Evaluation of a New Maintenance Concept for the Preservation of Highways

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abstract

Asphalt roads are gradually deteriorating over time and need road mending to remain in a good state. Inspections are performed to obtain information about the current state of the road; when the damage achieves the established standards, the road is repaired through a maintenance action that is considered as most cost-effective. Because of economies of scale it is to a certain extent economical to limit the number of maintenance services by integrating neighboring segments into a homogeneous section which is completely repaired. In this report we consider the question whether it is economically justified to adopt a maintenance concept in which the road is occasionally regenerated from junction to junction with a distance of several kilometers. The big advantage of junction-to-junction maintenance is that it can be done within special road barrier constructions which reduce the road capacity only slightly, so that the road can be maintained 24 hours a day.

keywords: road maintenance, preservation of highways, junction to junction regeneration, pilot-study, traffic congestion

1. Introduction

Roads play a crucial role in today's infrastructure as it directs most of the regional traffic in the industrial world. To guarantee a certain road quality roads must be regularly repaired, so that a substantial part of the government budget for infrastructural works is used for rehabilitation. Economy measures compel a cost-effective road rehabilitation policy, therefore planners of road engineering projects examine various maintenance concepts which could possibly reduce the rehabilitation costs in the long run. One of the most novel maintenance concepts is the junction-to-junction regeneration concept with local patchworks, which is described and evaluated in this report. Before we examine the economic advantage of junction-to-junction regeneration, it is good to consider the general problem of planning road engineering projects, and to see how mass motorization is complicating the enforcement of the projects, so that expensive road barrier constructions are needed to limit the traffic congestion during the execution of road engineering projects. The use of such barrier constructions can only be justified if the length of the road engineering project is several kilometers long, which is an imposed property of junction-to-junction regeneration.

1.1 Planning of Road Engineering Projects; Taking Advantage of the Economies of Scale Property

Planners of road engineering projects are unremittingly trying to construct maintenance programs which rehabilitate the roads as efficient as possible. Although a definite plan is usually made in the operational phase, it must fit in a certain maintenance concept which is economical in the long run. Such a maintenance concept is normally devised in the strategic planning phase in which the planning is regulated by a number of maintenance rules, and is practically necessary as most planners consider a finite planning horizon so that the long term consequences are not easily contemplated.

In both the strategic as in the operational planning phase there are two important questions :

1. In what way should a road be repaired, viz. *when* should *what* part obtain *which* maintenance action ?
2. What are the consequences of the maintenance plan with respect to the preservation costs, the average road condition and the pass-through of traffic ?

An example of a strategic maintenance concept is a periodic repavement every T years at which the road is brought into an almost-as-good-as-new state; if there arise aggravating damages then it is possible to repair them instantaneously by appropriate maintenance actions. The parameter-value T must be optimized which is not an easy task as the cost-effectiveness of a maintenance concept does not only depend on the parameter setting but also on the decisions made in the operational planning phase. In the operational phase one must decide whether to repair a damage instantaneously, or not, in view of the planned repavement. It is clear that the number of instantaneous treatments depends on the parameter value T. Therefore, the strategic planning must be geared to the decisions that are made in the operational phase as a result of the parameter setting. In other words, the strategic and the operational planning must be complementary to each other to have a maintenance concept which is cost-effective in the long run.

A fundamental aspect of the road maintenance planning is the timing of the rehabilitation actions; on the one hand one must rehabilitate the roads before the damage is bothering the motorists; on the other hand one must not repair the roads too soon as it is quite expensive to maintain small road-sections.

Road maintenance is often governed by a condition-based maintenance concept, since the deterioration of a road is locally different and stochastic, and inspections are relatively cheap to perform. There are several norms indicating when the damage is unacceptable and must be repaired; if such a norm is reached then the damage is called normative. A norm can therefore be seen as a failure-limit, where there are obvious failure costs. Since a road has various damage-features there are multiple failure modes; one of the failure modes could be normative cracking. Several actions could be undertaken to treat a certain damage, with a different effect on each of the damage features. Mostly one selects an action which lengthens the expected residual lifetime to such an extent that it is worth the cost.

An essential thing is that the actions fulfil the economies-of-scale property, so that the cost of the action per square meter decreases when the repaired area becomes larger. It is therefore natural to maintain larger sections instead of small patches, to benefit in some degree from the cost discounts. One could define junctions which may be a service station along the road or an exit, and completely regenerate the roads between two succeeding junctions at appropriate times, to reduce the number of small patchworks. It must be verified if such a maintenance concept is really worthwhile in the long run.

1.2 THE SITUATION IN THE NETHERLANDS

The Netherlands have a genuine dense network of national highways. Ultimo 1995 there were 2,208 kilometers of double carriage-ways plus 991 kilometers of clearways, with a surface of ± 80 km^2 which is about 0.2% of the Dutch soil. The roads are highly used; the Dutch motor park counted in 1995 roughly 6.6 million vehicles of which 5.6 million personal automobiles, with a total covered distance of 45.8 billion. The total heaviness of the traffic congestion was almost 5 million kilometer-minutes, where the traffic jams had an average length of roughly 4.4 kilometers. Interesting is that only 10.7 % of the total heaviness is caused by road maintenance. One expects that there will be 7.5 million vehicles in 2010, which is an increase of 13.6 % in 15 years. This means that roads are silting up, and that maintenance must be carefully planned to avoid kilometers-long traffic jams.

Figure 1.1: Dutch network of highways

The planning of the road engineering projects is carried out by the regional directorates of the Dutch Directorate General of Public Works and Water Management (Rijkswaterstaat), and is supported by the Road and Hydraulic Engineering Division (DWW) of the Directorate General. DWW is an advisory division for technological and environmental issues within the field of road and hydraulic engineering; it consists of roughly 240 staff members. The activities are structured in four core tasks: road-building, water defence, water management, and the supply of raw materials for civil engineering and industrial building.

The road-building staff is concerned with road constructions; it manages the quality of the roads and comes up with maintenance plans for the next years. The quality of the roads is measured in two ways: first by the automatic road analyzer which is a van with measurement equipment to determine the unevenness of the roads, and second by road experts who visually inspect the road for the detection of cracks and raveled spots. The results are stored in a database which can be invoked to set up a maintenance plan for a particular road. Next to the operational planning, there is some research on various maintenance concepts which might possibly reduce the long term maintenance cost. Special attention is paid to several kinds of road barrier systems which must redirect the traffic when the road is maintained as these barrier systems have a different impact on the traffic flow capacity. Even the road design is contemplated for the utilization of the road barrier systems, since most of the current roads are not entirely safe for the appliance of certain road barrier systems.

DWW currently plans the road rehabilitation by the so-called sector integration method. They construct patches of neighbouring segments which exhibit a similar damage pattern, to which they assign a specific action which is executed in a certain year. Information about the current state of the roads is obtained by inspections. For each road a plan is constructed for the next five years, which is updated every two years. In order to avoid traffic congestion, maintenance is often done at night much to the annoyance of many road workers. Therefore, there are several people who advocate junction-to-junction maintenance, as this will reduce the frequency of road engineering projects, and will create the possibility to maintain at the same time the road lighting. The main drawback of junction-to-junction maintenance is that it requires road barrier constructions which are really expensive; it has therefore to be investigated if junction-to-junction maintenance is not too costly.

1.3 LITERATURE OVERVIEW; A SURVEY OF ROAD MAINTENANCE MODELS

In the literature several road rehabilitation models can be found; a lot of OR-people within the road engineering research area are contemplating the road rehabilitation problem, which is not surprising as most industrialized countries spend yearly billions of dollars for the maintenance of roads, so that a small percentage of savings is soon a gain of several million dollars per year.

Golabi, Kulkarni & Way [1982] describe a Pavement Management System (PMS), developed for the Arizona Department of Transportation (ADOT) and Woodward-Clyde Consultants, which constructs for each mile of Arizona's 7,400 mile network of highways a maintenance policy, devises defensible one-year and five-year budgets, and predicts the effect of budget cuts on road conditions.

The heart of the Pavement Management System is an optimization unit called Network Optimization System (NOS), which produces maintenance policies such that the established quality standards are achieved. Within NOS there are two optimization models: a long term model which is used to minimize the long run average maintenance cost per year, and a short term model, which minimizes the total expected maintenance costs over a period of T year. Both models are Markov decision models where the state consists of four arguments: present raveling, present cracking, last-year change in cracking, and index to the first crack; the last argument is used to account for differences between the probabilities of deterioration of roads with no visible cracks but with different last non-routine maintenance actions. The models are solved by linear programming.

Wang & Zaniewski [1996] report that the Pavement Management System has lead to substantial savings, and that many other highways agencies are currently using a NOS-based pavement management system. However, they remark that ADOT never reached the steady-state condition because of fluctuations in budgeting and pavement behavior. Further it appeared that the transition probabilities change over time, as the pavement design methods. paving materials and paving technologies are continuously changing.

Bakó, Klafszky, Szántai & Gáspár [1995] present two different models for the planning of highway rehabilitation where they focus on the allocation of money to different road categories. The roads are divided into different categories according to their asphalt type, the kind of maintenance needed, and the AADT-class (Annual Average Daily Traffic) to which they belong. The first model is an optimization model for the calculation of the funds needed to achieve a prescribed improvement of the highway-network. For each of the road category there is a transition matrix for the condition of the roads, with a total of 41 condition-levels. The model can be used to test several strategies composed of quality constraints. The second model is an optimization model for the distribution of the funds to different road categories, given the total budget and the quality constraints, the model tries to maximize the average quality of the road-network. Both models are large-scale linear programming models with a special structure so that it can be efficiently solved. The models have been applied to Hungarian highways, and it appeared that they are really appropriate for the planning of road pavement improvements.

Worm & Van Harten [1996] distinguish four levels within their hierarchic planning approach :
Level I : finding a one-lane sector policy with infinite planning horizon
Level II : finding a one-lane sector policy with planning horizon T and time-windows

Level III: maintenance clustering into projects
Level IV: project assignment within global budget and quality constraints.

The model in level I is a steady-state Markov decision model, developed by Zwagemakers [1988], and minimizes the present value of the maintenance costs given a certain discount factor, through linear programming. The model in level II is a T-period Markov decision model which also minimizes the present value of the maintenance costs where to each possible condition at time T a present value is assigned which is already determined by the steady-state model of level I. In level III several adjacent lane sectors are integrated into lane-sections or carriage-sections by clustering techniques. The action which is performed on a lane- or carriage-section is the action for which the present value of the maintenance costs is the lowest. The clustering is done by formulating a network on the basis of the possible maintenance projects. If there are n sectors $s_1,..,s_n$, in order of appearance, then one tries to find the shortest path from node s_1 to node s_n , where the arcs $s_i \rightarrow s_j$ are defined by the candidate projects which are carried out from sector s_i up to and including sector s_j for all $i,j \in \{1,..,n\}$, $i < j$. The cost of an arc is just the present value of the maintenance costs associated with the project. The shortest path problem is solved by dynamic programming. Level IV is on a network-level and determines which road-engineering projects are to be carried out, by solving a binary programming problem where the decision variables are (0,1) flags for the execution of certain road engineering projects. The binary programming problem which minimizes the present value of the total maintenance costs under budget and quality constraints, is solved by the branch & bound method.

Sinha & Fwa [1993] come up with a systematic decision-making framework to enhance the efficiency and effectiveness of the existing maintenance management practice at the subdistrict highway level. They describe procedures for (a) assessment of maintenance needs, (b) establishment of performance standards, (c) determination of costs of maintenance treatments, (d) setting up an integrated database, (e) priority rating of maintenance activities, and (f) optimal programming and scheduling of maintenance activities.

A report of Timmer et al. [1993] notifies an important deficiency of many models used for the planning of road engineering projects, it appears that most models do not encourage the construction of large maintenance sections and are not combining maintenance actions in order to take advantage of the quantity rebate. Therefore, Timmer et al. developed a heuristic approach for constructing maintenance plans of several years, where treatments are aggregated by simple rules of thumb.

An overview of theoretic models for combining maintenance projects, is given by Cho & Parlar [1991], and Dekker, Van der Duyn Schouten & Wildeman [1997]. The problem with most theoretic models is that they do not recognize the geographical position of the projects which is really essential for road maintenance. It is the adjacency of the components which makes road maintenance an arduous multi-component maintenance problem, so that it is not very strange that maintenance projects are still combined in a heuristic way.

1.4 Evaluation of the Junction-to-Junction Regeneration Concept through a Pilot-Study

In this report we evaluate the junction-to-junction maintenance concept, which is to regenerate a carriage-way between two junctions when the overall quality does not meet the standards which must be specified within the strategic planning phase. A junction can be an access-road or an exit, but can also be an arbitrary point along the road; the distance between two junctions varies from 2 till 10 kilometers. If a whole junction-to-junction section is regenerated then the carriage-section is almost maintenance-free for the next ten years. However, junction-to-junction regeneration is a very lengthy project and therefore needs a permanent road barrier construction to redirect the vehicles during the time that the carriage-way is repaired, as there otherwise would be a enormous time loss due to the repetitive building of a temporary barrier construction. A disadvantage of a permanent barrier construction is that there may arise traffic jams when the traffic intensity is reasonably high since a barrier construction reduces to some extent the road capacity, however the permanent barrier constructions can be built in such a way that it reduces the road capacity only a bit. We evaluate the junction-to-junction maintenance approach under the assumption that the operational planning is done by the sector integration approach which is currently applied in the Netherlands. The sector integration approach first constructs a number of homogeneous sections by integrating a number of neighboring segments with roughly the same damage pattern into a section which will be completely repaired, and then specifies for each homogeneous section a maintenance action by a economic rule of thumb, and the year in which the action is carried out. Of course, if junction-to-junction maintenance is incorporated within a maintenance strategy which is primarily based on local maintenance, it is probably worthwhile to anticipate on the junction-to-junction regenerations by canceling local maintenance actions just in front of the regenerations to avoid lavish mendings. Several norm-values are established to support the planning in the operational planning phase, in such a way that the road is rehabilitated in a cost-efficient manner. Of course, we don't want the road to be heavily downgraded during certain periods; therefore we optimize the norm-values under a quality constraint, so that a minimum road-quality is guaranteed. The junction-to-junction maintenance concept is evaluated through a pilot-study

The aim of the pilot-study is to get insight in the economic consequences of the junction-to-junction maintenance approach for the preservation of Dutch highways, and for the traffic congestion when a certain road barrier system is applied. The preservation costs have to be weighed against the vehicle queuing loss, and the average condition of the road as a result of the applied maintenance concept.

