QUANTIFYING UNCERTAINTY IN ROAD PAVEMENT DESIGN BY SIMULATION

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ABSTRACT

Variation in parameters that affects the performance of a flexible pavement is a well-known fact. The handling of this phenomenon in pavement design has to a large extent in the past been based on the experience of the designer.

The computer program Cyrano is a tool that has been developed recently to predict the behaviour and consequences of various pavement configurations over a period of time. The uncertainty about the input is translated into the uncertainty about the output and displayed to the user. The program calculates stresses, strains and deflections at critical points in various layers of the pavement and uses transfer equations to yield values of critical output variables that reflect functional and structural failures. It also calculates the life cycle cost for each design. These values create a foundation on which the decision on the suitability of a particular design is taken.

The purpose of this paper is to demonstrate that the uncertainty in road pavement design can be quantified by simulation as demonstrated in Cyrano and the results used in competent decision making.

1. INTRODUCTION

Pavement design is partly a science and partly an art. Because of the artistic nature the designer has to have ‘feel’ for the outcome of his effort. As a science the pavement design is not an exact one, because of considerable uncertainty surrounding the input.

In many countries, particularly the developing ones, there may be a few pavement-design masters. Unfortunately, the majority of engineers and technicians who are daily making decisions on the construction, maintenance, financing and prioritizing of roads do not have the expertise of masters. To assist these people with their tasks special tools have been developed recently that predict the behaviour and consequences of various pavement configurations over a period of time. The uncertainty about the input is translated into the uncertainty about the output and displayed to the user. He or she then can judge whether the expectations about the future behaviour of the pavement are likely to materialize. If the outcome is unsatisfactory the user adjusts input parameters repeatedly, until the prognosis of pavement performance becomes favourable.

There are two major types of road pavement: rigid pavements (using concrete as the top layer) and flexible pavements (using asphalt as the top layer). In each case there are some 20 input variables, such as thicknesses and stiffnesses (moduli) of various pavement layers, anticipated axle loads, tyre pressures, speed and growth of traffic, and other. Apart from these, up to 30 constants are also required as input, such as initial amount of heavy-vehicle traffic, unit costs of various pavement layers, unit cost of repairs, anticipated period of use before the next intervention (maintenance action), properties of the used materials, and other.

The path from input to output is a long one. In case of rigid pavement the first step in the procedure is to enter the key input variables into an interim module which returns stresses and deflections at critical points in various layers of the pavement. These are fed into a set of so-called transfer equations. The transfer equations then yield values of critical output variables that reflect functional and structural failures. These values than create a foundation on which the decision on the suitability of a particular design is taken.

The main objective is to quantify the uncertainty in road pavement design and its consequences. This is done by means of computer simulation. The results are used for informed decision making. The paper demonstrates the approach and method to achieve this in practice.

2. HISTORY

Two computer programs have been developed in South Africa – cncPAVE for rigid pavements and its counterpart for flexible pavement called Cyrano. Both programs use the concepts mentioned above.

The output of cncPAVE informs the user about the extent of shattered concrete, pumping, faulting and cracking that afflict the surface after a certain period of time. The original edition of the program for concrete pavement was introduced in 2000 under the name of cncRISK. In 2002 the user’s comments and experience were used to update the program and issue the improved version under the name of cncPAVE. The program has been widely distributed under the auspices of the Cement and Concrete Institute of South Africa in this country as well as overseas. It has been continuously maintained and updated to reflect the latest developments.

In case of flexible pavements the output of Cyrano guides the user by displaying trends in the depth of surface deformation, percentage of cracked surface, the International Roughness Index (measure of riding quality), and the percentage of failed surface area that has to be repaired to restore the functionality of the road. As the cncPAVE program before, Cyrano has been developed by the authors in response to the need of handling the consequences of uncertainty in the design of flexible pavements as well. Its first version was released at the end of March 2006 to a group of 20 individually selected users. Based on their feedback the second version is planned to be commercially available later in 2006.

3. METHOD

In both programs the input is viewed as a set of random variables. Each variable has mean and a measure of variability, such as the standard deviation or the coefficient of variation. The input variables are assumed to have normal, triangular or empirical distributions, depending on the case.

