# The PERS System for Modelling Pavement Performance Based on Incremental-Recursive Techniques

B. Lund
*Dynatest Denmark A/S, Copenhagen, Denmark*

ABSTRACT: PERS is a software package developed by Dynatest for lifetime pavement analysis and pavement management. The concept is to use incremental-recursive models to predict the future damage to the pavement, from present pavement condition and the effects caused by traffic loading and climate. When the pavement condition has been evaluated during field testing in terms of elastic moduli, roughness, rutting etc, PERS calculates the future performance, in yearly or seasonal time increments, using user-defined damage models. Based on traffic loads and structural information the stress/strain levels are calculated for each layer, and the damage to all condition parameters for the season is derived from the models. The resulting pavement condition is then used, recursively, as input for the next time increment. By comparative graphics of predicted performance and historical condition data from field testing, it is possible to evaluate and calibrate the models to fit the measured performance of the pavement. Simulation of rehabilitation activities can be performed, by applying a rehabilitation alternative in any year of the analysis period. Many effects can be studied graphically, like all relevant costs to the agency and the users. Cost models can be user-defined. Further it is possible to let PERS calculate rehabilitation plans for the section, using a database of rehabilitation alternatives, and predefined critical limits for the condition data. Lastly it is possible to use all sectional rehabilitation plans in a budget based optimization, to find the overall most cost-effective solution for a road network

KEY WORDS: Pavement performance, incremental-recursive techniques, pavement management.

## 1 INTRODUCTION

The costs of pavement materials combined with the huge volumes of materials required for construction and maintenance of road networks, forms the basic need of reliable methods and effective tools for optimizing design and performance of road pavements. During the process, the timing of the rehabilitation activities is an important parameter to avoid waste of resources due to expensive rehabilitation because of late and essential reactive actions, or due to premature investments from poor planning and understanding of the nature of the failure. Another important issue during the design is not only to consider the requirements to service life as defined by the critical limits, but also to evaluate how the pavement performs from the initial state to the critical state. Again, this will influence the decisions for the timing and type of following rehabilitation activities.

Figure 1 illustrates the consequences of alternative performance graph with the same initial state and the same terminal state. As seen from the black and the blue performance graphs the effects on predicted user costs over the lifetime is dramatically affected by the shape of the graphs. The user costs can be vehicle operating costs, accidents costs, delay costs and loss in “aesthetic value”, related to the prediction of roughness, rutting, skid resistance and surface distresses.

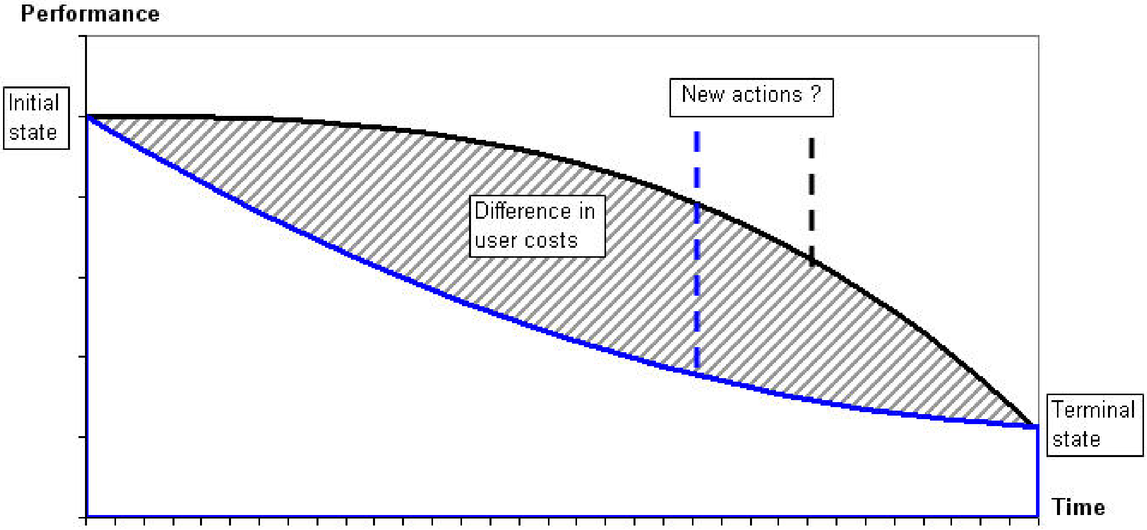


Figure 1: The importance of developing accurate performance models.

The methodology of PERS is based on using mechanistic-empirical techniques for modelling performance and effects of rehabilitation. These material specific models will be used in detailed effect/cost analysis over the chosen analysis period, and makes it possible to evaluate and find the best maintenance plans section by section. These plans are then used in a later network based optimization with budget constraints.

An important tool provided by PERS is to utilize historical data for the purpose of calibrating the performance models.

