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# A New Approach for Determining Middle and Long Term Maintenance Costs for Large Underground Works

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## 1. INTRODUCTION

Financing is a more and more crucial step in building large underground works, because the money amount is huge and its pay back takes a long time. Discussion can be very controversial in estimating the financial risk. For this, contractors must schedule, even grossly, all maintenance works for the tunnel life (in the range of about 100 years).
It appears that, for such a long period, the strategy of maintenance is a significant way for minimizing costs. Management and maintenance of civil infrastructures yields towards more risk based design, maintenance and management. This implies more life-cycle cost analysis-based strategies in maintaining infrastructures rather than budget driven corrective maintenance strategies. This will result in more cost efficient maintenance on the one hand, but more complex decisions on the other hand. Among the first type of decisions, functionality (performance) of a structure during its service life plays an important role, whereas, for the second, the costs are considered in priority. Generally the structural performance is to be maintained within accepted reliability ranges and at a minimum cost. To get an idea of how to achieve this, service life modelling predicting the tunnel performance during time is used to optimize maintenance, in order to reach a longer service life at a lower cost. In this way, the tool presented in this paper helps in comparing strategies of maintenance. As suggested before, this tool is designed for large works or set of tunnels. For most of French tunnels, an excel sheet is a satisfactory tool: maintenance is split into current annual maintenance on the one hand and multi-annual maintenance and exceptional maintenance on the other hand [1].
The following items summarize the structure of this paper.

- More than a tunnel

A tunnel is not only one or two tubes, as it is integrated in an infrastructure, around the tunnel one can find other buildings, such as the power supply building, ventilation power plant, shafts, linking tubes, service areas and sometime a part of the road or railway facility.

- Performance index and combination of index

Managing a large underground structure requires a global view of this complex system. It is easy to have a good perception of an isolated element, but with many elements it is not so obvious. We propose a new method to reduce this global view to a numerical combination of performance indexes.

- Ageing and wearing out, modelled by decreasing curves

The behaviour of each part of a tunnel follows a curve, decreasing with time that can be chosen among a large set of parametric functions and finely tuned.

- Repairs and upgrading

We distinguish in this part repairs that slightly increase the performance index each time the job is performed, from upgrades that are generalized repairs for reaching a new and better performance index.

- Costs

Each time a work is done, a cost is given depending on work installation and a number of units with a unit value. Unit is user-defined.

- Computer aspects and networking.

A computer code, on Internet network, summarizes all these concepts.

## 2. Definition of parts of a large underground work.

A large underground structure can be divided in several parts, for example corresponding to the different buildings or their different uses. Other considerations can be taken in account. Geology: if some length of a tube is in a difficult ground that can induce further problem, this part of the tube can be a separate part. Each part is geo referenced. The user can define as many parts as necessary. Simply, a part of a work is homogenous in its behaviour, and associated with its own functionalities that are its duties. As examples of functionalities we can find structural strength, efficiency of drainage, quality of pavement, efficiency of ventilation, luminosity, cleanliness, etc…

## 3. Evaluation of performance index or safety level or risk index.

One way to provide a good management, with reasonable costs and high performance, is to follow a model giving at any time a prediction of an index, or a small set of indexes that leads to a decision about maintenance works.

### 3.1 Inspections are compulsory.

Even if the performance of a tunnel could be predicted by a performance model, inspections would remain mandatory for controlling that this performance is really achieved. Although they do not prevent wearing out, inspections help to check the validity of models and to optimize the scheduling of interventions. Inspections performed by human beings, which are the regular type, will obviously detect spalling only after it has occurred. Inspections using non-destructive techniques, for example half-cell potential measurements, are able to detect corrosion initiation long before spalling occurs, but they are far more costly and time-consuming. So the manager has to find a mixed regime of routine, frequently based on continuous basic surveillance by the regular maintenance staff, yearly visual surveys by technical staff, periodical inspections, for example to detect signs of corrosion, usually every six years and sometimes potential measurements in case of suspicion of corrosion. Intrusive (small scale destructive) testing, for example samples to measure chloride profiles, is done when non-destructive testing indicates an increased probability of corrosion. All these inspections linked actions are part of the maintenance cost and allow the determination of a performance index. [2]

### 3.2 Related index and risk

A performance index is a number, in this paper ranging from 0 to 4, that globally indicates the ability of a tunnel to assume the aim for which it is built, in good conditions with a structure far from collapse and a good service for the users with low risk. There are two thresholds for each index, the first one in an alert, and we have to define some work as to increase the index over the threshold again (or use the tunnel with restriction in a degraded manner) ; the second one is an alarm that indicates high probability of failure or collapse, and the tunnel must be shut. Risk being seen as a combination of likelihood and consequence of a prejudicial event, this performance index can be related to likelihood, a high value signifying low hazard and vice versa.

