Contents

Volume 4 - Analytical Framework & Model Descriptions: Part D

Part D Road Map

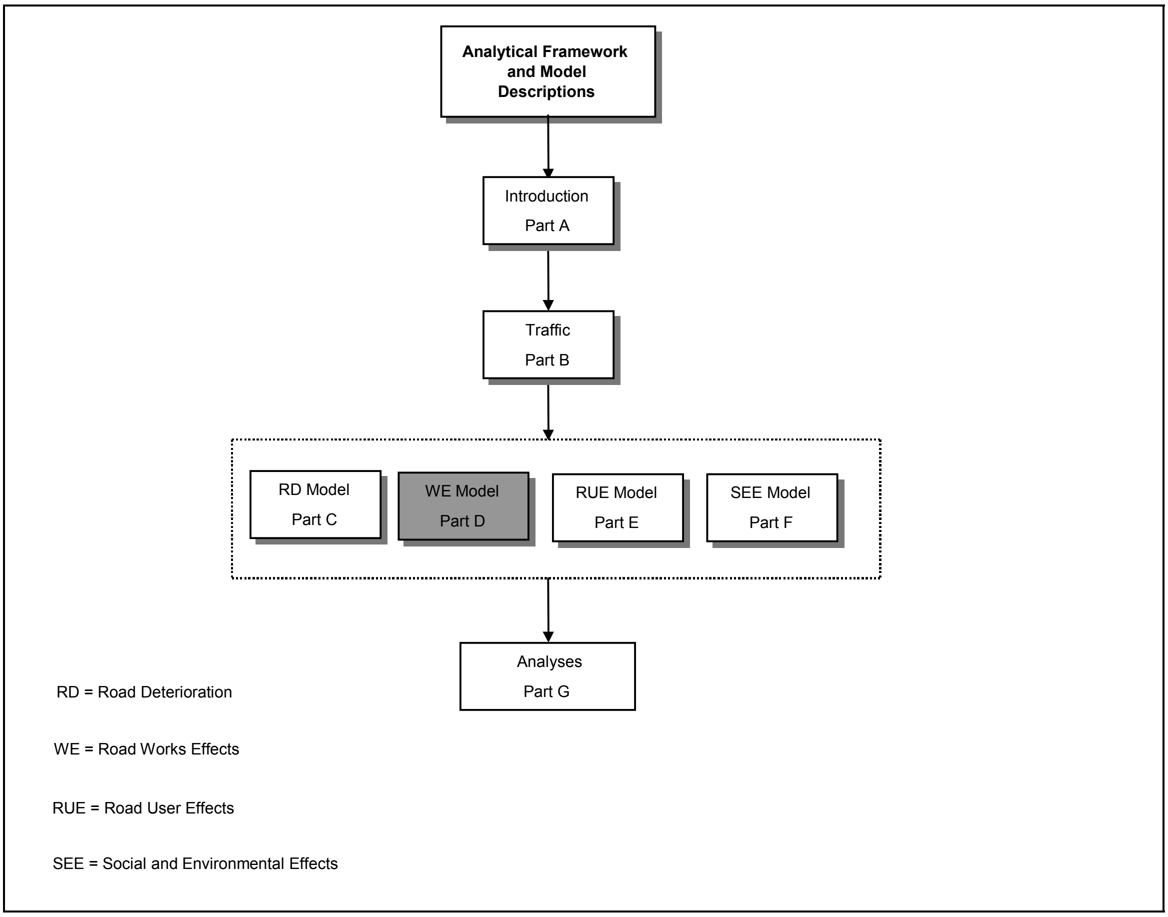

Figure D   Analytical Framework and Model Descriptions Road Map

D1 Types of roadworks

1 Introduction

The HDM-4 system includes relationships for modelling Road Deterioration (RD) (see Part C) and Road Works Effects (WE). In HDM-III these were combined into a single module called the RDME, *Watanatada et al. (1987)*. In HDM-4, RD and WE have been separated in order to meet the requirements to trigger the extended number and types of road works using a wider range of criteria based on threshold values of road user effects parameters.

Roadworks modelling in the context of the HDM-4 system imply the following:

- Defining roadworks in a logical manner to achieve a target standard
- Timing of works over the analysis period
- Calculation of the physical quantities or the amounts of works to be undertaken
- Estimating the costs of works which is part of the cash flow analysis used for economic analysis and budget preparation
- Resetting/changing one or more of the characteristics that define the road as a result of implementing the roadworks
- Resetting/changing the asset valuation of the road, as a result of implementing the roadworks.

Thus, the WE module is used to estimate road agency resource needs for road preservation and development. These needs are expressed in terms of the physical quantities and the monetary costs of works to be undertaken. Road agency costs are used together with road user costs and social and environmental costs to determine the economic viability of different road investment options and strategies.

This chapter describes the classification of road works and the generic framework for modelling road works effects in HDM-4. The detailed modelling logic for the different types of works are described separately for each of the three road surface classes (see Figure D1.1) as follows:

1 **Bituminous pavements** (see Chapter D2)

2 **Concrete pavements** (see Chapter D3)

3 **Unsealed roads** (see Chapter D4)

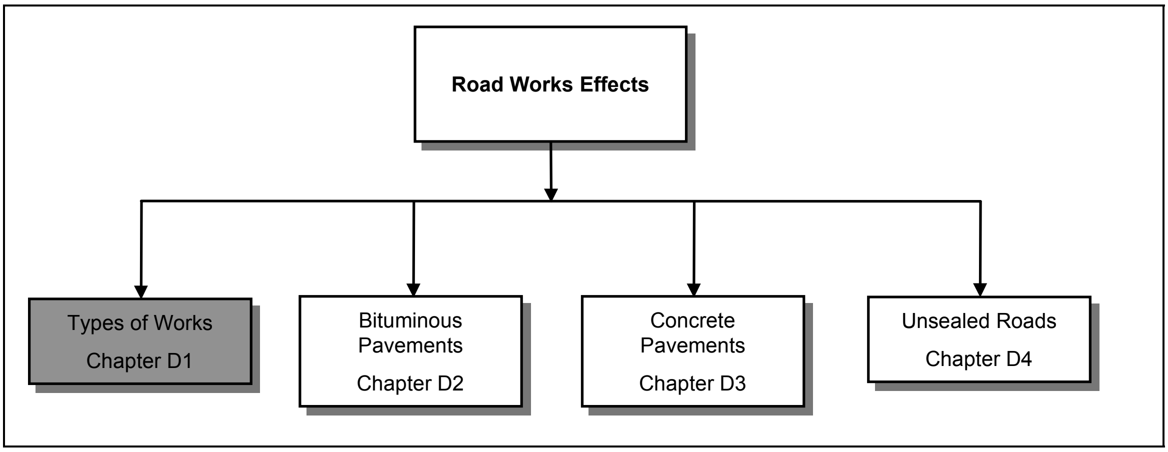

Figure D1.1 Road Works Effects modules

2 Road works classification

In HDM-4, road works are considered in a hierarchical structure of category, class, and type. Each works type comprises several works activities or operations. This classification of road works is presented in Table D1.1.

Table D1.1 Classification of road works in HDM-4

Works category	Works class	Works type	Works activity /operation
Preservation	Routine Maintenance	Routine Pavement	patching, edge-repair, crack sealing, spot-regravelling, shoulders repair, etc.
		Drainage	culvert repairs, clearing side drains, etc.
		Routine Miscellaneous	vegetation control, line-markings, signs, etc.
	Periodic Maintenance	Preventive Treatment	fog seal, rejuvenation, load transfer dowel retrofit, joint sealing, etc.
		Resurfacing (or Restoration)	surface dressing, slurry seal, cape seal, regravelling, slab replacement, diamond grinding, etc.
		Rehabilitation	thick overlay, mill and replace, inlay, bonded concrete overlay, unbonded concrete overlay
		Reconstruction	partial reconstruction, full pavement reconstruction
	Special	Emergency	clearing debris, repairing washout/subsidence, traffic accident removal, etc.
		Winter	snow removal, salting/gritting, etc.
Development	Improvement	Widening	partial widening, lane addition
		Realignment	horizontal and vertical geometric improvements, junction improvement
		Off-carriageway	shoulders addition, shoulders upgrading, NMT lane addition, side drain improvement, etc.
	Construction	Upgrading	upgrading by changing the road surface class
		New section	dualisation of an existing section, new section (link)

2.1 Works categories

Road works are divided under two categories:

1 **Preservation**

Preservation of the existing pavement involves performing maintenance works required to offset the deterioration of roads, and to lower road user costs by providing a smooth running surface, and keeping the road open on a continuous basis.

2 **Development**

Development works aim to expand road network capacity, provide stronger pavement, and improve road geometric characteristics in order to minimise the total cost of road transportation and mitigate environmental impacts.

2.2 Works classes

Within each category, road works are considered in classes. Works classes consider road works in terms of their frequency of application and the budget head used to fund them, *Robinson (1995)*.

2.2.1 Maintenance

There are three works classes under maintenance:

1 **Routine maintenance** (see Section 2.3.1)

Comprises works that may need to be undertaken each year.

2 **Periodic maintenance** (see Section 2.3.2)

Comprises works that are planned to be undertaken at intervals of several years.

3 **Special** (see Section 2.3.3)

Comprises works whose frequencies cannot be estimated with certainty in advance.

2.2.2 Development

Development works are divided into two classes as follows:

1 **Improvement** (see Section 2.3.4)

Comprises works that aim to provide additional capacity when a road is nearing the end of its design life or because there has been an unforeseen change in use of the road. These include measures of improving quality of service on existing roads such as relieving traffic congestion, road safety, road passability, etc.

2 **Construction** (see Section 2.3.5)

Works to create a new pavement or to build new road sections.

Each of the works classes described above is divided further into works types as discussed in Section 2.3.

2.3 Works types

Works types consider road works in terms of their impact (or effects) on the road infrastructure. Under each works type, there are several works activities or operations considered in terms of the pavement type to which they can be applied, and the technique used. Each works type has a default budget category (recurrent, capital or special). These budgets are discussed in Section 4.1. Recurrent and capital budgets may also be referred to as routine and periodic budgets, respectively.

2.3.1 Routine maintenance

Routine maintenance works are divided into the following works types:

- **Routine pavement**

  Works responding to minor pavement defects caused by a combination of traffic and environmental effects, for example, crack sealing, patching, edge repair; shoulders repair, non motorised transport (NMT) lane repair, spot-regravelling and grading.

- **Drainage**

  Clearing side drains, clearing culverts and culvert repairs.

- **Routine Miscellaneous**

  Includes all other works that are not modelled endogenously in HDM-4, for example, vegetation control, line-marking, road signs repair, guard rail repair, etc.

All routine works are considered under the **recurrent budget** (by default).

2.3.2 Periodic maintenance

Periodic maintenance works are divided into the following works types:

- **Preventive treatments**

  For bituminous pavements this is the addition of a thin film of surfacing to improve surface integrity and waterproofing that does not increase the strength of the pavement. This group includes:

  - fog sealing
  - rejuvenation

  For concrete pavements preventive treatments include:

  - joint sealing
  - load transfer dowels retrofit
  - longitudinal edge drains retrofit
  - tied concrete shoulders retrofit

  Preventive treatments are considered under **capital budget** (by default).

- **Resurfacing or Restoration**

  Resurfacing of bituminous pavements involves the addition of a thin surfacing to improve surface integrity and waterproofing, or to improve skid resistance, that does not increase the strength of the pavement significantly. For bituminous pavements this includes:

- single surface dressing
- double surface dressing
- slurry seal
- cape seal

Regravelling of unsealed roads is included under resurfacing.

Restoration works on concrete pavements includes:

- slab replacement
- full depth repair
- partial depth repair
- diamond grinding

Resurfacing is considered under **capital budget** (by default).

- **Rehabilitation**

The addition of thick surfacings, or the removal of part of the existing pavement and the addition of layers to restore or improve structural integrity and to increase the strength of the pavement. For bituminous pavements this group includes:

- open-graded asphalt overlay
- dense-graded asphalt overlay
- rubberised asphalt overlay
- mill-and-replace
- inlays

Rehabilitation of concrete pavements includes:

- bonded concrete overlay
- unbonded concrete overlay

Rehabilitation is considered under **capital budget** (by default).

- **Reconstruction**

The removal of part (both bound and unbound layers) or all of the existing pavement layers and the construction of a new pavement. This group includes:

- strengthening by multiple-layer overlays thicker than 125 mm
- granular overlays
- recycling of base
- membrane-interlayer overlays
- reconstruction of concrete pavements

Reconstruction is considered under **capital budget** (by default).

2.3.3 Special works

Special works are divided into the following works types:

- **Emergency**

  Comprises works undertaken to clear a road that has been cut or blocked. This group includes:

  - ❑ traffic accident removal
  - ❑ clearing debris
  - ❑ repairing washout/subsidence

  Emergency works is considered under **special budget** head (by default).

- **Winter**

  Comprises works undertaken to prevent the formation of ice or to remove snow from the pavement. This group includes:

  - ❑ salting/gritting
  - ❑ snow removal

  Winter works is considered under **special budget** head (by default).
  Note: Winter works are not modelled endogenously in this release.

2.3.4 Improvement works

Improvement works are divided into the following works types:

- **Full Reconstruction with minor widening**

  Full pavement reconstruction with the allowance for minor widening has been included under improvement works since it is unlikely to be funded from the maintenance budget. Full reconstruction is considered under **capital budget** (by default).

- **Widening**

  Comprises works that retain the existing pavement, but increase width throughout the length of the section. This group includes:

  - ❑ partial widening
  - ❑ lane addition

  Widening is considered under **capital budget** (by default).

- **Realignment**

  Comprises works that changes the road geometry for part of a section, but that retains some of the existing pavement structure. This group includes:

  - ❑ local geometric improvements

  Realignment works is considered under **capital budget** (by default).

- **Off-Carriageway Works**

  Comprises improvement works that is carried out off-carriageway on road features like NMT lanes. This group includes:

  - ❑ NMT addition or improvement

  Off-carriageway improvement works are considered under **capital budget** (by default).

2.3.5 Construction works

Construction works are divided into the following works types:

- **Upgrading**

  Involves changing the pavement surface class and improving geometric characteristics of an existing road section. This group includes upgrading:

  - An unsealed road to bituminous or rigid concrete pavement
  - A bituminous pavement to rigid concrete pavement
  - A low grade bituminous pavement to a high grade bituminous pavement
  - An earth road to a gravel road

  Pavement upgrading is considered under **capital budget** (by default).

- **New section**

  Comprises works to create a new pavement in an entirely new location. This group includes:

  - dualisation of existing road sections
  - new link construction

  New section works are considered under **capital budget** (by default).

  Note: Dualisation has not been included in this release.

3 Modelling framework

3.1 Road feature types

A road can be considered as a number of complementary features or elements, to each of which a variety of roadworks activities can be applied.

The different road works activities considered in HDM-4 can be divided into two groups as follows:

1 Those whose effects are modelled and their costs are used in economic analyses

2 Those that are not modelled but their costs can be considered in economic analyses

Each works activity that is modelled has effects on one or more of the following road feature types:

- **Carriageway**
- **Miscellaneous**
- **Non-motorised traffic lane**
- **Shoulders**
- **Special**

The above distinction provides a logical framework that enables a detailed modelling of road works effects on each of the feature types to be performed separately.

3.2 Works standards

Standards refer to the targets or levels of conditions and response that a road administration aims to achieve. Road agencies set up different standards that can be applied in practical situations in order to meet specific objectives which are related to functional characteristics of the road network system. A standard is defined by a set of operations or works activities with definite intervention criteria to determine when to carry them out. In general terms, intervention levels define the minimum level of service that is allowed.

A standard is user-defined according to the road surface class to which it is applied, the characteristics of traffic on the section, and the general operational practice in the study area based upon engineering, economic and environmental considerations.

Standards are grouped into three types for input purposes:

1 **Maintenance standards**

2 **Improvement/construction standards**

3 **New construction section standards**

For a given road feature, only one maintenance standard and/or improvement type will be effective in any analysis year for each section alternative being analysed.

The operation type plus the following information define a works standard:

- **Intervention criteria** (see Section 3.3)
- **Works design** (see Section 3.4)

- **Works duration** (see Section 3.5)
- **Unit cost (and optionally energy use)** (see Section 3.6)
- **Works effects** (see Section 3.7)

A standard may therefore comprise several operations each with definite intervention criteria to determine when to carry them out. The following sections (Sections 3.3 to 3.7) discuss briefly the information that is required to define a works standard. A detailed discussion of standards is given in the Applications Guide.

3.3 Intervention criteria

For each works activity, user-specified intervention criteria are used to determine the timing and limits on the works to be carried out. The intervention criteria can be defined by selecting and combining attributes using logical operators. The criteria that can be selected are either time-based or based on a physical attribute of the section, the traffic the flows on the section, or the road work:

- Time-based attributes: time intervals (for example, resurface at four years intervals, overlay when pavement age reaches 7 years) or point(s) in time for maintenance works (for example, resurface in year 2006, 2010, and 2014); and at a fixed time (for example, widen in the year 2005) for improvement and construction works
- Physically-based attributes: In response to critical threshold levels specified by the user in terms of any of the following:
  - Pavement condition
  - Pavement structure and strength
  - Drainage condition
  - Vehicle Speeds
  - Traffic volumes, loading and flows

Limits

In addition to the above criteria, user-specified limits can also be introduced by optionally combining appropriate intervention criteria in order to simulate realistic policies, *Watanatada et al. (1987)*. For example, it is recognised that practical considerations would normally preclude the situation of periodic maintenance being applied immediately before a major overlay or reconstruction was planned. Also due to the economic implications, different maintenance standards would be applied to a road section at different thresholds of traffic volume. Provision is therefore made to specify:

- Minimum and maximum intervals between successive works in order to comply with budget or other constraints (for example, time interval >5, <10)
- Maximum applicable roughness beyond which the works activity must not be done (for example, roughness < 12IRI)
- Minimum and maximum AADT threshold within which a standard is applicable on the road section (for example, Two-way AADT > 1000, < 5000)
- Last applicable year for the works (for example, year < 2010)
- Maximum annual quantity of the works (for example, maximum material < 1000m^2/km

Works Triggering

A works activity will be triggered when the user-specified criteria has been met. When more than one works activity meets the criteria for being applied in a given analysis year, the works hierarchy established for each road surface class and feature type is used to prioritise and select the highest placed activity. The details of these modelling logic are discussed for each road surface class in Chapters D2, D3 and D4.

3.4 Works design

Before implementing any contemplated road works, it is necessary to carry out a preliminary or coarse design of the operation. The preliminary design will be refined through technical and economic analyses of different alternative options, leading to a final detailed design that can be realised. Works design refers to the explicit specifications of the works activity by the user in terms of the following:

- **Pavement structure**

  Includes pavement type, strength, layer thickness and material properties.

- **Road geometry**

  Road length, width and number of lanes.

- **Road type and road class**

Note: No endogenous design or selection from alternative design options is performed.

3.5 Works duration

The duration of a road works determines when its effects should be considered within the logic of the analysis process. This is as follows:

- **For works of duration not greater than one year** (see Figure D1.2)

  It is assumed that the works are carried out at the end of the analysis year in which it has been scheduled or triggered, and its effects become effective at the beginning of the following analysis year. All maintenance works are considered under this category.

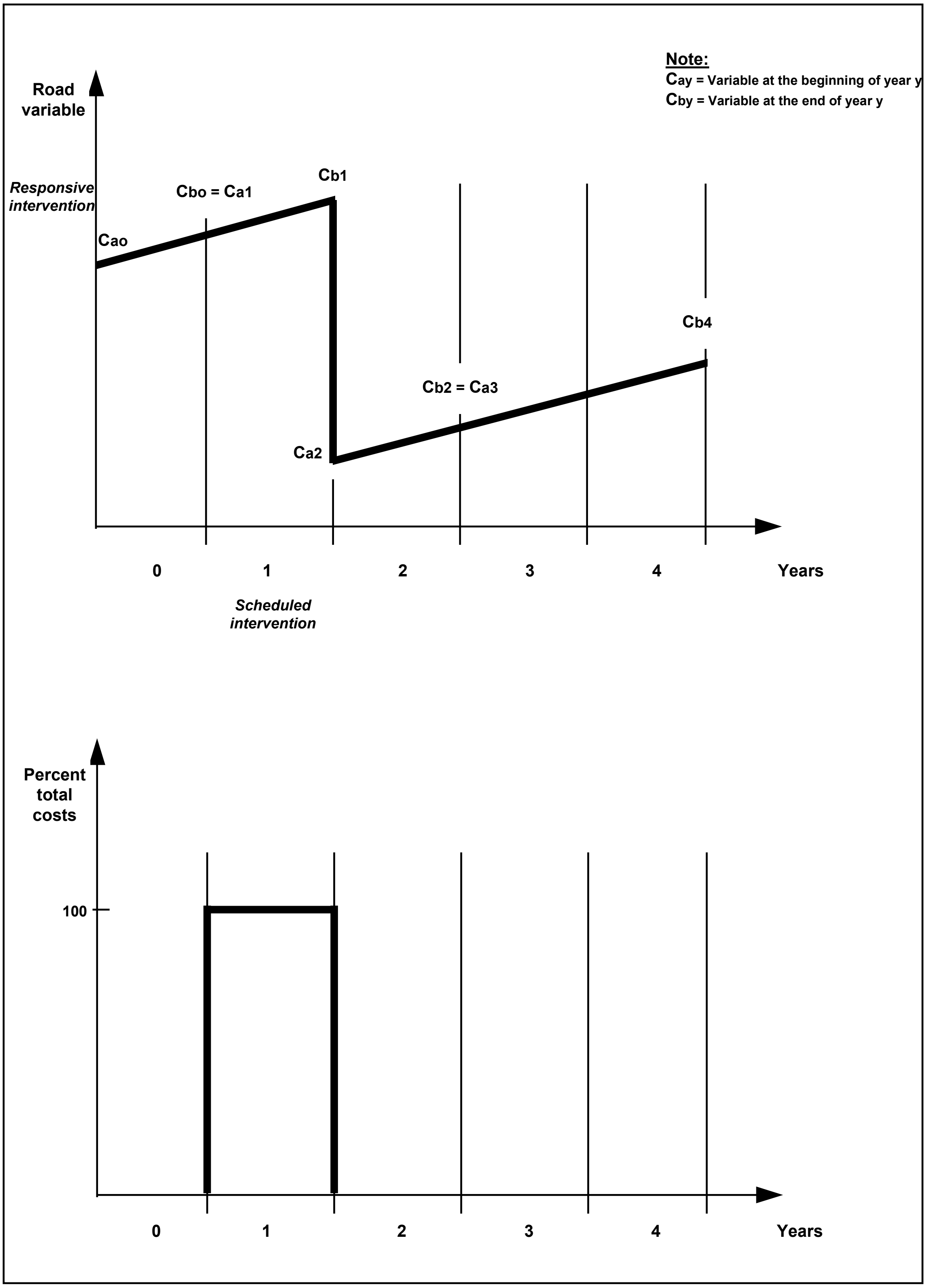

Figure D1.2 Modelling of road condition and costs for road works of one year duration

- **For works of duration greater than one year** (see Figure D1.3)

  Road characteristics are assumed to remain the same from the end of the first year of works until the end of the year of works completion. The effects of works become effective at the beginning of the analysis year following the year of works completion.

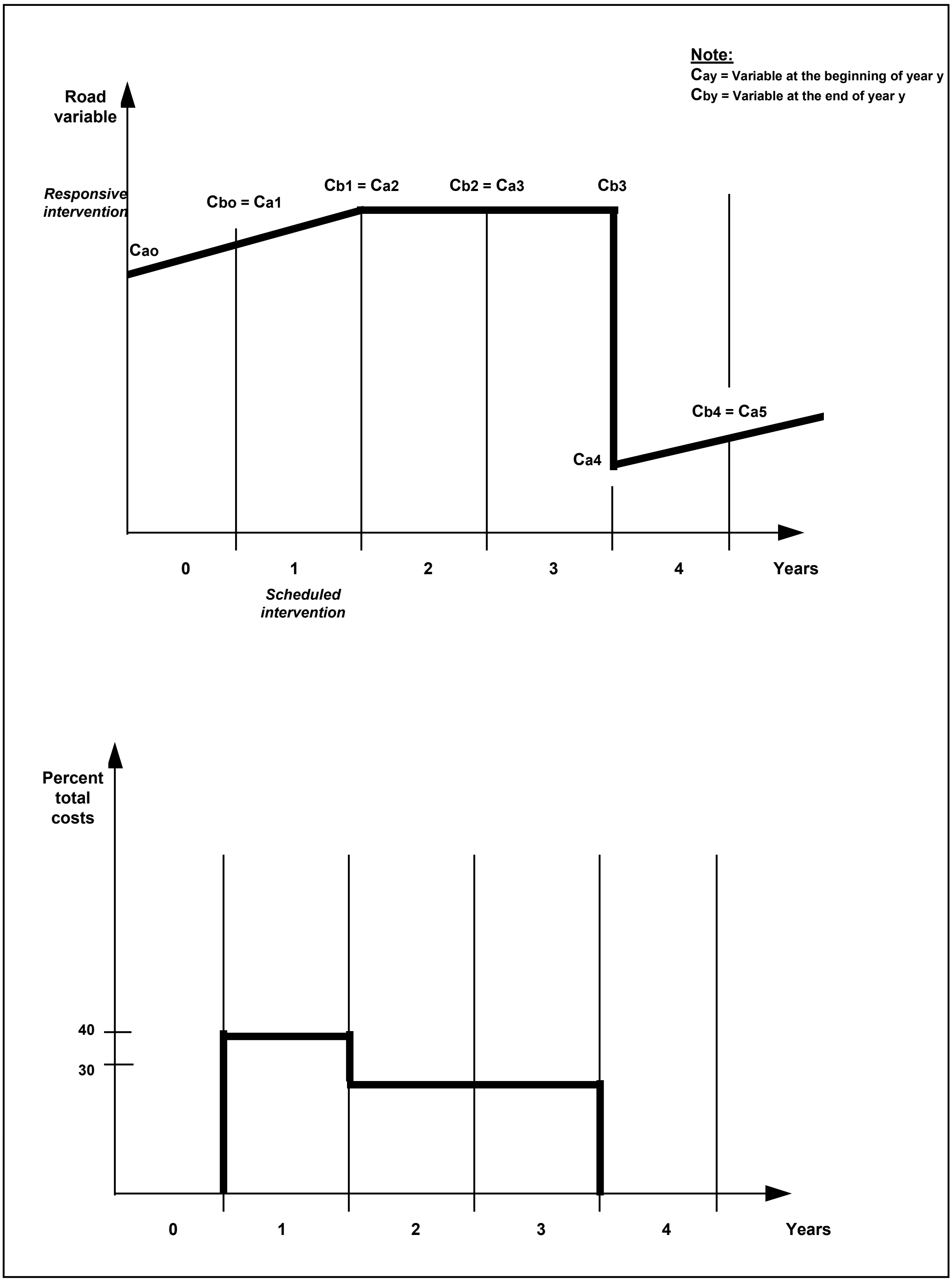

Figure D1.3 Modelling of road condition and costs for road works of duration greater than one year (for example, 3 years)

3.6 Unit costs of works

The user must specify the unit cost of each operation in economic and/or financial terms, using one of the following methods as may be appropriate:

- **Cost per square metre** (for example, overlay)
- **Cost per cubic metre** (for example, gravel resurfacing)
- **Cost per kilometre** (for example, upgrading a gravel road to a bituminous surface road)
- **Cost per kilometre per year** (for example, drainage works)
- **Lump sum cost per year** (for example, junction improvements)

Unit costs are used to multiply the physical quantities (or amount) of works in order to obtain the total cost required to implement the operation. The amount of each road works is computed for each year of the analysis period in which the works activity is applicable.

3.7 Works effects

When a works activity is performed, the immediate effects on road characteristics and road use need to be specified in terms of the following:

- **Pavement strength**
- **Pavement condition**
- **Pavement history**
- **Road deterioration calibration factors**
- **Road use patterns**

The change in characteristic can be specified in several ways, summarised as:

1. The parameter is set to zero; for example, after an overlay cracking becomes zero.
2. The parameter is reset to an absolute value, which is defined as part of the operation; for example, the roughness after an overlay is set to 2 m/km IRI.
3. The parameter is reset using a formula which may include other model parameters; for example, the roughness after an overlay is reset as a function of the previous roughness and the thickness of the overlay.
4. The parameter is not reset; for example, the carriageway width is unchanged after an overlay.

Details of the methods used for resetting the parameters that describe the road characteristics are given in Chapters D2, D3 and D4.

The long-term effects of a works operation are considered through the relevant models, for example:

- Rate of road deterioration (see Road Deterioration model in Part C)
- Changes in road user costs (see Road User Effects model in Part E)
- Changes in energy use and environmental impacts (see Social and Environmental Effects model in Part F)

Thus, both the immediate and long-term effects are combined to determine the benefits of carrying out different sets of roadworks activities at different times over the analysis period.

3.8 Asset Valuation

The asset valuation methodology used in links the capital value of the asset with its condition, which is predicted annually using the road deterioration (RD) and works effects (WE) models in HDM-4.

For the implementation of road asset valuation in HDM-4, only the following components are relevant:

- Road formation, drainage channels, and sub-grade, i.e. earthworks
- Road pavement layers
- Footways, footpaths and cycle-ways
- Bridges and structures
- Traffic facilities, signs and road furniture

When a works activity is performed, the affect on the asset valuation of the road needs to be specified accordingly:

- Routine maintenance: no change to asset value
- Periodic maintenance: road pavement layers component only.
- Improvement works: road formation and subgrade, road pavement layers, NMT lane only.

4 Costs to road administration

4.1 Annual costs and budget categories

The annual costs to road administration (or road agency costs) incurred in the implementation of road works will be calculated in economic and/or financial terms depending on the type of analysis being performed.

The costs of each works activity will be considered under the corresponding user-specified budget category, or under the default budget category (that is, capital, recurrent, or special) assigned to that particular operation, as discussed in Section 2.3.

The annual total costs to road administration for each investment option *j* will be calculated as follows:

$$RAC_j = CAP_j + REC_j + SPEC_j \qquad \text{...(4.1)}$$

where:

RAC_j	annual total road agency cost incurred under investment option *j* (*currency*)
CAP_j	annual road agency capital (or periodic) cost incurred under investment option *j* (*currency*)
REC_j	annual road agency recurrent (or routine) cost incurred under investment option *j* (*currency*)
$SPEC_j$	annual road agency special cost incurred under investment option *j* (*currency*)

For each investment option (or alternative), the annual total agency costs will be reported by works activities and by budget heads or categories.

4.2 Cost spread over works duration

In economic analysis (or cash flow analysis), road agency costs are considered as follows:

- **For works of duration not greater than one year**

  The total agency costs are incurred in the analysis year in which the works is scheduled or triggered by the specified responsive criteria. It is assumed that all maintenance works fall under this category (see Figure D1.2).

- **For works of duration greater than one year**

  The total agency costs are broken-down into annual cost streams according to user-specified percentages. The first percentage of the total costs is incurred in the analysis year in which the works is scheduled or triggered. Subsequent annual costs are incurred in each of the following years of works (see Figure D1.3).

The annual total costs to road administration are used in economic analyses of different investment options (see Part G).

4.3 Salvage value

The salvage value of construction works undertaken is the value of benefits remaining to be realised after the end of the analysis period. This may be specified by the user to represent the percentage of total costs incurred on permanent structures such as embankments, cuttings, bridges and drainage facilities.

The salvage value for each investment option is calculated as:

$$SALVA_j = \sum_{s=1}^{S} \sum_{w=1}^{W} SALVA_{jsw} \qquad ...(4.2)$$

where:

$SALVA_j$	salvage value of works performed under investment option *j* (*currency*)
$SALVA_{jsw}$	salvage value of works *w* performed on road section *s* under investment option *j* (*currency*) (see Chapters D2 and D4)

In the economic analysis of investment options, the salvage value $SALVA_j$ is considered as a benefit in the last year of analysis period (see Part G).

5 References

Paterson W.D.O., (1995)

Classification of Road Works - ISOHDM Working Paper
Communication to ISOHDM Secretariat, University of Birmingham, UK

Riley M., (1995)

Framework for Defining the Effects of Works on Road parameters in HDM-4 - ISOHDM Working Paper

Robinson R., (1995)

Road Works Classification, RR002\6_35
University of Birmingham, UK

Watanatada T., Harral C.G, Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987)

The Highway Design and Maintenance Standards Model - Volume 1 Description
World Bank, John Hopkins University Press

Watanatada T., Harral C.G., Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987)

The Highway Design and Maintenance Standards Model - Volume 2 User's Manual
World Bank, John Hopkins University Press

D2 Bituminous Pavements

1 Introduction

This chapter describes the detailed modelling of Road Works Effects for bituminous pavements (see Figure D2.1).

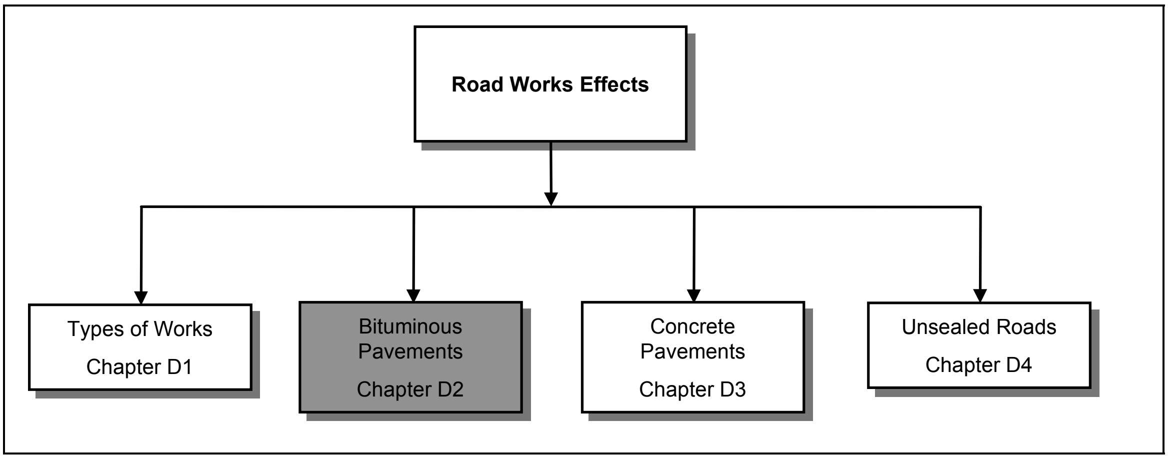

Figure D2.1 Road Works Effects modules

The methods of defining works activities and intervention criteria, the calculation of physical quantities of works and the costs to road administration, and works effects on road characteristics and road use are discussed for the following works classes:

- **Routine maintenance** (see Section 3)
- **Periodic maintenance** (see Section 4)
- **Special works** (see Section 5)
- **Improvement works** (see Section 6)
- **Construction works** (see Section 7)

The modelling logic described comprises the overall computational procedure, the hierarchical ranking of works activities and pavement type resets after works. The background of the modelling logic is given in *Watanatada et al. (1987)*.

A list of research documents referenced from this chapter is given in Section 8.

2 Modelling logic

2.1 Overall computational procedure

The overall computational procedure for modelling road works that is applied in each analysis year can be summarised by the following steps:

- Determine the works standard(s) that is applicable in the given year. Only one maintenance standard and/or one improvement standard can be applied to a road section feature in any analysis year. One or more new section construction's can be triggered in a given year.
- Check the intervention criteria and the limits defined for works in the following order:
  - first improvement works, then
  - maintenance works
- Apply drainage works (if specified).
- Identify and apply the works activity at the top of the hierarchy.
- Compute the physical quantities of works.
- Compute works effects and reset modelling parameter values to reflect post-works road geometry, pavement structure, strength, condition, history, and road use.
- Apply any other works whose effects on pavement performance are not modelled endogenously, (for example, routine-miscellaneous works).
- Calculate the costs of works by applying unit costs to the physical quantities of works.
- Calculate the effect on the section's asset valuation.
- Store results for economic analysis and for use in the following analysis year.

2.2 Hierarchy of works

A works activity (or an operation) is triggered when any one or a combination of the user-specified criteria has been met. When more than one works activity meets the criteria for being applied in a given analysis year, the highest placed operation for the particular road feature is selected.

Table D2.1 shows the hierarchy of works activities that are applicable to the carriageway. The operation **new road construction section** is placed at the top of the list as number 1 and creates a new analysis section. Upgrading is the highest ranked operation that effects an existing analysis section and takes priority over all the other operations, while routine pavement works (that is, patching, edge-repair, and crack sealing) placed at the bottom are given the lowest priority.

Table D2.1 Hierarchy of road works applicable to the carriageway

Works type	Works activity / operation	Hierarchy	Unit cost
New section	Construction of a new analysis section	1	per km
Upgrading	Upgrading to a new surface class	2	per km
Realignment	Geometric realignment	3	per km
Widening	Lane addition	4	per m^2 or per km
	Partial widening	5	per m^2 or per km
Reconstruction	Pavement reconstruction	6	per m^2 or per km
Rehabilitation	Mill and replace	7	per m^2
	Overlay rubberised asphalt	8	per m^2
	Overlay dense-graded asphalt	9	per m^2
	Overlay open-graded asphalt	10	per m^2
	Inlay	11	per m^2
	Thin overlay	12	per m^2
Resurfacing (Resealing)	Cape seal with shape correction	13	per m^2
	Cape seal	14	per m^2
	Double surface dressing with shape correction	15	per m^2
	Double surface dressing	16	per m^2
	Single surface dressing with shape correction	17	per m^2
	Single surface dressing	18	per m^2
	Slurry seal	19	per m^2
Preventive Treatment	Fog sealing	20	per m^2
	Rejuvenation	21	per m^2
Routine Pavement	Edge-repair[1]	22	per m^2
	Patching[1]	22	per m^2
	Crack sealing[1]	22	per m^2
Drainage	Drainage	23	Per km

Note:

[1] Routine pavement works (that is, crack sealing, patching, edge-repair) have the same ranking, and all of them can be performed in the same analysis year.

An improvement, or construction works, of a fixed specification is applied to a given road section only once during the analysis period. This rule applies particularly to improvement works that have been defined as responsive to the levels of user-specified intervention criteria based on road user effects parameters.

Routine pavement works, defined by the user, can be applied as separate operations in each year, or used to repair some distresses before applying the higher-priority works (for example, preventive treatment, resealing, or overlays). In the former case, routine pavement works are performed every year in which no periodic maintenance works are applied. In the latter case, routine pavement works are considered to be an integral part of the periodic maintenance works, and are referred to as **preparatory works**. Although preparatory works are automatically triggered and performed together with the periodic maintenance works, the amount and cost of each of the operations involved are modelled and reported separately.

Drainage works are applied in any given analysis year, if specified by the user, regardless of the hierarchy for carriageway works activities given in Table D2.1. Improvement of side drains takes priority over routine drainage maintenance should both works be applicable in an analysis year.

The operations that apply to shoulders and non-motorised transport (NMT) lanes are also performed in any analysis year, if specified by the user, regardless of the works hierarchy described above. Shoulder or NMT lane improvement works takes priority over shoulders repair or NMT lane repair, respectively.

For all road feature types, if more than one works activity of the same operation type (for example, different specifications of **overlay**) are applicable in an analysis year, the one with the highest cost takes priority over the others.