## 2 INCREMENTAL-RECURSIVE METHODS

PERS utilizes damage predictions by incremental-recursive methods combined with the mechanistic derived pavement responses in terms of stresses and strains calculated for each layer interface. The method is based on dividing the lifetime into minor time increments, typically a year or a season. At the beginning of each time increment the present condition is used as input for calculating the damage over the time increment considering the applied traffic loading. A new condition can then be calculated as input for the next time increment.

In the widely used empirical relationships for predicting damage only the terminal condition is predicted as a function of the total number of load repetitions over the period. Parameters in the relationship would normally be the present condition in terms of strain/stress level and elastic modulus as expressed in the equation $N = a * \text{strain}^b * E^c$, where N is number of load repetitions causing a defined damage, E the elastic modulus and a, b, c are constants calibrated for the specific material under the local conditions regarding climatic and traffic characteristics. Miner’s law is then assumed, allowing to sum damages linearly over the design period.

In a pavement management system where timing of the activities is important in order to minimize the total lifetime costs for the society, it would not be realistic to operate with linear damage models. If damage e.g. were defined as fatigue cracking, you would not expect a linear development of the amount of cracked surface with time. It is more reasonable to assume that the relative decrease of the elastic moduli is a nonlinear function of the past number of load repetitions as illustrated in figure 2.

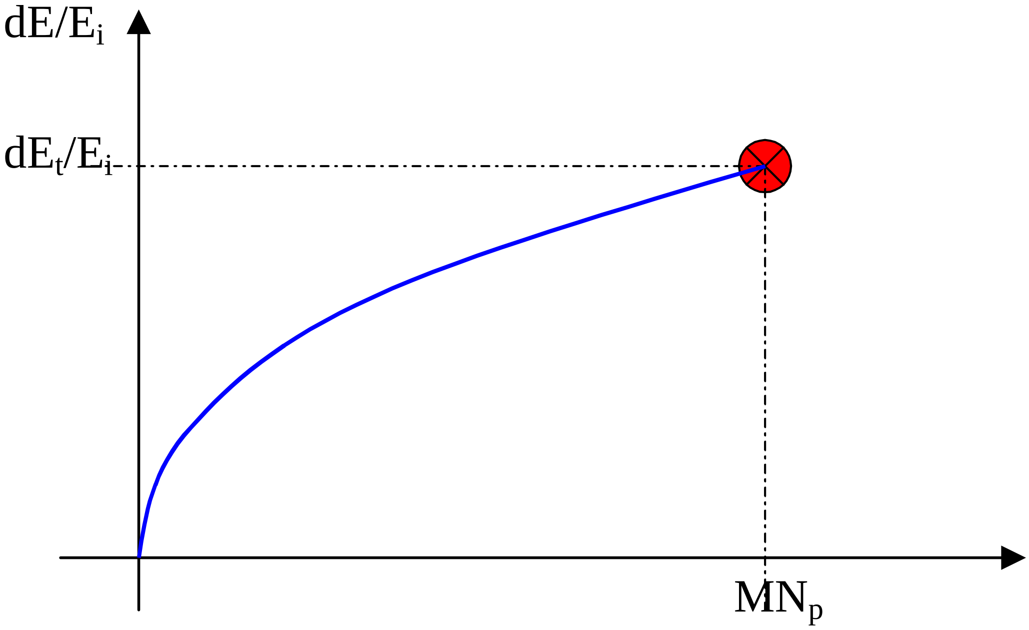


Figure 2: Nonlinear damage modelling. (Ullidtz, 2005).

$MN_p$ is the accumulated number of load repetitions, $E_i$ is the initial elastic modulus and dE is the decrease in modulus. The damage function can then be expressed as in equation 1.

$$Damage = A * \left[ \frac{N}{10^6} * \left\{ \frac{RT}{R_{ref}} * \left( \frac{E}{E_{ref}} \right)^{k1} \right\}^{k2} \right]^{k3}$$

Equation 1: Damage model used for incremental-recursive performance prediction.

In PERS damage with respect to relative decrease in elastic modulus, to IRI (roughness) and rutting can be entered according to this model for each material type defined by the user. A, $R_{ref}$, $E_{ref}$, k1, k2, k3 are constants defined by the user. RT is response type, which can be either stress or strain and $R_{ref}$ is a reference response, and $E_{ref}$ the reference modulus.

During the analysis PERS will calculate the predicted damages layer by layer in the pavement structure, and combine them to get the total predicted performance of the structure. It is also possible to set up models for predicting surface wear and friction. These models are entered as a function of tire contact pressure and traffic. Effects of ageing and water penetration can be defined as well.

All of the mechanistic modelling is based on the input of elastic modulus. The elastic moduli are usually derived through backcalculation of deflection bowls measured with the Falling Weight Deflectometer. The method for calculation of the responses can be selected by the user as either Odemark-Boussinesq (MET) or Linear Elastic Theory (LET) using Waterways Experiment Station's program (WESLEA)

For practical and financial reasons field testing with the Falling Weight Deflectometer may only be carried out on a fraction of the road network. For the part of the network where the structural information is not present, PERS offers the facility to use pure empirical relationships as a function of traffic or age of the pavement. These relationships can also be used in combination with the mechanistic models to secure a minimum decrease in performance caused by other factors than the load repetitions. Chapter 6 describes the use of this alternative.

