Continuous Assessment of Performance History of Pavement Structures in France

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ABSTRACT

An overview is provided of observations made in connection with maintenance operations conducted on more than 11 000 km of French national roads as part of a preventive maintenance program, which also covered state-run (nonconcessionary) freeways. The primary purpose of making these observations was to evaluate the performance under traffic of various new or reconstructed (resurface, overlaid) pavement structures in order to assess the results of the design options made and to determine where changes were required. Making the observations also made it possible to reveal and analyze any abnormal conditions and to evaluate maintenance costs. The observations indicated the consistency of pavement design rules applied in France, and the validity of the decision to develop hydraulic-binder-treated granular materials. Road network managers now have a relatively wide range of pavement construction and reconstruction techniques, which are both operational and competitive not only with respect to initial capital cost but also to subsequent maintenance. A road data bank also enables comparisons between projects completed or those to be completed, and specific project data permit an assessment of service levels actually achieved. This provides a means of rectifying pavement designs and comparing the performance of different structures.

After the long, harsh winter of 1962-1963, which revealed the shortcomings of maintenance on France's road network at that time, the French highway department laid the groundwork for a comprehensive highway engineering program (design, maintenance), which it has implemented since 1969. There are three aspects to this program:

1. Design of new pavements capable of handling aggressive commercial traffic (13-ton legal axle weight). This design is based on a set of standards: a catalog of precalculated standard structures (1), and directives concerning the manufacture and placement of materials whose use is provided for in the catalog (2).
2. Rehabilitation of unsuitable old pavements (the coordinated overlays program initiated in 1969). This program has already enabled the resurfacing of some 20 000 km of France's 28 000-km road network. This reconstruction program is based on the directives mentioned previously and a design guide for flexible pavement overlays (3).
3. Scheduled preventive maintenance of new or reconstructed roads, a policy that was initiated in 1972, based on the application of a preventive maintenance guide (4).

At the same time, and as part of a more global policy of service to the user--covering in particular the geometrical, environmental, and road operation aspects--information handling facilities have been developed: the road data bank. These facilities are currently operational and provide considerable potential for the efficient use of the large amount of data collected. Much of these data are provided by surveys and through projects completed in accordance with the maintenance policy and specifications just described, providing an exceptional experimental field for the reliable evaluation of in situ pavement behavior.

In this paper, an assessment is provided of observations concerning maintenance tasks carried out in France on more than 11 000 km of national roads within the framework of a preventive maintenance program, as well as on nonconcessionary freeways. Most of the pavements (newly constructed or resurfaced) were opened to traffic between 1970 and 1983, the oldest being 25 years old.

The ultimate aim of such an assessment is first to determine the performance under traffic of various new or overlaid pavement structures in order to assess the technical options adopted and define changes, if needed. It is also designed to detect and analyze any abnormal conditions and, finally, to evaluate maintenance costs and provide (with certain reservations) for future needs, thereby contributing to the working out of corresponding budgets.

At this stage, two objections may occur to the reader:

1. First, the performance of various pavement designs is judged by maintenance work actually carried out. It would have to be verified that the service levels actually obtained are comparable with one another. At this stage, this can be reasonably assumed because of existing preventive maintenance guide specifications.
2. Finally, the perspective for making a sound judgment is limited with regard to most of the standard structures appearing in the basic documents currently governing the structural design of new pavements and flexible pavement overlays. This lack of perspective--which is due both to the average age of the structures and the pavement lengths involved (the population of certain structures is relatively small)--means that great care is required in interpretation, particularly because major technological developments may have taken place since the launching of the coordinated reconstruction program in 1969.

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For the most common structures considered here, the trends observed nevertheless appear to be clear and provide solid grounds for assessing existing and foreseeable highway engineering technology.

On a more general level, these investigations indicated the following:

• Effectiveness of the pavement design specifications used, even though certain points require additional study;
• The value of an important decision of the seventies; namely, the development of hydraulic-binder-treated granular material (HBTGM); and
• The existence of a relatively broad range of application-ready competitive pavement construction and resurfacing methods currently available to highway engineers and authorities.

(Note that in France, the HBTGM technique is a standard technique for both the subbase and base layers. The technique involves, in particular, the use of cement, slag, fly ash or other hydraulic binders, high-quality granular materials, and treatment in plant and not in situ.)

France's road data bank makes it possible to compare work performed or to be performed, and the parameters will permit an evaluation of the effectiveness of highway service. A means of adjusting design parameters and evaluating the performance of structures will thus be provided.

It is with this in mind that the methods and computer programs developed can be made available to all agencies who so desire, with the common approach adopted making it possible to communicate in the same language and make valid comparisons.

The methodology is meant to be open ended and perfectible. The authors are interested in receiving suggestions concerning both the methods used and the results achieved, in particular from agencies, contractors, and materials and equipment suppliers.

OBJECTIVES

New or resurfaced pavement structures are monitored regularly for four purposes:

1. To assess the comparative behavior of various groups of pavement structures in situ, in both physical and financial terms;
2. To allow a judgment concerning decisions made about design specifications and the selection of road-building techniques and materials;
3. To provide data for technological forecasting; and
4. To contribute to the reliable estimation of future maintenance budgets.

