Design and Assessment of Long-Life Flexible Pavements

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Improved strategies for design and condition assessment are required for flexible pavements, which carry the heaviest volumes of traffic, to decrease the need for maintenance and thereby cause less disruption to the road user. The current philosophy and criteria for design are reviewed, and information that has been collected since the last revision of standards in 1984 on the performance of roads is considered. Results demonstrate that the deterioration of thick, well-constructed, fully flexible pavements is not structural and that deterioration generally starts at the surface in the form of cracking and rutting. The evidence suggests that fatigue and structural deformation originating deep within the pavement structure are not the prevalent modes of deterioration. It also shows that changes that occur to the structural properties of the bituminous materials over the life of the road are crucial to the understanding of its behaviour. They imply that a road built above a minimum strength will remain structurally serviceable for a considerable period, provided an appropriate condition assessment strategy is adopted to enable nonstructural deterioration, in the form of cracks and surface deformation, to be detected and remedied before it can have a serious impact on the structural integrity of the road.

The current pavement design method used in the United Kingdom for fully flexible pavements was established by considering the performance of a wide range of experimental pavements that formed part of the trunk road network (*1*). The method developed was based on the interpretation of the structural performance of these roads in terms of theoretical design concepts.

A design life of 40 years was advocated, which was achieved by strengthening the road after about 20 years. Calculation of the costs of flexible roads over 40 years, taking into account variability of pavement performance, cost of traffic delays, and other costs associated with strengthening, showed this to be the optimum design strategy. Since this method was introduced, traffic levels and the consequent disruption at roadworks has continued to increase (Figure 1). Economic considerations indicate that it is now cost-effective to increase the design life of very heavily trafficked routes to at least 40 years, without the requirement for structural strengthening, in order to reduce future maintenance and the associated traffic delay costs.

In addition, more knowledge has become available, over the last 10 years, on the performance of heavily trafficked roads. This has indicated that deterioration, as either cracking or deformation, is far more likely to be found in the surfacing than deeper in the pavement structure; this evidence is in conflict with conventional theory. Also, it was found that the great majority of the thick pavements examined have maintained their strength or become stronger over time, rather than gradually weakening with trafficking as assumed in the current pavement assessment method based on deflection measurements.

FIGURE 1 Disruption to road users on heavily trafficked roads.

This paper reviews design concepts and draws together up-to-date information from full-scale experimental pavements, studies of deterioration mechanisms on the road network, long-term deflection monitoring of motorways, and condition assessment reports prepared to aid the design of structural maintenance. All of this information is required to produce a design method and strategy for condition assessment for roads expected to last at least 40 years without the need for structural maintenance (*2*). These roads are described as long-life roads. The help of the Highways Agency, in allowing information to be used from extensive research programmes that the Transport Research Laboratory (TRL) has undertaken on behalf of the Highways Agency over many years, is gratefully acknowledged.

PAVEMENT PERFORMANCE

Current U.K. pavement design for fully flexible pavements is based on an interpretation of the observed performance of a number of experimental roads, which had carried up to 20 million standard axles (msa), using structural theory. Considerable extrapolation of the observed performance trends was necessary to provide current designs for over 100 msa.

A staged construction is adopted for trunk roads in the United Kingdom. The road is initially designed to reach an investigatory condition after about 20 years, which is considered to be the ideal timing to use. To use the existing strength of the road to good effect in designing a strengthening overlay to extend life for another 20 years. If the road passes beyond that condition, overlay is considered less effective and reconstruction is necessary. The investigatory condition can be related to the transient deflection under a standard wheel load moving at creep speed. This deflection is believed to increase gradually with increasing traffic until the deflection and the level of rutting and cracking indicate the need for strengthening, as first described by Kennedy and Lister (*3*).

Designs for future traffic levels necessarily have to be based on observations of the performance of full-scale pavements under the lower traffic levels experienced in the past. If the requirement is to design future roads for similar traffic flows, this will not present a problem. However, if the traffic growth rate is substantially greater, there may be economic advantage in designing the structural life of the road to last much longer. In this situation, the problem is how current knowledge, based on previous experience, be best used to design pavements expected to carry much higher levels of traffic. In the previous revision of design standards it was necessary to assume that the measured performance trends could be extrapolated to give realistic estimates of future performance. The question that needed to be considered was whether these extrapolations represented the best means of predicting future performance.