## 3 PERFORMANCE ANALYSIS

The general feature for studying the predicted performance as well as the historical data is a graphical screen giving all the performance curves. An example is given in figure 3 for a specific road section.

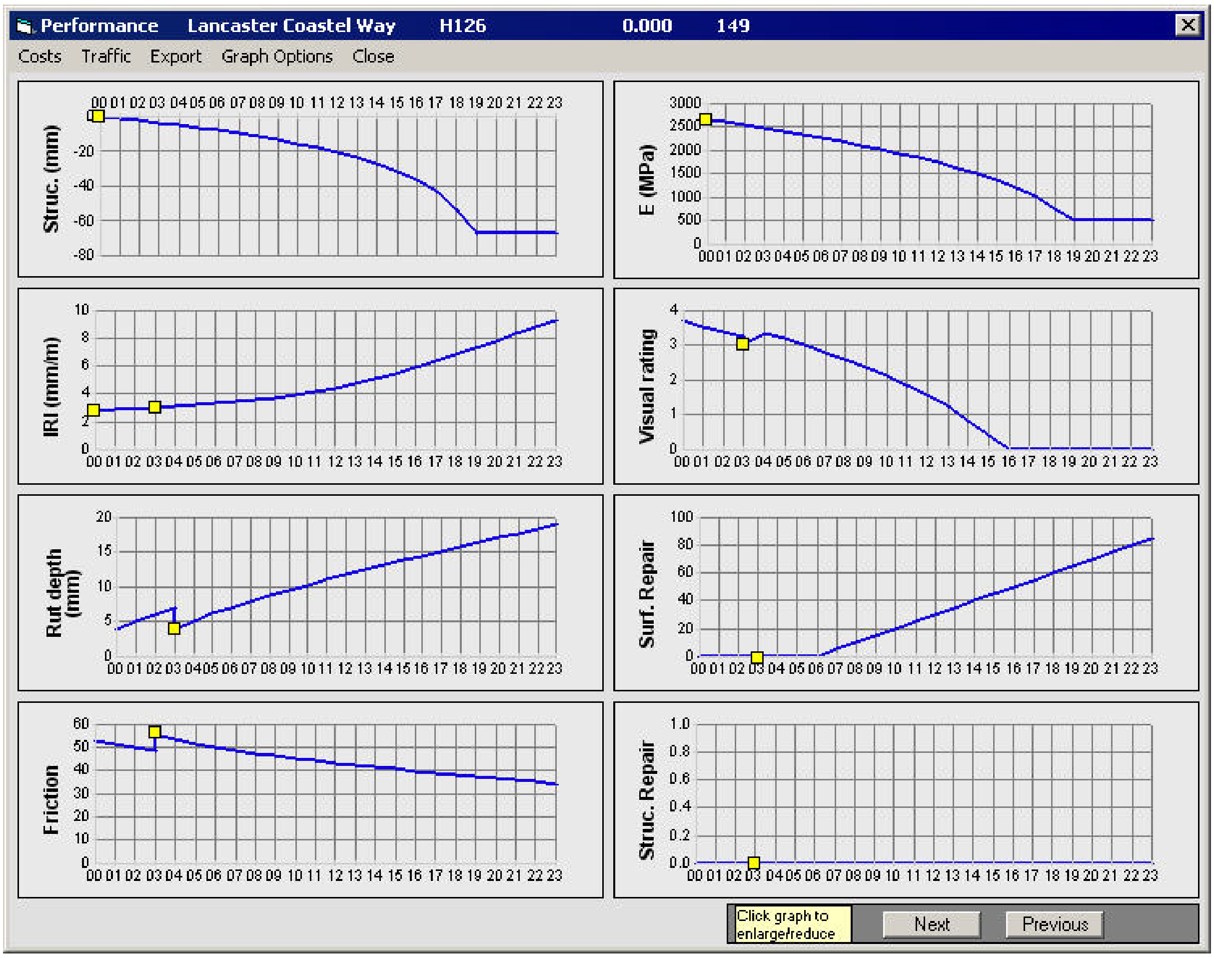
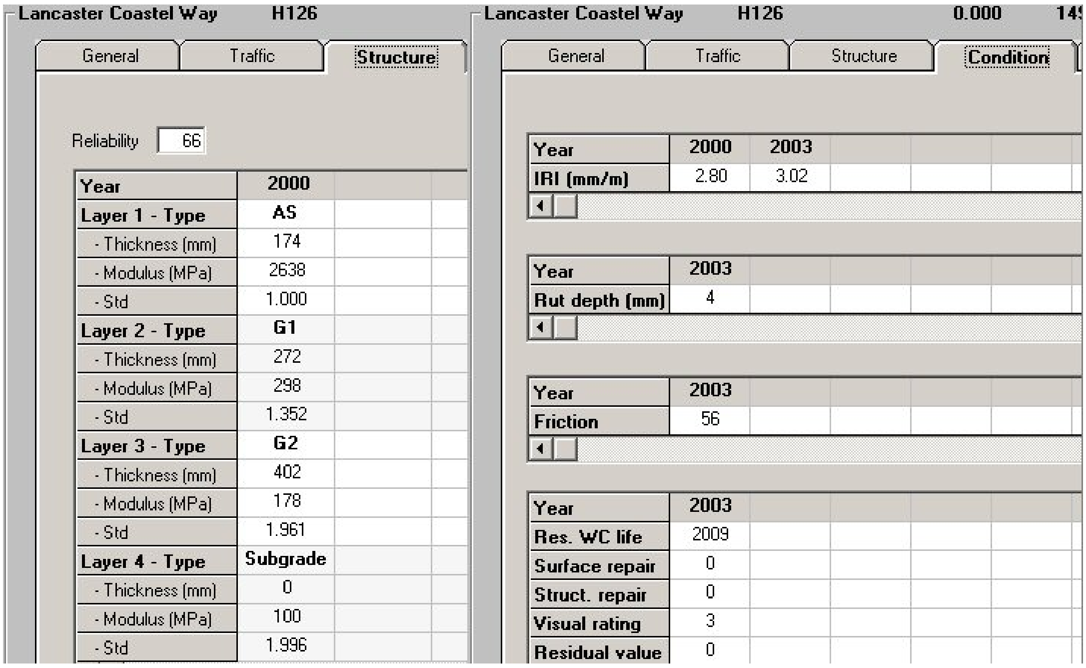