The input uncertainty is translated into output uncertainty by means of computer simulation. Typically, the simulation outcome has two forms – distribution and/or random-walk scenario. While distributions are useful when one wishes to determine confidence intervals, random-walk scenarios are preferable for revealing the trends, such as the increasing development of cracks and ruts from year to year. Although other methods of quantifying uncertainty, such as the so-called Point Estimate Method and Interval Arithmetic, are used sporadically as well, the construction of distributions and random walk scenarios is the predominant technique.

Despite the complexity of calculations, the simulations are done fast thanks to the very powerful processors with which computers are equipped today. This high speed facilitates an effective trial-and-error process. After a few such trials even the users with limited experience can see the situation clearly and make rational decisions.

4. PAVEMENT DESIGN CONCEPTS

The *Cyrano* program is based on mechanistic design concepts, which means that stresses, strains and deflections are calculated at different positions in a pavement when the layer characteristics and loading is known. The calculation of stress and strain is done using the program Elsym5 and in order to do this, material properties as normally used in designing pavement structures have to be converted to a stiffness modulus for the material and its Poisson's ratio. These stresses and strains are used in transfer functions to estimate the number of load applications to failure.

The transfer functions used in Cyrano to calculate number of load applications to failure are based on the performance of materials as tested on the road pavements under normal traffic loading, under HVS loading and in the laboratory, the information of which is provided in the SAMDP document (Theyse et al., 1996). The estimation of the percentage cracking of the surface is based on the expected number of load applications to failure in the form of cracks visible on the surface and total measurable deformation on the surface is a function of deformation of all the pavement layers.

During the life of the pavement the stiffness modulus values of the different layers will change, either because of cracking or as a result of ageing. Cyrano provides the opportunity for the user to allow the stiffness properties to change with loading or time:

- The modulus of the bituminous surface may change with time due to aging or the development of fatigue cracking
- The modulus of the top of the surface of the base may change with loading due to crushing or mechanical breakdown
- The modulus of the base and that of the subbase, if they are stabilized, may change due to cracking as a result of loading (fatigue).

Asphalt stiffens at the surface of the top layer with age thus decreasing its expected number of loads to cracking. However when cracking, even micro cracking, starts to develop, the asphalt loses stiffness. It is important to note that tensile strains are usually higher at the top of a thin asphalt layer (thinner than 50mm) and thus the expected life of thin asphalt is usually more affected by age stiffening.

The modulus at the top of the base is a function of the modulus of the rest of the base and it can diminish through cracking and thereby also reduce the stiffness at the top. The modulus of the top part of the base, however, is affected by traffic loading especially if the pavement surface is relatively thin.

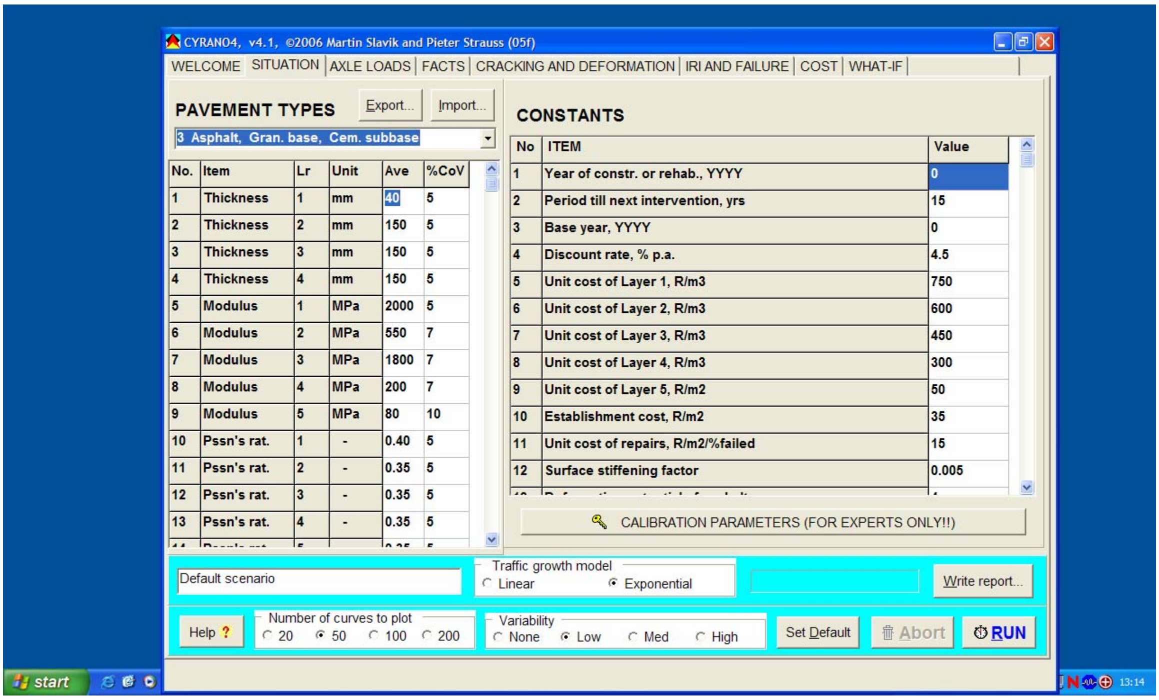
A lower modulus value for the top of the base layer will have an influence on the strain in the asphalt surface. An adjustment factor to make provision for this event was derived from the separate modeling of a weak interlayer between the asphalt and the base using finite element analyses.