Rutting

Rutting is the result of deformation in one or more of the pavement layers. At one extreme it is restricted to the uppermost asphalt layer or layers, termed *surface rutting*. At the other extreme, the main component of deformation arises in the subgrades, and this is termed *structural deformation*. Deformation within the upper asphalt layers does not have a serious effect on the structural integrity of the pavement. On the other hand, excessive structural deformation is a symptom that the load-spreading ability of the asphalt and granular layers is insufficient to protect the subgrade and, if unchecked, will lead eventually to a breakup of the pavement structure. Measurement of the rutting profile at the road surface only is not sufficient to identify the source of the rutting. The consequences for pavement design and maintenance of deformation originating solely at the surface or deep within the pavement structure are substantially different.

A summary of mean rates of rutting of asphalt pavements is shown in Figure 2. The figure indicates a discontinuous relationship between the rate of rutting and pavement thickness, with data forming in two clusters. Pavements with less than about 180 mm of asphalt material deform at a high rate, but thicker pavements deform at a rate about two orders of magnitude less; the sudden transition suggests a threshold effect.

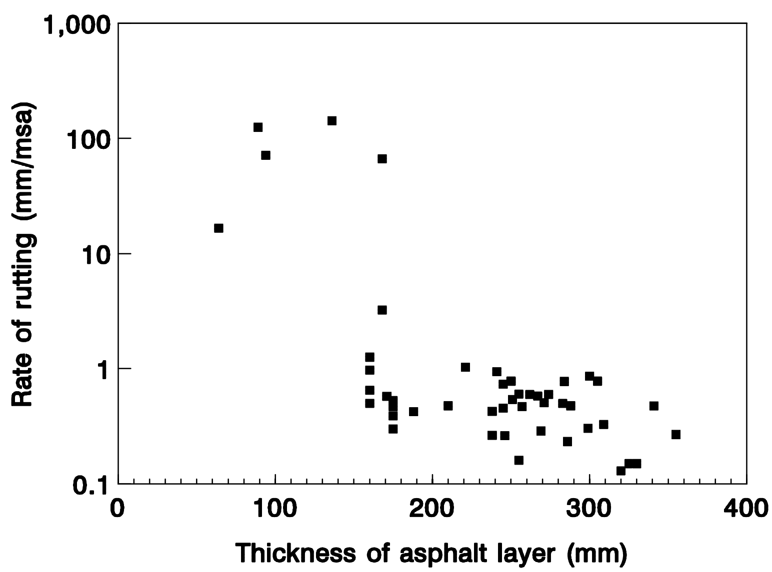

FIGURE 2 Rate of rutting of trunk roads.

Above about 180 mm there is no correlation between the rate of rutting and pavement thickness. The results suggest that for these thicker pavements nearly all the rutting is due to deformation within the upper layers and that the traffic-induced strains in the subgrade are too low to cause structural deformation. It is apparent that below thicknesses of about 180 mm, the much higher traffic-induced subgrade strains have a much greater effect.

Fatigue

The road base is the most important structural layer of the road. All modern analytical design methods for flexible pavements include a criterion, based on laboratory studies, to guard against the possibility of fatigue cracks initiating at the underside of the road base. These methods consider fatigue cracking, caused by repeated traffic loading, to be the major component of structural deterioration. Investigation of the road base fatigue mechanism in full-scale pavements is much more difficult than in the laboratory and it has been noted that, although surface cracking is often observed, there is little evidence of fatigue cracking in the road base of in-service asphalt pavements in the United Kingdom (*4, 5*). Furthermore, it is known that the stiffness of asphalt road base increases with time, and this influences its fatigue resistance. However, this effect has received little attention in the past in relation to road base performance.

The absence of positive evidence of fatigue prompted TRL to initiate an investigation into the residual fatigue life of asphalt road bases from heavily and lightly trafficked areas of the same motorways. The aim was to compare the structural properties of samples of road base measured in the laboratory with the overall condition of the pavements from which they were extracted. This work (*6, 7*) helped to improve basic understanding of the mechanisms of structural deterioration.