Figure 3: Historical and predicted performance for a road section.

The present year is 2004, and the graphs show the performance data for the road section for the years 2000 to 2023 based on the measured conditions indicated by the yellow squares, and the models entered for the pavement layers. The upper left graph indicates the loss in bearing capacity due to decreasing moduli. The values are expressed as the amount of overlay required to reproduce the initial bearing capacity from year 2000. It is seen that a cut off value to the models is met in year 2019, as defined by the user. From the rut depth graph and the friction graph it is seen that the models respects the measured data in year 2003, where they "resets" the input to the incremental-recursive procedure.

It is also possible to let the graphics show the modelling without respecting the measured data. This will highlight the difference between the model prediction and measured data, and is a useful feature for calibrating the models.

The input tables for the sectional pavement structure and surface condition data is shown in figure 4.



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Reliability 66

| Year | 2000 |
|---|---|
| Layer 1 - Type | AS |
| - Thickness (mm) | 174 |
| - Modulus (MPa) | 2638 |
| - Std | 1.000 |
| Layer 2 - Type | G1 |
| - Thickness (mm) | 272 |
| - Modulus (MPa) | 298 |
| - Std | 1.352 |
| Layer 3 - Type | G2 |
| - Thickness (mm) | 402 |
| - Modulus (MPa) | 178 |
| - Std | 1.961 |
| Layer 4 - Type | Subgrade |
| - Thickness (mm) | 0 |
| - Modulus (MPa) | 100 |
| - Std | 1.996 |

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| Year | 2000 | 2003 |
|---|---|---|
| IRI (mm/m) | 2.80 | 3.02 |

| Year | 2003 |
|---|---|
| Rut depth (mm) | 4 |

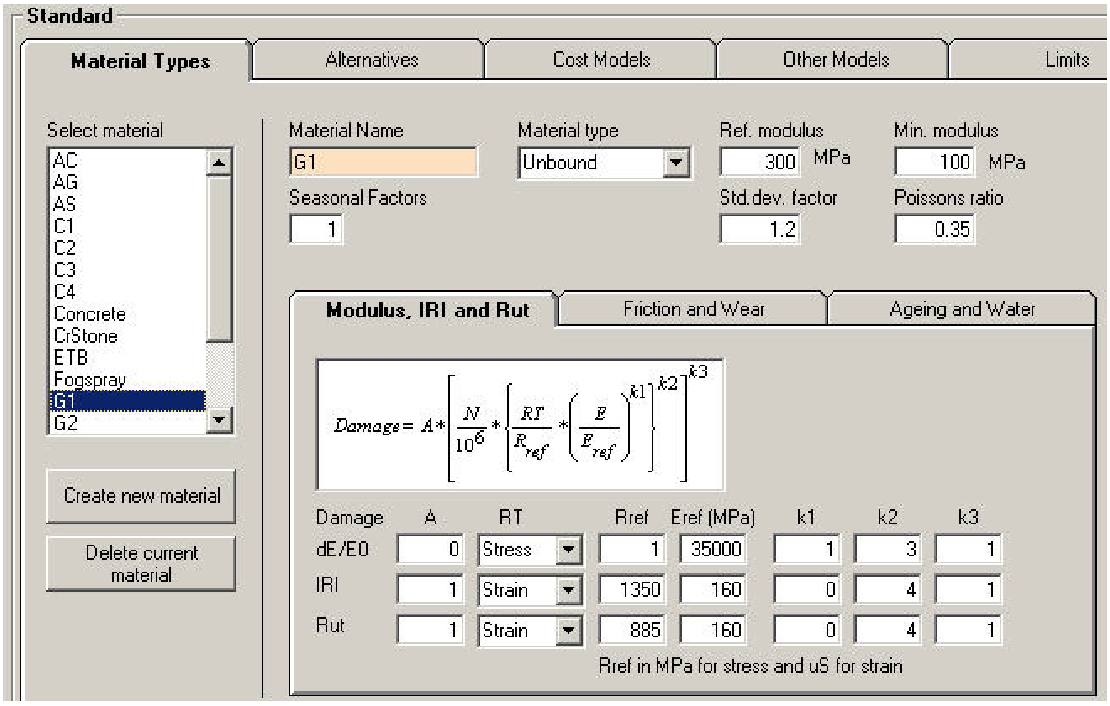
| Year | 2003 |
|---|---|
| Friction | 56 |