METHODOLOGY

For the various groups of pavement structures used in statistically significant quantities, the distribution by age and traffic class was determined. For each category defined, successive maintenance operations were specified by date of implementation and type. All maintenance work performed, for both structural and surface aspects (permeability, stripping, peeling, etc.), was taken into account. Moreover, by an automatic statistical adjustment method, it was possible to calculate the probability of maintenance interventions at a given age of the pavement structure in question. The required data acquisition is carried out each year by a correspondent appointed in each of the seven Centres d'Etudes Techniques de l'Equipement (CETE) (Technical Study Centers for Equipement, which are regional agencies, backing the technical departments of the central government office) and the Regional Equipment Laboratories of the Paris region. The data are transmitted regularly to the Bordeaux CETE, which acts as a retrieval center for these studies and developed the data processing and operating systems.

CHARACTERISTICS OF THE POPULATION CONCERNED

The studies presented here cover a total of 11 210 km, or 2580 km of new pavement and 8630 km of resurfaced pavements. The initial works (construction or resurfacing) were carried out between January 1, 1960, and December 31, 1983, and all maintenance work carried out up to December 31, 1983, has been taken into account.

To avoid having an overly specific environment, which would induce nonrepresentative local patterns, the population (in the statistical sense) adopted for this study includes only sections of pavements on national roads or public freeways located outside of towns. Moreover, any sections likely to cause special problems of inputting or interpretation were removed from the sample (e.g., crossroads, road widening, sections of insufficient length).

Three groups of structures were considered for new pavements and four for resurfacing. Table 1 gives the length involved and the weighted mean age in 1983 for each group and Figure 1 shows the typical cross sections. For all the sections defined, the study consisted of indicating the age of the pavement structure at maintenance interventions and the nature of the tasks performed. Maintenance tasks were divided into five types:

TABLE 1 Length and Weighted Mean Age of Pavement Structures

Structures Studied	Length (km)	Weighted Mean Age (yr)
Resurfacing with hydraulic-binder-treated granular material before 1975 (R/HBTGM < 75)	2 230	11.3
Resurfacing with hydraulic-binder-treated granular material in 1975 and after (R/HBTGM > 75)	2 560	5.9
Resurfacing with bituminous concrete (R/BC) strictly 10 cm thick	970	7.8
Resurfacing with bitumen-treated granular material (R/BTGM)	2 870	7.3
New pavements with HBTGM base and subbase (N HBTGM/HBTGM)	1 450	6.3
New pavements with BTGM base on HBTGM subbase (N BTGM/HBTGM)	530	6.4
New pavements with BTGM base on untreated granular material subbase (N/BTGM/UGM)	600	9.9
Total	11 210	
Average		7.8

Note: Pavements in cement concrete represent only 116 km on the network in question and were unable to be taken into account in the current study.

• Type 1: Surface dressing or similar [slurry seal, surface regeneration with application of less than 2 cm of new material, bituminous concrete (BC) of thickness < 3 cm].
• Type 2: BC in a 3- or 4-cm layer (or surface regeneration with application of more than 2 cm of material).
• Type 3: BC in a layer of 5 to 8 cm.
• Type 4: BC in a layer of 9 to 14 cm.
• Type 5: Reconstruction (base layer and wearing course).

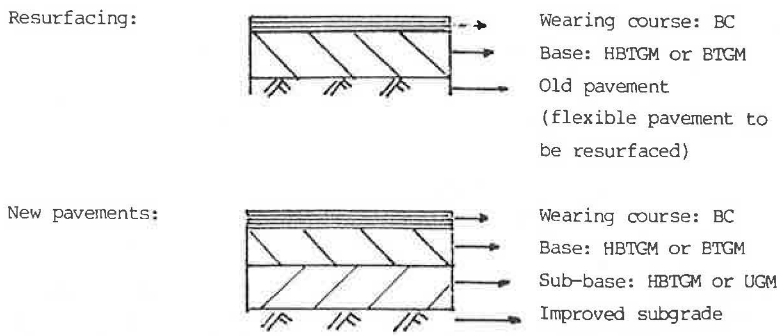

FIGURE 1 Typical cross sections.

Because of data acquisition difficulties, sealing of cracks was not taken into account.

SIGNIFICANCE AND LIMITS OF ANALYSIS

The analysis made endeavored to relate maintenance requirements to two explanatory variables: the construction (or resurfacing) technique and traffic. Other important parameters are also involved in such a correlation, including the environment, in particular, the climate; this was taken into account indirectly by an analysis of regional disparities (which are only partly explained by climatic differences). Other parameters could not be taken into account at the current stage of the study for want of reliable recording or interpretation facilities. In particular, such parameters are

- Subgrade bearing capacity class (which is taken into account in structured design),
- Structural design (considered to be in conformity with applicable documents and methods during the design phase),
- Material quality, manufacture, and placement conditions (assumed to be in conformity with current specifications), and
- Local climatic data (temperature, precipitation, and sunshine).

The method and practical conditions of the study, while they do not affect the validity of the conclusions given in the following list, nevertheless require certain reservations and great care regarding their interpretation, particularly if used for planning purposes.

- With experience, every technique is gradually improved, and only radical changes that can be easily located in time have been able to be taken into account. Accordingly, resurfacing with HBTGM applied before 1975 has been distinguished from HBTGM resurfacing done in 1975 and after because at that time the design rules were thoroughly modified.
- Numerous coordinated reconstruction projects employed HBTGM for special reasons, such as frost protection. The stresses on the various structures are therefore not always strictly comparable.
- The maintenance work performed does not always correspond to the work required, notably because when carried out suitable techniques were not available for all cases (thin-layer coated maintenance materials, surface dressings for heavy traffic, crack sealing, etc.).
- Finally, and above all, a causal analysis on the basis of maintenance work actually performed presupposes that budgetary constraints are not significant and do not introduce excessive trade-offs between what is needed and what is done, and also that decision-making rules are uniform for all the roads studied.