We perform a pilot-study on a road of 4 kilometers length with two lanes on each carriage-way; we do this for two asphalt-roads: dense asphalt roads, and porous asphalt roads. Each lane is divided into segments of 100 meters length. A segment is exposed to cracking, raveling, longitudinal unevenness and transversal unevenness, which are modeled by independent Brownian motions of which the parameter-values are estimated through expert-judgement. There are seven possible actions to repair a road, each with a different effect on the deterioration processes. The choice between the different action is based on the equivalent annual cost which measures the cost-effectiveness of an action. We simulate the road maintenance process with, and without, appliance of junction-to-junction maintenance. We perform a steady-state simulation to analyze the consequences of the maintenance policy in the long run. For the junction to junction maintenance approach we must optimize two parameter-values: a norm-percentage which indicates when junction-to-junction maintenance must be performed, and a delay-percentage when the local maintenance is halted to avoid lavish mendings just before the road is completely regenerated by node-to-node maintenance. Both percentages refer to the number of segment bearing (almost) normative damage, and are optimized through simulation-optimization.

2. Problem Formulation

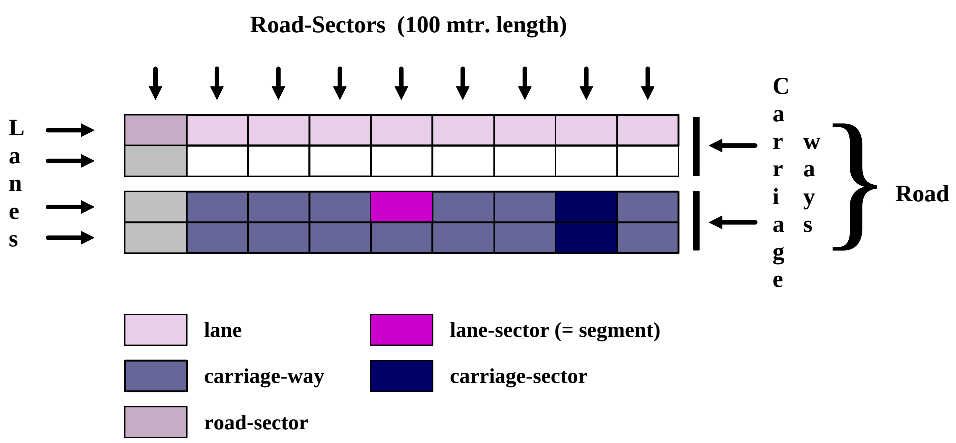
In this section we present the full details of the road rehabilitation problem. First we describe the properties of the roads including the damage features. Then we describe the maintenance actions and their effects on the roads. A economic rule is presented to determine the most cost-effective maintenance action given a certain damage pattern. Next, we present formulas for the costs and the duration of the maintenance actions. Part of the rehabilitation costs is made because of the redirection of traffic; we will describe different kinds of road barrier constructions and their impact on the road capacity. A traffic congestion model is developed to calculate the number of vehicle loss hours due to an engineering project. Then we will describe the current section integration approach, and how junction-to-junction regenerations can be incorporated within that approach.

2.1 Road Features

A road is a part of the civil infrastructure that supports the motorized traffic to move from one place to another place. In general, roads are composed of two carriage-ways which are in turn composed of lanes. For planning purposes the road is divided is sectors of 100 meters length. The following road elements can be recognized :

- carriage-way : part of the road that is especially destined for the traffic in one direction
- lane : part of the carriage-way on which motor vehicles can run only in tandem
- road-sector : part of the road of 100 meters length
- carriage-sector : part of the carriage-way of 100 meters length
- lane-sector : part of a lane of 100 meters length (also called a segment).

Figure 2.1 : configuration of a 2x2-lanes road



Roads are generally made of asphalt-concrete. Two types of asphalt roads can be distinguished:

(1) dense asphalt roads with a hermetic concrete structure
(2) porous asphalt roads with a permeable concrete structure.

The latter asphalt roads are more and more used although they are more expensive to rehabilitate; they proved to be less noisy than dense asphalt roads, and reduce splash and spray of eroded asphalt.

The main damage features are :

- cracking : network of longitudinal and transversal cracks
- raveling : dislodgment of fine aggregate
- longitudinal unevenness : unevenness in the length of the road
- transversal unevenness : depth of ruts caused by traffic

The first two damage features are inspected by road experts; the latter two by the Automatic Road Analyzer (ARAN) which is a van geared with measurement equipment which registrates the unevenness of the road. Longitudinal unevenness is measured according to the International Roughness Index (IRI), while transversal unevenness is measured in terms of the average number of millimeters difference in height.

The seriousness of cracking is usually expressed as a percentage of the road-length that is damaged in the form of cracks, and the seriousness of raveling as a percentage of the road-surface that is stained with raveled parts. However, the current routine of the road-experts is to inspect these damages visually and to specify only the estimated residual lifetime, viz. the time that remains till the damage becomes unacceptable.

The seriousness of the damage can be classified in :
- not normative
- almost normative
- normative

If the damage is normative (= unacceptable) then it is mandatory to repair the damage; if it is almost normative then it may be already repaired although it is not mandatory, and if the damage is not normative then it is not necessary to repair the damage.

For each damage feature there are two norm-values : a warning-level and a failure-limit. If the damage is beneath the warning-level then the damage is not normative; if the damage is above the warning-level but beneath the failure-limit then the damage is almost normative; and if the damage is above the failure-limit then the damage is normative (see figure 2.2).

Figure 2.2 : classification of the damage

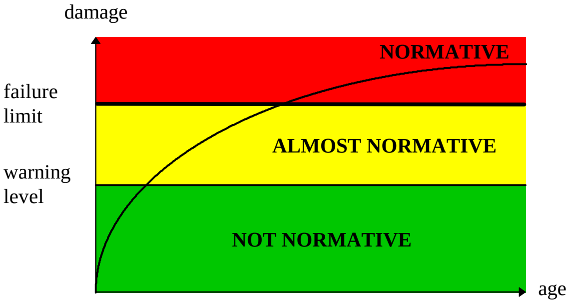


Table 2.1 specifies the norm-values for each damage feature, which can be used to determine the seriousness of the damage.

Table 2.1 : norm-values per damage feature

damage feature	*not normative*	*almost normative*	*normative*
cracking	≤ 18¾ %	18¾ -25%	≥ 25%
raveling	≤ 22½ %	22½ -30%	≥ 30%
transversal unevenness	≤ 15 MM	15-18 MM	≥ 18 MM
longitudinal unevenness	≤ 2½ IRI	2½ -3½ IRI	≥ 3½ IRI

source : ‘basisboek Groot Onderhoud Asfaltbetonverhardingen’
Van der Horst, et al. - DWW Rijkswaterstaat, 1991

The warning-limit for cracking and raveling are different compared to the levels specified in the DWW's source-book; we changed these values to have for all damage features a roughly equal duration between the passage of the warning level and the passage of the failure-limit.

Each damage process has its own deterioration process; a functional description for these deterioration processes has to be estimated; we assembled the following data through expert judgment of DWW's road experts.

per road damage feature and asphalt type :

→ the probabilities α_i : i=1,2,3,4 that the failure-limit will be reached within $t_i=5\cdot i$ years if the road is currently as-good-as-new.

→ the speed of the deterioration process: decreasing, constant or increasing.

→ the minimal, mean, and maximal duration, denoted by T^{min}, T^{mean} and T^{max} respectively, of the time that elapses till the damage reaches the failure-limit if the road is currently as-good-as-new.

The results of the expert judgment are given in tables 2.2, 2,3 and 2.4.

Table 2.2 : assembled failure probabilities

damage feature	*asphalt type*	α_1	α_2	α_3	α_4
cracking	dense	0.00	0.10	0.70	0.90
raveling	dense	0.00	0.20	0.50	0.80
longitudinal unevenness	dense	0.00	0.10	0.20	0.30
transversal unevenness	dense	0.00	0.50	0.85	0.95
cracking	porous	0.00	0.00	0.10	0.50
raveling	porous	0.00	0.40	0.90	1.00
longitudinal unevenness	porous	0.00	0.10	0.20	0.30
transversal unevenness	porous	0.00	0.00	0.25	0.70

Table 2.3 : conjectured speed of deterioration

damage feature	*speed*
cracking	increasing
raveling	increasing
longitudinal unevenness	constant
transversal unevenness	first decreasing, then increasing

Table 2.4 : conjectured life-times

damage feature	*asphalt type*	T^{min}	T^{mean}	T^{max}
cracking	dense	8	14	>15
raveling	dense	10	15	>15
longitudinal unevenness	dense	7	>15	>15
transversal unevenness	dense	6	12	>15
cracking	porous	15	>15	>15
raveling	porous	8	12	>15
longitudinal unevenness	porous	7	>15	>15
transversal unevenness	porous	12	>15	>15

Except for longitudinal unevenness the damage features have a distinct deterioration process for the dens and the porous asphalt road. In general, the dense asphalt road is more sensitive for cracking and transversal unevenness than the porous asphalt road, while the porous asphalt road is more sensitive for raveling than the dense asphalt road.

2.2 MAINTENANCE ACTIONS AND THEIR EFFECTS

A road can be repaired through several actions; the following six types of maintenance actions can be recognized :

- conservation : addition of a thin wear-coat
- regeneration : repavement / remix of the top-coat
- replacement : milling and inlay of the top-coat
- overlaying : addition of a new layer of asphalt
- rutfilling : addition of emulsion concrete to expunge the ruts
- profile correction : adjustment of the road profile by milling and leveling

In table 2.5 one can see which damage features are handled by the different types of maintenance

Table 2.5 : types of maintenance actions and their impact on the road

damage feature	*conservation*	*regeneration*	*replacement*	*overlay*	*rut-filling*	*profile correction*
cracking		*x*	*x*	*x*		
raveling	*x*	*x*	*x*	*x*		
longitudinal unevenness				*x*		*x*
transversal unevenness	*x*	*x*	*x*	*x*	*x*	

In the Netherlands conservation is prohibited for roads with a daily traffic intensity of 20,000 vehicles or more, because of chipping. Since most roads have a traffic intensity beyond the 30,000 vehicles per 24 hours we neglect the possibility of conservation.

For the dense and porous asphalt roads there are - conservation actions excluded - seven concrete maintenance packages possible. The effects of the maintenance packages are shown in table 2.6

Table 2.6 : possible maintenance packages and their effects on the remaining lifetime

package	*road type*	*latitude*	*cracking*	*raveling*	*longitudinal unevenness*	*transversal unevenness*
1^d rut-filling (cold)	dense	lane	6	t	t	10
2^d 40u/i (5%) + DAC	dense	carriage-way	12	t+4	t+3	8
3^d 60u/i (75%) + DAC	dense	carriage-way	12	10	t+3	12
4^d milling and leveling	dense	carriage-way	t	t	10	8
5^d milling + OAC + DAC	dense	carriage-way	12	t+8	10	12
6^d 100 u/i (100 %)	dense	lane	10	t+5	t	12
7^d 40 u/i (100 %)	dense	lane	10	t+2	t	12
1^p 50u/i (100%)	porous	lane	9	t	t	10
2^p 40 u/i (5%)+50STA+PAC	porous	carriage-way	9	t+4	t+3	8
3^p 60u/i (75%)+50STA+PAC	porous	carriage-way	9	10	t+3	12
4^p milling and leveling +PAC	porous	carriage-way	t	t	10	8
5^p milling + 100STA + PAC	porous	carriage-way	9	t+8	10	12
6^p 150u/i (100%)	porous	lane	9	t+5	t	12
7^p 50u/i (100%)	porous	lane	9	t	t	10

source : DWW Rijkswaterstaat, Delft;
DAC = dense asphalt concrete; PAC : porous asphalt concrete; OAC open asphalt concrete;
STA = gravel asphalt; α u/i (β %) : milling and inlay of α MM asphalt layer with β % new asphalt.

The road type in table 2.6 indicates for which asphalt road the maintenance package is appropriate. The latitude indicates if the package can be performed on a single lane, or has to be performed carriageway-width. The effects of the maintenance packages on the damage features, are given in nominal terms or in relative terms. If the effect is a number, say c, then the expected residual lifetime after execution of the maintenance package is c years, If the effect is given in relative terms, say t+c, then the expected residual lifetime after execution of the maintenance package, is the expected residual lifetime just before the execution of the maintenance package plus c years.

The maintenance packages can be classified in small-scale maintenance which can be carried out per carriage-way- or lanesector, and large-scale maintenance which is restricted to a length of at least 400 meters. The only maintenance packages which are appropriate for junction-to-junction maintenance are the regeneration actions : 2^{d-p}, and 3^{d-p}.

Table 2.7 : characterization of the actions

package	*sort of maintenance*	*execution*
1^{d-p}	rut-filling	small-scale
2^{d-p}	regeneration - remix technique	large-scale $^+$
3^{d-p}	regeneration - repave technique	large-scale $^+$
4^{d-p}	profile correction	small-scale
5^{d-p}	overlay	large-scale
6^{d-p}	thorough replacement	large-scale
7^{d-p}	minor replacement	large-scale

(+) : appropriate for junction-to-junction maintenance

For the determination of the most cost-effective package DWW uses a statistic called the Equivalent Annual Cost (EAC) which is defined as :

$$\text{EAC} = \frac{\text{unit price of the package}}{\text{expected gain in years of the package}} \tag{2.1}$$

where the expected gain in years of a package is the expected residual lifetime right after performance of the maintenance package minus the expected residual lifetime just before the performance of the maintenance package. The EAC can be interpreted as the price that is paid for one year of gain in the expected residual lifetime; cost effective packages have in general a low EAC. The package with the lowest EAC is considered as the most cost-effective action.

The costs of the maintenance packages depend on the unit-price of the packages and the size of the area on which the package is performed. The unit-prices are given in Table 2.8.

Table 2.8 : unit-prices of maintenance packages

nr.	*DFL./m²*	*nr.*	*DFL./m²*
1^d	8.50	1^p	17.65
2^d	10.15	2^p	25.05
3^d	24.60	3^p	39.50
4^d	13.90	4^p	29.80
5^d	21.90	5^p	36.30
6^d	33.00	6^p	40.30
7^d	15.00	7^p	17.65

source : DWW Rijkswaterstaat, Delft;
unit prices for region Eastern Netherlands, august 1996.

