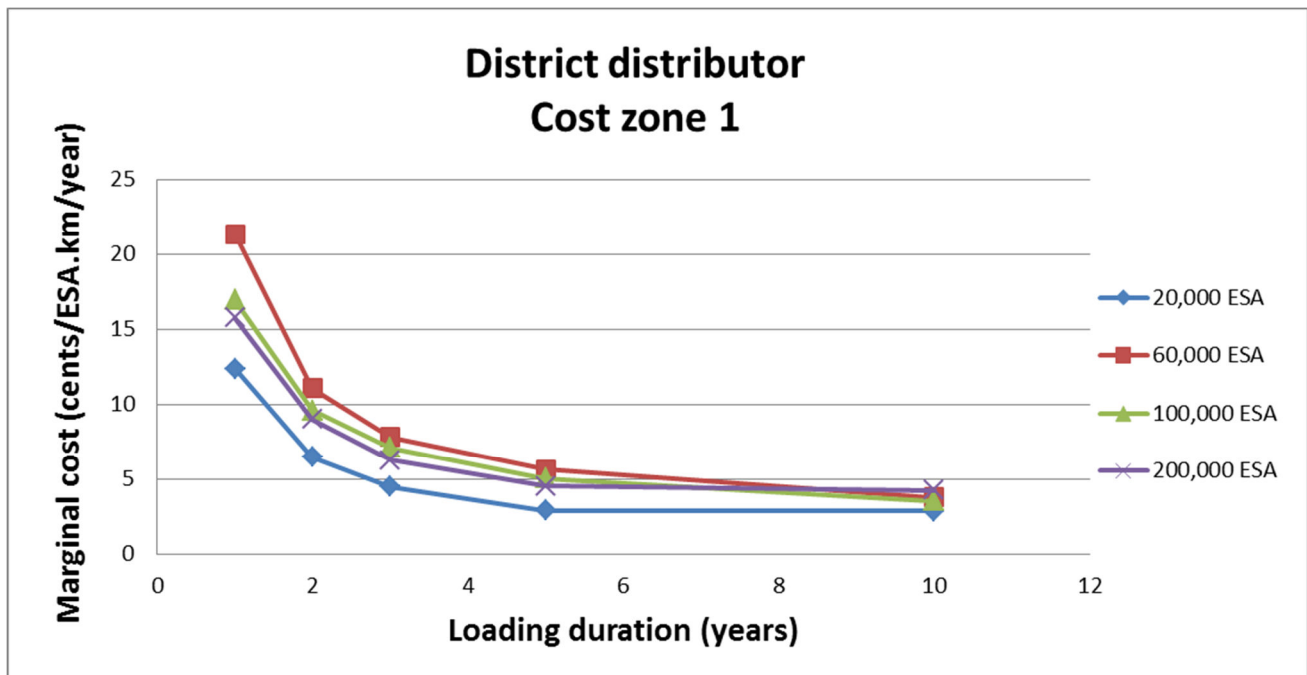


Figure A 2: Marginal cost chart for regional distributors in cost zone 1

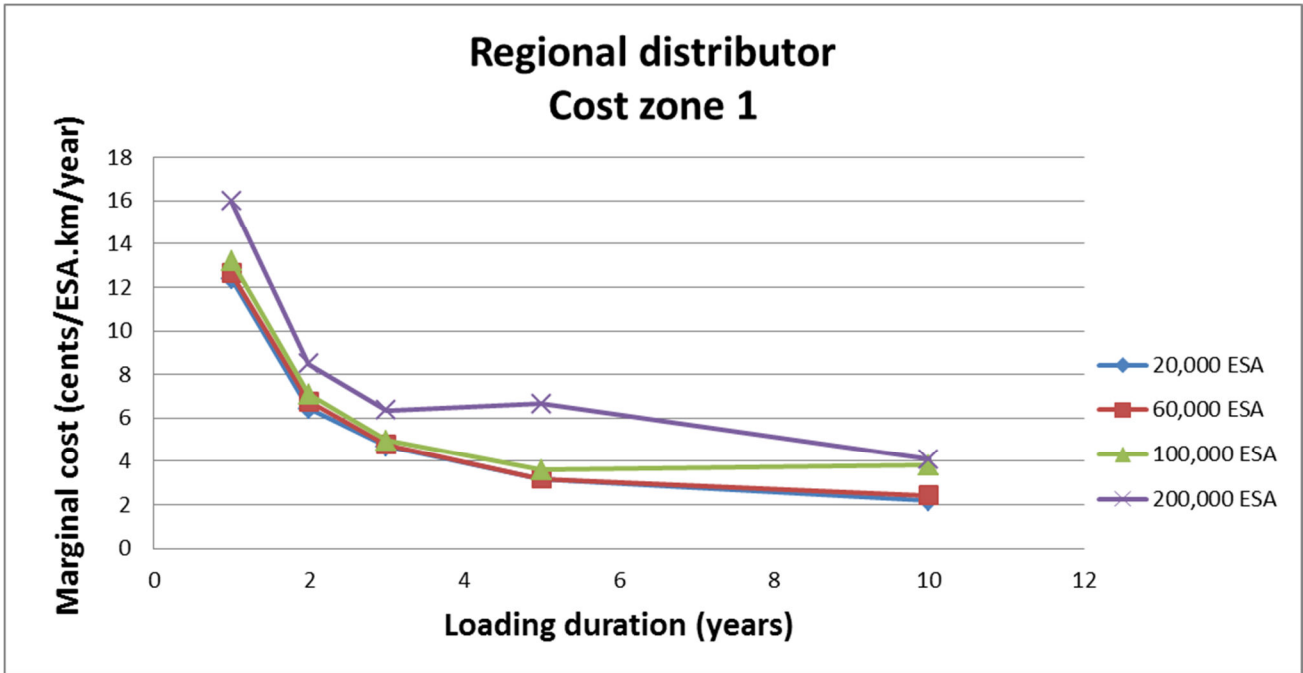


Figure A 3: Marginal cost chart for local distributors in cost zone 1

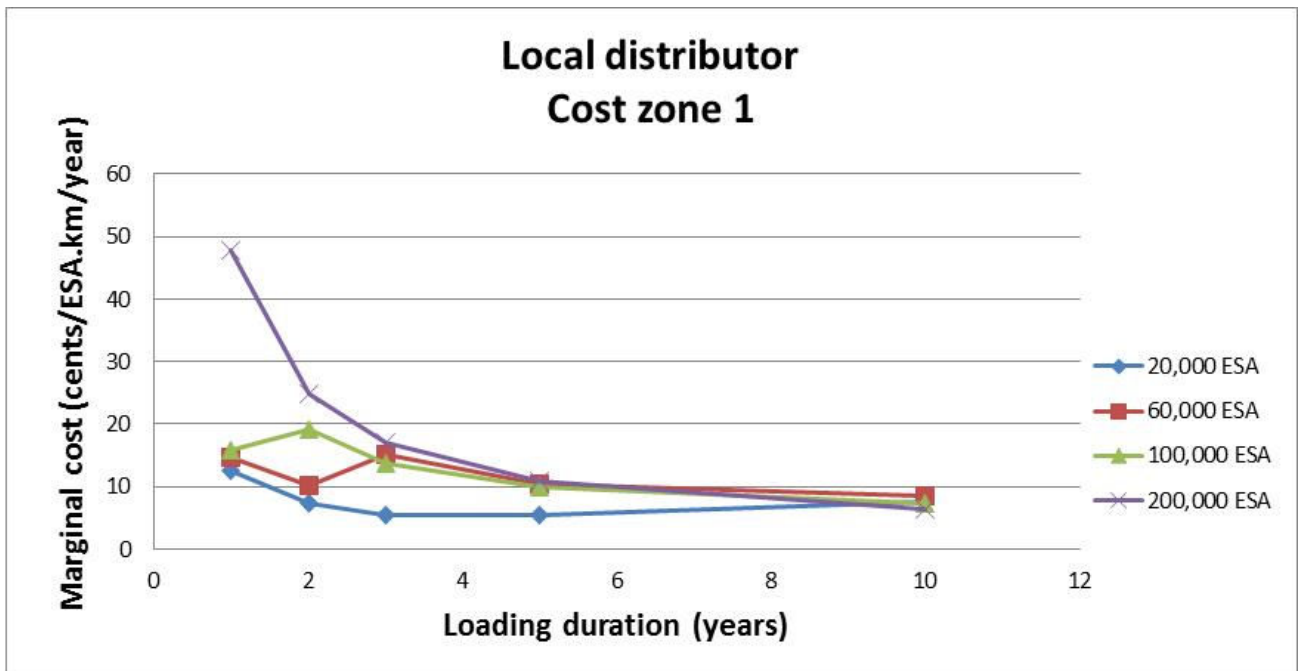


Figure A 4: Marginal cost chart for access roads in cost zone 1

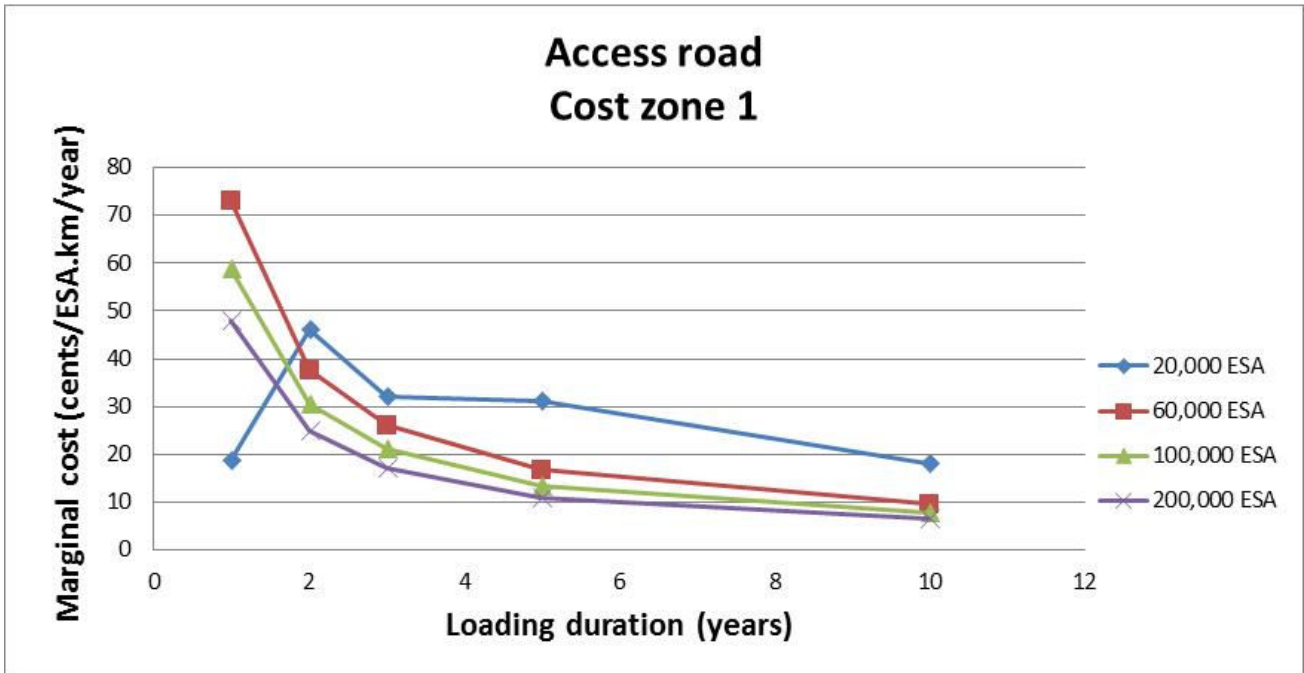


Figure A 5: Marginal cost chart for district distributors in cost zone 2

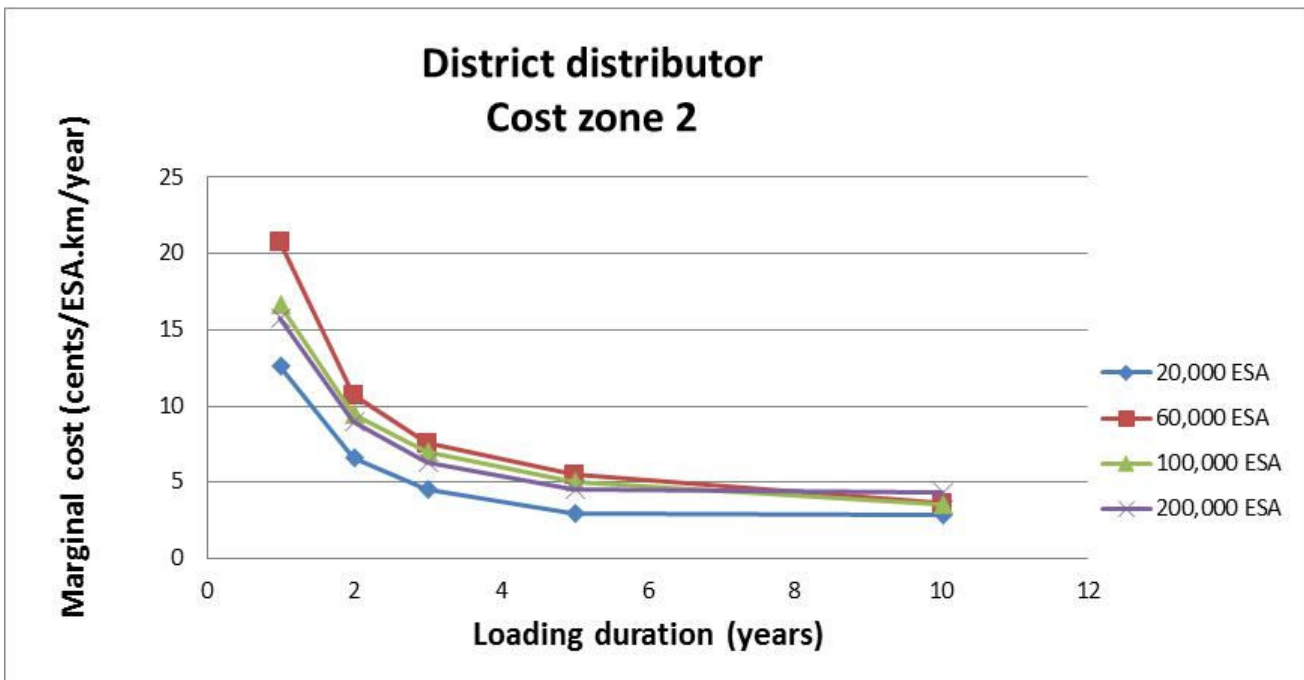


Figure A 6: Figure C1.1: Marginal cost chart for regional distributors in cost zone 2

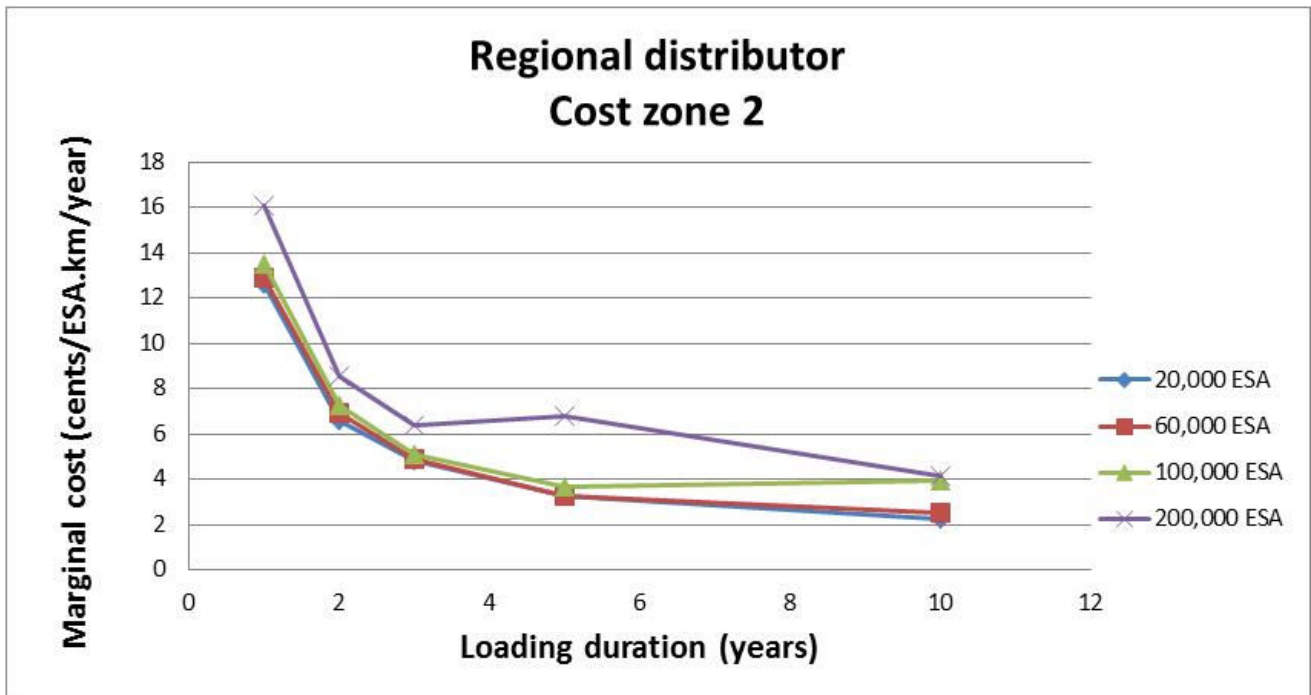


Figure A 7: Figure C1.2: Marginal cost chart for local distributors in cost zone 2