In other words, it has been assumed that the provisions of the Preventive Maintenance Guide Specifications are correctly applied by all agencies and that they actually make it possible, in conformity with the objective assigned to them, to constantly provide a comparable level of service on all pavements, irrespective of their initial structure. In practice, until 1983, budgetary constraints made it possible to a large extent to meet maintenance requirements, and accordingly have not introduced major bias into the results, whether in absolute value or in relative value.

MAIN RESULTS

Computerized data processing produces two types of printouts: (a) for each structure, maintenance performed year by year, through successive maintenance work and by type of task (Type 1, 2, 3, 4 or 5); and (b) cumulative maintenance frequencies, giving for each age the percentage of length maintained on sections having at least the age in question, both by type of structure and for successive maintenance operations. Each of these printings covers the sphere of action of each CETE. For all of France, it was possible to add a distinction by traffic class to these data.

These results are translated into more explicit curves, the chief of which are shown in the figures later in this paper. It should be noted that the traffic considered is that for 1980 expressed in numbers of vehicles exceeding 5 tons of payload, average annual daily traffic (AADT) on the busiest lane, and not the traffic of the first year of service. In the following table, TE is exceptional traffic.

Traffic Class	No. of Heavy Vehicles
T3	50-150
T2	150-300
T1	300-750
T0	750-2,000
TE	>2,000

ANALYSIS OF CUMULATIVE MAINTENANCE FREQUENCIES BY TECHNIQUE

National Results

Only the curves concerning structures having a sufficient population (cumulative length of sections) for their statistical interpretation to be reliable have been selected. This criterion rules out most breakdowns according to the type of maintenance task performed. However, such information is provided in a later section entitled Analysis of Type and Cost of Maintenance Tasks.

Resurfacing with Bituminous Concrete (R/BC)

This resurfacing technique is special because it often represents a gradual-strengthening solution, used chiefly in regions with mild climates. Under such conditions (Figure 2), the need for rapid service is not surprising (50 percent of the length was resurfaced after 7 yr). The influence of traffic is small, which tends to indicate that this solution has been used discerningly.

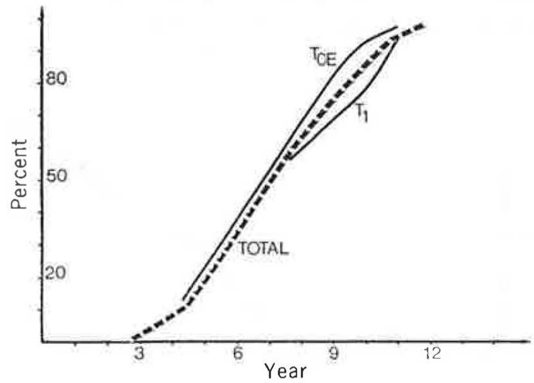

FIGURE 2 Percentage of length maintained as a function of age on pavements resurfaced with 10 cm of bituminous concrete.

Bases in Hydraulic-Binder-Treated Granular Materials

Figure 3 shows the radically different behavior of the resurfaced pavements in HBTGM applied before and after 1975, the year representing a turning point marking the almost systematic use of layers 25 cm thick and greater. This figure shows the importance of good structural design of semirigid pavements, which is also the subject of discussions at the international level.

Figure 4 shows that the maintenance performed on

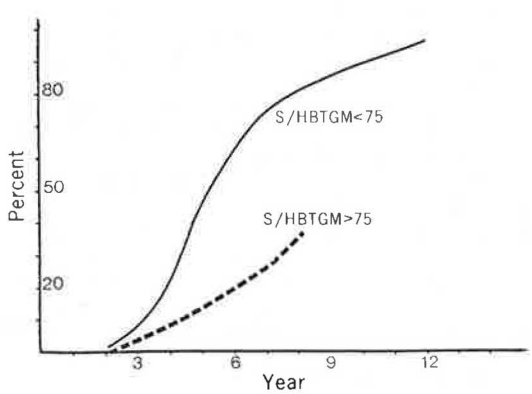

FIGURE 3 Percentage of length maintained as a function of age on pavements resurfaced with hydraulic-binder-treated granular material (all traffic).

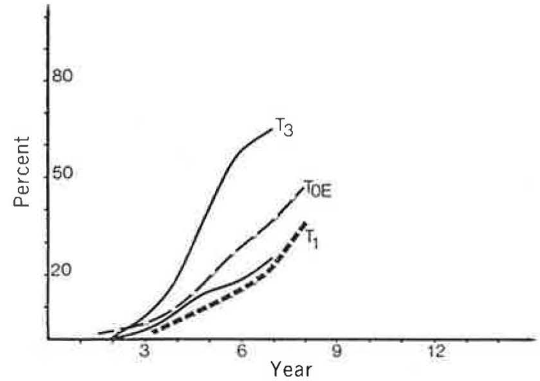

FIGURE 4 Percentage of length maintained as a function of age on pavements resurfaced with hydraulic-binder-treated granular material after 1975.

resurfacing with hydraulic-binder-treated granular material after 1975 (R/HBTGM > 75) differs according to the various traffic classes. For light traffic (T3), major maintenance requirements appear, but the population is too small to draw any definite conclusions. Very dense traffic (T0 and TE) requires far more maintenance than T1 and T2 levels of traffic. In these cases, the thicknesses of the wearing courses and the quality of the BC/HBTGM interfaces perhaps require more thorough study.