Investigation of Roadbase Fatigue in U.K. Motorways

Short sections of four motorways (Table 1), representing a range of age and traffic loading, were selected for detailed investigation. All the pavements examined carried more traffic than they were originally designed to carry.

Cores were cut to enable the structural properties of materials that had been subjected to heavy commercial traffic in the wheelpath of Lane 1 to be compared to the lightly trafficked material of the same age and nominal composition from between the wheelpaths in Lane 3. A comparison of the laboratory-measured residual fatigue life of the lower road base is shown in Table 2.

TABLE 1 Pavements Investigated

Site	Age (years)	Cumulative traffic (msa)	Road Base	Thickness of asphalt (mm)
M4	11	22	HRA	230
M5	19	66	DBM	300
M1	23	71	DBM	350
M62	21	57	DBM	300

TABLE 2 Comparison of Fatigue Life of Road Base

Site	Lane	Number of Tests	Relative Fatigue Life of Road Base
M4	1	80	1.0
	3	76	1.5
M5	1	35	1.0
	3	33	0.7
M1	1	19	1.0
	3	11	1.6
M62	1	28	1.0
	3	31	0.4
Mean	1	162	1.0
	3	151	1.1

If traffic was responsible for weakening the road base, the residual fatigue life of road base material subjected to heavy traffic, in Lane 1, would be significantly lower than that of the lightly trafficked material, between the wheelpaths of Lane 3. Table 2 shows that there was no consistent difference between these measured residual fatigue lives. Most of the difference was accounted for by variations of binder hardness and binder content between the samples extracted from the two lanes. When these factors were taken into account, none of the differences were statistically significant.

All the material tested had a residual fatigue life lower than that of new material. Although traffic loading could not account for this reduction, age will have been an important factor. It is well established that the aging of binders results in an increase in stiffness and a reduction in residual fatigue life of the road base. These changes are unlikely to result in fatigue cracking of the pavement. Calculations using the relationships developed in this study show that the increase in elastic stiffness with age produces a reduction in the traffic-induced, tensile strain responsible for fatigue at the underside of the road base. This reduction more than compensates for any reduction in the laboratory fatigue life of the aged road base. The net effect is that the predicted fatigue life of the road increases with age. This would explain why no positive evidence of fatigue was found.

Structural Assessments

Structural assessments of asphalt roads have failed to detect any evidence of road base fatigue damage. There are no authoritative reports of cracks propagating upwards. In older roads, apart from the absence of road base cracks, the measured elastic stiffness modulus of road base material extracted from the road is usually substantially higher than that expected for new construction. This is indicative that fatigue weakening is not occurring.

In a study carried out by the Road and Hydraulic Engineering Division of the Dutch Ministry of Transport, 176 sections of flexible pavement were examined in order to verify their pavement design method (*8*). This study revealed that in pavements with an asphalt pavement thickness greater than 160 mm, cracks initiated at the surface and generally did not penetrate the full depth of the asphalt. In thinner pavements, where the asphalt was fully cracked, a structural analysis indicated that the cracks also initiated at the surface and propagated downwards. The overall conclusion of this work was that, *conventional fatigue will rarely or never be the predominant failure mechanism, but surface cracking will be the main cause of structural distress.*

Surface Cracking

Cracking observed at the surface of thick, mature, flexible pavements is relatively common. The most usual form is longitudinal cracks in the wheel tracks. This has often been regarded as evidence of conventional fatigue in which cracks have initiated at the bottom of the road base and then propagated to the surface. However, where this cracking has been investigated by cutting cores, it has invariably been found that the propagation is downwards rather than upwards.

Longitudinal surface cracks have been observed at 10 sites investigated by TRL. At these sites, provided the crack had not propagated into the road base, there was no observable or measurable damage to the road base directly beneath the cracks. An example of longitudinal cracking in the M1 site is shown in Figure 3.

Surface cracking is not always longitudinal. At other sites transverse cracks occurred in all lanes of each carriageway, and they were not confined to wheel tracks. As with longitudinal cracking, transverse cracks generally penetrated only up to 100 mm into the surfacing.