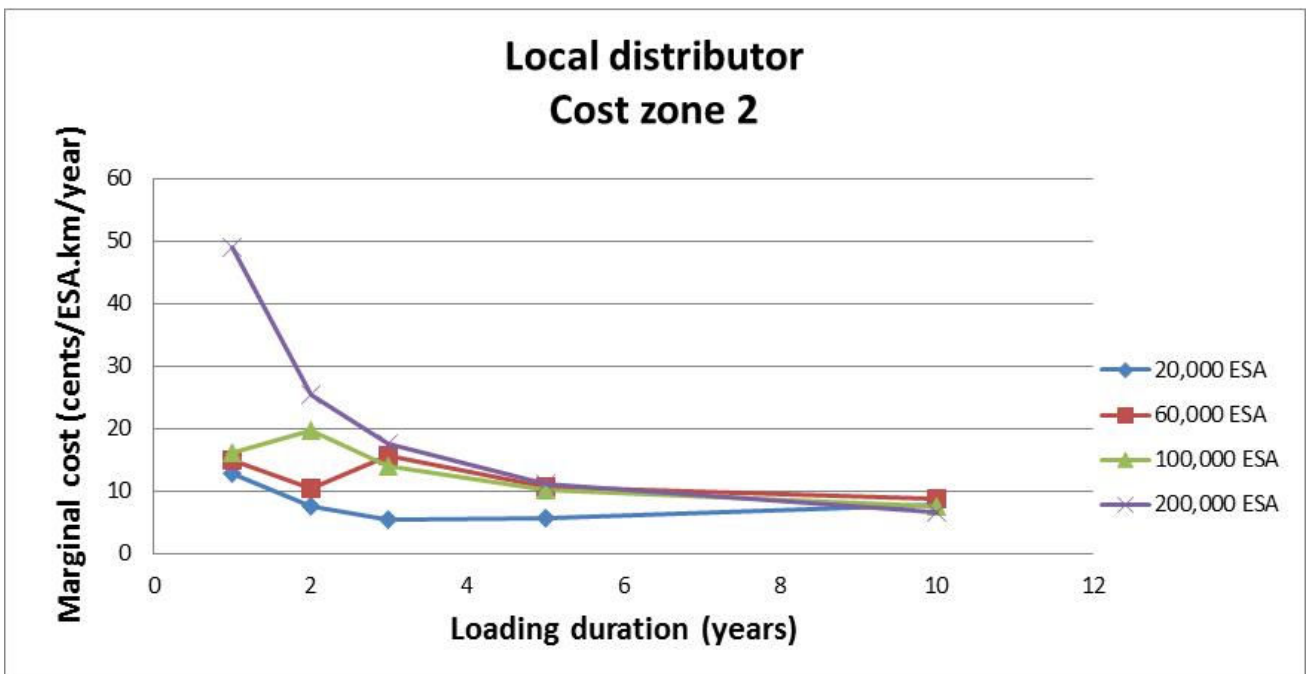


Figure A 8: Marginal cost chart for access roads in cost zone 2

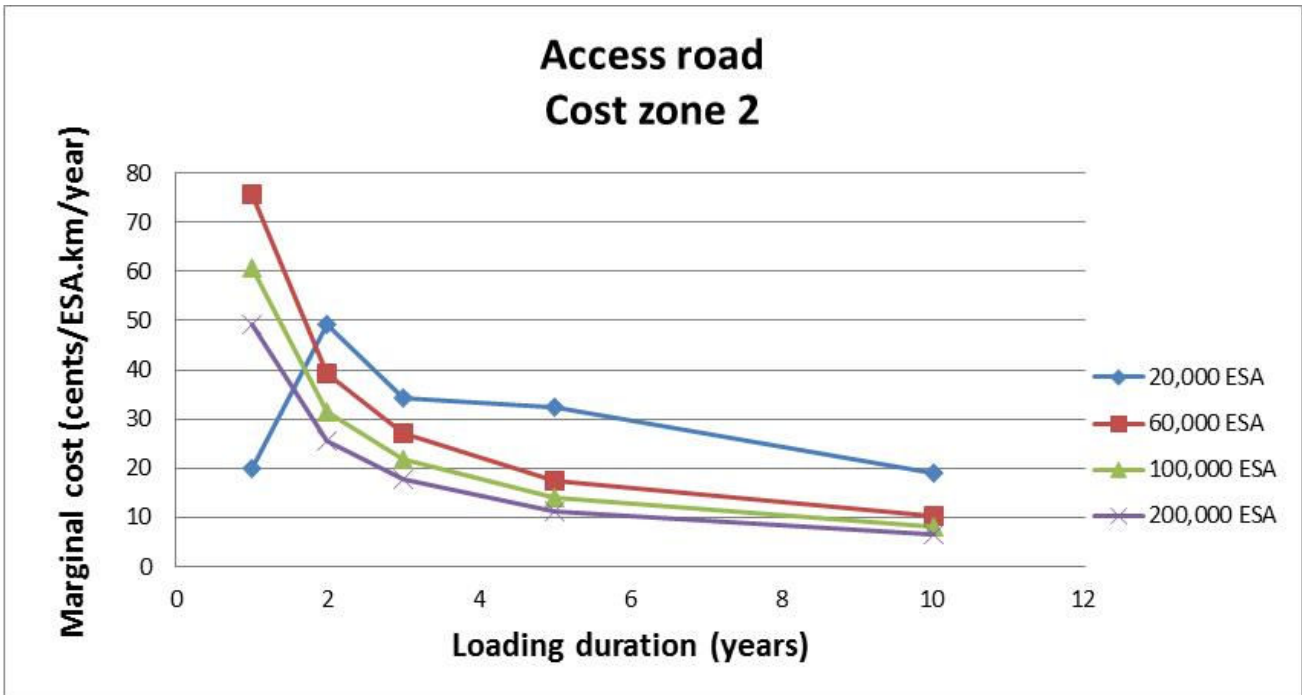


Figure A 9: Marginal cost chart for district distributors in cost zone 3

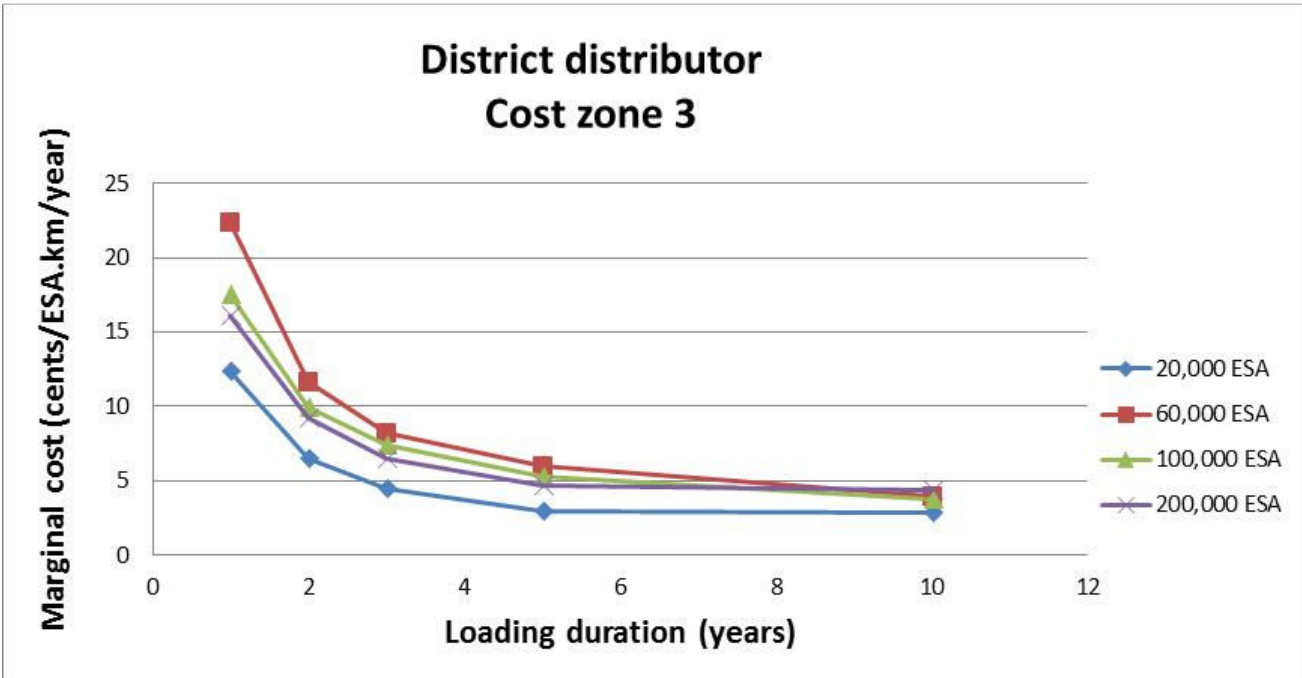


Figure A 10: Marginal cost chart for regional distributors in cost zone 3

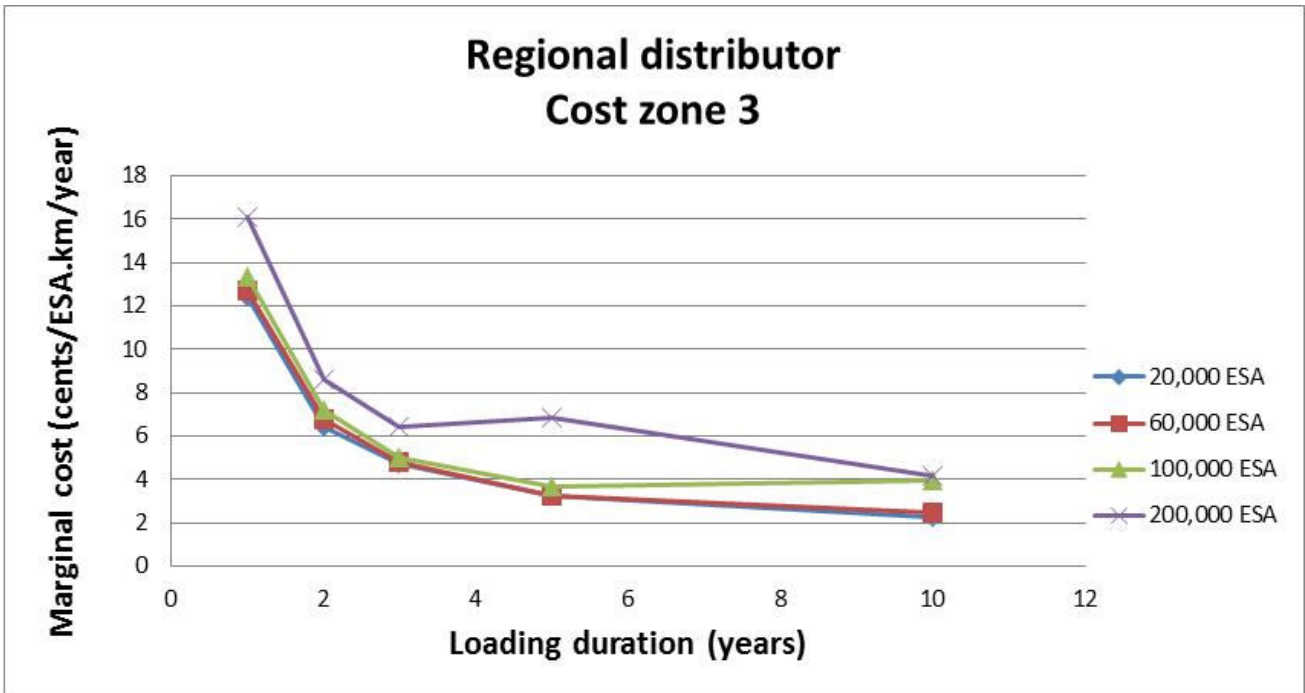


Figure A 11: Marginal cost chart for local distributors in cost zone 3

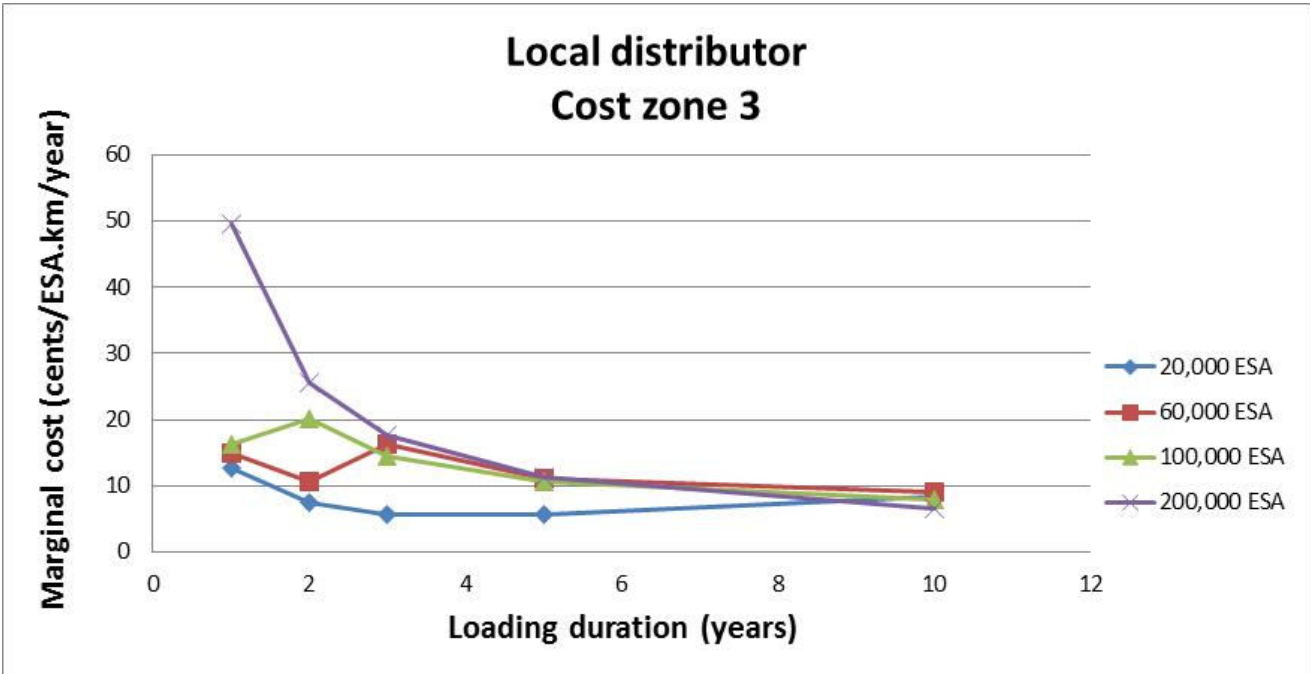


Figure A 12: Marginal cost chart for access roads in cost zone 3