Figure 5, concerning new pavements, shows that the present all-HBTGM structures are subject to far earlier maintenance under dense traffic. It is possible that in practice the structures are sometimes undersized by comparison with the reference catalog and that problems remain concerning subbase-base bonding in certain cases.

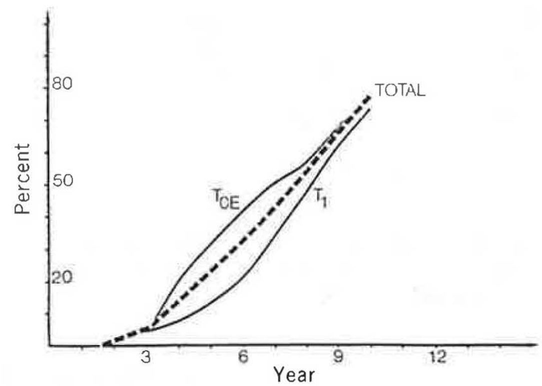

FIGURE 5 Percentage of length maintained as a function of age on new pavements with base and subbase layers in hydraulic-binder-treated granular material.

On the whole, it appears that, by comparison with Figure 6 [all structures taken together, except resurfacing with hydraulic-binder-treated granular material before 1975 (R/HBTGM < 75)], which will be used as a reference, the R/HBTGM > 75 structures are located exactly at the median point (50 percent will probably be resurfaced at 9 yr), whereas the new pavements with base and subbase layers in hydraulic-binder-treated granular material (N HBTGM/ HBTGM) show a less favorable result (median age of first maintenance is 7 3/4 yr), particularly under intense traffic (50 percent at 7 yr).

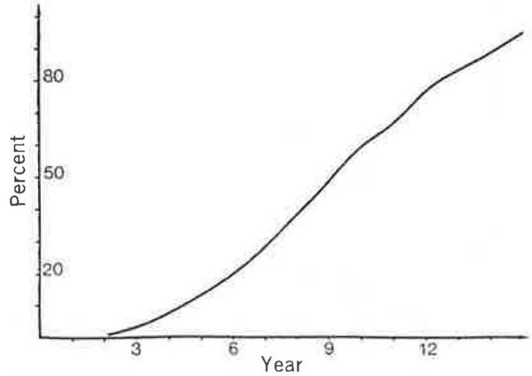

FIGURE 6 Percentage of length maintained as a function of age on all new and resurfaced pavements (excluding overlays with hydraulic-binder-treated granular material before 1975 and bituminous concrete overlays).

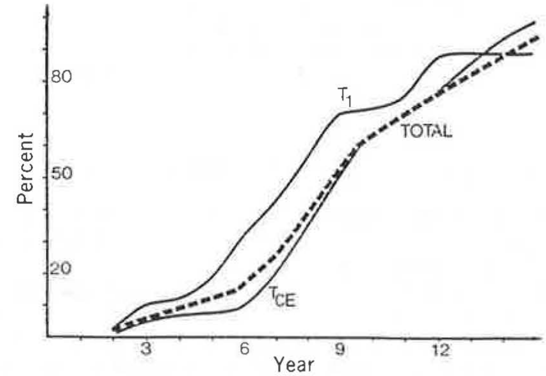

FIGURE 8 Percentage of length maintained as a function of age on new pavements with a base layer in bitumen-treated granular material and subbase in hydraulic-binder-treated granular material.

Bases in Bitumen-Treated Granular Material

Figure 7 shows the remarkable overall behavior of resurfacing with bitumen-treated granular material (R/BTGM) (50 percent maintained for more than 9 1/2 yr), irrespective of the level of traffic (which appears to confirm the validity and uniformity of their design).

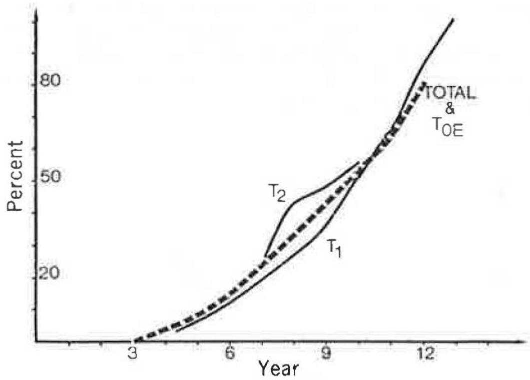

FIGURE 7 Percentage of length maintained as a function of age on pavements resurfaced with bitumen-treated granular material.

Figures 8 and 9, concerning new pavements with a BTGM base layer, show that the overall behavior of these pavements is satisfactory (50 percent maintained for approximately 9 yr). In this respect, two points should be noted. First, Figure 8 clearly shows (in spite of an inadequate population after Year 9) a peculiar feature of mixed pavements handling traffic at the level of T1. Such pavements appear to require maintenance relatively soon after their commissioning. No satisfactory explanation can at present be proposed for this, and a thorough study of the phenomenon should be made. At the same time, it should be noted that two differentiated subunits appear within this group of structures: pavements built in the sphere of action of the Western CETE (50 percent of the total length), behaving significantly better than others with respect to the date of execution of first maintenance. Second, the performance record of BTGM and subbase in untreated granular material (BTGM/UGM) is good, which should help to dispel concerns about this.