Deformation of the base is a function of the sum of principal stresses in the middle of the layer. The equation used is based on work done by Herman Wolff and regression analyses on data generated from Heavy Vehicle Simulator (HVS) testing (Wolff, 1992).

The top of the base layer, which may have a lower stiffness modulus compared to that of the base, will also contribute to deformation of the pavement; it will either deform vertically or show horizontal movement due to the shear strain in the crushed layer. An equation was derived from separate 3D finite element modeling of a weak interlayer between the asphalt and the base.

Area failed is calculated by combining the area cracked and the total deformation of the pavement as measured on the surface.

An idea of the input required for the above is apparent in the screen shot shown in Fig.1. In the example discussed the pavement structure is 40 mm asphalt on top of 150 mm crushed stone base and 150 mm subbase.



PAVEMENT TYPES

3 Asphalt, Gran. base, Cem. subbase

No.	Item	Lr	Unit	Ave	%CoV
1	Thickness	1	mm	40	5
2	Thickness	2	mm	150	5
3	Thickness	3	mm	150	5
4	Thickness	4	mm	150	5
5	Modulus	1	MPa	2000	5
6	Modulus	2	MPa	550	7
7	Modulus	3	MPa	1800	7
8	Modulus	4	MPa	200	7
9	Modulus	5	MPa	80	10
10	Pssn's rat.	1	-	0.40	5
11	Pssn's rat.	2	-	0.35	5
12	Pssn's rat.	3	-	0.35	5
13	Pssn's rat.	4	-	0.35	5

CONSTANTS

No	ITEM	Value
1	Year of constr. or rehab., YYYY	0
2	Period till next intervention, yrs	15
3	Base year, YYYY	0
4	Discount rate, % p.a.	4.5
5	Unit cost of Layer 1, R/m3	750
6	Unit cost of Layer 2, R/m3	600
7	Unit cost of Layer 3, R/m3	450
8	Unit cost of Layer 4, R/m3	300
9	Unit cost of Layer 5, R/m2	50
10	Establishment cost, R/m2	35
11	Unit cost of repairs, R/m2/%failed	15
12	Surface stiffening factor	0.005