The works activities whose effects on pavement performance are not modelled endogenously (for example, emergency works, winter maintenance, and routine- miscellaneous works) are applied in a given analysis year, if specified by the user, regardless of any works hierarchy.

2.3 Pavement types reset

Maintenance works reset pavement types in accordance with pavement classification (see Table D2.2 and Table D2.3).

Table D2.2 Pavement type resets after maintenance works

Works activity	Existing pavement type							
	AMGB	**AMSB**	**AMAB**	**AMAP**	**STGB**	**STSB**	**STAB**	**STAP**
Routine works	AMGB	AMSB	AMAB	AMAP	STGB	STSB	STAB	STAP
Preventive Treatment	AMGB	AMSB	AMAB	AMAP	STGB	STSB	STAB	STAP
Reseal	STAP	STAP / STSB	STAP	STAP	STGB	STSB	STAB	STAP
Overlay	AMAP	AMAP / AMSB	AMAP	AMAP	AMGB	AMSB	AMAB	AMAP
Inlay	AMGB	AMSB	AMAB	AMAP	STGB	STSB	STAB	STAP
Mill & replace to intermediate surface layer	**AP	**AP	**AP	**AP	N/A	**SB	**AB	**AP
Mill & replace to base	**GB	**SB	**AB	**AP	**GB	**SB	**AB	**AP

Source: *NDLI (1995)*

Notes:

** Indicates that these two characters are dependent on the specific works activity (or operation) and the surface material

N/A Not applicable

Table D2.3 Maintenance effects on resultant surface material

Maintenance works	Resultant surface material options
All resealings	SBSD, DBSD, CAPE, SL, PM
All overlays, including thin overlay	AC, HRA, PMA, RAC, CM, SMA, PA
Mill and replace	SBSD, DBSD, CAPE, SL, PM, AC, HRA, PMA, RAC, CM, SMA, PA

Notes: For the definition and full description of the abbreviated surface materials refer to Chapter C2.

3 Routine maintenance

The routine maintenance works on bituminous roads whose effects on pavement performance are modelled, comprises the following operations:

- **Patching** (see Section 3.1)
- **Crack sealing** (see Section 3.1.6)
- **Edge-repair** (see Section 3.3)
- **Drainage works** (see Section 3.4)

Other routine maintenance works (for example, vegetation control, repairs to road appurtenances, etc.) are considered in the analyses only in terms of their costs to the road administration.

3.1 Patching

Patching is used to repair the following distresses:

- **Potholing**
- **Wide Structural Cracking**
- **Transverse Thermal Cracking**
- **Ravelling**

The user may specify patching to repair the individual distress.

3.1.1 Potholing only

Patching may be specified to repair only potholing by specify the percentage of potholing area to be patched (Ppt), the time-lapse to patching (TLTP), and one or more intervention criterion which may impose a criterion defining the maximum annual quantity of patching.

The recommended intervention criterion are as follows:

- Potholing
- Maximum material quantity
- Year
- Roughness
- Two-way AADT

The progression of potholes is affected by the patching policy assigned to the section, as the Ppt and TLTP which are defined as part of the pothole patching work item. The effect of the frequent patching policy on the road deterioration models is described in Volume 4 Part C2 Section 7.2.

If the intervention criteria defined includes a condition-responsive criterion then patching is triggered from start-of-year pavement condition; this may to produce unexpected results, and road condition evolution should be checked prior to economic analysis.

For both options the total area patched is given by Equation 3.1:

$$APAT_p = MIN\lfloor APAT_{plim}, ASP_p \rfloor \qquad ...(3.1)$$

and the parameter ASP_p is calculated as follows:

$$ASP_p = Ppt * APOT_{bw} * CW * 10^{-1} \qquad ...(3.2)$$

where:

$APAT_p$	total area of potholes patched during the analysis year (m^2/km)
$APAT_{plim}$	maximum annual quantity of patching, input by the user (m^2/km)
$APOT_{bw}$	area of potholing to be patched (= $APOT_b$) (% of total carriageway area)
ASP_b	total pothole patching quantity during the analysis year, including those that were patched during the year, and those that are patched at end of year
Ppt	percentage of potholing area to be patched, input by the user (default = 100%)

All other parameters are as defined previously.

When patching is performed, the area of potholing is reduced by the amount of patching. The areas of wide structural cracking and of ravelling is not changed by the patching.

The percentage repaired of potholing is calculated as follows:

If $ASP_p > APAT_{plim}$

then:

$$Ppt = \left[\frac{10 * APAT_{plim}}{APOT_{bw} * CW} \right] \qquad ...(3.3)$$

otherwise:

Ppt equals the user-specified value (or the default value = 100%)

3.1.2 Wide structural cracking only

Patching may be specified to treat only wide structural cracking by specify a fixed percentage of wide structural cracking area (Pcw) to be patched, and one or more intervention criterion which may impose a criterion defining the maximum annual quantity of patching.

The recommended intervention criterion are as follows:

- Wide Structural Cracking
- Maximum material quantity
- Year
- Roughness
- Two-way AADT

The total area to be patched is given by

$$APAT_w = MIN[APAT_{wlim}, ASP_w] \qquad ...(3.4)$$

and the parameter ASP_w is calculated as follows:

$$ASP_w = Pcw * ACW_{bw} * CW * 10^{-1} \qquad ...(3.5)$$

where:

$APAT_w$	total area of wide structural cracks patched (m^2/km)
$APAT_{wlim}$	maximum annual quantity of patching, input by the user (m^2/km)
ACW_{bw}	area of wide structural cracking before patching works (= ACW_b) (% of total carriageway area)
Pcw	percentage of wide structural cracking area to be patched, input by the user (default = 100%)

All the other variables are as defined previously.

When patching is performed, the area of wide structural cracking is reduced by the amount of patching. The areas of potholing, transverse thermal cracking, and of ravelling will not be changed by the patching.

The percentage repaired of wide structural cracking is calculated as follows:

If $ASP_w > APAT_{wlim}$, then

$$Pcw = \left[\frac{10 * APAT_{wlim}}{ACW_{bw} * CW}\right] \qquad ...(3.6)$$

otherwise:

Pcw	equals the user-specified value (or the default value = 100%)

3.1.3 Transverse Thermal cracking only

Patching may be specified to treat only transverse thermal cracking by specify a fixed percentage transverse thermal cracking area (Pct) to be patched, and one or more intervention criterion which may impose a criterion defining the maximum annual quantity of patching.

The recommended intervention criterion are as follows:

- Transverse Thermal Cracking
- Maximum material quantity
- Year
- Roughness
- Two-way AADT

The total area to be patched is given by

$$APAT_t = MIN[APAT_{tlim}, ASP_t] \quad ...(3.7)$$

and the parameter ASP_t is calculated as follows:

$$ASP_t = Pct * ACT_{bw} * CW * 10^{-1} \quad ...(3.8)$$

where:

$APAT_t$	total area of transverse thermal cracks patched (m^2/km)
$APAT_{tlim}$	maximum annual quantity of patching, input by the user (m^2/km)
ACT_{bw}	area of transverse thermal cracking before patching works (= ACT_b) (% of total carriageway area)
Pct	percentage of transverse thermal cracking area to be patched, input by the user (default = 100%)

All the other variables are as defined previously.

When patching is performed, the area of transverse thermal cracking is reduced by the amount of patching. The areas of potholing, wide structural cracking, and of ravelling will not be changed by the patching.

The percentage repaired of transverse thermal cracking is calculated as follows:

If $ASP_t > APAT_{tlim}$, then

$$Pct = \left[\frac{10 * APAT_{tlim}}{ACT_{bw} * CW}\right] \quad ...(3.9)$$

otherwise:

Pct equals the user-specified value (or the default value = 100%)

3.1.4 Ravelling only

Patching may be specified to treat only ravelled by specify a fixed percentage of ravelled area (Prv) to be patched, and one or more intervention criterion which may impose a criterion defining the maximum annual quantity of patching.

The recommended intervention criterion are as follows:

- Ravelling
- Maximum material quantity
- Year
- Roughness
- Two-way AADT

The total area to be patched is given by

$$APAT_v = MIN[APAT_{vlim}, ASP_v] \qquad ...(3.10)$$

and the parameter ASP_v is calculated as follows:

$$ASP_v = Prv * ARV_{bw} * CW * 10^{-1} \qquad ...(3.11)$$

where:

$APAT_v$	total area of ravelling patched (m^2/km)
$APAT_{vlim}$	maximum annual quantity of patching, input by the user (m^2/km)
ARV_{bw}	area of ravelling before patching works (= ARV_b) (% of total carriageway area)
Prv	percentage of ravelling area to be patched, input by the user (default = 100%)

All the other variables are as defined previously.

When patching is performed, the area of ravelling is reduced by the amount of patching. The areas of potholing, wide structural cracking, and of transverse thermal cracking will not be changed by the patching.

The percentage repaired of ravelling is calculated as follows:

If $ASP_v > APAT_{vlim}$, then

$$Prv = \left[\frac{10 * APAT_{vtlim}}{ARV_{bw} * CW}\right] \qquad ...(3.12)$$

otherwise:

Prv	equals the user-specified value (or the default value = 100%)

3.1.5 Total area and cost of patching

The total patched area APAT (m^2/km) is given by:

$APAT = APAT_p + APAT_w + APAT_t + APAT_v$

The total area patched (TAPAT), in square meters, is given by the product of APAT and the section length (L), in kilometres. The total cost of patching performed on the entire road section is obtained using:

$$TCOST_{APAT} = L * \left(APAT_p * COST_p + APAT_w * COST_w + APAT_t * COST_t + APAT_v * COST_v\right)$$

where

$TCOST_{APAT}$	Total cost of patching on the entire road
$COST_p$	Unit cost of pothole patching per m^2
$COST_w$	Unit cost of patching wide structural cracks per m^2

$COST_t$	Unit cost of patching transverse thermal cracks per m^2
$COST_v$	Unit cost of patching ravelled area per m^2

from the product of TAPAT and the user specified unit cost per square meter.

3.1.6 Effects of patching

In all the options for defining patching works, the effects of patching on pavement condition are computed as follows:

Potholing

$$NPT_{aw} = NPT_{bw} * \left[1 - \frac{Ppt}{100}\right] \qquad ...(3.13)$$

where:

NPT_{aw}	number of potholes per km after patching works
NPT_{bw}	number of potholes per km before patching works (= NPT_b)
NPT_b	number of potholes per km at the end of the year

The change in the number of potholes per km due to works (ΔNPT_w) is given by:

$$\Delta NPT_w = NPT_{bw} - NPT_{aw} \qquad ...(3.14)$$

Wide Structural Cracking

$$ACW_{aw} = ACW_{bw} * \left[1 - \frac{Pcw}{100}\right] \qquad ...(3.15)$$

$$\Delta ACW_w = ACW_{bw} - ACW_{aw} \qquad ...(3.16)$$

$$ACA_{aw} = ACA_{bw} - \Delta ACW_w \qquad ...(3.17)$$

$$ACX_{aw} = 0.62 * ACA_{aw} + 0.39 * ACW_{aw} \qquad ...(3.18)$$

$$ACRA_{aw} = ACA_{aw} + ACT_{bw} \qquad ...(3.19)$$

where:

ACW_{aw}	area of wide structural cracking after patching works (% of total carriageway area)
ACA_{aw}	area of all structural cracking after patching works (% of total carriageway area)
ACA_{bw}	area of all structural cracking before patching works (= ACA_b) (% of total carriageway area)

ACA_b area of all structural cracking at the end of the year (% of total carriageway area)

ACX_{aw} area of indexed cracking after patching works (% of total carriageway area)

$ACRA_{aw}$ total area of cracking after patching works (% of total carriageway area)

ACT_{bw} area of transverse thermal cracking before patching works (= ACT_b) (% of total carriageway area)

ACT_b area of transverse thermal cracking at the end of the year (% of total carriageway area)

ΔACW_w reduction in area of wide structural cracking due to patching works (= ΔACW_{pat}) (% of total carriageway area)

Transverse Thermal Cracking

$$ACT_{aw} = ACT_{bw} * \left[1 - \frac{Pct}{100}\right] \qquad ...(3.20)$$

$$ACRA_{aw} = ACA_{aw} + ACT_{aw} \qquad ...(3.21)$$

where:

ACT_{aw} Area of transverse thermal cracking after patching works (% of total carriageway area)

ACT_{bw} Area of transverse thermal cracking before patching works (= ACT_b) (% of total carriageway area)

ACT_b Area of transverse thermal cracking at the end of the year (% of total carriageway area)

The change in the area of transverse thermal cracking due to works (ΔACT_w) is given by:

$$\Delta ACT_w = ACT_{bw} - ACT_{aw} \qquad ...(3.22)$$

Ravelling

$$ARV_{aw} = ACV_{bw} * \left[1 - \frac{Prv}{100}\right] \qquad ...(3.23)$$

where:

ARV_{aw} area of ravelling after patching works (% of total carriageway area)

Roughness

Roughness after patching is calculated as follows:

$$RI_{aw} = MAX\left\{\begin{array}{l} 0.5, \\ RI_{bw} \quad - \ MIN\left\{\begin{array}{l}\left[a0 * (\Delta CRX_w + \Delta ACT_w) + \Delta RI_t \text{ - } a1 * MIN\left(\frac{APAT}{(10 * CW)}, 10\right)\right], \\ (a2 - RI_{bw})\end{array}\right\} \end{array}\right\}$$

...(3.24)

and:

$$\Delta RI_{pat} = RI_{bw} - RI_{aw}$$ ...(3.25)

where:

RI_{aw}	roughness after patching works (IRI m/km)
RI_{bw}	roughness before patching works (= RI_b) (IRI m/km)
RI_b	roughness at the end of the year (IRI m/km)
APAT	total patched area (m^2/km) (for computing increase in roughness due to depression or protrusion of patches)
ΔCRX_w	reduction in the area of indexed structural cracking due to patching works (= ACX_{bw} - ACX_{aw})
ACX_{bw}	area of indexed structural cracking before patching works (= ACX_b) (% of total carriageway area)
ACX_b	area of indexed structural cracking at the end of the year (% of total carriageway area)
ΔRI_t	reduction in roughness due to patching works (IRI m/km)
ΔRI_{pat}	reduction in roughness due to pothole patching works (IRI m/km)
CW	carriageway width (m)
A0 to a2	user-definable model coefficients (default = 0.0066, 0.01 and 16.0 respectively)

The model coefficient a1 in Equation 3.24 above represents an average depression or protrusion of about 2 mm for skin patches. When the standard of workmanship observed in maintenance patching differs significantly from this, care should be taken by user in results analysis, as coefficients are not user editable.

The reduction in roughness due to the patching of potholes is calculated as follows, based on *Watanatada et al. (1987)*:

$$\Delta RI_t = 0.378 * \left(\frac{0.1 * \Delta NPT_{uw}}{10 * CW}\right)$$ ...(3.26)

and

$$\Delta NPT_{uw} = NPT_{bu} - NPT_{aw}$$ ...(3.27)

where:

ΔRI_t	reduction in roughness due to pothole patching (IRI m/km)
ΔNPT_{uw}	Reduction in number of unpatched potholes per km due to patching
CW	carriageway width (m)

3.2 Crack sealing

Crack sealing treats transverse thermal cracking and wide structural cracking. However, it is assumed that crack sealing is not applied to treat wide structural cracking if the area of wide structural cracking exceeds 20 % (that is, ACW_b>20).

The user may specify crack sealing by specifying the percentage of the area with transverse thermal cracking (Pcrt) and/or the percentage of the area with wide structural cracking (Pcrw) to be sealed in each year, and one or more intervention criterion which may include a criterion defining a limit of the maximum area.

The recommended intervention criterion are as follows:

- Wide Structural Cracking
- Transverse Thermal Cracks
- Maximum material quantity
- Year
- Roughness
- Two-way AADT

The carriageway area sealed is computed as follows:

$$ACSL = MIN\left(ACSL_{lim}, ASEAL\right) \qquad ...(3.28)$$

$$ASEAL = \left[(Pcrt * ACT_{bw}) + (Pcrw * ACW_{bw})\right] * CW * 10^{-1} \qquad ...(3.29)$$

where:

ACSL	area of crack sealing (m^2/km)
$ACSL_{lim}$	maximum annual quantity of crack sealing, input by the user (m^2/km)
ACT_{bw}	area of transverse thermal cracking before crack sealing (= ACT_b) (% of total carriageway area)
ACW_{bw}	area of wide structural cracking before crack sealing (% of total carriageway area)
Pcrt	percentage of transverse thermal cracking area to be sealed, input by the user (%)
Pcrw	percentage of wide structural cracking area to be sealed, input by the user (%)

The values of ACW_{bw}, ACA_{bw}, and RI_{bw} to be used in Equations 3.29 above, 3.35 below, 3.36 below and 3.39 below are obtained as follows:

if both crack sealing and patching are specified to be performed in a given analysis year, it is assumed that patching takes priority over crack sealing in reducing the area of wide structural cracking, thus:

$$ACW_{bw} = ACW_b - \Delta ACW_{pat} \quad ...(3.30)$$

$$ACA_{bw} = ACA_b - \Delta ACW_{pat} \quad ...(3.31)$$

$$RI_{bw} = RI_b - \Delta RI_{pat} \quad ...(3.32)$$

where:

ΔACW_{pat} reduction in area of wide structural cracking due to patching works (% of total carriageway area). This is calculated using Equation 3.25 above, with the subscript *w* replaced with *pat*

ACA_{bw} adjusted area of all structural cracking before crack sealing (after patching) (% of total carriageway area)

RI_{bw} adjusted roughness before crack sealing works (after patching) (IRI m/km)

ΔRI_{pat} roughness after patching works (IRI m/km). This is calculated using Equation 3.25 above

otherwise:

$$ACW_{bw} = ACW_b$$

$$ACA_{bw} = ACA_b$$

$$RI_{bw} = RI_b$$

The total area of crack sealing (TACSL), in square metres, is given by the product of ACSL and the section length (L), in kilometres. The total cost of crack sealing performed on the entire road section is computed by multiplying TACSL by the user-specified unit cost per square metre.

3.2.1 Effects of crack sealing

The effects of crack sealing on pavement condition are reset as follows:

Cracking

When crack sealing is performed, it is assumed that the treatment of transverse thermal cracking takes priority over that of wide structural cracking, and no crack sealing is performed to fix wide structural cracking until transverse thermal cracking is completely repaired.

The areas of cracking are reduced by the amount of sealing as follows:

$$ACT_{aw} = ACT_{bw} - MIN\left[Pcrt * ACT_{bw} * 10^{-2}, \frac{ACSL}{(10 * CW)}\right] \quad ...(3.33)$$

$$\Delta ACW_w = MAX\left\{0, \left[\frac{ACSL}{(10 * CW)}\right] - [ACT_{bw} - ACT_{aw}]\right\} \quad ...(3.34)$$

$$ACW_{aw} = ACW_{bw} - \Delta ACW_w \quad ...(3.35)$$

$$ACA_{aw} = ACA_{bw} - \Delta ACW_w \quad ...(3.36)$$

$$ACX_{aw} = 0.62 * ACA_{aw} + 0.39 * ACW_{aw} \quad ...(3.37)$$

$$ACRA_{aw} = ACA_{aw} + ACT_{aw} \quad ...(3.38)$$

where:

ACT_{aw}	area of transverse thermal cracking after crack sealing works (% of total carriageway area)
ACT_{bw}	area of transverse thermal cracking before crack sealing works (= ACT_b) (% of total carriageway area)
ΔACW_w	reduction in area of wide structural cracking due to crack sealing (% of total carriageway area)
ACW_{aw}	area of wide structural cracking after crack sealing works (% of total carriageway area)
ACW_{bw}	adjusted area of wide structural cracking before crack sealing (% of total carriageway area)
ACA_{bw}	adjusted area of all structural cracking before crack sealing (% of total carriageway area)
ACA_{aw}	area of all structural cracking after crack sealing works (% of total carriageway area)
ACX_{aw}	area of indexed cracking after crack sealing works (% of total carriageway area)
$ACRA_{aw}$	Total area of cracking after crack sealing works (% of total carriageway area)

Roughness

Crack sealing has some little effect on roughness, which is computed as follows:

$$RI_{aw} = RI_{bw} - a0 * \Delta ACRA \quad ...(3.39)$$

$$\Delta ACRA_w = ACRA_{bw} - ACRA_{aw} \quad ...(3.40)$$

where:

RI_{aw}	roughness after crack sealing works (IRI m/km)
RI_{bw}	adjusted roughness before crack sealing works (IRI m/km)

$\Delta ACRA_w$	reduction in the total area of cracking due to crack sealing (% of total carriageway area)
a0	model coefficient (default = 0.0066)

3.3 Edge-repair

The user may specify edge-repair by specifying the percentage area of edge-break to be repaired in each year (Pver), and one or more intervention criterion which may include a criterion defining a limit of the maximum annual quantity of edge-repair.

The recommended intervention criterion are as follows:

- Edgebreak
- Maximum material quantity
- Year
- Roughness
- Two-way AADT

The area of edge-repair is computed as follows:

$$AVERP = MIN\left\{AVERP_{lim},\ \left[Pver * AVEB_{bw} * CW * 10^{-1}\right]\right\} \qquad ...(3.41)$$

where:

AVERP	Area of edge-repair (m^2/km)
$AVERP_{lim}$	maximum annual quantity of edge-repair, input by the user (m^2/km)
$AVEB_{bw}$	total area of edge-break before edge-repair works (= $AVEB_b$) (% of total carriageway area)
$AVEB_b$	Total area of edge-break at the end of the year (% of total carriageway area)
Pver	percentage of edge-break area to be repaired, input by the user (%), default = 100

The product of AVERP and the section length (L), in kilometres, gives the total area of edge-repair (TAVER) in square metres. The total cost of edge-repair performed on the entire road section is computed by multiplying TAVER by the user-specified unit cost per square metre.

3.3.1 Effects of edge-repair

When edge-repair is performed, the area of edge-break is reduced by the amount repaired as follows:

$$AVEB_{aw} = \left[AVEB_{bw} - \frac{AVERP}{(CW * 10)}\right] \qquad ...(3.42)$$

where:

$AVEB_{aw}$ Area of edge-break after edge-repair works (% of total carriageway area)

All other parameters are as defined previously.

3.4 Drainage works

Drainage maintenance is an important works activity that prevents accelerated pavement deterioration. Drainage works is modelled through its effects on pavement strength.

The user may specify drainage works by specifying a drainage maintenance cost factor (DMCF), and defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- Drainage Factor
- Year
- Interval

The unit costs of drainage works is specified in terms of *currency* per km per year. The annual costs are obtained by multiplying the length of the road by the unit cost.

3.4.1 Effects of drainage works

When drainage works is performed, the drainage factor after works (DF_{aw}) is reset as follows:

$$DF_{aw} = MAX\,[DF_{dmin}, (DF_{bw} - \Delta DF_{w})] \qquad ...(3.43)$$

and:

$$\Delta DF_{w} = (DF_{dmax} - DF_{dmin}) * DMCF \qquad ...(3.44)$$

where:

DF_{aw} drainage factor after maintenance works

DF_{bw} drainage factor before maintenance works

DF_{dmax} maximum drainage factor, denoting very poor drainage condition for drain type *d*

DF_{dmin} minimum drainage factor, denoting excellent drainage condition for drain type *d*

ΔDF_{w} change in DF due to the drainage works performed

DMCF drainage maintenance cost factor, defined as the ratio of the annual cost of drainage works performed to the annual cost required to maintain the drainage system in excellent condition

The drainage factor after works is used to compute the adjusted structural number of pavement (SNP).

3.5 Other routine works

The effects of the following routine works on pavement performance are not modelled endogenously, and therefore only their costs are considered in an analysis:

- **Shoulders repair**
- **NMT lanes repair**
- **Routine miscellaneous works**
  For example, vegetation control, road sign repairs and replacement, line marking, guard rail repair, etc.

If specified by the user, the works activities are applied in a given analysis year regardless of the works hierarchy.

The recommended intervention criterion are as follows:

- Year
- Interval
- Two-way AADT (Shoulder & NMT lane repair only)

The unit cost should be specified in terms of *currency* per km per year, and the annual cost of the operation is obtained from the product of the road section length and the unit cost.

4 Periodic maintenance

The periodic maintenance works on bituminous roads comprises the following:

- **Preventive treatment** (see Section 4.1)
- **Resealing** (see Section 4.2)
- **Overlay** (see Section 4.4)
- **Mill and replace** (see Section 4.5)
- **Inlays** (see Section 4.6)
- **Reconstruction** (see Section 4.7)

4.1 Preventive treatment

Preventive treatments include fog sealing and rejuvenation. These can be triggered by the user defining one or more intervention criterion. If defining time-based interval criterion the surfacing preventive treatment age (AGE1) is used to determine the elapsed time period. Preventive treatment is not applied if:

$ACRA_b \geq 5$,

$ARV_b \geq 5$, or

$NPT_a > 0$.

The recommended intervention criterion are as follows:

- Total carriageway cracked
- Ravelling
- Roughness
- Year
- Interval
- Two-way AADT

4.1.1 Quantities and costs

If performed, the amount of preventive treatment is given by:

$$APVT = 1000 * CW \qquad ...(4.1)$$

where:

APVT	area of road treated (m^2/km)
$ACRA_b$	total area of cracking at the end of the year (% of total carriageway area)
ARV_b	area of ravelling at the end of the year (% of total carriageway area)

The total area treated (TAPVT), in square metres, is given by the product of APVT and the section length (L), in kilometres. The total cost of preventive treatment performed is computed by multiplying TAPVT by the user-specified unit cost per square metre

4.1.2 Effects of preventive treatment

The effects of preventive treatment are reset as follows:

- **Surface distresses**

  When preventive treatment is performed, any surface distress (which is minimal) is reset to zero.

- **Pavement strength**

  The pavement structure and strength remains unaltered.

- **Surfacing age**

  Preventive treatment age (AGE1) is reset to zero.

- **Cracking and ravelling retardation**

  Preventive treatment has the effects of delaying the initiation of cracking and ravelling. These effects are considered in the models through changes in the cracking retardation time (CRT) and ravelling retardation factor (RRF) as described below:

  - The cracking retardation time after preventive treatment is reset as follows:

$$CRT_{aw} = MIN\left[CRT_{bw} + \frac{CRM}{YXK}, \frac{CRTMAX}{YXK}, 8\right] \quad ...(4.2)$$

$$YXK = MAX(0.1, YAX) \quad ...(4.3)$$

where:

CRT_{aw}	cracking retardation time after preventive treatment (years)
CRT_{bw}	cracking retardation time before preventive treatment (years)
CRM	change in cracking retardation time due to preventive treatment
CRTMAX	maximum limit on the value of cracking retardation time
YAX	annual number of axles of all vehicle types (millions per lane)

  - The ravelling retardation factor after preventive treatment is reset as follows:

For surface type AM:

$$RRF_{aw} = 1 \quad ...(4.4)$$

For surface type ST:

$$RRF_{aw} = MIN[RRF_{bw} * RRM, RRFMAX] \quad ...(4.5)$$

where:

RRF_{aw}	ravelling retardation factor after preventive treatment
RRF_{bw}	ravelling retardation factor before preventive treatment
RRM	change in ravelling retardation factor due to preventive treatment
RRFMAX	maximum limit on the value of ravelling retardation factor

The default values for CRM, CRTMAX, RRM and RRFMAX for rejuvenation and fog sealing are given in Table D2.4 and Table D2.5, respectively.

Table D2.4 Model parameters for rejuvenation

Pavement type	Surface material	HSOLD value	CRM	CRTMAX	RRM	RRFMAX
AMGB	All	0	1.5	3.0	1.15	2.0
	All except CM	> 0	1.5	3.0	1.15	2.0
	CM	> 0	0.75	1.5	1.15	2.0
AMAB	All		1.5	3.0	1.15	2.0
AMAP	All		1.5	3.0	1.15	2.0
AMSB	All		1.5	3.0	1.15	2.0
STGB	All	0	3.0	6.0	1.15	2.0
		> 0	1.5	3.0	1.15	2.0
STAB	All	0	1.5	3.0	1.15	2.0
STAP	All		1.5	3.0	1.15	2.0
STSB	All		1.5	3.0	1.15	2.0

Source: *Watanatada et al. (1987)*

Table D2.5 Model parameters for fog sealing

Pavement type	Surface material	HSOLD value	CRM	CRTMAX	RRM	RRFMAX
AMGB	All	0	0.8	1.6	1.3	3.0
	All except CM	> 0	0.8	1.6	1.3	3.0
	CM	> 0	0.4	0.8	1.3	3.0
AMAB	All		0.8	1.6	1.3	3.0
AMAP	All		0.8	1.6	1.3	3.0
AMSB	All		0.8	1.6	1.3	3.0
STGB	All	0	1.6	3.2	1.3	3.0
		> 0	0.8	1.6	1.3	3.0
STAB	All	0	0.8	1.6	1.3	3.0
STAP	All		0.8	1.6	1.3	3.0
STSB	All		0.8	1.6	1.3	3.0

Source: *Watanatada et al. (1987)*

4.2 Preparatory Works

If the area of cracks (structural and thermal), or potholes, or transverse thermal cracking or edge break are not zero at the end of the year, preparatory works are assumed to be carried out along with resealing or overlay works.

4.2.1 Preparatory works options

The preparatory works are user-selected in configuration, according to the following options.

Table D2.6 Preparatory Works Options

Preparatory works activity	Reseal	Default	Overlay	Default
Structural cracks	Patch wide only	✓	Patch wide only	
	Seal wide only		Seal wide only	
	Patch wide & Seal		Patch wide & Seal	
	Seal all		Seal all	
	Nothing		Nothing	✓
Transverse thermal cracking	Patch		Patch	
	Seal	✓	Seal	
	Nothing		Nothing	✓
Edge break	Repair	✓	Repair	✓
	Nothing		Nothing	
Potholes	Patch	✓	Patch	✓

The options can be described as follows:

Structural cracks

- o Patch wide only: wide structural cracks are partially patched (see specifications hereafter), no other action is performed.
- o Seal wide only: wide structural cracks are totally sealed, no other action is performed.
- o Patch wide and seal: wide structural cracks are first partially patched (see specifications hereafter), all remaining cracks are then sealed.
- o Seal all: all structural cracks are totally sealed.

Transverse thermal cracks

- o Patch: transverse thermal cracks are partially patched (see specifications below), no other action is performed.
- o Seal: transverse thermal cracks are totally sealed.

Edge break

- o Repair: the area of edge break is totally repaired.

Potholing

- o Patch: the area of potholing is totally repaired.

Ravelled areas do not need any preparatory works.

Only one option is can be selected for each preparatory works activity.

4.2.2 Preparatory Works quantity

Patching

Patching activities as preparatory works are designed to repair the most severe distress. It is assumed that:

- For wide cracks and transverse cracks, the decision to patch is linked to a threshold in distress extent: under this threshold, no patching is carried out; above this threshold, patching is limited in extent to the most severely damaged areas, expressed by a percentage of the quantity between actual extent and triggering threshold. Threshold values and percentages are user defined in configuration.
- Potholes are systematically patched.

The quantities are computed as follows.

- **Patching Structural cracks**

If "Patch wide only" or "Patch wide & Seal" option was selected for Structural cracks, patching quantity is computed as

$$APAT_{cw} = 10 * CW * \max\left[CWPATPER * \left(ACW_b - TRIACW\right), 0\right] \quad \ldots(4.6)$$

otherwise

$$APAT_{cw} = 0$$

where

$APAT_{cw}$	is the area (in m²/km) of preparatory patching for wide cracks
CW	is the carriageway width
CWPATPER	is the percentage of Wide cracks in excess of TRIGACW to be patched (user defined, default 10%)
ACW_b	is the area of wide structural cracking at the end of the year (% of total carriageway area)
TRIGACW	is the area (in percent) of wide cracks that triggers wide cracks patching (user defined, default 20%)

CWPATPER and TRIGACW are user defined in configuration.

- **Patching Transverse Thermal Cracks**

If "Patch" option was selected for Transverse thermal cracks, patching quantity is computed as

$$APAT_{ct} = 10 * CW * \max\left[CTPATPER * \left(ACT_b - TRIGACT\right), 0\right] \qquad ...(4.7)$$

otherwise

$$APAT_{ct} = 0$$

where

$APAT_{ct}$	is the area (in m²/km) of preparatory patching for transverse thermal cracks
CTPATPER	is the percentage of transverse cracks in excess of TRIGACT to be patched (user defined, default 20%)
ACT_b	is the area of transverse thermal cracking at the end of the year (% of total carriageway area)
TRIGACT	is the area (in percent) of transverse cracks that triggers transverse cracks patching (user defined, default 10%)

All other parameters are as defined previously.

CTPATPER and TRIGACT are user defined in configuration.

- **Patching Potholes**

Patching quantity is computed as

$$APAT_p = 10 * CW * APOT_b \qquad ...(4.8)$$

where

$APAT_p$	is the area (in m²/km) of preparatory patching for potholes
$APOT_b$	is the area of potholes at the end of the year (% of total carriageway area)

All other parameters are as defined previously.

- **Total Patching Quantity**

Patching total quantity is computed as

$$APAT = APAT_{cw} + APAT_{ct} + APAT_{p} \qquad \ldots(4.9)$$

where

APAT is the total area (in m²/km) of preparatory patching

All other parameters are as defined previously.

Crack Sealing

- **Sealing Structural Cracks**

If "Seal all" option was selected for Structural cracks, sealing quantity is computed as

$$ACSL_{sc} = 10 * CW * ACA_{b} \qquad \ldots(4.10)$$

If "Seal wide only" option was selected for Structural cracks, sealing quantity is computed as

$$ACSL_{sc} = 10 * CW * ACW_{b} \qquad \ldots(4.11)$$

If "Patch wide & Seal" option was selected for Structural cracks, sealing quantity is computed as:

$$ACSL_{sc} = 10 * CW * ACW_{rb} \qquad \ldots(4.12)$$

ACW_{rb} is computed as

$$ACW_{rb} = ACW_{b} - \max\left[CWPATPER * (ACW_{b} - TRIGACW), 0\right] \qquad \ldots(4.13)$$

If "Patch wide only" or "Nothing" option was selected for Structural cracks, sealing quantity is:

$$ACSL_{sc} = 0$$

where

$ACSL_{sc}$ is the area (in m²/km) of crack sealing due to structural cracking

ACW_{rb} is the area of wide structural cracking still to seal at the end of the year (% of total carriageway area)

All other parameters are as defined previously.

- **Sealing Transverse Thermal Cracks**

If "Seal" option was selected for Structural cracks, sealing quantity is computed as

$$ACSL_{ct} = 10 * CW * ACT_{b} \qquad \ldots(4.14)$$

If "Patch" or "Nothing" option was selected for Transverse thermal cracks, sealing quantity is:

$$ACSL_{ct} = 0$$

where

$ACSL_{ct}$ is the area (in m²/km) of crack sealing due to transverse thermal cracking

All other parameters are as defined previously.

- **Total Sealing Quantity**

The total area of preparatory crack sealing is computed as:

$$ACSL = ACSL_{sc} + ACSL_{ct} \quad \text{...(4.15)}$$

where

ACSL is the total area (in m²/km) of crack sealing

All other parameters are as defined previously.

Edge-repair

If "Repair" option was selected for Ed, edge repair quantity is computed as

$$AVERP = 10 * CW * AVEB_b \quad \text{...(4.16)}$$

otherwise

$$AVERP = 0$$

where

AVERP is the area (in m²/km) of preparatory edge repair

$AVEB_b$ is the area of edge-break at the end if the year (% of total carriageway area)

All other parameters are as defined previously.

4.2.3 Effects of Preparatory Works

The effects of preparatory works on pavement condition are computed as follows:

- **Potholing**

The number of potholes per km after preparatory works NPT_{ap} is reset to 0.

The change in the number of potholes per km due to works (ΔNPT_p) is given by

$$\Delta NPT_p = NPT_b$$

- **Edge break**

The area of edge break per km after preparatory works $AVEB_{ap}$ is computed as:

$$AVEB_{ap} = AVEB_b - AVERP \quad \text{...(4.17)}$$

The change in the area of edge break per km due to works (ΔAEB_p) is given by

$$\Delta AEB_p = AVEB_b - AVEB_{ap} \quad \text{...(4.18)}$$

- **Cracking**

Wide Structural cracking

The reduction in area of wide structural cracking due to preparatory works (% of total carriageway area) ΔACW_p is given by equations 4.19 to 4.21

If "Patch wide only" option was selected for Structural cracks, the change in wide structural cracks due to preparatory works is given by

$$\Delta ACW_p = \max[CWPATPER * (ACW_b - TRIGACW), 0] \quad \ldots(4.19)$$

If "Seal wide only" or "Patch wide & Seal" or "Seal all" option was selected for Structural cracks, the change in wide structural cracks due to preparatory works is given by

$$\Delta ACW_p = ACW_b \quad \ldots(4.20)$$

otherwise

$$\Delta ACW_p = 0 \quad \ldots(4.21)$$

All Structural cracking

The reduction in area of all structural cracking due to preparatory works (% of total carriageway area) ΔACA_p is given by equations 4.22 to 4.24.

If "Patch wide only" or "Seal wide only" option was selected for Structural cracks, the change in all structural cracks due to preparatory works is given by

$$\Delta ACA_p = \Delta ACW_p \quad \ldots(4.22)$$

If "Patch wide & Seal" or "Seal all" option was selected for Structural cracks, the change in all structural cracks due to preparatory works is given by

$$\Delta ACA_p = ACA_b \quad \ldots(4.23)$$

otherwise

$$\Delta ACA_p = 0 \quad \ldots(4.24)$$

Transverse thermal cracking

The reduction in area of transverse thermal cracking due to preparatory works (% of total carriageway area) ΔACT_p is given by equations 4.25 to 4.27.

If "Patch" option was selected for transverse thermal cracking, the change in transverse thermal cracks due to preparatory works is given by:

$$\Delta ACT_p = \max[CTPATPER * (ACT_b - TRIGACT), 0] \quad \ldots(4.25)$$

If "Seal" option was selected for transverse thermal cracking, the change in transverse thermal cracking due to preparatory works is given by

$$\Delta ACT_p = ACT_b \quad \ldots(4.26)$$

otherwise

$$\Delta ACT_p = 0 \quad \ldots(4.27)$$

Area of indexed cracking

The reduction in the area of indexed cracking due to preparatory works ΔCRX_p is given by:

$$\Delta CRX_p = ACX_b - ACX_{ap} \qquad \ldots(4.28)$$

where

$$\Delta ACX_{ap} = 0.62 * ACA_{ap} + ACA_{ap} + 0.39 * ACW_{ap} \qquad \ldots(4.29)$$

$$\Delta ACA_{ap} = ACA_b - \Delta ACA_p \qquad \ldots(4.30)$$

$$ACW_{ap} = ACW_b - \Delta ACW_p \qquad \ldots(4.31)$$

- **Ravelling**

As ravelling is not eligible for preparatory works, the reduction in the area of ravelling due to preparatory works (% of total carriageway area) ΔARV_p :

$$\Delta ARV_p = 0 \qquad \ldots(4.32)$$

- **Roughness**

Roughness after preparatory works is calculated as follows:

$$RI_{ap} = RI_b \ \text{-}\min\left\{\left[a0 * \left(\Delta CRX_p + \Delta ACT_p\right) + \Delta RI_t - a1 * \min\left(\frac{APAT}{10 * CW}, 10\right)\right], a2\right\} \qquad \ldots(4.33)$$

where

RI_{ap}	Roughness after preparatory works (IRI, m/km)
RI_b	Roughness at the end of the year (IRI, m/km)
APAT	Total patched area (m²/km) (for computing increase in roughness due to depression or protrusion of patches
ΔCRX_p	Reduction in area of indexed structural cracking due to preparatory works (% of total carriageway area)
ΔRI_t	Reduction in roughness due to preparatory works (IRI, m/km)
ΔRI_{pat}	Reduction in roughness due to pothole patching (IRI, m/km)
CW	Carriageway width (m)
a0 to a2	Coefficients (values = 0.0066, 0.01 and 4.6 respectively)

4.3 Resealing works

Resealing without shape correction can repair surface distress but cause little change to roughness or structural strength of the pavement. However, resealing with shape correction can achieve some reduction in roughness through the filling of depressions and repair of damaged areas. The corrective material is assumed to be bituminous, with an average thickness of less than 50 mm and placed to a quality of less than that of automatic-levelling paver-finishers, *Watanatada et al. (1987)*.