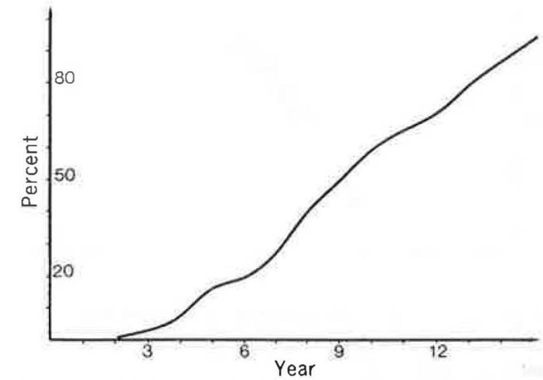

FIGURE 9 Percentage of length maintained as a function of age on new pavements with a base layer in bitumen-treated granular material and subbase in untreated granular material.

Synthesis

Table 2 provides a summary of the main information drawn from Figures 2-9.

If former deviations (R/HBTGM < 75) and the R/BC corresponding to a different strategy are excluded, it can be observed that (a) only the N HBTGM/HBTGM structure received maintenance significantly earlier than the other structures [chiefly in the case of very heavy traffic (T0 and TE levels)], and (b) the R/HBTGM > 75 and R/BTGM structures perform better than new pavements, which can be partly explained by better compliance with design rules and no doubt improved subbase uniformity.

Table 3 presents serious failures by type of structure, defined on the basis of two criteria: (a) the percentage of the length receiving maintenance during the first 3 yr; and (b) the percentage of the length maintained twice in 10 yr.

The data in Table 3 confirm that resurfaced pavements perform better than new pavements; and that the R/BC structures, although they experience few immediate failures, in many cases leave the pavement undersized and require relatively rapid subsequent compensation, which is normal within the framework of a progressive strategy.

The failure rate brought to light is on average relatively low. It does not call into question the design (although certain points remain to be examined) because this can be explained by hazards related to the materials and supports. On the whole,

TABLE 2 First Maintenance on Various Structures

Structure	Percentage Maintained at 5 yr	8 yr	10 yr	Median Age at First Maintenance (yr)
R/HBTGM < 75 (reminder)	45	81	90	5 1/4
R/BC	18	63	85	7
R/HBTGM > 75	14	36	–	9[a]
R/BTGM	7	33	54	9 3/4
N HBTGM/HBTGM	23	52	76	7 3/4
N BTGM/HBTGM	11	37	64	8 3/4
N BTGM/UGM	17	41	61	9
Total[b] HBTGM[c] + BTGM = Reference	12	38	61	9

Note: See Table 1 for definitions of structures.
[a]Estimate.
[b]Weighted average based on length (see Table 1 for lengths).
[c]R/HBTGM < 75 and R/BC excluded.

the results of the assessment can be regarded as satisfactory. In particular, the small spread observed around the mean date of occurrence of first maintenance indicates the effectiveness of design methods (catalogs) and the quality of the materials.

REGIONAL RESULTS

Regional analysis faces various uncertainties stemming notably from the often small size of the populations concerned. Moreover, it should be considered that local adaptations may be made to specifications established on the national level, which may result in different maintenance thresholds and consequently different service needs. In addition, reactions to certain problems (e.g., cracking) may be very different.

Without going into detail concerning the regional differences observed, it should be pointed out in particular that (a) new pavements have a wider spread of performance than resurfaced pavements, which can perhaps be explained by the greater preciseness and the centralization inherent in coordinated overlay projects; and (b) regions in northern and northeastern France require more maintenance on the average than do the other regions. Particularly affected are new pavements with base and subbase layers in HBTGM (N HBTGM/ HBTGM).

A research program will be worked out to allow a thorough study of the causes of the disparities observed. The authors are relying on this causal analysis to explain the good performance of regional projects as well as the shortcomings; important progress factors should be revealed in this way.

ANALYSIS OF TYPE AND COST OF MAINTENANCE TASKS

The considerations discussed in the preceding section refer only to the time at which first maintenance operations were performed on the various groups of structures. The conclusions drawn from this initial phase may undergo closer analysis taking into account the nature of the maintenance work performed.

To facilitate the making of summaries and comparisons, it was found helpful to define a global index of the cost of maintenance work. Adopting as reference (Index 1) the cost per square meter of Task No. 1 (surface dressing or similar) and considering the unit costs and average tonnages of the materials employed for Tasks 2 to 5, the following mean cost scale can be derived:

Type of Task	Cost Index
1	1
2	2.5
3	5
4	7
5	10

This procedure avoids any effects of price fluctuation. It should be noted that crack sealing has not been taken into account, which could affect slightly the results obtained for HBTGM, even though the financial cost is low (cost index is approximately 0.15).

By assigning these indices to the percentages of lengths on which the various types of tasks were performed, a weighted mean cost index (WMCI) can be obtained for each type of task. An analysis of this procedure is given in Table 4.

It should be pointed out that the development of maintenance techniques, particularly with the obligation to save bitumen, led to the development of surface dressings and thin-layer mix materials from 1981 onwards. This does not affect the comparisons made.

To obtain a higher level of aggregation, it is interesting to consider a global indicator incorporating both the date of first maintenance and the type of maintenance. The authors have adopted the ratio M/WMCI, where M is the median age at first maintenance (given in Table 2). It should be noted that this ratio can differ from those used in other countries, where reference is made to the service life or to the initial construction cost. In France, the latter comparison would be of no interest because the application of the catalog of structures (1) leads to the adoption of the same service life regardless of the type of structure considered. The choice is made after a call for bids, the most inexpensive structure then being selected. Comparing different structures of different cost and different service lives would thus be meaningless. The ratio adopted here, in contrast, reflects damage experienced by the structures and contributes to the verification of the initial assumptions.