### 3.3 Combination (weighted logarithmic addition)

The tunnel is thus divided into parts, each one having its functionalities and specific performance indexes. All performance index levels are quantified by a mark between 0 and 4. To obtain the global tunnel operating level, all performance indexes are combined using weighted logarithmic addition (see annex 1).

The logarithmic addition is defined in a limited range of values and avoids any overstep of the previous boundaries. If S is the maximum value (here 4), the addition (Sum) of two performance index levels s and t is given by the formula:

$$Sum = s + t - ( s * t ) / S$$

Each level can be weighted ($w(i)$) assuming that $\Sigma(w(i)) = 1$.

### 3.4 Alarms and degraded use

When the global index of performance becomes too low (a threshold given by the manager) an alert is given to him. An accurate analysis must be done leading to an action to increase the performance index, or to the use of the work in a degraded manner. By knowing at any time all performance indexes and the global performance index, the manager of the tunnel has values to compare different strategies of maintenance in terms of quality of service.
In the next paragraph we shall see the cost impact on decision.

## 4. Ageing and wearing out.

In all parts of tunnel, each performance index decrease with time. A curve defined by a mathematical function with 1 to 4 parameters describes the ageing phenomena. A set of functions is given in annex 2.
The input parameters of the model have to be adjusted in a way that the calculated results correspond to the real behaviour checked by inspections.

### 4.1 Ageing of concrete

There can be many factors playing a role in the deterioration of a tunnel lining, such as carbonation, chloride induced corrosion of reinforcement and other physical, chemical or biological degradations. Usually, for non reinforced lining there is no problem with corrosion or carbonation but frost-defrost, combined with chlorides ingress is very harmful.

#### 4.1.1 Carbonation

The speed of ingress follows a square root law. It is a very slow process that allows steel corrosion to occur when the concrete covering the reinforcement gets at pH lower than 9.36. In plain concrete, carbonation has rather a positive effect as it hardens the concrete and decreases its porosity.

#### 4.1.2 Deterioration of concrete due to chloride ingress

For undersea works, corrosion of reinforcements is considered as being one of the main critical deterioration causes in reinforced tunnel linings (for example in segmental linings). Corrosion initiation due to chloride ingress may lead to spalling of the concrete cover. After a while, this may lead to loss of the structural safety and likely requires repair action. Thus, it has consequences for the availability and maintenance costs of the tunnel. Therefore, in a performance-based design, the chloride concentration is one of the limiting factors on the performance of a structure. Following the research led by TNO [3], the model is based on a curve with two periods. The first one lasts the necessary time so that the chloride concentration reaches the reinforcement, the second one when the corrosion occurs on the reinforcement. This chloride ingress modelling is based on a principally probabilistic approach in which the uncertainties on most input parameters are taken into account. The probabilistic calculations for chloride ingress in this model are diffusion based, closely following the DuraCrete approach [4].

### 4.2 Pavement wearing out

A pavement is often made of an asphalt surface and a foundation layer. A regular maintenance of the surface delays the foundation deterioration. We have there a typical maintenance strategy, either doing nothing for a long time and repairing the foundation layer, or maintaining the road surface in good condition, and repairing the foundation later. The owner also has to consider the disturbance of the users.
Following British observations, the decrease of the performance index of a pavement is a parabola with down concavity.[5]

### 4.3 Drainage and sintering

Drainage of water behind the lining is a very important system for a good behaviour, but also in cold regions, to avoid ice stalactites that can fall on the users. The evolution of a drainage system depends mainly on the water quality leading the speed of sintering. The performance index of a drainage system can be the ratio between the maximum flow without sintering and the actual flow with sintering in the drainage pipes.

Three maintenance strategies are discussed by Leismann [6]: Either chemical avoidance of deposit, either periodic washing, or repair by drilling when the drain is filled due to poor maintenance.