Resealing works can be triggered by the user defining one or more intervention criterion. If defining time-based interval criterion the surfacing age (AGE2) is used to determine the elapsed time period.

The recommended intervention criterion are as follows:

- Total carriageway cracked
- Ravelling
- Texture Depth (except slurry seal)
- Skid resistance (except slurry seal)
- Total damaged area
- Rut depth mean (with shape correction only)
- Rut depth std. dev. (with shape correction only)
- Roughness
- Year
- Interval
- Two-way AADT

A resealing works is specified using the following:

- New surfacing thickness
- Layer strength coefficient
- Surface material, and
- Construction defect indicator for bituminous surfacing (CDS).
- Asset valuation of the road pavement layers

4.3.1 Quantities and costs

If performed, the amount of resealing is calculated as follows:

$$ARSL = 1000 * CW \qquad ...(4.34)$$

where:

ARSL carriageway area resealed (m^2/km)

Before a reseal is performed, it is often necessary to carry out some preparatory works. It is assumed that the amounts of preparatory works carried out along with resealing are as specified in the section 2.2 Preparatory Works above.

The total area resealed (TARSL), in square metres, is obtained from the product of ARSL and the section length (L), in kilometres. The total cost of resealing is obtained by multiplying TARSL by the user-specified unit cost per square metre. The additional areas and costs of preparatory patching, crack sealing and of edge-repair are reported separately under patching, crack sealing and edge-repair, respectively.

4.3.2 Effects of resealing

Resealing resets the pavement structure as described below:

- **Pavement type**

  Pavement type after resealing works is reset as defined in Table D2.2 and Table D2.3 above.

- **Surfacing layer thickness**

  The total surface thickness after works is given by:

$$HS_{aw} = HS_{bw} + HSNEW_{aw} \qquad ...(4.35)$$

where:

HS_{aw}	total surface thickness after resealing (mm)
HS_{bw}	total surface thickness before resealing (mm)
$HSNEW_{aw}$	user-specified thickness of reseal (mm)

The thickness of the old, underlying bituminous surfacing after works is given by:

$$HSOLD_{aw} = HSNEW_{bw} + HSOLD_{bw} \qquad ...(4.36)$$

where:

$HSOLD_{aw}$	thickness of old surfacing after works (mm)
$HSOLD_{bw}$	total thickness of previous, underlying surfacing layers before works (mm)
$HSNEW_{bw}$	thickness of the most recent surfacing before works (mm)

- **Pavement strength**

  To take account of the net strengthening of the pavement due to both maintenance and cracking, the pavement strength parameters are updated through the following steps:

  - Calculate the **dry season SNP** after works as follows:

$$SNP_{daw} = MAX[1.5, (SNP_{dbw} + 0.0394 * a_{sw} * HSNEW_{aw} - dSNPK)] \qquad ...(4.37)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after resealing works
SNP_{dbw}	dry season adjusted structural number of pavement before resealing works
dSNPK	reduction in the adjusted structural number of pavement due to cracking (existing before resealing)
a_{sw}	layer strength coefficient of the reseal (see Chapter C2 - Table D2.7)

- Calculate the parameter *f*, defined as the ratio of **wet season SNP** to **dry season SNP** using DF_{aw} and $ACRA_{aw}$ as detailed in Chapter C2
- Calculate the parameter *fs* as specified for the different Road Deterioration models, see Chapter C2
- Calculate the annual average adjusted structural number of pavement (SNP)

The Benkelman beam deflection after works is given by:

$$DEF_{aw} = DEF_{bw} * \left(\frac{SNP_{aw}}{SNP_{bw}}\right)^{-1.6} \quad ...(4.38)$$

where:

SNP_{aw}	adjusted structural number of pavement after works
SNP_{bw}	adjusted structural number of pavement before works
DEF_{aw}	Benkelman beam deflection after works (mm)
DEF_{bw}	Benkelman beam deflection before works (mm)

- **Construction defects indicators**

  The construction defect indicator for bituminous surfacing (CDS) is reset to a user specified value. If this is not specified, a **good construction quality** is assumed, with the CDS value set to 1.0.

- **Pavement surface distresses**

  Resealing works resets surface distresses to zero, and thereafter the pavement condition is considered to be new.

- **Rutting**

  The following resealing operations has no effect on rutting:

  - single surface dressing without shape correction
  - double surface dressing without shape correction
  - cape seal without shape correction
  - slurry seal

The effect of resealing works with shape correction on rutting is user-specified. If these are not specified, the mean rut depth is calculated for each works activity from the following expression, as given by *Riley (1995):*

$$RDM_{aw} = a0 * RDM_{bw} \qquad ...(4.39)$$

where:

RDM_{aw}	mean rut depth after works (mm)
RDM_{bw}	mean rut depth before works (= RDM_b) (mm)
a0	user-definable coefficient (default = 0.15)

- **Roughness**

The effects of resealing works on roughness are user-specified. If these are not specified, the roughness is calculated for each works activity in the following manner:

First, the roughness value at the end of the year is adjusted to take account of **preparatory works** using equations of section 2.2 above. The adjusted roughness after preparatory works (RI_{ap}) is then used to compute the final roughness after resealing works as follows (*NDLI, 1995*):

- Single and double bituminous surface dressing without shape correction

$$RI_{aw} = RI_{ap} - MAX\{0,\ MIN[a0 * (RI_{ap} - a1), a2]\} \qquad ...(4.40)$$

where:

RI_{aw}	roughness after resealing works (m/km)
a0 to a2	user-definable parameters (defaults = 0.3, 5.4, 0.5 respectively)

- Slurry Seal and Cape Seal without shape correction

$$RI_{aw} = RI_{ap} - MAX\{0,\ MIN[a0 * (RI_{ap} - a1), a2 * Hsl]\} \qquad ...(4.41)$$

where:

RI_{aw}	roughness after resealing works (m/km)
Hsl	thickness of slurry seal or cape seal in mm (that is, $HSNEW_{aw}$)
a0 to a2	user-definable parameters (defaults = 0.3, 4.6, 0.09 respectively)

- Cape Seal, SBSD and DBSD with Shape Correction

$$RI_{aw} = RI_{ap} - MAX\{\ 0,\ MIN[a0 * Hsc * RI_{ap}, a1 * Hsc * MAX\ (0,\ (RI_{ap} - a2))]\}$$

$$...(4.42)$$

where:

RI_{aw}	roughness after resealing works (m/km)
Hsc	the thickness of reseal including shape correction layer (that is, $HSNEW_{aw}$) (mm), Hsc = MIN(Hsc, 45)
a0 to a2	user-definable parameters (defaults = 0.0075, 0.0225, 4.0 respectively)

- **Texture depth and skid resistance**

  Resealing resets texture depth and skid resistance to the user-specified values. If these are not specified, texture depth after works (TD_{aw}) is reset to the default value of initial texture depth given in Table D2.; skid resistance after works ($SFC50_{aw}$) is reset to 0.6 for all types of reseals.

Table D2.7 Default values for Initial Texture Depth (ITD)

Surface type	Surface material	Initial Texture Depth (ITD) in mm
AM	AC	0.7
	HRA	0.7
	PMA	0.7
	RAC	0.7
	CM	0.7
	SMA	0.7
	PA	1.5
ST	SBSD	2.5
	DBSD	2.5
	CAPE	0.7
	SL	0.7
	PM	1.5

- **Previous cracking**

The area of previous cracking (PCRA and PCRW) is updated to equal the cracking in the current surfacing before resealing, and a weighting (*w*) of the cracking in the previous surfacing, as follows:

- if $CRAi_{bw} \geq PCRi_{bw}$

$$PCRi_{aw} \geq PCRi_{bw} \qquad ...(4.43)$$

- if $CRAi_{bw} < PCRi_{bw}$

$$PCRi_{aw} = w * CRAi_{bw} + (1 - w) * PCRi_{bw} \qquad ...(4.2)$$

$$w = MIN(0.70 + 0.1 * HSNEW_{aw},\ 1) \qquad ...(4.3)$$

where:

$PCRi_{aw}$	area of previous cracking type *i* (*i* = all structural cracking or wide structural cracking) after works (% of total carriageway area)
$CRAi_{bw}$	area of cracking type *i* before works (% of total carriageway area)
$PCRi_{bw}$	area of previous cracking type *i* before works (% of total carriageway area)
w	weighting used for averaging the cracking in the old and new surfacing layers
$HSNEW_{aw}$	thickness of the reseal (mm)

The number, per km, of previous transverse thermal cracking (PNCT) is also reset in the same way as for **all** and **wide** structural cracking using Equations 4.43 above, 4.44 above and 4.45 above, except for the following definitions:

$PCRi_{aw}$	number of previous transverse thermal cracking after works (per km)
$CRAi_{bw}$	number of transverse thermal cracking before works (per km)
$PCRi_{bw}$	number of previous transverse thermal cracking before works (per km)

- **Pavement age**

  The surfacing age (AGE2) and the preventive treatment age (AGE1) is reset to zero after resealing works.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

4.4 Overlay

Overlay works can be triggered by the user defining one or more intervention criterion. If defining time-based interval criterion the rehabilitation age (AGE3) is used to determine the elapsed time period.

If a user specifies a minimum applicable overlay interval, an overlay is not performed if the rehabilitation/overlay age (AGE3) is less than the user-specified minimum applicable overlay-interval. An overlay is also not performed if either the preventive treatment age (AGE1) or the surfacing age (AGE2) is less than the respective minimum preventive treatment or resurfacing intervals. If the minimum intervals have not been defined within any of the standards that have been assigned to the road section, the following default values (in years) are used: preventive treatment - 2 years, resealing - 4 years.

An overlay is always performed when AGE3 exceeds the user-specified maximum allowable overlay interval. In all cases, an overlay is not performed if the last applicable year or maximum applicable roughness has been exceeded (if defined in the intervention criteria).

The recommended intervention criterion are as follows:

- Total carriageway cracked
- Ravelling
- Potholing
- Roughness
- Cumulative ESAL
- Total damaged area
- Rut depth mean
- Rut depth std. dev.
- Year

- Interval
- Two-way AADT

Overlay is specified using the following:

- New surfacing thickness.
- Layer strength coefficient.
- Surface material.
- Construction defect indicator for bituminous surfacing (CDS).
- Asset valuation of the road pavement layers

4.4.1 Quantities and costs

If performed, the amount of overlay is given by:

$$AOVL = 1000 * CW \qquad ...(4.46)$$

where:

AOVL	overlay area (m^2/km)
CW	carriageway width (m)

Before overlay is performed, it is often necessary to carry out some preparatory works. It is assumed that the amounts of preparatory works carried out along with overlay are as specified in the section 2.2 Preparatory Works above.

4.4.2 Effects of overlay

Overlay resets the pavement structure as described below:

- **Pavement type**

  The pavement type after overlay is reset as detailed in Table D2.2 and Table D2.3. The surface material after works is user-specified.

- **Surface thickness**

  The total surface thickness after works is obtained in the following manner:

$$HS_{aw} = HS_{bw} + HSNEW_{aw} \qquad ...(4.47)$$

where:

HS_{aw}	total surface thickness after overlay works (mm)
HS_{bw}	total surface thickness before overlay works (mm)
$HSNEW_{aw}$	user-specified thickness of overlay (mm)

The thickness of the old, underlying bituminous surfacing after works is calculated using Equation 4.36 above.

- **Pavement strength**

The pavement strength parameters are updated to take account of the net change in pavement strength due to the new overlay and the underlying cracks (if any), as follows:

- The dry season adjusted structural number of pavement is given by:

$$SNP_{daw} = MAX\ [1.5,\ (SNP_{dbw} + 0.0394 * a_{sw} * HSNEW_{aw} - dSNPK)] \qquad ...(4.48)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after overlay works
SNP_{dbw}	dry season adjusted structural number of pavement before overlay works
dSNPK	reduction in the adjusted structural number of pavement due to cracking
$HSNEW_{aw}$	thickness of the overlay (mm)
a_{sw}	layer strength coefficient of the overlay

- The wet season adjusted structural number of pavement (SNP_{waw}) and the annual average adjusted structural number of pavement (SNP_{aw}) after works are then calculated as discussed in Section 4.3.

The Benkelman beam deflection after works is computed using Equation 4.38 above.

- **Construction defects indicators**

The construction defect indicator for bituminous surfacing CDS is reset to a user specified value. If these are not specified, a **good construction quality** is assumed, with the CDS value set to 1.0.

- **Pavement surface distresses**

Overlay works resets surface distresses to zero, and thereafter the pavement condition is considered to be new.

- **Rutting**

The effects of overlay on rutting are user-specified. If these are not specified, the mean rut depth is calculated as follows:

$$RDM_{aw} = a0 * RDM_{bw} \qquad ...(4.49)$$

where:

RDM_{aw}	mean rut depth after works (mm)
RDM_{bw}	mean rut depth before works (= RDM_b) (mm)
a0	user-definable coefficient (default = 0.15)

- **Roughness**

The effects of overlay on roughness are user-specified. If these are not specified, the roughness value after works is calculated in the following manner:

The roughness value at the end of the year is adjusted to take account of **preparatory works** using equations of section 2.2 above. The adjusted roughness after preparatory works (RI_{ap}) is then used to compute the final roughness after overlay as follows.

The overlay-roughness relationship for a specified overlay thickness, overlay technique, and an existing pavement type can be represented diagrammatically as in Figure 4.01. This is referred to as a bilinear model.

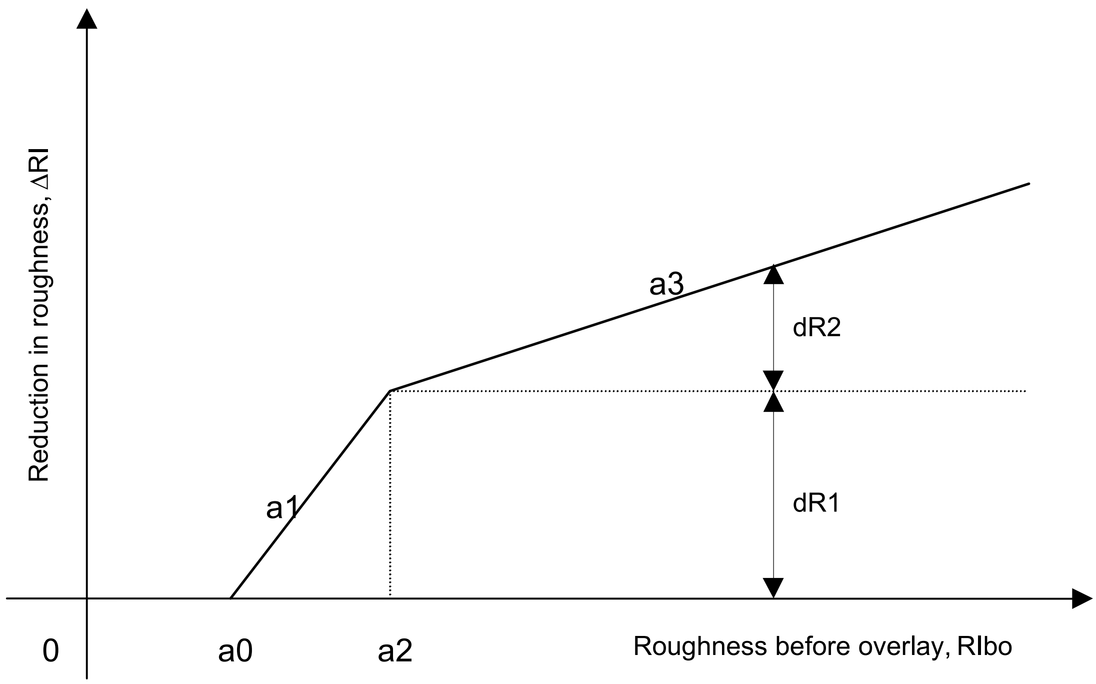

Figure 4.01: Effects of overlay on roughness

The reduction in roughness after overlay, ΔRI, is given by the sum of dR1 and dR2, and this is expressed as follows (*Odoki, 2001*):

$$\Delta RI = MAX\{0, a1*[MIN(a2, RI_{ap}) - a0] + a3*MAX[0, (RI_{ap} - a2)]\} \quad ...(4.50)$$

and

$$RI_{aw} = RI_{ap} - \Delta RI \quad ...(4.51)$$

where:

ΔRI	reduction in roughness after overlay (IRI m/km)
RI_{aw}	roughness after overlay (IRI m/km)
RI_{ap}	adjusted roughness after preparatory patching works (IRI m/km)
a0 to a3	user-definable parameters

The user-definable parameters a0 to a3 of the bilinear model are shown in Figure 4.01 and defined as follows:

a0	minimum roughness after overlay (IRI m/km)
a1	slope of the first line (line 1) (default = 0.9)
a2	intersection point of the two lines (bilinear model) (IRI m/km)
a3	slope of the second line (line 2)

The default values of parameters a0, a2 and a3 are computed as a function of the thickness of overlay as follows:

$$a0 = 1 + 0.018 * MAX[0, (100 - HSNEW_{aw})] \quad ...(4.52)$$

$$a2 = MAX[4.0, 2.1 * EXP(0.019 * HSNEW_{aw})] \quad ...(4.53)$$

$$a3 = MIN\{a1, MAX[0, (0.01 * HSNEW_{aw} - 0.15)]\} \quad ...(4.54)$$

where:

$HSNEW_{aw}$ Thickness of overlay (mm)

The user may opt to use a linear relationship by defining the model parameters accordingly. This is done by using the equivalent of line 2 only with line 1 set to zero. In this case, the reduction in roughness is given by:

$$\Delta RI = MAX\lfloor 0, (RI_{ap} - a0) - \Delta RITr \rfloor \quad ...(4.55)$$

where

$$\Delta RITr = MAX\{0, a1 * \lfloor MIN(a2, RI_{ap}) - a0 \rfloor + a3 * MAX\lfloor 0, (RI_{ap} - a2) \rfloor\} \quad ...(4.56)$$

For the linear relationship the default parameter values are set as follows: a0 = a2, a2 = 1.0, a1 = 0, and a3 is computed using equation (4.54):

$$a3 = MAX[0, (0.8 - 0.01 * HSNEW_{aw})] \quad ...(4.57)$$

- **Texture depth and skid resistance**

After overlay, the texture depth and the skid resistance are reset to the user-specified values. If these are not specified, texture depth after works (TD_{aw}) is reset to the default value of initial texture depth given in Table D2.; skid resistance after works ($SFC50_{aw}$) is reset to 0.5 for all overlays.

- **Previous cracking**

The amounts of previous cracking (PCRA, PCRW, and PNCT) are reset using Equations 4.43 above and 4.44 above. The weighting factor (w) of the cracking in the previous surfacing is computed as follows:

- For asphalt roadbase (AB), asphalt pavement (AP) and granular roadbase (GB):

$$w = MAX\left[\frac{HSNEW_{bw}}{HSOLD_{aw}},\ 0.6\right] \qquad ...(4.58)$$

- For stabilised roadbase (SB)

$$w = MAX\left[\frac{HSNEW_{bw}}{(HSOLD_{aw} + HBASE)},\ 0.6\right] \qquad ...(4.59)$$

where:

w	weight used for averaging the cracking in the old and new surfacing layers
HBASE	thickness of the base layer in the original pavement (required only for SB roadbase types) (mm)
$HSOLD_{aw}$	thickness of old surfacing after works (mm)
$HSNEW_{bw}$	thickness of the most recent surfacing before works (mm)

- **Pavement age**

The rehabilitation age (AGE3), the surfacing age (AGE2), and the preventive treatment age (AGE1) are reset to zero after overlay works.

- **Asset Valuation**

After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

4.5 Mill and replace

This operation involves the removal of all or part of the existing bituminous surfacing and replacing it with a new bituminous surfacing. It is usually performed to correct defects that have occurred mainly due to poor construction quality and the bituminous material being too rich or brittle, or where the road surface levels need to comply with some requirements related to drainage facilities, bridge underpasses and other such structures.

Mill and replace works, which is a type of Rehabilitation works, can be triggered by the user defining one or more intervention criterion. If defining time-based interval criterion the rehabilitation age (AGE3) is used to determine the elapsed time period.

A mill and replace works is not performed if the rehabilitation age (AGE3) is less than the user-specified minimum applicable interval, or if the last applicable year has been exceeded (if defined). A mill and replace works is always performed when AGE3 exceeds the user-specified maximum allowable interval (if defined).

The recommended intervention criterion are as follows:

- Total carriageway cracked

- Ravelling
- Potholing
- Roughness
- Cumulative ESAL
- Total damaged area
- Rut depth mean
- Rut depth std. dev.
- Year
- Two-way AADT

The following information is required to specify mill and replace works:

- New surfacing thickness
- Layer strength coefficient
- Surface material
- Depth of milling
- Construction defect indicator for bituminous surfacing
- Asset valuation of the road pavement layers

4.5.1 Quantities and costs

If performed, the amount of mill and replace is given by:

$$AMR = 1000 * CW \qquad ...(4.56)$$

where:

AMR	Area of carriageway milled and replaced (m^2/km)
CW	carriageway width (m)

The total amount of mill and replace works (TAMR), in square metres, is obtained from the product of AMR and the section length (L), in kilometres. The total cost of mill and replace works is obtained by multiplying TAMR by the user-specified unit cost per square metre.

4.5.2 Effects of mill and replace

Mill and replace works resets the pavement structure as described below:

- **Pavement type**

  After mill and replace, the pavement type is reset as detailed in Table D2.2 and Table D2.3. The surface material after works is user-specified.

  The following conditions determine which kind of mill and replace activity is being applied:

if $MILLD \geq HS_{bw}$ then it is a **mill and replace to roadbase**

if $MILLD < HS_{bw}$ then it is a **mill and replace to intermediate layer**

- **Surface thickness**

The total surface thickness after works is obtained as described below:

$$HS_{aw} = HS_{bw} + HSNEW_{aw} - MILLD \qquad ...(4.57)$$

where:

HS_{aw} total surface thickness after works (mm)

HS_{bw} total surface thickness before works (mm)

$HSNEW_{aw}$ user-specified thickness of new surfacing (mm)

MILLD depth of milling (mm)

The thickness of the old, underlying bituminous surfacing after works is given by:

$$HSOLD_{aw} = MAX(HSNEW_{bw} + HSOLD_{bw} - MILLD,\ 0) \qquad ...(4.58)$$

where:

$HSOLD_{aw}$ thickness of old surfacing after works (mm)

$HSNEW_{bw}$ thickness of the most recent surfacing before works (mm)

$HSOLD_{bw}$ total thickness, in mm, of previous, underlying surfacing layers before works

- **Pavement strength**

The pavement strength parameters are updated to take account of the net change in pavement strength due to the new bituminous surfacing and the depth of milling as follows:

- If $MILLD \leq HSNEW_{bw}$, then the **dry season adjusted structural number of pavement** is given by:

$$SNP_{daw} = MAX[1.5, (SNP_{dbw} - 0.0394 * a_{hsn} * MILLD + 0.0394 * a_{sw} * HSNEW_{aw})]$$

...(4.59)

- If $HSNEW_{bw} < MILLD \leq HS_{bw}$, then the **dry season adjusted structural number of pavement** is calculated as follows:

$$SNP_{daw} = MAX\left\{1.5, \begin{bmatrix} SNP_{dbw} - 0.0394 * a_{hsn} * HSNEW_{bw} + 0.0394 * a_{sw} \\ * HSNEW_{aw} - 0.0394 * a_{hso} * (MILLD - HSNEW_{bw}) \end{bmatrix}\right\}$$

...(4.60)

- If $MILLD > HS_{bw}$, then the **dry season adjusted structural number of pavement** is given by:

$$SNP_{daw} = MAX\left\{1.5, \begin{bmatrix} SNP_{dbw} - 0.0394 * a_{hsn} * HSNEW_{bw} - 0.0394 * a_{hso} * HSOLD_{bw} \\ - 0.0394 * a_b * (MILLD - HS_{bw}) + a_{sw} * HSNEW_{aw} \end{bmatrix}\right\} \quad ...(4.61)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after works
SNP_{dbw}	dry season adjusted structural number of pavement before works
a_{hsn}	strength coefficient of the most recent surfacing before works
a_{hso}	strength coefficient of the old surfacing before works
a_{sw}	strength coefficient of the new surfacing after works
a_b	strength coefficient of the roadbase layer

The wet season adjusted structural number of pavement (SNP_{waw}) and the annual average adjusted structural number of pavement (SNP_{aw}) after works are calculated using the same procedure as discussed in Section 4.2.

The Benkelman beam deflection after works is calculated using Equation 4.38 above.

- **Construction defects indicators**

The construction defect indicator for bituminous surfacing (CDS) is reset to a user specified value. If these are not specified, a **good construction quality** is assumed, with the CDS value set to 1.0.

- **Pavement surface distresses**

Mill and replace works resets surface distresses to zero, and thereafter it is assumed that the pavement behaves as if new.

- **Rutting**

Mill and replace resets rutting to zero by default, unless the user specifies a different value.

- **Roughness**

The effects of mill and replace on roughness are user-specified. If these are not specified, the following default values are used:

For AM surface type, RI_{aw} = 2.0 (IRI m/km)

For ST surface type, RI_{aw} = 2.8 (IRI m/km)

- **Texture depth and skid resistance**

After mill and replace, the texture depth and the skid resistance are reset to the user-specified values. If these are not specified, texture depth after works (TD_{aw}) is reset to the default value of initial texture depth given in Table D2.; skid resistance after works ($SFC50_{aw}$) is reset to the following default values:

For surface type AM, $SFC50_{aw} = 0.5$

For surface type ST, $SFC50_{aw} = 0.6$

- **Previous cracking**

The amounts of previous cracking (PCRA, PCRW, and PNCT) are reset as follows:

If $MILLD < HSNEW_{bw}$, then the amounts of previous cracking are reset as follows:

if $CRAi_{bw} \geq PCRi_{bw}$

$$PCRi_{aw} = wf * CRAi_{bw} \quad ...(4.41)$$

if $CRAi_{bw} < PCRi_{bw}$

$$PCRi_{aw} = wf * CRAi_{bw} + (1 - w) * PCRi_{bw} \quad ...(4.63)$$

$$wf = w * \left\{1 - \left[\frac{MILLD}{HSNEW_{bw}}\right]\right\} \quad ...(4.64)$$

The weighting (w) of the cracking in the previous surfacing is computed as follows:

- For asphalt base (AB), asphalt pavement (AP) and granular roadbase (GB)

$$w = MAX\left[\frac{HSNEW_{bw}}{HSOLD_{aw}}, 0.6\right] \quad ...(4.65)$$

- For stabilised base (SB)

$$w = MAX\left[\frac{HSNEW_{bw}}{(HSOLD_{aw} + HBASE)}, 0.6\right] \quad ...(4.66)$$

if $MILLD \geq HSNEW_{bw}$

then:

$$PCRi_{aw} = wg * PCRi_{bw} \quad ...(4.67)$$

$$wg = MAX\left[0, \frac{HS_{bw} - MILLD}{HSOLD_{bw}}\right] \quad ...(4.47)$$

Equation 4.68 above assumes that if MILLD = HS_{bw} any cracking in the roadbase is rectified before surfacing.

All the parameters used in Equations 4.65 above to 4.68 above are as defined previously under resealing and overlay.

- **Pavement age**

The rehabilitation/overlay age (AGE3), the surfacing age (AGE2), and the preventive treatment age (AGE1) is reset to zero after a mill and replace works.

- **Asset Valuation**

After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

4.6 Inlays

Inlay is a special works activity, considered under Rehabilitation, that is normally applied to treat rutting along wheelpaths (and this involves some milling of the existing pavement layers). It is therefore typically defined as a **condition-responsive** works, in which an inlay of fixed specifications is applied when the level of pavement defect exceeds the user-specified values.

Inlay is not performed if the user-specified last applicable year or the maximum applicable roughness has been exceeded (if defined in the intervention criteria).

The recommended intervention criterion are as follows:

- Total damaged area
- Rut depth mean
- Rut depth std. dev.
- Year
- Roughness
- Two-way AADT

To define an inlay works, the percentage of total carriageway area to be repaired, the construction quality factors, and the asset valuation of the road pavement layers should be specified.

4.6.1 Quantities and costs

If performed, the amount of inlay is given by:

$$\text{AINLY} = 10 * \text{Pin} * \text{CW} \qquad \text{...(4.69)}$$

where:

AINLY area of inlay (m^2/km)

Pin area to be repaired (% of the total carriageway area) (0 < Pin < 100)

It is likely that patching, crack sealing and edge-repair will be carried out along with inlay works. The modelling logic assumes therefore that first inlay is performed, and then patching and crack sealing repairs the remaining areas of potholes and cracking. The amounts of patching, crack sealing and edge-repair that may be performed are computed as follows:

- **Patching**

$$\text{APAT} = 10 * \text{CW} * \left\{ \Delta\text{ACW}_{pat} + \text{APOT}_b * \left[1 - \frac{\text{Pin}}{100} \right] \right\} \qquad \text{...(4.70)}$$

$$\Delta\text{ACW}_{pat} = \text{MAX}\left\{ \left[\text{CWPATPER} * \left(\text{ACW}_b - \text{TRIGACW} \right) * \left(1 - \frac{\text{Pin}}{100} \right) \right], 0 \right\}$$

...(4.71)

where:

APAT	area of patching (m^2/km)
ΔACW_{pat}	area of wide structural cracking treated by patching (% of the total carriageway area)

- **Crack sealing**

It is assumed that crack sealing repairs the entire remaining area of transverse thermal cracking and wide structural cracking as follows:

$$ACSL = 10 * CW * \left[P_{acw} * ACW_{bcs} + P_{act} * ACT_b * \left(1 - \frac{Pin}{100}\right)\right] \quad ...(4.51)$$

$$ACW_{bcs} = ACW_b - \left[\Delta ACW_{pat} + ACW_b * \left(1 - \frac{Pin}{100}\right)\right] \quad ...(4.73)$$

where:

ACSL	area sealed (m^2/km)
P_{acw}	proportion of wide structural cracking to be sealed (default = 1.0)
P_{act}	proportion of transverse thermal cracking to be sealed (default = 1.0)

- **Edge-repair**

The amount of edge-repair is calculated using Equation 4.9 **Error! Reference source not found.**.

The total amount of inlay (TAINLY), in square metres, is obtained from the product of AINLY and the section length (L), in kilometres. The cost of inlay is obtained by multiplying TAINLY by the user-specified unit cost per square metre. The additional areas and costs of patching, crack sealing and of edge-repair are reported separately under patching, crack sealing and edge-repair, respectively.

4.6.2 Effects of inlays

Inlays does not alter the pavement type and surface thickness, since it is assumed that the same surface material of the existing pavement is used for inlay works.

To take account of the net strengthening of the pavement due to maintenance, the **dry season structural number of pavement** is updated as follows:

$$SNP_{daw} = MAX(1.5, SNP_{dbw}) \quad ...(4.74)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after works
SNP_{dbw}	dry season adjusted structural number of pavement before works

The wet season adjusted structural number of pavement (SNP_{waw}) and the annual average adjusted structural number of pavement (SNP_{aw}) after works is then calculated as discussed in Section 4.2 above for resealing works.

The Benkelman beam deflection after works is computed using Equation 4.13 above.

- **Construction defects indicators**

  The construction defect indicator for bituminous surfacing (CDS) is reset to a user specified value. If these are not specified, a **good construction quality** is assumed, with a CDS value of 1.0.

- **Pavement surface distresses**

  After inlay works, surface distresses are reset as follows:

  - Potholes are reset to zero (that is, $NPT_{aw} = 0$), because of the additional patching that is assumed to be performed during inlay works.
  - Cracking is reset as follows:

$$ACW_{aw} = MAX\left\{\left[ACW_b - \left(\Delta ACW_{inlay} + \Delta ACW_{pat} + \Delta ACW_{cs}\right)\right], 0\right\} \quad ...(4.75)$$

$$\Delta ACW_{inlay} = ACW_b * \left(1 - \frac{Pin}{100}\right) \quad ...(4.76)$$

$$\Delta ACW_{cs} = P_{acw} * \left[ACW_b - \left(\Delta ACW_{inlay} + \Delta ACW_{pat}\right)\right] \quad ...(4.77)$$

$$ACA_{aw} = ACA_b - \left(ACW_b - ACW_{aw}\right) \quad ...(4.78)$$

$$ACT_{aw} = P_{act} * ACT_b \quad ...(4.79)$$

    where the parameters P_{acw} and P_{act} are as defined in Equation 4.51 above

    The amounts of indexed cracking (ACX_{aw}) and total area of cracking ($ACRA_{aw}$) are reset after inlay works using Equations 3.32 above and 3.33 above, respectively.

  - Ravelling is reset as follows:

$$ARV_{aw} = ARV_b * \left(1 - \frac{Pin}{100}\right) \quad ...(4.80)$$

    where:

    ARV_{aw} area of ravelling after works (% of the total carriageway area)

    ARV_{bw} area of ravelling before works (= ARV_b) (% of the total carriageway area)

  - Edge-break is reset to zero (that is, $AVEB_{aw} = 0$), due to the edge-repair works that is assumed to be performed during inlay works.

- **Rutting**

  The effects of inlay on rutting are user-specified. If these are not specified, the mean rut depth is calculated as follows:

$$RDM_{aw} = a0 * RDM_{bw} \qquad ...(4.81)$$

where:

RDM_{aw}	mean rut depth after works (mm)
RDM_{bw}	mean rut depth before works (= RDM_b) (mm)
a0	user-definable coefficient (default = 0.15)

- **Roughness**

Inlay reduces roughness by treating rutting, all the potholes, transverse thermal cracking and wide structural cracking. The effect of inlay on roughness is user-specified. If these are not specified, the values of roughness after works is computed as follows:

$$RI_{aw} = MAX\left[a0, RI_{bw} - a1 * \Delta RDS_w - \Delta RI_t - a2 * \left(\Delta CRX_w + \Delta ACT_w\right)\right] \qquad ...(4.82)$$

where:

RI_{aw}	roughness after inlay (IRI m/km)
RI_{bw}	roughness before works (= RI_b) (IRI m/km)
ΔRDS_w	reduction in rut depth standard deviation due to inlay works (mm) (=DS_{bw} – RDS_{aw}, where RDS_{aw} is calculated using RDM_{aw})
ΔRI_t	reduction in roughness due to pothole patching (IRI m/km)
ΔCRX_w	reduction in the amount of indexed cracking due to inlay works (= ACX_b - ACX_{aw})
a0 to a2	user-definable parameters (defaults = 2.8, 0.088, and 0.0066 respectively)

The value of ΔRI_t is computed using Equation 3.26 above to 3.27 above with NPT_{bu} taken as equal to NPT_{bw} (= NPT_b), since all existing potholes should be patched.

- **Texture depth and skid resistance**

Inlay resets texture depth and skid resistance in the same way as described for **mill and replace** in Section 4.4.2 above.

- **Previous cracking**

The amounts of previous cracking (PCRA, PCRW, and PNCT) are reset as follows:

$$PCRi_{aw} = \left(1 - \frac{Pin}{100}\right) * PCRi_{bw} \qquad ...(4.83)$$

where:

$PCRi_{aw}$	amount of previous cracking type *i* (*i* = all structural cracking or wide structural cracking or transverse thermal cracking) after inlay works
$PCRi_{bw}$	amount of previous cracking type *i* before inlay works

- **Pavement age**

The surfacing age after inlays is reset as follows:

$$AGEi_{aw} = \left(1 - \frac{Pin}{100}\right) * AGEi_{bw} \qquad ...(4.84)$$

where:

$AGEi_{aw}$	AGE type *i* (*i* = 1, 2 or 3) after inlay works (years). (**This value should be adjusted to an integer**)
$AGEi_{bw}$	AGE type *i* before inlay works (years)

- **Asset Valuation**

After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

4.7 Reconstruction

Pavement reconstruction refers to all works that require the re-specification of the surfacing and roadbase types.

Reconstruction may be specified either as a maintenance standard or as an improvement standard if the works involve minor widening of the carriageway.

Note: the latter is permitted only for the sake of convenience in the modelling logic as discussed in Section 6.1.

Reconstruction can be triggered by the user defining one or more intervention criterion. If defining time-based interval criterion the construction age (AGE4) is used to determine the elapsed time period.

Reconstruction is not performed if:

AGE4 is less than the minimum reconstruction interval (if defined)

AGE1, AGE2 and AGE3 are less than their respective minimum intervals (if defined)

It is a construction-opening year

Reconstruction is always performed if AGE4 exceeds the maximum allowable reconstruction interval, if specified by the user. In all cases, reconstruction is not performed if the last applicable year (if defined by the user) has been exceeded.

The recommended intervention criterion are as follows:

- Total damaged area
- Total carriageway cracked
- Ravelling
- Potholing
- Roughness

- Cumulative ESAL
- Total damaged area
- Rut depth mean
- Rut depth std. dev.
- Year
- Two-way AADT

Reconstruction as a maintenance standard is specified using the following:

- New pavement type
- Surface material
- Surfacing thickness
- Structural number of pavement (SN) of the layers above the subgrade
- Relative compaction
- Construction defect indicators
- Asset valuation of the road pavement layers

For stabilised roadbases, the base thickness and the resilient modulus are also required.

4.7.1 Quantities and costs

If performed, the amount of pavement reconstruction is given by:

$$ARCON = 1000 * CW \qquad ...(4.85)$$

where:

ARCON area of road reconstructed (m^2/km)

CW carriageway width (m)

The total area reconstructed is given by:

$$TARCON = ARCON * L \qquad ...(4.86)$$

where:

TARCON total carriageway area reconstructed (m^2)

L section length (m)

The total cost of reconstructing the entire road section is obtained from the product of TARCON and the unit cost per square metre, or from the product of the section length (L) and the unit cost per kilometre.