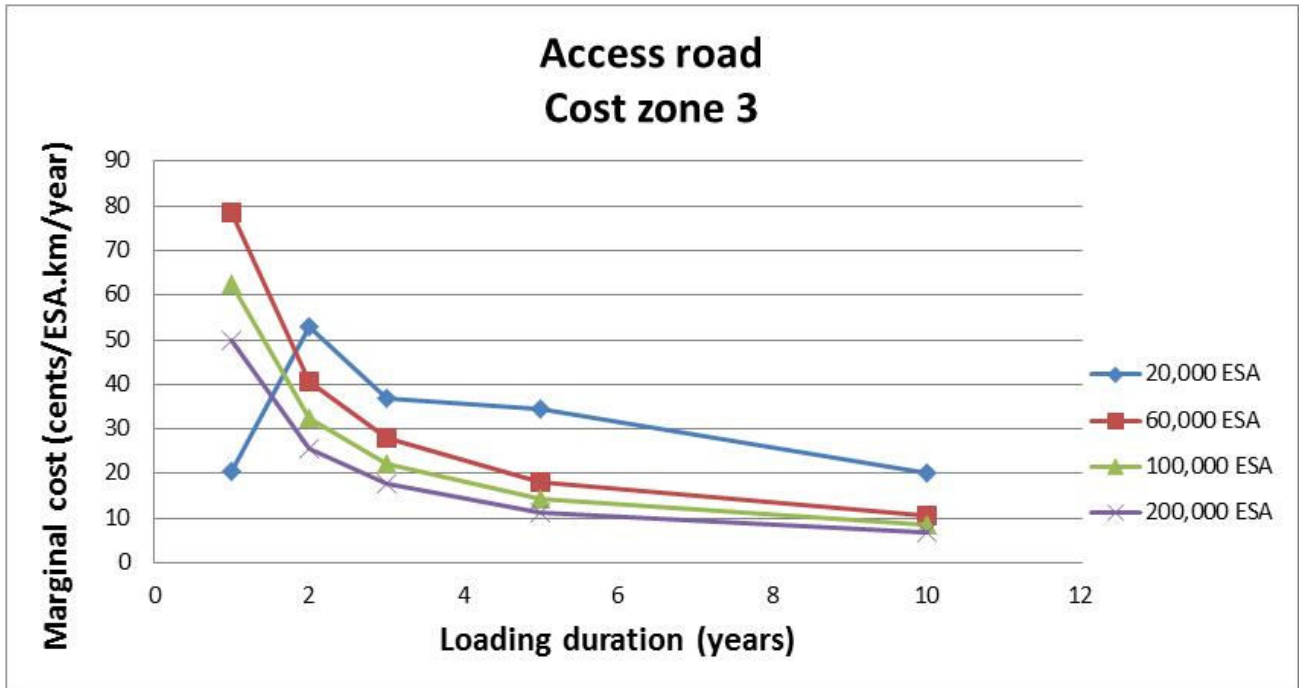


Figure A 13: Marginal cost chart for district distributors in cost zone 4

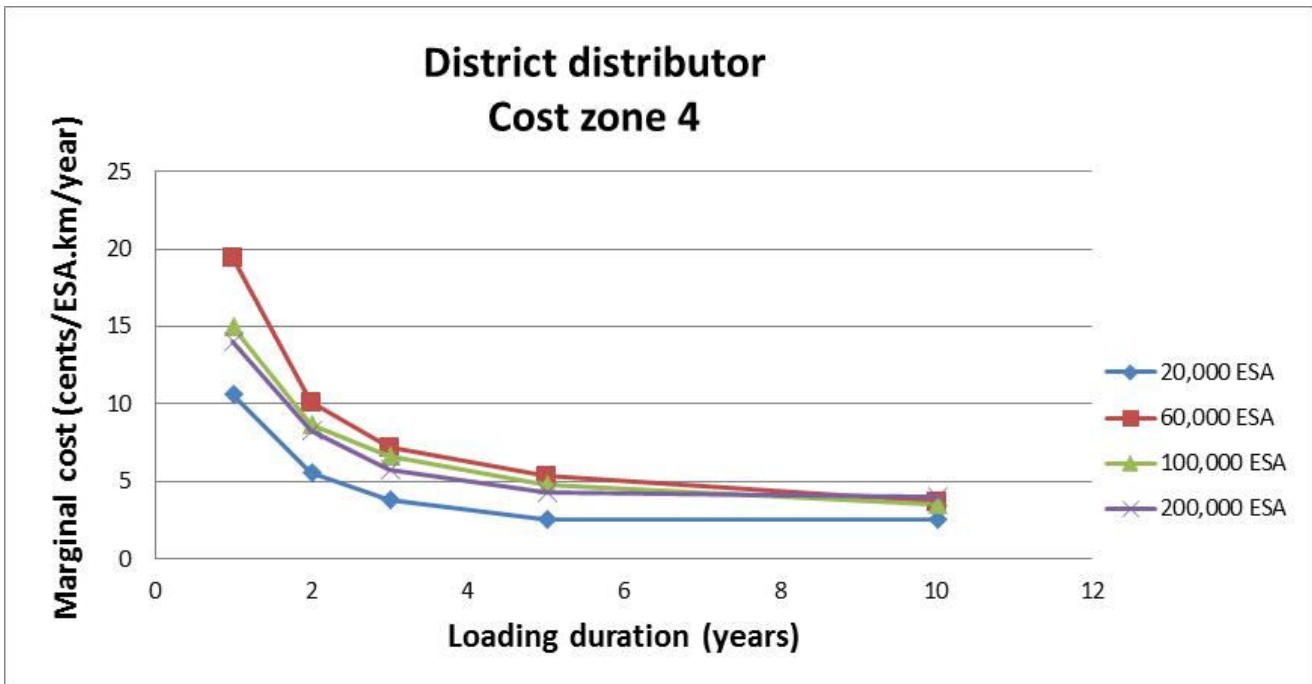


Figure A 14: Marginal cost chart for regional distributors in cost zone 4

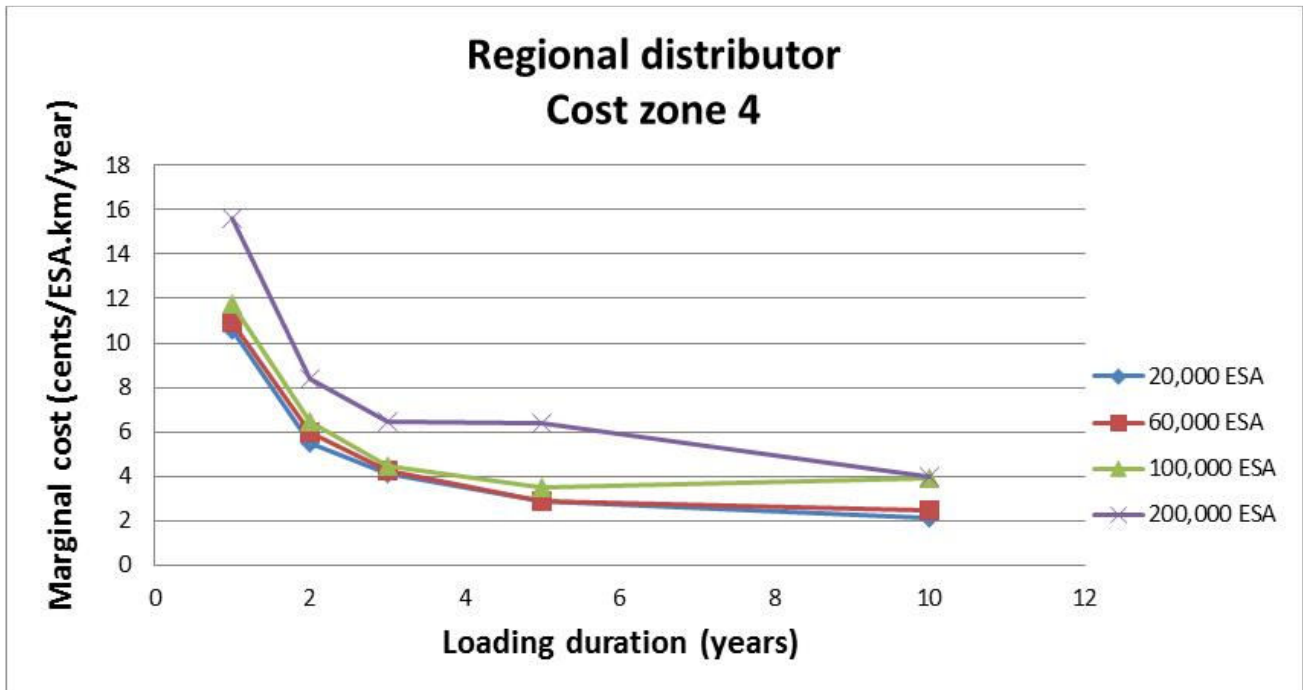


Figure A 15: Marginal cost chart for local distributors in cost zone 4

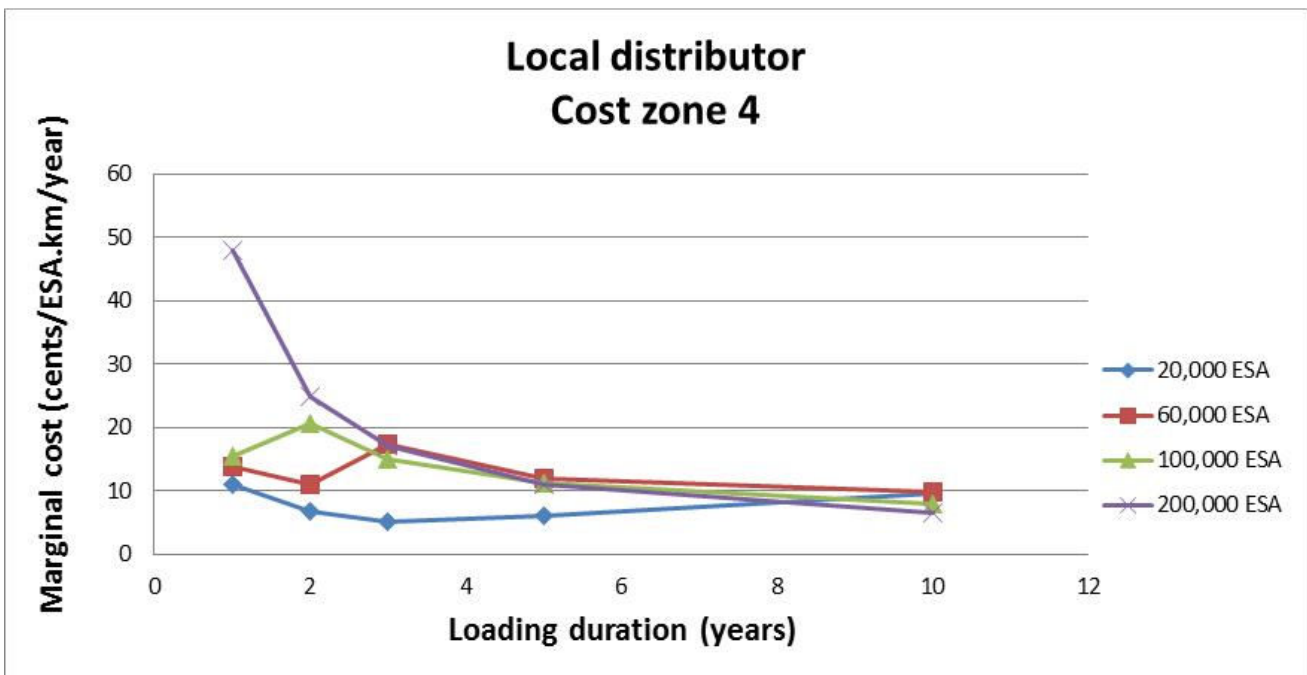
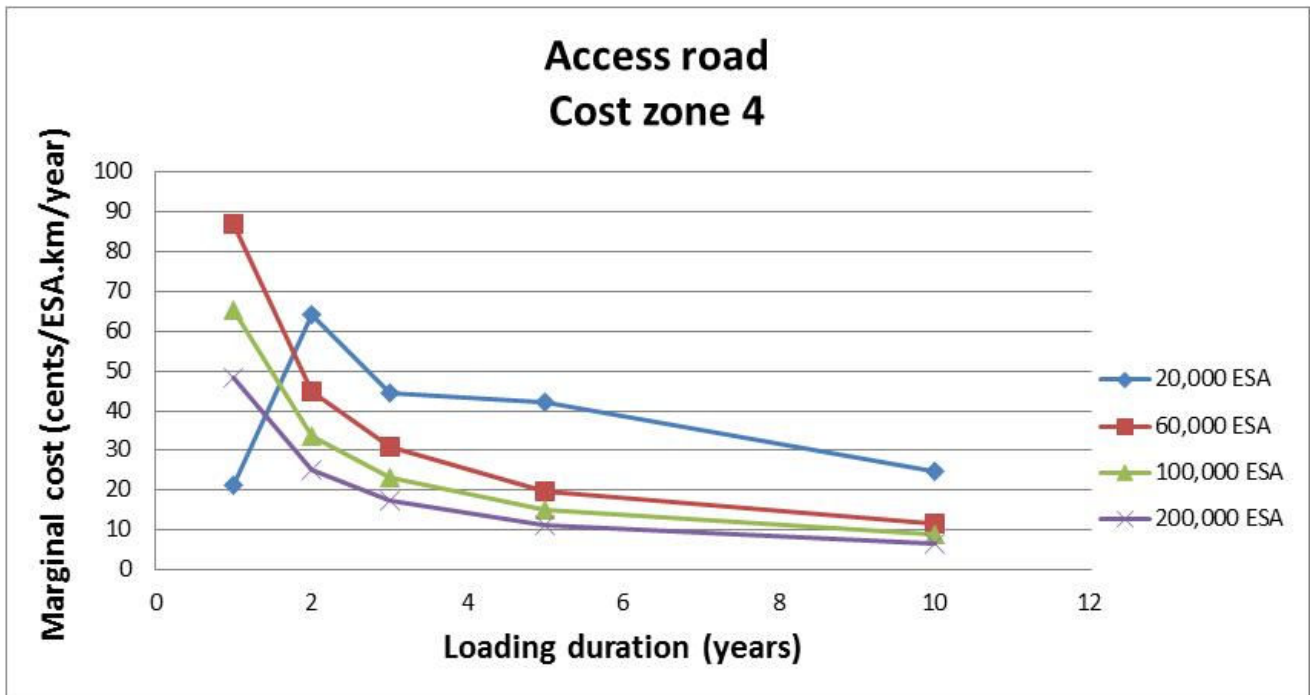


Figure A 16: Marginal cost chart for access roads in cost zone 4



A.2 Marginal Cost Total (Cents/esa.km)