It is thus possible to construct Table 5, which presents the short-term efficiency of the various structures (the ratio increases with the structure's performance).

TABLE 3 Assessment of Early Maintenance Operations

	Percentage of Length Maintained: R/BC	R/HBTGM > 75	R/BTGM	N HBTGM/HBTGM	N BTGM/HBTGM	N BTGM/UGM	Mean
During first 3 years	2	3	1	4	7[a]	3	2.5
Twice in 10 years	12	1.2[b]	2	6.5	3	2	3

Note: See Table 1 for definitions of structures.
[a]Note that smoothing of the curve would result in adoption of the value 5 percent. This value, which is relatively high, is chiefly due to failures observed on half of the population (pavements constructed outside Western CETE).
[b]8 years.

TABLE 4 Percentage of Length and Weighted Mean Cost Index During First Maintenance by Type of Task for Various Structures

Structure and Population (rounded)	Percentage of Length					Weighted Mean Cost Index
	Task 1[a]	Task 2[b]	Task 3[c]	Task 4[d]	Task 5[e]	
R/HBTGM < 75 (2230 km)	20	6.5	66.5	4	3	4.3
R/BC (970 km)	23	10.5	53	11	2.5	4.2
R/HBTGM > 75 (2560 km)	49	17	23	7	4	3
R/BTGM (2870 km)	29	17	43	8	3	3.7
Weighted average R (6400 km)	36	16	37	8	3	3.5
N HBTGM/HBTGM (1450 km)	13	11.5	53	14	8.5	4.9
N BTGM/HBTGM (530 km)	5	36.5	55.5	0	3	4
N BTGM/UGM (600 km)	18	6.5	57	13	5.5	4.7
Weighted average N (2580 km)	12.5	15.5	54.5	11	6.5	4.7
Weighted average (8980 km)[f]	29	16	42	9	4	3.8

Note: See Table 1 for definitions of structures. The percentages given are means calculated during the period 1974 to 1982.
[a]Cost index = 1.
[b]Cost index = 2.5.
[c]Cost index = 5.
[d]Cost index = 7.
[e]Cost index = 10.
[f]Not including the R/HBTGM < 75.

The tables confirm most of the trends previously noted, in particular: (a) the good performance of recent overlays, particularly those in HBTGM (Table 5); and (b) the relatively less favorable behavior of new pavements; when maintenance is required, it concerns a layer of 5 to 8 cm of BC in more than 50 percent of the cases (Table 4). The data in Table 4 also indicate that the breakdown of the various tasks is unequal. In particular, it is interesting to observe the high proportion of HBTGM overlays maintained by a surface dressing (in 49 percent of cases) during the first maintenance after commissioning.

Before proceeding with a more general analysis of the relation between traffic and maintenance performed, the influence of traffic on the type of task should be noted, even if the populations are sometimes too small for the analysis to be comprehensive. The data in Tables 6 and 7, concerning overlays and new pavements of significant length, indicate that the following logic is generally complied with: the higher the traffic density, the more costly the maintenance.

GLOBAL ANALYSIS OF TRAFFIC EFFECTS

The current study would not be complete without a comparison of stresses experienced by groups of structures studied in terms of loads borne. The data available are not detailed, but an order of magnitude is adequate to indicate the relevant trends in this respect.

By using a method similar to that used for maintenance task costs, an index of weighted mean traffic borne by each structure has been determined on the basis of the following scale (corresponding to the mean of each class, with Index 1 for the mean of class T3, or 100 commercial vehicles/day/direction).

Traffic Class	Traffic Index Adopted
T3	1
T2	2
T1	5
T0	13
TE	22

Table 8 gives the results of the detailed calculations.

It can thus be seen that

- Overlays are on average less traveled on than new pavements;
- The R/HBTGM > 75 structures bear lighter traffic than do the other overlays. Priority was given to the resurfacing of roads handling the heaviest traffic.
- The N BTGM/UGM structures are among the most traveled on, with a good part of them being for freeway pavements.

However, to put these considerations in perspective, it should be noted that the maintenance requirements of a structure (for equivalent design) do not vary in proportion to the level of traffic handled. Concerning this point, the authors note the theoretical maintenance scenarios evaluated for various structures and various traffic densities at the 1981 Road and Energy Symposium in Paris (5) (see Table 9).

If the calculation method described previously (Table 4) is applied to the data in Table 9, it can be observed that the WMCI ranges from 2.8 (between 8 and 10 years) for T3, to 4 (at 8 or 9 years) for T0. It is possible to determine an adjustment relating the WMCI to the traffic index (iT) between the two limits:

$$\text{WMCI} = 2.8 + 1.11 \log iT.$$

It should also be pointed out that the conclusions of the Organisation for Economic Cooperation and Development's report on the Impacts of Heavy Freight Vehicles indicate that the maintenance-versus-traffic-expense curve has an elasticity of 0.1 to 0.2 (6); that is, maintenance expenses increase 5 to 10 times less quickly than traffic (mean for several countries). The results obtained by these two approaches are in agreement and indicate the relatively small influence of traffic on maintenance expenditures.

Three conclusions may be made:

1. Differences in levels of traffic cannot justify the differences in behavior observed between one structure and another.
2. The BTGM/UGM structure appears to be valid for use under high traffic densities, which is not

TABLE 5 Short-Term Efficiency of Various Structures

Technique	Structure							
	R/HBTGM < 75	R/BC[a]	R/HBTGM > 75	R/BTGM	N HBTGM/HBTGM	N BTGM/HBTGM	N BTGM/UGM	Mean
M/WMCI	1.2	1.7	3	2.6	1.6	2.2	1.9	2.4

Note: See Table 1 for definitions of structures.
[a]The concept of efficiency is different for a progressive strategy; the value given here could not be compared directly with the other values.