The unit prices are based on a certain standard-area, which is 2,000m^2 for the packages 1^{d-p}, 6^{d-p} and 7^{d-p}, and 10,000m^2 for the packages 2^{d-p}, 3^{d-p}, 4^{d-p} and 5^{d-p} To calculate the cost of a maintenance package for an arbitrary area, one can apply the following formula :

$$\text{maintenance cost} = \left(\text{unit price per m}^2\right) \cdot \text{area} \cdot \left\{1 - \text{discount coefficient} \cdot \left(1 - \frac{\text{standard area}}{\text{area}}\right)\right\} \tag{2.2}$$

The discount coefficient is for all maintenance packages 0.1, thus the maximum discount with regard to the unit price is 10%. When maintenance is done at night the unit prices should be multiplied by a surcharge factor which is contemporarily 1.15.

The duration of the maintenance activities depends on the workspeed of the activity and the number of effective workhours per day which depends on the number of shifts and the kind of road barrier construction used. The workspeed of the different maintenance packages is presented in Table 2.9.

Table 2.9 : workspeed maintenance packages #

nr.	*meters/hr*	*nr.*	*meters/hr*
1^d	100	1^p	100
2^d	$11^1/_9$	2^p	9½
3^d	$8^1/_3$	3^p	7½
4^d	$33^1/_3$	4^p	$16^2/_3$
5^d	$13^1/_3$	5^p	$13^1/_3$
6^d	25	6^p	$16^2/_3$
7^d	50	7^p	40

(#) : estimated data

The workspeeds are based on a certain road-width, which is 3,5 meters for the packages 1^{d-p}, 6^{d-p} and 7^{d-p}, and 12,5 meters for the packages 2^{d-p},3^{d-p},4^{d-p} and 5^{d-p}.

To calculate the duration of a maintenance activity one can apply the following formula

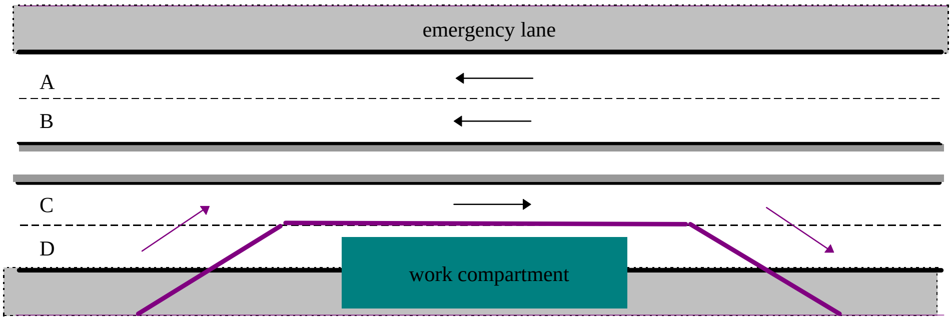
$$\text{duration} = \frac{\text{length of the section (in metres)}}{\text{workspeed (in meters per hour)} * \text{ effective workhours per day}} + \text{setup time} \tag{2.3}$$

where the setup time and duration are expressed in days. The setup-time is generally the time needed to set up and break down a permanent road barrier construction; this time depends on the applied road barrier system.

2.3 Road Barrier Systems; Their Costs, Safety, and Traffic Flow Capacities

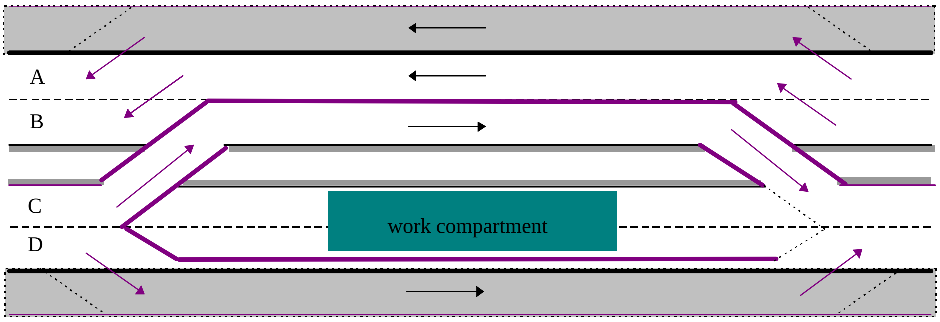
Several types of road-barrier systems can be applied to carry off the traffic from the lanes on which a work compartment is formed. For a 2x2 road, there are 3 possible barrier systems, viz.: a 2-1 system which closes a lane so that the road becomes a 2x1 road, a 3-1 system which closes a lane, and opens a third lane on the carriage-way back to redirect part of the traffic on the way there, and a 4-0 system which closes both lanes, and opens a third and fourth lane on the carriage-way back to redirect all the traffic on the way there.

Figure 2.3 : 2-1 road barrier system (traditional maintenance)



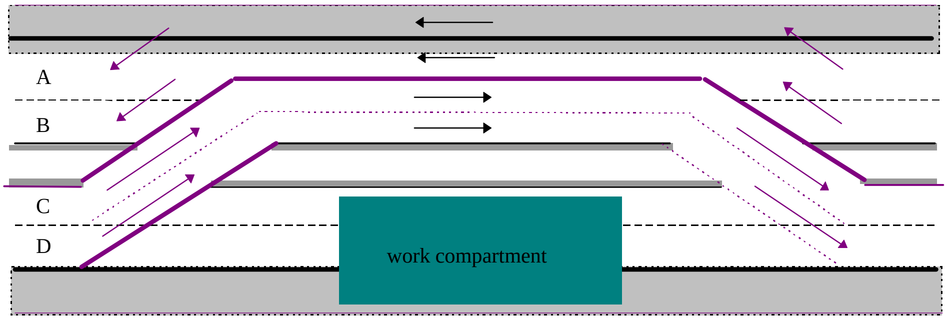
2-1 road barrier system : one of the lanes - in this case lane D - is closed, so that only three of the four lanes are open.

Figure 2.4 : 3-1 road barrier system



3-1 road barrier system : two lanes on a carriage-way - in this case lanes C and D - are closed; the traffic on lane D is sent to the adjacent emergency lane; the traffic on lane C to lane B, that of lane B to lane A, and the traffic on lane A to its adjacent emergency lane. Shortly after the traffic has passed the work compartment it is redirected to its initial lanes.

Figure 2.5 : 4-0 road barrier system



4-0 road barrier system : two lanes on a carriage-way - in this case lanes C and D - are closed where the traffic is sent to the other carriage-way which is now partitioned in four lanes at the expense of the emergency lane; the lanes are narrowed with roughly a half meter so that it requires some concentration of the motorists to stay between the temporarily marked lines. Shortly after the traffic has passed the work compartment it is redirected to the initial lanes.

The advisory group 'dry infrastructure' of Oranjewoud investigated the possible consequences of the various road barrier constructions, they examined among other things the construction costs, the flow capacity, and the safety of the different road barrier systems.

The costs of the different kinds of road barrier constructions are expounded in Table 2.10.

Table 2.10 : construction costs of different road barrier systems

item(s)	*2-1 system*	*3-1 system*	*4-0 system*
boarding	DFL. 550.- / night	DFL. 9,600.-	DFL. 8,500.-
road beaconing	DFL. 960.- / night	DFL. 34,500.-	DFL. 5,100.-
temporary marking	-	DFL. 16,700.- / km.	DFL. 16,700.- / km
guard rails	-	DFL. 8,700.-	DFL. 8,700.-
crossing (2x)	-	DFL. 26,700.-	DFL. 26,700.-
barriers	-	DFL. 36,500.- / km.	DFL. 36,000.- /km

source : supplement report "Verkennend onderzoek naar de haalbaarheid van 'knoop tot knoop' onderhoud op 2x2 strooks autosnelwegen door middel van het 3-1 en het 4-0 afzettingssysteem", Oranjewoud Capelle a/d IJsel, 1995; item-costs are based on a carriageway-width of 12.5 meters.

The flow capacities of a 2x2 lanes carriage-way under various road barrier systems have only been estimated for a road with a carriageway-width of 11.5 meters; based on the results of Oranjewoud we estimated the flow capacities for a road with carriageway-width of 12.5 meters. The results are given in Table 2.11.

Table 2.11 : conjectured traffic flow capacities

road barrier system	this way	other way
no barriers	4,200 mvh	4,200 mvh
2-1 system	2,000 mvh	4,200 mvh
3-1 system	3,600 mvh	3,800 mvh
4-0 system	3,500 mvh	3,500 mvh

capacities are for a 2x2 lanes road with a carriageway-width of 12.5 meters; mvh : motorvehicles per hour.

Table 2.12 : Safety of the road barrier systems

road barrier system	motorist	roadworker
2-1 system	-	-
3-1 system	+	-
4-0 system	-	+

- : somewhat dangerous, + : rather safe

The safety-aspect of the road barrier systems concerns the safety of the motorists and that of the roadworkers. Oranjewoud summarized their findings in the following table :

The 2-1 road barrier system is generally used for traditional maintenance, which is done at night and quite unsafe for the motorists and the roadworkers, as there is only one lane available and the sight is seriously diminished by the dark. Besides, the anticipation ability of the motorists to unexpected events is generally lower at night, mostly because they are tired, or are driving under influence of alcohol.

The 3-1 road barrier system is pretty safe for the motorist; it has a greater flow capacity than the 4-0 barrier system, and the lateral distances between the motorvehicles are somewhat greater. For the roadworkers the 3-1 road barrier system is less safe then the 4-0 barrier system, because the traffic is on both carriage-ways and sometimes passing the work compartment on both sides.

The 4-0 road barrier system is the most safest road barrier system for the roadworkers as the traffic is reasonably insulated. A disadvantage of the 4-0 road barrier system is that all the traffic is now on one carriage-way where the lanes are fairly narrow, so that collisions are more likely to occur. If a motorvehicle runs aground then it is very difficult to keep the traffic going as there is no possibility to set the motorvehicle aside.

The time necessary to set up a road barrier construction and to break it down depends on the applied system. It takes one day to set up or pull down a 3-1 or a 4-0 road barrier system, and approximately 1 hour to set up or pull down a 2-1 barrier system. In the case of a 3-1/2-1 barrier system, an extra day/hour is needed to shift the work compartment from one lane to the other lane, which happens during a carriageway-width maintenance activity. It should be emphasized that a 3-1 and a 4-0 road barrier construction is a permanent construction so that it reduces the road capacity 24 hours per day. The duration of an engineering project depends on the number of shifts that is performed during a day. An engineering project that is carried out within a permanent barrier construction counts about 8 effective work-hours per day if there is only one shift from 8:00 till 16:00, and about 16 effective workhours per day, if there also a night-shift which is done somewhere between 19:00 and 6:00.

A 2-1 road barrier system is a temporary road barrier system so that it must be set up and pulled down, every night that the road is traditionally repaired. Taking the time into account which is necessary to set up, and pull down the barrier system, a 2-1 road barrier system counts about 6 effective work-hours per day if lane-width maintenance is done, and about 5 effective work-hours if carriageway-width maintenance is done, because of the lane switch.

Table 2.13 summarizes the set-up times associated with the different road barrier systems.

Table 2.13 : setup time road maintenance

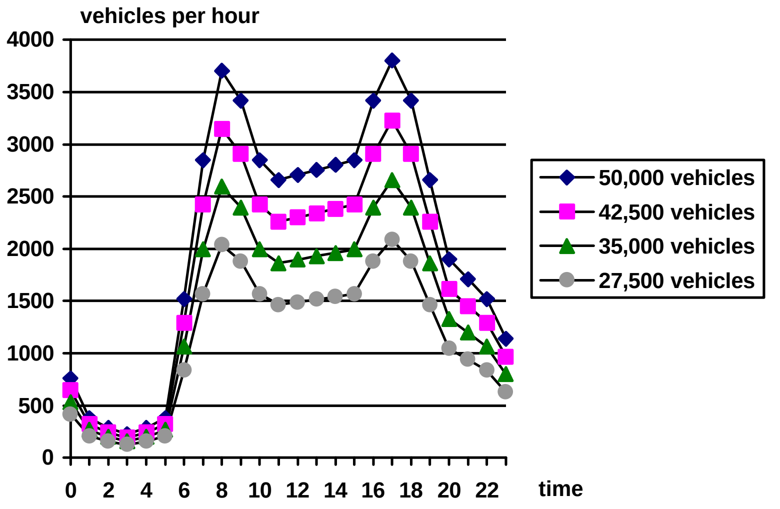
road barrier	lane-width	carriageway-width
2-1 system	2 hrs / night	3 hrs /night
3-1 system	2 days	3 days
4-0 system	2 days	2 days

An engineering project within a permanent road barrier system is socially more appealing than a 2-1 system, since roadworkers are somewhat averse to traditional maintenance as it disrupts their biological clock, as well as their family life. It is also safer than a 2-1 barrier system, so the question remains whether a permanent road barrier system is not too expensive, or causing an annoying amount of traffic jams.

2.4 Traffic Aspects

Road maintenance usually requires a traffic-free area, so that one or more lanes must be closed. This closure generally reduces the road capacity, so that in districts with a fairly high traffic intensity there may arise traffic jams. In the Netherlands, about one-tenth of the total traffic jam heaviness is due to the execution of road engineering projects. The traffic intensity of a road changes per hour, with typical rush hours between 7:00 - 9:00 and 16:00-19:00 during which traffic jams are likely to occur. Therefore one strives for maintenance during the traffic-low hours, so that the decreased road capacity is still higher than the average number of motorvehicles that is passing the road. In Figure 2.6 the approximate course of the hourly traffic intensity is displayed.

Figure 2.6 : hour-to-hour traffic intensity



source : AVV Rijkswaterstaat - Team Analyse

If the hourly traffic intensity exceeds the road capacity, then one can expect a traffic jam. This makes the 2-1 road barrier system, which reduces the road capacity to 2,000 vehicles per hour, somewhat inappropriate for a maintenance project that is carried out in the daytime on a road with a traffic intensity of more than 40,000 vehicles per 24 hours. The traffic intensity at hour H, H=0,1,..,23 can be roughly approximated by multiplying the 24-hours traffic intensity by the average traffic fraction of hour H listed in Table 2.14.