### 4.4 Equipments

As it is man-built, equipment wear out is well known in a statistic manner. If equipment is numerous, like lamps in a tube, the performance index can be easily related to the number of non-working lamps and one knows the attrition rate of lamps. For single equipment, the performance index is related to the MTBF (mean time before failure) usually given by the builder. In wide tunnels the number of equipment is large. The notion of part of tunnel described before may be used without spatial reference, saying for example that lamps are a part of tunnel.

### 4.5 Interactions

A tunnel is a global system, and when an action is done somewhere inside, consequences must be taken into account on other index performance levels. So indexes can be linked each other and action can have effects, positive or negative, on other performance. The pavement ageing described before is an example.

## 5. Repairs and upgrading.

The most important repair strategies that may be distinguished are rebuilding, corrective repair and preventive repair.

### 5.1 Repairs

In case of corrective repair, only damaged spots are repaired; whereas in case of preventive repair, measures are taken that prevent actual damage to occur. Preventive repair consists in suppressing the bad effect. Consequently the costs are incurred earlier in time, but large-scale maintenance costs are avoided.

### 5.2 Upgrading

In this case, large works are defined and the use of the underground structure may be difficult to conciliate with the works. All performance indexes will probably be set at the highest level, but the cost is very heavy.

## 6. Costs and prioritization.

When it comes to establishing an economic maintenance management plan for the future, the tunnel operator has to carry out a ranking of either the parts of his tunnel(s) or between tunnels within a whole infrastructure network. As tunnel owners most frequently do not have the financial means to undertake all the necessary maintenance actions at a time in order to assure the structural safety and serviceability of their entire structure(s), it is an important task to prioritize the facilities (here: tunnels, parts of tunnels), as well as the interventions (type, intervals, costs).

The prioritization of the facilities is carried out in two steps. First, a purely technical prioritization is carried out based on the condition assessment, e.g. with the periodical inspections. This condition assessment not only leads to a classification of the inspected parts of a tunnel, but also leads to the ranking of whole tunnels in a network.

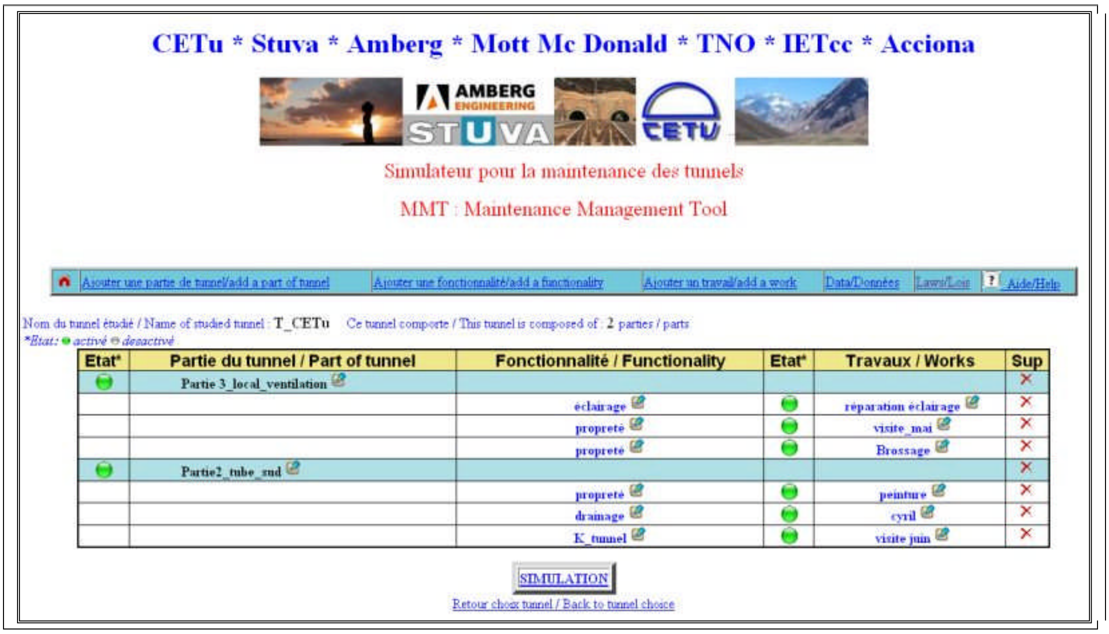
The basis for the second step, the financial prioritization, is the choice of an appropriate intervention strategy.