4.7.2 Effects of reconstruction

After reconstruction, the pavement type is reset to the new type specified by the user. All bituminous pavement types are permitted, except STAP and AMAP. The required modelling parameters of the surfacing and roadbase/sub-base layers are reset as described below:

- **Pavement strength**

  The dry season adjusted structural number of pavement is computed as follows:

$$SNP_{daw} = SN_{new} + SNSG_s \qquad ...(4.66)$$

$$SNSG_s = 3.51 * \log_{10}CBR - 0.85 * (\log_{10}CBR)^2 - 1.43 \qquad ...(4.67)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after reconstruction works
SN_{new}	user-specified new dry season structural number of pavement for the layers above the subgrade. This value may be obtained from the sum of SNBASU and SNSUBA as described in Chapter C2
CBR	in situ subgrade CBR in dry season. Note also that $SNSG_s$ equals $SNSUBG_s$ (see Chapter C2) by assuming a sub-base thickness of about 183 mm

The Benkelman beam deflection after reconstruction works is given by:

$$DEF_{aw} = a0 * (SNP_{aw})^{-1.6} \qquad ...(4.89)$$

where:

SNP_{aw}	adjusted structural number of pavement after reconstruction works
DEF_{aw}	Benkelman beam deflection after reconstruction works (mm)
a0	coefficient depending upon the roadbase type (a0 = 6.5 for GB, AB and AP; a0 = 3.5 for SB roadbase type)

- **Construction quality**

  The construction defect indicators for bituminous surfacing (CDS), and the construction defect indicator for the roadbase, (CDB), are reset to user specified values. If these are not specified, a **good construction quality** is assumed, with the CDS value set to 1.0 and the CDB value set to 0.

- **Pavement surface distresses**

  Surface distresses (that is, edge-break, potholing, cracking and ravelling) are all reset to zero.

- **Rutting**

  After reconstruction, the mean rut depth is reset to zero.

- **Roughness**

  Pavement reconstruction resets roughness to a user-specified value. The roughness after works depends on the construction quality. The following values are used as defaults:

  For AM surface type, RI_{aw} = 2.0 (IRI m/km)

  For ST surface type, RI_{aw} = 2.8 (IRI m/km)

- **Texture depth and skid resistance**

  Reconstruction resets texture depth and skid resistance in the same way as described for **mill and replace** in Section 4.5.2.

- **Previous cracking**

  The area of previous cracking (PCRA, PCRW, and PNCT) is reset to zero.

- **Road deterioration factors**

  The cracking retardation time, ravelling retardation factor and the other road deterioration factors are also reset to user-specified values.

- **Pavement age**

  The pavement ages: AGE1, AGE2, AGE3, and AGE4 are all reset to zero.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

5 Special works

The effects of the following special works on pavement performance are not modelled endogenously, and therefore only their costs can be considered in an analysis:

- **Emergency works**

  For example, (repairing washout/subsidence, clearing debris, traffic accident removal, etc.).

- **Winter maintenance**

If specified, the works activities are applied in a given analysis year regardless of the works hierarchy given in Table D2.1.

The recommended intervention criterion are as follows:

- Year
- Interval

Their unit costs are specified in terms of *currency* per kilometre per year, and the annual costs are obtained by multiplying the road section length (L) by the unit cost.

6 Improvement works

Road improvement works aim to provide additional capacity and comprises the following:

- **Partial widening**
- **Lane addition**
- **Realignment**
- **Non-carriageway improvement works**

  For example, improvement or addition of shoulders, NMT lanes, and side drains.

Although it is not an improvement works, reconstruction that involves minor widening of the carriageway is modelled using the logic framework for improvement works.

6.1 Reconstruction with minor widening

Pavement reconstruction with minor widening (see also notes given in Section 4.7) can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- Total carriageway cracked
- Ravelling
- Potholing
- Roughness
- Cumulative ESAL
- Total damaged area
- Rut depth mean
- Rut depth std. dev.
- Year

Reconstruction works are specified using the following:

- New pavement type
- Surface material
- Surfacing thickness
- Structural number of pavement (SN_{new}) of the layers above the subgrade
- Relative compaction
- Increase in carriageway width
- Construction defect indicators
- For stabilised roadbases, the base thickness and the resilient modulus are also required.
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes.

6.1.1 Quantities and costs

If performed, the amount of pavement reconstruction is given by:

$$ARCON = 1000 * CW_{aw} \qquad ...(6.1)$$

where:

ARCON area of road reconstructed (m^2/km)

CW_{aw} new carriageway width after reconstruction works (m)

The total area reconstructed is given by:

$$TARCON = ARCON * L \qquad ...(6.2)$$

where:

TARCON total carriageway area reconstructed (m^2)

L road section length (km)

The total cost (CSTCON) of reconstructing the entire road section is obtained from the product of TARCON and the unit cost per square metre, or from the product of the section length and the unit cost per kilometre.

The salvage value is given by:

$$SALVA = PCTSAV * CSTCON \qquad ...(6.3)$$

where:

SALVA salvage value of the works (currency)

PCTSAV percent of total cost salvageable (%)

6.1.2 Effects of reconstruction

After reconstruction, the pavement type, strength, condition, age, deterioration factors, and construction quality indicators as described in Section 4.7.2. In addition, the new carriageway width after reconstruction with minor widening is given by:

$$CW_{aw} = CW_{bw} + \Delta CW \qquad ...(6.4)$$

where:

CW_{aw} carriageway width after reconstruction works (m)

CW_{bw} carriageway width before reconstruction works (m)

ΔCW user-specified increase in carriageway width (m)

The effective number of lanes after works is reset to a new value $ELANES_{aw}$, which should be input by the user. If this is not specified $ELANES_{aw}$ will be reset to the value of NLANES (that is, the number of lanes for the road section) see Part B Section 5.2.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

6.2 Widening

There are two operations included under **widening**, **lane addition** and **partial widening**. The major distinction is that partial widening does not increase the number of lanes. Both widening operations do not alter the road alignment.

Widening works can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Two-way AADT
- Peak period Volume Capacity Ratio
- Daily average Volume Capacity Ratio
- Year

The following information is required to specify a widening works:

- New road type
- Road class
- Increase in carriageway width for **partial widening**
- Additional number of lanes and increase in carriageway width for **lane addition**
- Pavement type for the entire section
- Pavement details of the widened area of the carriageway
- Construction quality indicators
- Whether or not the existing carriageway is to be provided with a new surfacing
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes

6.2.1 Quantities and costs

If performed, the amount of widening works is given by:

$$AWDN = 1000 * \Delta CW \qquad ...(6.5)$$

where:

AWDN widened area of carriageway (m^2/km)

ΔCW increase in carriageway width (m)

The total area of widening over the entire section is given by the expression:

$$TAWDN = AWDN * L \quad ...(6.6)$$

where:

TAWDN total widened area of carriageway for the entire section (m^2)

L road section length (km)

The cost of widening (CSTWDN) is obtained from the product of TAWDN and the unit cost per square metre, or from the product of the section length and the unit cost per kilometre.

The salvage value is given by:

$$SALVA = PCTSAV * CSTWDN \quad ...(6.7)$$

where:

SALVA salvage value of the works (currency)

PCTSAV percent of total cost salvageable (%)

Additional works

It is likely that widening works will include re-surfacing or at least repairs of the severely damaged area of the existing carriageway. The additional works that may be required are modelled as described below. (Note that **re-surfacing** or **re-surfaced** has been used to denote the provision of a new bituminous surfacing and to distinguish it from **resurfacing** as a type of roadwork).

Case1: re-surfacing the existing carriageway

If the existing carriageway is to be re-surfaced either by an overlay or resealing (as determined from the user-specified new pavement type after works), the amount of re-surfacing works for the entire road section is given by:

$$TANSF = 1000 * CW_{bw} * L \quad ...(6.8)$$

where:

TANSF total carriageway area re-surfaced (m^2)

L road section length (km)

- **An overlay is provided over the existing carriageway**

  TANSF would be denoted as TAOVL, and the total cost of overlay is obtained from the product of TAOVL and the unit cost of overlay per square metre.

Before overlay is performed, it is often necessary to carry out some preparatory works. The amounts of preparatory works to be performed for the entire road section is computed as follows:

- **Patching**

$$TAPAT = 10 * CW_{bw} * APOT_b * L \qquad ...(6.9)$$

where:

TAPAT total area of preparatory patching (m^2)

The total cost of preparatory patching is obtained from the product of TAPAT and the unit cost of patching per square metre.

- **Edge-repair**

$$TAVER = 10 * CW_{bw} * AVEB_b * L \qquad ...(6.10)$$

where:

TAVER total area of edge-repair (m^2)

$AVEB_{bw}$ area of edge-break before widening works (= $AVEB_b$) (% of total carriageway area)

The total cost of edge-repair is obtained from the product of TAVER and the unit cost of edge-repair per square metre.

- **The existing carriageway is resealed**

ANSF would be denoted by TARSF, and the total cost of resealing is obtained from the product of TARSF and the unit cost of resealing per square metre.

Before resealing is applied, the amount of preparatory works that may be required for the entire road section is computed as follows:

- **Patching**

$$TAPAT = 10 * CW_{bw} * L * \{MAX[0.1 * (ACW_b - 20), 0] + APOT_b\} \qquad ...(6.11)$$

where:

TAPAT total area of preparatory patching (m^2)

All other parameters are as defined previously.

The total cost of preparatory patching is obtained from the product of TAPAT and the unit cost of patching per square metre.

- **Crack sealing**

It is assumed that 100% of transverse thermal cracking is sealed, and the amount of crack sealing performed is given by:

$$TACSL = 10 * CW_{bw} * ACT_{bw} * L \qquad ...(6.12)$$

where:

TACSL	total area of crack sealing (m^2)
ACT_{bw}	area of transverse thermal cracking before widening works (= ACT_b) (% of total carriageway area)

The total cost of crack sealing is obtained from the product of TACSL and the unit cost of crack sealing per square metre.

- **Edge-repair**

  The total area of edge-repair is calculated using Equation 6.10 above. The total cost of edge-repair is obtained from the product of TAVER and the unit cost of edge-repair per square metre.

Case 2: no re-surfacing of the existing carriageway

If the existing carriageway is not to be re-surfaced, it is assumed that the following amounts of patching, crack sealing and edge-repair are performed along with the widening works:

- **Patching**

  Assuming that 100% of severely damaged area is patched, the amount of patching is computed as follows:

$$TAPAT = 10 * CW_{bw} * L * ADAMS_{bw} \qquad ...(6.13)$$

where:

TAPAT	total carriageway area patched (m^2)
$ADAMS_{bw}$	severely damaged carriageway area before widening works (= $ADAMS_b$) (% of total carriageway area)

- **Crack sealing**

  The total amount of crack sealing is calculated using Equation 6.12 above.

- **Edge-repair**

  Assuming that all the edge-break area is repaired, the amount of edge-repair works is given by Equation 6.10 above.

The total cost of widening works is the sum of carriageway widening cost and the cost of additional works comprising re-surfacing of the existing carriageway and **preparatory works**. The amount and cost of re-surfacing works are reported separately under resealing or overlay. Similarly, the amounts and costs of patching, of crack sealing and edge-repair are reported separately under patching, crack sealing and edge-repair, respectively.

In economic analysis, it is assumed that the cost of all these additional works is incurred in the last construction year.

6.2.2 Effects of widening

After widening, the pavement type is reset to the new type specified by the user. The required modelling parameters are also reset to user-specified values, or computed endogenously as described below:

- **Carriageway width**

The new carriageway width after widening is given as follows:

$$CW_{aw} = CW_{bw} + \Delta CW \qquad ...(6.14)$$

where:

CW_{aw}	carriageway width after widening works (m)
CW_{bw}	carriageway width before widening works (m)
ΔCW	increase in carriageway width (m)

For partial widening, the increase in carriageway width (ΔCW) is specified directly by the user. For lane addition, the increase in carriageway width is user-specified, if this is not specified the increase will be given by:

$$\Delta CW = \frac{ADDLN * CW_{bw}}{NLANES_{bw}} \qquad ...(6.15)$$

where:

ADDLN	additional number of lanes, input by the user
$NLANES_{bw}$	number of lanes before widening works

For lane addition, the number of lanes after widening works ($NLANES_{aw}$) is equal to the number of lanes before works ($NLANES_{bw}$) plus the user-specified additional number of lanes (ADDLN).

The effective number of lanes after works is reset to a new value $ELANES_{aw}$, which should be input by the user. If this is not specified, $ELANES_{aw}$ will be reset to the value of $NLANES_{aw}$ (that is, the number of lanes for the road section following widening) see Part B Section 5.2.

- **Thickness of surfacing layers**

  - **Case 1: re-surfacing the existing carriageway**

    If the existing carriageway is to be re-surfaced, the thickness of new surfacing after widening works is obtained as follows:

$$HSNEW_{aw} = \frac{(CW_{bw} * HRESF + \Delta CW * HSNEW_{ww})}{CW_{aw}} \qquad ...(6.16)$$

where:

$HSNEW_{aw}$ new surfacing thickness after widening works (mm)

$HSNEW_{ww}$ surfacing thickness of the widened part of the carriageway (mm)

HRESF user-specified thickness of the re-surfacing layer on the existing carriageway (mm)

The thickness of old surfacing after widening is given as:

$$HSOLD_{aw} = \frac{(CW_{bw} * HS_{bw})}{CW_{aw}} \quad ...(6.17)$$

where:

$HSOLD_{aw}$ thickness of old surfacing after widening works (mm)

HS_{bw} total surfacing thickness of the existing carriageway before widening works (mm)

- **Case 2: no re-surfacing of the existing carriageway**

  If the existing carriageway is not to be re-surfaced, the thickness of new surfacing after widening works is obtained as follows:

$$HSNEW_{aw} = \frac{(CW_{bw} * HSNEW_{bw} + \Delta CW * HSNEW_{ww})}{CW_{aw}} \quad ...(6.18)$$

where:

$HSNEW_{aw}$ new surfacing thickness after widening works (mm)

$HSNEW_{bw}$ new surfacing thickness before widening works (mm)

$HSNEW_{ww}$ surfacing thickness of the widened part of the carriageway (mm)

The thickness of old surfacing after widening is given as:

$$HSOLD_{aw} = \frac{(CW_{bw} * HSOLD_{bw})}{CW_{aw}} \quad ...(6.19)$$

where:

$HSOLD_{aw}$ thickness of old surfacing after widening works (mm)

$HSOLD_{bw}$ thickness of old surfacing before widening works (mm)

- **Pavement strength**

  The **dry season adjusted structural number of pavement** is reset to the weighted average of that of the existing carriageway and that of the widened part of carriageway, as follows:

$$SNP_{daw} = SNP_{dexcw} * SNP_{dww} * \left[\frac{(CW_{bw} + \Delta CW)}{(CW_{bw} * [SNP_{dww}]^5 + \Delta CW * [SNP_{dexcw}]^5)} \right]^{0.2}$$

...(6.20)

$$SNP_{dww} = SN_{dww} + SNSG_s \qquad ...(6.21)$$

❑ If the existing carriageway is to be re-surfaced

$$SNP_{dexcw} = MAX[1.5, (SNP_{dbw} + 0.0394 * a_{resf} * HRESF - dSNPK)] \qquad ...(6.22)$$

❑ If the existing carriageway is **not** to be re-surfaced

$$SNP_{dexcw} = MAX[1.5, (SNP_{dbw} - dSNPK)] \qquad ...(6.23)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after widening works
SNP_{dbw}	dry season adjusted structural number of pavement before widening works
SNP_{dww}	dry season adjusted structural number of pavement of the widened part of the carriageway
SN_{dww}	user-specified structural number of pavement (of the layers above the subgrade) of the widened part of the carriageway. This may be computed in a similar manner to that described for SN_{new} in Equation 4.66 above
$SNSG_s$	subgrade contribution to the structural number of pavement, calculated using Equation 4.67 above
dSNPK	reduction in the adjusted structural number of pavement due to cracking
a_{resf}	strength coefficient of the re-surfacing layer on the existing carriageway

All other parameters are as defined previously.

The Benkelman beam deflection after widening works is given by:

$$DEF_{aw} = DEF_{bw} * \left[\frac{SNP_{aw}}{SNP_{bw}} \right]^{-1.6} \qquad ...(6.24)$$

where:

DEF_{aw}	benkelman beam deflection after works (mm)
DEF_{bw}	benkelman beam deflection before works (mm)
SNP_{aw}	adjusted structural number of pavement after works
SNP_{bw}	adjusted structural number of pavement before works

- **Surface material**

If the existing carriageway is to be re-surfaced, the surface material after works is reset to that specified for the widening works. This is based on the assumption that the same surfacing material is used for the re-surfacing.

If the existing carriageway is **not** to be re-surfaced, the surface material after works is reset as follows:

If	CW_{bw} is greater than ΔCW, the surface material after widening works is reset to that of the existing carriageway.
Otherwise	the surface material after widening works is reset to that of the widened part of the carriageway.

- **Construction quality**

The construction defect indicators for bituminous surfacing (CDS) and the construction defect indicator for the roadbase (CDB) are reset to a weighted average computed in the following manner:

$$CDi_{aw} = \left[\frac{(CDi_{bw} * CW_{bw} + CDi_{ww} * \Delta CW)}{CW_{aw}} \right] \qquad ...(6.25)$$

where:

CDi_{aw}	construction defect indicator *i* (*i*=CDS or CDB) after widening
CDi_{bw}	construction defect indicator *i* before widening works
CDi_{ww}	construction defect indicator *i* specified for the widening works

- **Pavement surface distresses**

If the existing carriageway is to be re-surfaced, the amounts of all surface distresses after widening works are reset to zero.

If the existing carriageway is **not** to be re-surfaced, the areas of edge-break, potholing, transverse thermal cracking, wide structural cracking and ravelling after widening works are all reset to zero. The area of all structural cracking and the total area of cracking are calculated as follows:

$$ACA_{aw} = \left[\frac{(ACA_b - ACW_b) * CW_{bw}}{CW_{aw}} \right] \qquad ...(6.26)$$

$$ACRA_{aw} = ACA_{aw} \qquad ...(6.27)$$

where:

ACA_{aw}	area of all structural cracking after widening works (% of total carriageway area)
$ACRA_{aw}$	total area of cracking after widening works (% of total carriageway area)

- **Rutting**

The mean rut depth is reset to a user-specified value. If this is not specified, the mean rut depth is calculated as follows:

$$RDM_{aw} = \left[\frac{(CW_{bw} * a0 * RDM_{bw})}{CW_{aw}}\right] \qquad ...(6.28)$$

where:

RDM_{aw}	mean rut depth after widening works (mm)
RDM_{bw}	mean rut depth before widening works (mm)
a0	user-definable coefficient (default = 0.15 if the existing carriageway is to be re-surfaced, otherwise a0 = 1.0)

- **Roughness**

After widening works, roughness is reset to a user-specified value. If this is not specified, the value of roughness is obtained as follows:

- If the existing carriageway is to be re-surfaced the following values are used as defaults:

  For AM surface type: RI_{aw} = 2.0 (IRI m/km)

  For ST surface type: RI_{aw} = 2.8 (IRI m/km)

- If the existing carriageway is **not** to be re-surfaced, it is assumed that patching and crack sealing that may be performed on the existing carriageway would affect the roughness after widening works as follows:

$$RI_{aw} = \left[\frac{(RI_n * \Delta CW + CW_{bw} * RI_{ap})}{CW_{aw}}\right] \qquad ...(6.29)$$

$$RI_{ap} = RI_{bw} - MIN\{[a0 * (\Delta CRX_w + \Delta ACT_w) + \Delta RI_t], a1\} \qquad ...(6.30)$$

where:

RI_{aw}	roughness after widening works (IRI m/km)
RI_{bw}	roughness before widening works (= RI_b) (IRI m/km)
RI_n	user-specified roughness for new construction, (default = 2.0 for AM, and 2.8 for ST)
RI_{ap}	roughness after patching and crack sealing (IRI m/km)
ΔCRX_w	reduction in the area of indexed structural cracking, (= ACX_b - ACX_{aw})
ΔACT_w	reduction in the area of transverse thermal cracking (= ACT_b)
ΔRI_t	reduction in roughness due to pothole patching (IRI m/km)
a0 and a1	user-definable model coefficients (default = 0.0066 and 4.6 respectively)

The value of ΔRI_t is computed using Equations 3.20 **Error! Reference source not found.** to 3.22 **Error! Reference source not found.** by taking ΔNPT_w as equal to NPT_{bw} (= NPT_b), since all existing potholes should be patched.

- **Texture depth and skid resistance**

After widening, texture depth and skid resistance is reset to user-specified values. If these are not specified, the values of texture depth and skid resistance after works are obtained in the following manner:

- The existing carriageway is to be re-surfaced

Texture depth after works (TD_{aw}) is reset to the default value of initial texture depth given in Table D2.; and skid resistance after works ($SFC50_{aw}$) is reset to the following default values:

For surface type AM: $SFC50_{aw} = 0.5$

For surface type ST: $SFC50_{aw} = 0.6$

- The existing carriageway is **not** to be re-surfaced

The values of texture depth and skid resistance after works are computed as follows:

$$TD_{aw} = \left[\frac{(TD_{bw} * CW_{bw} + ITD * \Delta CW)}{CW_{aw}}\right] \quad ...(6.31)$$

$$SFC50_{aw} = \left[\frac{(SFC50_{bw} * CW_{bw} + SFC50_n * \Delta CW)}{CW_{aw}}\right] \quad ...(6.32)$$

where:

TD_{aw}	texture depth after widening works (mm)
TD_{bw}	texture depth before widening works (mm)
ITD	default initial texture depth as given in Table D2.
$SFC50_{aw}$	skid resistance after widening works, SCRIM
$SFC50_{bw}$	skid resistance before widening works, SCRIM
$SFC50_n$	default skid resistance at 50 km/h (= 0.5 for AM, and 0.6 for ST)

- **Previous cracking**

- If the existing carriageway is to be re-surfaced

The amounts of previous cracking (PCRA, PCRW, and PNCT) are reset as follows:

if $CRAi_b \geq PCRi_{bw}$

$$PCRi_{aw} = \left[\frac{(CW_{bw} * CRAi_{bw})}{CW_{aw}}\right] \quad ...(6.33)$$

if $CRAi_b < PCRi_{bw}$

$$PCRi_{aw} = \left\{ \frac{CW_{bw} * [w * CRAi_b + (1-w) * PCRi_{bw}]}{CW_{aw}} \right\} \quad ...(6.34)$$

The weighting factor (*w*) is obtained in the following manner:

If the re-surfacing is an overlay (that is, surface type AM) consider roadbase types as follows:

for roadbase types AB, AP, GB:

$$w = MAX\left\{\left[\frac{HSNEW_{bw}}{HSOLD_{aw}}\right], 0.6\right\} \quad ...(6.35)$$

for roadbase type SB:

$$w = MAX\left\{\left[\frac{HSNEW_{bw}}{(HSOLD_{aw} + HSBASE)}\right], 0.6\right\} \quad ...(6.36)$$

If the re-surfacing is a reseal (that is, surface type ST)

$$w = MIN(0.70 + 0.1 * HSNEW_{aw}, 1) \quad ...(6.37)$$

where:

$PCRi_{aw}$	amount of previous cracking type *i* (*i* = all structural cracking, wide structural cracking, or transverse thermal cracking) after works
$CRAi_b$	amount of cracking type *i* at the end of the year
$PCRi_{bw}$	amount of previous cracking type *i* before widening works
w	weighting used for averaging the cracking in the old and new surfacing layers
HBASE	thickness of the roadbase layer in the original pavement (required for the roadbase type SB only) (mm)
$HSOLD_{aw}$	thickness of old surfacing after widening works (mm)
$HSNEW_{bw}$	thickness of the most recent surfacing before works (mm)
$HSNEW_{aw}$	thickness new surfacing after widening works (mm)

- If the existing carriageway is not to be re-surfaced, the area of previous cracking (PCRA, PCRW, and PNCT) is reset as follows:

$$PCRi_{aw} = \left[\frac{(CW_{bw} * PCRi_{bw})}{CW_{aw}}\right] \quad ...(6.38)$$

All the parameters are as defined previously.

- **Pavement age**

The pavement ages after widening are reset as follows:

- If the existing carriageway is to be re-surfaced by an overlay, AGE1, AGE2 and AGE3 are reset to zero. AGE4 is calculated from the expression:

$$AGE4_{aw} = \left[\frac{(CW_{bw} * AGE4_{bw})}{CW_{aw}} \right] \quad (\textit{returns an integer value}) \qquad ...(6.39)$$

- If the existing carriageway is to be resurfaced by resealing, AGE1 and AGE2 are reset to zero. AGE3 and AGE4 are given as:

$$AGEi_{aw} = \frac{(CW_{bw} * AGEi_{bw})}{CW_{aw}} \quad (\textit{for } i = 3 \textit{ or } 4) \qquad ...(6.40)$$

- If the existing carriageway is not to be re-surfaced, the pavement ages are calculated as follows:

$$AGEi_{aw} = \frac{(CW_{bw} * AGEi_{bw})}{CW_{aw}} \qquad ...(6.41)$$

where:

$AGEi_{aw}$ AGE type *i* (*i* = 1, 2, 3 or 4) after widening works (years)

$AGEi_{bw}$ AGE type *i* before widening works (years)

- **Road deterioration factors**

  The cracking retardation time, ravelling retardation factor and the other road deterioration factors (that is, the K factors) are also reset to user-specified values.

- **Speed factors**

  These are the speed limit, speed enforcement factor, roadside friction factor, non-motorised transport and motorised transport speed reduction factors and acceleration noise, which depend primarily on the individual road section.

- **Traffic flow pattern (road use)**

  The data that describes the hourly traffic flow distribution are also reset to a user-specified type.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

6.3 Realignment

Refers to local geometric improvements of road sections, which may also result in a reduction of the road length. It is assumed that the carriageway width remains unaltered when a realignment works is performed.

Realignment works can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Peak period Volume Capacity Ratio

- Daily average Volume Capacity Ratio
- Two-way AADT
- Year

A realignment works is specified using the following:

- New road type
- Road class
- Proportion of new construction - defined as the ratio of new construction length to the section length after realignment works
- Length adjustment factor
- Road geometry for the whole section
- Pavement details of the new realigned segments
- Construction quality indicators
- Whether or not the non-realigned segments (or parts) of the existing carriageway is provided with a new surfacing (that is, re-surfaced)
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes

6.3.1 Quantities and costs

If performed, the total amount of realignment works is given by:

$$REAL = Pconew * L_{aw} \qquad ...(6.42)$$

$$L_{aw} = L_{bw} * LF \qquad ...(6.43)$$

where:

REAL	length of road realigned (km)
L_{aw}	section length after realignment works (km)
L_{bw}	section length before realignment works (km)
LF	length adjustment factor, (LF > 0)
Pconew	proportion of new construction, (0 < Pconew < 1)

The cost of realignment (CSTREAL) is obtained from the product of REAL and the user-specified unit cost per kilometre.

The salvage value is given by:

$$SALVA = PCTSAV * CSTREAL \qquad ...(6.44)$$

where:

SALVA	salvage value of the works (currency)

PCTSAV percent of total cost salvageable (%)

Additional works

It is likely that realignment works will include re-surfacing or at least repair of the severely damaged area of the existing carriageway segments that are not to be realigned. These additional works are modelled as described below.

Case 1: re-surfacing the non-realigned segments

If the non-realigned segments of the existing carriageway are to be re-surfaced either by an overlay or resealing, the amount of re-surfacing works for the entire road section is given by:

$$TANSF = 1000 * CW * L_{aw} * (1 - Pconew) \qquad ...(6.45)$$

where:

TANSF total carriageway area re-surfaced (m^2)

- If an overlay were provided over the non-realigned parts of the existing carriageway, TANSF would be denoted as TAOVL, and the total cost of overlay is obtained from the product of TAOVL and the unit cost of overlay per square metre.

  Before overlay is performed, the amounts of preparatory works to be performed for the entire road section are computed as follows:

  - **Patching**

    $$TAPAT = 10 * CW * APOT_b * L_{aw} * (1 - Pconew) \qquad ...(6.46)$$

    where:

    TAPAT total area of preparatory patching (m^2)

    The total cost of preparatory patching is obtained from the product of TAPAT and the unit cost of patching.

  - **Edge-repair**

    $$TAVER = 10 * CW * AVEB_b * L_{aw} * (1 - Pconew) \qquad ...(6.47)$$

    where:

    TAVER total area of edge-repair (m^2)

    $AVEB_{bw}$ area of edge-break before realignment works (= $AVEB_b$) (% of total carriageway area)

    The total cost of edge-repair is obtained from the product of TAVER and the unit cost of edge-repair.

- If the non-realigned parts of the existing carriageway were resealed, ANSF would be denoted by TARSF, and the total cost of resealing is obtained from the product of TARSF and the unit cost of resealing per square metre.

  Before resealing is applied, the amounts of preparatory works to be performed for the entire road section are computed as follows:

  - **Patching**

    $$TAPAT = 10 * CW * L_{aw} * (1 - Pconew) * \{MAX[0.1 * (ACW_b - 20), 0] + APOT_b\} \quad ...(6.48)$$

    where:

    TAPAT total area of preparatory patching (m^2)

    The total cost of preparatory patching is obtained from the product of TAPAT and the unit cost of patching per square metre.

  - **Crack sealing**

    It is assumed that 100% of transverse thermal cracking on the non-realigned parts of the existing carriageway is sealed, and the amount of crack sealing performed is given by:

    $$TACSL = 10 * CW * L_{aw} * (1 - Pconew) * ACT_{bw} \quad ...(6.49)$$

    where:

    TACSL total area of crack sealing (m^2)

    ACT_{bw} area of transverse thermal cracking before realignment works (=ACT_b) (% of total carriageway area)

    The total cost of crack sealing is obtained from the product of TACSL and the unit cost of crack sealing per square metre.

  - **Edge-repair**

    The total area of edge-repair is calculated using Equation 6.47 above. The total cost of edge-repair is obtained from the product of TAVER and the unit cost of edge-repair per square metre.

Case 2: no re-surfacing of the non-realigned segments

If the non-realigned parts of the existing carriageway are not to be re-surfaced, it is assumed that the following amounts of patching, crack sealing and edge-repair are performed along with the realignment works:

- **Patching**

  Assuming that 100% of severely damaged area is patched, the amount of patching is computed as follows:

  $$TAPAT = 10 * CW * L_{aw} * (1 - Pconew) * ADAMS_{bw} \quad ...(6.50)$$

where:

TAPAT	total carriageway area patched (m^2)
$ADAMS_{bw}$	severely damaged carriageway area before realignment works (=$ADAMS_b$) (% of total carriageway area)

- **Crack sealing**

  The total amount of crack sealing is calculated using Equation 6.49 above.

- **Edge-repair**

  Assuming that all the edge-break area is repaired, the amount of edge-repair works is given by Equation 6.47 above.

The total cost of realignment works is the sum of carriageway realignment cost and the cost of additional works comprising re-surfacing of the existing carriageway and **preparatory works**. The amount and cost of re-surfacing works are reported separately under resealing or overlay. Similarly, the amounts and costs of patching, of crack sealing and edge-repair are reported separately under patching, crack sealing and edge-repair, respectively.

In economic analysis, it is assumed that the costs of all these additional works are incurred in the last construction year.

6.3.2 Effects of realignment

After realignment, the pavement type is reset to the new type specified by the user. The required modelling parameters are also reset to user-specified values, or computed endogenously as described below:

- **New length**

  The new length of the road section after realignment is given by Equation 6.43 above.

- **Thickness of surfacing layers**

  - **Case 1: re-surfacing non-realigned segments**

    If the non-realigned parts of the existing carriageway are to be re-surfaced, the thickness of new surfacing after realignment works is obtained as follows:

$$HSNEW_{aw} = [(1 - Pconew) * HRESF + Pconew * HSNEW_{rw}] \quad ...(6.51)$$

where:

$HSNEW_{aw}$	new surfacing thickness after realignment works (mm)
$HSNEW_{rw}$	surfacing thickness of the new construction parts of the carriageway (mm)
HRESF	user-specified thickness of the re-surfacing layer on the existing carriageway (mm)

The thickness of old surfacing after realignment works is given by:

$$HSOLD_{aw} = (1 - Pconew) * HS_{bw} \quad ...(6.52)$$

where:

$HSOLD_{aw}$	thickness of old surfacing after realignment works (mm)
HS_{bw}	total surfacing thickness of the existing carriageway before realignment (mm)

- **Case 2: no resurfacing of non-realigned segments**

If the non-realigned parts of the existing carriageway are **not** to be re-surfaced, the thickness of new surfacing after realignment works is obtained as follows:

$$HSNEW_{aw} = [(1 - Pconew) * HSNEW_{bw} + Pconew * HSNEW_{rw}] \quad ...(6.53)$$

where:

$HSNEW_{aw}$	new surfacing thickness after realignment works (mm)
$HSNEW_{bw}$	new surfacing thickness before realignment works (mm)
$HSNEW_{rw}$	surfacing thickness of the new construction parts of the carriageway (mm)

The thickness of old surfacing after realignment works is given by:

$$HSOLD_{aw} = (1 - Pconew) * HSOLD_{bw} \quad ...(6.54)$$

where:

$HSOLD_{aw}$	thickness of old surfacing after realignment works (mm)
$HSOLD_{bw}$	thickness of old surfacing before realignment works (mm)

- **Pavement strength**

The **dry season adjusted structural number of pavement** is reset to the weighted average of the structural number of the non-realigned parts of the existing carriageway and that of the newly constructed segments, as follows:

$$SNP_{daw} = [(1 - Pconew) * SNP_{dexcw} + Pconew * SNP_{drw}] \quad ...(6.55)$$

$$SNP_{drw} = SN_{drw} + SNSG_{s} \quad ...(6.56)$$

If the non-realigned parts of the existing carriageway are to be re-surfaced:

$$SNP_{dexcw} = MAX[1.5, (SNP_{dbw} + 0.0394 * a_{resf} * HRESF - dSNPK)] \quad ...(6.57)$$

If the non-realigned parts of the existing carriageway are **not** to be re-surfaced:

$$SNP_{dexcw} = MAX[1.5, (SNP_{dbw} + 0.0394 * a_{resf} * HRESF - dSNPK)] \quad ...(6.58)$$

where:

SNP_{daw}	dry season adjusted structural number of pavement after works
SNP_{dbw}	dry season adjusted structural number of pavement before works
SNP_{drw}	dry season adjusted structural number of pavement of the newly constructed parts of carriageway
SN_{drw}	user-specified structural number of pavement (of the layers above the subgrade) of the realigned parts of the carriageway. This may be computed in a similar manner to that described for SN_{new} in Equation 4.66 above
$SNSG_s$	subgrade contribution to the structural number of pavement, calculated using Equation 4.67 above
dSNPK	reduction in the adjusted structural number of pavement due to cracking
HRESF	thickness of the re-surfacing layer on the non-realigned parts of the existing carriageway
a_{resf}	strength coefficient of the re-surfacing layer on the non-realigned parts of the existing carriageway

The Benkelman beam deflection after realignment works is given by:

$$DEF_{aw} = DEF_{bw} * \left(\frac{SNP_{aw}}{SNP_{bw}}\right)^{-1.6} \qquad \text{...(6.59)}$$

where:

DEF_{aw}	Benkelman beam deflection after works (mm)
DEF_{bw}	Benkelman beam deflection before works (mm)
SNP_{aw}	adjusted structural number of pavement after works
SNP_{bw}	adjusted structural number of pavement before works

- **Surface material**

If the existing carriageway is to be re-surfaced, the surface material after works is reset to that specified for the realignment works. This is based on the assumption that the same surfacing material is used for the re-surfacing.

If the existing carriageway is **not** to be re-surfaced, the surface material after works is reset as follows:

if	Pconew is less than 0.5, the surface material after works is reset to that of the existing carriageway.
otherwise	the surface material after works is reset to that of the realigned parts of the carriageway.

- **Construction quality**

The construction defect indicators for bituminous surfacing (CDS) and the construction defect indicator for the roadbase (CDB) is reset to a weighted average computed as follows:

$$CDi_{aw} = [CDi_{bw} * (1 - Pconew) + CDi_{rw} * Pconew] \qquad ...(6.60)$$

where:

CDi_{aw}	construction defect indicator *i* (*i*=CDS or CDB) after works
CDi_{bw}	construction defect indicator *i* before works
CDi_{rw}	construction defect indicator *i* specified for the realignment works

- **Pavement surface distresses**

If the non-realigned parts of the existing carriageway are to be re-surfaced the surface distresses (that is, edge-break, potholing, cracking and ravelling) are all reset to zero.

If the non-realigned parts of the existing carriageway are **not** to be re-surfaced, the area of edge-break, potholing, transverse thermal cracking, wide structural cracking and ravelling are reset to zero. The area of all structural cracking and total area of cracking after realignment works are reset as follows:

$$ACA_{aw} = \frac{[(1 - Pconew) * (ACA_b - ACW_b)]}{LF} \qquad ...(6.61)$$

$$ACRA_{aw} = ACA_{aw} \qquad ...(6.62)$$

where:

ACA_{aw}	area of all structural cracking after realignment works (% of total carriageway area)
$ACRA_{aw}$	total area of cracking after realignment works (% of total carriageway area)

All other parameters are as defined previously.

- **Rutting**

The mean rut depth is reset to a user-specified value. If this is not specified, the mean rut depth is calculated as follows:

$$RDM_{aw} = [(1 - Pconew) * a0 * RDM_{bw}] \qquad ...(6.63)$$

where:

RDM_{aw}	mean rut depth after realignment works (mm)
RDM_{bw}	mean rut depth before realignment works (mm)
a0	user-definable coefficient (default = 0.15 if the non-realigned parts of the existing carriageway are to be re-surfaced, otherwise a0 = 1.0)

- **Roughness**

After realignment works, roughness is reset to a user-specified value. If this is not specified, the value of roughness is obtained as follows:

- If the non-realigned parts of the existing carriageway are to be re-surfaced the following values are used as defaults:

  For AM surface type: RI_{aw} = 2.0 (IRI m/km)

  For ST surface type: RI_{aw} = 2.8 (IRI m/km)

- If the non-realigned parts of the existing carriageway are **not** to be re-surfaced, roughness after realignment works is reset as follows:

$$RI_{aw} = \left[RI_n * Pconew + (1 - Pconew) * RI_{ap}\right] \quad ...(6.64)$$

$$RI_{ap} = RI_{bw} - MIN\left\{\left[a0 * \left(\Delta CRX_w + \Delta ACT_w\right) + \Delta RI_t\right], a1\right\} \quad ...(6.65)$$

where:

RI_{aw}	roughness after realignment works (IRI m/km)
RI_{bw}	roughness before realignment works (= RI_b) (IRI m/km)
RI_n	user-specified roughness for realignment new construction, (default = 2.0 for AM, and 2.8 for ST)
RI_{ap}	roughness after patching and crack sealing (IRI m/km)
ΔCRX_w	reduction in the area of indexed structural cracking, (= ACX_b - ACX_{aw})
ΔACT_w	reduction in the area of transverse thermal cracking (= ACT_b)
ΔRI_t	reduction in roughness due to pothole patching (IRI m/km)
a0 and a1	user-definable model coefficients (default = 0.0066 and 4.6 respectively)

The value of ΔRI_t is computed using Equations 3.20 **Error! Reference source not found.** to 3.22 **Error! Reference source not found.** by taking ΔNPT_w as equal to NPT_{bw} (= NPT_b), since all existing potholes should be patched.