Table 2.14 : hour-to-hour traffic fractions

hour	0	1	2	3	4	5	6	7	8	9	10	11
fraction	2L	L	¾ L	$^3/_5$ L	¾ L	L	4L	7½ L	9 ¾ L	9 L	7½ L	7L
hour	12	13	14	15	16	17	18	19	20	21	22	23
fraction	$7^1/_8$ L	7¼ L	$7^3/_8$ L	7½ L	9L	10L	9L	7L	5L	4½ L	4L	3L

L= 1/131.6

A simple traffic congestion model is developed to assess the number of vehicle loss hours when a certain road barrier construction is applied and the road has a certain traffic intensity. Within the model the following assumptions are made:

(1) traditional maintenance is done between 22:00 hr. and 6:00 hr. during which the maintained carriage-way has a traffic-flow capacity of 2,000 vehicles per hour; the traffic on the other carriage- way is not hindered and has therefore a traffic-flow capacity of 4,200 vehicles per hour.
Between 6:00 hr. and 22:00 hr. the carriage-ways have the normal traffic-flow capacities.
(2) when maintenance is done within a permanent 3-1 road barrier system, then the traffic-flow capacity is 3600 vehicles per hour from 0:00 hr. till 24:00 hr.; the traffic capacity on the way back is 3800 vehicles per hour as the lanes are a bit narrowed.
(3) when maintenance is done within a permanent 4-0 road barrier system, then the traffic-flow capacity is for both directions 3500 vehicles per hour from 0:00 hr. till 24:00 hr.

The traffic congestion model describes a simple arrival-departure process with time-dependent arrival and departure rates. The arrival rates are given by the hourly traffic intensities which can be calculated from Table 2.14, and the departure rates are equal to the traffic flow capacities.

We calculated the vehicle loss hours for traffic intensities up to 60,000 vehicles per hour, with an increment of 2,500 vehicles per hour; the results are given in Table 2.15.

Table 2.15 : total vehicle queuing loss per 24-hours caused by different road barrier systems
*(*aggregated over all vehicles on both carriage-ways)

24 hours traffic intensity	*road barrier system* 2-1 *(at night)*	3-1 *(24 hours)*	4-0 *(24 hours)*
45,000 vcw	-	-	-
47,500 vcw.	-	5 hours	178 hours
50,000 vcw	-	291 hours	1,430 hours
52,500 vcw	-	1,407 hours	4,358 hours
55,000 vcw	-	4,204 hours	9,394 hours
57,500 vcw	-	8,456 hours	16,250 hours
60,000 vcw	-	13,965 hours	33,134 hours

vcw = vehicles per carriage-way; both carriage ways are 12.5 meters broad

Table 2.16 gives the average and maximum queuing time of a vehicle as a consequence of a road engineering project if it is carried out within a 3-1 or a 4-0 road barrier system.

Table 2.16 : mean (maximum) queuing time for a vehicle
(on the maintained carriage-way)

24 hours traffic intensity	*road barrier system* 3-1 *(24 hours)*	4-0 *(24 hours)*
45,000 vcw	-	-
47,500 vcw	-	0 (2) minutes
50,000 vcw	0 (4) minutes	1 (5) minutes
52,500 vcw	1 (6) minutes	3 (11) minutes
55,000 vcw	3 (15) minutes	5 (21) minutes
57,500 vcw	6 (23) minutes	9 (30) minutes
60,000 vcw	10 (33) minutes	17 (47) minutes

vcw = vehicles per carriage-way; both carriage ways are 12.5 meters broad

It appears that the 3-1 and 4-0 barrier systems are less adequate for roads with high traffic intensities; when the traffic intensity approaches 60,000 vehicles per 24 hours, then one can expect that some motorists will experience a waiting time of thirty minutes or more, which can be hardly tolerated.

The Dutch Ministry of Waterways and Public Works incurs for each vehicle loss hour that is caused by a road engineering project a penalty of DFL.30.- to compare the seriousness of the traffic jams with the costs of the road engineering projects.

2.5 THE CURRENT PLANNING METHODOLOGY

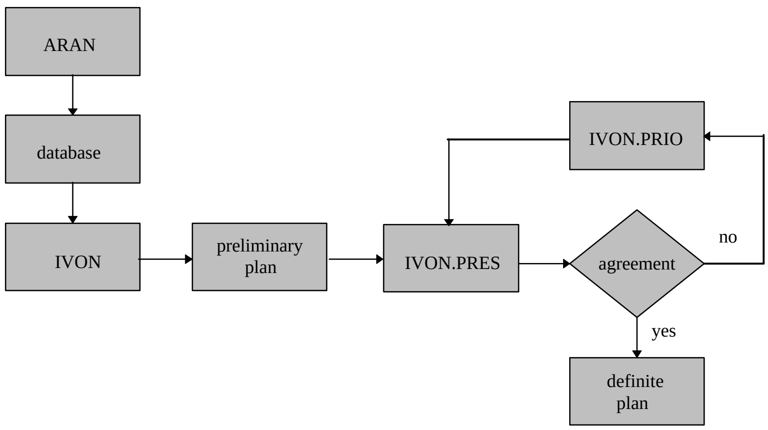
DWW uses for the planning of road engineering projects a system called IVON, which is an information system for the rehabilitation of Dutch highways. All the information relevant for the maintenance planning is stored in a database which consists of three information-systems, namely:

- the highway location system (RWLS) with information about the position and the configuration of the highways.
- the system (WEGZWA) with empirical knowledge about asphalt-toplayers
- the road-measurements system (WEGMET) with information on the current state of the road, mostly measured by the Automatic Road Analyzer (ARAN)

The planners of DWW construct within IVON for each carriage-way a maintenance plan for ten years by the so-called sector-integration method which is discussed later. The results are presented in a system called IVON.PRES, which is not only giving a technical maintenance plan, but also a prognosis of the costs in the next ten years, and a road map in which the road engineering projects are visualized. The print-out is given to road-experts who examine the roads on the spot, in order to adjust the plan whenever necessary. The adjustments are specified within IVON.PRIO which calculates the consequences of the adjustments, while checking the validity of the plan. After the adjustments are made a definite plan is obtained which is mainly fixed for the first five years.

Figure 2.7 gives a schematic representation of DWW's planning methodology.

Figure 2.7 : Flow Diagram of DWW's planning methodology



The planning is done by the sector integration approach which consists of the following steps :

step 1 : fetch from the database the current state of the road-segments

step 2 : calculate for each segment the expected residual lifetimes

→ for each damage feature the expected residual lifetime is computed, viz. the time that is left till the damage crosses its failure-limit; this is done by linear interpolation.

step 3 : construct homogeneous sections

→ adjacent segments for which hold that the differences between the residual lifetimes are all beneath a certain threshold are aggregated into a homogeneous section

step 4 : select for each homogeneous section the most 'cost-effective' maintenance package

→ for each package the annual equivalent cost (AEC) is computed - see equation (2.1); the package with the lowest AEC is chosen.

step 5 : improve the maintenance plan

→ several possible adjustments are made, and evaluated with IVONPRIO; if the adjustment appears to be cost-effective then the adjustment is established, otherwise it is nullified.

step 6 : make a cost-prognosis for the next years

→ for each planning year an assessment is made of the maintenance costs, in order to set a budget for a certain region.

Most of the steps are half-automated, the planner must use his own experience and intuition to construct a full maintenance plan.

2.6 MODIFYING THE CURRENT PLANNING METHODOLOGY WITH JUNCTION TO JUNCTION REGENERATIONS

Within the sector integration approach all the maintenance is done at local spots. Because of the quantity-rebate of the maintenance activities, and the enormous set-up costs of permanent road barrier constructions which allow for maintenance by day, it may be beneficial to perform every now and then junction-to-junction regenerations in order to reduce the nightly patchworks which are quite expensive.

Junction-to-junction regenerations are commonly maintenance projects of several kilometers length; the full carriage-way is regenerated, mostly within a 3-1 or a 4-0 road barrier system if the highway consists of 2x2 lanes. Table 2.17 shows the duration and the costs of regenerating a 4 kilometers long carriage-way..

Table 2.17 : maintenance and road barrier costs of generating a 4 kilometers long carriage-way within a 3-1 / 4-0 barrier system

3-1 barrier system	action 2^d	action 3^d	action 2^p	action 2^p
duration	45 (+3) days	60 (+3) days	53 (+3) days	68 (+3) days
road barrier cost	Dfl. 292,300	Dfl. 292,300	Dfl. 292,300	Dfl. 292,300
maintenance cost	Dfl. 466,900	Dfl. 1,131,600	Dfl. 1,152,300	Dfl. 1,817,000
total cost	Dfl. 759,200	Dfl. 1,423,900	Dfl. 1,444,600	Dfl. 2,109,300
4-0 barrier system	action 2^d	action 3^d	action 2^p	action 2^p
duration	45 (+2) days	60 (+2) days	53 (+2) days	68 (+2) days
road barrier cost	Dfl. 259,800	Dfl. 259,800	Dfl. 259,800	Dfl. 259,800
maintenance cost	Dfl. 466,900	Dfl. 1,131,600	Dfl. 1,152,300	Dfl. 1,817,000
total cost	Dfl. 726,700	Dfl. 1,391,400	Dfl. 1,412,100	Dfl. 2,076,800

The total cost of a road engineering project is the sum of the road barrier cost and the maintenance cost. However this cost does not take the vehicle queuing loss into account which is penalized with DFL. 30.- per hour. To calculate the social cost of a road engineering one must add to the total cost of the road engineering project the vehicle queuing cost. The vehicle queuing cost can be simply calculated from Table 2.18, by multiplying the total vehicle queuing hours with the hourly penalty cost. The number of vehicle loss hours can be calculated by the duration of the maintenance project in days with the number of vehicle queuing hours per 24 hours calculated through the traffic congestion model (see Table 2.15).

Table 2.18 : vehicle queuing hours caused by several node to node activities within a 3-1 and a 4-0 road barrier system.

3-1 road barrier system	action 2^d	action 3^d	action 2^p	action 2^p
45,000 vcw / 24 hours	0 hrs.	0 hrs.	0 hrs.	0 hrs.
47,500 vcw / 24 hours	240 hrs.	315 hrs.	280 hrs.	355 hrs.
50,000 vcw / 24 hours	13,968 hrs.	18,333 hrs.	16,296 hrs.	20,661 hrs.
52,500 vcw / 24 hours	67,536 hrs.	88,641 hrs.	78,792 hrs.	99,897 hrs.
55,000 vcw / 24 hours	201,792 hrs.	264,852 hrs.	235,424 hrs.	298,484 hrs.
57,500 vcw / 24 hours	405,888 hrs.	532,728 hrs.	473,536 hrs.	600,376 hrs.
60,000 vcw / 24 hours	670,320 hrs.	879,795 hrs.	782,040 hrs.	991,515 hrs.
4-0 road barrier system	action 2^d	action 3^d	action 2^p	action 2^p
45,000 vcw / 24 hours	0 hrs.	0 hrs.	0 hrs.	0 hrs.
47,500 vcw / 24 hours	8,366 hrs.	11,036 hrs.	9790 hrs.	12,460 hrs.
50,000 vcw / 24 hours	67,210 hrs.	88,660 hrs.	78,650 hrs.	100,100 hrs.
52,500 vcw / 24 hours	204,826 hrs.	270,196 hrs.	239,690 hrs.	305,060 hrs.
55,000 vcw / 24 hours	441,518 hrs.	582,428 hrs.	516,670 hrs.	657,580 hrs.
57,500 vcw / 24 hours	763,750 hrs.	1007,500 hrs.	893,750 hrs.	1137,500 hrs.
60,000 vcw / 24 hours	1557,298 hrs.	2054,308 hrs.	1822,370 hrs.	2319,380 hrs.

vcw = vehicles per carriage-way; both carriage ways are 12.5 meters broad

To extend the current planning methodology with junction to junction regenerations, one must first specify junctions, and then indicate at what moment a junction-to-junction section is regenerated. The specification of junctions is quite arbitrary; one can select indiscriminate points provided that they are recognizable, and the distance between any two subsequent points is not too short to justify the use of permanent road barrier systems. The moment at which junction-to-junction is done can be conditioned upon the number of segments which are - for any of the four damage features - in an (almost) normative state; a segment is in an almost normative state if the damage has reached the warning level. If the percentage of segments that is in an (almost) normative state is greater than or equal to a certain norm percentage, then one can compel junction-to-junction maintenance.

However, one should realize that it is not sensible to furbish several patches of the carriage-way just before it is completely regenerated. Therefore, there is a second percentage also based on the number of segments in an (almost) normative state, which indicates from what moment the local patchwork is abandoned till the carriage-way is obtaining junction-to-junction maintenance.

Thus, we extend the section integration method with a norm percentage L and a postpone-percentage D. If the percentage of segments in an (almost) normative state is lower than D, then a sector integration plan is made up; if the percentage is greater than or equal to D but smaller than L, then the local patchwork is abandoned till the carriage-way is regenerated; and if the percentage is greater than or equal to then the carriage-way is regenerated from junction to junction. We call this approach the junction-to-junction maintenance approach.

2.7 The key question : is it worthwhile to utilize junction to junction regenerations ?

Before DWW is adopting the junction-to-junction maintenance approach it wants to know if this approach can be economically justified. Because of the complex structure of the road maintenance problem, the economic advantage of junction-to-junction regenerations can not be determined analytically. Therefore we decided to verify the economic benefit of junction-to-junction regenerations by simulation. We consider a 2x2 lanes carriage-way of 4 kilometers length, and try to determine the long term consequences of the sector integration approach; then we try to determine the long-term consequences of the junction-to-junction maintenance approach; the percentages L and D are determined by simulation-optimization.

A problem arises if we try to simulate the sector-integration approach, as some steps are quite open and leave the precise execution to the planners, this means that the planning approach can not be exactly replicated by a full-automated algorithm. Therefore we developed an algorithm which is a rough plagiarism of the sector-integration method, and can be fully executed by a PC. By extending the algorithm with the option to utilize junction-to-junction regenerations we can also simulate the junction-to-junction maintenance approach.

The simulation-program makes use of deterioration-functions; these functions are estimated from data which are obtained by expert-judgment. In chapter 3 it is explained how these deterioration processes are estimated. Within the pilot-study each road-segment has four independent deterioration processes. Through simulation we try to determine whether it is really worthwhile to utilize junction-to-junction regenerations. In chapter 4 the pilot-study is described more in detail.

3. Replication of the Deterioration Processes

To verify the quality of a maintenance concept we must first find equations which broadly replicate the deterioration processes of the road. These equations are then used to simulate the whole road rehabilitation process to assess the economic consequences of the maintenance concept. Since it was too difficult to estimate the deterioration processes from the historic road deterioration and mending data of DWW, we decided to estimate the deterioration processes through expert-judgement. In section 3.1 we describe the general model for the replication of the deterioration processes. In section 3.2 it is explained how the parameter-values are estimated. A special model is used for transversal unevenness, in order to obtain an s-shaped wear curve; this model is explained in section 3.3. Section 3.4 presents the results of the estimation process.