Figure A 17: Marginal cost total chart for district distributors in cost zone 1

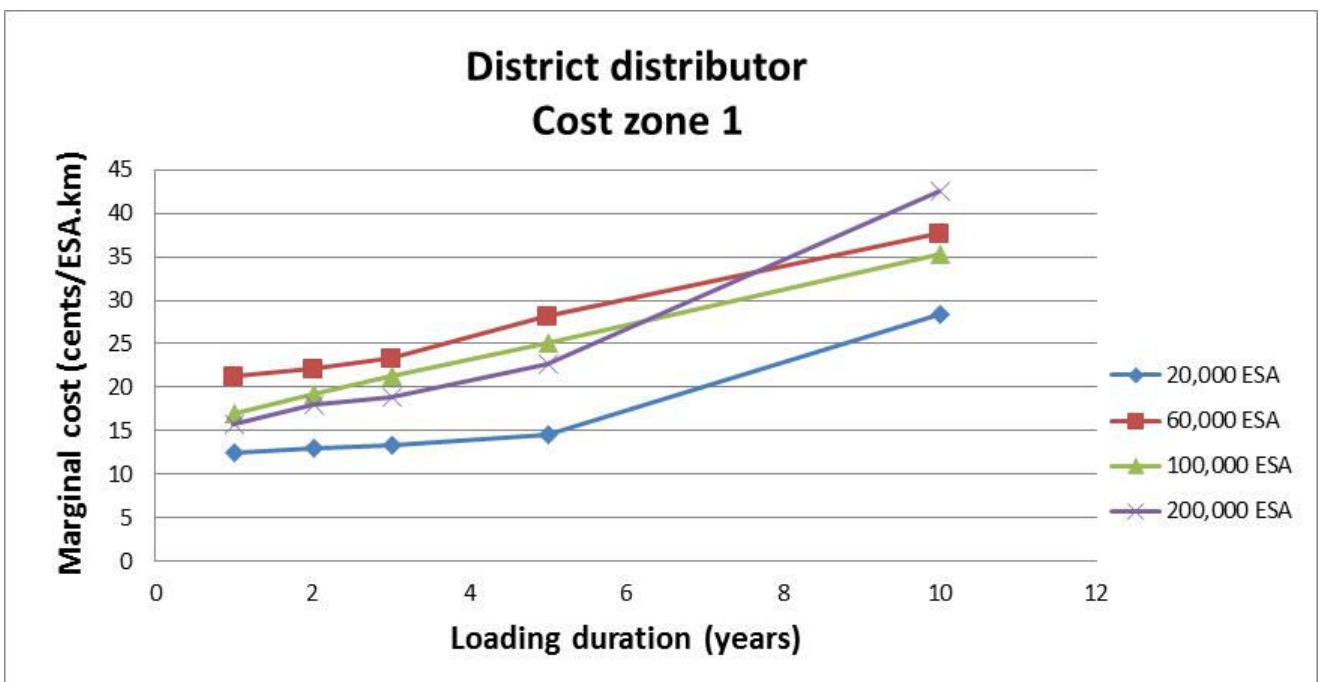


Figure A 18: Marginal cost total chart for regional distributors in cost zone 1

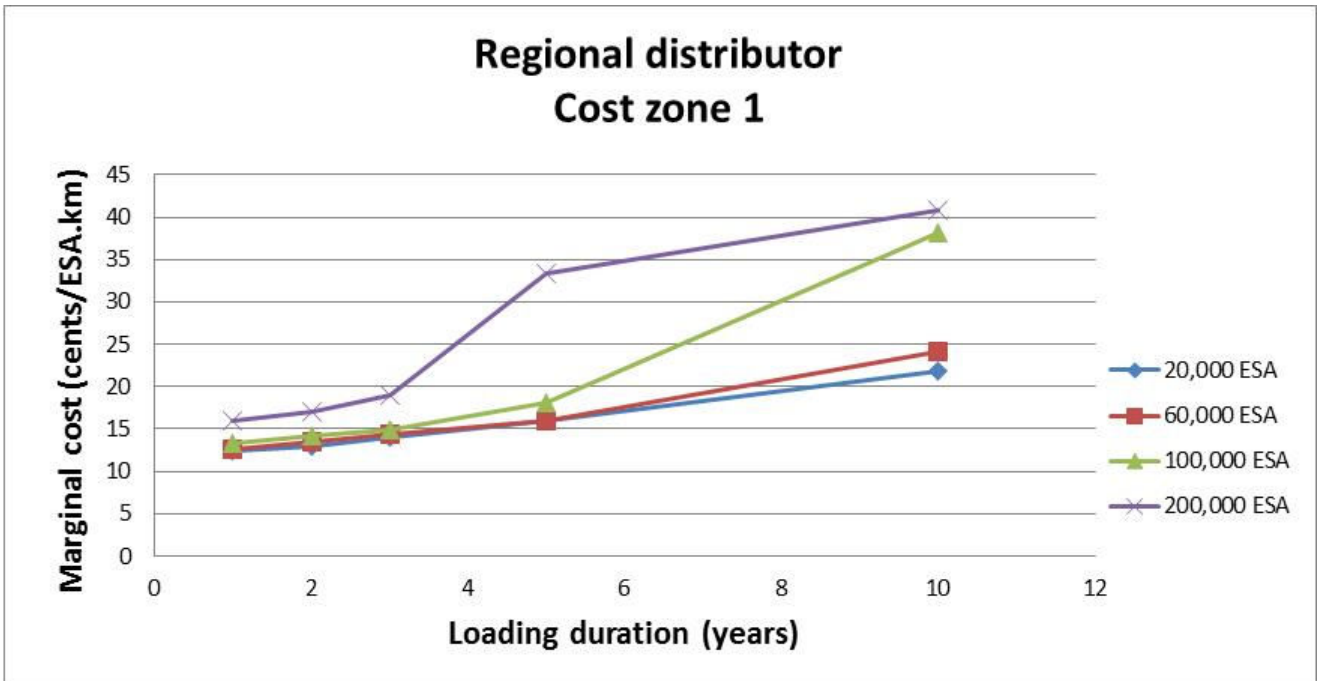


Figure A 19: Marginal cost total chart for local distributors in cost zone 1

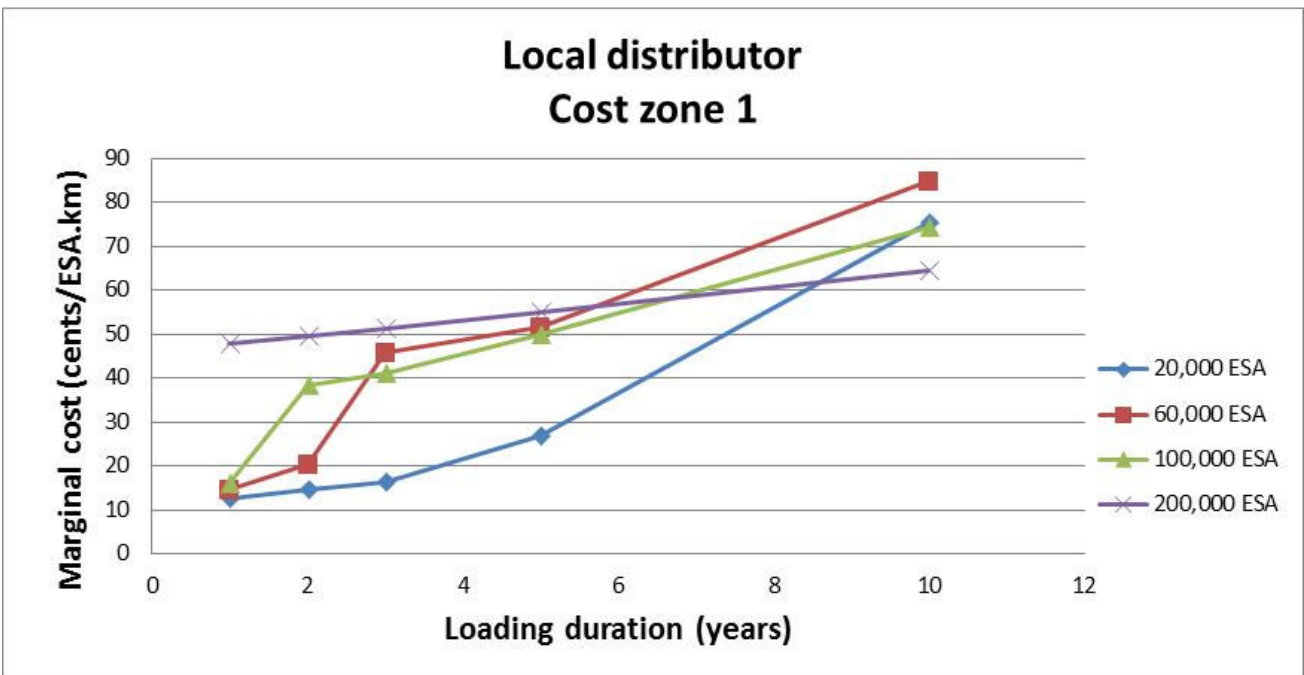


Figure A 20: Marginal cost total chart for access roads in cost zone 1

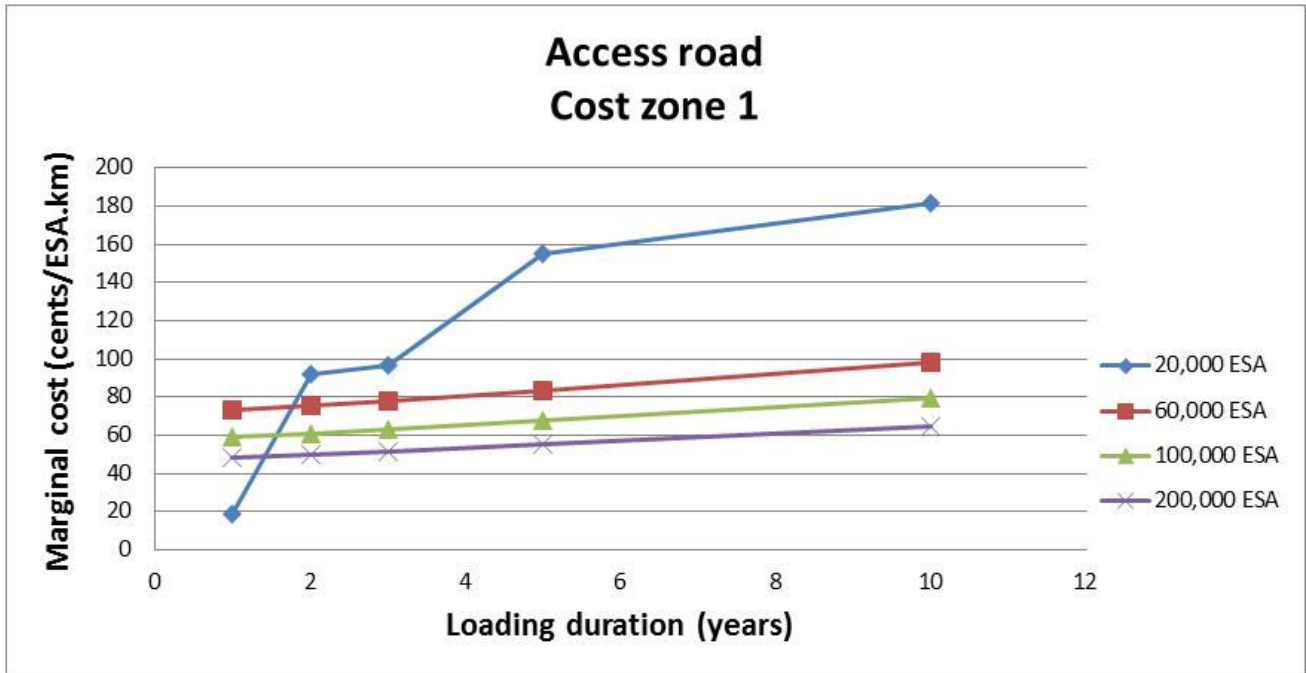


Figure A 21: Marginal cost total chart for district distributors in cost zone 2

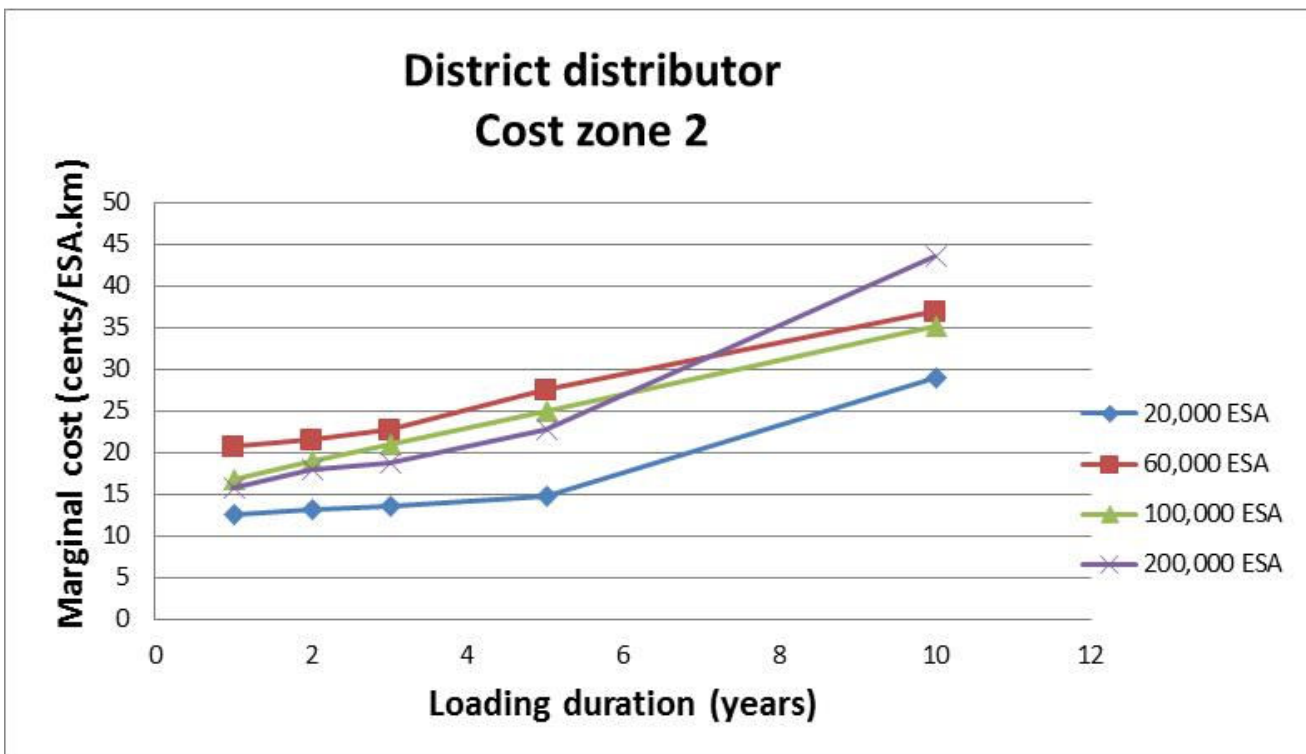


Figure A 22: Marginal cost total chart for regional distributors in cost zone 2