Default scenario

Traffic growth model
○ Linear ● Exponential

Number of curves to plot
○ 20 ● 50 ○ 100 ○ 200

Variability
○ None ● Low ○ Med ○ High

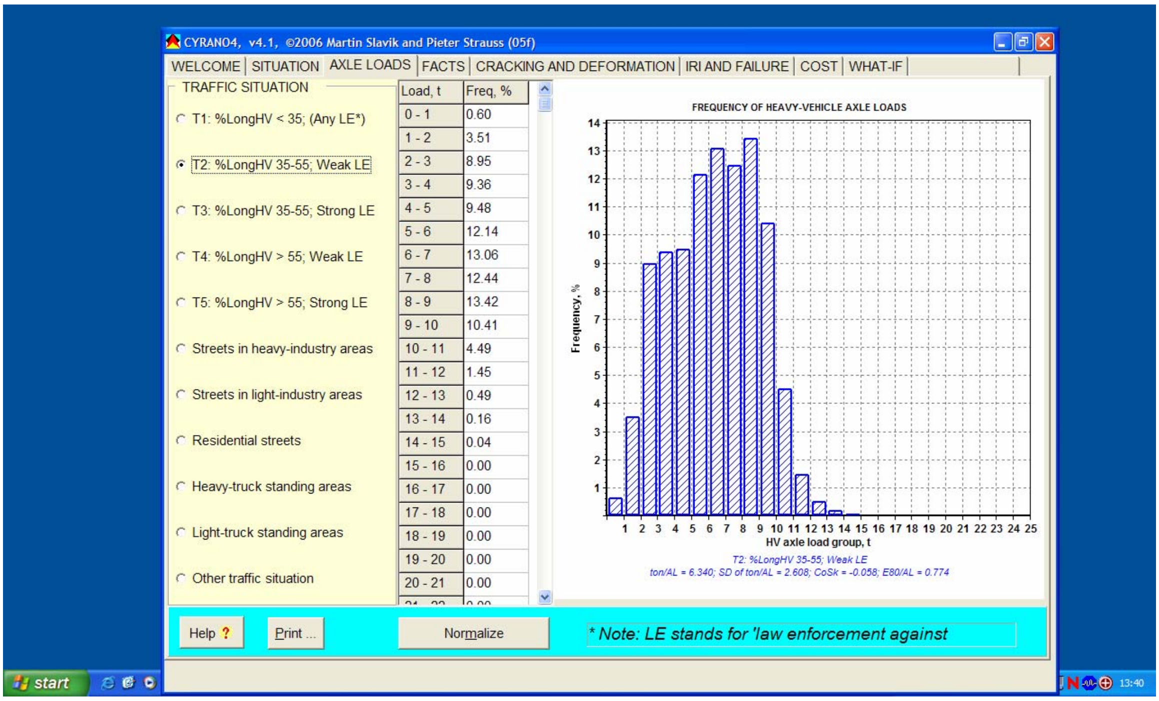
Fig.1. Screen shot of the SITUATION Paqe of the Cyrano program with some of the required input items.

5. TRAFFIC LOADING

Satisfactory performance of the pavement is outcome of the balance between demand and capacity. Traffic loading information is input - the demand side of this balance. It consists of numeric inputs, viz.

- Average Daily Truck Traffic, ADTT0, heavy vehicles per day in the most exposed lane at the beginning of the first year of operation;
- Heavy-vehicle traffic growth, % p.a., over the period of study;
- Average number of axles per heavy vehicle;
- Average speed of heavy vehicles.

The main input regarding traffic loading is the distribution of axle loads. This is usually an empirical distribution obtained from the operation of almost 100 weigh-in-motion (WIM) stations situated on the South African major roads. An example of such distribution is in the screen shot shown in Fig.2.



TRAFFIC SITUATION

○ T1: %LongHV < 35; (Any LE*)
● T2: %LongHV 35-55; Weak LE
○ T3: %LongHV 35-55; Strong LE
○ T4: %LongHV > 55; Weak LE
○ T5: %LongHV > 55; Strong LE
○ Streets in heavy-industry areas
○ Streets in light-industry areas
○ Residential streets
○ Heavy-truck standing areas
○ Light-truck standing areas
○ Other traffic situation

Load, t	Freq, %
0 - 1	0.60
1 - 2	3.51
2 - 3	8.95
3 - 4	9.36
4 - 5	9.48
5 - 6	12.14
6 - 7	13.06
7 - 8	12.44
8 - 9	13.42
9 - 10	10.41
10 - 11	4.49
11 - 12	1.45
12 - 13	0.49
13 - 14	0.16
14 - 15	0.04
15 - 16	0.00
16 - 17	0.00
17 - 18	0.00
18 - 19	0.00
19 - 20	0.00
20 - 21	0.00

T2: %LongHV 35-55; Weak LE
ton/AL = 6.340; SD of ton/AL = 2.608; CoSk = -0.058; E80/AL = 0.774

* Note: LE stands for 'law enforcement against

Fig.2. Distribution of axle loads observed in 2005 at a WIM station representative of roads with a medium percentage of long trucks and weak law enforcement against overloading.