TABLE 6 Percentage Maintained by Type of Task and Traffic Class for Various Overlay Structures

	R/BC		R/HBTGM			R/BTGM		
Task	T1	T0E	T2	T1	T0E	T2	T1	T0E
Type 1	33	16	61	46	51	57	32	14
Type 2	8	10	32	12	9	7	20	17
Types 3-5	59	74	7	42	40	36	48	69

Note: See Table 1 for definitions of structures. Traffic classes are defined in the section Main Results.

TABLE 7 Percentage Maintained by Type of Task and Traffic Class for Various New Pavement Structures

	N HBTGM/ HBTGM		N BTGM/ HBTGM		N BTGM/ UGM	
Task	T1	T0E	Total	T0E	Total	T0E
Type 1	34	4	5	5	18	4
Type 2	5	13	36	16	7	7
Types 3-5	61	83	59	79	75	89

Note: See Table 1 for definitions of structures. Traffic classes are defined in the section Main Results.

provided for in the current design catalog for new structures. This is why it would be interesting to know the subgrades on which structures of this type were built (because, even more than other structures, flexible structures adapt to a subgrade that cannot be deformed).

3. The requirements estimated at the Road and Energy Symposium are similar to what is actually observed in the current assessment. For the T1 level of traffic (500 commercial vehicle/day/direction on average), the predicted WMCI was 3.6 at 8 or 9 years, while the results of the current study indicate a mean WMCI of 3.8 at 9 years for 700 commercial vehicles/day/direction. However, the predicted theoretical breakdown of the various tasks is not obtained; current practice indicates much greater use of surface dressings, at the same time compensated for by more costly maintenance on other sections.

APPLICATIONS TO FORECASTING OF MAINTENANCE REQUIREMENTS

Apart from the evaluation that can be made of the performance of given structures and the questions thus raised, other applications have been considered for the assessment presented here. Such applications are (a) determination of the long-term discounted cost of construction and maintenance scenarios, and (b) forecasting of future maintenance budgets.

For both of these applications, the curves presented in the figures have been converted into maintenance probabilities at a given age by means of a computerized adjustment program. It turns out that Gauss's (normal) and Galton's (log-normal) laws are adjusted with satisfactory coefficients of correlations, Galton's law being slightly more suitable. This is in particular due to the curves' passing through the point of origin, which is not the case with Gauss's law. However, the computer costs involved make its use too costly compared with the advantage it affords.

The authors have not considered it worthwhile to present an evaluation of future maintenance budgets merely on the basis of the assessment of pavement structural behavior because various obstacles exist and a suitable methodology would first have to be worked out. The analysis made concerns the first maintenance work, and the population of subsequent maintenance operations recorded is too small to determine significant means and standard deviations, or to establish a reliable relationship between the nature of two consecutive maintenance operations. Additional analysis would be required, namely, a forecast of technical developments and their relative cost, the costs associated with maintenance, and in particular the nuisance caused to the users, which is particularly noticeable in the case of regular works (e.g., crack sealing). It should also be noted that the assessment worked out is largely a reflection of previous maintenance budgets and that no forecast of needs could be confined to a mere extrapolation from past trends.

Similarly, the authors have not considered it worthwhile to calculate the discounted cost of maintenance, or of long-term construction (or resurfacing) plus maintenance, for the various structures considered. In addition to the reasons already mentioned, the following should also be noted:

- To allow for a mean cost of construction or resurfacing by technique would falsify the analysis because there is reason to believe that, in each specific case, the structure with the lowest initial cost was used. The real question is determining the initial capital investment difference that can be

TABLE 8 Percentage of Length Bearing Given Traffic and Weighted Traffic Index by Traffic Class for Various Structures

	Length Bearing Given Traffic (%)					
Structure and Population (rounded)	Traffic Class T3[a]	Traffic Class T2[b]	Traffic Class T1[c]	Traffic Class T0[d]	Traffic Class TE[e]	Weighted Traffic Index[f]
R/HBTGM < 75 (2230 km)	1	10	49	39	1	795
R/BC (970 km)	3	14.5	53	29	0.5	685
R/HBTGM > 75 (2560 km)	8	26	56	10	0	470
R/BTGM (2870 km)	6	14.5	50	29	0.5	673
N HBTGM/HBTGM (1450 km)	2	9	48	38	3	820
N BTGM/HBTGM (530 km)	0	7	46	33	14	981
N BTGM/UGM (600 km)	4	17.5	32	26.5	20	983
Weighted Mean (rounded)	4.5	15	50	28	2.5	700 (T1 high level)

Note: See Table 1 for definitions of structures. Traffic classes are defined in the section Main Results.

[a]Index = 1.
[b]Index = 2.
[c]Index = 5.
[d]Index = 13.
[e]Index = 22.
[f]The result obtained was multiplied by 100, giving the order of magnitude of the mean traffic borne by the structure, expressed in heavy vehicles per direction (AADT).