FIGURE 3a Longitudinal cracking in the near-side wheelpath of the M1 site.

FIGURE 3b Longitudinal cracking in the near-side wheelpath of the M1 site.

The mechanism of surface cracking is complex, and there is no satisfactory explanation of this phenomenon. Calculation of the traffic-induced stresses at the pavement surface is complicated because the vertical contact stresses are nonuniform and radial horizontal forces are present. Consequently, significant horizontal tensile stresses can be generated at the surface of the pavement.

Thermally generated stresses will also contribute toward the initiation and propagation of surface cracks. This is especially so for transverse cracking in which thermal stresses are likely to be the principal cause of the tensile condition required for crack initiation. Age hardening of the binder in the wearing course, especially the top few millimeters, will also play a part, with hardening over time progressively reducing the ability of the wearing course to withstand the thermal and traffic-generated stresses at the surface.

Curing of Asphalt

It has long been known that the bitumen in pavement layers stiffens with time. Whereas a gradual hardening of the main structural layers appears to be beneficial, and is more accurately described as *curing*, excessive ageing of the wearing course can lead to cracks initiating at the surface.

During the mixing and laying process, the penetration of the bitumen in standard dense bitumen macadam (DBM) typically drops from an initial nominal value of 100 to about 70. In subsequent service, further reduction takes place resulting in values often as low as 20 after 20 years. Chaddock and Pledge (*9*) demonstrated, in test pavements, that the curing behaviour was variable and that the stiffness of DBM road base could change by over 100 percent during the first year in service.

In addition to the test pavements, data on the curing of road base material from a large number of in-service roads has been collected by TRL. These data include the measured properties of the recovered binder and stiffnesses of materials from pavements of different ages. Figure 4 shows the variation of penetration of the recovered binder, with time, for DBM road base manufactured with a nominal 100 penetration grade binder.

Figure 4 clearly illustrates that the penetration has reduced from about 70, shortly after laying, to a value in the range of 20 to 50 after 15 years. These binder changes will result in a progressive increase in the elastic stiffness modulus, which is a measure of load-spreading ability. This increase in stiffness of asphalt materials has major implications for pavement design.

Long-Term Pavement Strength

The fact that the elastic stiffness, and hence the load-spreading ability of asphalt road base, in thick, well-constructed roads increases steadily over time is an indication that traffic-associated deterioration of the road base does not occur. This improvement in load-spreading ability should manifest as a reduction in deflection over the life of the road.

The measurement of pavement deflections under a slow-moving, standard wheel load is the normal method of routine pavement structural assessment in the United Kingdom. The deflections are expected to increase with the passage of traffic, reflecting a weakening of the structure. Increased deflections imply increases of the traffic-induced strains in the road base and subgrade, which are considered to control pavement deterioration. The deflection histories of 10 heavily trafficked sections of motorway were examined to investigate whether the strength of thick, fully flexible pavements reduces with time and traffic. Pavement deflection is routinely measured on the trunk road network using deflectographs similar to that shown in Figure 5 (*10*). Deflection trends, based on measurements with deflectographs of four motorways that had carried up to 48 msa, are shown in Figure 6.

The deflections of these sites show considerable fluctuations that may be partly due to the difficulty of applying accurate temperature corrections, seasonal variations in the subgrade strength, and variation in alignment of successive surveys. Further confirmation of these deflection trends has been provided by falling weight deflectometer (FWD) measurements on the same sites (Figure 7). Unlike the deflectograph surveys these deflection measurements have been carried out on