- **Texture depth and skid resistance**

After realignment, texture depth and skid resistance is reset to user-specified values. If these are not specified, texture depth and skid resistance after works are obtained in the following ways:

- If the non-realigned segments of the existing carriageway are to be re-surfaced, texture depth after works (TD_{aw}) is reset to the default value of initial texture depth given in Table D2.; and skid resistance after works ($SFC50_{aw}$) is reset to the following default values:

  For surface type AM: $SFC50_{aw}$ = 0.5

  For surface type ST: $SFC50_{aw}$ = 0.6

- If the non-realigned segments of the existing carriageway are **not** to be re-surfaced, the values of texture depth and skid resistance after works are computed as follows:

$$TD_{aw} = TD_{bw} * (1 - Pconew) + ITD * Pconew \quad ...(6.66)$$

$$SFC50_{aw} = SFC50_{bw} * (1 - Pconew) + SFC50_{n} * Pconew \quad ...(6.67)$$

where:

TD_{aw}	texture depth after realignment works (mm)
TD_{bw}	texture depth before realignment works (mm)
ITD	default initial texture depth as given in Table D2.
$SFC50_{aw}$	skid resistance after realignment works, SCRIM
$SFC50_{bw}$	skid resistance before realignment works, SCRIM
$SFC50_{n}$	default skid resistance at 50 km/h (= 0.5 for AM, and 0.6 for ST)

- **Previous cracking**

If the non-realigned parts of the existing carriageway are to be re-surfaced, the amount of previous cracking (PCRA, PCRW, and PNCT) is reset as follows:

- if $CRAi_b \geq PCRi_{bw}$

$$PCRi_{aw} = \frac{[(1 - Pconew) * CRAi_b]}{LF} \quad ...(6.68)$$

- if $CRAi_b < PCRi_{bw}$

$$PCRi_{aw} = \frac{\{(1 - Pconew) * [w * CRAi_b + (1 - w) * PCRi_{bw}]\}}{LF} \quad ...(6.69)$$

The weighting factor (*w*) is obtained in the following manner:

If the re-surfacing is an overlay (that is, surface type AM), the value of *w* is obtained as follows:

- for roadbase types AB, AP, GB

$$w = MAX\left[\frac{HSNEW_{bw}}{HSOLD_{aw}}, 0.6\right] \quad ...(6.70)$$

- for roadbase type SB

$$w = MAX\left[\frac{HSNEW_{bw}}{(HSOLD_{aw} + HBASE)}, 0.6\right] \quad ...(6.71)$$

If the re-surfacing is a reseal (that is, surface type ST), the value of *w* is given by:

$$w = MIN\ (0.70 + 0.1 * HSNEW_{aw}, 1) \quad ...(6.72)$$

where:

$PCRi_{aw}$	amount of previous cracking type *i* (*i* = all structural cracking, wide structural cracking or transverse thermal cracking) after works

$CRAi_b$	amount of cracking type *i* at the end of the year
$PCRi_{bw}$	amount of previous cracking type *i* before realignment works
LF	length adjustment factor
w	weighting used for averaging the cracking in the old and new surfacing layers
HBASE	thickness of the roadbase layer in the original pavement (required for SB roadbase type only) (mm)
$HSOLD_{aw}$	thickness of old surfacing after realignment works (mm)
$HSNEW_{bw}$	thickness of the most recent surfacing before works (mm)
$HSNEW_{aw}$	thickness of new surfacing after realignment works (mm)

If the non-realigned parts of the existing carriageway are **not** to be re-surfaced, the amount of previous cracking (PCRA, PCRW, and PNCT) is reset as follows:

$$PCRi_{aw} = \left\{ \frac{[(1 - Pconew) * PCRi_{bw}]}{LF} \right\} \quad ...(6.73)$$

All the parameters are as defined previously.

- **Pavement age**

The pavement ages after realignment are reset as follows:

- If the non-realigned parts of the existing carriageway are to be re-surfaced by an **overlay**, AGE1, AGE2 and AGE3 are reset to zero. AGE4 is calculated as follows:

$$AGE4_{aw} = (1 - Pconew) * AGE4_{bw} \text{ (\textit{returns an integer value})} \quad ...(6.74)$$

- If the non-realigned parts of the existing carriageway are to be re-surfaced by **resealing**, AGE1 and AGE2 are reset to zero. AGE3 and AGE4 are calculated from the expression:

$$AGEi_{aw} = (1 - Pconew) * AGEi_{bw} \quad (i = 3 \text{ or } 4) \quad ...(6.75)$$

- If the non-realigned parts of the existing carriageway are **not** to be re-surfaced, the pavement ages are calculated as follows:

$$AGEi_{aw} = (1 - Pconew) * AGEi_{bw} \quad ...(6.76)$$

where:

$AGEi_{aw}$	AGE type *i* (*i* = 1, 2, 3 or 4) after realignment works (years)
$AGEi_{bw}$	AGE type *i* before realignment works (years)

- **Deterioration factors**

The cracking retardation time, ravelling retardation factor and the other road deterioration factors (that is, the K factors) are also reset to user-specified values.

- **Speed factors**

  These are the speed limit, speed enforcement factor, roadside friction factor, non-motorised transport and motorised transport speed reduction factors, and acceleration noise which depend primarily on the individual road section.

- **Traffic flow pattern (road use)**

  The data that describes the hourly traffic flow distribution are also reset to a user-specified type.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

6.4 Non-carriageway improvement

The major non-carriageway improvement works considered relate to NMT lanes.

6.4.1 NMT lanes

The effects of Non-Motorised Transport (NMT) lane upgrading and NMT lane addition are modelled as described below:

NMT lane upgrading

This involves upgrading the pavement type of the existing NMT lanes to a new type. The upgrading of NMT lanes can be triggered by the user by defining one or more intervention criterion

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Year

The following information is required to specify upgrading NMT lanes:

- New road type
- New surface type
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes.

It is assumed that the geometry details are the same as that of the existing road section.

If performed, the total amount of works is given in terms of the total length of NMT lanes constructed as follows:

$$NMTL_{aw} = L * NMTLN \qquad ...(6.77)$$

where:

$NMTL_{aw}$ total length of NMT lanes upgraded (km)

L road section length (km)

NMTLN number of existing NMT lanes

The total cost of NMT lane upgrading is obtained from the product of $NMTL_{aw}$ and the user-specified unit cost per lane per kilometre.

The effects of upgrading NMT lane is reflected by specifying new values for the speed reduction factors, and resetting the data that describe the resulting traffic flow pattern.

NMT lane addition

This includes the addition of NMT lanes of all types, and can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Year

The addition of new NMT lanes is specified by the number of lanes, the road type, the pavement surface type, and the asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes. It is assumed that the geometry details are the same as that of the road section.

If performed, the total amount of works is given in terms of the total length of NMT lanes constructed as follows:

$$NMTL_{aw} = L * NEWLN \qquad ...(6.78)$$

where:

$NMTL_{aw}$ total length of NMT lanes constructed (km)

L road section length (km)

NEWLN number of new NMT lanes constructed

The total cost of NMT lane construction is obtained from the product of $NMTL_{aw}$ and the user-specified unit cost per lane per kilometre.

The effects of NMT lane addition should be reflected by specifying new values for the speed reduction factors, and resetting the data that describe the resulting traffic flow pattern.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

7 Construction

Construction works comprises the following:

- **Upgrading** (see Section 7.1)
- **Construction of a new section (or link)** (see Section 7.2)

7.1 Upgrading

This operation involves both pavement upgrading and geometric improvements of an existing road. Normally pavement upgrading would change the existing surface class to another surface class of a higher performance grade. For example, a bituminous pavement road may be upgraded to a rigid concrete pavement road. The modelling framework also allows for the upgrading of a **lower-grade** bituminous pavement to a **higher-grade** bituminous pavement.

Upgrading works can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Peak period Volume Capacity Ratio
- Daily average Volume Capacity Ratio
- Two-way AADT
- Cumulative ESAL
- Year

An upgrading works is specified by the:

- Road type
- Road class
- Road geometric characteristics
- Pavement details
- Length adjustment factor
- Increase in width
- Additional number of lanes
- Construction quality indicators
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes.

7.1.1 Quantities and costs

If performed, the total amount of upgrading works is given by:

$$LUPGRD = L_{aw} \qquad ...(7.1)$$

$$L_{aw} = LF * L_{bw} \qquad ...(7.2)$$

where:

LUPGRD	amount of upgrading works (km)
L_{aw}	road length after upgrading works (km)
L_{bw}	road length before upgrading works (km)
LF	length adjustment factor (LF > 0)

The total cost of upgrading (CSTUPGRD) is obtained from the product of LUPGRD and the user-specified unit cost per kilometre.

The salvage value is given by:

$$SALVA = PCTSAV * CSTUPGRD \qquad ...(7.3)$$

where:

SALVA	salvage value of the works (currency)
PCTSAV	percent of total cost salvageable (%)

7.1.2 Effects of upgrading

After upgrading, the required modelling parameters are reset to user-specified values, or computed endogenously as described below:

- **New length**

  The new length of the road section after upgrading is given by Equation 7.2 above.

- **Carriageway width**

  The new carriageway width after upgrading is given as follows:

$$CW_{aw} = CW_{bw} + \Delta CW \qquad ...(7.4)$$

where:

CW_{aw}	carriageway width after upgrading works (m)
CW_{bw}	carriageway width before upgrading works (m)
ΔCW	increase in carriageway width (m)

The number of lanes after upgrading ($NLANES_{aw}$) is equal to the number of lanes before works ($NLANES_{bw}$) plus the user-specified additional number of lanes (ADDLN).

The effective number of lanes after works is reset to a new value $ELANES_{aw}$, which should be input by the user. If this is not specified, $ELANES_{aw}$ will be reset to the value of $NLANES_{aw}$ (that is, the number of lanes for the road section following upgrading) see Part B Section 5.2.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

- **Pavement characteristics**

  The new pavement characteristics are reset according to the new road surface class specified by the user as described in Sections 7.1.3 and 7.1.4.

7.1.3 Bituminous pavements

If the new road surface class is bituminous, the pavement type, structure, strength and layer material properties are reset to the user-specified values or calculated endogenously.

Note: In this case the pavement types STAP and AMAP are not permissible options.

- **Pavement strength**

  The dry season adjusted structural number of pavement (SNP_{daw}) is computed using the specified structural number of pavement (SN_{new}) from Equations 4.66 above and 4.67 above. The Benkelman beam deflection after upgrading works will be given as:

$$DEF_{aw} = a0 * (SNP_{aw})^{-1.6} \qquad ...(7.5)$$

where:

DEF_{aw}	Benkelman beam deflection after works (mm)
SNP_{aw}	adjusted structural number of pavement after works
a0	coefficient depending upon the roadbase type (a0 = 6.5 for types GB and AB; a0 = 3.5 for SB base type)

- **Pavement surface distresses**

  After upgrading, the pavement condition is new, and all distress values are therefore set to zero.

- **Rutting**

  After upgrading, the mean rut depth is set to zero.

- **Roughness**

  Roughness after upgrading is set to a user-specified value. If this is not specified, the following default values are used:

  For AM surface type: RI_{aw} = 2.0 (IRI m/km)

  For ST surface type: RI_{aw} = 2.8 (IRI m/km)

- **Texture depth and skid resistance**

  After upgrading, texture depth and skid resistance is reset to the user-specified values. If these are not specified, texture depth after works (TD_{aw}) is reset to the default value of initial texture depth given in Table D2.; and skid resistance after works ($SFC50_{aw}$) is reset to the following default values:

For surface type AM: $SFC60_{aw} = 0.5$

For surface type ST: $SFC50_{aw} = 0.6$

- **Pavement ages**

  After upgrading, all the pavement age parameters (that is, AGE1, AGE2, AGE3 and AGE4) are reset to zero.

- **Previous cracking**

  The amounts of previous cracking are all reset to zero.

- **Road deterioration factors**

  The deterioration factors for modelling the performance of the new pavement are reset to user-specified values.

- **Speed factors**

  These are the speed limit, speed enforcement factor, acceleration noise, roadside friction factor, non-motorised transport factor, and the speed reduction factor due to motorised transport which depend primarily on the individual road section.

- **Traffic flow pattern (road use)**

  The data that describes the hourly traffic flow distribution are also reset to a user-specified type.

7.1.4 Rigid concrete pavements

If the new surface class is rigid concrete, the required modelling parameters for concrete pavement are used. The pavement condition is set to new, and the history data is reset to reflect a completely new construction.

The new section length, carriageway width, number of lanes, speed factors and traffic flow pattern are reset as described above for bituminous pavements.

7.2 New section

The construction of a new section can only be scheduled and not triggered by responsive intervention criteria. In a project analysis, a new road section (that is, a new link) can be specified as a section alternative within a selected project alternative.

The required components for defining a new section are as follows:

- All the data items that are required to define a road section in HDM-4, including the asset valuation. The user can specify these items using aggregate data. Note that the pavement types STAP and AMAP are not valid options.
- Traffic data
  - diverted traffic - traffic that is diverted from the nearby routes and other transport modes.
  - generated traffic – additional traffic that occurs in response to the new investment.
- Construction costs, duration and salvage value.
- Exogenous benefits and costs.
- Maintenance standards, and future improvements to be applied after opening the new section to traffic.

The amount of new construction can be expressed in terms of the number of kilometres constructed (NEWCON) and this is equal to the new section length. The total cost of construction (CSTNEW) is obtained from the product of NEWCON and the user-specified unit cost per kilometre.

The salvage value is given as:

$$SALVA = PCTSAV * CSTNEW \qquad ...(7.6)$$

where:

SALVA salvage value of the works (currency)

PCTSAV percent of total cost salvageable (%)

8 References

NDLI, (1995)

Modelling Road Deterioration and Maintenance Effects in HDM-4. Final Report Asian Development Bank Project RETA 5549. N.D. Lea International, Vancouver, Canada

Riley M., (1995)

Framework for Defining the Effects of Works on Road parameters in HDM-4. Communication to the ISOHDM

Watanatada T., Harral C.G., Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987a)

The Highway Design and Maintenance Standards Model: Volume-1 Description. The World Bank, John Hopkins University Press

Watanatada T., Harral C.G., Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987b)

The Highway Design and Maintenance Standards Model: Volume- 2 User's Manual World Bank, John Hopkins University Press

D3 Concrete Pavements

1 Introduction

This chapter describes the detailed modelling of road works effects for rigid concrete roads in HDM-4 (see Figure D3.1). It is based on the specification documents prepared by the Latin American Study Team in Chile (*LAST, 1995;* and *LAST, 1996*).

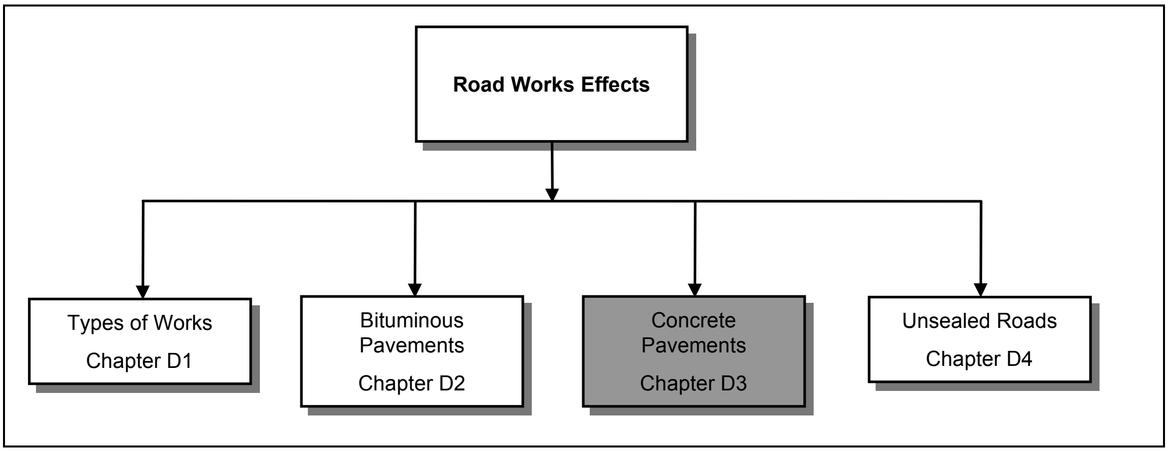

Figure D3.1 Road Works Effects modules

The methods of defining works activities and intervention criteria, the calculation of physical quantities of works and the costs to road administration, and works effects on road characteristics and road use are discussed for the following works classes:

- **Routine maintenance**
- **Periodic maintenance**
- **Special works**
- **Construction works**

The modelling logic described comprises the overall computational procedure, the hierarchical ranking of works activities and pavement type resets after works. The background of the modelling logic is given in *LAST (1996)*.

Table D3.1 shows the maintenance works activities for the different pavement surface types considered in HDM-4.

Table D3.1 Maintenance works for concrete pavements

Works class	Works type	Works activities	Pavement surface type		
			JP	JR	CR
Routine	Routine maintenance	Vegetation control, line marking, drain cleaning, etc.	✔	✔	✔
Periodic	Preventive treatment	Load transfer dowels retrofit	✔		
		Tied concrete shoulders retrofit	✔	✔	
		Longitudinal edge drains retrofit	✔	✔	
		Joint sealing	✔	✔	
	Restoration	Slab replacement	✔		
		Full depth repair		✔	✔
		Partial depth repair	✔		
		Diamond grinding	✔	✔	
	Rehabilitation	Bonded concrete overlay	✔	✔	✔
		Unbonded concrete overlay	✔	✔	✔
	Reconstruction	Pavement reconstruction	✔	✔	✔

Notes:

✔ indicates that the works activity is applicable to the pavement surface type

JP Jointed plain

JR Jointed reinforced

CR Continuously reinforced

2 Modelling logic

The modelling of concrete pavement performance is considered in two separate phases:

- **Phase 1**

  Refers to the time before any major periodic maintenance or reconstruction.

- **Phase 2**

  Refers to the time after the pavement has received a major maintenance or has been reconstructed.

This chapter discusses the Phase 2 modelling logic. Phase 1 modelling logic is described in Chapter C3.

2.1 Overall computational procedure

The overall computational procedure for modelling road works that is applied in each analysis year can be summarised by the following steps:

1 Determine the road works standard(s) that is applicable in the given year. Only one maintenance standard and/or one improvement standard can be applied to a road feature in any analysis year.

2 Check the intervention criteria and the limits defined for works included within the standard. A scheduled operation takes priority over a responsive operation of the same type.

3 Identify and apply the highest-priority works activity.

4 Compute the physical quantities of works.

5 Compute works effects and reset modelling parameter values to reflect post-works road geometry, pavement structure, strength, condition, history, and road use.

6 Check intervention criteria, identify and apply the next highest-priority works activity.

7 Repeat (4), (5) and (6).

8 Apply any other works whose effects on pavement performance are not modelled endogenously in HDM-4, (for example, routine maintenance works).

9 Calculate the costs of works by applying unit costs to the physical quantities of works.

10 Store results for economic analysis and for use in the following analysis year.

2.2 Hierarchy of works

A works activity (or an operation) will be triggered when any one or a combination of the user-specified criteria has been met. When more than one works activity meet the criteria for being applied in a given analysis year, the highest-priority operation for the particular road feature will be applied first, and their effects will be computed to reset road characteristics.

Most interventions on concrete pavements will require a combination of several preventive and restoration works activities. The activities defined within a standard should therefore address properly the causes of pavement deterioration and repair them.

Table D3.2 shows the hierarchy of works activities that are applicable to the carriageway for JP concrete pavements.

Table D3.2 Maintenance works applicable to JP concrete carriageway

Works type	Works activity / operation	ID code	Hierarchy	Unit cost
Reconstruction	Pavement reconstruction	REC	1	per m^2
Rehabilitation	Unbonded concrete overlay	UOL	2	per m^2
	Bonded concrete overlay	BOL	3	per m^2
Restoration	Slab replacement	SLR	4	per m^2
	Partial depth repair	PDR	5	per m (joint length)
	Diamond grinding*	DGR	6	per m^2
Preventive treatment	Load transfer dowels retrofit*	DWL	7	per m (joint length)
	Tied concrete shoulders retrofit*	TCS	7	per km
	Longitudinal edge drains retrofit*	RED	7	per km
	Joint sealing*	SLJ	7	per m (joint length)

Note:

* Works activity can be applied together with slab replacement or partial depth repair in the same analysis year

Table D3.3 shows the hierarchy of works activities that are applicable to the carriageway for JR concrete pavements.

Table D3.3 Maintenance works applicable to JR concrete carriageway

Works type	Works activity / operation	ID code	Hierarchy	Unit cost
Reconstruction	Pavement reconstruction	REC	1	per m^2
Rehabilitation	Unbonded concrete overlay	UOL	2	per m^2
	Bonded concrete overlay	BOL	3	per m^2
Restoration	Full depth repair	FDR	4	per m^2
	Diamond grinding*	DGR	5	per m^2
Preventive treatment	Tied concrete shoulders retrofit*	TCS	6	per km
	Longitudinal edge drains retrofit*	RED	6	per km
	Joint sealing*	SLJ	6	per m (joint length)

Note:

* Works activity can be applied together with full depth repair in the same analysis year

Table D3.4 shows the hierarchy of works activities that are applicable to the carriageway for CR concrete pavements.

Table D3.4 Maintenance works applicable to CR concrete carriageway

Works type	Works activity / operation	ID code	Hierarchy	Unit cost
Reconstruction	Pavement reconstruction	REC	1	per m^2
Rehabilitation	Unbonded concrete overlay	UOL	2	per m^2
	Bonded concrete overlay	BOL	3	per m^2
Restoration	Full depth repair	FDR	4	per m^2

The works activities whose effects on pavement performance are not modelled endogenously in HDM-4 (for example, emergency works, winter maintenance, and routine maintenance works) will be applied in a given analysis year, if specified by the user, regardless of any works hierarchy.

2.3 Road characteristics reset

When a road works activity is performed, two kinds of effects on the road characteristics are considered:

1 The immediate effect on the road geometry, pavement type, strength, condition, age (or history), status, etc.

2 The long-term effect on pavement performance.

The RD model parameters are reset to reflect the effects of the works activity and are subsequently used to predict the long-term performance of the pavement.

This chapter discusses in detail the immediate effects of different works activities. The long-term effect on pavement performance is modelled using the Phase 1 models described in Chapter C3, with some adjustments introduced to shift the performance curve either vertically, horizontally or both in order to maintain continuity at the point of time the intervention was applied.

3 Routine maintenance

The routine maintenance activities on concrete roads include vegetation control, drain cleaning, road marking, repair to road appurtenances, and sign posts. These are considered in the analyses only in terms of their costs to the road administration. The effect of drainage on pavement performance is accounted for through the drainage coefficient (Cd), as defined by *AASHTO (1993)*.

Routine maintenance works should be **scheduled** at a fixed interval of time (a minimum of one-year), and will be performed on an annual basis. If specified by the user, routine maintenance works will be applied in any analysis year regardless of the works hierarchy.

The unit cost should be specified in terms of currency per kilometre per year, and the annual cost of routine maintenance is obtained from the product of the road section length and the unit cost.

4 Preventive treatment

The preventive maintenance works on concrete pavements comprises the following:

- Load transfer dowels retrofit (see Section 4.1).
- Tied concrete shoulders retrofit (see Section 4.2).
- Longitudinal edge drains retrofit (see Section 4.3).
- Joint sealing (see Section 4.4).

4.1 Load transfer dowels retrofit

This is a technique used to increase the load transfer efficiency of JP concrete pavements by cutting slots and inserting dowels at undoweled joints (and cracks).

Retrofitting load transfer dowels can be scheduled at a fixed point in time defined by the calendar year.

Quantities and costs

If performed, the amount of works is given by:

$$LDOW = \frac{5280 * CW}{1.6093 * JTSPACE} \quad ...(4.1)$$

where:

LDOW	joint length fitted with load transfer dowels (m/km)
CW	carriageway width (m)
JTSPACE	average transverse joint spacing (ft)

The product of LDOW and the section length (L) in kilometres gives the total length of joints fitted with load transfer dowels (TLDOW) in metres. The total cost of retrofitting load transfer dowels is computed by multiplying TLDOW by the user-specified unit cost per metre length.

The effects

Load transfer restoration has the ability to increase the structural capacity of a pavement.

After works, the pavement type will be reset to JP concrete pavement with dowels, and the progression of cracking, faulting and spalling will be computed using the models for JP concrete pavements with dowels. If the dowel diameter is less than 20 mm, the model for JP concrete pavement without dowels will be used. The user should also specify whether or not the dowels fitted are protected against corrosion.

Figure D3. shows the effect of retrofitting load transfer dowels on faulting in JP concrete pavements without dowels.

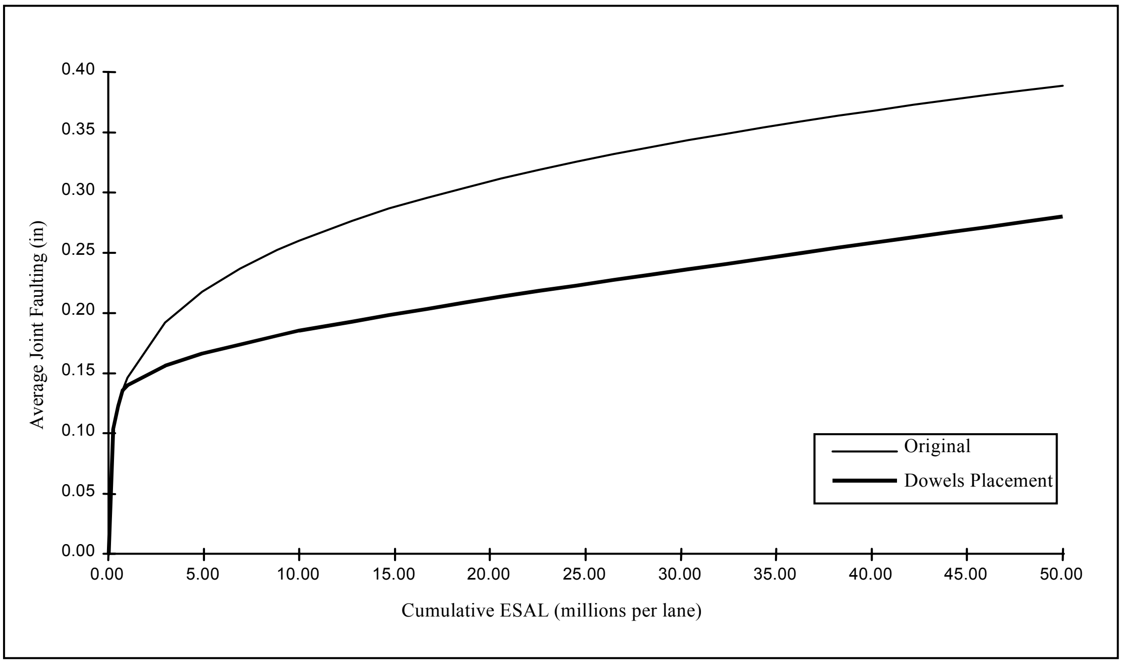

Figure D3.2 Retrofitting load transfer dowels effect on transverse joint faulting in JP concrete pavements without dowels

4.2 Tied concrete shoulders retrofit

This is the addition of tied concrete shoulders to an existing JP or JR concrete pavement.

Retrofitting tied concrete shoulders can be scheduled at a fixed point in time defined by the calendar year.

Quantities and costs

If performed, the amount of works is given as follows:

$$TCS = L \qquad ...(4.2)$$

where:

TCS	amount of tied concrete shoulders retrofitted (km)
L	road section length (km)

The total cost of retrofitting tied concrete shoulders is computed by multiplying TCS by the user-specified unit cost per kilometre.

The effects

Retrofitting tied concrete shoulders can increase the structural capacity of a pavement by decreasing the critical stresses at the concrete edge and by decreasing the deflections at the corners.

The value of the parameter LTE_{sh} used in the equations for predicting cracking and faulting will be updated as described in Table D3.5.

Table D3.5 Cracking and faulting model parameter values

	Pavement construction status	Parameter	
		WIDENED	LTE_{sh} (%)
1	No widened lane or tied concrete shoulders	0	0
2	Widened outside lanes provided	1.0	20
3	Concrete shoulders placed during initial pavement construction	1.0	20
4	Concrete shoulders placed after initial pavement construction	0.5	10

Figure shows the effect of retrofitting tied concrete shoulders on cracking in JP concrete pavements without dowels.

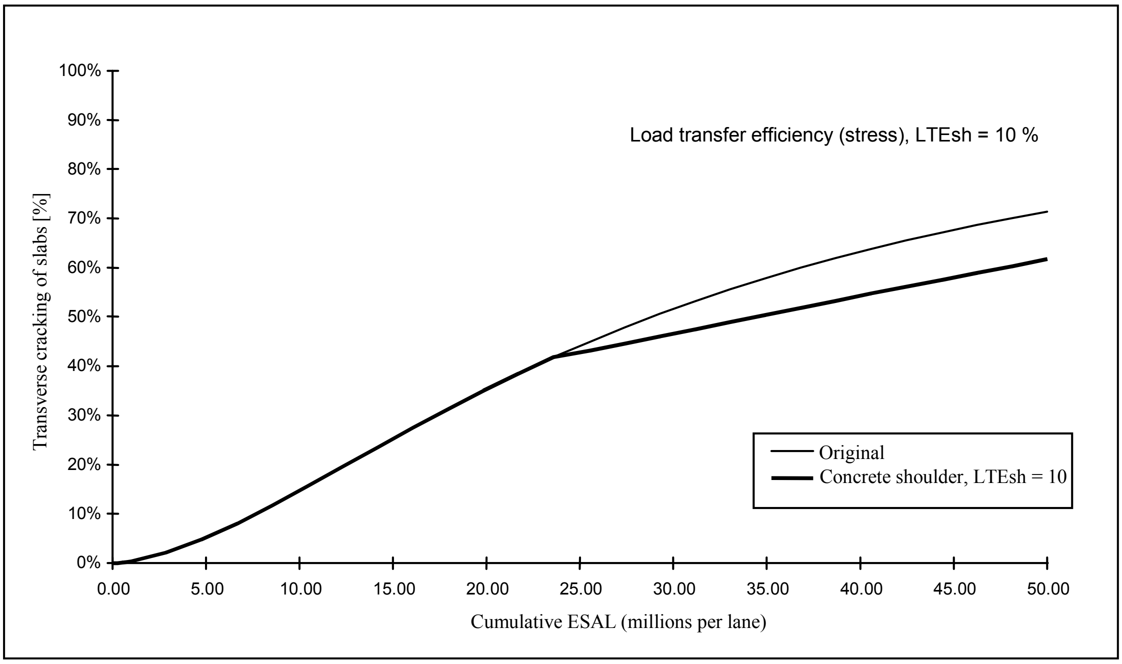

Figure D3.3 Retrofitting tied concrete shoulder effect on transverse cracking in JP concrete pavements

Figure D3. shows the effect of retrofitting tied concrete shoulders on faulting in JP concrete pavements without dowels.

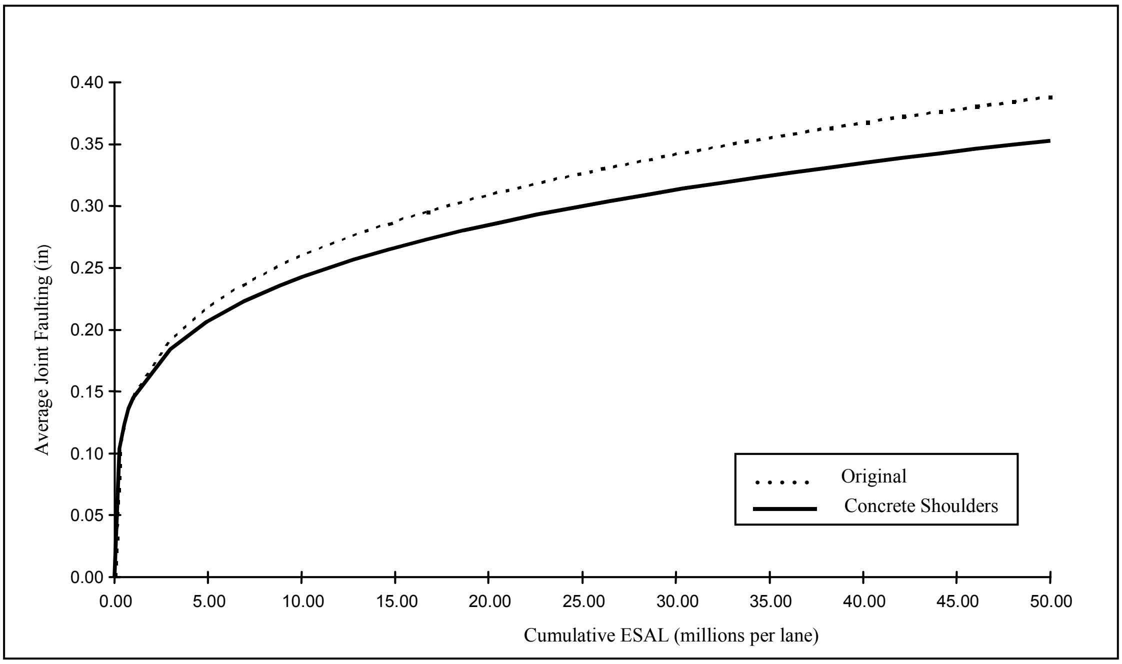

Figure D3.4 Retrofitting tied concrete shoulders effect on joint faulting in JP concrete pavements without dowels

Figure D3. shows the effect of retrofitting tied concrete shoulders on faulting in JP concrete pavements with dowels.

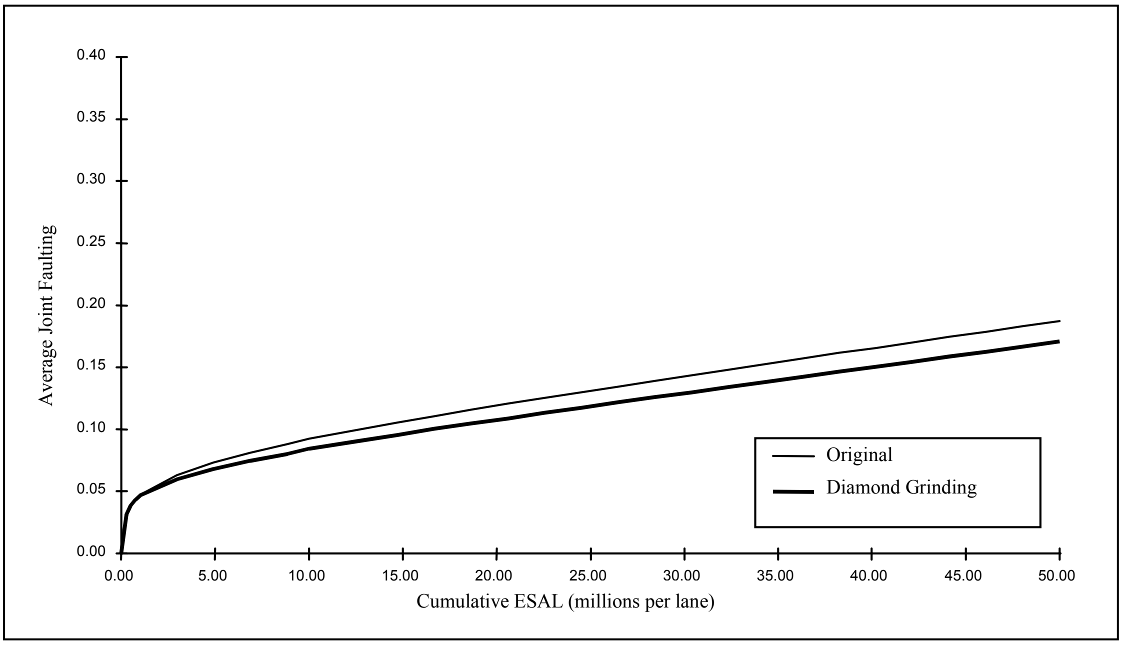

Figure D3.5 Retrofitting tied concrete shoulders effect on joint faulting in JP concrete pavements with dowels

4.3 Longitudinal edge drains retrofit

This refers to the technique used to add longitudinal drains (or lateral drains) to an existing pavement system to aid in the rapid removal of water from the system.

Retrofitting longitudinal edge drains can be scheduled at a fixed point in time defined by the calendar year.

Quantities and costs

If performed, the road section length gives the amount of works, as follows:

$$RED = L \qquad ...(4.3)$$

where:

RED amount of tied concrete shoulders retrofitted (km)

L road section length (km)

The total cost of retrofitting longitudinal edge drains is computed by multiplying RED by the user-specified unit cost per kilometre.

The effects

Since many pavement distresses can be attributed to water, removing it decreases the opportunity for deterioration and increases the pavement's life.

After retrofitting longitudinal edge drains, the parameter Cd (drainage coefficient) used in the equation for calculating faulting should be reset to the user-specified value. The maximum value of Cd is 1.25.

Figure D3. shows the effect of retrofitting longitudinal edge drains on faulting in JP concrete pavements without dowels.

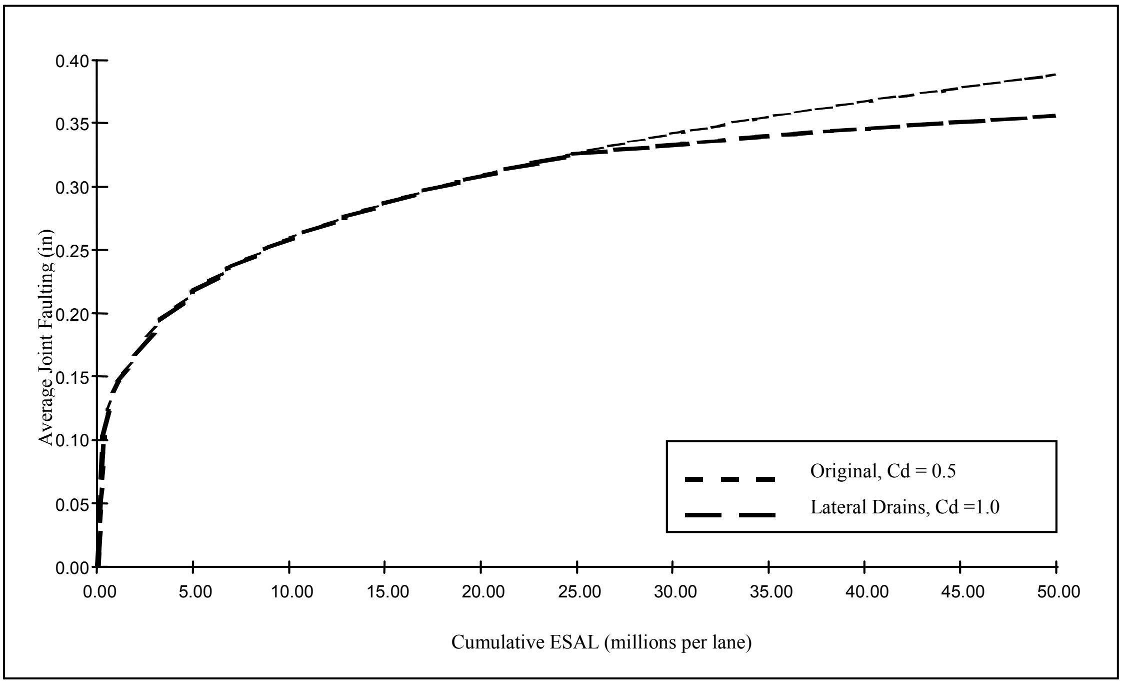

Figure D3.6 Lateral drains placement on joint faulting in JP concrete pavements without dowels

Figure D3. shows the effect of retrofitting longitudinal edge drains on faulting in JP concrete pavements with dowels.