TABLE 9 Theoretical Maintenance Scenarios Planned for Various Structures and Traffic Densities

	Traffic Class T0		Traffic Class T1		Traffic Class T2		Traffic Class T3	
Structure	Time (yr)	Maintenance	Time (yr)	Maintenance	Time (yr)	Maintenance	Time (yr)	Maintenance
Structures treated with	4	33% CS	3	33% CS	4	30% CS	4	30% CS
hydraulic binders	5	33% CS	4	33% CS	5	30% CS	5	30% CS
	6	33% CS	5	33% CS				
	8	60% 4-cm BC	8	20% SD	8	20% SD	8	40% SD
		40% 8-cm BC		40% 4-cm BC		40% 4-cm BC		
				40% 8-cm BC		40% 6-cm BC	10	20% 4-cm BC
								40% 6-cm BC
	12	50% CS	12	50% CS	12	60% CS	15	40% CS
	16	60% 4-cm BC	16	20% SD	16	20% SD		
		40% 8-cm BC		40% 4-cm BC		40% 4-cm BC	18	40% 6-cm BC
				40% 8-cm BC		40% 6-cm BC		
	24	60% 4-cm BC	24	20% SD	24	20% SD	20	20% 4-cm BC
		40% 8-cm BC		40% 4-cm BC		40% 4-cm BC		40% SD
				40% 8-cm BC		60% 6-cm BC		
Composite structures	5	20% CS	5	20% CS				
with a hydrocarbon	9	60% 4-cm BC	9	20% SD	9	20% SD	10	40% SD
base		40% 8-cm BC		40% 4-cm BC		40% 4-cm BC		20% 4-cm BC
				40% 8-cm BC		40% 6-cm BC		40% 6-cm BC
	17	60% 4-cm BC	17	20% SD	17	20% SD	20	40% SD
		40% 8-cm BC		40% 4-cm BC		40% 4-cm BC		20% 4-cm BC
				40% 8-cm BC		40% 6-cm BC		40% 6-cm BC
	25	60% 4-cm BC	25	20% SD	25	20% SD		
		40% 8-cm BC		40% 4-cm BC		40% 4-cm BC		
				40% 8-cm BC		40% 6-cm BC		
WMCI (at 8–10 yr)[a]	4.0		3.6		3.2		2.8	

Note: The WMCI calculated in this way is the same for both groups of structures in question (at a given traffic density) when allowance is not made for crack sealing and the present cost account method is used.

[a]The WMCI was calculated using the following indices: SD (surface dressing): 1; CS (crack sealing): 0; and BC (bituminous concrete): 4 cm–3, 6 cm–4.5, and 8 cm–5.5.

offset by differences in maintenance costs, which implies a more global calculation, incorporating factors other than those provided by the current assessment. Moreover, this analysis remains to be made.

• It would be necessary to take into account not only the median date of maintenance but also the spread around this mean, which requires a more thorough study.

However, the assessment of structural performance summarized in this paper may provide a precious basis for estimating future maintenance needs, to the extent that it provides a distribution of pavements by age and clear information on the type and date of first maintenance. However, among other things, pavement mechanics should be applied to determine a relation between the various types of successive maintenance operations in order to comply with the objective assigned to the entire national network, namely, to constantly provide a high level of service and adapt the pavement structure to prevent foreseeable traffic growth.

GENERAL CONCLUSIONS

In addition to the specific conclusions and avenues of research outlined in this paper, it appears to be necessary to make four general conclusions, in spite of the reservations expressed throughout the study concerning the interpretation of results.

First, applicable design specifications in France for new pavements as well as for flexible pavement overlays are consistent and valid. However, certain specific problems deserve study, among which are the following:

• Research on the causes of the disparities observed with respect to maintenance of overlays in HBTGM as a function of traffic.

• For new pavements in HBTGM, verification of structural design, both theoretical and practical, and study of base-subbase bonding, which would enable closer analysis of immediate failures.

• Analysis of the causes of certain regional disparities.

• Study of the possibility of making more extensive use of BTGM/UGM under heavy traffic loads (after analysis of the subgrades).

Second, concerning the past, the major innovation of the seventies was the development of HBTGMs in pavement subbases, and the decisions made by the French highway authorities in this respect are now confirmed as being highly judicious, both technically and economically.

Third, concerning the present, a relatively wide range of operational pavement construction and reconstruction techniques is now available, competitive in all respects, none of which appears to involve additional initial cost because of the reduced subsequent maintenance requirements.

Fourth, concerning the future, the results achieved on R/BC apparently justify the belief that this progressive resurfacing strategy could be developed in temperate regions (e.g., seaboards).

It should be noted that the authors have not dealt with the case of cement concrete pavements, which are therefore not encompassed by the conclusions. Moreover, the results set out above should be extended by more general studies, in particular: (a) detailed theoretical study of the link between types of successive maintenance operations, and (b) more global and more precise updated long-term calculations for various structures and strategies.

The facilities set up for this assessment should be maintained. However, the basic data will be supplied by the road data bank, which is able to merge and sort the different files and permit rapid detailed statistical correlations (e.g., data on soil types). Some of the information expected from the pursual of this project includes (a) regular updating of the trends described here; (b) illustration of phenomena that do not appear at present for want of sufficient populations and perspective; and (c) analysis of maintenance sequences beyond the first maintenance, and in particular the probability of occurrence of a maintenance operation of a given type according to the nature of tasks previously carried out.

Finally, it should be emphasized that the current assessment of the performance of pavement structures is simply a report on observed deviations from and approaches to problems in the form of explanatory hypotheses. However, it cannot as such explain the causes and the solutions to be found, which require additional studies and research. Therefore, it is essential to warn against the making of hasty conclusions concerning the choice of pavement structures and also against possible misinterpretations.

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