As a short summary, an intervention strategy is the reasonable combination of different maintenance activities, e.g. preventative, corrective maintenance or repair actions. All these actions have consequences on the performance level curve on the one hand (technically), and on the other hand on the cost curve (financially).

The financial prioritization is carried out by means of adding up the yearly costs of the interventions in each tunnel in different years, e.g. for the next five years. Then, adjustments to the prioritization can be made according to the available yearly budget and trying not to get to far away from the technical prioritization. If necessary, the intervention strategy has to be adjusted, in order not to exceed the yearly budget.

7. Framework of the tool.

During the EC project "Tunconstruct" a prototype called "MMT" for "Maintenance Management Tool" was established.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Simulateur pour la maintenance des tunnels

MMT : Maintenance Management Tool

Nom du tunnel étudié / Name of studied tunnel : T_CETu Ce tunnel comporte / This tunnel is composed of : 2 parties / parts

*Etat: ● activé ○ desactivé

| Etat* | Partie du tunnel / Part of tunnel | Fonctionnalité / Functionality | Etat* | Travaux / Works | Sup |
|---|---|---|---|---|---|
| ● | Partie 3_local_ventilation | | | | ✕ |
| | | éclairage | ● | réparation éclairage | ✕ |
| | | propreté | ● | visite_mai | ✕ |
| | | propreté | ● | Brossage | ✕ |
| ● | Partie2_tube_sud | | | | ✕ |
| | | propreté | ● | peinture | ✕ |
| | | drainage | ● | cyril | ✕ |
| | | K_tunnel | ● | visite juin | ✕ |

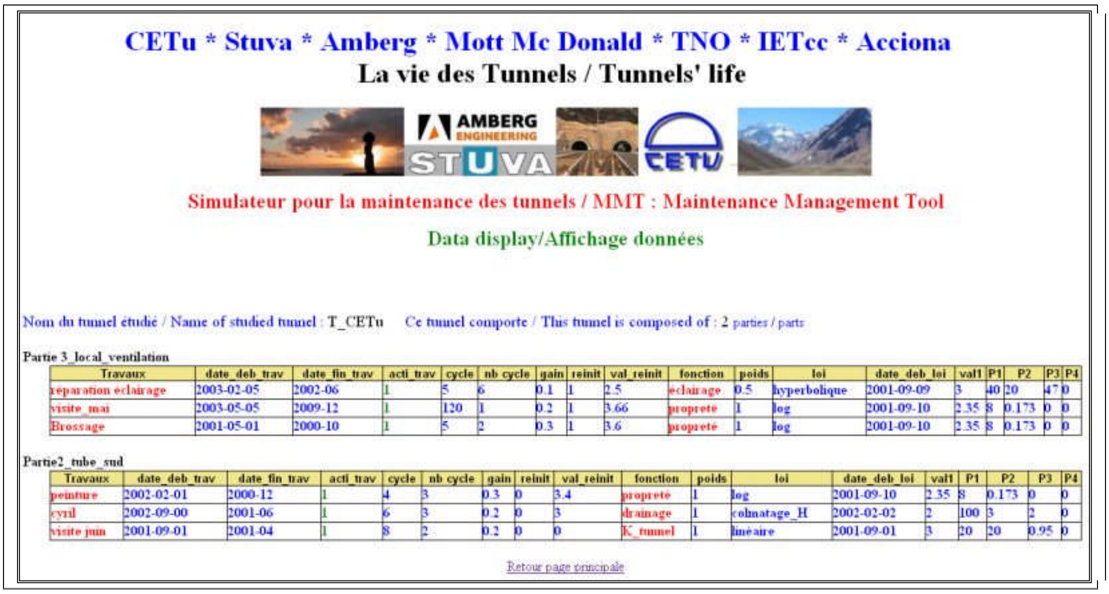
Figure 1 : Main page of MMT where all commands are available.
*The top blue line is for adding part of tunnel, functionalities and works. The green circular dots are for activating or desactivating part of tunnels or works aiming to easiest comparisons. The pencil dot allows reading or modifying part of tunnel, functionalities and works.*

The MMT supports the tunnel owner in maintenance tasks. By means of performance level curves representing each phenomenon (functionality), and thanks to the cost curves that depend on the scheduled actions (works), the owner can adjust the parameters of the works (interventions, time intervals and costs) until he reaches the available yearly budget. The MMT is able to overlap the costs for different functionalities and to combine different types of works with different costs at different times in a period.
The MMT aims at evaluating the functional level of a tunnel and the expenditures that must be incurred to reach a given functional level. The global functional level is the result of the combination of individual functions which level of performance can be improved separately by performing specific works.