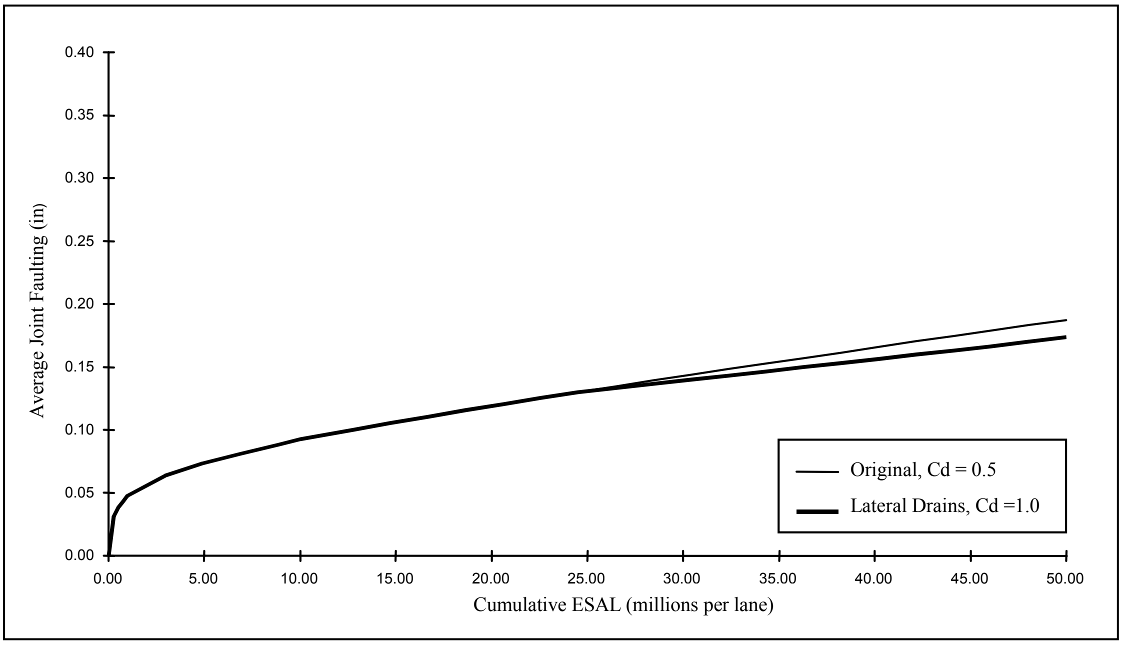

Figure D3.7 Lateral drains placement effect on joint faulting in JP concrete pavements with dowels

4.4 Joint sealing

Joint sealing is applied to minimise infiltration of surface water and incompressible material into the joint system. Minimising the amount of water in and under a pavement reduces the potential for subgrade softening, pumping, and erosion of the subgrade/sub-base fines. Minimising the amount of incompressible material reduces the potential for spalling and blow-ups.

Joint sealing works can be defined in one of the following ways:

- **Option 1: Scheduled**

  Joint sealing is applied at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive seals is specified, and the joint sealing is applied in an analysis year *t* defined as follows:

$$t = \text{interval} + \text{tprev} \qquad ...(4.4)$$

$$\text{tprev} = \max(\text{tstart}, \text{tlast}) - \text{tstart} \qquad ...(4.5)$$

where:

t	analysis year, defined relative to the start year of the analysis period
interval	a fixed interval between successive joint sealings (years)
tprev	number of years since last joint sealing or start year of analysis period

tstart	start year of analysis period, defined by calendar year
tlast	last year in which joint sealing was applied, defined by calendar year

Quantities and costs

If performed, the amount of joint sealing is calculated as follows:

$$LJSL = \frac{5280 * CW}{1.6093 * JTSPACE} + (1000 * NLNGJTS) \qquad ...(4.6)$$

where:

LJSL	amount of joint sealing (m/km)
CW	carriageway width (m)
NLNGJTS	number of longitudinal joints
JTSPACE	average transverse joint spacing (ft)

The product of LJSL and the section length (L) in kilometres gives the total length of joints sealed (TLJSL) in metres. The total cost of joint sealing is computed by multiplying TLJSL by the user-specified unit cost per metre length.

The effects

Joint sealing has an effect only on the progression of spalling. This effect is modelled through the parameters AGE and seal type used in the spalling equation. Following joint sealing, the seal type will be reset to the user-specified type and AGE will be reset to zero.

Figure D3. shows the effect of joint sealing on spalling in JP concrete pavements without dowels.

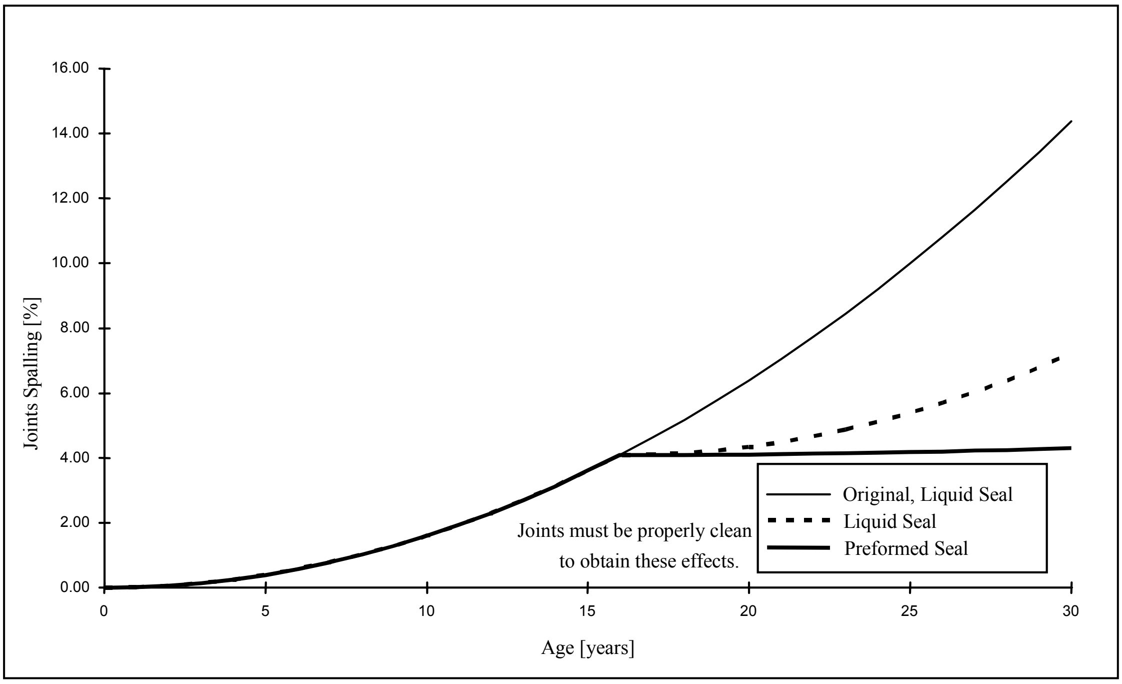

Figure D3.8 Joint sealing effect on joint spalling in JP concrete pavements

Figure D3. shows the effect of joint sealing on spalling in JR concrete pavements.

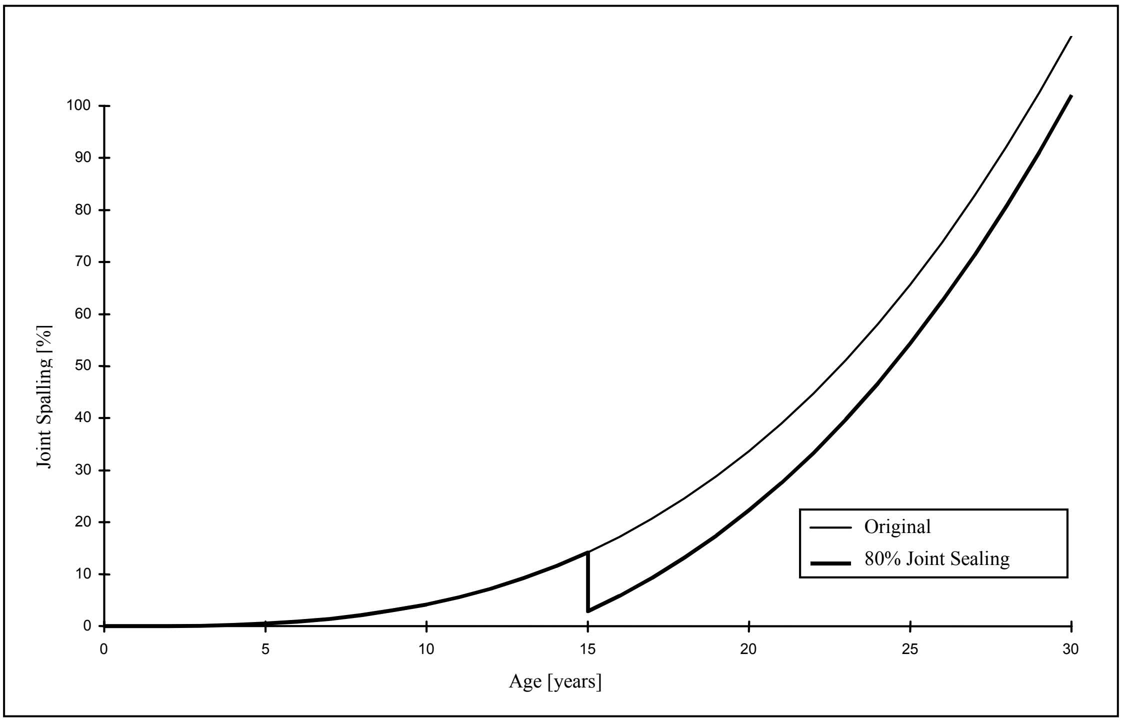

Figure D3.9 Joint sealing effect on joint spalling in JR concrete pavements

5 Restoration works

The following four generic types of restoration works are modelled:

1 **Slab replacement**

2 **Full depth repair**

3 **Partial depth repair**

4 **Diamond grinding**

5.1 Slab replacement

Slabs that are extensively and severely damaged need to be replaced. This works activity normally involves slab stabilisation to restore support to concrete slabs by filling small voids that develop underneath the slab at joints, cracks, or the pavement edge. These voids (not much deeper than 3 mm) are usually caused by pumping, consolidation, and subgrade failure due to high deflections at the joints, cracks, and pavement edge.

Slab replacement works can be defined in one of the following ways:

- **Option 1: Scheduled**

  A slab replacement works is performed at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive slab replacement works is specified, and the slab replacement works is applied in an analysis year t defined by Equations 4.4 above and 4.5 above.

- **Option 3: Condition - Responsive**

  Slab replacement is performed when the level of pavement defect (cracking) exceeds the user-specified value.

In all cases, slab replacement will not be performed if the user-specified last applicable year or maximum applicable roughness has been exceeded.

A slab replacement works will be specified using the percentage of damaged slabs to be replaced.

Quantities and costs

If performed, the amount of slab replacement works is calculated as follows:

$$SLB = \frac{0.3048 * JTSPACE * CW * REPSLBS}{1.6093 * (NLNGJTS + 1)} \quad \text{...(5.1)}$$

$$REPSLBS = \frac{PCRACK * PCTREP * NTSLBS}{(100 * 100)} \quad \text{...(5.2)}$$

$$NTSLBS = \frac{5280 * (NLNGJTS + 1)}{JTSPACE} \quad \text{...(5.3)}$$

where:

SLB	slab replacement area (m^2/km)
JTSPACE	average transverse joint spacing (ft)
CW	carriageway width (m)
REPSLBS	number of replaced slabs per mile
PCRACK	percent of slabs cracked
PCTREP	percent of cracked slabs to be replaced, input by the user
NTSLBS	number of slabs per mile
NLNGJTS	number of longitudinal joints

The product of SLB and the section length (L) in kilometres gives the total slab replacement area (TSLB) in square metres. The total cost of slab replacement is computed by multiplying TSLB by the user-specified unit cost per square metre.

The effects

The immediate effects of slab replacement on cracking, spalling and faulting are computed as described below. The long-term effect on pavement distress progression is modelled by applying weighting factors based on the proportions of the new and old slabs.

Cracking

The amount of cracking remaining after works is given by:

$$PCRACK_{aw} = \frac{100 * (CRKSLBS - REPSLBS)}{NTSLBS} \qquad ...(5.4)$$

where:

$PCRACK_{aw}$	percent of cracked slabs remaining after works
CRKSLBS	number of cracked slabs per mile
REPSLBS	number of replaced slabs per mile
NTSLBS	number of slabs per mile

The number of cracked slabs before works is given by:

$$CRKSLBS = \frac{PCRACK_{bw} * NTSLBS}{100} \qquad ...(5.5)$$

where:

CRKSLBS	number of cracked slabs per mile
$PCRACK_{bw}$	percent of cracked slabs before works

NTSLBS number of slabs per mile

Figure D3. shows the effect of slab replacement on cracking in JP concrete pavements without dowels.

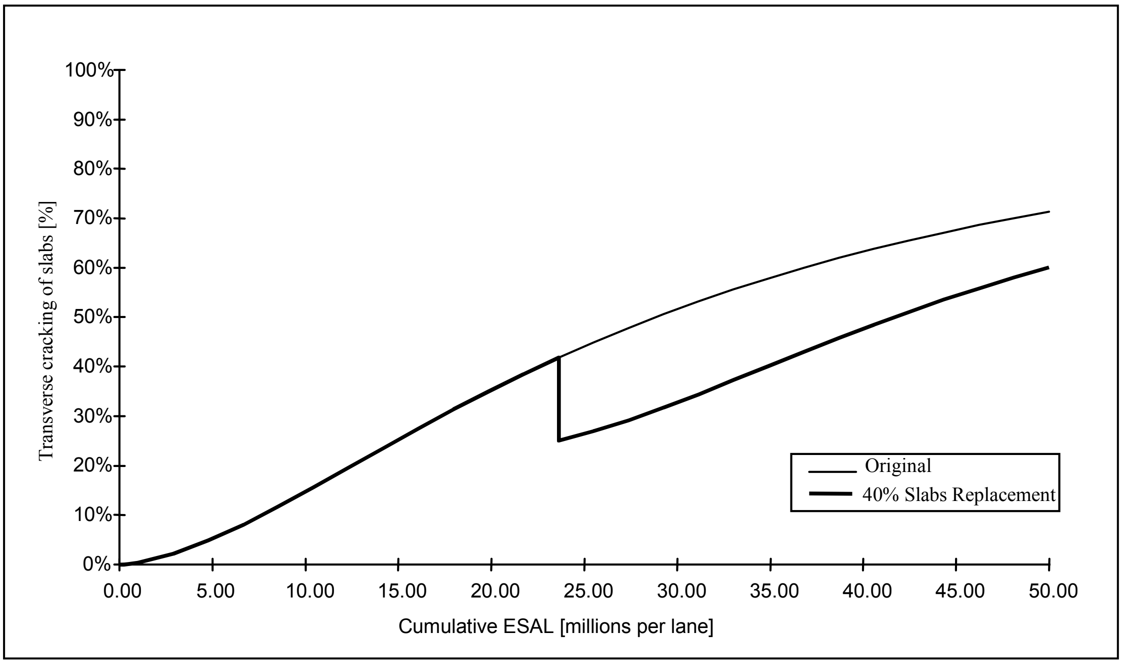

Figure D3.10 Slab replacement effect on transverse cracking of slabs in JP concrete pavements

Spalling

The amount of spalling remaining after works is given by:

$$SPALL_{aw} = \frac{SPALL_{bw} * (NTSLBS - REPSLBS)}{NTSLBS} \quad ...(5.6)$$

where:

$SPALL_{aw}$ percentage of spalled transverse joints remaining after works

$SPALL_{bw}$ percentage of spalled transverse joints before works

NTSLBS number of slabs per mile

REPSLBS number of replaced slabs per mile

Faulting

The amount of faulting remaining after works is given by:

$$FAULT_{aw} = \frac{FAULT_{bw} * (NTSLBS - REPSLBS)}{NTSLBS} \quad ...(5.7)$$

where:

$FAULT_{aw}$	average transverse joint faulting after works (inches)
$FAULT_{bw}$	average transverse joint faulting before works (inches)
NTSLBS	number of slabs per mile
REPSLBS	number of replaced slabs per mile

Figure D3.4 shows the effect of slab replacement on faulting in JP concrete pavements without dowels.

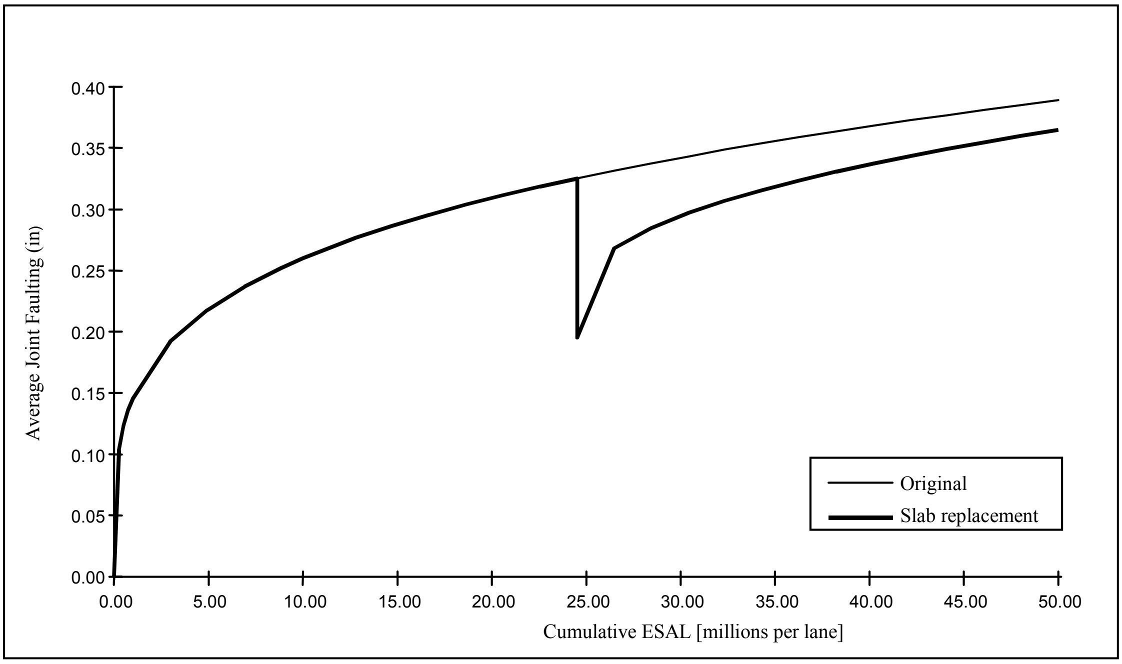

Figure D3.4 Slab replacement effect on joint faulting in JP concrete pavements without dowels

Figure D3.5 shows the effect of slab replacement on faulting in JP concrete pavements with dowels.

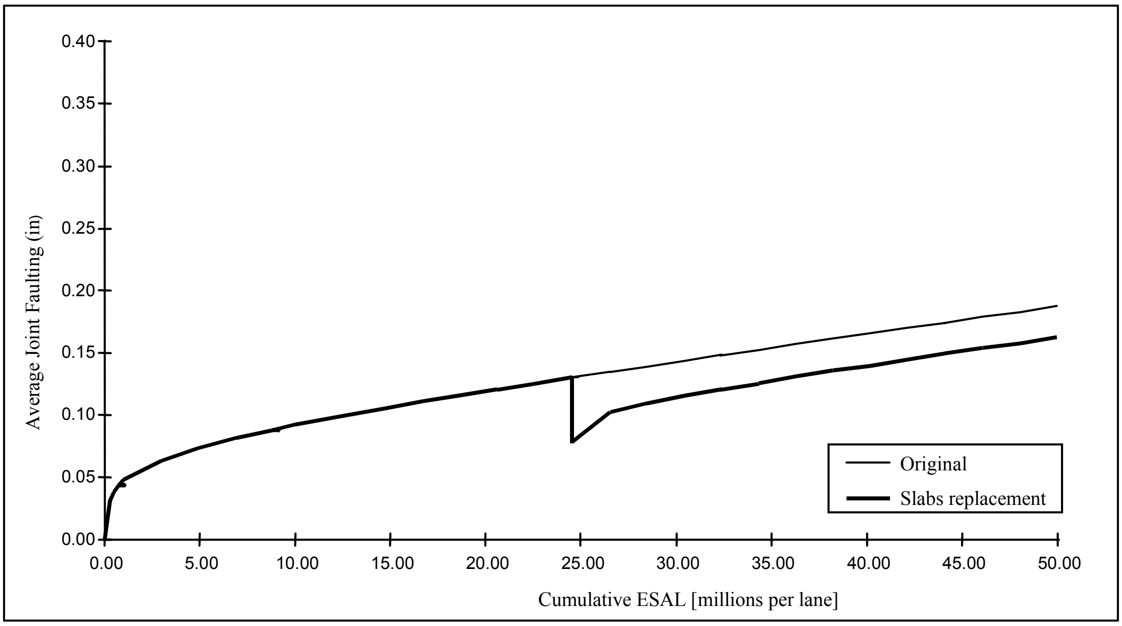

Figure D3.5 Slab replacement effect on joint faulting in JP concrete pavements with dowels

5.2 Full depth repairs

This technique is most often used on JR concrete pavements to repair joint deterioration that extends more than one third of the slab depth. It consists of removing and replacing a portion of the existing slab from the top right up to the bottom. Joint deterioration includes cracking, breaking and spalling of slab edges on either side of a transverse or longitudinal joint or crack. Full depth repairs are also applied to repair shattered slabs and punchouts in CR concrete pavements.

Full depth repair can be defined in one of the following ways:

- **Option 1: Scheduled**

  A full depth repair works is performed at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive full depth repair works is specified, and the full depth repair is applied in an analysis year t defined by Equations 4.4 above and 4.5 above.

- **Option 3: Condition - Responsive**

  Full depth repair is performed when the level of pavement defects (cracking, spalling and failures) exceeds the user-specified values.

In all cases, full depth repair will not be performed if the user-specified last applicable year or maximum applicable roughness has been exceeded.

The amounts of works and effects of full depth repair are calculated depending on the pavement surface type, as described below.

5.2.1 JR concrete pavements

Quantities and costs

The amount of full depth repairs on JR concrete pavements is computed as follows:

$$FDR = \frac{(CKAREA + SPAREA)}{1.6093} \qquad ...(5.8)$$

where:

FDR	area of full depth repair (m^2/km)
CRAREA	area of deteriorated transverse cracks repaired (m^2)
SPAREA	area of spalling repaired (m^2)

The area of deteriorated transverse cracks repaired is given by:

$$CRAREA = \frac{CW * PCTCKS * DCRACK_{bw} * 2 * CKWDTH}{100} \qquad ...(5.9)$$

where:

CRAREA	area of deteriorated transverse cracks repaired (m^2)
CW	carriageway width (m)
PCTCKS	percentage of deteriorated transverse cracks to be repaired, input by the user
$DCRACK_{bw}$	number of deteriorated transverse cracks per mile before works
CKWDTH	width considered on each side of a deteriorated transverse crack (m)

The area of spalling repaired is given by:

$$SPAREA = \frac{CW * PCTSPL * SPALL_{bw} * NJTS * 2 * JTWDTH}{100 * 100} \qquad ...(5.10)$$

where:

SPAREA	area of spalling repaired (m^2)
CW	carriageway width (m)
PCTSPL	percentage of spalled transverse joints to be repaired, input by the user
$SPALL_{bw}$	percentage of spalled transverse joints before works
NJTS	number of transverse joints per mile
JTWDTH	width considered on each side of a transverse joint (m)

The number of transverse joints per mile (NJTS) is given by:

$$NJTS = \frac{1.5 * 5280}{JTSPACE} \quad ...(5.11)$$

where:

NJTS	number of transverse joints per mile
JTSPACE	average spacing of transverse joints (ft)

The product of FDR and the section length (L) in kilometres gives the total area of full depth repair (TFDR) in square metres. The total cost of full depth repair is computed by multiplying TFDR by the user-specified unit cost per square metre.

The effects

Following full depth repair, pavement defects will be reduced as detailed below.

- **Cracking**

  The amount of cracking remaining after works is given by:

$$DCRACK_{aw} = \left(1 - \frac{PCTCKS}{100}\right) * DCRACK_{bw} \quad ...(5.12)$$

  where:

$DCRACK_{aw}$	number of deteriorated transverse cracks per mile remaining after works
PCTCKS	percentage of deteriorated transverse cracks to be repaired, input by the user
$DCRACK_{bw}$	number of deteriorated transverse cracks per mile before works

  Figure D3.6 shows the effect of full depth repair on cracking in JR concrete pavements.

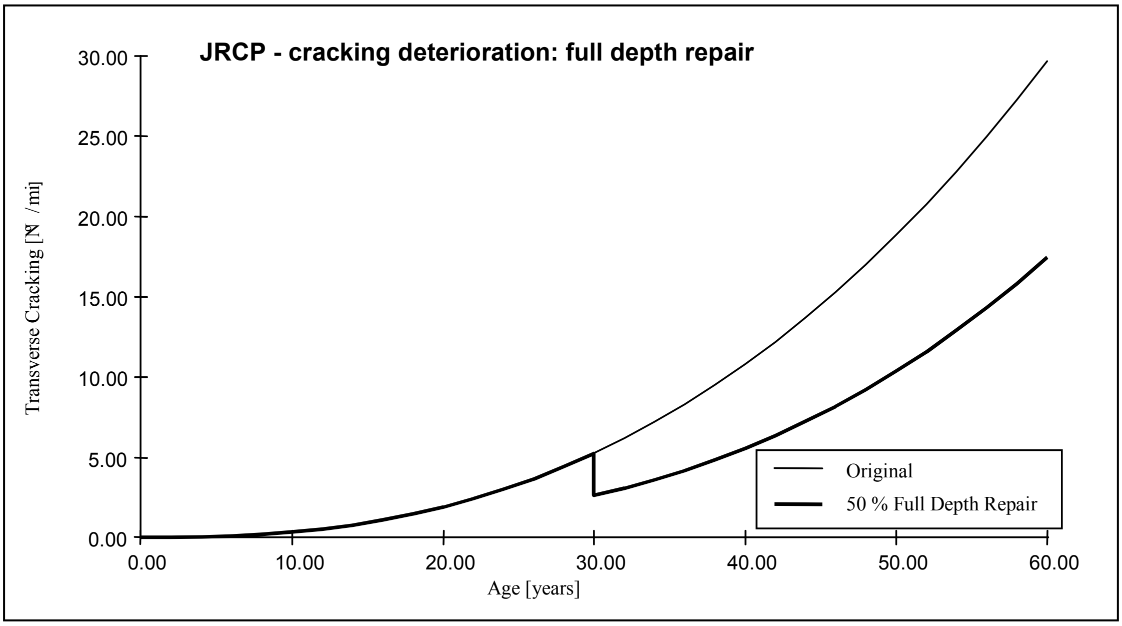

Figure D3.6 Full depth repair effect on deteriorated transverse cracking in JR concrete pavements

- **Spalling**

The amount of spalling remaining after works is given by:

$$SPALL_{aw} = \left(1 - \frac{PCTSPL}{100}\right) * SPALL_{bw} \qquad ...(5.13)$$

where:

$SPALL_{aw}$	percentage of spalled transverse joints remaining after works
PCTSPL	percentage of spalled transverse joints to be repaired, input by the user
$SPALL_{bw}$	percentage of spalled transverse joints before works

Figure D3.7 shows the effect of full depth repair on spalling in JR concrete pavements.

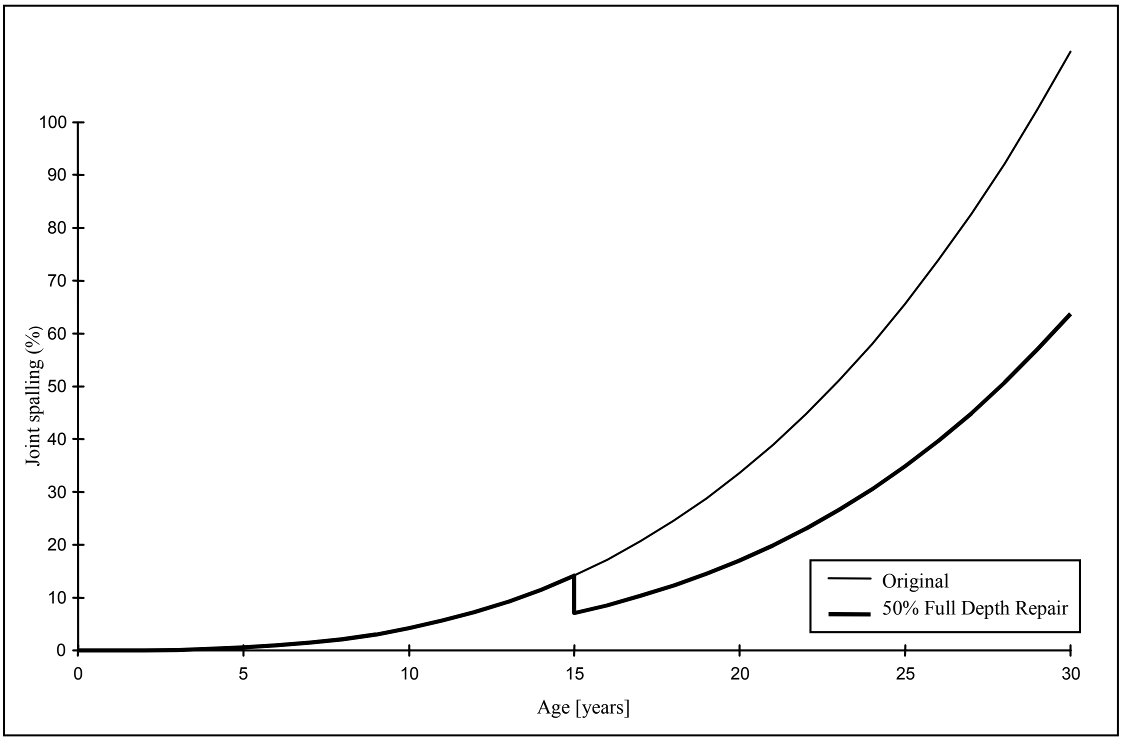

Figure D3.7 Full depth repair effect on joint spalling in JR concrete pavements

- **Faulting**

The amount of faulting remaining after works is given by:

$$FAULT_{aw} = \frac{FAULT_{bw} * (NJTS - REPJTS)}{NJTS} \qquad ...(5.14)$$

where:

$FAULT_{aw}$	average transverse joint faulting after works (inches)
$FAULT_{bw}$	average transverse joint faulting before works (inches)
NJTS	number of transverse joints per mile
REPJTS	number of repaired transverse joints per mile

The number of repaired transverse joints is given by:

$$REPJTS = \frac{PCTSPL * SPALL_{bw} * NJTS}{100} \qquad ...(5.15)$$

where:

REPJTS	number of repaired transverse joints per mile
PCTSPL	percentage of spalled transverse joints to be repaired, input by the user
$SPALL_{bw}$	percentage of spalled transverse joints before works (%)

NJTS Number of transverse joints per mile

Figure D3.8 shows the effect of full depth repair on faulting in JR concrete pavements.

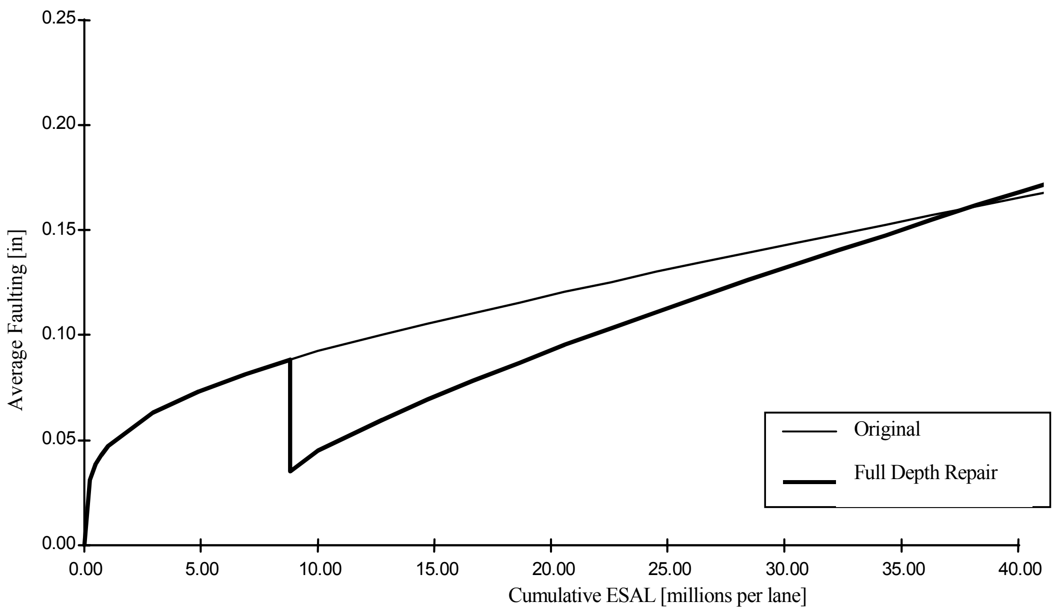

Figure D3.8 Full depth repair effect on faulting in JR concrete pavements

5.2.2 CR concrete pavements

Quantities and costs

The amount of full depth repairs on CR concrete pavements is computed as follows:

$$FDR = \frac{PCTFAIL * FAIL_{bw} * FRESA}{1.6093 * 100} \quad ...(5.16)$$

where:

FDR	area of full depth repair (m^2/km)
PCTFAIL	Percentage of failures to be repaired, input by the user
$FAIL_{bw}$	Number of failures per mile before works
FRESA	Average restoration area of each failure (m^2)

The product of FDR and the section length (L) in kilometres gives the total area of full depth repair (TFDR) in square metres. The total cost of full depth repair is computed by multiplying TFDR by the user-specified unit cost per square metre.

The effects

Following full depth repair, pavement defects will be reduced as follows:

- **Failures**

  The amount of failures remaining after works is given by:

$$FAIL_{aw} = \left(1 - \frac{PCTFAIL}{100}\right) * FAIL_{bw} \qquad ...(5.17)$$

where:

$FAIL_{aw}$	number of failures per mile remaining after works
PCTFAIL	percentage of failures to be repaired, input by the user
$FAIL_{bw}$	number of failures per mile before works

Figure D3.9 shows the effect of full depth repair on failures in CR concrete pavements.

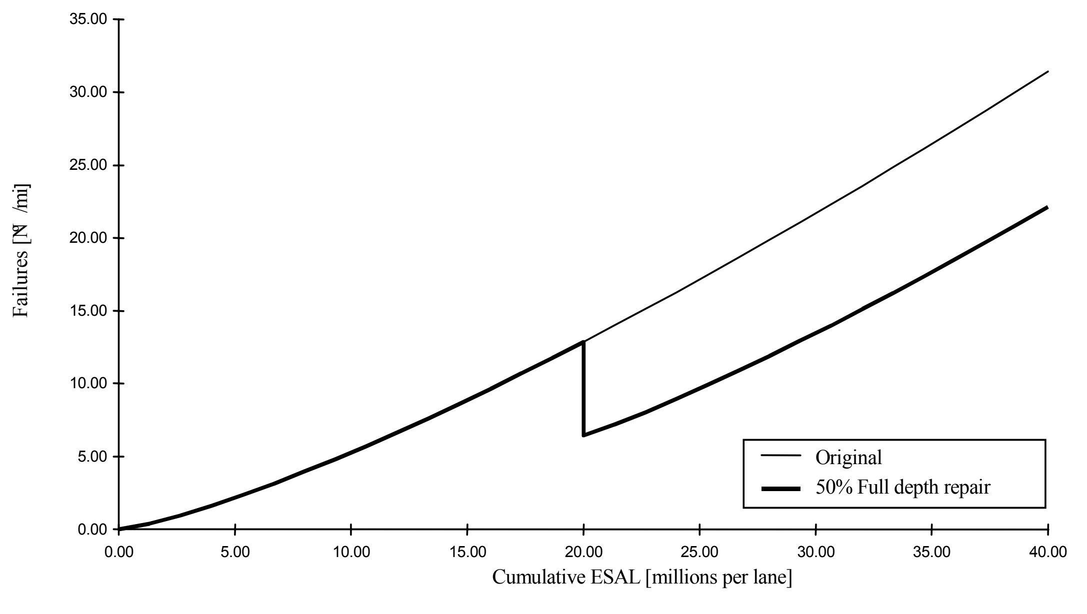

Figure D3.9 Full depth repair effect on failures in CR concrete pavements

5.3 Partial depth repairs

This technique is used on JP concrete pavements to repair surface deterioration in the top one third of the slab. If the deterioration extends deeper than one third of the slab depth, the slab should be replaced. Generally partial depth repairs are performed at transverse joints, however they may also be applied anywhere in the slab where surface defects occur.

Partial depth repair can be defined in one of the following ways:

- **Option 1: Scheduled**

  A partial depth repair works is performed at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive partial depth repair works is specified, and the partial depth repair is applied in an analysis year *t* defined by Equations 4.4 above and 4.5 above.

- **Option 3: Condition - Responsive**

  Partial depth repair is performed when the level of pavement defect (cracking) exceeds the user-specified value.

In all cases, resealing will not be performed if the user-specified last applicable year or maximum applicable roughness has been exceeded.

Quantities and costs

If performed, the amount of works is calculated as follows:

$$PDR = \frac{0.6214 * CW * PREPJTS * SPALL_{bw} * NJTS}{100 * 100} \qquad ...(5.18)$$

where:

PDR	amount of partial depth repair (m/km)
CW	carriageway width (m)
PREPJTS	percentage of spalled transverse joints to be repaired, input by the user
$SPALL_{bw}$	percentage of spalled transverse joints before works
NJTS	number of transverse joints per mile

The product of PDR and the section length (L) in kilometres gives the total length of partial depth repair (TPDR) in metres. The total cost of partial depth repair is computed by multiplying TPDR by the user-specified unit cost per metre.

The effects

Following partial depth repair, spalling will be reduced as follows:

$$SPALL_{aw} = \left(1 - \frac{PREPJTS}{100}\right) * SPALL_{bw} \qquad ...(5.19)$$

where:

$SPALL_{aw}$	percentage of spalled transverse joints remaining after works
PREPJTS	percentage of spalled transverse joints to be repaired, input by the user
$SPALL_{bw}$	percentage of spalled transverse joints before works

Figure D3.10 shows the effect of partial depth repair on spalling in JP concrete pavements without dowels.