3.1 Deterioration Modeling

The deterioration processes cracking, raveling and longitudinal unevenness are modeled by the following Wiener process (see also Burger [1991]):

$$D_t = \mu\, t^{q} + \sigma \sqrt{t}\cdot U,\ t \geq 0 \qquad (3.1)$$

where D_t is the stochastic damage t time-units after it is removed by road mending with D_0=0. The parameter q > 0 is the shape parameter of the deterioration process D_t ; if q = 1 then the deterioration is constant in time, if q < 1 then the deterioration is decelerating in time, and if q > 1 then the deterioration is accelerating in time. The parameter $\mu > 0$ is the trend parameter of the deterministic part $\mu\, t^{q}$, and the parameter $\sigma \geq 0$ the volatility parameter of the stochastic part $\sigma \sqrt{t}\cdot U$, where U is a random variable with a standard normal distribution which is denoted by

$$\Phi(\mathrm{u}) := P(U \le \mathrm{u}) = \int_{-\infty}^{\mathrm{u}} \frac{1}{\sqrt{2\pi}} \mathrm{e}^{-\frac{x^2}{2}} \mathrm{d}x, \quad \mathrm{u} \in (-\infty, \infty) \; . \tag{3.2}$$

Thus D_t is normally distributed with mean μt^q and variance $\sigma^2 t$. Denote by F > 0 the failure-limit of the deterioration process D_t , then the probability that the damage D_t is beyond the failure-limit F is given by:

$$G(t; F, \mu, q, \sigma) = 1 - \Phi\left(\frac{F - \mu t^q}{\sigma \sqrt{t}} \right), \; t \ge 0 \tag{3.3}$$

3.2 ESTIMATION OF THE PARAMETERS

The parameters μ, q and σ are estimated by doing a least squares regression on the failure probabilities α_i i=1,..,4 which are obtained by expert judgment - see section 2. The parameter q is restricted to a value smaller than 1 if the road expert believe that the damage proliferates less than proportional; if the road experts believe that the damage proliferates more, the parameter q is restricted to a value greater than 1. If it is thought that the damage grows constantly in time then the parameter q is set to 1. Another restriction is that the parameter q must be the same for the dense asphalt road as for the very open asphalt road to assure that the deterioration process has for both types of roads a congruent shape.

Then there are several restrictions with respect to the time at which the process D_t crosses the failure bound F. First we restricted the deviation between the time at which the deterministic function μt^q crosses the failure bound F, and the time T^{mean} given by the road-experts at which they expect the damage will pass the failure-limit, to a maximum of 20% of the time given by the road-experts, that is

$$\left| \left(\frac{F}{\mu} \right)^{\frac{1}{q}} - T^{mean} \right| \le 0.2 \cdot T^{mean} \tag{3.4}$$

Further we set an upperbound on the probability that the failure limit will be reached before the time T^{min} given by the road experts which is considered as the earliest time at which the process D_t may pass the failure limit F. We restricted this probability to a maximum of 2.5%, thus:

$$\mu \cdot T^{min\,q} + z_{0.975} \cdot \sigma \cdot \sqrt{T^{min\,q}} \le F \tag{3.5}$$

where z_χ is the χ-th percentile of a standard normal distribution.
We also set an upperbound (2.5%) on the probability that the failure limit will be reached after the time T^{max} given by the road experts which is considered as the latest time at which the process D_t may pass the failure limit F, viz.

$$\mu \cdot T^{max\,q} + z_{0.025} \cdot \sigma \cdot \sqrt{T^{max\,q}} \ge F \tag{3.6}$$

We mention that $z_{0.025} \approx -1.96$, and $z_{0.975} \approx 1.96$.

Under these restrictions we enumeratively determined the parameters μ, q and σ, for which the sum of squared errors, given by

$$\sum_{i=1}^{4} \left(G(t_i; \mu, q, \sigma) - \alpha_i \right)^2 \tag{3.7}$$

is minimal, with $t_1=5$, $t_2=10$, $t_3=15$ and $t_4 = 20$, and α_i : i=1,2,3,4 the probabilities that the failure-limit will be reached within t_i years when the road is currently as-good-as-new.

The parameters are simultaneously estimated for the dense and very open asphalt road. In fact we minimized the sum of equation (3.7) for the dense asphalt road, and equation (3.7) for the porous asphalt road, by which five parameter values are obtained; two trend parameters: μ_{dense} and μ_{porous} , two volatility parameters: σ_{dense} and σ_{porous}, and one shape parameter q.

Nota bene, the answers obtained by expert-judgement are not all appropriate as the road-experts considered a planning horizon of 15 years. They specified “ > 15 “ when they believed that the mean time till failure: T^{mean} exceeds a duration of 15 years; the same holds for the maximum duration till failure: T^{max}. Therefore we replaced equation (3.4) by

$$\left(\frac{F}{m}\right)^{\frac{1}{q}} > 15 \qquad (3.8)$$

if $T^{mean} > 15$, and equation (3.6) by

$$m \cdot 15^q + z_{0.10} \cdot s \cdot \sqrt{15^q} \le F \qquad (3.9)$$

if $T^{max} > 15$. The last equation guarantees that the probability that the failure limit will be reached after 15 years is greater than or equal to 10 %.

Further we remark that during the implementation we scaled the deterioration process by dividing the deterioration variable D_t and the parameters μ and σ through the failure limit F, so that we could estimate for each damage feature with a failure limit of 1.

The complete model is given in appendix A.

3.3 Obtaining an s-shaped wear curve

The deterioration process transversal unevenness is modeled by a slightly different Wiener process, namely:

$$D_t = m\, t^{q(t;m)} + s\sqrt{t} \cdot U, \; t \ge 0 \qquad (3.10)$$

where

$$q(t;m) = \frac{q}{\sqrt{e^{1-\left(2\cdot t\cdot\left(\frac{F}{m}\right)^{-1/q}-1\right)^2}}} \qquad (3.11)$$

to make sure that the process D_t has an s-shaped wear curve, first the damage proliferates less than proportional in time, and later - after time-point $½\cdot(F/μ)^{1/q}$ - it proliferates more than proportional in time.
It can be seen that the process D_t for transversal unevenness is also normally distributed, but with shape parameter $m\, t^{q(t;μ)}$ and variance s^2 t. Observe that the time at which the deterministic function $m\, t^{q(t;μ)}$ crosses the failure-limit F, is $(F/μ)^{1/q}$, and that the function q(t;μ) is decreasing when $t \le ½\cdot(F/μ)^{1/q}$ and increasing when $t > ½\cdot(F/μ)^{1/q}$.

The equations for the optimization of the parameters μ, q and σ within equation (3.10) are the same as equations (3.4) - (3.7), where the parameter q is substituted by q(t;μ).

3.4 Resulting Deterioration Functions

The results of the estimation process are displayed in Table 3.1; the parameter values of the damage features: cracking, raveling and longitudinal unevenness correspond to equation (3.1), and the parameter values of transversal unevenness to equation (3.10).

Table 3.1 estimated parameters

damage feature	*asphalt type*	*m*	*q*	*s*	*s.s.e.*
cracking	dense	1.25	7/6	1.75	0.1096
raveling	dense	1.2	7/6	1.8	0.2340
longitudinal unevenness	dense	0.175	1	0.42	0.0885
transversal unevenness	dense	7.56	1/3	1.26	0.2750
cracking	porous	0.75	7/6	0.75	0.0376
raveling	porous	1.5	7/6	2.1	0.1699
longitudinal unevenness	porous	0.175	1	0.42	0.0885
transversal unevenness	porous	6.66	1/3	0.9	0.0662

s.s.e. : sum of squared errors, measured as $\sum_{i=1}^{4}\left(G(t_i;F,m,q,s) - a_i\right)^2$

The errors can be due to an erroneous specification of the model, or a misjudgement of the road experts. DWW examined the consequences of the model (see Table 3.2) and found them quite convincing, so that they agreed on the use of the estimated deterioration functions for the evaluation of the junction-to-junction maintenance approach.

Table 3.2 : consequences

damage feature	*asphalt type*	*5 year*	*10 year*	*15 year*	*20 year*	*25 year*	*min.*	*mean*	*max.*
cracking	dense	0.0%	11.5%	74.4%	98.1%	99.9%	8.4	13.0	19.6
raveling	dense	0.0%	1.5%	40.2%	88.2%	99.1%	10.5	15.8	23.8
longitudinal unevenness	dense	0.3%	9.4%	29.5%	50.0%	66.2%	7.3	20.0	>50
transversal unevenness	dense	0.4%	9.4%	89.1%	100%	100%	7.3	13.5	15.6
cracking	porous	0.0%	0.0%	0.6%	46.6%	97.0%	16.0	20.2	25.2
raveling	porous	0.0%	11.5%	74.4%	98.1%	99.9%	8.4	13.0	19.6
longitudinal unevenness	porous	0.3%	9.4%	29.5%	50.0%	66.2%	7.3	20.0	>50
transversal unevenness	porous	0.0%	0.5%	5.6%	55.6%	100%	13.2	19.7	22.2

The charts corresponding to the replicated deterioration processes are shown in Figures 3.1-3.7; in each figure there are three curves; the middle curve labeled as ‘average’ is the deterministic course of the deterioration process; the area between the curves ‘2.5th pct.’ and ‘97.5th pct.’ is a symmetric 95% confidence interval around the deterministic course.

Fitted Deterioration Functions

Figure 3.1 : Cracking; Dense Asphalt

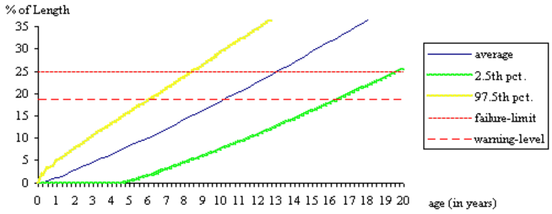


Figure 3.2 : Cracking; Porous Asphalt

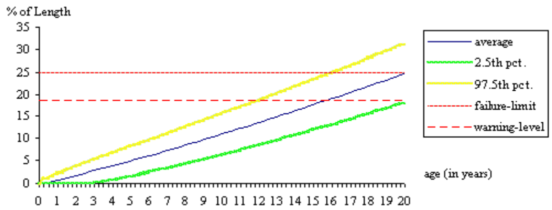


Figure 3.3 : Raveling; Dense Asphalt

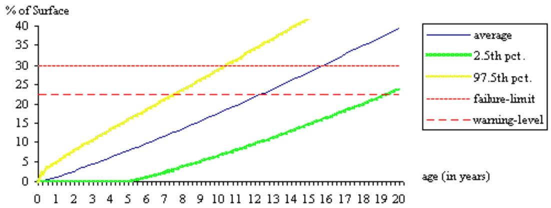


Figure 3.4 : Raveling; Porous Asphalt

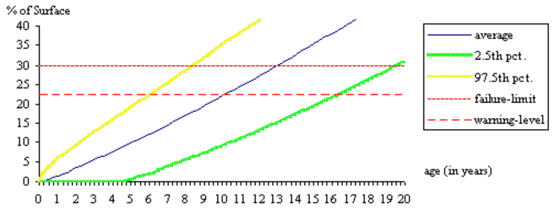


Figure 3.5 : Longitudinal Unevenness

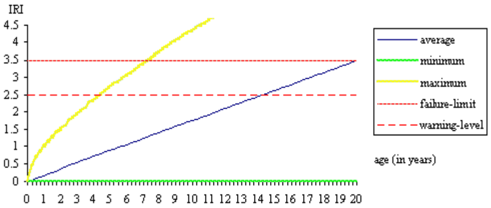


Figure 3.6 : Transversal Unevenness; Dense Asphalt

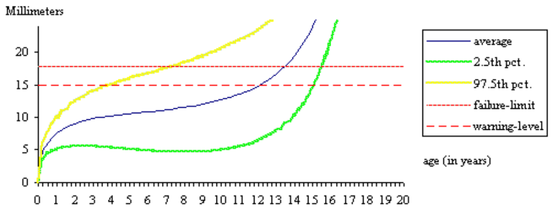


Figure 3.7 : Transversal Unevenness; Porous Asphalt

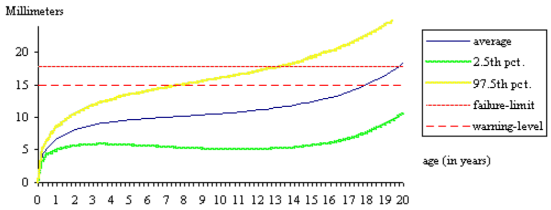


Figure 3.1 visualizes the replicated cracking process for a dense asphalt road. The chart shows that cracking is a highly stochastic process if the road is made of dense asphalt; the damage can become normative within 10 years, but can also be below the warning level 15 years after it has been completely removed. The convex shape of the deterministic course indicates that the deterioration process accelerates in the course of time.

Figure 3.2 displays the replicated cracking process for a porous asphalt road. Clearly, a road with a porous asphalt toplayer is more able to resist cracking than a road with a toplayer of dense asphalt. The probability that the damage will become normative within 15 years is almost negligible.

Raveling is also accelerating in the course of time. In Figure 3.3 one can see that a dense asphalt road is not expected to ravel within 10 years, despite the capriciousness of the deterioration process; the expected duration till the damage becomes normative is about 16 years.

While a porous asphalt road is more able to resist cracking than a dense asphalt road, it is less able to resist raveling. Figure 3.4 shows that raveling can already become normative after 8 years. Raveling is in general the most critical damage feature of a porous asphalt road.

The process longitudinal unevenness is approximately the same for dense and porous asphalt roads. In Figure 3.5 one can that longitudinal unevenness is a really capricious process, it can become normative within 10 years, but also after 50 years.

Figure 3.6 shows the estimated s-shaped curve for the course of transversal unevenness in the case of a dense asphalt road. Within the first year there are already ruts with a depth of 5 millimeters, but then the speed of rut-forming decreases till the road is half its expected lifetime after which the deterioration is getting fast. Transversal unevenness is in general the most critical damage feature of dense asphalt roads.

Porous asphalt roads are more able to persist the forming of ruts then dense asphalt roads. In Figure 3.7 one can see that transversal unevenness will not be a problem for the first 12 years. The expected duration till a porous asphalt road is getting normative ruts is about 20 years.