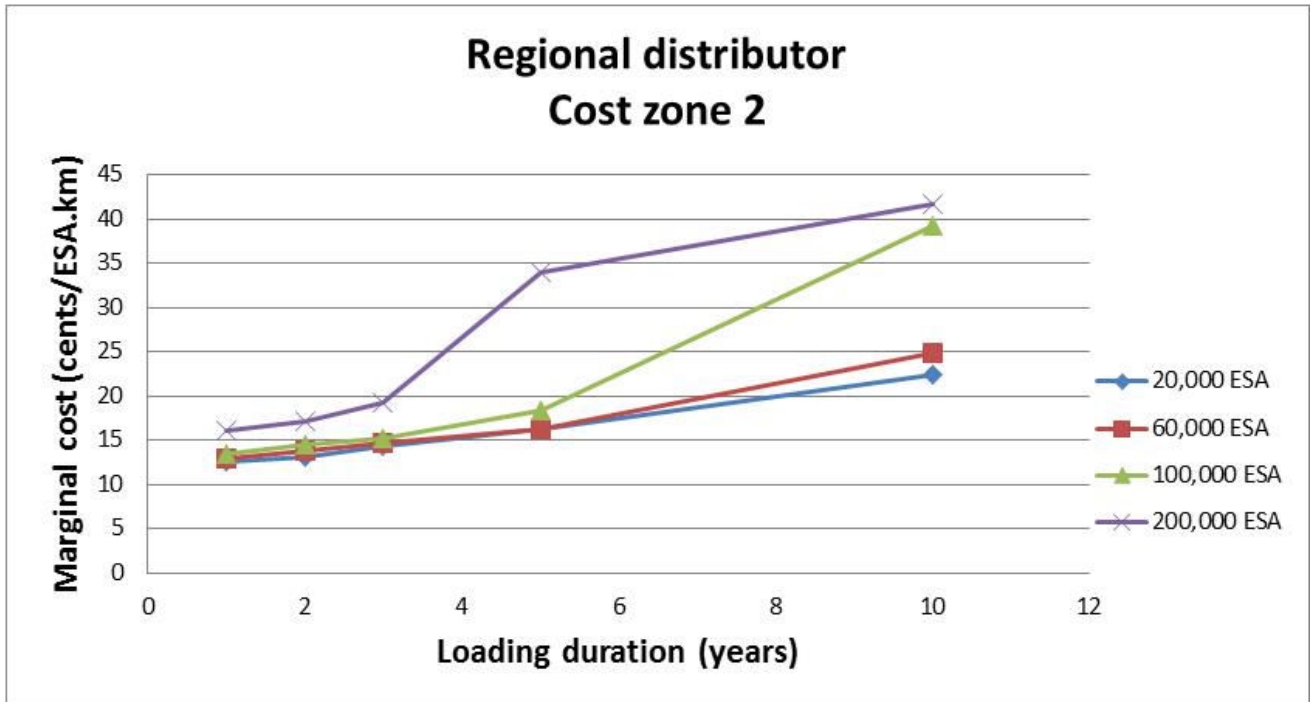


Figure A 23: Marginal cost total chart for local distributors in cost zone 2

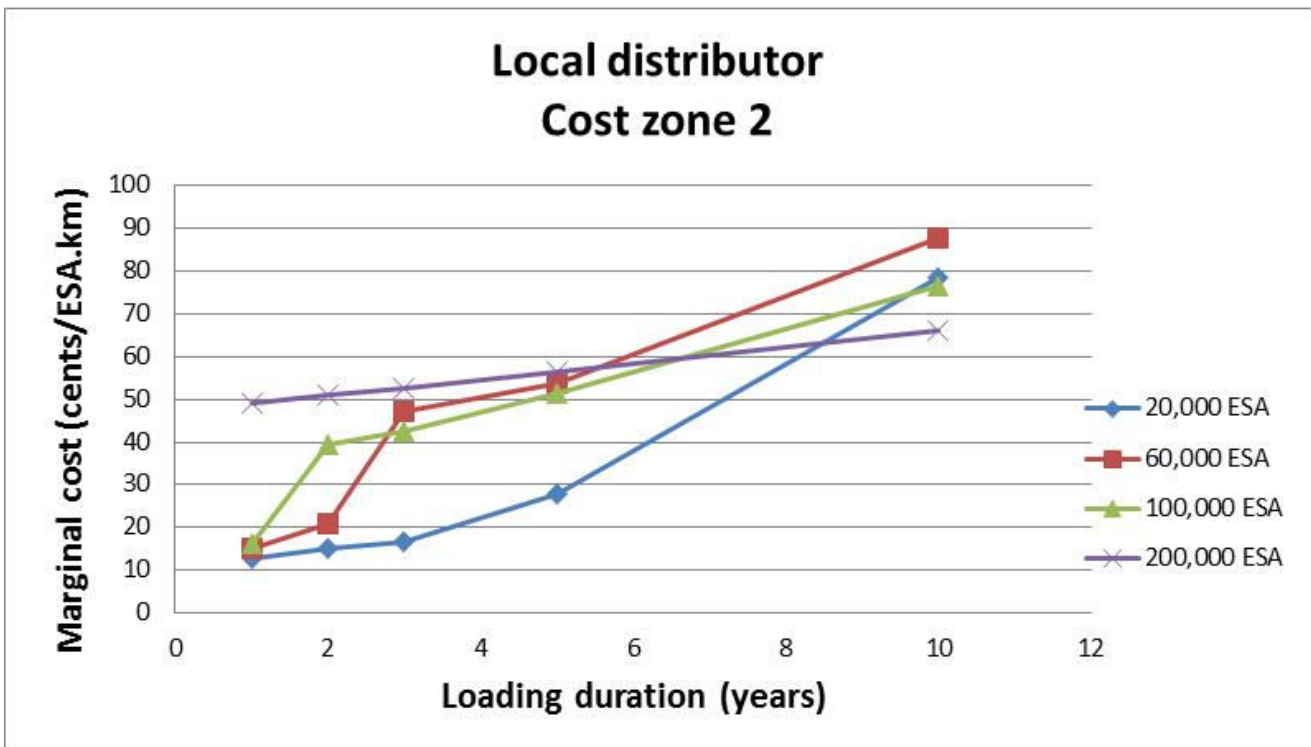


Figure A 24: Marginal cost total chart for access roads in cost zone 2

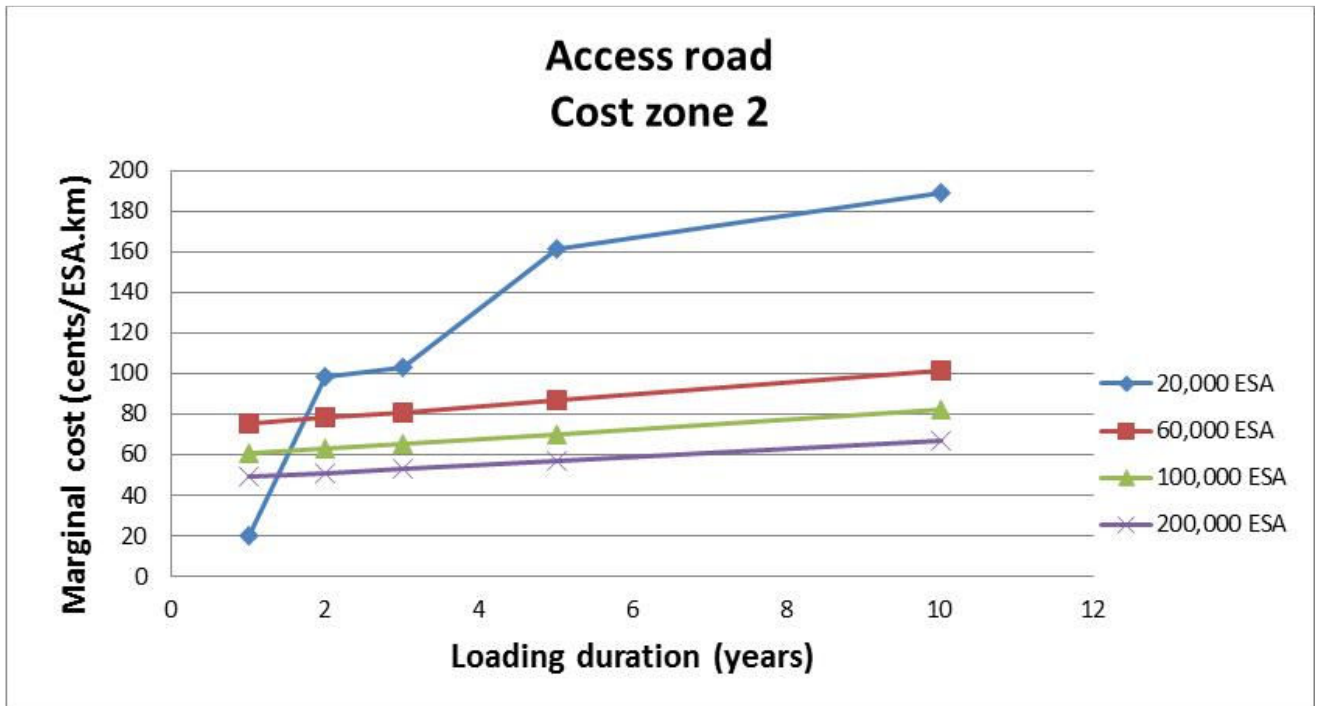


Figure A 25: Marginal cost total chart for district distributors in cost zone 3

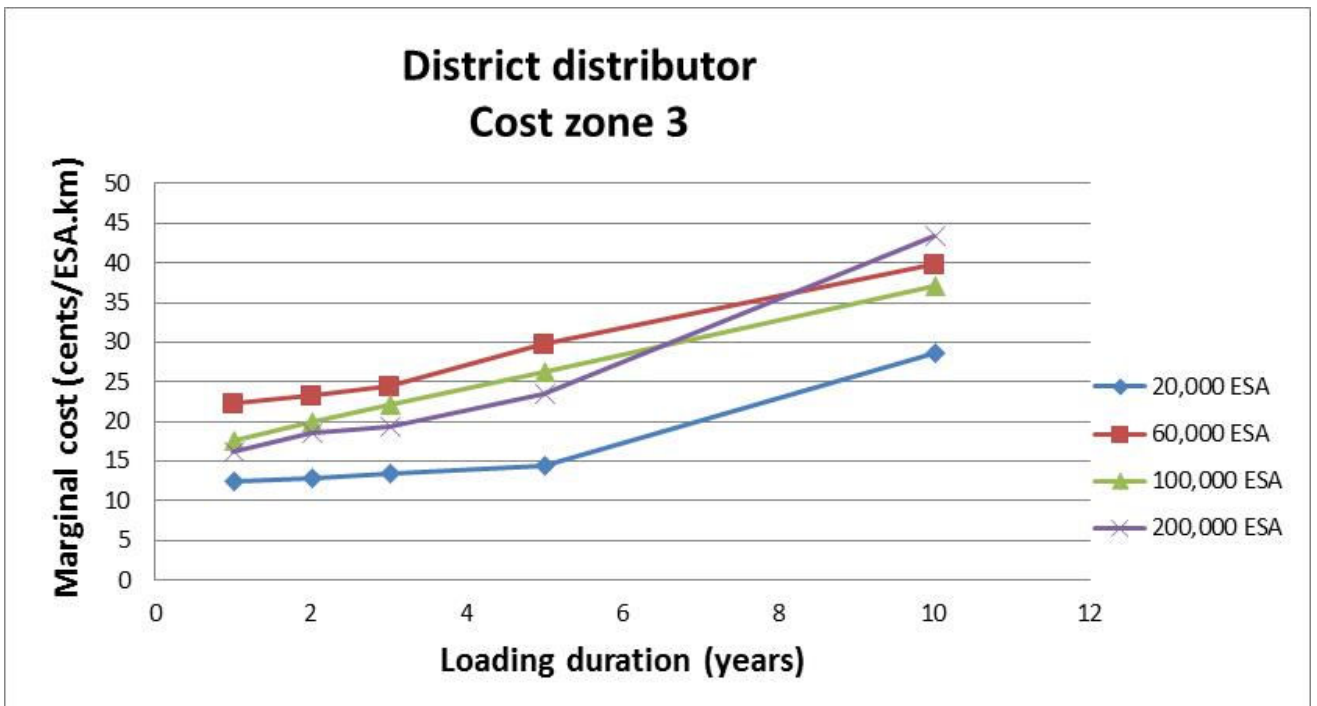


Figure A 26: Marginal cost total chart for regional distributors in cost zone 3

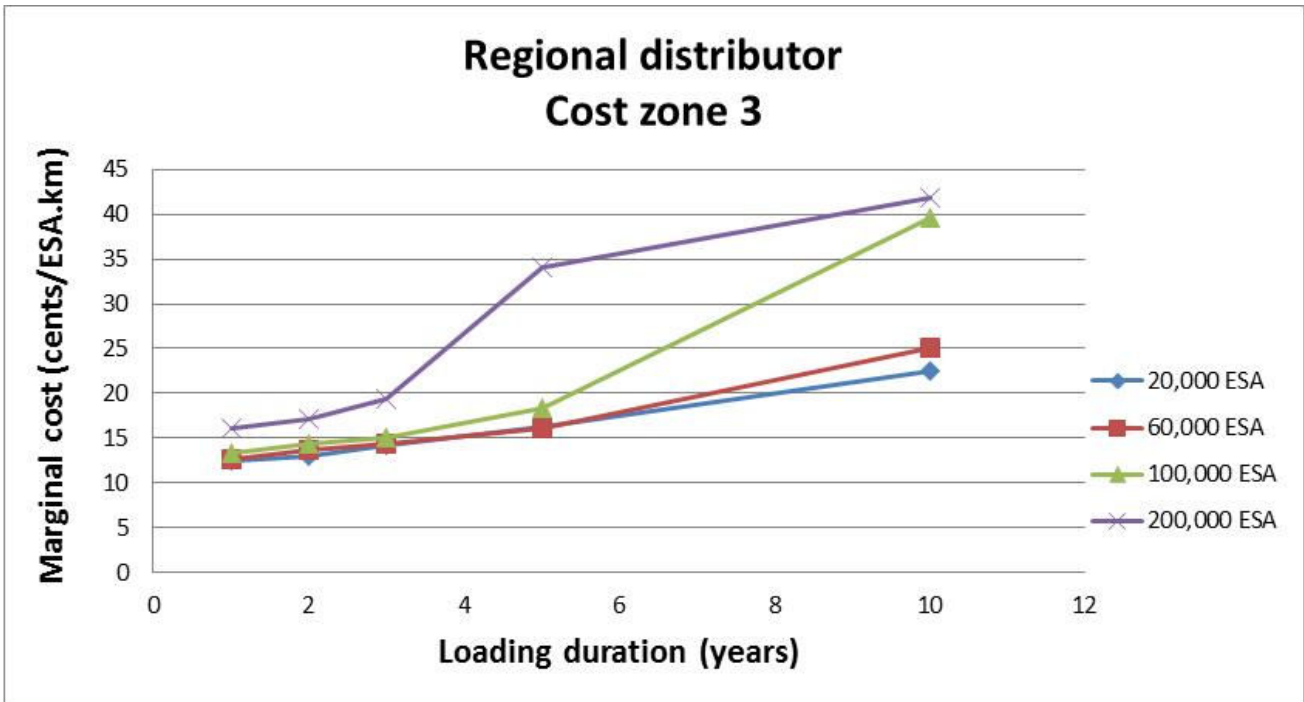


Figure A 27: Marginal cost total chart for local distributors in cost zone 3