Two additional input items are needed in addition to the above, viz. the average lateral distance between the truck dual wheels, and the average value of surface pressure imposed by truck tyres.

The Cyrano caters for two types of heavy-vehicle traffic growth – linear and exponential. For high growth rates the exponential model tends to give unrealistic values of daily truck traffic at the end of long study periods. For moderate growth rates and/or moderately long study periods the two models produce similar results. For this reason the use of the linear model is recommended in general.

6. LIFE COST OF PAVEMENT

The life cost of pavement, in R/m^2, is calculated for the period of study which is the period till next intervention. The cost consists of the capital cost of construction (or rehabilitation), and the cost of repair at the end of the period, which is needed to restore the original functionality of the pavement.

The capital cost consists of the cost of individual pavement layers, and the cost of establishment. The capital cost of the top four layers is calculated from the actual thicknesses of these layers, and the unit costs of the respective layers, in R/m^3. The cost of subgrade, as well as the cost of establishment, in R/m^2, is then added to obtain the total. The total is discounted, using the given discount rate, to the base year.

The cost of pavement repair is derived from the percentage of surface failed at the end of the study period which is multiplied by the unit cost of repair, in R/m^2 per one percent of failed surface.

The repair cost is discounted from the year of intervention to the base year, to obtain the present worth of the repair cost, which is then added to the present worth of the capital and establishment costs. The final sum is the life cost of pavement.

Since some of the input variables used in the above calculations are random variables, so is the cost of pavement. Because of its random nature it has a distribution. An example of such distribution is in the screen shot shown in Fig.3.

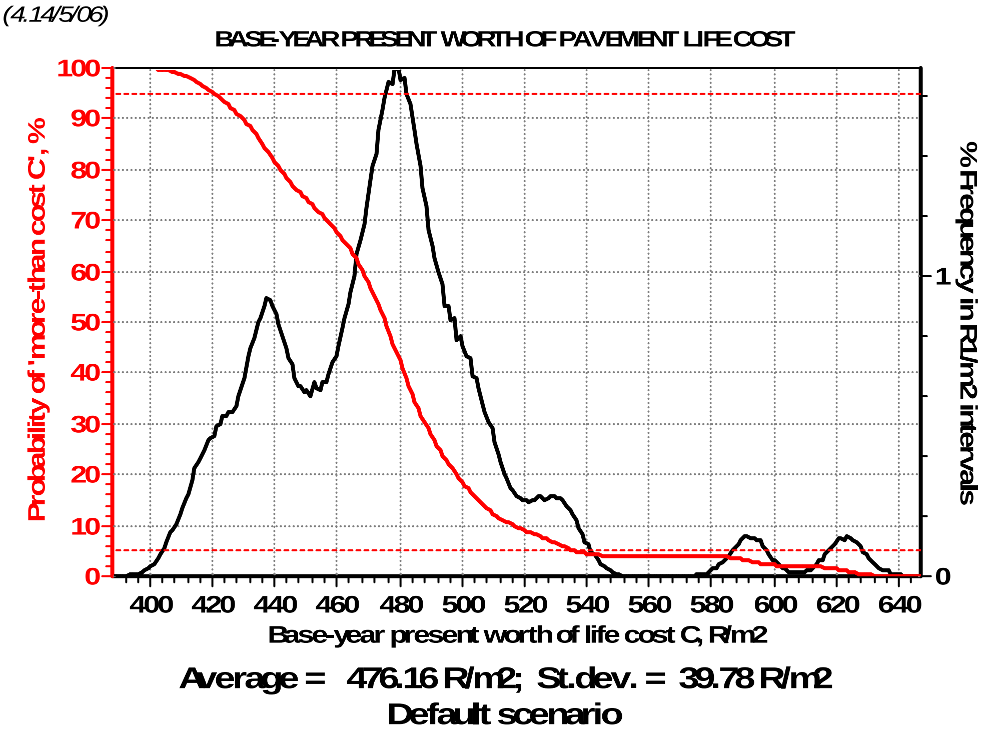


Fig.3. An example of the pavement life cost viewed as random variable. The 90 % confidence interval of the cost, in this case, stretches from R420/m^2 to R540/m^2 – see the intersections of the upper and lower red broken lines with the thick red curve.