It looks somewhat strange that the 2.5th percentile curve in Figures 3.6 and 3.7 is not monotonically increasing, as there is an interval in which the deterministic course of the deterioration is fairly flat so that it can be dominated by stochastic fluctuations. Thus it can occur that there is a marginal decrease in the deterioration process, which is not quite unrealistic as part of the stochastic fluctuations is constituted of measuring errors.

4. Description of the Pilot-Study

Within our pilot-study we consider a 2x2 lanes road of 4 kilometers length; the road is divided in sectors of 100 meters length so that there are in total 160 lanesectors (segments). Each lanesector has four deterioration processes: cracking, raveling, longitudinal unevenness and transversal unevenness; we assume that these processes behave independently of eachother, and are also independent of the deterioration processes of neighboring segments. We simulate the maintenance process under a certain maintenance approach: the sector integration approach or the junction-to-junction maintenance approach. We do this for two types of asphalt roads: dense asphalt roads, and porous asphalt roads. For the junction-to-junction maintenance approach we need to optimize two control-parameters: the norm percentage L, and the postpone-percentage D; this is done through simulation-optimization. The purpose of the pilot-study is to compare the long-term consequences of the two maintenance approaches. In section 4.1 we describe how we generate the yearly deterioration of the 160 segments. Then we explain how the sector-integration approach is replicated, the algorithm is given in section 4.2. In section 4.3 it is explained how this algorithm can be extended with junction-to-junction regenerations to replicate the junction-to-junction maintenance approach. Section 4.4 describes the simulation procedure for evaluating the long term consequences of a maintenance approach, and in section 4.5 the optimization of the control parameters is explained.

4.1 Generating the Yearly deterioration

The deterioration of a segment is generated per damage feature, for which we use the deterioration functions estimated in section 3. Each segment has a current state, defined by

$$S = (Cr, Rv, Lo, Tr) \tag{4.1}$$

where *Cr*: seriousness of cracking in percentage of road-length, *Rv*: seriousness of raveling in percentage of road-surface, *Lo* : longitudinal unevenness in IRI, and *Tr* : transversal unevenness in millimeters.
From this state we determine per damage feature the virtual time. Suppose that the current damage is D for a damage feature with deterioration function (3.1), then the virtual time *t** corresponding to the damage D is calculated by taking the inverse of the deterministic part $\mu \cdot t^q$, thus

$$t^* = \left(\frac{D}{m}\right)^{1/q} \tag{4.2}$$

In the case of (3.10), t* is the root of the equation

$$t = \left(\frac{D}{m}\right)^{1/q(t;m)} \tag{4.3}$$

which is solved numerically.

With the virtual time t*, we can generate the yearly increment ΔD by drawing a random number U~N(0,1), and applying the formula

$$\Delta D = m \cdot (t^*+1)^q - D + s \cdot U \tag{4.4}$$

if the deterioration function has the form (3.1), and

$$\Delta D = m \cdot (t^*+1)^{q(t^*+1;m)} - D + s \cdot U \tag{4.5}$$

if the deterioration function has the form (3.10).

Adding this increment to the current damage gives the damage for the next year: D+ΔD.

Due to the stochastic term σ·U the increment ΔD can be negative if σ is sufficiently large, which is not odd as there may be errors within the observation of the damage. An occasional improvement is practically not giving much problems as the maintenance decisions depend on the condition-level of the observed damage, which is rarely improving by a negative increment.

Since longitudinal unevenness is a carriageway-width damage feature, we generate the deterioration per carriage-sector and not per lane-sector. Notice that longitudinal unevenness can only be managed by carriageway-width actions.

4.2 Algorithm for Replicating the Sector Integration Approach

The sector-integration approach is replicated by a phase-wise assignment of maintenance packages to road-segments. A number of quality poor carriage- and lane-sections are formed which are entirely repaired, for which a maintenance package is selected based on the equivalent annual cost. Then we look for segments which need small maintenance to assure that the damage is no longer normative. For these segments we also determine the most cost-effective action on the basis of the EAC-criterion. The algorithm which fully executes the sector integration approach is described below.

algorithm for replicating the sector integration approach

Denote a carriage-way by w=1,2 and denote their lanes by i=w-1,w; let the sectors j=1,..,40 be in order of geographical appearance, and denote by segment (i,j) the lanesector on lane i and sector j. Call a segment *affected* if one of the deterioration processes has reached the warning level, and otherwise *unaffected*. Call an *affected* segment *lane-affected* if the affection is not (merely) caused by longitudinal unevenness. The sector-integration method can be replicated by performing the following steps.

step 1[a] : construct carriage-sections

Construct for each carriage-way w=1,2 carriage-sections of at least 400 meters which must be completely repaired. Do this as follows: check for every 400 meter block: j=4,..,40, the state of the segments (i,k), i=2w-1,2w, k=j-3,..,j; if all eight segments are *affected*, then label the carriage-sectors (w,j), k=j-3,..,j as *candidate*-sectors; other sectors are labeled as *non-candidates*. Call a *candidate*-sector of which one of the deterioration processes has reached the failure limit an *integrator*. Adjacent carriage-sectors labeled as *candidates* with at least one segment being an *integrator* are integrated into a *carriage-section*.

step 1[b] : determine for each carriage-section a cost-effective maintenance package

Determine for each carriage-section R the 'most' cost-effective maintenance package by calculating the EAC-odds for the packages which are appropriate for maintaining a carriage-section with a length of at least 400 meters. The EAC-odds for an ordered action-set $\{a_1,..,a_n\}$ with respect to a carriage-section R, is calculated by comparing the mutual EAC's of the packages $a_1,..,a_n$ for each segment within the carriage-section.

The EAC of a package a for road-segment (i,j) is defined as :

$$EAC_{i,j}(a) = \frac{\text{unit price of action a}}{\text{expected gain in years of action a for segment (i, j)}} \quad (4.6)$$

where the expected gain in years is the difference between the expected residual lifetime just before action a is performed, and the expected residual lifetime just after action a is performed.

The EAC-odds for the ordered action-set $\{a_1,..,a_n\}$ with respect to the carriage-section R, is defined as :

$$\text{EAC-odds}(\{a_1,..,a_n\}; R) = (v_1(\{a_1,..,a_n\}; R), .., v_n(\{a_1,..,a_n\}; R)) \quad (4.7)$$

where

$$v_k(\{a_1,..,a_n\};R) := \sum_{(i,j)\in R} \prod_{\substack{h=1 \\ h\neq k}}^{n} 1_{\{EYC_{(i,j)}(a_k) < EYC_{(i,j)}(a_h)\}}$$

with $1_{\{.\}}$ the indication function.

Since the packages appropriate for repairing a carriage-section with a length of at least 400 meters are the packages 2,3 and 5, we calculate the EAC-odds ({2,3,5};R).

The action a_k with the highest odds-value $v_k(\{2,3,5\}; S)$, is chosen.

step 2[a] : construct lane-sections

Construct for each lane i=1..4 lane-sections of at least 400 meters which must be completely repaired. Do this as follows: check for every 400 meter block : j=4,..,40, the state of the segments (i,k), k=j-3,..,j; if all four segments are lane-*affected* and none of them has been integrated within a carriage-section, then label the lane-sectors (i,j), k=j-3,..,j as *candidate*-sectors; other sectors are labeled as *non-candidates*. Call a *candidate*-sector of which a deterioration processes other than longitudinal unevenness has reached the failure limit an *integrator*. Adjacent lane-sectors labeled as *candidates* with at least one segment being an *integrator* are integrated into a *lane-section*.

step 2[b] : determine for each lane section a cost-effective maintenance package

Determine for each lane-section W the 'most' cost-effective maintenance package by calculating the EAC-odds for the packages which are appropriate for maintaining a lane-section with a length of at least 400 meters; the EAC-odds are defined by (4.7). Since the only appropriate lane-section packages are the packages 6 and 7, we calculate the EAC-odds ({6,7};W).

The action a_k with the highest odds-value $v_k(\{6,7\}; W)$, is chosen.

step 3 : recondition single segments for which the damage is still normative

Given the results of the packages executed on carriage- and lane-sections, perform package 1 (rut-filling) on those segments which still have normative ruts (transversal unevenness) or cracks, and package 4 (leveling) on segments which still suffer from normative unevenness in the longitudinal direction. The packages 1 and 4 are corrective maintenance packages, and will not be performed on segments with not normative or almost normative damage.

4.3 ALGORITHM FOR REPLICATING THE JUNCTION-TO-JUNCTION MAINTENANCE APPROACH

By extending the sector-integration algorithm with junction-to-junction regenerations we can replicate the junction-to-junction maintenance approach. The decision to regenerate a carriage-way can be based on the overall quality of the carriage-way; let the overall poorness be expressed by a percentage of segments having at least damage feature which is (almost) normative, viz. the percentage segments that is *affected*. Junction-to-junction regeneration is performed if and only if the overall poorness is greater than or a equal to a certain norm-percentage L. To avoid patchworks just before the carriage-way is regenerated we work with a postpone-percentage D; if this percentage is reached then maintenance is postponed till the norm-percentage L is reached, then the carriage-way is fully regenerated. During the period that the overall quality is between the percentages L and D, only small maintenance is carried out to expunge any normative damage.

The junction-to-junction maintenance approach can be replicated by the following statement :
If the overall poorness is smaller than D, then perform steps 1-3 of the sector integration approach; otherwise if the overall poorness is smaller than L, then perform step 3 of the sector integration method. If the overall poorness is greater than or equal to L than perform junction-to-junction regeneration.

There are two possible techniques for regenerating a carriage-way: by the remix-technique (package 2), or by the repave technique (package 3). To determine the 'most' cost-effective technique we calculate the EAC-odds, defined by (4.7), for actions 2 and 3. Denote by Z the junction-to-junction carriage-way; if $v_1(\{2,3\}; Z)$ is greater than or equal to $v_2(\{2,3\}; Z)$, then action 2 is chosen; else if $v_1(\{2,3\}; Z)$ is smaller than $v_2(\{2,3\};Z)$, then action #3 is chosen.

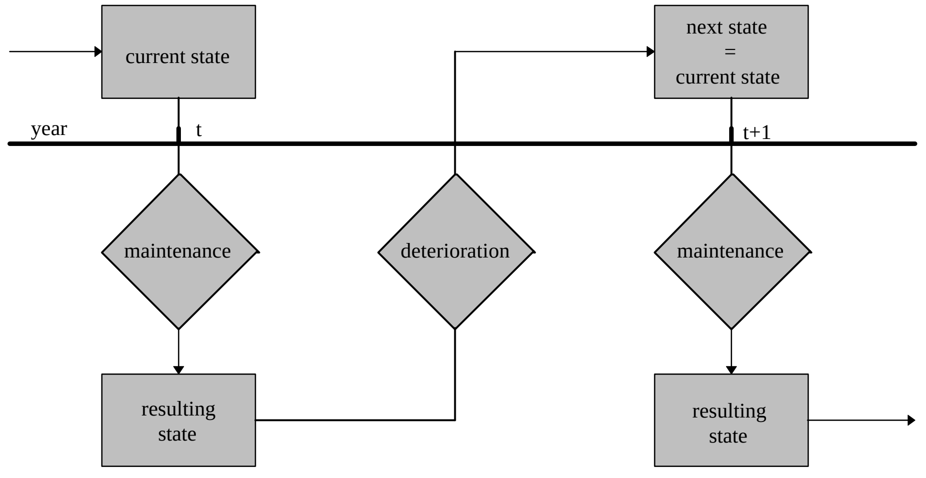
4.4 SIMULATION OF THE MAINTENANCE PROCESS

We now try to determine the long term consequences of the sector integration approach and the junction-to-junction maintenance approach for a 2x2 lanes road of 4 kilometers length, we do this for a dense asphalt road and a porous asphalt road. The long-term consequences are approximated by a 'steady-state' simulation which is terminated after 2,500 years, and is preceded by a start-up simulation of 30 years to obtain a proper initial state.

For each of the maintenance approaches we try to determine the following long-term statistics:
- the yearly average rehabilitation costs, composed of maintenance and road barrier costs
- the yearly average vehicle loss hours for different traffic intensities
- the long-run quality of the road, indicated by percentages of segments with i) not normative, ii) almost normative, and iii) normative damage.

The simulation approach is in fact a repetitive execution of the following steps:
1) update the current state of the segments
2) assign to the segments maintenance packages by one of the maintenance algorithms
3) compute the maintenance costs, the road barrier costs, the vehicle queuing loss, the average quality of the road, the frequency and the average size of the maintenance packages
4) determine for each segment the resulting state after execution of the road engineering projects
5) generate for all segments the one-year deterioration from their resulting states to determine their next states

Figure 4.1 : Diagrammatic Representation of the Simulation Process



The road is initially ‘as-good-as-new’, meaning that S=(0,0,0,0) for all segments. Starting with the initial state, we assign road engineering projects with the sector integration algorithm or the junction-to-junction regeneration algorithm. We then calculate the costs of the road engineering projects, taking the quantity rebate into account, and determine the expected amount of traffic jams which depends on the traffic intensity and the type of road barrier systems used. We also keep track with the frequency and the average magnitude of the maintenance packages, and the overall quality of the road.
Then we try to determine the effect of the road engineering projects on the state of the segments, for which we use Table 2.6. Consider a damage feature, and assume that the current damage is D, and that the deterministic part of the deterioration function, estimated in chapter 3, is given by H(t), which is $\mu \cdot t^{q}$ in the case of (3.1) and $\mu \cdot t^{q(t;\mu)}$ in the case of (3.10). Given a damage D we calculate the corresponding virtual age t* by either (4.2), or (4.3).

The virtual age after execution of a maintenance package can be calculated from the current virtual age t* and the effects in Table 2.6. If the effect is x (= nominal effect) then the virtual age after execution of the maintenance package is 12-x (this is because the nominal effect is representing the residual lifetime with a reference lifetime of 12 years), and if the effect is t+x (= relative effect), then the residual lifetime after execution of the maintenance package is the maximum of t*-x and 0.

Denote the virtual age after execution of the maintenance package by T. Putting T in the function H gives the resulting damage for the considered damage feature. We do this for all damage-features, so that we obtain the state of the segment after execution of the maintenance package. Then we generate per damage feature the one-year deterioration of the segment for which we use the virtual age after execution of the maintenance package (see section 4.1), such that the damage becomes $H(T+1)+\sigma \cdot U$.

4.5 Optimization of the Control Parameters

The control-parameters L and D are optimized by simulation-optimization; we verify the long-run total rehabilitation costs for several combinations of control-values through steady state simulation. We do this with a precision of 5%. To guarantee a minimum road-quality we imposed the restriction L ≤ 75% . A test simulation indicated that the long term overall poorness of the sector integration approach was around the 50%, so that we imposed a lower-bound of 50% for L. The postpone-percentage D is bounded by 50% and L, so that we have 21 combinations of parameter-values to evaluate.