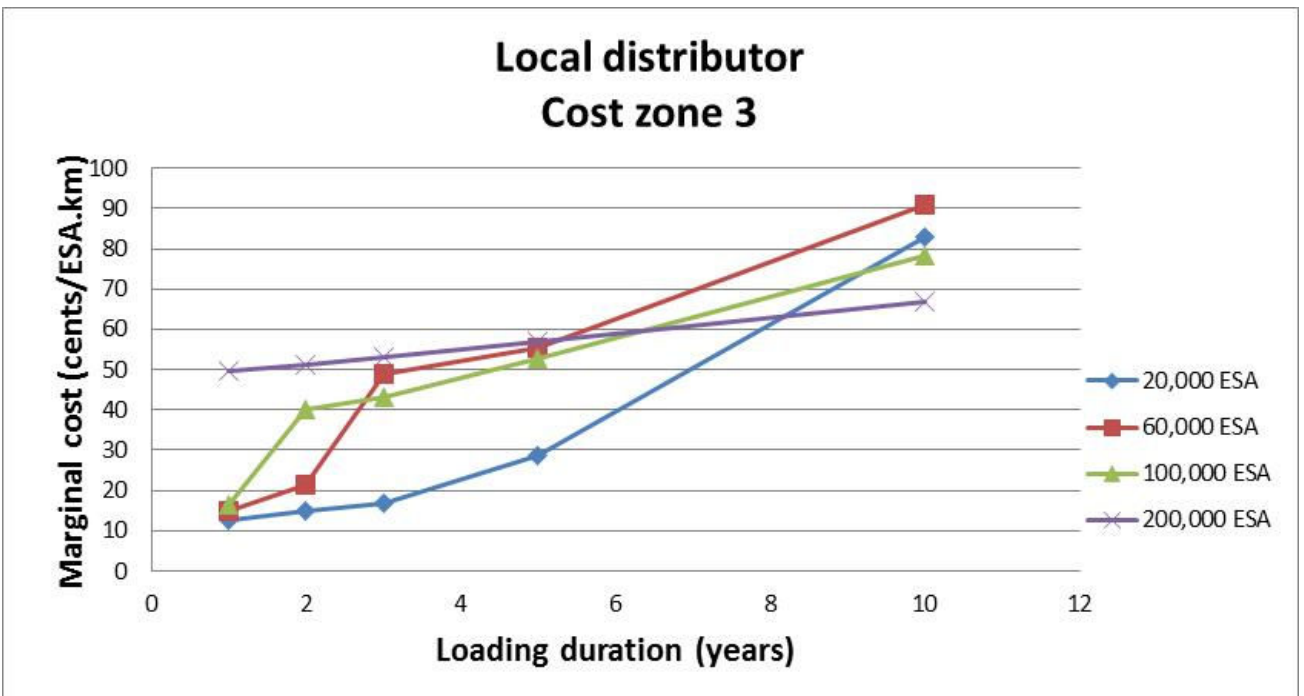


Figure A 28: Marginal cost total chart for access roads in cost zone 3

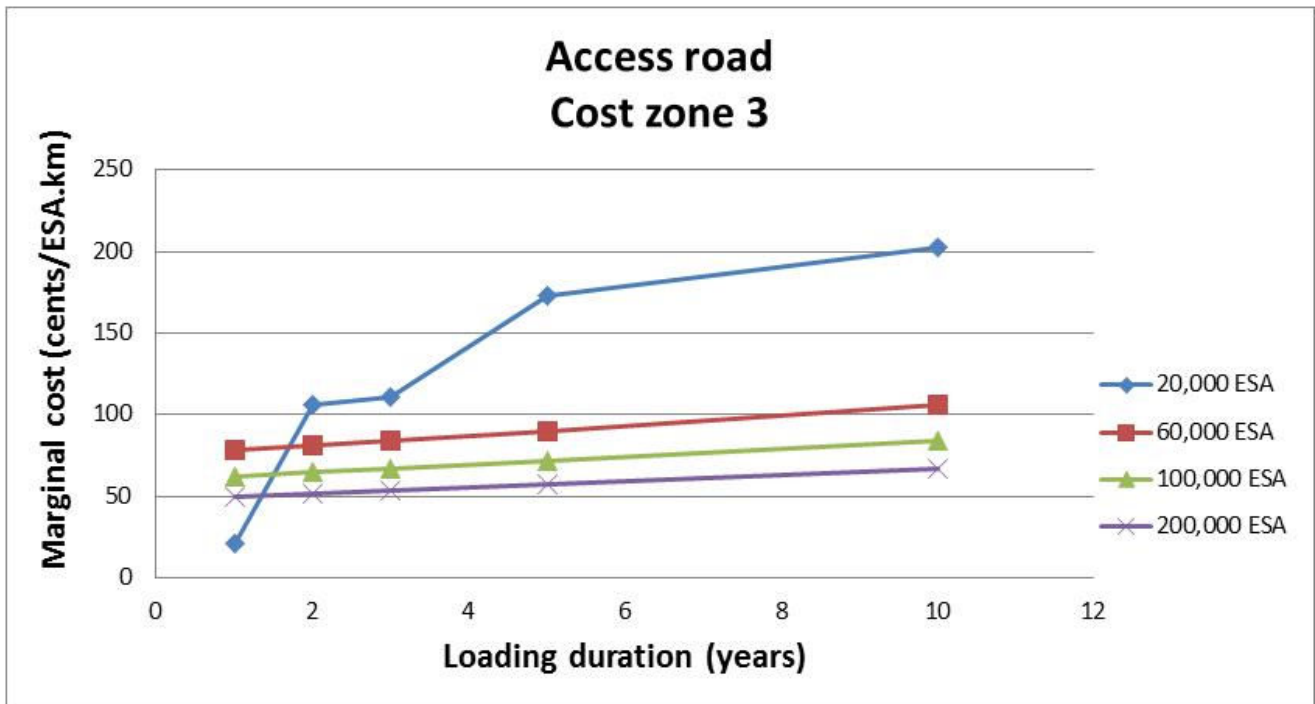


Figure A 29: Marginal cost total chart for district distributors in cost zone 4

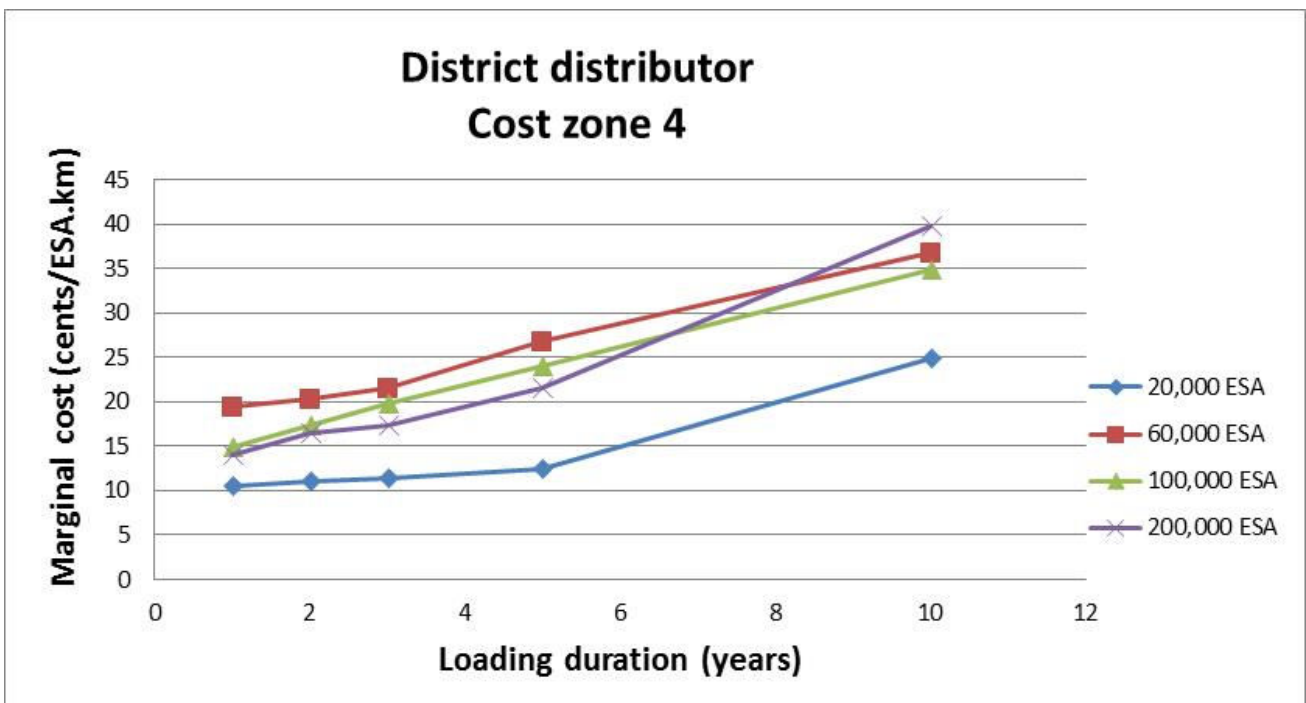


Figure A 30: Marginal cost total chart for regional distributors in cost zone 4

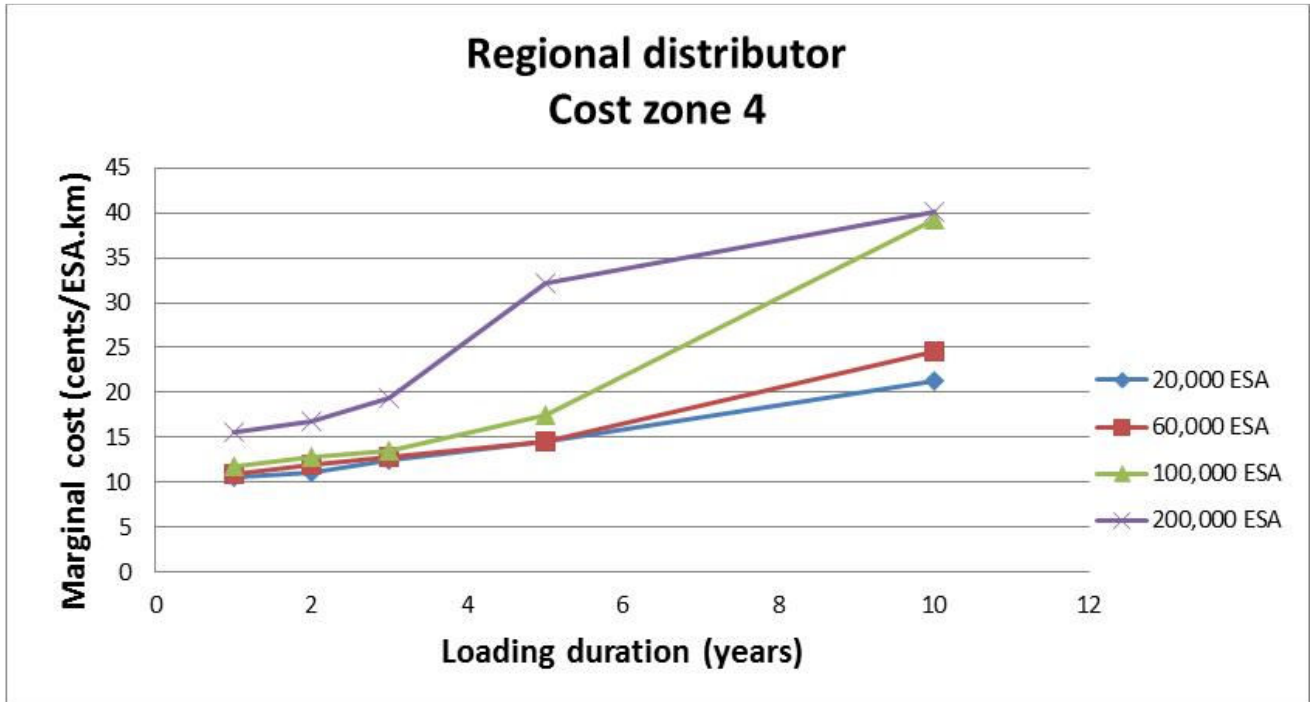


Figure A 31: Marginal cost total chart for local distributors in cost zone 4

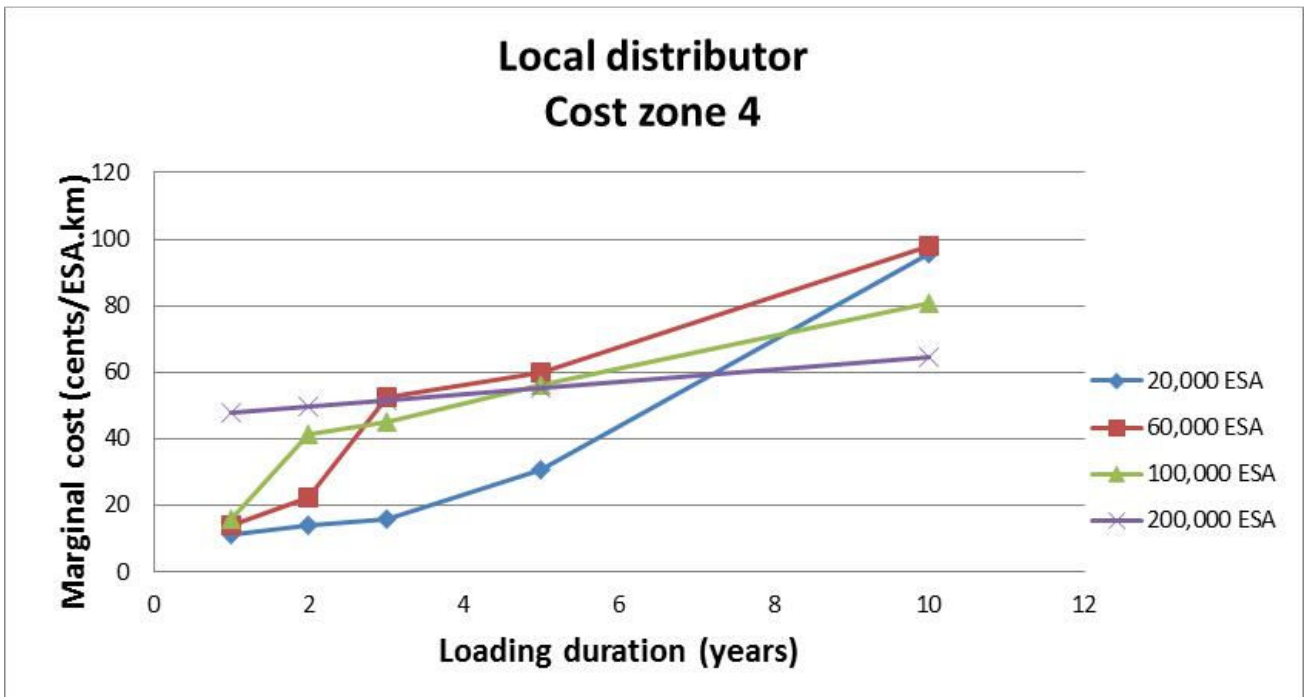
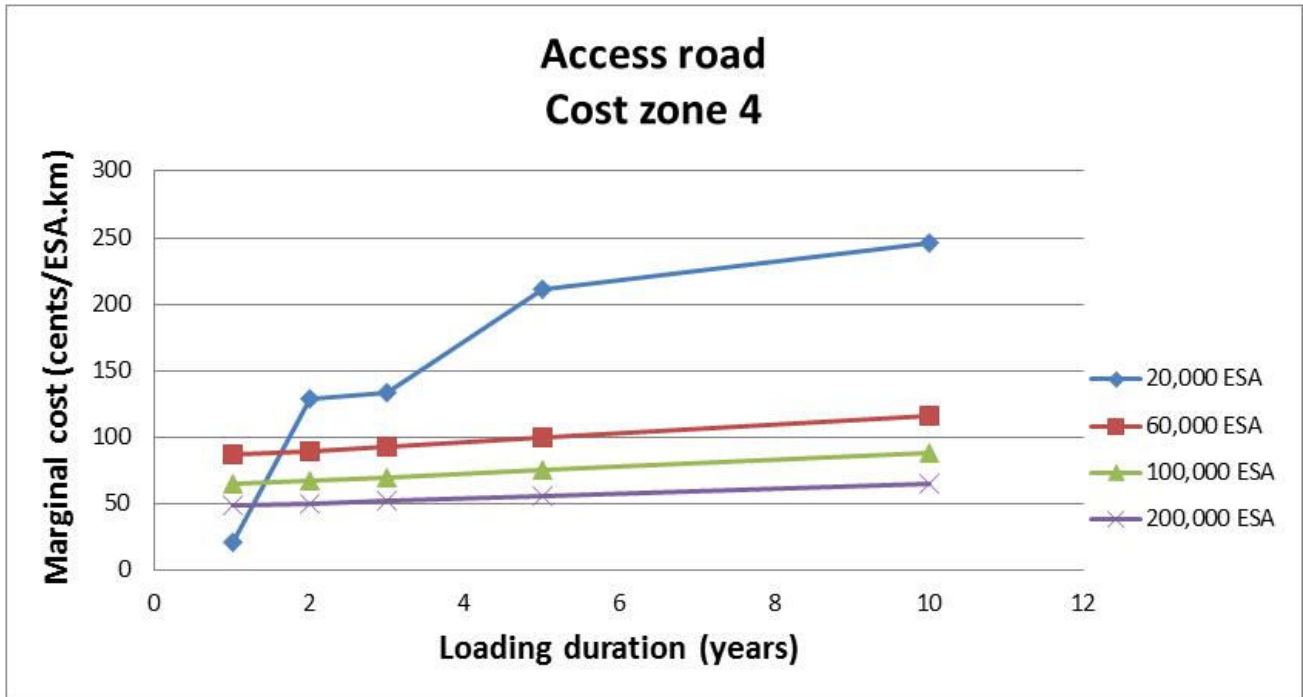


Figure A 32: Marginal cost total chart for access roads in cost zone 4



A.3 Total cost (dollars/km)