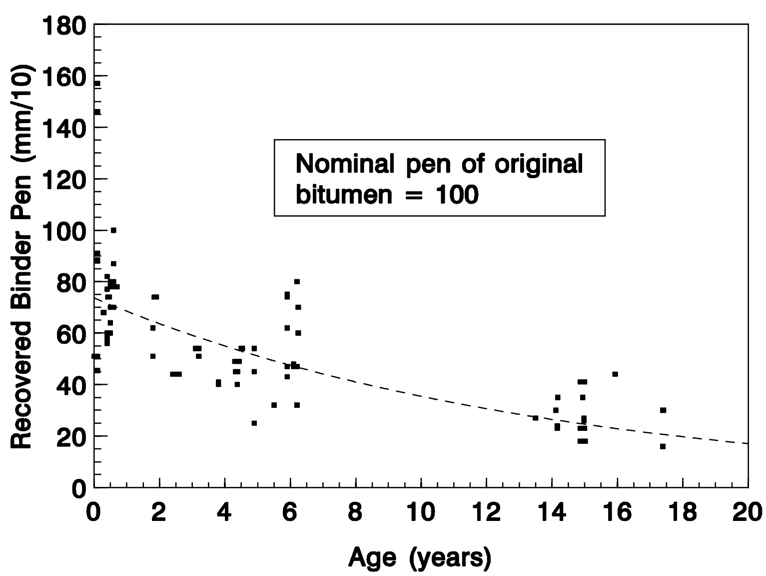

FIGURE 4 Change in PG of binder with time.

FIGURE 5 Deflectograph survey in progress.

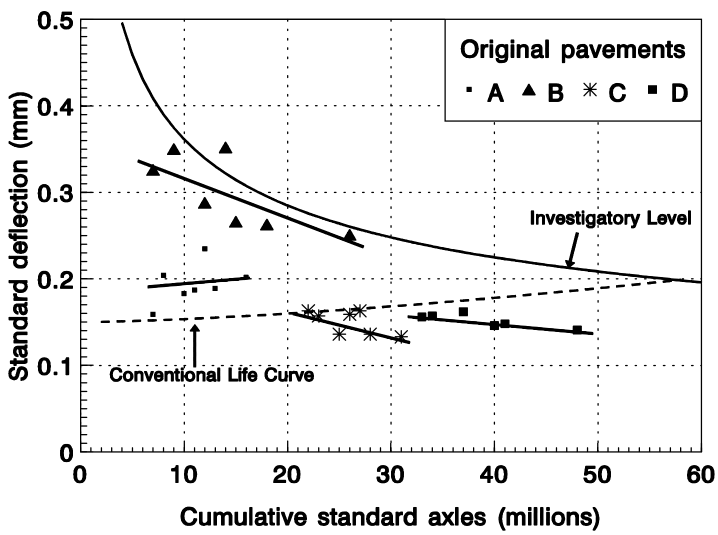

FIGURE 6 Deflection histories of in-service motorways—deflectograph measurements.

exactly the same points each year. Examples of trends from two of the sites over a 13-year period are given in Figure 8.

With one exception, which shows no decisive trend either way, all the sections show a trend of steady or decreasing deflection with age and traffic. These decreases imply that the overall stiffnesses of the pavements are increasing over time and that any traffic-related deterioration is more than offset by curing of the road base or strengthening of the foundation. For whatever reason, the road is becoming stiffer with time, and, hence, the traffic-induced stresses and strains in the road base and the subgrade, which are considered to be responsible for structural deterioration, are decreasing.

FIGURE 7 FWD carrying out measurements.