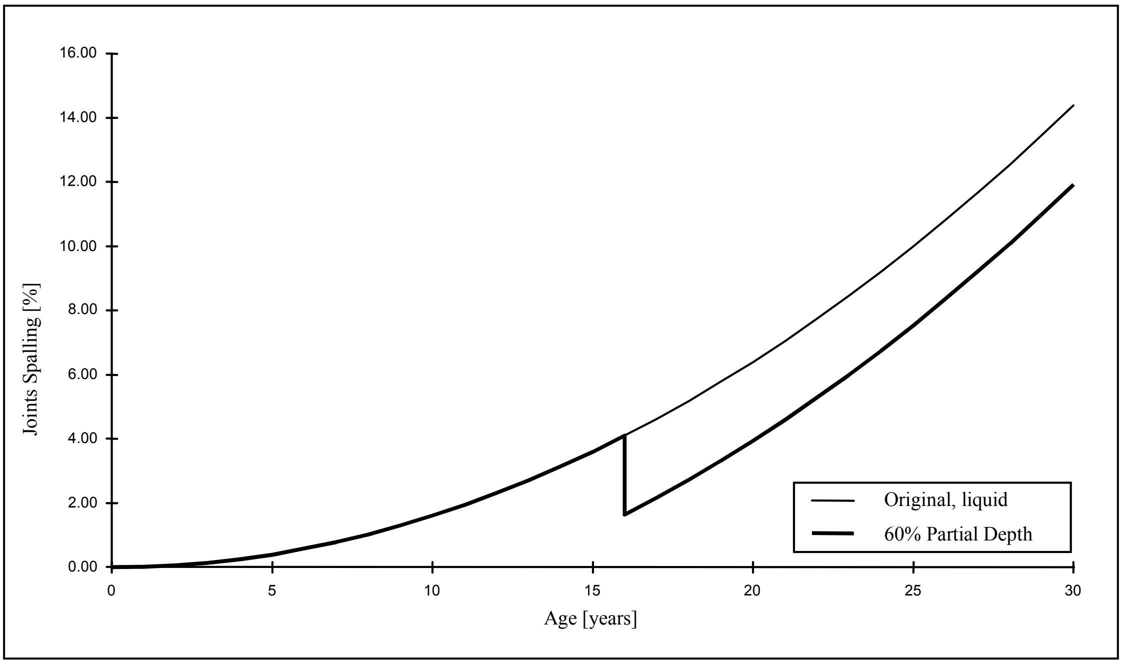

Figure D3.10 Partial depth repair effect on joint spalling in JP concrete pavements

5.4 Diamond grinding

Diamond grinding is used to restore or improve the rideability of a pavement by providing smooth level surface. It removes faulting at joints, slab warping, and surface deformations caused by studded tyres. Diamond grinding can also be used to correct inadequate slope for drainage and excessive surface polishing, and to increase surface friction by creating a roughened corduroy-like surface capable of draining water and reducing hydroplaning potential.

Diamond grinding works can be defined in one of the following ways:

- **Option 1: Scheduled**

  Diamond grinding is performed at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive diamond grinding is specified, and the grinding works is performed in an analysis year *t* defined by Equations 4.4 above and 4.5 above.

- **Option 3: Condition - Responsive**

  Diamond grinding is performed when the level of pavement defect (faulting and roughness) exceeds the user-specified values.

In all cases, diamond grinding will not be performed if the user-specified last applicable year or maximum applicable roughness has been exceeded.

Quantities and costs

If performed, the amount of diamond grinding works is calculated as follows:

$$DGR = 1000 * CW \qquad ...(5.20)$$

where:

DGR	diamond grinding area (m^2/km)
CW	carriageway width (m)

The product of DGR and the section length (L) in kilometres gives the total area of diamond grinding (TDGR) in square metres. The total cost of diamond grinding is computed by multiplying TDGR by the user-specified unit cost per square metre.

The effects

It is considered that the first application of diamond grinding will not reduce slab thickness. However, when performed for the second (or more time) diamond grinding will reduce the slab thickness as follows:

$$SLABTHK_{aw} = SLABTHK_{bw} - GRIND \qquad ...(5.21)$$

where:

$SLABTHK_{aw}$	slab thickness after diamond grinding (mm)
$SLABTHK_{bw}$	slab thickness before diamond grinding (mm)
GRIND	depth of grinding (mm)

Diamond grinding will remove all faulting, that is, faulting is reset to zero and thereafter the pavement distress modes will be modelled using the reduced slab thickness.

Roughness after diamond grinding will be computed using the Phase 1 model based on the amounts of distresses remaining.

Figure D3.11 shows the effect of diamond grinding on faulting in JP concrete pavements without dowels.

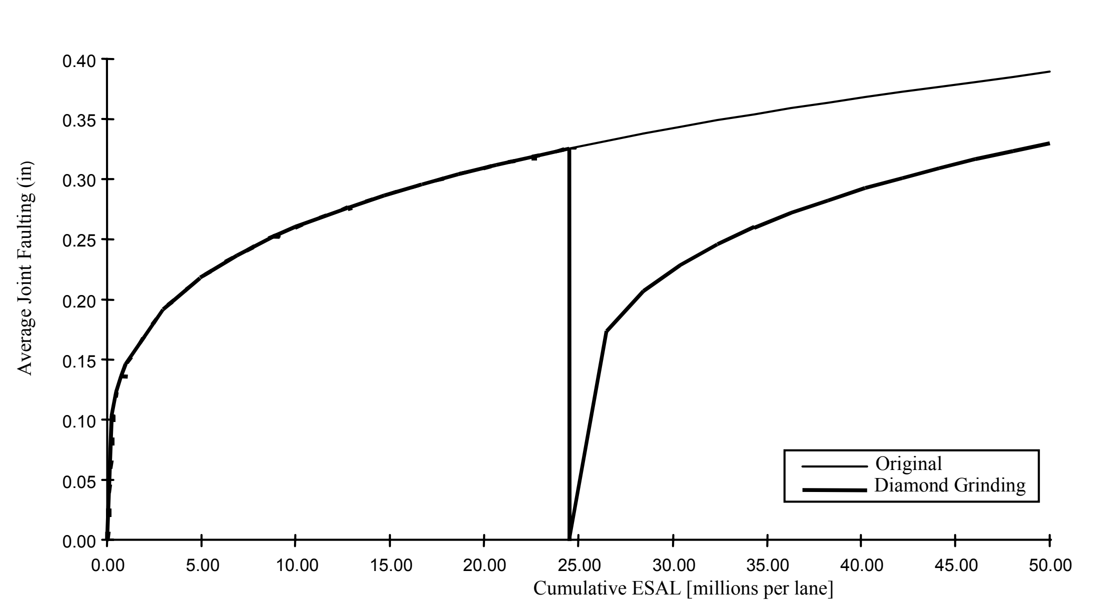

Figure D3.11 Diamond grinding effect on joint faulting in JP concrete pavements without dowels

Figure D3.12 shows the effect of diamond grinding on faulting in JP concrete pavements with dowels.

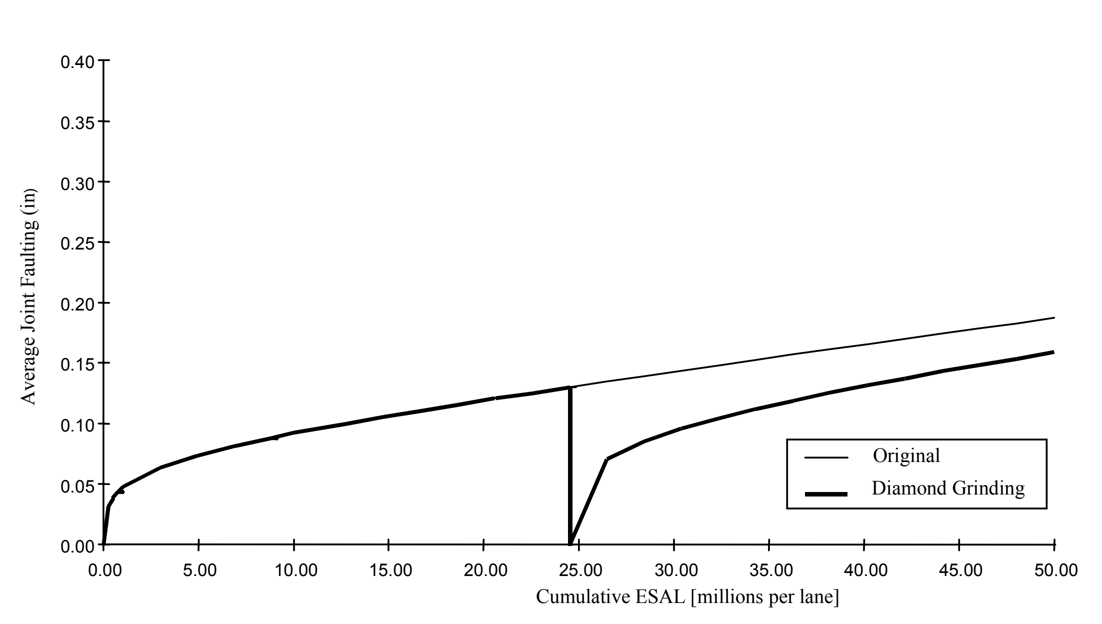

Figure D3.12 Diamond grinding effect on joint faulting in JP concrete pavements with dowels

6 Rehabilitation

A concrete pavement may require a new surfacing layer either because the riding quality has become unacceptable or for structural strengthening. There are two basic types of concrete overlays on existing concrete pavements that are modelled in HDM-4 under rehabilitation works:

- **Bonded concrete overlays**
- **Unbonded concrete overlays**

6.1 Bonded concrete overlays

The techniques used for constructing bonded concrete overlays ensure that the new concrete overlay adheres to the existing concrete. Bonded overlays increase the structural capacity of the existing pavement by creating a thicker monolithic section. The thickness of bonded overlays depends primarily on the condition of the existing pavement, the traffic level and the required life. Typically, unbonded concrete overlays are less than 100 mm thick. Due to their monolithic nature, the underlying concrete is the main load carrying section of the pavement structure and therefore it must be in good condition to carry the traffic load. Bonded overlays can also be used to improve the skid resistance of an existing pavement.

A bonded concrete overlay works can be defined in one of the following manners:

- **Option 1: Scheduled**

  A bonded concrete overlay of fixed specifications is applied at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive bonded concrete overlay is specified, and the overlay is performed in an analysis year t defined by Equations 4.4 above and 4.5 above.

- **Option 3: Condition - Responsive**

  Bonded concrete overlay is performed when the level of pavement defect (cracking, failures and/or roughness) exceeds the user-specified values.

In all cases, bonded concrete overlay will not be performed if the user-specified last applicable year or maximum applicable roughness has been exceeded.

6.1.1 JP concrete pavements

Quantities and costs

If bonded concrete overlay is performed on a JP concrete pavement, the amount of works is calculated as follows:

$$BOL = 1000 * CW \qquad ...(6.1)$$

where:

BOL	bonded concrete overlay area (m^2/km)
CW	carriageway width (m)

Before concrete overlay is applied, it is often necessary to carry out some **preparatory works.** For JP concrete pavements, this is equal to the amount of slab replacement to be performed (SLB), computed using Equations 5.1 above to 5.3 above.

The total amount of bonded concrete overlay (TBOL) in square metres is obtained from the product of BOL and the section length (L) in kilometres. The total cost of bonded concrete overlay is obtained by multiplying TBOL by the user-specified unit cost per square metre. The additional areas and cost of preparatory works will be reported separately under slab replacement.

The effects

The pavement type after bonded concrete overlay will not change. The seal type for JP concrete pavements will be changed to the user-specified type.

- **Slab thickness**

  Bonded concrete overlay will reset the concrete slab thickness as follows:

$$SLABTHK_{aw} = SLBATHK_{bw} + OVLTHK \qquad ...(6.2)$$

where:

$SLABTHK_{aw}$	slab thickness after bonded concrete overlay (mm)
$SLABTHK_{bw}$	slab thickness before bonded concrete overlay (mm)
OVLTHK	thickness of bonded concrete overlay (mm)

- **Cracking**

  The amount of cracking remaining after bonded concrete overlay works is computed using Equation 5.4 above. Thereafter, cracking progression is predicted using the Phase 1 RD model with the new slab thickness ($SLABTHK_{aw}$) and the new values of the maximum permissible number of equivalent standard axle load repetitions during each temperature gradient (N_{tg}). The cumulative fatigue damage (FD) is maintained and used in the calculation of the new N_{tg} values (see Section 4 of Chapter C3).

  Figure D3.13 shows the effect of bonded concrete overlay on cracking in JP concrete pavements.

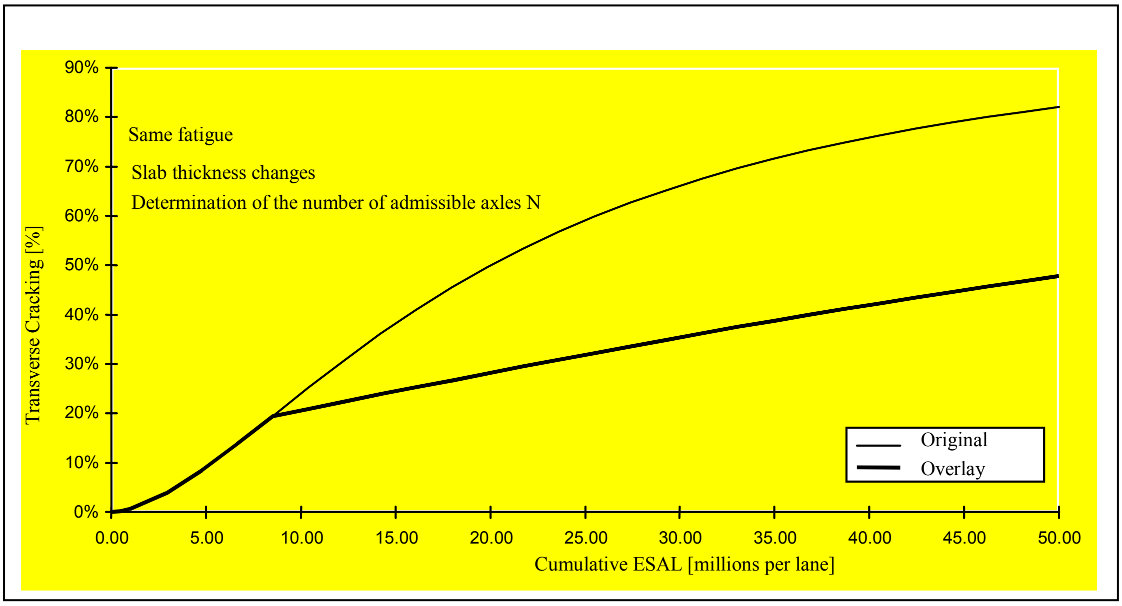

Figure D3.13 Bonded concrete overlay effect on cracking in JP concrete pavements

- **Faulting**

Faulting after bonded concrete overlay will be reset to zero. Thereafter, the progression of faulting will be computed using the Phase 1 RD model. The value of NE4 (cumulative traffic loading in equivalent standard axle loads) will be reset to zero.

Figure D3.14 shows the effect of bonded concrete overlay on faulting in JP concrete pavements without dowels.

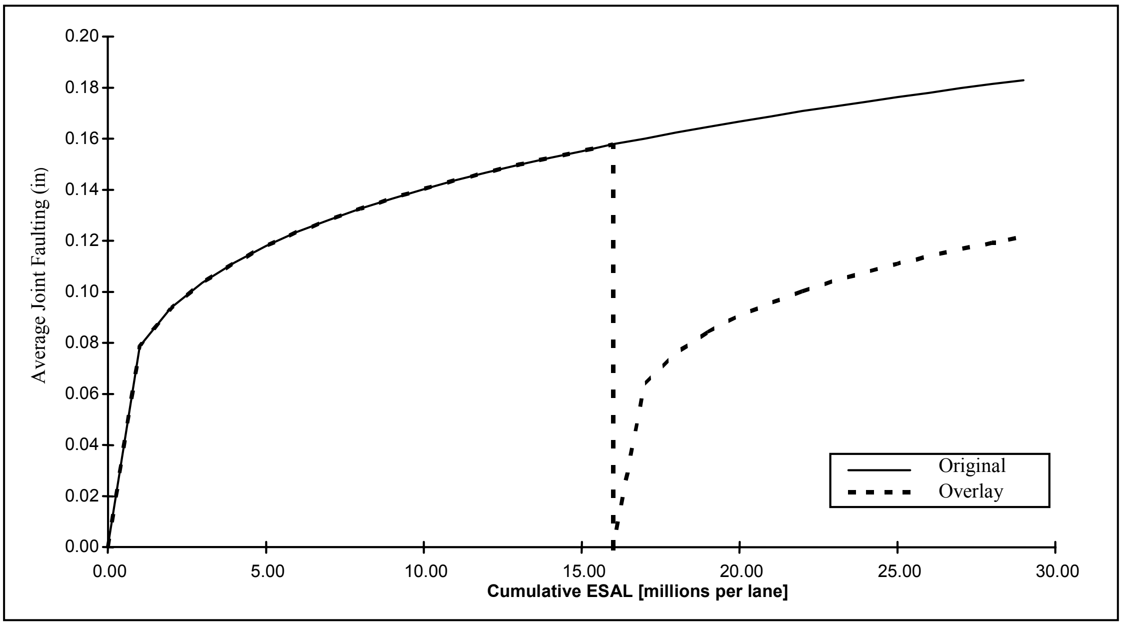

Figure D3.14 Bonded concrete overlay effect on joint faulting in JP concrete pavements without dowels

Figure D3.15 shows the effect of bonded concrete overlay on faulting in JP concrete pavements with dowels

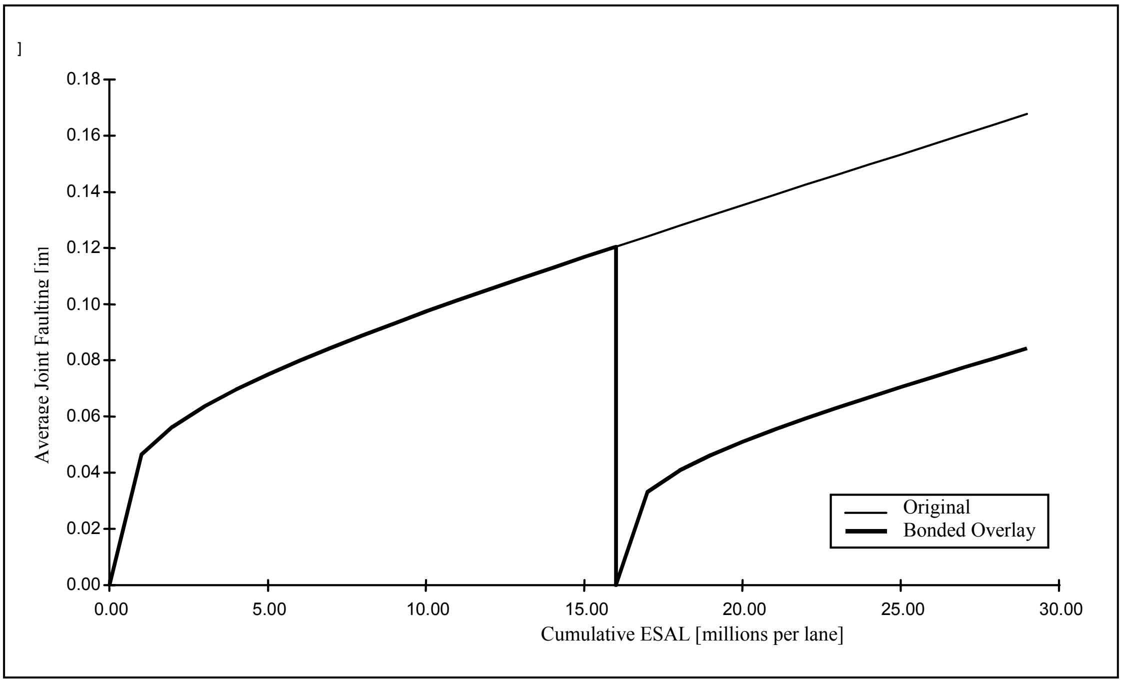

Figure D3.15 Bonded concrete overlay effect on faulting in JP concrete pavements with dowels

- **Spalling**

Spalling after bonded concrete overlay will be reset to zero. Thereafter, spalling progression will be computed using the Phase 1 RD model with the parameter pavement age (AGE) counted since the time of overlay.

Figure D3.16 shows the effect of bonded concrete overlay on spalling in JP concrete pavements with dowels.

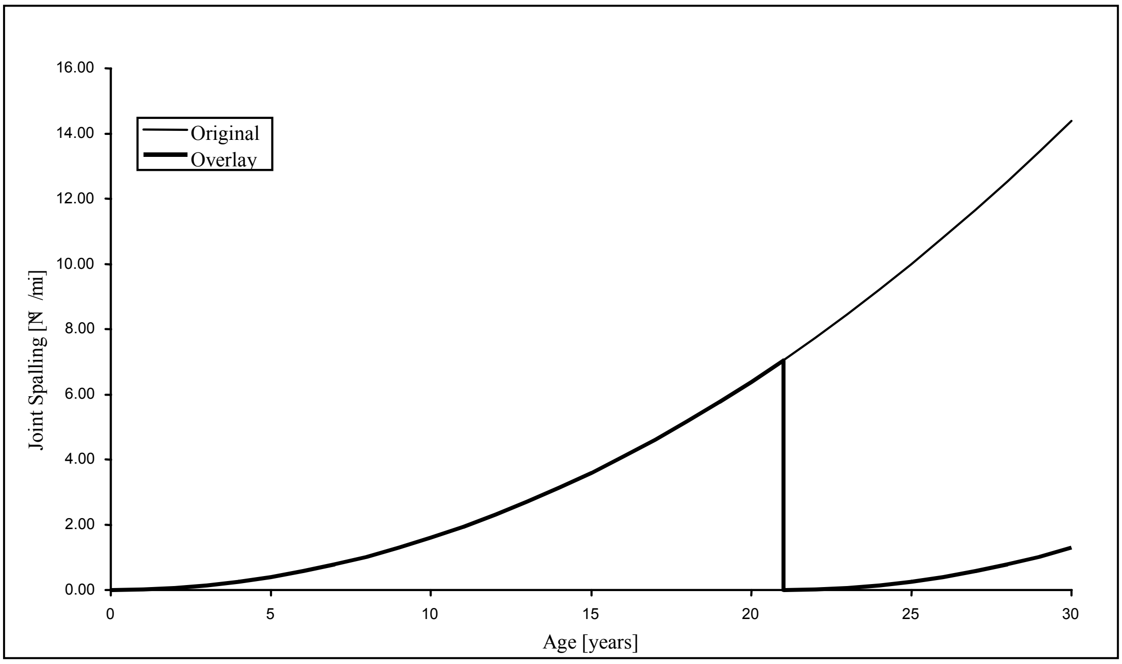

Figure D3.16 Bonded concrete overlay effect on joint spalling in JP concrete pavements with dowels

- **Roughness**

  Roughness after bonded concrete overlay will be reset to a new value, and its progression computed using the Phase 1 RD model based on the amounts of cracking, spalling, and faulting remaining.

6.1.2 JR concrete pavements

Quantities and costs

If bonded concrete overlay is performed on a JR concrete pavement, the amount of works (BOL), in square metres per kilometre, is calculated using Equation 6.1 above.

The amount of preparatory works required will be given by the amount full depth repair to be performed (FDR), which is computed using Equations 5.8 above and 5.11 above.

The total amount of bonded concrete overlay (TBOL) in square metres is obtained from the product of BOL and the section length (L) in kilometres. The total cost of bonded concrete overlay is obtained by multiplying TBOL by the user-specified unit cost per square metre. The additional areas and cost of preparatory works will be reported separately under full depth repair.

The effects

- **Slab thickness**

  The new slab thickness after works is calculated as follows:

$$SLABTHK_{aw} = SLABTHK_{adj} + OVLTHK \qquad ...(6.3)$$

where:

$SLABTHK_{aw}$	slab thickness after bonded concrete overlay (mm)
$SLABTHK_{adj}$	adjusted slab thickness to account for the effect of the remaining cracking (mm)
OVLTHK	thickness of bonded concrete overlay (mm)

- **Cracking**

  The adjusted slab thickness to account for the effect of the remaining cracking is given by:

$$SLABTHK_{adj} = SLABTHK_{bw} * \left[1 - 0.5 * \left(\frac{DCRACK_{aw}}{MAXCKS}\right)\right] \qquad ...(6.4)$$

where:

$SLABTHK_{adj}$	adjusted slab thickness to account for the effect of the remaining cracking (mm)
$SLABTHK_{bw}$	slab thickness before bonded concrete overlay (mm)
$DCRACK_{aw}$	number of deteriorated transverse cracks per mile remaining after bonded concrete overlay (mm)

MAXCKS maximum number of deteriorated transverse cracks per mile

The maximum number of deteriorated transverse cracks per mile (MAXCKS) is given by:

$$MAXCKS = \frac{3 * 5280}{JTSPACE} \qquad ...(6.5)$$

where:

MAXCKS maximum number of deteriorated transverse cracks per mile

JTSPACE average transverse joint spacing (ft)

If $DCRACK_{aw}$ is greater than MAXCKS, then set $DCRACK_{aw}$ to be equal to MAXCKS.

The amount of cracking remaining after works is computed using Equation 5.12 above. Thereafter, cracking progression is computed using the Phase 1 RD model with the new slab thickness ($SLABTHK_{aw}$) and new pavement age (AGE) counted since performing the concrete overlay.

Figure D3.17 shows the effect of bonded concrete overlay on cracking in JR concrete pavements.

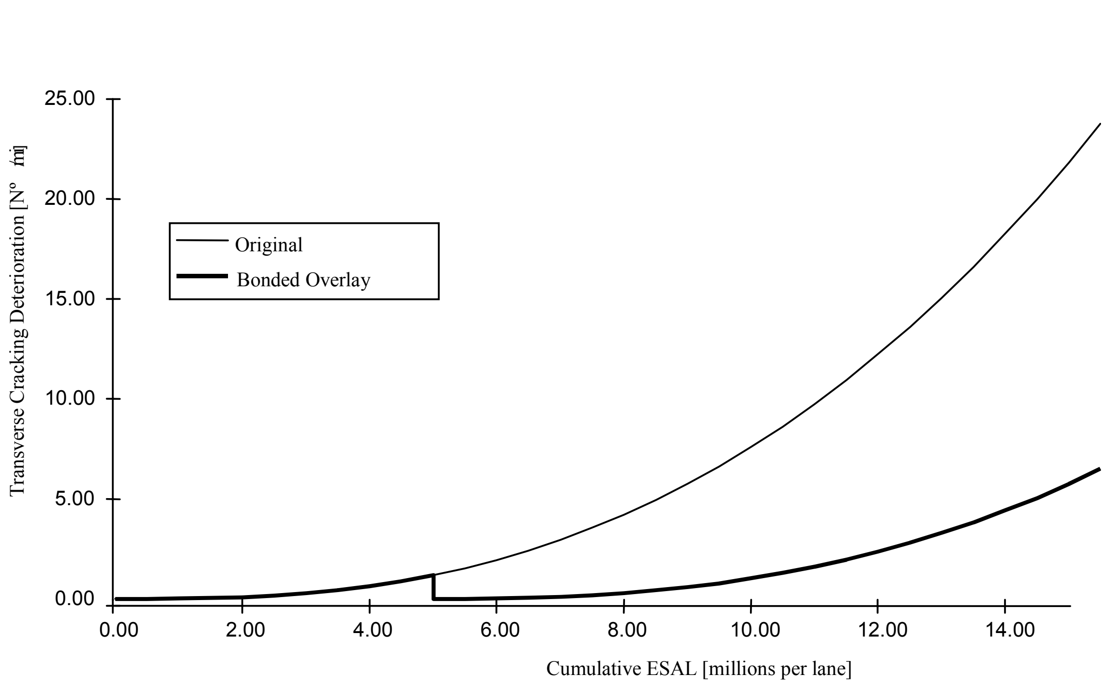

Figure D3.17 Bonded concrete overlay effect on cracking in JR concrete pavements

- **Faulting**

Faulting will be reset to zero. Thereafter the progression of faulting will be computed using the Phase 1 RD model. The value of NE4 (cumulative traffic loading in equivalent standard axle loads) will be reset to zero.

Figure D3.18 shows the effect of bonded concrete overlay on faulting in JR concrete pavements.

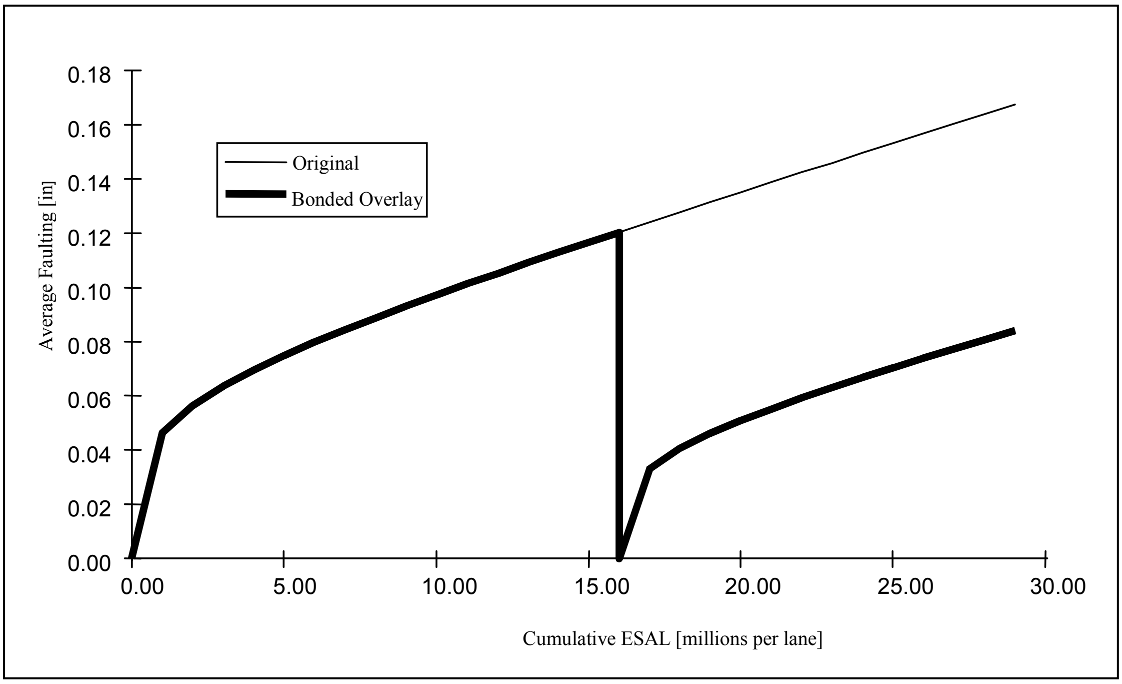

Figure D3.18 Bonded concrete overlay effect on faulting in JR concrete pavements

- **Spalling**

Spalling after bonded concrete overlay will be reset to zero. Thereafter spalling progression will be computed using the Phase 1 RD model with the parameter pavement age (AGE) counted since the time of overlay.

Figure D3.19 shows the effect of bonded concrete overlay on spalling in JR concrete pavements.

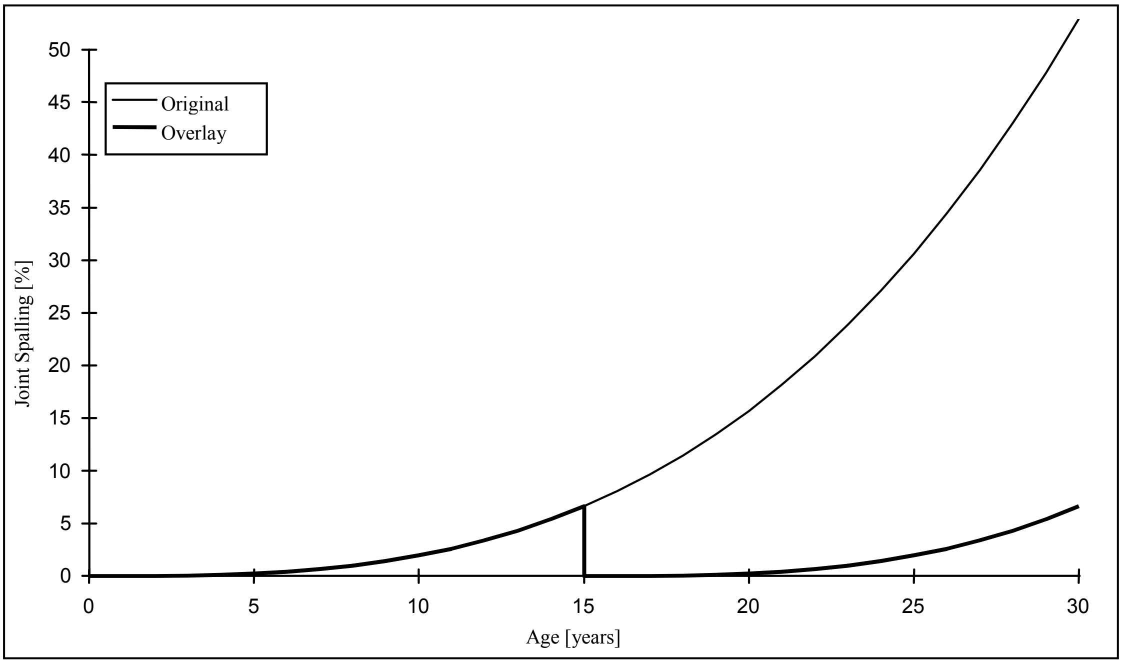

Figure D3.19 Bonded concrete overlay effect on joint spalling in JR concrete pavements

- **Roughness**

  Roughness after bonded concrete overlay will be reset to a new value, and its progression is computed using the Phase 1 RD model based on the PSR value.

6.1.3 CR concrete pavements

Quantities and costs

If bonded concrete overlay is performed on a CR concrete pavement, the amount of works (BOL), in square metres per kilometre, is calculated using Equation 6.1 above.

The amount of preparatory works required will be given by the amount full depth repair to be performed (FDR), which is computed using Equation 5.16 above.

The total amount of bonded concrete overlay (TBOL) in square metres is obtained from the product of BOL and the section length (L) in kilometres. The total cost of bonded concrete overlay is obtained by multiplying TBOL by the user-specified unit cost per square metre. The additional areas and cost of preparatory works will be reported separately under full depth repair.

The effects

Following bonded concrete overlay the slab thickness will be reset as expressed by Equation 6.2 above.

- **Failures**

  The number of failures after bonded concrete overlay will be reset to zero.

  Figure D3.20 shows the effect of bonded concrete overlay on failures in CR concrete pavements.

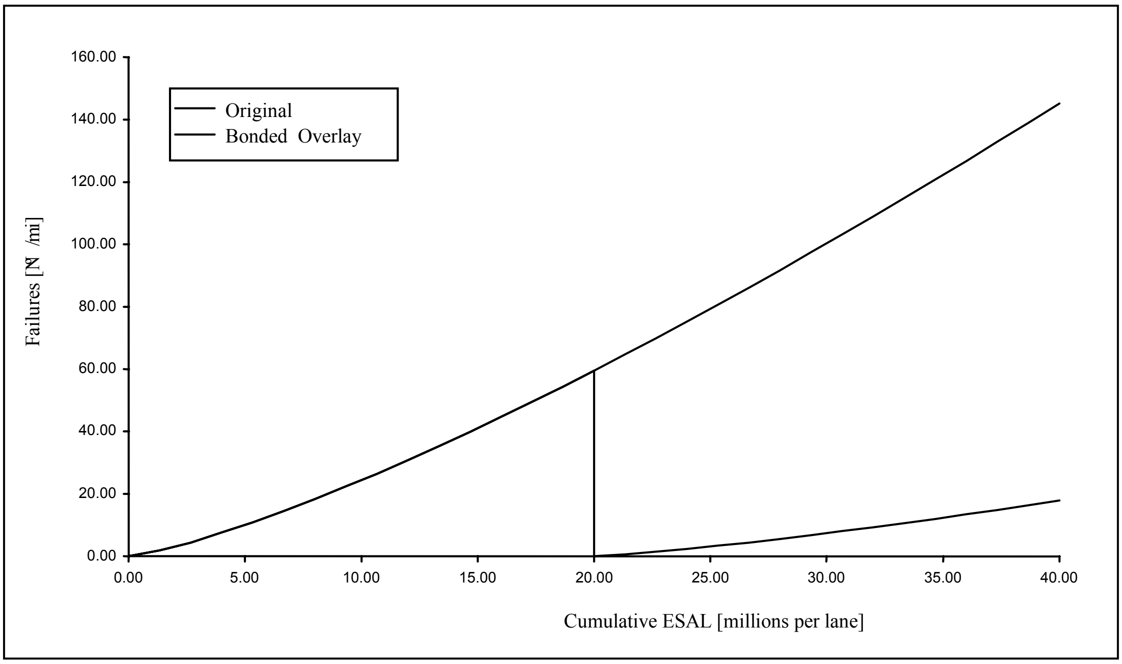

Figure D3.20 Bonded concrete overlay effect on failures in CR pavements

- **Roughness**

  Roughness after bonded concrete overlay will be reset to a new value, and its progression is computed using the Phase 1 RD model based on the PSR value.

6.2 Unbonded concrete overlays

The techniques used for constructing unbonded concrete overlays ensure that the new concrete layer does not adhere to the existing concrete. This involves placing a separation interlayer, usually of asphaltic concrete, over the existing concrete and then constructing a new concrete pavement on top of the interlayer. Unbonded concrete overlays on heavily trafficked roads are typically greater than 150 mm and for lightly trafficked roads not less than 100 mm. Because the two concrete layers are separated and act independently of each other, the unbonded concrete overlay behaves as a new concrete pavement on top of a very rigid support. The separation interlayer helps to delay the onset of reflection cracking.

An unbonded concrete overlay works can be defined in one of the following ways:

- **Option 1: Scheduled**

  An unbonded concrete overlay is performed at a fixed point in time defined by the calendar year.

- **Option 2: Scheduled**

  A fixed interval between successive unbonded concrete overlays is specified, and the overlay is performed in an analysis year t defined by Equations 4.4 above and 4.5 above.

- **Option 3: Condition - Responsive**

  Unbonded concrete overlay is performed when the level of pavement defect (cracking, failures and/or roughness) exceeds the user-specified values.

In all cases, unbonded concrete overlay will not be performed if the user-specified last applicable year or maximum applicable roughness has been exceeded.

Quantities and costs

If performed, the amount of unbonded concrete overlay works is calculated as follows:

$$UOL = 1000 * CW \qquad ...(6.6)$$

where:

UOL	unbonded concrete overlay area (m^2/km)
CW	carriageway width (m)

The total amount of unbonded concrete overlay (TUOL) in square metres is obtained from the product of UOL and the section length (L) in kilometres. The total cost of unbonded concrete overlay is obtained by multiplying TUOL by the user-specified unit cost per square metre.

The effects

After unbonded concrete overlay, the roadbase type will change to rigid/concrete base (RB). The seal type for JP and JR concrete pavements will be changed to the user-specified types. It is considered that the pavement will behave as new and the performance will be modelled using the Phase 1 RD models. Roughness after unbonded concrete overlay will be reset to the user-specified value.

7 Reconstruction

Pavement reconstruction refers to all works that require the re-specification of part or the entire pavement structure and characteristics, which involves the removal and replacement of the surfacing, roadbase and sub-bases. The re-specification of concrete pavement reconstruction also allows for the adjustment to roadside geometry and safety features, and to improve or add drainage structures.

Reconstruction may be specified in one of the following ways:

- **Option 1: Scheduled**

  A pavement reconstruction works is to be performed at a fixed point in time defined by the calendar year.

- **Option 2: Responsive**

  A reconstruction works of fixed specifications is applied when the levels of the user-specified intervention criteria, based on pavement condition, are met. Reconstruction will not be performed if the last applicable year has been exceeded.