All data are stored in a small database.

The tunnel is divided into parts, each owning it owns functionalities. The manager using MMT tool defines the different parts of her/his tunnel, finds the functionalities for each part and specifies the different types of works that can enhance each individual functionality level.
All functionality levels are quantified by a mark between 0 and 4.
To obtain the tunnel global operating level, all functionalities are combined using weighted logarithmic addition.

A tunnel is defined by its name and GPS coordinates. Other data can be added. A part of tunnel is also defined by its name, and local coordinates. Functionality is defined by its name, a starting date, an initial functionality level and a decreasing law. A work is defined by its name, a starting date, cycle duration and a number of cycles. A cost of a maintenance work is defined by an installation cost, an elementary cost and a quantity, and the name of this quantity (unit ). Every time a work is performed, the corresponding functionality level value is increased as well as the cost of maintenance. The decrease law can be chosen between a set of mathematical laws, and a law simulator helps the user to choose the law and determine its parameters.


CETu * Stuva * Amberg * Mott Mc Donald * TNO * IETcc * Acciona

La vie des Tunnels / Tunnels' life

Simulateur pour la maintenance des tunnels / MMT : Maintenance Management Tool

Data display/Affichage données

Nom du tunnel étudié / Name of studied tunnel : T_CETu     Ce tunnel comporte / This tunnel is composed of : 2 parties / parts

Partie 3_local_ventilation

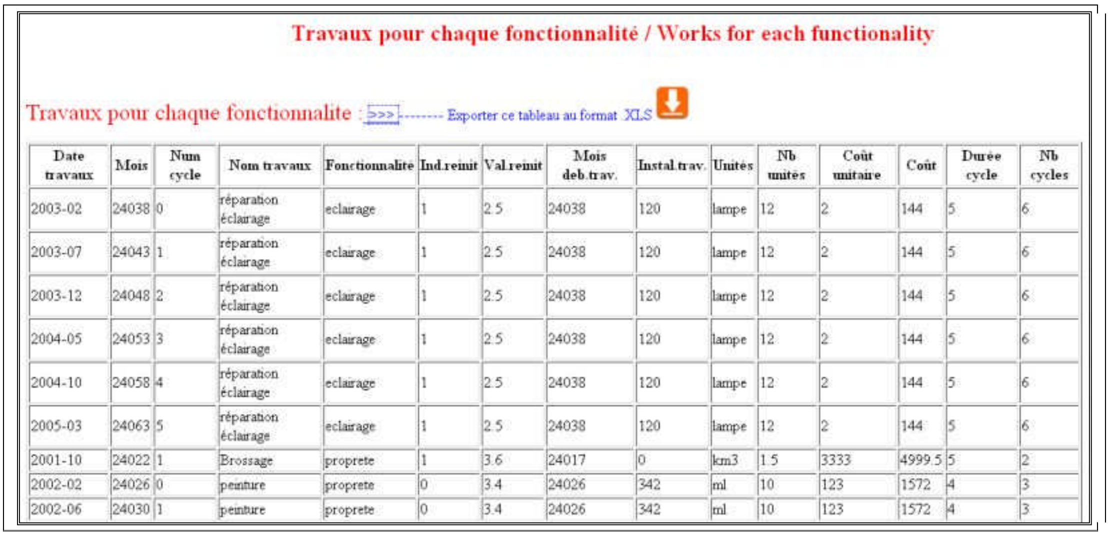
| Travaux | date_deb_trav | date_fin_trav | acti_trav | cycle | nb cycle | gain | reinit | val_reinit | fonction | poids | loi | date_deb_loi | val1 | P1 | P2 | P3 | P4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| réparation éclairage | 2003-02-05 | 2002-06 | 1 | 5 | 6 | 0.1 | 1 | 2.5 | éclairage | 0.5 | hyperbolique | 2001-09-09 | 3 | 40 | 20 | 47 | 0 |
| visite_mai | 2003-05-05 | 2009-12 | 1 | 120 | 1 | 0.2 | 1 | 3.66 | propreté | 1 | log | 2001-09-10 | 2.35 | 8 | 0.173 | 0 | 0 |
| Brossage | 2001-05-01 | 2000-10 | 1 | 5 | 2 | 0.3 | 1 | 3.6 | propreté | 1 | log | 2001-09-10 | 2.35 | 8 | 0.173 | 0 | 0 |