7. MAIN OUTPUT

The main output of a Cyrano simulation run is displayed in two graphs. One graph shows the cracking and deformation, the other the International Roughness Index (IRI) and the percentage of failed surface. Apart from the life cost, these four output variables are the most important ones. They are called decision variables – variables in terms of which the user arrives at the decision on the quality of his or her pavement design.

All four decision variables are plotted as trends, i.e. as functions of time. The number of load applications after 14 years, in this example, is about 9 million E80. Time is on the horizontal axis, a value of the decision variable after a given period of time on the vertical one. Usually a bunch of at least 50 curves is plotted for each decision variable, to show the dispersion of possible trends and thus give the user an appreciation of the uncertainty about the output brought about by the uncertainty about the input.

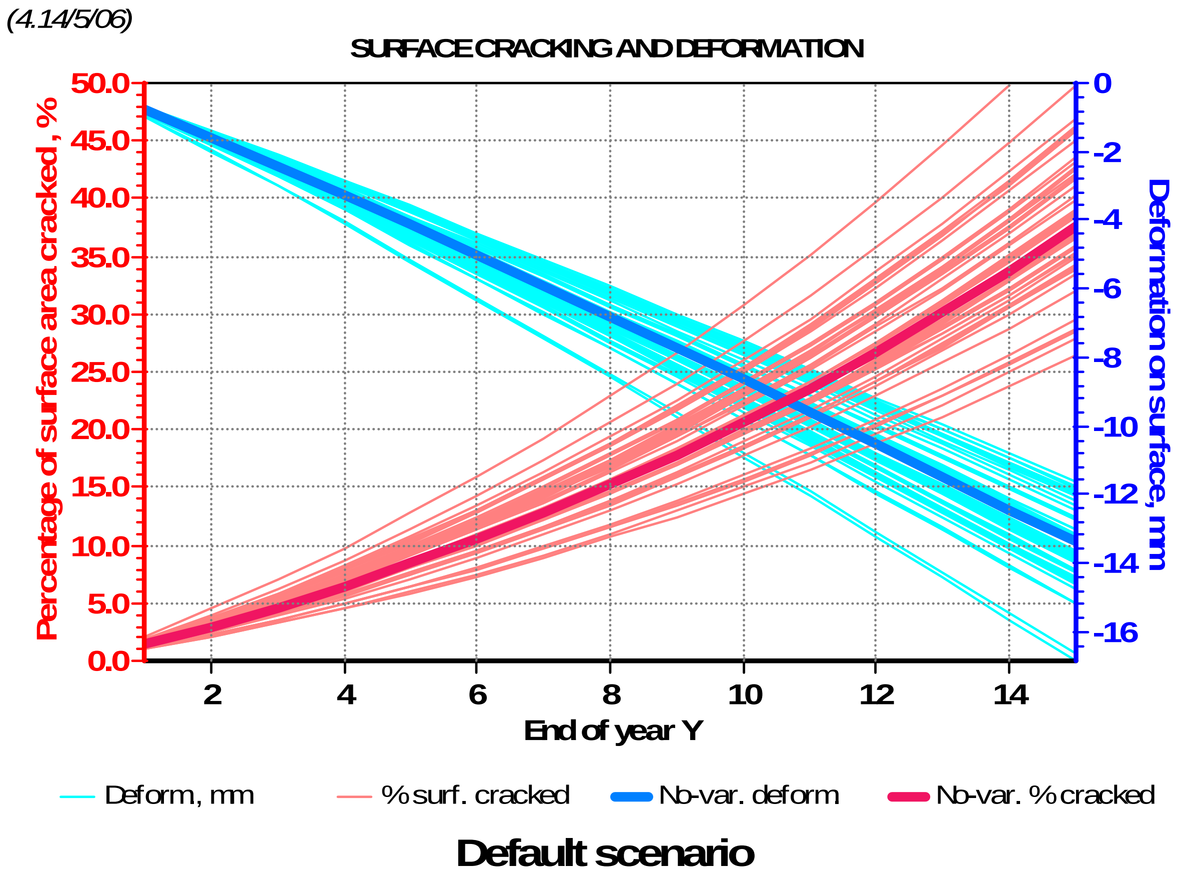


Fig.4. An example of the trends in the development of surface cracking and rutting (deformation) over the study period of 15 years.