| Year | 2003 |
|---|---|
| Res. WC life | 2009 |
| Surface repair | 0 |
| Struct. repair | 0 |
| Visual rating | 3 |
| Residual value | 0 |

Figure 4: Input screen for condition data.

Each set of data is related to the year of testing, and additional columns with new test data can be entered over time. The pavement structure is defined by a number of layers with a material name, layer thickness and modulus. The material name refers to the database of materials as defined by the user, and where PERS will read all the necessary information about performance models used in the analysis. An example for the unbound material type "G1" can be seen from figure 5. In this case the constant A for the modulus model is entered as 0, meaning that no deterioration of the elastic modulus is considered.

This setup of materials forms a part of a complete parameter setup. The other parts are setup of rehabilitation alternatives, user cost models and critical limits to the conditions, all used with the effect/cost analysis. It is possible to define a range of different parameter setups to be used with different part of the road network. That makes it possible to define different models for different climatic regions, or to define different tables of rehabilitation alternatives to be used with different road classes. The effect/cost analysis can be run automatically for a user-defined group of sections connected to a specific parameter setup.



Material Name: G1

Material type: Unbound

Ref. modulus: 300 MPa

Min. modulus: 100 MPa

Seasonal Factors: 1

Std.dev. factor: 1.2

Poissons ratio: 0.35

$$Damage = A*\left[\frac{N}{10^6}*\left\{\frac{RT}{R_{ref}}*\left(\frac{E}{E_{ref}}\right)^{k1}\right\}^{k2}\right]^{k3}$$

| Damage | A | RT | Rref | Eref (MPa) | k1 | k2 | k3 |
|---|---|---|---|---|---|---|---|
| dE/E0 | 0 | Stress | 1 | 35000 | 1 | 3 | 1 |
| IRI | 1 | Strain | 1350 | 160 | 0 | 4 | 1 |
| Rut | 1 | Strain | 885 | 160 | 0 | 4 | 1 |

Rref in MPa for stress and uS for strain

Figure 5: Input screen for materials and performance models.

## 4 LOADS AND TRAFFIC

PERS allows flexible setup of load types. In classical use of mechanistic – empirical modelling, all future traffic is combined into one number of standard axle loads (ESALs), and responses are calculated under this load.