Partie2_tube_sud

| Travaux | date_deb_trav | date_fin_trav | acti_trav | cycle | nb cycle | gain | reinit | val_reinit | fonction | poids | loi | date_deb_loi | val1 | P1 | P2 | P3 | P4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| peinture | 2002-02-01 | 2000-12 | 1 | 4 | 3 | 0.3 | 0 | 3.4 | propreté | 1 | log | 2001-09-10 | 2.35 | 8 | 0.173 | 0 | 0 |
| cyril | 2002-09-00 | 2001-06 | 1 | 6 | 3 | 0.2 | 0 | 3 | drainage | 1 | colmatage_H | 2002-02-02 | 2 | 100 | 3 | 2 | 0 |
| visite juin | 2001-09-01 | 2001-04 | 1 | 8 | 2 | 0.2 | 0 | 0 | K_tunnel | 1 | linéaire | 2001-09-01 | 3 | 20 | 20 | 0.95 | 0 |

Retour page principale

Figure 2  : Display of all used data.
*At any time the user can have a view of all the working data.*


Travaux pour chaque fonctionnalité / Works for each functionality

Travaux pour chaque fonctionnalite : >>> -------- Exporter ce tableau au format XLS

| Date travaux | Mois | Num cycle | Nom travaux | Fonctionnalite | Ind.reinit | Val.reinit | Mois deb.trav. | Instal.trav. | Unités | Nb unités | Coût unitaire | Coût | Durée cycle | Nb cycles |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2003-02 | 24038 | 0 | réparation éclairage | eclairage | 1 | 2.5 | 24038 | 120 | lampe | 12 | 2 | 144 | 5 | 6 |
| 2003-07 | 24043 | 1 | réparation éclairage | eclairage | 1 | 2.5 | 24038 | 120 | lampe | 12 | 2 | 144 | 5 | 6 |
| 2003-12 | 24048 | 2 | réparation éclairage | eclairage | 1 | 2.5 | 24038 | 120 | lampe | 12 | 2 | 144 | 5 | 6 |
| 2004-05 | 24053 | 3 | réparation éclairage | eclairage | 1 | 2.5 | 24038 | 120 | lampe | 12 | 2 | 144 | 5 | 6 |
| 2004-10 | 24058 | 4 | réparation éclairage | eclairage | 1 | 2.5 | 24038 | 120 | lampe | 12 | 2 | 144 | 5 | 6 |
| 2005-03 | 24063 | 5 | réparation éclairage | eclairage | 1 | 2.5 | 24038 | 120 | lampe | 12 | 2 | 144 | 5 | 6 |
| 2001-10 | 24022 | 1 | Brossage | proprete | 1 | 3.6 | 24017 | 0 | km3 | 1.5 | 3333 | 4999.5 | 5 | 2 |
| 2002-02 | 24026 | 0 | peinture | proprete | 0 | 3.4 | 24026 | 342 | ml | 10 | 123 | 1572 | 4 | 3 |
| 2002-06 | 24030 | 1 | peinture | proprete | 0 | 3.4 | 24026 | 342 | ml | 10 | 123 | 1572 | 4 | 3 |

Figure 3 : Output of all elements of tunnel life
*After giving to the MMT a window time (between two dates corresponding to when the owner wants to know accurately the activity in the chosen part of tunnel), the export to a spread sheet is available.*

The use of this tool can be shared between several people as it is a web tool. This point implies that rights are defined for each user; some of them specialized in one element of tunnel, others partial analysis and others global analysis. The every day provided data from any computer assure a permanent management.