It is clear from the above plots that the prediction of decision variable such as rutting after, say, 4 years is relatively easy – the dispersion of possibilities after only 4 years of road operation is moderate. This, certainly, is not the case after 15 years; the graph shows that, in the case studied, the rutting can be anywhere between 12 and 17 mm. However, not all possibilities between 12 and 17 mm are equally probable; the most probable are those lying close to the thick blue (‘average’) curve.

The graph in Fig.5 shows the simulated random-walk scenarios that resulted in the IRI and Percentage failed surface trends.

The relatively broad ‘broom’ of the percentage-of-failed-surface curves are sending out a clear signal that, due to the uncertainty in input, we cannot be very sure about the percentage of road surface that may need repair after 15 years; it can be as little as 12 %, but with bad luck, it can be a whopping 40 %. If we wish to use one representative figure the thick average curve suggests the value of about 20 %.

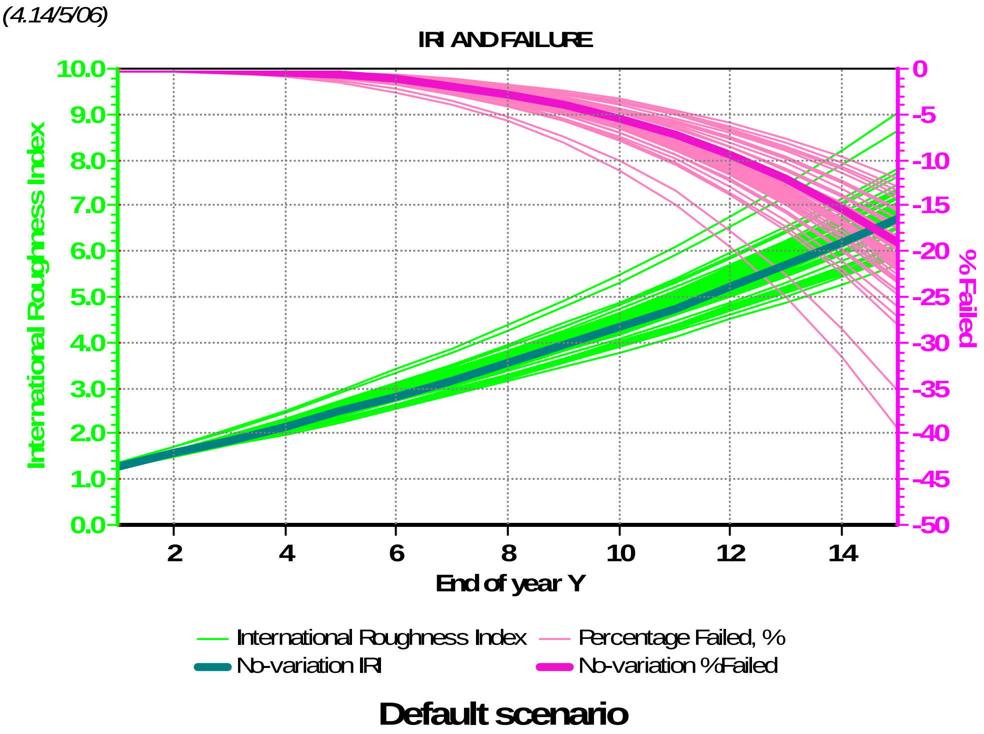


Fig.5. An example of the trends in the development of the International Roughness Index and the Percentage of failed surface over the study period of 15 years.

8. TABULAR OUTPUT

One whole page of the program is dedicated to tabular output - the so-called Facts page. Among other things, the table shows the total E80 growing from year to year, the components of deformation in the sub-surface layers, and the deterioration of layer stiffnesses over time. This information is appreciated when one plans the road rehabilitation and its continuation in the next life cycle. If the top layer only, or the top plus the base layers are replaced, the residual stifnesses of the layers below these can conveniently be found at the bottom of the Facts page.

In a similar spirit, the uncertainty can be reduced and pavement performance forecasts improved within the same life cycle. If the stiffnesses are actually measured, say, after 5 years, Cyrano accepts these as starting values, and new forecasting based on the measured values is done onwards from this point.