Figure A 33: Total cost chart for district distributors in cost zone 1

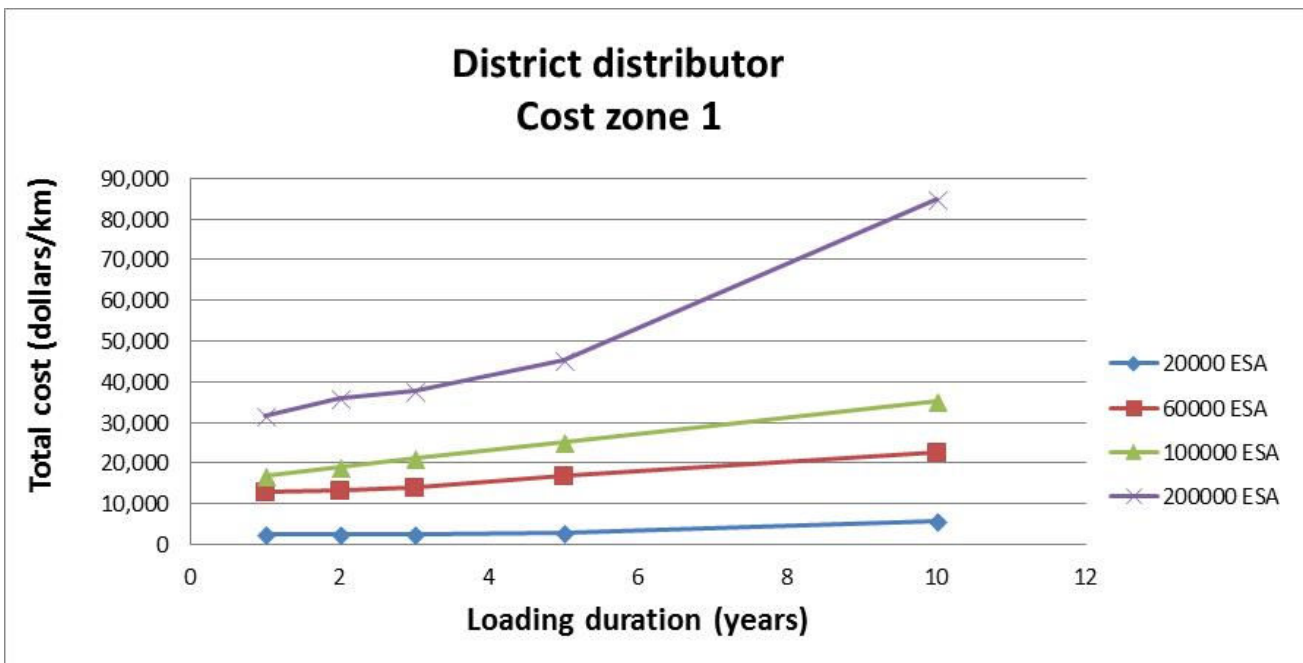


Figure A 34: Total cost chart for regional distributors in cost zone 1

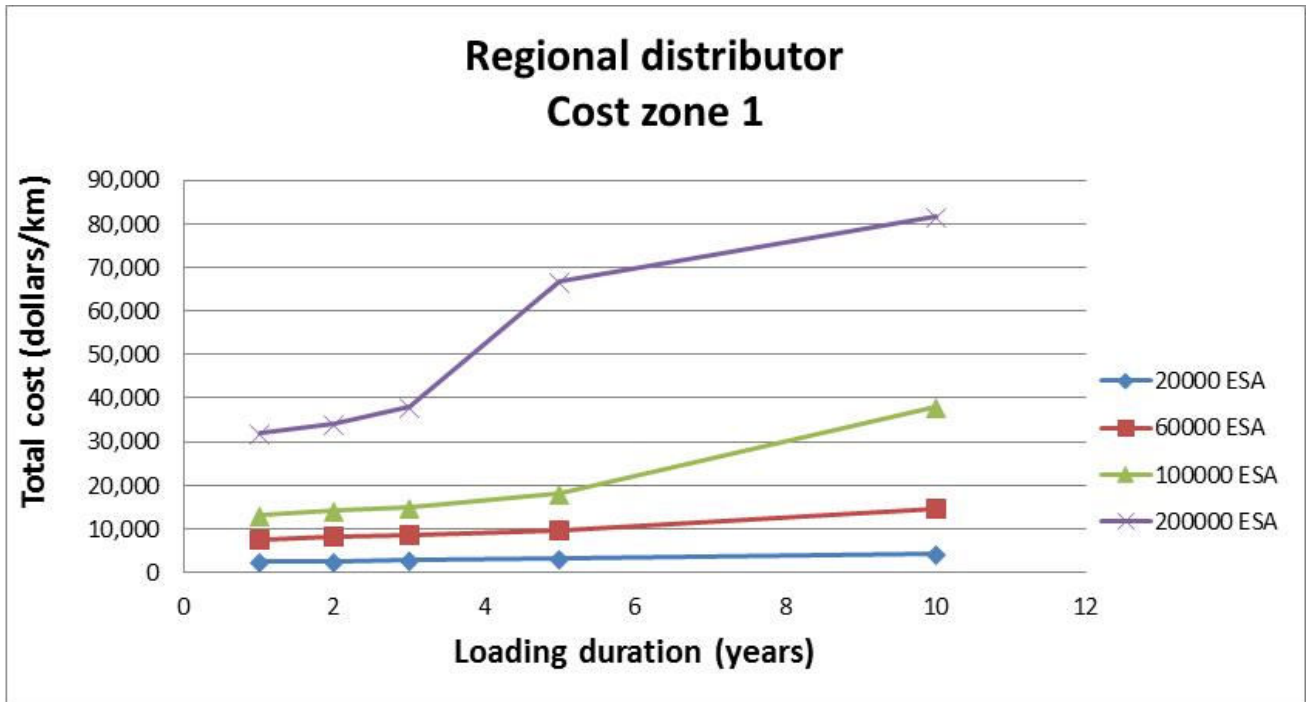


Figure A 35: Total cost chart for local distributors in cost zone 1

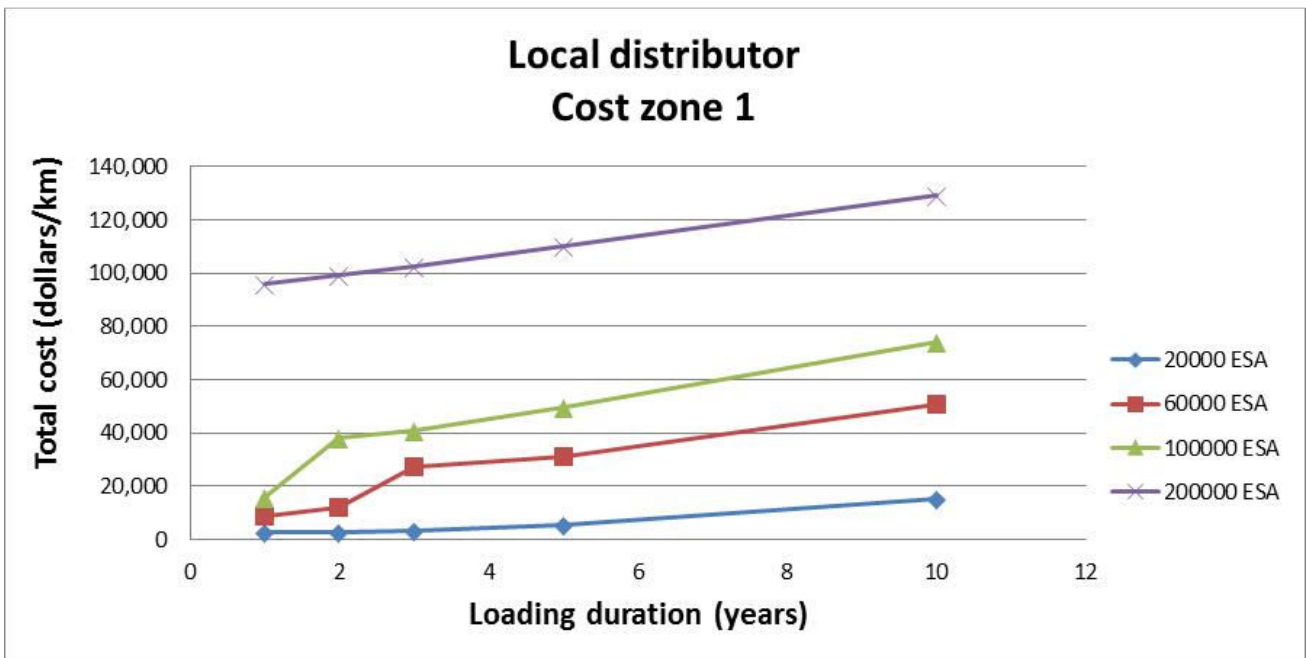


Figure A 36: Total cost chart for access roads in cost zone 1

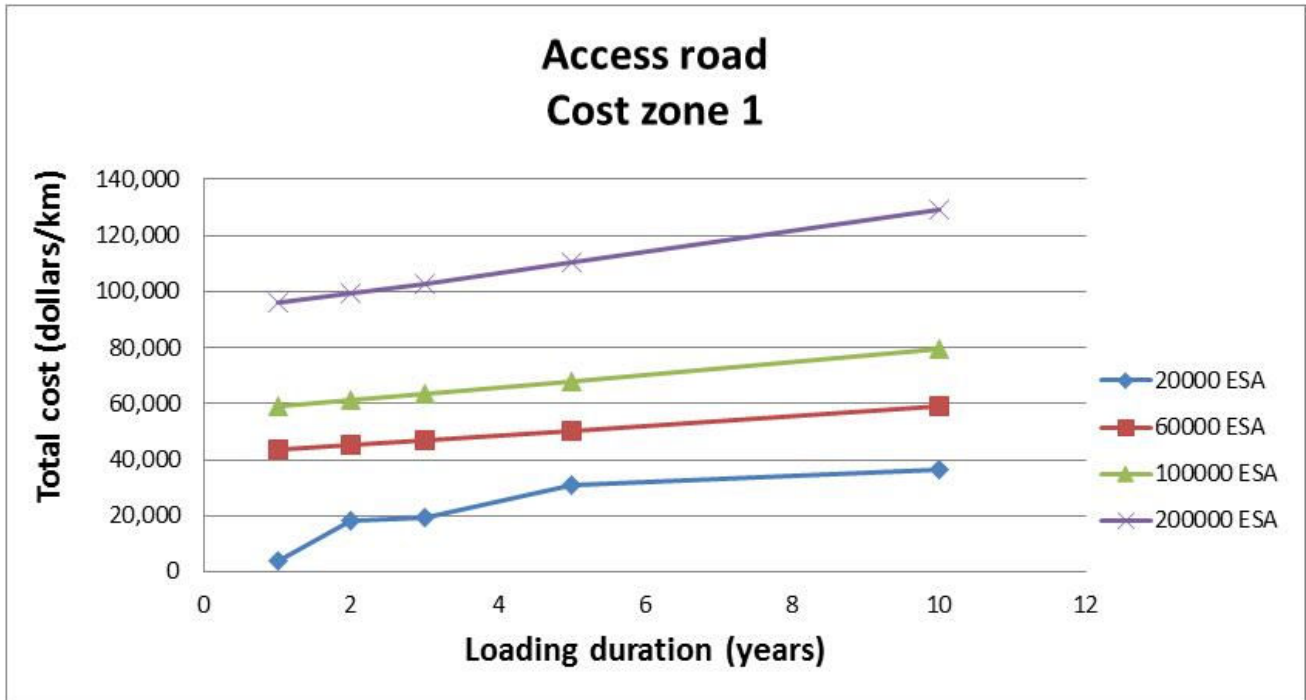


Figure A 37: Total cost chart for district distributors in cost zone 2

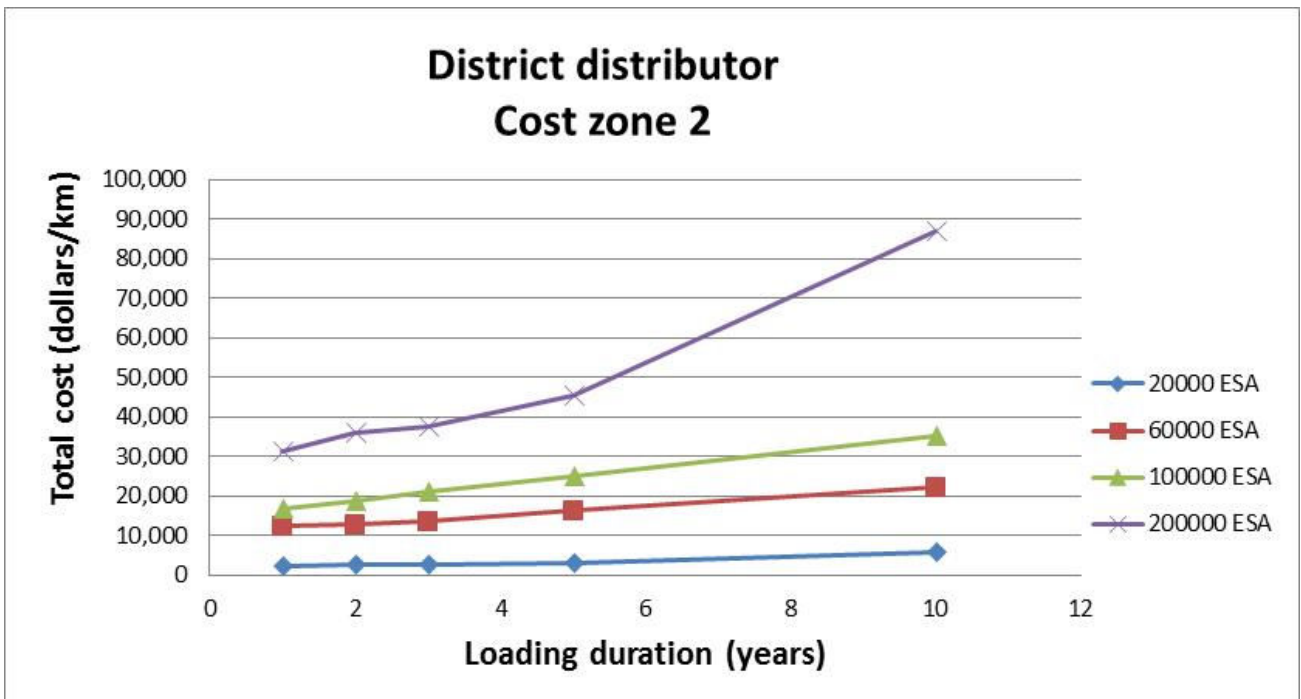


Figure A 38: Total cost chart for regional distributors in cost zone 2

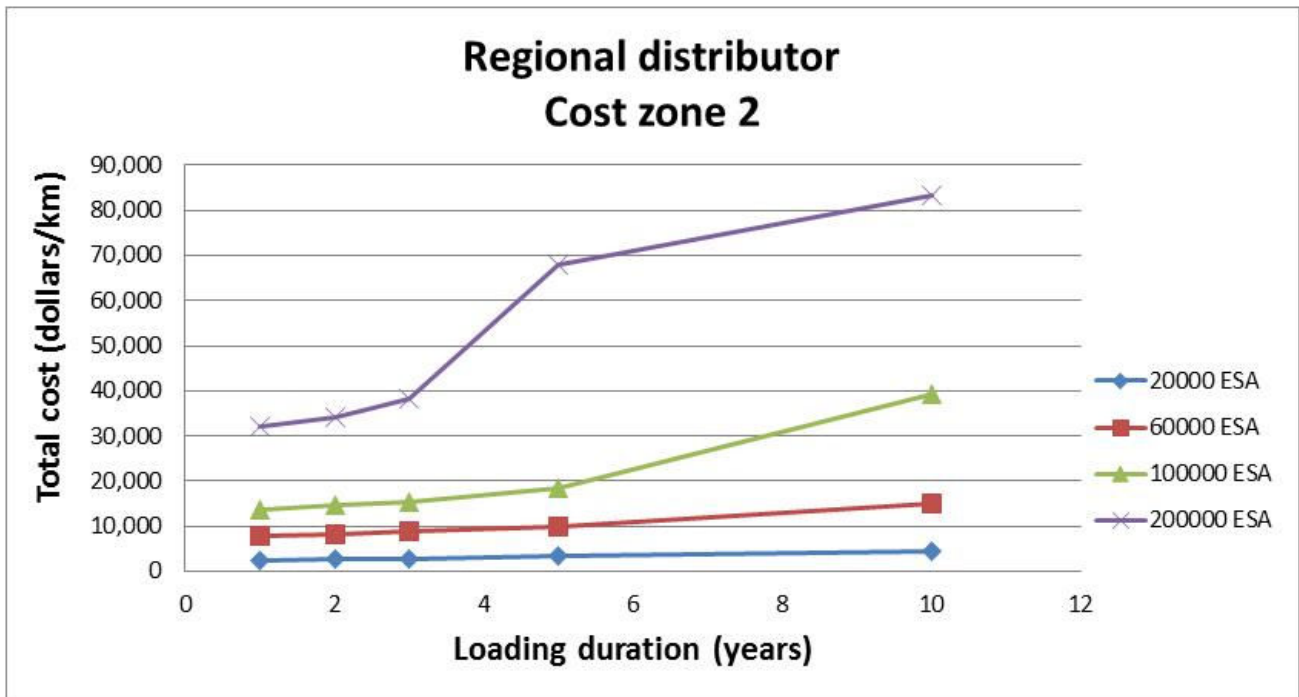


Figure A 39: Total cost chart for local distributors in cost zone 2

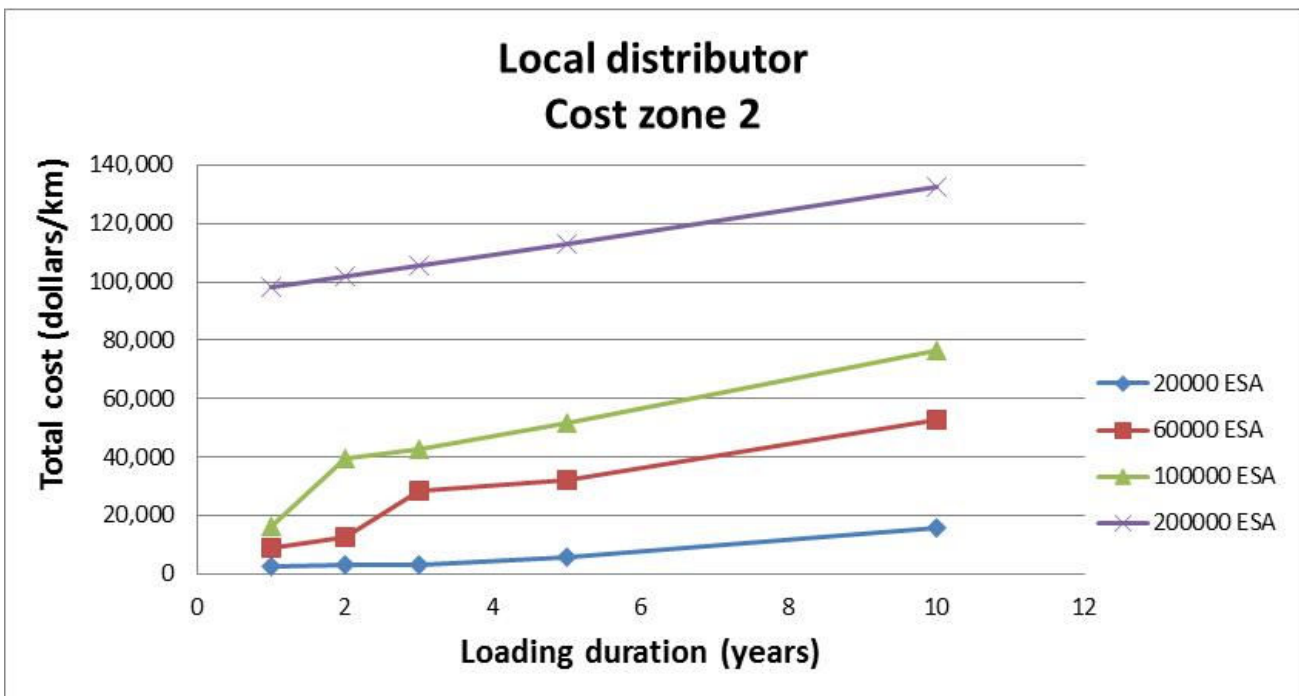


Figure A 40: Total cost chart for access roads in cost zone 2