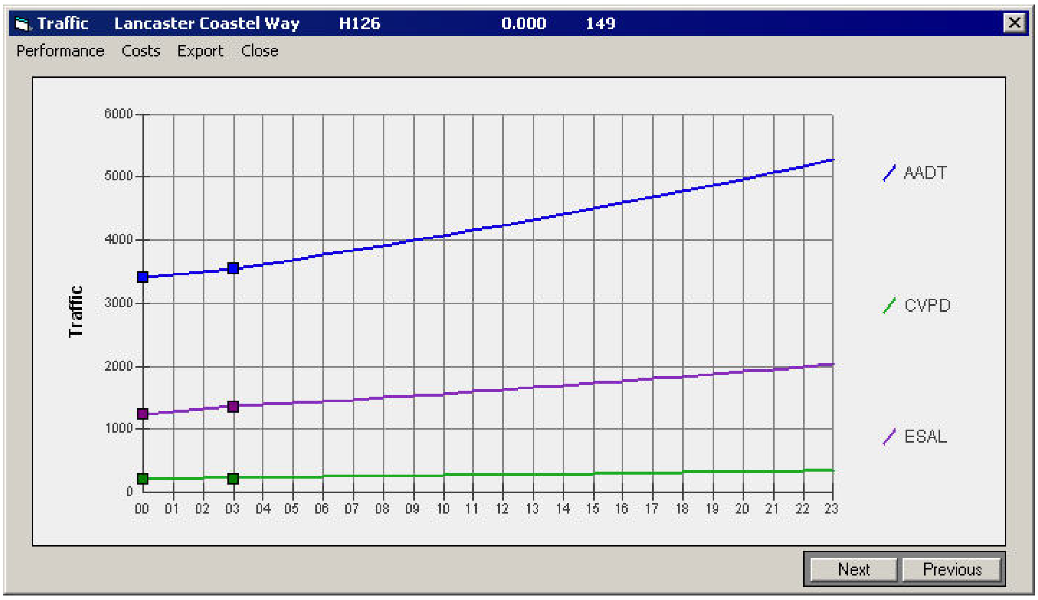


Figure 6: Presentation of predicted traffic used in the performance modelling

With PERS up to 24 different load types can be defined with their load, axle and wheel configurations, and the damage caused by each load will be considered during the recursive-incremental modelling. It assumes then that the user has information about the traffic for each defined load type.

A further advantage of the incremental-recursive method is, that the timing of the load repetitions is considered. There is usually a certain traffic growth rate expected over the analysis period, meaning that an increasing number of traffic loads are distributed over a decreasing strength of the pavement with time. Figure 6 shows the graphical representation of traffic data. In this case a standard setup of traffic has been chosen, giving the ESAL used for performance modelling, and the AADT used for user cost calculations.

## 5 EVALUATION OF REHABILITATION ALTERNATIVES

The performance graphs can be used as well to reflect the effect of applied rehabilitation activities during the analysis period. It is further possible to let the program do an analysis of the section with the purpose of detecting the best possible maintenance plan, based on the database of allowable rehabilitation alternatives, and with the restrictions to the performance parameters set by the user in the parameter setup. In figure 7 an example of results from this is illustrated.

| Agency | Total | Year | Action | Year | Action |
|---|---|---|---|---|---|
| 65092 | 508786 | 2009 | Recyc250 | | |
| 75787 | 368929 | 2009 | Heavy Rehab | | |
| 82224 | 521384 | 2005 | Seal | 2011 | Heavy Rehab |
| 83696 | 503120 | 2004 | Seal | 2011 | Heavy Rehab |
| 90330 | 233446 | 2007 | Heavy Rehab | 2022 | Seal |
| 95565 | 191158 | 2006 | Heavy Rehab | 2021 | Seal |
| 109313 | 140605 | 2005 | Heavy Rehab | 2020 | Overlay40 |
| 116965 | 113238 | 2004 | Heavy Rehab | 2019 | Overlay40 |

Figure 7: Results of evaluation of maintenance strategies for a section.

Each line forms a maintenance plan for the section. The suggestions are sorted according to increasing agency costs. The solution giving the lowest total cost is marked with green background. In this case it is “Heavy Rehab” in year 2004 followed by “Overlay40” in year 2019. All costs are discounted back to the present year. The length of the analysis period can be set up to 30 years. Usually the maintenance plan with the most interest are the cheapest for the agency or the cheapest for the society, where all user costs are included. When solutions are provided in between these, it is mainly to allow flexibility in a later road network optimization with budget restraints, where timing of the activities are influenced by the money available for each year.

With a normal selection of rehabilitation alternatives available, the combination of activities and timing grows to an astronomical amount, and systematically evaluating all of them, including all the complex performance analyses would be impossible. To reduce the number of combinations dramatically, performance “trigger” values are entered together with the critical limits in order to avoid analyzing rehabilitation activities in years where all performance data are outside the range between “trigger” value and critical value.

It is possible to view the section performance graph for one of the solutions by clicking the appropriate line as seen in figure 8:

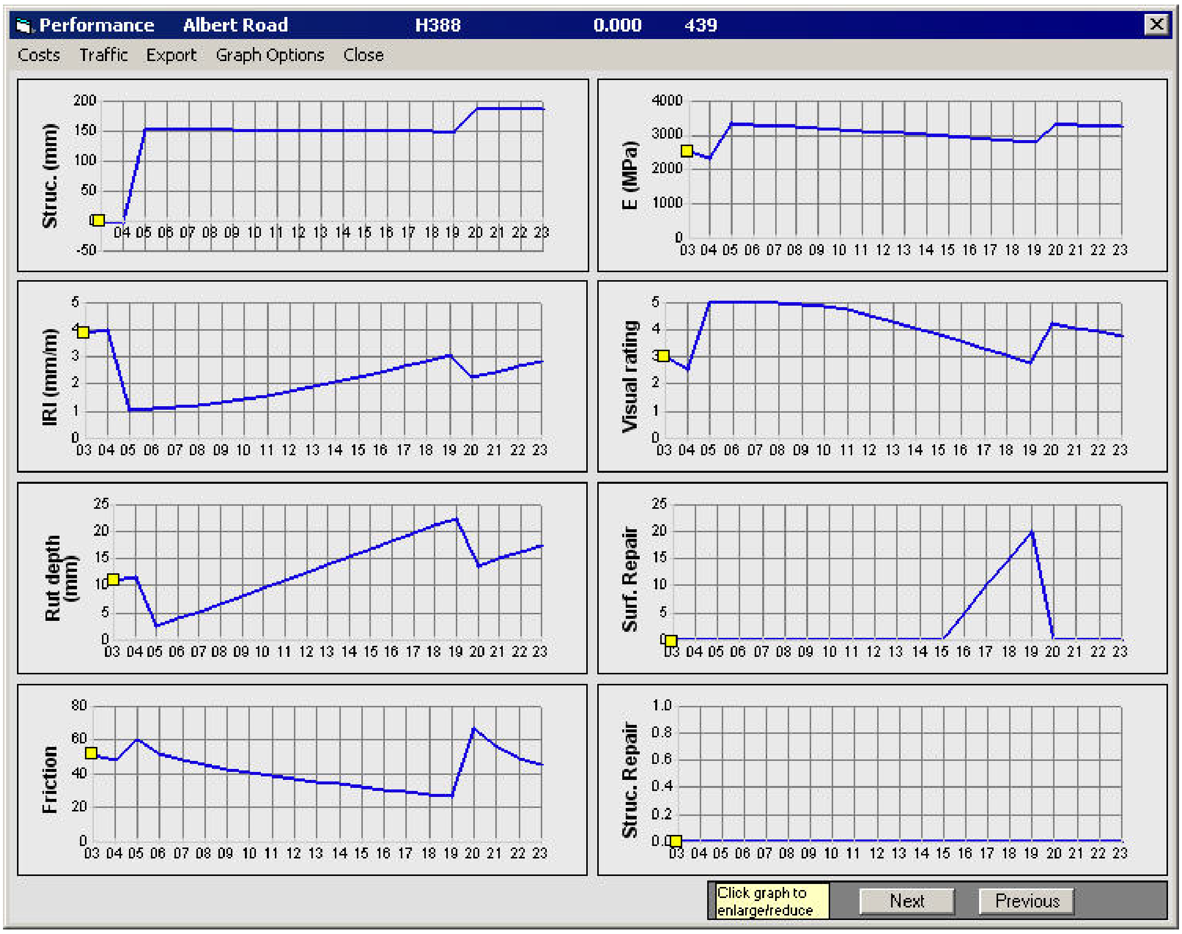


Figure 8: Performance with applied rehabilitation activities in the years 2005 and 2019

The cost part of the Effect/cost analysis can be viewed graphically as well. Costs can include vehicle operating costs, agency costs for rehabilitations and routine maintenance, accident costs, delay costs, costs of loss in “aesthetic value” and capital costs in terms of loss in bearing capacity and depreciation of wearing courses.

An example of prediction of vehicle operating costs (VOC) is shown in figure 9 as accumulated VOC over the analysis period. VOC can be modelled as a function of predicted roughness and friction. The example illustrates the VOC of the solution from figure 8 with applied rehabilitation activities in the years 2005 and 2019. When there is no increase in VOC in the years 2005 to 2014, it is because the predicted IRI is lower than the cut off value for the model. Similar graphics are available for all type of costs.

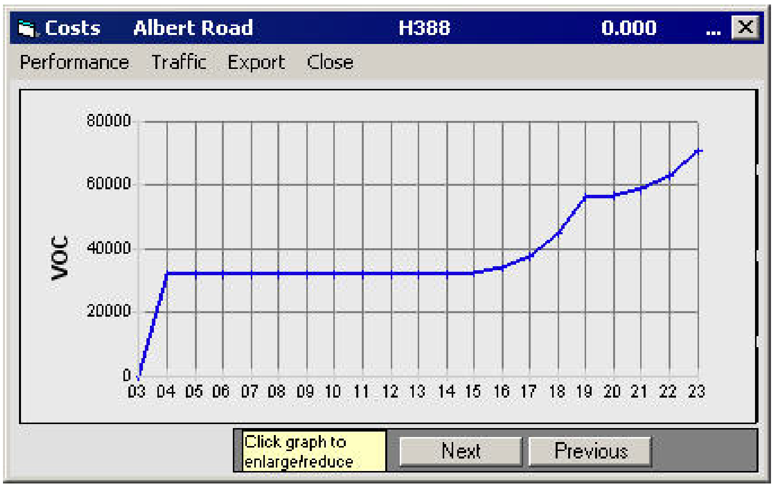


Figure 9: Modelling of vehicle operating costs

## 6 EMPIRICAL RELATIONSHIPS

As an alternative to the mechanistic based prediction models it is possible to set up pure empirical relations as a function of age of pavement or accumulated traffic. Those may be used where structural evaluation has not been carried out, or they may be used in combination with the mechanistic models to ensure a minimum decrease in performance as a function of deterioration not related to the structural condition.

$$\mathrm{IRI} = IRI_0 + A * \left(\frac{N}{10^6}\right)^B$$

Equation 2: Example of empirical prediction model.