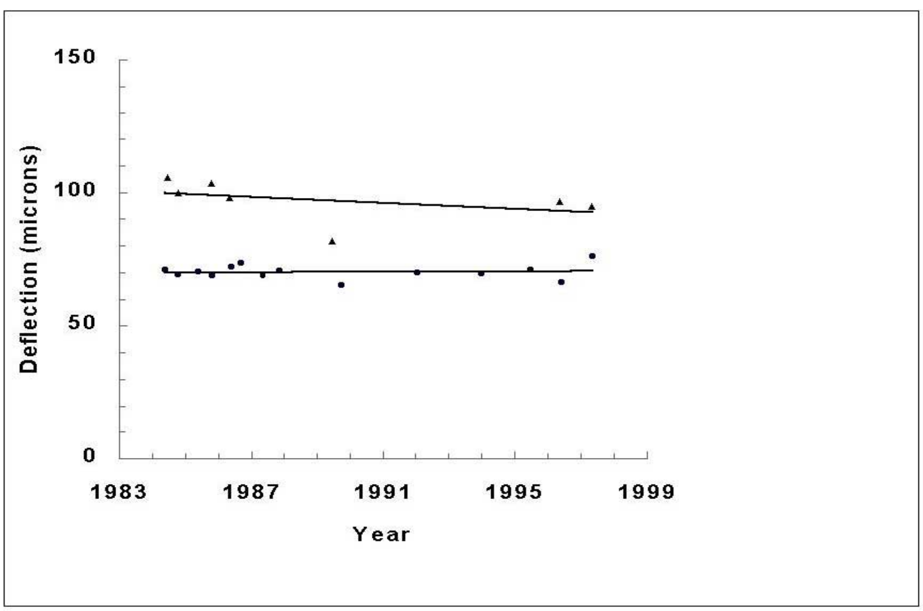

FIGURE 8 Deflection histories of in-service motorways—FWD measurements.

CONSIDERATIONS FOR LONG-LIFE PAVEMENT DESIGN

The conclusion from the review of information on the performance of flexible roads in the United Kingdom is that, above a threshold strength, the road will remain structurally serviceable for a considerable period provided that nonstructural deterioration, in the form of surface-initiated cracks and deformation, is detected and remedied before it can have a serious impact on the integrity of the road. To achieve a long life it is also necessary for the road to be well constructed with good quality asphalt and a good foundation so that deterioration does not result from construction or material inadequacies.

Threshold Strength, Curing, and Traffic Flow

Curing implies that the road is most vulnerable to damage from traffic when it is first laid, before its structural properties have had time to improve. Provided that the road is built strong enough initially, so that its main structural layers are not weakened by traffic loading, curing will progressively improve the load-spreading ability of these layers and make the road progressively less vulnerable to traffic-induced structural damage. This type of behavior implies that there is a minimum threshold strength above which the pavement should have a very long but indeterminate structural life. It is therefore reasonable to assume that the initial strength of the road should be a major factor in determining its future life.

Roads constructed to meet the demands of present-day traffic levels, which may be 10 or 20 times higher than those encountered on many of the older in-service roads, will need to be initially stronger to avoid excessive deterioration in their early life. A conservative calculation indicates that a road constructed with a thickness of more than 260 mm of asphalt would have a long but indeterminate life for traffic of up to 5 msa per year and that 270 mm would be sufficient for any traffic loading. This higher thickness would ensure long life, even if curing did not take place, provided that the effective thickness of the asphalt layer was not reduced by deterioration due to cracking.

Surface Cracking

Surface cracking, in a road that is built just above the minimum strength required for long life, may weaken the road and accelerate the deterioration. To prevent this from occurring, it will be necessary to adopt conservative designs to enable the road to withstand some surface cracks. Timely remedial action should be taken before these cracks can have a severe structural impact on the road; however, cracks may propagate up to 100 mm into the road before this action is taken. The most conservative assumption is to assume that the material down to the depth of the crack penetration does not contribute to load spreading. This would imply that a road constructed with a total of 370 mm of asphalt material would be able to tolerate a surface-initiated crack propagating 100 mm into the road even if the effect of curing was very small.

Provision for Future Changes in Vehicle Characteristics

The current legal maximum axle load is 10.5 tonnes, and this was increased to 11.5 tonnes in 1999. An increase in the thickness of the bound layer of 20 mm would be more than sufficient to provide extra load-spreading ability to compensate for this increase in legal maximum axle load.

Risk of Premature Failure

The addition of the conservative estimates to allow for the factors discussed above suggests that a pavement consisting of 390 mm of asphalt material is sufficient for a long-life road. This summation introduces further conservatism since, for example, surface cracks, if they occur at all, will normally appear several years after the road is laid. By this time the road base will have cured, and the remaining thickness will be well above the threshold strength for a long-life road. A pavement of this thickness will be able to tolerate opening traffic well in excess of 5 msa per year even if the asphalt in the main structural layers does not cure.

A practical way forward is to use the existing design curves for traffic levels up to the level of the threshold strength and then regard the design as long life, with no additional thickness required to provide longer life. Figure 9 illustrates possible design curves using the three standard road base materials that are characterised by three different levels of elastic stiffness or load-spreading ability.