We try to find those parameter-values for L and D that minimize the total rehabilitation costs, composed of maintenance and road barrier costs. For each combination of parameter-values we approximate the long run average rehabilitation costs by performing a steady-state simulation which terminates after 300 years. Each simulation starts with the same seed-value so that the deterioration has the same stochastic increments $\sigma \cdot U$, from year to year.

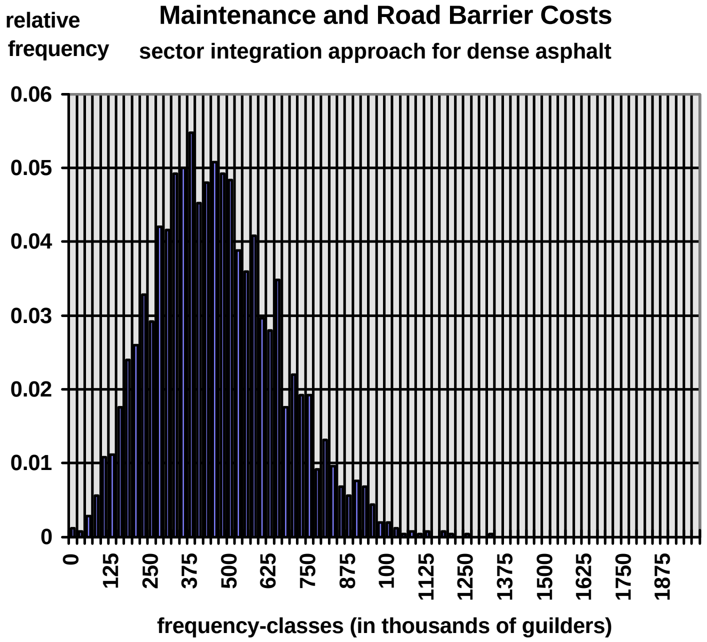
5. Results

In this section the results of the pilot-study are presented; first we show the long run consequences of the two maintenance approaches for dense asphalt roads, and then we show the long run consequences for porous asphalt roads. For the junction-to-junction maintenance approach the long run consequences are determined for optimized parameter values L and D (see Appendix B) which appeared to be 60% and 75% for dense asphalt roads, and 65% and 75% for porous asphalt roads. We will present the long run average preservation costs, the average quality of the road in the long run, the frequency and the average size of the particular maintenance projects, and the average heaviness of the traffic jams caused by maintenance activities. We emphasize that all the patchworks and corrective maintenance activities within the sector integration approach are done within 2-1 road barrier systems, at night (= traditional maintenance). Thus, the vehicle queuing costs of the sector integration approach are ‘hidden’ in the extra night surcharge of the maintenance packages which is 15% for each package.

5.1 Dense Asphalt Roads

Starting with the long run preservation costs under the sector integration approach, it appears that these costs are almost normally distributed with a mean of Dfl. 470.402.- per year, and a standard deviation of Dfl.200,713.- per year. There is only a small tail to the right (see Figure 5.1), so that the median of the preservation costs, which is Dfl. 466,043.- per year, is somewhat smaller than the average preservation costs. The considerable variation within the preservation costs is a pure consequence of the phenomenon that there are in some years four or five homogeneous sections repaired while in other years there are only small corrective actions done.

Figure 5.1 : yearly preservation costs for dense asphalt roads in the absence of junction-to-junction regenerations.



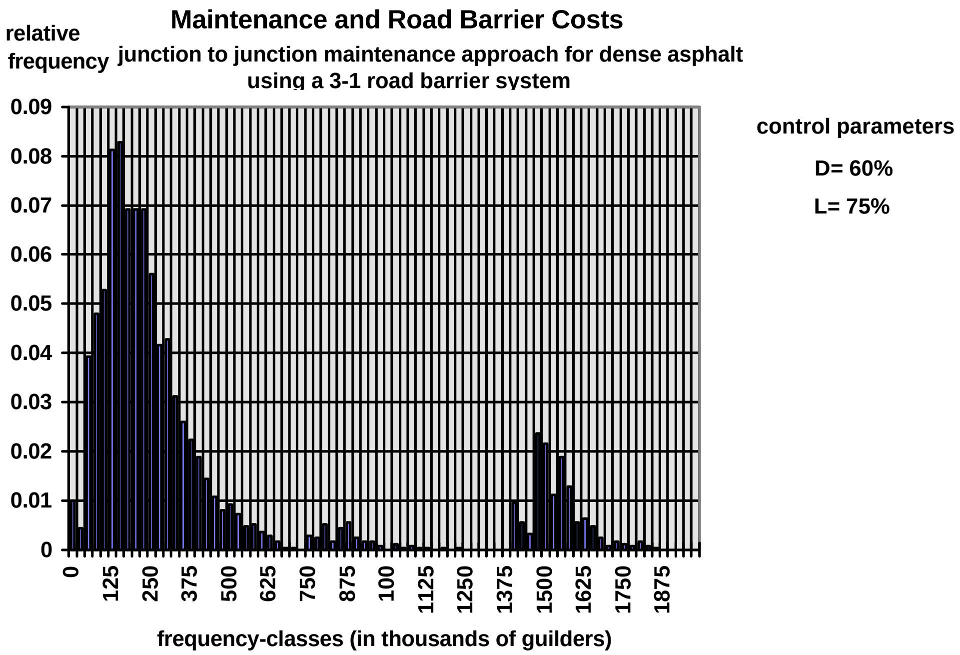
Therefore the 70%, and the 95% confidence intervals of the annual preservation costs are pretty wide :

70 % confidence interval : between Dfl. 277,226.- and Dfl 688,636.-
95 % confidence interval : between Dfl. 145,982.- and Dfl. 923,684.-

The proportions of maintenance cost and road barrier costs are 94.4% and 5.6% respectively.

Since 15% of the maintenance costs are ‘hidden’ vehicle queuing costs we have a long run average vehicle queuing cost of Dfl. 66,609.-. The ‘hidden’ vehicle queuing costs are independent of the traffic intensity.

Figure 5.2 : yearly preservation costs for dense asphalt roads when junction-to-junction regeneration are applied.



If the junction-to-junction maintenance approach is applied then there is more fluctuation in the preservation costs, however the long run average preservation costs are lower compared to the costs made under the sector integration approach. The average preservation costs are Dfl. 431,130.- per year with a standard deviation of Dfl. 477,514.- The empirical distribution function visualized in Figure 5.2 shows several humps in the probability density of the preservation costs. The first hump corresponds to the patchworks and the small maintenance actions, and is more to the left of the big hump of the sector integration approach. The second hump around Dfl. 1,600,000.- is due to junction-to-junction regenerations, which causes a enormous skewness in the probability density function. The median of the preservation costs is Dfl. 253,107.- which is substantially lower than the average preservation costs.

The variation in the preservation costs is also expressed in the 70% and 95% confidence intervals :

70 % confidence interval : between Dfl. 277,226.- and Dfl 688,636.-
95 % confidence interval : between Dfl. 145,982.- and Dfl. 923,684.-

The proportions of maintenance and road barrier costs are 87.3% and 12.7% respectively.

The above outcomes hold for the case in which a 3-1 system is used for junction-to-junction regenerations.

For a 4-0 system the average cost is Dfl 425,748.- since the long run road barrier costs are 5,382 cheaper when the 4-0 system is applied instead of the 3-1 system.

For both systems the 'hidden' vehicle queuing costs are Dfl. 43,858.- per year.

When the traffic intensity is sufficiently high the junction-to-junction maintenance approach causes traffic jams. Table 5.1 shows the vehicle queuing costs for different traffic intensities and different road barrier systems.

Table 5.1 : long run average vehicle queuing cost per year caused by maintenance, for dense asphalt roads ('hidden' costs included)

traffic intensity	traditional maintenance	with complete regenerations under 3-1 road barrier system	with complete regenerations under 4-0 road barrier system
≤ 45,000 vcw per 24 hours	Dfl. 66,609.-	Dfl. 43.858.-	Dfl. 43.858.-
47,500 vcw per 24 hours	Dfl. 66,609.-	Dfl. 45.358.-	Dfl. 96.238.-
50,000 vcw per 24 hours	Dfl. 66,609.-	Dfl. 130.948.-	Dfl. 464.758.-
52,500 vcw per 44 hours	Dfl. 66,609.-	Dfl. 464.968.-	Dfl. 1.326.568.-
55,000 vcw per 24 hours	Dfl. 66,609.-	Dfl. 1.302.118.-	Dfl. 2.808.838.-
57,500 vcw per 24 hours	Dfl. 66,609.-	Dfl. 2.574.778.-	Dfl. 4.826.818.-
60,000 vcw per 24 hours	Dfl. 66,609.-	Dfl. 4.179.780.-	Dfl. 9.796.378.-

vcw = vehicles per carriage-way; both carriage ways are 12.5 meters broad

It follows that junction-to-junction regenerations should not be applied to roads with a traffic intensity of 50,000 or more vehicles per 24 hours. The 3-1 road barrier system is more cost efficient than the 4-0 barrier system if and only if the daily traffic intensity is greater than the 45,000 vehicles.

If we look at the overall quality of the road under the two maintenance approaches then we see an long run average poorness of 59.0 % under the sector integration approach and 45.9 % under the junction-to-junction maintenance approach. The behavior of the road quality is quite different under the two maintenance approaches; under the sector integration approach the average road poorness converges to 59% while the average poorness under the junction-to-junction maintenance approach is fluctuating from 30% till 75%; the former percentage is the average poorness just after a carriage-way has been completely regenerated, and the latter percentage the average poorness just before the carriage-way is completely regenerated. In Figure 5.3 and 5.4 one can see the long run consequences per damage feature; it appears that raveling is much better controlled under the junction-to-junction maintenance approach than under the sector integration approach. For the other three damage features there are no significant differences.

Figure 5.3 : long run seriousness of damage - dense asphalt roads, in the absence of junction-to-junction regenerations.

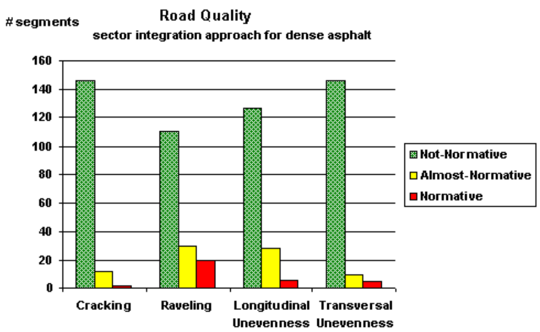
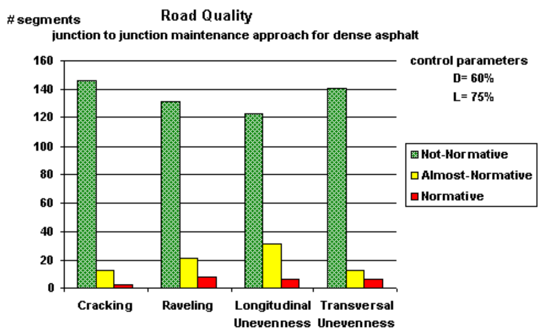


Figure 5.4 : long run seriousness of damage - dense asphalt roads, when junction-to-junction regenerations are applied



For both maintenance approaches it holds that raveling and longitudinal unevenness are the most serious damage features; cracking and transversal unevenness are well under control.
The average time between two successive regenerations is 12 years, which roughly matches the conjectured lifetime of a dense asphalt layer which is 10 to 12 years.

The selection of the maintenance packages is also different under the two maintenance approaches. In Figure 5.5 and 5.6 one can see the relative percentages of maintenance packages which are executed on a road segment. Obviously, the proportion of the regeneration actions 2 and 3 is much higher under the junction-to-junction regeneration approach than under the sector integration approach, it increases from 20% to 48% which is almost the half of the road-mendings. If junction-to-junction regenerations are applied then the road needs less to be overlaid and to be replaced. The proportion of overlays reduces from 16% to 6% while that of replacements reduces from 36% to 8%, indicating that there are less patchworks done.

Figure 5.5 : selection of packages - dense asphalt roads, in the absence of junction-to-junction regenerations.

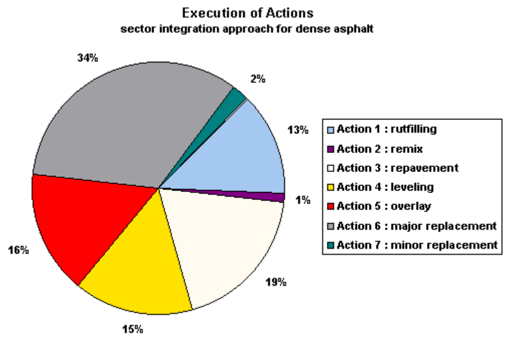
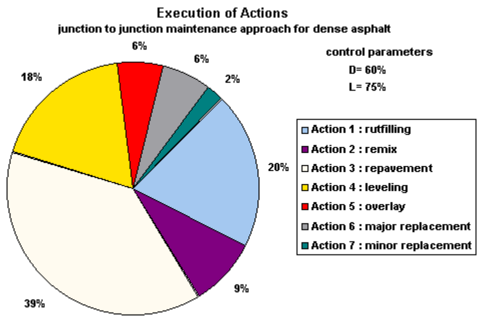


Figure 5.6 : selection of packages - dense asphalt roads, when junction-to-junction regenerations are applied



Interesting is that the proportion of rutfillings increases, probably because of the decrease in local patchworks; the same holds for leveling-actions. The average number of lane-width patchworks decreases from 2.66 to 0.87 sections per year while the average number of carriageway-width patchworks decreases from 1.34 to 0.37 sections per year. We also looked at the length of the homogeneous sections, and it appeared that the average length of the sections is under both approaches around the 500 meters.

The average number of segments obtaining small maintenance increases from 8.7 to 11.3 per year; thus the utilization of junction-to-junction regenerations decreases the number of local patchworks but increases the number of small corrective maintenance actions.

5.2 Porous Asphalt Roads

Porous asphalt roads are more expensive than dense asphalt roads and require also a higher maintenance budget, but for the remaining the results of the pilot study are quite analogous to that of dense asphalt roads.