Quantities and costs

If performed, the amount of pavement reconstruction is given by:

$$REC = 1000 * CW_{aw} \qquad ...(7.1)$$

where:

REC	area of pavement reconstruction (m^2/km)
CW_{aw}	carriageway width after works (m)

The total area of reconstruction (TREC) in square metres is obtained from the product of REC and the road section length (L) in kilometres. The total cost of pavement reconstruction is obtained by multiplying TREC by the user-specified unit cost per square metre.

The effects

After reconstruction, the pavement type will be reset to the new type specified by the user. The pavement will behave as new and the performance will be modelled using the Phase 1 RD models. Roughness will be reset to the user-specified value. The calibration factors for modelling pavement deterioration will also be reset to user-specified values.

8 Special works

The effects of the following special works on pavement performance are not modelled endogenously in HDM-4, and therefore only their costs can be considered in an analysis:

- **Emergency works**

  For example, repairing washout/subsidence, clearing debris, traffic accident removal, etc.

- **Winter maintenance**

These works will be **scheduled** at a fixed interval of time (minimum of one-year interval), and will be performed on an annual basis. If specified, these works activities will be applied in a given analysis year regardless of the works hierarchy.

Their unit costs will be specified in terms of currency per kilometre per year, and the annual costs will be obtained by multiplying the road section length (L) by the unit cost.

9 New construction

The construction of a new section can only be scheduled and not triggered by responsive intervention criteria. In a project analysis, a new road section (that is, a new link) can be specified as a section alternative within a selected project alternative.

The required components for defining a new section are as follows:

- **Road section data**

  All the data items that are required to define a road section in HDM-4. The user can specify these items using aggregate data.

- **Traffic data**

  - diverted traffic

    traffic that is diverted to the new section (link) from the nearby routes and other transport modes.

  - generated traffic

    additional traffic that occurs in response to the new investment.

- **Construction costs and duration**
- **Exogenous benefits and costs**
- **Maintenance standards**

  Applied after opening the new section to traffic.

The amount of new construction can be expressed in terms of the number of kilometres constructed (NEWCON) and this is equal to the new section length. The total cost of construction is obtained from the product of NEWCON and the user-specified unit cost per kilometre.

The new pavement will be modelled using the Phase 1 RD models discussed in Chapter C3.

10 References

AASHTO, (1993) American Association of State Highway and Transportation Officials

Guide for Design of Pavement Structures
Washington D.C., USA

LAST, (1995)

Concrete pavement performance equations
Latin American Study Team
International Study of Highway Development and Management Tools
Santiago, Chile

LAST, (1996)

Modelling road design and maintenance effects for pavements in HDM-4
Final Report, FICEM, Latin American Study Team
International Study of Highway Development and Management Tools
Santiago, Chile

D4 Unsealed Roads

1 Introduction

This chapter describes the detailed modelling of Road Works Effects for unsealed roads (see Figure D4.1).

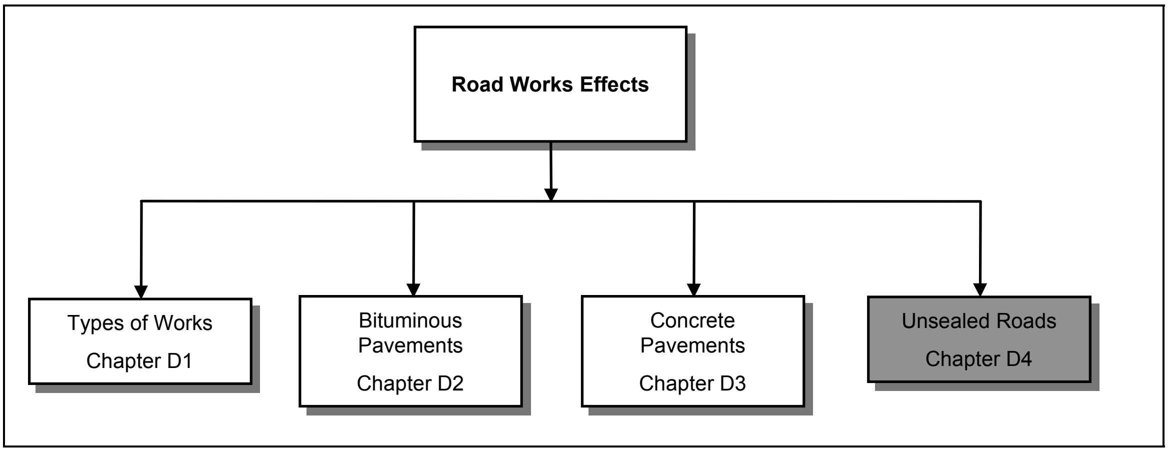

Figure D4.1 Road Works Effects modules

The methods of defining works activities and intervention criteria, the calculation of physical quantities of works and the costs to road administration, and works effects on road characteristics and road use are discussed for the following works classes:

- **Maintenance** (see Section 3)
- **Improvement** (see Section 4)
- **Construction** (see Section 5)

The modelling logic described comprises the overall computational procedure, the hierarchical ranking of works activities and pavement type resets after works.

A list of research documents referenced from this chapter is given in Section 6.

2 Modelling logic

An unsealed road is considered to comprise two layers, a **gravel surfacing** and a **subgrade**. A gravel road has both layers, but an earth road has a zero thickness of gravel surfacing and its surface characteristics are those of the subgrade. When a gravel road loses all of its gravel surfacing, then its classification reverts to that of earth road. Upon gravel resurfacing, all unpaved roads become gravel roads by definition of the new surfacing layer. The background of the modelling logic is given in *Watanatada et al. (1987)* and *Paterson (1987)*.

2.1 Overall computational procedure

The overall computational procedure for modelling works on unsealed roads that are applied in each analysis year can be summarised by the following steps:

- Determine the works standard(s) that is applicable in the given year. Only one maintenance standard and/or one improvement standard can be applied to a road section feature in any analysis year. One or more new section construction's can be triggered in a given year.
- Check the intervention criteria and the limits defined for works in the following order:
  - improvement works then maintenance works
- Identify and apply the highest-ranking works activity.
- Compute the physical quantities of works.
- Compute works effects and reset modelling parameter values to reflect post-works road geometry, pavement structure, strength, condition, history, and road use.
- Apply any other work activities whose effects on pavement are not modelled endogenously, (for example, routine-miscellaneous maintenance).
- Calculate the costs of works by applying unit costs to the physical quantities of works.
- Calculate the effect on the section's asset valuation.
- Store results for economic analysis and for use in the following analysis year.

2.2 Hierarchy of works

A works activity (or an operation) is triggered when any one or a combination of the user-specified criteria has been met. When more than one works activity meets the criteria for being applied in a given analysis year, the highest placed operation for the particular road feature is selected.

Table D4.1 shows the hierarchy of works activities that are applicable to the carriageway. The operation **new road construction section** is placed at the top of the list as number 1 and creates a new analysis section. Upgrading is the highest ranked operation that effects an existing analysis section and takes priority over all the other operations, while routine pavement works (that is, spot-regravelling and grading) are given the lowest priority.

Table D4.1 Hierarchy of road works applicable to the carriageway

Works type	Works activity / Operation	Hierarchy	Unit cost
New section	Construction of a new analysis section	1	per km
Upgrading	Upgrading to a new surface class	2	per km
Realignment	Geometric realignment	3	per km
Widening	Lane addition	4	per m^2 or per km
	Partial widening	5	per m^2 or per km
Resurfacing	Regravelling	6	per m^3
Routine	Spot regravelling [1]	7	per m^3
Pavement	Grading [1]	7	per km

Notes:

1 Spot regravelling and grading have the same ranking, and both of them can be performed in the same analysis year

An improvement or construction works of fixed specifications is applied to a given road section only once during the analysis period. This rule applies particularly to improvement works that have been defined as responsive to the user-specified intervention criteria based on road user effects parameters.

Spot regravelling and grading can be defined by the user to be applied as separate works activities in each year, or defined to repair areas of severe depression and reduce roughness before applying the higher-ranking works (for example, regravelling, widening). In the former case, spot regravelling or grading is performed every year in which no periodic maintenance or capital works is applied. In the latter case, spot regravelling is considered to be an integral part of the periodic maintenance or capitals works, and is referred to as **preparatory works**. Although preparatory works are automatically triggered and performed together with the capital works, the amount and the cost of each of the works activities involved is modelled and reported separately.

The works activities that apply to Non-Motorised Transport (NMT) lanes are applied in any analysis year, if specified by the user, regardless of the works hierarchy given in Table D4.1. NMT lane improvement works takes priority over NMT lane repair, respectively.

For all road feature types, if more than one works activity of the same operation type (for example, different specifications of regravelling) are applicable in a given analysis year, the one with the highest cost takes priority over the others.

The following works activities whose effects are not modelled endogenously:

- **Emergency works**
- **Winter maintenance**
- **Routine-miscellaneous maintenance**

are applied in a given analysis year, if specified by the user, regardless of any works hierarchy.

3 Maintenance works

The maintenance of unsealed roads comprises the following operations:

- **Periodic grading** (see Section 3.1)
- **Spot regravelling** (see Section 3.2)
- **Gravel resurfacing** (see Section 3.3)
- **Routine-miscellaneous maintenance of drainage and verges** (see Section 3.4)

Maintenance of gravel surfacing is accounted each analysis year through the surfacing thickness and the net change from material loss, spot regravelling and gravel resurfacing maintenance. The material loss from earth roads, although computed, is accounted only for the purpose of predicting **spot regravelling** quantities and is otherwise ignored, *Watanatada et al. (1987)*.

3.1 Periodic grading

Periodic grading by motorised or towed grader to restore surfacing gravel from the shoulders to the roadway and to reduce roughness is one of the principal routine maintenance for unsealed roads. The periodic grading of unpaved roads is usually undertaken on a more-or-less regular basis for management purposes, either seasonally or frequently enough to keep the roughness within tolerable limits.

The recommended intervention criterion are as follows:

- Roughness
- Year
- Interval
- Two-way AADT

Using the recommended intervention criterion, Grading is typically specified by the user to be performed at time intervals throughout the year specified in days (**intervals**), or traffic passes (**Two-way AADT**) between successive gradings, or in response to condition (**roughness**).

The user must also select the type of grading to be performed from the following list:

- Non-motorised grading, bush or tyre dragging
- Light motorised grading, little or no water, no roller compaction
- Heavy motorised grading with water and light roller compaction

3.1.1 Quantities and costs

When performed, the amount of grading works (LGRD) is equal to the road section length in kilometres. The cost of grading is obtained from the product of LGRD and the unit cost per kilometre. The annual cost of grading is obtained by multiplying this product with the number of grading performed in a given year.

3.1.2 Effects of grading

The average roughness between successive grading (RI_{avg}) is computed as a function of the number of days between grading (DG) as described in Part C - Chapter C4. If the user has specified an **interval** criterion, DG is specified directly by the user. If the **Two-way AADT** or **Roughness** criterion has been specified, DG is determined as follows:

If DGMAX < DG'

$$DG = DGMAX \qquad ...(3.1)$$

If $DGMIN < DG' \leq DGMAX$

$$DG = DG' \qquad ...(3.2)$$

If $DG' \leq DGMIN$

$$DG = DGMIN \qquad ...(3.3)$$

where:

DGMAX	the maximum allowable time interval between successive grading, in days, specified by the user as an option or equal to the default value of 10,000 days
DG'	the number of days between successive grading determined from the traffic or roughness parameter
DGMIN	the minimum applicable time interval between successive grading, in days, specified by the user as an option or equal to the default value of 5 days

The parameter DG' is determined as follows:

for the traffic-responsive (**Two-way AADT**) criterion:

$$DG' = \frac{VEHG}{AADT} \qquad ...(3.4)$$

for the roughness-responsive (**Roughness**) criterion:

$$DG' = \left(\frac{1}{c}\right) * \log_e \left\{ \frac{(RIMAX_j - RIMAX_0)}{[RIMAX_j - (1-a) * RIMIN_j - a * RIMAX_0]} \right\} \qquad ...(3.5)$$

where:

$$c = \left[-0.001 * \left(0.461 + 0.0174 * ADL + 0.0114 * ADH - \frac{0.0287 * ADT * MMP}{1000} \right) \right]$$

VEHG	the traffic interval between successive grading, in vehicles, specified by the user
$RIMAX_j$	the maximum roughness of material *j* (m/km IRI)
$RIMIN_j$	the minimum roughness of material *j* (m/km IRI)
$RIMAX_O$	the maximum allowable roughness specified by the user (m/km IRI)
A	model parameters which is defined in Chapter C4, Section 3.3

If no grading is specified, the long-term average roughness (RI_{lta}) is equal to the maximum roughness, as follows:

$$RI_{lta} = RIMAX_j \qquad ...(3.6)$$

Note that if the historic maintenance of the section has been nil-grading over several years, then the existing roughness is the best estimate of the average roughness and the user can provide this by specifying RIMAX endogenously with a value equal to the existing roughness.

3.2 Spot regravelling

Spot regravelling provides repair to areas of severe depression (gravel loss, rutting, etc.), and may triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- Gravel thickness
- Year
- Maximum material quantity
- Roughness
- Two-way AADT

The user must also specify the volume of material to replace. This can be done in one of two ways:

- **Fixed Material Volume**

  The user supplies the volume of material per kilometer (VGS) to add per year which is applied to the section.

- **Responsive Material Volume**

  The user specifies the percentage of material loss which is to be replaced (Pmla). A percentage of gravel or subgrade material loss in the current analysis year is then replaced subject to a maximum limit per year (if defined). In this option VGS is computed as follows:

$$VGS = Pmla * MLA * (CW + SW) * 10^{-2} \qquad ...(3.7)$$

where:

VGS	the in-place volume of material added due to the spot regravelling (m^3/km)
Pmla	percentage of annual material loss to be replaced, specified by the user (%)
MLA	annual material loss (mm)
CW	carriageway width (m)
SW	shoulder width (m)

3.2.1 Quantities and costs

When spot regravelling is performed, the added material is assumed to be the same type as the existing. The total amount of spot regravelling performed is given by:

$$TVGS = VGS * L \qquad ...(3.8)$$

where:

TVGS	Total amount of spot regravelling for the road section (m^3)
L	road section length (km)

The cost of spot regravelling is computed as the product of TVGS and the unit cost of material per cubic metre.

3.2.2 Effects of spot regravelling

- **Gravel thickness**

  For gravel roads, the thickness of the gravel layer is increased to reflect the volume of material added, according to the following formula (trapezoidal rule):

$$\Delta THGS = \frac{VGS}{(CW + SW)} \qquad ...(3.9)$$

$$THG_{aw} = THG_{bw} + \Delta THGS \qquad ...(3.10)$$

  where:

$\Delta THGS$	the increase in gravel thickness due to spot regravelling (mm)
THG_{aw}	gravel thickness after works (mm)
THG_{bw}	gravel thickness before works (mm)

All the other parameters are as defined previously.

- **Roughness**

  Spot regravelling is predicted to reduce the average roughness on the assumption that the gravel is applied in the major depressions and potholes that have appeared in the surface in the upper ranges of roughness. Roughness levels above 15 m/km IRI (190 QI) are invariably associated with the presence of visible birdbath type depressions or potholes, which become larger or more frequent as the roughness level increases, and these can be effectively patched, with high benefits, by spot regravelling. Over the roughness range of 11 to 15 IRI m/km (that is, 150 to 190 QI), such patchable birdbath depressions are frequently observed but not always present so that, in this range, spot regravelling may not always be effective. For example, spot regravelling is not effective maintenance on corrugations or on runoff-induced surface erosion, which conditions commonly induce roughness levels within this range. At roughness levels below 11.6 IRI m/km (that is, 150 QI) spot regravelling is considered to be ineffective on roughness. This logic is defined in the following algorithm, adopting the roughness to volume of depression ratio as equal to 2 QI per m^3/lane/km), allowing for the spot regravelling to be only 60% effective (that is, 1.2 QI per m^3/lane/km), and adopting an average effective lane width of 3 m:

$$RI_{avg(aw)} = MAX\left\{11.5, \left[RI_{avg(bw)} - MIN\left(1, \frac{\left[RI_{avg(bw)} - 11.5\right]}{3.1}\right) * \frac{0.277 * VGS}{CW}\right]\right\} \quad ...(3.11)$$

where:

$RI_{avg(aw)}$	average roughness after spot regravelling (m/km IRI)
$RI_{avg(bw)}$	average roughness before spot regravelling (m/km IRI)

All other parameters are as defined previously.

The effects of spot regravelling are illustrated in *Watanatada et al. (1987)*. It should be noted that spot regravelling affords only a temporary repair of depressions, and that the most effective means is by grading, or in severe cases by scarifying, grading and recompacting.

3.3 Gravel resurfacing

Gravel resurfacing is performed to replace or augment the gravel-surfacing layer in response to material loss. A gravel resurfacing works may triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- Roughness
- Gravel thickness
- Year
- Interval
- Two-way AADT

However, gravel resurfacing is not performed if either of the following is true:

- The analysis year is a construction year, or
- The final thickness specified in a scheduled policy is smaller than the predicted thickness at the end of the analysis year before the resurfacing decision.

3.3.1 Quantities and costs

When performed, the amount of regravelling is given by:

$$TVGR = VGR * L \quad ...(3.12)$$

where:

TVGR	amount of regravelling for the entire road section (m^3)
VGR	the in-place volume of gravel added due to the regravelling (m^3/km)

The volume of gravel added per km is computed according to the following trapezoidal formula:

$$VGR = (THG_{aw} - THG_{bw}) * (CW + SW) \quad ...(3.13)$$

All the parameters are as defined previously.

The cost of regravelling is obtained from the product of TVGR and the unit cost per cubic metre.

Preparatory works

If roughness before works (RI_{bw}) is greater than 11.6 IRI m/km, it is assumed that the following amount of spot regravelling is performed before gravel resurfacing:

$$VGS = \frac{(RI_{bw} - 11.5) * CW_{bw}}{0.277 * \{MIN[1, (RI_{bw} - 11.5)/3.1]\}} \quad ...(3.14)$$

where:

VGS	volume of spot regravelling (m^3/km)
RI_{bw}	roughness before works (= RI_b) (m/km IRI)

The additional cost of spot regravelling is obtained by multiplying the product of VGS and the section length (L) by the user-specified unit cost per cubic metre.

3.3.2 Effects of gravel resurfacing

- **Pavement type**

  When gravel resurfacing is performed the pavement type is set to **gravel** (GRUP) regardless of the previous surface type.

- **Gravel age**

  After regravelling, the gravel age (GAGE) is reset to zero.

- **Gravel thickness**

  The thickness of the gravel surfacing is increased according to the formula below:

  If the final gravel thickness is specified:

$$THG_{aw} = THG_0 \quad ...(3.15)$$

  If an increase in the gravel thickness is specified:

$$THG_{aw} = THG_{bw} + \Delta THG \quad ...(3.16)$$

  where:

THG_0	the final gravel thickness after gravel resurfacing, specified by the user (mm)
ΔTHG	the increase in the gravel thickness due to gravel resurfacing, specified by the user (m)

- **Material properties**

The existing surface material is changed to the material specified by the user (which may still be of the same attributes as the existing). The surface material attributes (P075, P425, P02, D95, PI, RIMIN and RIMAX) are replaced either by the new values provided by the user, or by the default values from the previous gravel attributes.

- **Roughness**

  Roughness after regravelling is reset to a user specified value. If this is not specified, the roughness after works is reset to the minimum allowable value, RIMIN, in IRI m/km units.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

3.4 Routine-miscellaneous maintenance

This includes drainage maintenance, vegetation control, safety installations, and other items that are not modelled as affecting the riding quality of the pavement. A lump sum cost per km per year is used as the basis for costing routine maintenance. Because the unpaved road deterioration relationships employed are based on the assumption of adequate drainage, the cost of drainage maintenance should be included, when it is normally done. Otherwise, some allowance due to the lack of drainage, for example, in the form of frequent road closures, washouts, etc., should be incorporated in the economic analysis.

When specified by the user, the total annual cost of routine-miscellaneous maintenance is obtained from the product of the section length (L) and the unit cost per kilometre per year.

4 Improvement works

Improvement works for unsealed roads comprises the following:

- **Widening** (see Section 4.1)
- **Realignment** (see Section 4.2)

4.1 Widening

The operations included under widening are **lane addition** and **partial widening**. The difference between the two is that partial widening does not increase the number of lanes. It is considered that these operations do not alter the road alignment, hence there is no change in section length.

Widening works can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Two-way AADT
- Peak period Volume Capacity Ratio
- Daily average Volume Capacity Ratio
- Year

The following information is required to specify a widening works:

- Road type.
- Road class.
- Increase in width for **partial widening**.
- Additional number of lanes and increase in carriageway width for **lane addition**.
- Pavement type for the entire section.
- Pavement details of the widened area of carriageway.
- Whether or not the existing carriageway is resurfaced.
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes.

4.1.1 Quantities and costs

If performed, the amount of widening works is given by:

$$AWDN = 1000 * \Delta CW \qquad ...(4.1)$$

where:

AWDN widened area of carriageway (m^2/km)

ΔCW increase in carriageway width (m)

The total area of widening over the entire road section is given by:

$$TAWDN = AWDN * L \qquad ...(4.2)$$

where:

TAWDN widened area of carriageway (m^2)

L road section length (km)

The cost (CSTWDN) of widening the section is obtained from the product of TAWDN and the user-specified unit cost per square metre, or from the product of the section length L and the unit cost per kilometre.

The salvage value is given as:

$$SALVA = PCTSAV * CSTWDN \qquad ...(4.3)$$

where:

SALVA salvage value of the works (currency)

PCTSAV percent of total cost salvageable (%)

Additional works

It is likely that widening works will involve resurfacing, or repair to the severely damaged area of the existing carriageway. The required additional works are modelled as described below:

- **Case 1: resurfacing the existing carriageway**

  If the existing carriageway is to be resurfaced, the amount of gravel resurfacing to be provided is given by:

  $$VGR = (THG_{aw} - THG_{bw}) * (CW_{bw} + SW) \qquad ...(4.4)$$

  where:

  VGR volume of regravelling (m^3/km)

  THG_{aw} gravel thickness after works (mm)

  THG_{bw} gravel thickness before works (mm)

  CW_{bw} carriageway width before works (m)

  SW shoulder width (m)

  The total amount of regravelling the existing carriageway is given as:

$$TVGR = VGR * L \qquad ...(4.5)$$

where:

TVGR	total volume of regravelling the existing carriageway (m^3)

The cost of regravelling the existing carriageway is obtained from the product of TVGR and the user-specified unit cost per cubic metre.

- **Case 2: no resurfacing of the existing carriageway**

  If the existing carriageway is **not** to be resurfaced, it is assumed that spot regravelling and grading the full length of the existing carriageway is performed along with the widening works.

  If roughness before works, RI_{bw}, is greater than 11.6 IRI m/km, the amount of spot regravelling performed is computed using Equation 3.14 above. The additional cost of spot regravelling is obtained by multiplying the product of VGS and the section length (L) by the user-specified unit cost per cubic metre.

  The amount of grading performed (LGRD) is equal to the road section length (L) in kilometres, and the additional cost of grading is obtained from the product of LGRD and the user-specified unit cost per kilometre.

The total cost of widening works is the sum of the carriageway widening cost and the cost of additional works comprising regravelling of the existing carriageway, or grading and any spot regravelling performed. The costs and the amounts of the additional works are reported separately under regravelling, grading or spot regravelling.

In economic analysis, it is assumed that these additional costs are incurred in the last construction year.

4.1.2 Effects of widening

It is considered that widening works do not alter the road surface class. After widening, the required modelling parameters are reset as described below:

- **Carriageway width**

  The new carriageway width after works is given as follows:

$$CW_{aw} = CW_{bw} + \Delta CW \qquad ...(4.6)$$

where:

CW_{aw}	carriageway width after works (m)
CW_{bw}	carriageway width before works (m)
ΔCW	increase in carriageway width (m)

For partial widening the increase in carriageway width (ΔCW) is specified directly by the user. For lane addition, the increase in carriageway width is user-specified. If this is not specified the increase in width is given by:

$$\Delta CW = \frac{(ADDLN * CW_{bw})}{NLANES_{bw}} \qquad ...(4.7)$$

where:

ADDLN	additional number of lanes, input by the user
$NLANES_{bw}$	number of lanes before works

For lane addition, the number of lanes after widening works ($NLANES_{aw}$) is equal to the number of lanes before works ($NLANES_{bw}$) plus the user-specified additional number of lanes (ADDLN).

- **Gravel thickness**

  - Gravel thickness after widening is calculated as a weighted average as follows:

$$THG_{aw} = \frac{(CW_{bw} * THG_{excw} + \Delta CW * THG_{ww})}{CW_{aw}} \qquad ...(4.8)$$

where:

THG_{aw}	gravel thickness after widening works (mm)
THG_{ww}	gravel thickness on the widened part of the carriageway (mm)
THG_{bw}	gravel thickness before widening works (mm)
THG_{excw}	gravel thickness over the existing carriageway after widening works (mm)

All other parameters are as defined previously.

  - The gravel thickness over the existing carriageway after widening (THG_{excw}) is obtained as follows:

If the existing carriageway is to be regravelled:

$$THG_{excw} = THG_{bw} + \Delta THG_{gr} \qquad ...(4.9)$$

and the pavement type is set to **gravel** (GRUP) regardless of the previous pavement type

If the existing carriageway is **not** to be regravelled:

$$THG_{excw} = THG_{bw} + \Delta THGS \qquad ...(4.10)$$

where:

ΔTHG_{gr}	increase in gravel thickness over the existing carriageway due to regravelling (mm)
$\Delta THGS$	increase in gravel thickness over the existing carriageway due to spot regravelling (mm)

- The increase in gravel thickness over the existing carriageway due to spot regravelling (ΔTHGS) is obtained as follows:

  If pavement type is gravel (GRUP):

  ΔTHGS is computed using Equation 3.9 above

  If pavement type is earth (EAUP):

  ΔTHGS is set to zero

- **Surface material properties**

After widening, the surface material properties (SMPi) are reset as follows:

- If the existing carriageway is to be regravelled, all the surface material properties are reset to those of the new gravel material.
- If the existing carriageway is **not** to be regravelled

$$SMPi_{aw} = \left[\frac{(CW_{bw} * SMPi_{bw} + \Delta CW * SMPi_{ww})}{CW_{aw}}\right] \qquad ...(4.11)$$

where:

$SMPi_{aw}$	surface material property *i* after widening works, (*i* = P075, P425, P02, PI, D95)
$SMPi_{bw}$	surface material property *i* before widening works (*i* = P075, P425, P02, PI, D95)
$SMPi_{ww}$	Surface material property *i* of the widened part of the carriageway works (*i* = P075, P425, P02, PI, D95)

- **Roughness**

Roughness after widening (RI_{aw}) is reset to a user-specified value. If this is not specified, reset RI_{aw} to the minimum allowable roughness (RIMIN) in IRI m/km units.

- **Gravel age**

The gravel age (GAGE) after widening works is reset as follows:

- If the existing carriageway is to be regravelled, GAGE is reset to zero.
- If the existing carriageway is **not** to be regravelled, GAGE is calculated as follows:

$$GAGE_{aw} = \left[\frac{(CW_{bw} * GAGE_{bw})}{CW_{aw}}\right] \qquad ...(4.12)$$

where:

$GAGE_{aw}$	gravel age after widening works (years) (Note: returns an integer value)
$GAGE_{bw}$	gravel age before widening works (years)

- **Material loss calibration factors**

  After widening works, the material loss calibration factors (that is, K_{gl} and K_{kt}) are reset to user-specified values.

- **Speed factors**

  These are the speed limit, speed enforcement factor, roadside friction factor, non-motorised transport and motorised transport speed reduction factors, and acceleration noise which depends primarily on the individual road section.

- **Traffic flow pattern** (road use)

  The data that describes the hourly traffic flow distribution is also reset to a user-specified type.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

4.2 Realignment

Refers to local geometric improvements of existing roads, which may also result in a reduction of the road length. It is assumed that the carriageway width remains unaltered when a realignment works is performed.

Realignment works can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Peak period Volume Capacity Ratio
- Daily average Volume Capacity Ratio
- Two-way AADT
- Year

A realignment works is specified by the following information:

- Road type.
- Road class.
- Proportion of new construction - defined as the ratio of new construction length to the section length before works.
- Length adjustment factor.
- Geometry details.
- Pavement type for the entire section.
- Pavement details of the new construction segments.
- Whether or not the non-realigned segments of the existing carriageway is regravelled.

- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes.

4.2.1 Quantities and costs

If performed, the total amount of realignment works is given by:

$$REAL = Pconew * L_{aw} \qquad ...(4.13)$$

$$L_{aw} = L_{bw} * LF \qquad ...(4.14)$$

where:

REAL	length of road realigned (km)
Pconew	proportion of new construction (0 < Pconew < 1)
L_{aw}	new section length after realignment works (km)
L_{bw}	section length before realignment works (km)
LF	length adjustment factor (LF > 0)

The cost of realignment (CSTREAL) is obtained from the product of REAL and the user-specified realignment unit cost per kilometre.

The salvage value is given by:

$$SALVA = PCTSAV * CSTREAL \qquad ...(4.15)$$

where:

SALVA	salvage value of the works (currency)
PCTSAV	percent of total cost salvageable (%)

Additional works

It is assumed that the following amounts of additional works would be carried out together with the realignment works:

- **Case 1: resurfacing the non-realigned segments**

  If the non-realigned parts of the existing carriageway are to be resurfaced, the amount of regravelling works is given as follows:

$$VGR = \left(THG_{aw} - THG_{bw}\right) * (CW + SW) \qquad ...(4.16)$$

  where:

VGR	volume of regravelling (m^3/km)
THG_{aw}	gravel thickness after realignment works (mm)
THG_{bw}	gravel thickness before realignment works (mm)

CW carriageway width (m)

SW shoulder width (m)

The total amount of regravelling the non-realigned parts of the existing carriageway is given by:

$$TVGR = VGR * (1 - Pconew) * L_{aw} \qquad ...(4.17)$$

where:

TVGR total volume of regravelling the non-realigned parts of the existing carriageway (m^3)

The cost of regravelling the non-realigned parts of the existing carriageway is obtained from the product of TVGR and the user-specified unit cost per cubic metre.

- **Case 2: no resurfacing of the non-realigned segments**

If the non-realigned parts of the existing carriageway are not to be resurfaced, it is assumed that the following amounts of grading and spot regravelling are performed along with the realignment works:

- **Grading**

$$LGRD = (1 - Pconew) * L_{aw} \qquad ...(4.18)$$

where:

LGRD total length of road graded (km)

All the other parameters are as defined previously.

The cost of grading the non-realigned parts of the existing carriageway is obtained from the product of LGRD and the user-specified unit cost per kilometre.

- **Spot regravelling**

If roughness before works (RI_{bw}) is greater than 11.6 IRI m/km, the amount of spot regravelling performed on the non-realigned parts of the existing carriageway is computed as follows:

$$TVGS = VGS * (1 - Pconew) * L_{aw} \qquad ...(4.19)$$

where:

TVGS volume of spot regravelling performed on the non-realigned parts of the existing carriageway (m^3)

VGS volume of spot regravelling computed using Equation 3.14 given above (m^3/km)

The cost of spot regravelling the non-realigned parts of the existing carriageway is calculated from the product of TVGS and the user-specified unit cost per cubic metre.

The total cost of realignment works is the sum of realignment construction cost and the cost of additional works comprising regravelling of the non-realigned parts of the existing carriageway, or grading and any spot regravelling performed. The additional costs and the amounts of works should be reported separately under regravelling, grading or spot regravelling.

In economic analysis it is assumed that these additional costs are incurred in the last construction year.

4.2.2 Effects of realignment

It is considered that realignment works do not alter the road surface class. The required modelling parameters are reset as described below:

- **New section length**

  The new length of the road section after realignment is given by Equation 4.14 above.

- **Gravel thickness**

  - Gravel thickness after realignment is calculated as follows:

    $$THG_{aw} = [(1 - Pconew) * THG_{excw} + Pconew * THG_{rw}] \qquad ...(4.20)$$

    where:

THG_{aw}	gravel thickness after realignment works (mm)
THG_{excw}	gravel thickness of the non-realigned parts of the existing carriageway after realignment works (mm)
THG_{rw}	gravel thickness of the realigned parts of the carriageway (mm)
THG_{bw}	gravel thickness before realignment works (mm)

  - The gravel thickness over the non-realigned parts of the existing carriageway after a realignment works is obtained as follows:

    If the non-realigned parts of the existing carriageway are to be regravelled

    $$THG_{excw} = THG_{bw} + \Delta THG_{gr} \qquad ...(4.21)$$

    and the pavement type is set to **gravel** (GRUP) regardless of the previous pavement type.

    If the non-realigned parts of the existing carriageway are **not** to be regravelled

    $$THG_{excw} = THG_{bw} + \Delta THGS \qquad ...(4.22)$$

    where:

ΔTHG_{gr}	increase in gravel thickness over the non-realigned parts of the existing carriageway due to regravelling (mm)

$\Delta THGS$ increase in gravel thickness over the non-realigned parts of the existing carriageway due to spot regravelling (mm)

- The increase in gravel thickness over the non-realigned parts of the existing carriageway due to spot regravelling ($\Delta THGS$) is obtained as follows:

  If pavement type is gravel (GRUP):

  $\Delta THGS$ is computed using Equation 3.9 above

  If pavement type is earth (EAUP):

  $\Delta THGS$ is set to zero

- **Surface material properties**

After realignment works, the surface material properties (SMPi) are reset as follows:

- If the non-realigned parts of the existing carriageway are to be regravelled, all the surface material properties are reset to those of the new gravel material
- If the non-realigned parts of the existing carriageway are **not** to be regravelled

$$SMPi_{aw} = [(1 - Pconew) * SMPi_{bw} + Pconew * SMPi_{rw}] \qquad ...(4.23)$$

where:

$SMPi_{aw}$ surface material property *i* after realignment works, (*i* = P075, P425, P02, PI, D95)

$SMPi_{bw}$ surface material property *i* before realignment works, (*i* = P075, P425, P02, PI, D95)

$SMPi_{rw}$ surface material property *i* for the realigned road segments after works, (*i* = P075, P425, P02, PI, D95)

- **Roughness**

Roughness after realignment works (RI_{aw}) is reset to a user-specified value. If this is not specified, reset RI_{aw} to the minimum allowable roughness (RIMIN) in IRI units of m/km.

- **Gravel age**

The gravel age (GAGE) after realignment works is reset as follows:

- If the non-realigned parts of the existing carriageway are to be regravelled, GAGE is reset to zero.
- If the non-realigned parts of the existing carriageway are **not** to be regravelled, GAGE is calculated as follows:

$$GAGE_{aw} = [(1 - Pconew) * GAGE_{bw}] \qquad ...(4.24)$$

where:

$GAGE_{aw}$ gravel age after realignment works (returns an integer value, in years)

$GAGE_{bw}$ gravel age before realignment works (years)

- **Material loss calibration factors**

  After realignment, the material loss calibration factors (that is, K_{gl} and K_{kt}) are reset to user-specified values.

- **Speed factors**

  These are the speed limit, speed enforcement factor, roadside friction factor, non-motorised transport and motorised transport speed reduction factors, and acceleration noise which depend primarily on the individual road section.

- **Traffic flow pattern (road use)**

  The data that describes the hourly traffic flow distribution is also reset to a user-specified type.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

5 Construction works

Construction works for unsealed roads comprises the following:

- **Upgrading** (see Section 5.1)
- **New section** (see Section 5.2

5.1 Upgrading

An unsealed road can be upgraded to a bituminous or concrete pavement. It is also possible to upgrade an earth road to a gravel road, although both are of the same surface class.

Upgrading works can be triggered by the user defining one or more intervention criterion.

The recommended intervention criterion are as follows:

- MT Mean speed
- MT Minimum speed
- Peak period Volume Capacity Ratio
- Daily average Volume Capacity Ratio
- Two-way AADT
- Cumulative ESAL
- Year

An upgrading works are specified by the following information:

- Road type.
- Road class.
- Length adjustment factor.

- Increase in width.
- Additional number of lanes.
- Geometry details of the entire road section.
- New pavement details (according to the new pavement type).
- Other modelling parameters that depend on the new pavement type (for example, construction quality indicators for bituminous roads).
- Asset valuation of the Road formation and subgrade, road pavement layers, and NMT lanes.

5.1.1 Quantities and costs

If performed, the amount of upgrading works in kilometres of road length is given by:

$$LUPGRD = L_{aw} \qquad ...(5.1)$$

where:

LUPGRD	amount of upgrading works (km)
L_{aw}	new road length after works (= L_{bw}*LF) (km)

The total cost of upgrading (CSTUPGRD) is obtained from the product of LUPGRD and the user-specified unit cost per kilometre.

The salvage value is given as:

$$SALVA = PCTSAV * CSTUPGRD \qquad ...(5.2)$$

where:

SALVA	salvage value of the works (currency)
PCTSAV	percent of total cost salvageable (%)

5.1.2 Effects of upgrading

After upgrading, the pavement type is reset to the new type specified by the user. Depending upon the new pavement type, the required modelling parameters are obtained in the following ways:

- Pavement structure, strength, layer material properties and construction quality are set to user-specified values.
- Pavement condition after works is reset to **as new.**
- Pavement history data is reset to reflect new construction.
- Calibration factors are user-specified.
- **Carriageway width and number of lanes**

  The new carriageway width after upgrading is calculated using Equation 4.6 above.

The increase in carriageway width is either specified directly by the user, or calculated using Equation 4.7 above.

The number of lanes after upgrading works ($NLANES_{aw}$) is equal to the number of lanes before works ($NLANES_{bw}$) plus the user-specified additional number of lanes (ADDLN).

- **Speed factors**

  These are the speed limit, speed enforcement factor, roadside friction factor, non-motorised transport and motorised transport speed reduction factors, and acceleration noise which depend primarily on the individual road section.

- **Traffic flow pattern** (road use)

  The data that describes the hourly traffic flow distribution is also reset to a user-specified type.

- **Asset Valuation**

  After the work the parameters for asset valuation will be reset as described in Volume 4 Part G4 Section 3.4 Reset of parameters after roadworks.

5.2 New section

The construction of a new section can only be scheduled and not triggered by responsive intervention criteria. In a project analysis, a new section (that is, a new link) can be specified as a section alternative within a selected project alternative, as described in the Applications Guide.

The required components of the new section to be constructed is defined using the following information:

- **Road section data**

  All the data items that are required to define a road section in HDM-4, including the asset valuation. The user is able to specify these data items in aggregate terms.

- **Traffic data**

  - diverted traffic - traffic that is diverted from the nearby routes and other transport modes
  - generated traffic – additional traffic that occurs in response to the new investment

- **Construction costs, duration and salvage value**
- **Exogenous benefits and costs**
- **Maintenance and improvement standards**

  To be applied after opening the new section to traffic.

The amount of new construction can be expressed in terms of the number of kilometres constructed (NEWCON) and this is equal to the new road section length. The total cost of construction is obtained from the product of NEWCON and the user-specified unit cost per kilometre.

6 References

Paterson W.D.O., (1987)

Road Deterioration and Maintenance Effects
World Bank Publications, Washington D.C.

Watanatada T., Harral C.G., Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987)

The Highway Design and Maintenance Standards Model - Volume 1 Description
World Bank, John Hopkins University Press

Watanatada T., Harral C.G., Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987)

The Highway Design and Maintenance Standards Model - Volume 2 User's Manual
World Bank, John Hopkins University Press