The models are in general expressed as seen in equation 2, where traffic (N) in this case is used as the depending parameter. The constants $\mathrm{IRI}_0$, A and B can be calibrated for each section. Facilities exist for automatically calibrating the models, based on existing measurements, and allowable ranges for the constants given by the user. Similar models can be entered for prediction of rut depth, surface wear and friction. In case no existing measurements are present for a section, the models can be automatically calibrated using general input for the initial and terminal condition.

## 7 NETWORK OPTIMIZATIONS

When sectional rehabilitation suggestions have been carried out for the whole road network or for any group of sections, it is possible to generate a complete maintenance plan using optimization algorithms with the goal of minimizing the total costs under the given yearly budget restraints. It may also be chosen to base the plan on the cheapest solution for the agency or the minimum total costs without considering the yearly budget levels. Further, it is possible to only respect the budget for a specific number of years.

Different options are available for the selection of method of budget based optimizations. The “Decremental” and “Incremental” methods starts respectively with the solution with minimum total costs and the solution with minimum agency costs and make use of an algorithm based on Toyoda’s "effective gradient" to search for the solution that will give the minimum overall costs, while respecting the budgets. The “Genetic” method makes use of a genetic algorithm to find improvements to any existing solution. The “Fit Budget” option is based on the genetic algorithm, but pursue the combined goal of minimizing the total costs and minimizing the difference between yearly budget and yearly costs over the optimization period.

The detailed results can be viewed in terms of sectional maintenance lists, and the overall network results can be saved for later study, and comparisons with optimizations carried out under different assumptions. In figure 10 is shown a graphical comparison between 2 optimizations, with the effects on the overall predicted performance of the road network.

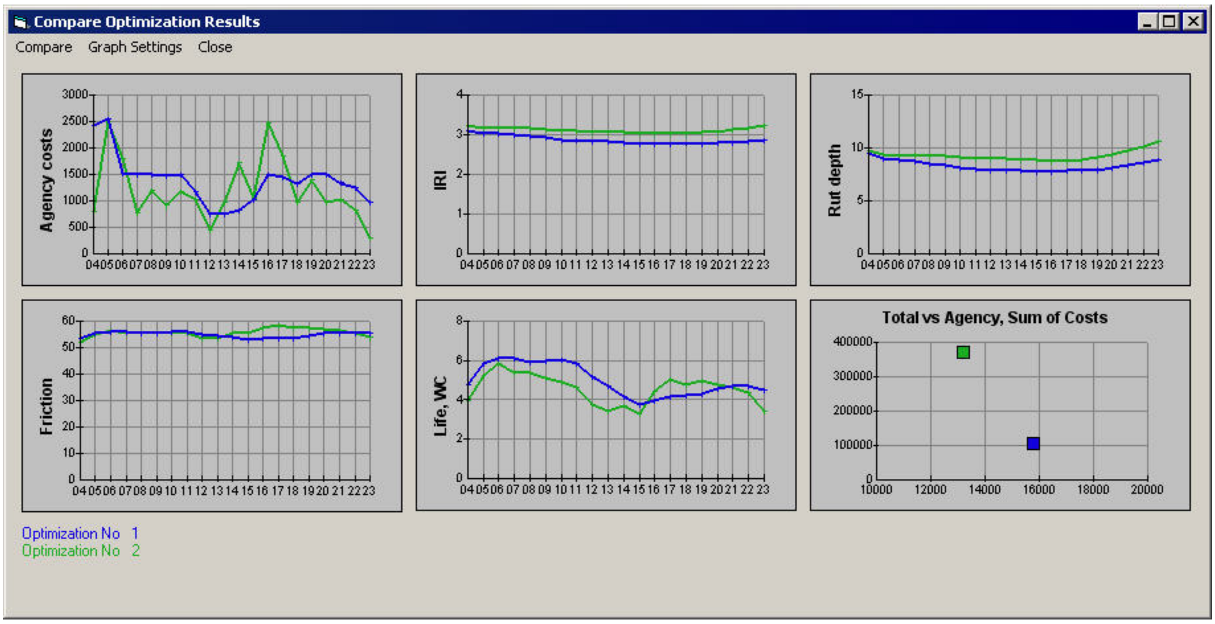


Figure 10: Comparisons of road network level performance.

The green curves reflect the solution with the cheapest agency costs, while the blue curves gives the results of an optimization with the goal of achieving the most cost-effective solution under a given budget. The effects on the “Total” graph in the lower right corner are obvious, with a significant reduction in total cost for the additional invested agency costs. It is also seen that in the first couple of years, expenses can not be kept under the budget level, which is a typical sign of a road network, where rehabilitation activities have been constantly pushed forward for short term money saving purposes. For all four performance graphs the terminal condition of the road network is improved, compared to the cheapest solution.

## REFERENCES

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