Under the sector integration approach the long run preservation costs are Dfl. 713,988.- per year with a standard deviation of Dfl. 306,688.-.; again, the distribution function has a tail to the right. Approximately 14.3% of the preservation costs can be considered as ‘hidden’ vehicle queuing costs. The average poorness is 55.1% ; it appears that raveling is a more serious damage feature for porous asphalt roads than for dense asphalt roads; 1 out of 4 segments bears normative raveling while other damage features are well under control. Interesting is that the segments are in 47% of the cases overlaid, and in 39% of the cases replaced; they are rarely regenerated, which indicates that regeneration is not very cost-effective for the rehabilitation of porous asphalt roads.

Under the junction-to-junction maintenance approach the long run average preservation cost is Dfl. 706,577.- per year if the regenerations are done within a 3-1 road barrier construction, and Dfl. 702,833.- per year if the regenerations are done within a 4-0 road barrier construction; the standard deviation is around Dfl. 675,000.-.
The results are obtained with a delay percentage of D=65% and a norm percentage of L=75%, which appeared to be the optimal parameter-values in our grid-search (see Appendix B). About 11.6% of the preservation costs can be considered as ‘hidden’ vehicle queuing costs. The average time between two

successive regenerations is 17.2 years, which is somewhat larger than the conjectured lifetime of a porous asphalt road (15 years). When a carriage-way is regenerated the preservation costs can amount Dfl. 2,500.000.- which is extremely high. However, if a carriage-way is regenerated then little has to be done in the next few years, so if we look at the fluctuation in the preservation costs over several years then the variation is substantially smaller. If we look at the road quality than it appears that raveling is much better controlled under the junction-to-junction maintenance approach than under the sector integration approach; only 1 out of 8 segments is bearing normative raveling; as a consequence the average poorness is reduced to 45.6%. A disadvantage of the junction-to-junction maintenance approach is that the road quality is less stable than under the sector-integration approach, that is because the road quality is getting worse when the overall poorness has exceeded the delay percentage D; no preventive actions will be carried out till the overall poorness has reached the norm percentage L, at which the road will be regenerated so that the road-quality will be almost as-good-as-new.

A positive thing of junction-to-junction maintenance is that it reduces the traffic congestion if the traffic intensity is not overly high. If the traffic intensity is 45,000 vehicles per 24 hours or lower then one could best apply the 4-0 system as the cost of a 4-0 road barrier construction is cheaper than that of a 3-1 road barrier construction. However, if the traffic intensity is higher than 45,000 vehicles per 24 hours than the 3-1 system should be preferred as the 4-0 system will cause severe traffic jams. If the traffic intensity is above the 50,000 vehicles per 24 hours then junction-to-junction regenerations should be avoided as the vehicle queuing costs can be tremendous high.

In fact there is not much difference between dense asphalt roads and porous asphalt roads. With junction-to-junction regenerations on can reduce the long run average preservation cost, and improve the average road quality. However there is more fluctuation in the yearly expenses and also a more unstable road quality.

5.3 'OPTIMAL' MAINTENANCE POLICY

Should junction-to-junction regenerations be applied from an economic viewpoint ? The answer depends on the traffic intensity of the road. Table 5.3 and 5.4 give the long run consequences of the sector integration approach, and the junction-to-junction maintenance approach in the case that the 3-1 system is used, and in the case that the 4-0 system is used.

Table 5.3 long run average preservation and queuing cost per year, for dense asphalt roads

traffic intensity	traditional maintenance	with complete regenerations under 3-1 road barrier system	with complete regenerations under 4-0 road barrier system
≤ 45,000 vcw per 24 hours	Dfl. 470.402.-	Dfl. 431,130.-	Dfl. 425,748.-
47,500 vcw per 24 hours	Dfl. 470.402.-	Dfl. 432,630.-	Dfl. 478,128.-
50,000 vcw per 24 hours	Dfl. 470.402.-	Dfl. 518,220.-	Dfl. 846,648.-
52,500 vcw per 24 hours	Dfl. 470.402.-	Dfl. 852,240.-	Dfl. 1.708,458.-
55,000 vcw per 24 hours	Dfl. 470.402.-	Dfl. 1.689,390.-	Dfl. 3.190,728.-
57,500 vcw per 24 hours	Dfl. 470.402.-	Dfl. 2.962,050.-	Dfl. 5,208,708.-
60,000 vcw per 24 hours	Dfl. 470.402.-	Dfl. 4.567,052.-	Dfl. 10,178,268.-

vcw = vehicles per carriage-way; both carriage ways are 12.5 meters broad

Table 5.4 : long run average preservation and queuing cost per year, for porous asphalt roads

traffic intensity	traditional maintenance	with complete regenerations under 3-1 road barrier system	with complete regenerations under 4-0 road barrier system
≤ 45,000 vcws per 24 hours	Dfl. 713,988.-	Dfl. 706,577.-	Dfl. 702,833.-
47,500 vcw per 24 hours	Dfl. 713,988.-	Dfl. 707,807.-	Dfl. 745,763.-
50,000 vcw per 24 hours	Dfl. 713,988.-	Dfl. 777,767.-	Dfl. 1,047,743.-
52,500 vcw per 24 hours	Dfl. 713,988.-	Dfl. 1,050,797.-	Dfl. 1,753,973.-
55,000 vcw per 24 hours	Dfl. 713,988.-	Dfl. 1,735,097.-	Dfl. 2,968,673.-
57,500 vcw per 24 hours	Dfl. 713,988.-	Dfl. 2,775,377.-	Dfl. 4,622,333.-
60,000 vcw per 24 hours	Dfl. 713,988.-	Dfl. 4,123,187.-	Dfl. 8,694,743.-

vcw = vehicles per carriage-way; both carriage ways are 12.5 meters broad

For both asphalt roads it appears worthwhile to incorporate junction-to-junction regenerations if the traffic intensity is smaller than 50,000 vehicles per 24 hours; the 3-1 system should be preferred to the 4-0 system if and only if the daily traffic intensity is beyond the 45,000 vehicles. If the daily traffic intensity is beyond the 50,000 vehicles then junction-to-junction regenerations must be strongly dissuaded.

Table 5.5 summarizes our recommendations.

Table 5.5 : advised maintenance policy

traffic intensity	junction-to-junction regenerations	road barrier system	economic benefit (*) dense asphalt roads	economic benefit (*) porous asphalt roads
≤ 45,000 vcw per 24 hours	yes	4-0	9.5%	1.6%
≈ 47,500 vcw per 24 hours	yes	3-1	≈ 8.0%	≈ 0.9%
≥ 50,000 vcw per 24 hours	no	traditional	0.0%	0.0%

(*) : with respect to the current maintenance approach.

The economic benefit of junction-to-junction regenerations is most considerable for dense asphalt roads with a traffic intensity of at most 45,000 vehicles per 24 hours. For porous asphalt roads the benefit is much smaller. One should realize that the above recommendations disregard the safety of the different road barrier systems, so that one may deviate from the advocated maintenance policy. An amenity of junction-to-junction maintenance is that the 3-1 and 4-0 road barrier systems are more safe than the 2-1 system used for traditional maintenance, thus we think that junction-to-junction regenerations should be really performed if the traffic intensity is not too high.

The above results are obtained for a four kilometers long 2x2 lanes asphalt road. Because of the economies-of-scale property of the regenerations, we think that the junction-to-junction regeneration approach will be more advantageous if the sections are somewhat larger. However there is already an 8% discount if a carriage-way of 4 kilometers length is regenerated, and because the maximum discount is 10% we think that the outcomes for a 10 kilometers long asphalt road will not be overly different from that of a 4 kilometers long asphalt road. Sections smaller than 4 kilometers will rarely occur, thus we think that the results are quite general.

6. Conclusions

The pilot-study which we performed to determine the economic benefit of junction-to-junction regenerations indicated that for roads with a daily traffic intensity of less than 50,000 vehicles on each carriage-way it is really worthwhile to carry out such large-scale engineering projects. It is very important that when a regeneration project is on hand preventive patchworks are deferred to prevent excesssive repairs. The junction-to-junction maintenance approach requires a well balanced set of control-values, indicating when preventive maintenance must be postponed and when junction-to-junction regeneration must be carried out. It can lead to a reduction in the long run average preservation cost of 9.5% for dense asphalt roads, and 1.6% for porous asphalt roads. However, the yearly expenses are heavily fluctuating, which will smooth out on a network level. The junction-to-junction maintenance approach is causing a more cyclical road quality; since the road is from time to time regenerated the segments are having a roughly equal deterioration process. The reason why junction-to-junction regenerations should not be applied on roads with a daily traffic intensity of more than 50,000 per 24 hours, is that they cause severe traffic jams so that the average vehicle queuing cost exceeds the reduction in the average preservation cost.

The average quality of the road is also improving under the junction-to-junction maintenance approach, mainly because it effectively treats raveling for which there are in general no small corrective maintenance actions as the only effective action is the addition of a thin wear coat which is prohibited for roads with a traffic intensity of more than 20,000 vehicles per 24 hours because of chipping. A disadvantage of the junction-to-junction maintenance approach is that the quality of the road is less stable than under the sector integration approach; it moves from an almost ‘as-good-as-new’ state to a ‘heavily deteriorated’ state urging regeneration which brings the road into an almost ‘as-good-as-new’ state, thus the quality is obviously following a cyclical course.

We considered two road barrier systems for the redirection of the traffic from the carriage-way which is to be maintained from junction to junction. The results indicated that the 4-0 road barrier system should be preferred to the 3-1 system from an economic viewpoint, if and only if the daily traffic intensity is not higher than 45,000 vehicles. For safety reasons one may deviate from this economic rule of thumb.

We emphasize that the above conclusions are based on roads with two lanes on each carriage-way. The cost-effectiveness of junction-to-junction regenerations for three or four-lanes highways is not quite clear, and should be investigated before they are employed.

Appendix A : Model for Fitting a Deterioration Function

We are solving the following optimization problem:

$$\min_{q}\left\{\begin{array}{l}\displaystyle\min_{m_{\text{dense}},\, s_{\text{dense}}}\sum_{i=1}^{4}\left(G(t_i; m_{\text{dense}}, q, s_{\text{dense}}) - a_{\text{dense},i}\right)^2 \\ \displaystyle + \min_{m_{\text{porous}},\, s_{\text{porous}}}\sum_{i=1}^{4}\left(G(t_i; m_{\text{porous}}, q, s_{\text{porous}}) - a_{\text{porous},i}\right)^2\end{array}\right\} \tag{A.1}$$

subject to

$$\left|\left(\frac{F}{m_{\text{asphalt}}}\right)^{\frac{1}{q}} - T^{\text{mean}}_{\text{asphalt}}\right| \leq 0.2 \cdot T^{\text{mean}}_{\text{asphalt}} \quad \text{for asphalt = dense and porous;} \tag{A.2}$$

$$m_{\text{asphalt}} \cdot T^{\text{min}\ q}_{\text{asphalt}} + z_{0.975} \cdot s_{\text{asphalt}} \cdot \sqrt{T^{\text{min}\ q}_{\text{asphalt}}} \leq F \quad \text{for asphalt = dense and porous;} \tag{A.3}$$

$$m_{\text{asphalt}} \cdot T^{\text{max}\ q}_{\text{asphalt}} + z_{0.025} \cdot s_{\text{asphalt}} \cdot \sqrt{T^{\text{max}\ q}_{\text{asphalt}}} \geq F \quad \text{for asphalt = dense and porous;} \tag{A.4}$$

with a possible restriction on the q parameter (see section 3).

Appendix B : Results Grid-Search

For the determination of the optimal parameter-values D and L we performed a grid-search where the long run consequences are determined by a steady-state simulation which is terminated after 300 years. The results are given in the following two tables.

table B.1 : long run consequences dense asphalt roads

D	*L*	*long run average preservation costs*	*long run average poorness*
50 %	50 %	Dfl. 511,748	39.1 %
50 %	55 %	Dfl. 496,370	43.2 %
55 %	55 %	Dfl. 491,968	42.7 %
50 %	60 %	Dfl. 472,959	44.1 %
55 %	60 %	Dfl. 480,703	45.3 %
60 %	60 %	Dfl. 467,420	43.4 %
50 %	65 %	Dfl. 460,331	44.1 %
55 %	65 %	Dfl. 454,123	44.5 %
60 %	65 %	Dfl. 458,030	45.2 %
65 %	65 %	Dfl. 467,133	47.1 %
50 %	70 %	Dfl. 438,344	45.0 %
55 %	70 %	Dfl. 440,256	44.0 %
60 %	70 %	Dfl. 447,987	44.9 %
65 %	70 %	Dfl. 456,142	47.7 %
70 %	70 %	Dfl. 460,943	49.1 %
50 %	75 %	Dfl. 428,785	45.4 %
55 %	75 %	Dfl. 432,636	45.5 %
60 %	75 %	Dfl. 426,544	45.4 %
65 %	75 %	Dfl. 444,693	46.6 %
70 %	75 %	Dfl. 459,456	50.6 %

table B.2 : long run consequences porous asphalt roads

D	*L*	*long run average preservation costs*	*long run average poorness*
50 %	50 %	Dfl. 851,794	37.6 %
50 %	55 %	Dfl. 809,836	36.6 %
55 %	55 %	Dfl. 805,799	36.3 %
50 %	60 %	Dfl. 789,922	37.6 %
55 %	60 %	Dfl. 777,005	37.0 %
60 %	60 %	Dfl. 758,502	39.5 %
50 %	65 %	Dfl. 770,107	37.8 %
55 %	65 %	Dfl. 746,521	38.0 %
60 %	65 %	Dfl. 732,656	39.8 %
65 %	65 %	Dfl. 736,715	44.4 %
50 %	70 %	Dfl. 745,926	39.1 %
55 %	70 %	Dfl. 742,049	39.4 %
60 %	70 %	Dfl. 726,672	42.1 %
65 %	70 %	Dfl. 703,147	45.1 %
70 %	70 %	Dfl. 714,542	49.5 %
50 %	75 %	Dfl. 718,267	40.9 %
55 %	75 %	Dfl. 714,402	40.8 %
60 %	75 %	Dfl. 710,442	43.0 %
65 %	75 %	Dfl. 701,067	45.0 %
70 %	75 %	Dfl. 707,006	50.1 %

Table B.1 shows that the 'optimal' parameter-values for dense asphalt roads are D=60%, and L=75%., while Table B.2 shows that for porous asphalt roads the 'optimal' parameter-values are D=65%, and L=75% .

Recall that in the junction-to-junction maintenance approach the execution of preventive patchworks is abandoned if the overall poorness reaches the postpone-percentage D, and that the road is regenerated from junction to junction when the overall poorness reaches the norm-percentage L.

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