9. WHAT-IF FACILITY

Often one wishes to see the relation between a decision variable, such as IRI, and one selected input item, such as the modulus of the base. The what-if facility built in Cyrano plots a relationship specified by the user as a set of three the average-value trends, over a period of 20 years. Those three trends reflect the minimum, medium and maximum value scenarios. An example of the relation between the IRI and the base modulus, with other input variables kept steady, is shown in Fig.6.

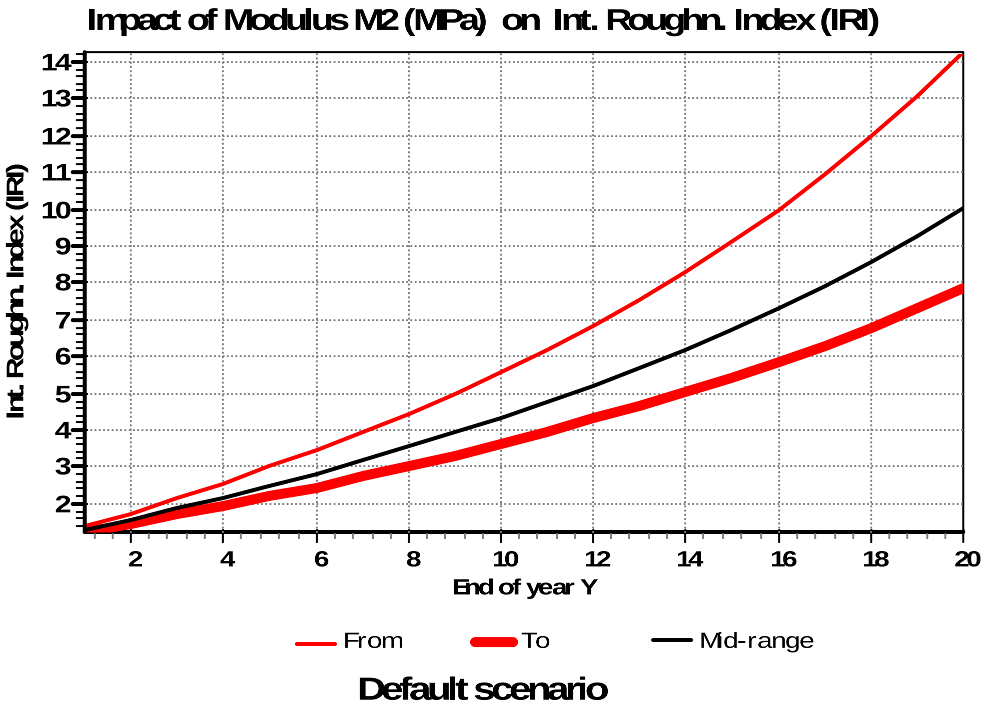


Fig.6. Example of a relation between IRI and base modulus. The thin red curve is plotted for the initial base stiffness (modulus) of 440 MPa, the thick red curve for 660 MPa, and the 'middle scenario' for 550 MPa.

The fast developing separation between the curves leaves one in no doubt that the IRI is very sensitive to base modulus for this particular example.

10. CONCLUSION

Pavement design has traditionally been based on deterministic values for input parameters and consequently the output also is deterministic. Since variation affects the input, the design method should take this into account and reflect in the output the risk of failure and the likely extent of failure with time. The programs such as cncPAVE and Cyrano allow the designer to accommodate the input variation and, using transfer functions that have been commonly used the last two decades in South Africa, predict the area failed with time stochastically. The output in this format makes it possible to judge the quality of design from the probabilistic point of view and thus with greater confidence. The method also allows rapid experimentation with various pavement configurations by which the user's learns quickly with the full view of his decision on one side, and the consequences of this decision on the other.

11. REFERENCES

[1] Theyse, HL, De Beer M and Rust M, 1996. *Overview of the South African Mechanistic Design Analysis Method.* Division Publication DP- 96/005, Tranportek, CSIR, Pretoria.

[2] Wolff, H, 1992. *The Elasto-Plastic Behaviour of Granular Pavement Layers in South Africa.* Ph.D. Dissertation, University of Pretoria.