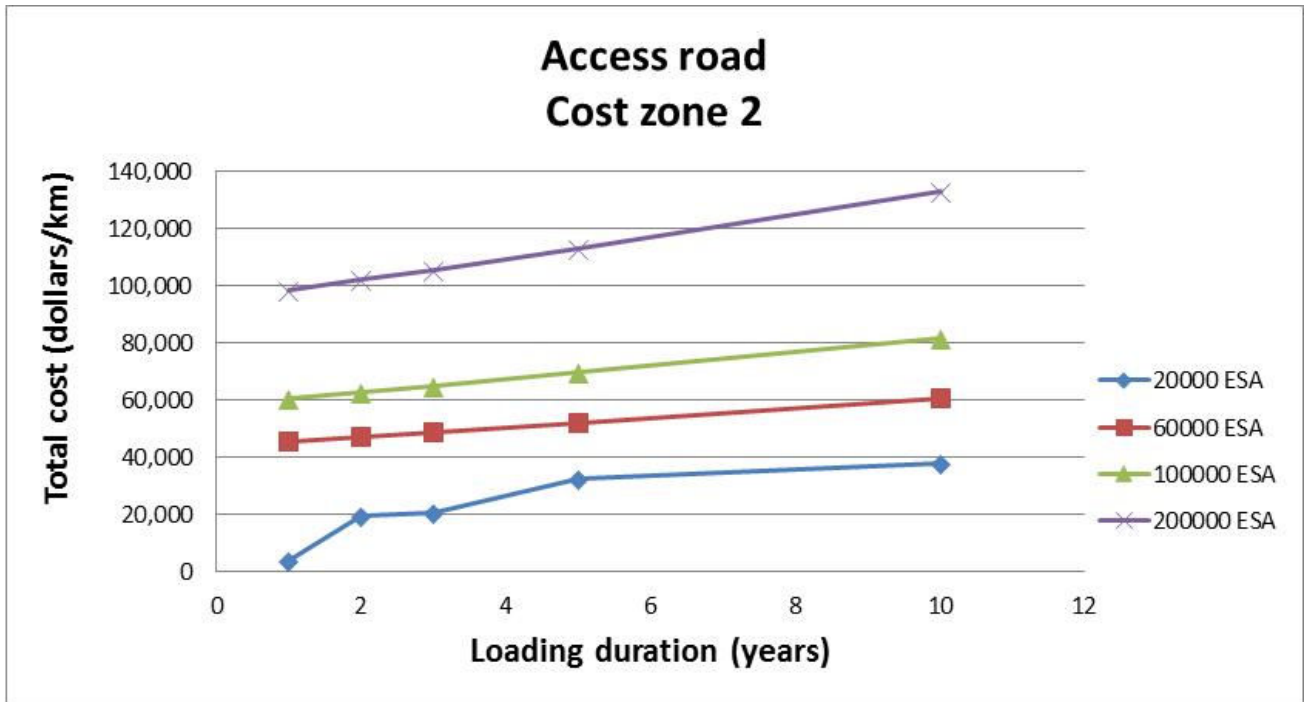


Figure A 41: Total cost chart for district distributors in cost zone 3

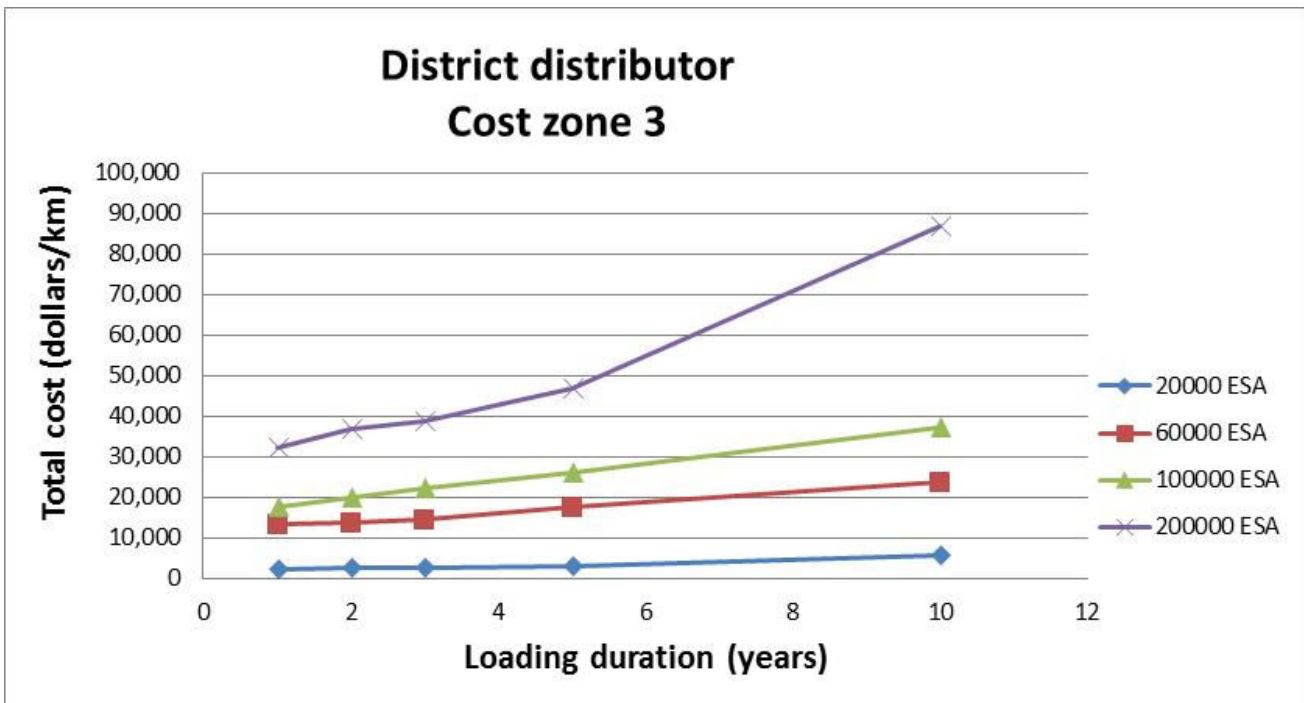


Figure A 42: Total cost chart for regional distributors in cost zone 3

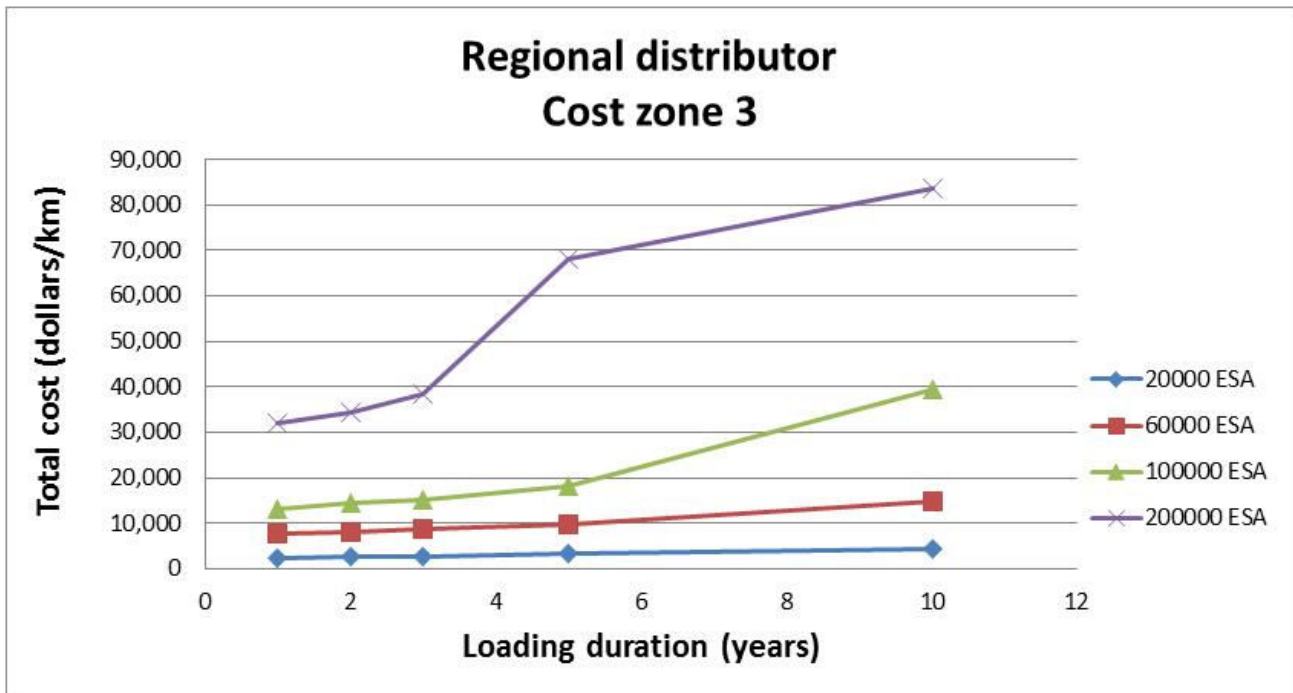


Figure A 43: Total cost chart for local distributors in cost zone 3

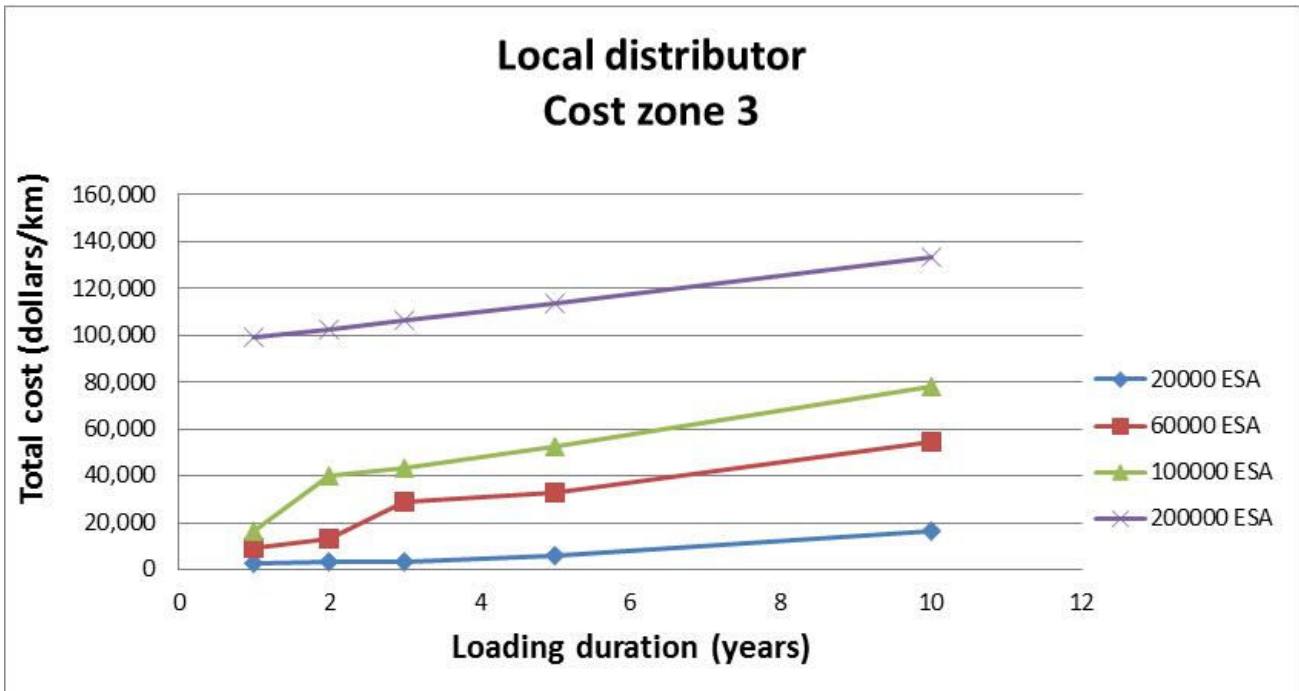


Figure A 44: Total cost chart for access roads in cost zone 3

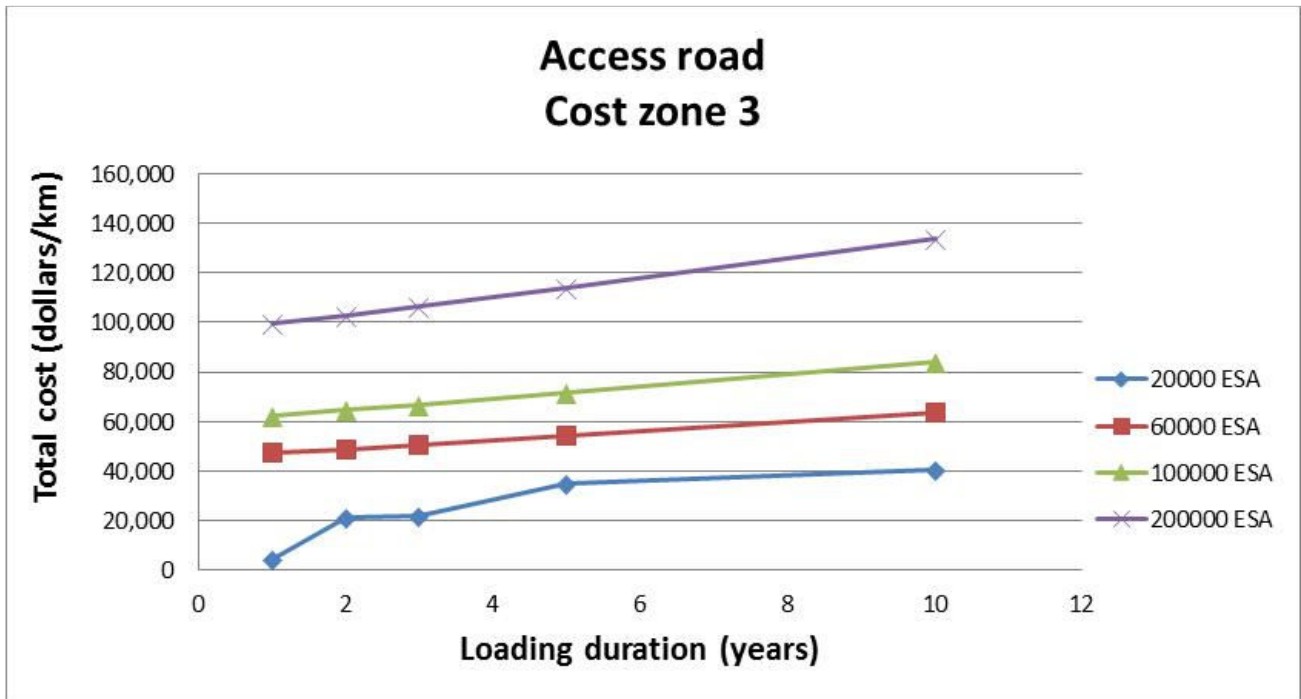


Figure A 45: Total cost chart for district distributors in cost zone 4

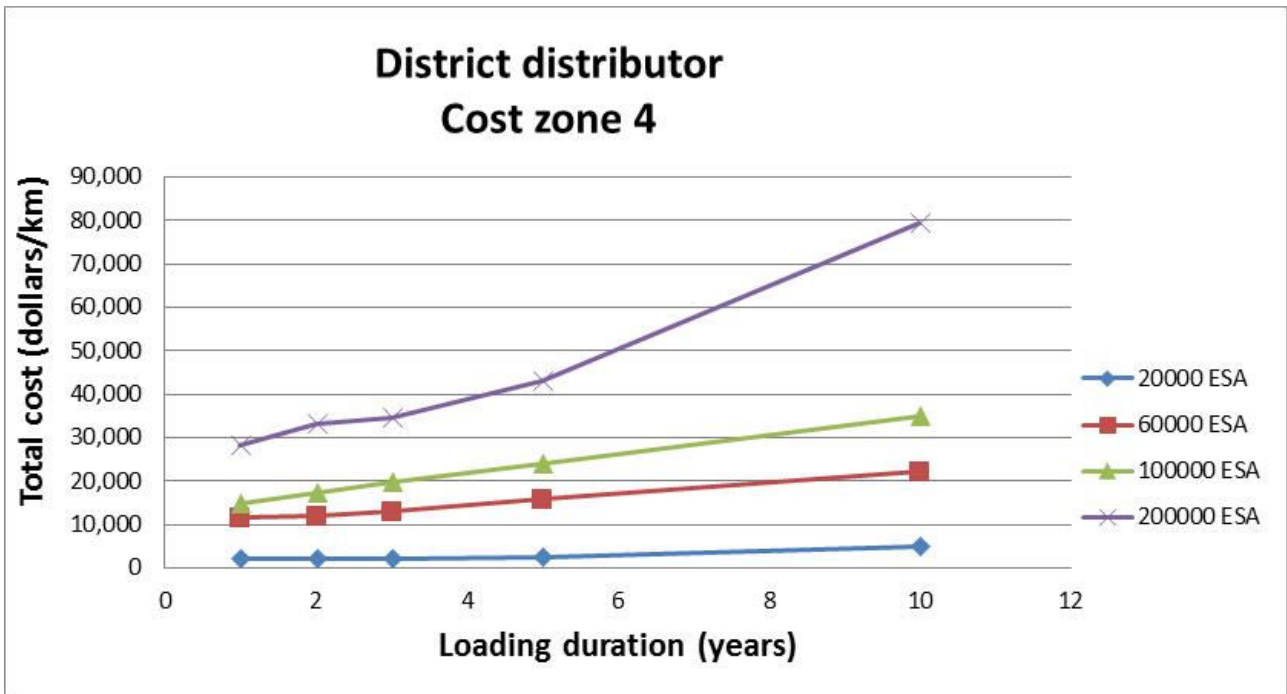


Figure A 46: Total cost chart for regional distributors in cost zone 4

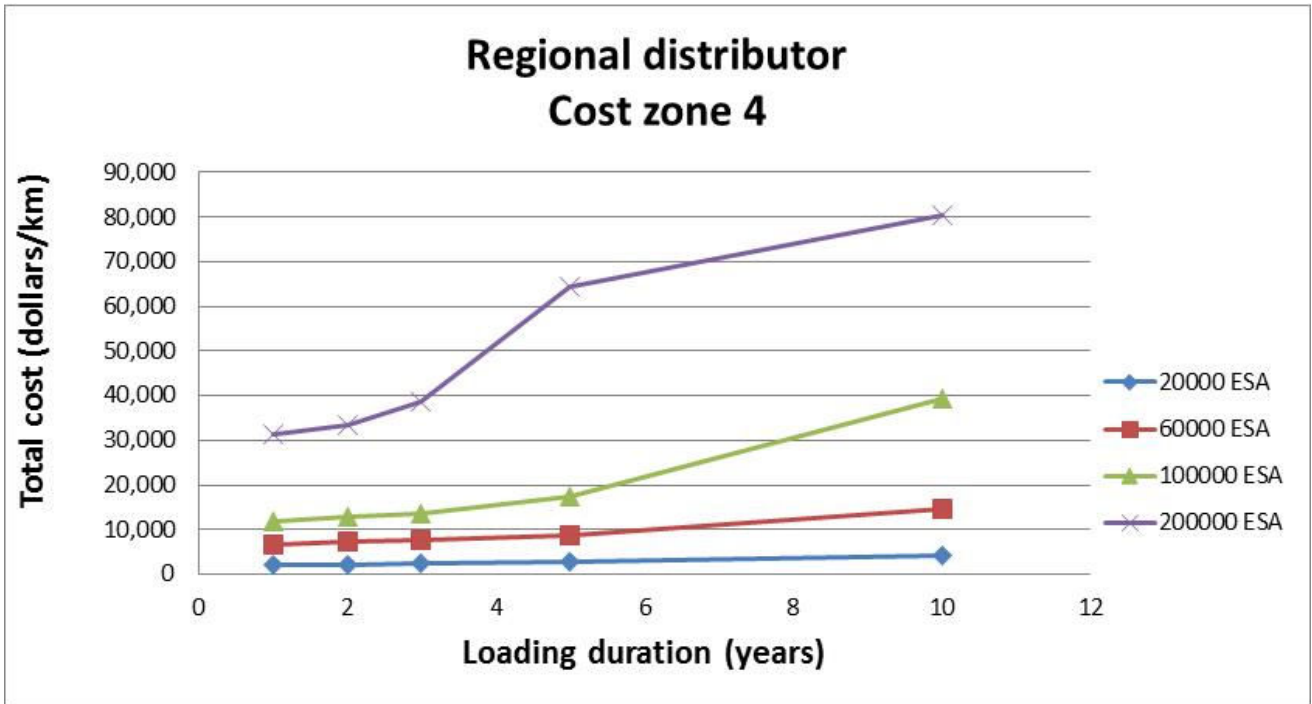


Figure A 47: Total cost chart for local distributors in cost zone 4

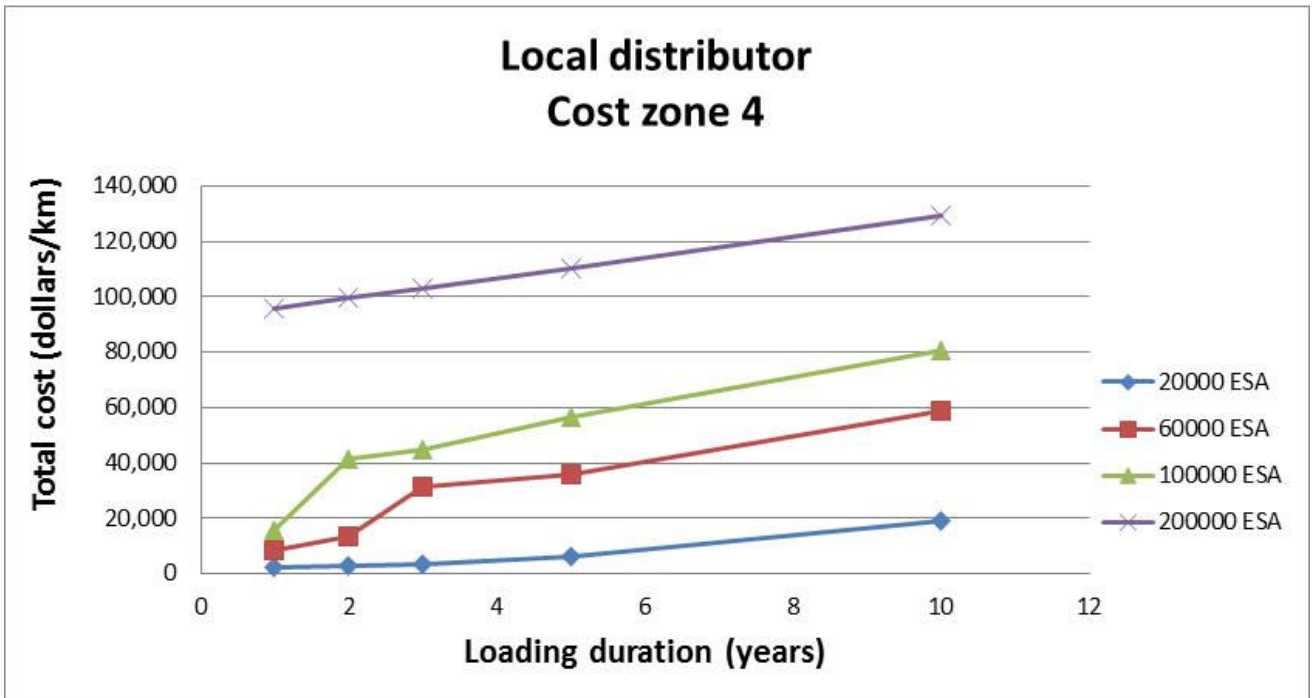


Figure A 48: Total cost chart for access roads in cost zone 4