## 8. Conclusion

- Because the availability of a tunnel is a very important (expensive) aspect, the maintenance strategies for the tunnel lining should ideally be considered in accordance with the maintenance of other tunnel elements. For example, if a correlation between maintenance of the concrete tunnel lining is made with the maintenance of the asphalt road, then inspection and repair timing could possibly be synchronised for both tunnel elements. This would reduce the closure time of the tunnel and therefore also the costs. Nevertheless, even though synchronisation would significantly reduce the costs, making a correlation between both tunnel elements is quite ambitious as both have different life cycles and different maintenance requirements.
- When more experience has been gathered for maintaining tunnel costs, such a maintenance management tool like MMT with cost calculations could be tied in with more large scale Life Cycle Analyses for big systems including many other societal aspects that are monetarised such as CO2 footprint, tunnel closure, traffic jams etc.
- Government administration, also contractors and short term tunnel managers should benefit from such tools because they might have to show what the remaining state of the tunnel and future maintenance costs are, especially if insurance companies are also involved.

## 9. Acknowledgements

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## ANNEX 1 : Logarithmic addition

For using performance level in a mathematical manner we have to consider

- Performance level can be quantified, for example : P = Max of P / Present value of P
- Absolute performance is impossible as it is not a reality.
- What is a level performance twice? Not twice it value.
- Performance level is bounded between two values 0 and S, with 0 = no performance, 1 = danger, 1.5 = satisfying, S = maximum value of performance.

For setting a computational approach we assume that performance is like a filter, (sun glasses for example) as we can add filters but never cut the light. For light, we have a physical law for absorption that is $I_2 = I_1 \exp(-a * T)$ where $I_2$ and $I_1$ are intensities of light after and before the filter, a is the coefficient of absorption and T is the thickness of the medium. Using the addition of thickness of two medium, and the fact that performance level belongs to a bounded domain (0,S), the logarithmic addition of two performance levels is defined by

$$s \,(+)\, t = s + t - (s * t) / S$$

the logarithmic subtraction by $s \,(-)\, t = S\,(s - t) / (S - t) \quad \text{for } s >= t$

and the logarithmic multiplication by $n \,(*)\, s = S - S(1 - s/S)\, n$

It can be shown that with these three operators, (0 - S) is an ordered positive vector cone that allows, associability, neutral element, commutability, unit element, double distributability. It is said positive as scalar multiplication rules only for positive scalars.

## ANNEX 2 : Some aging functions proposed in Maintenance Management Tool.

A number of decreasing function are given to the user using until four parameters. All functions can be drawn inside MMT giving to the user a good perception of it. For all function the first parameter is the number of months (month is the time unit) giving a fall of 1. The second parameter is usually related to the initial speed of decreasing. We give there some functions, a help is available inside MMT.

- Linear : only one parameter
- Parabolic: two parameters that can define upward and downward the concavity.
- Cubic: three parameters.
- Hyperbolic: two parameters.
- Logarithmic: two parameters.
- Square root: two parameters.
- Drainage 1: based on the drain geometry and the shape of deposit, three parameters.
- Etc.

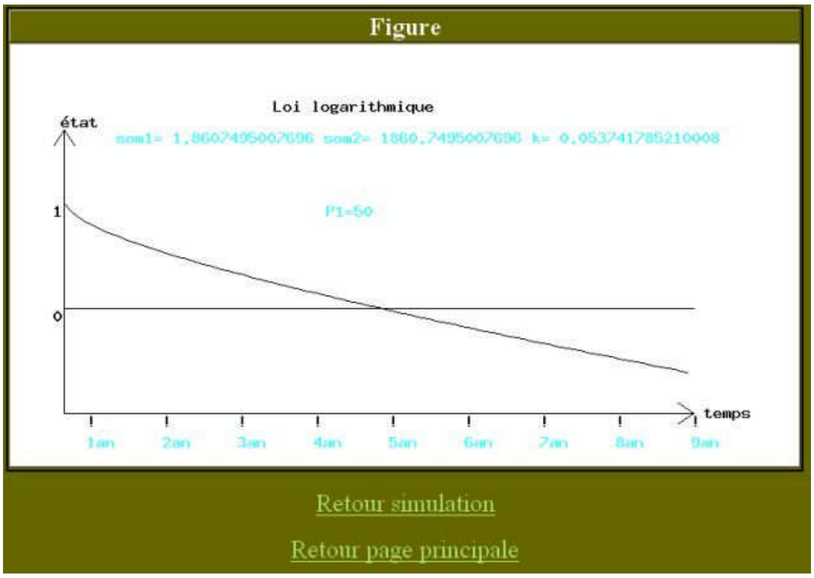

Figure 4 : Using the law simulator
*A display for a better choice of decreasing law*