These designs will have built-in conservatism, but some conservatism can be justified, considering the economic importance of these roads. A thickness of less than 200 mm for the asphalt paving is not recommended even for lightly trafficked roads that are required to endure for 40 years. Thin roads may be at risk of structural deformation and rapid propagation of surface-initiated cracks through the full thickness of asphalt.

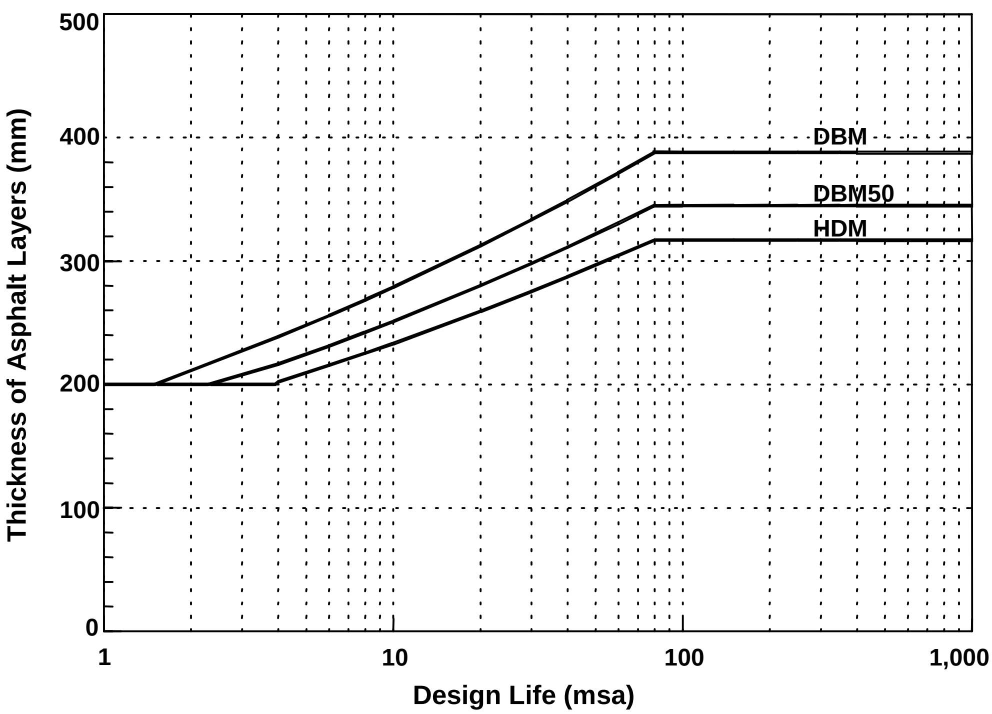

FIGURE 9 Design curve to include long-life pavements.

Pavement Condition Assessment

Premature structural failure may be brought about by poor construction practice or by failure to remedy surface distress. To ensure a long life, procedures need to be developed in which regular inspections of pavement condition are carried out and timely action taken to remedy any surface deterioration detected. This may therefore require a redefining of the methods of monitoring conditions at the network level and redefining levels for detailed investigation and preventative maintenance.

Network Condition Monitoring

The present approach to monitoring the condition of the network is dominated by estimates of structural residual life based on deflection measurements (*11*). The research work reported in this paper, together with other related work carried out for the Highways Agency in the condition assessment field, has raised questions about the validity of the existing deflection design method for some pavements. Apparently, thick flexible pavements do not deteriorate as expected at least in deflection terms. Rather than a slow initial increase of deflection with time and traffic, followed by an unpredictable and rapid increase to failure, many examples of such pavements have been observed to either not deteriorate or even to improve in deflection terms. Thus the present deflection design method, as embodied in the PANDEF software program, will predict ever shorter residual lives as traffic passes over a pavement, even if the deflection level shows no sign of increasing. The deflections measured on such pavements need a different type of interpretation from that currently provided.

On the basis of the observed behaviour of such pavements, criteria to identify long-life in-service pavements on the network can be identified from deflection measurements in conjunction with their layer thicknesses as shown in Figure 10. The main long-life zone may be delineated by

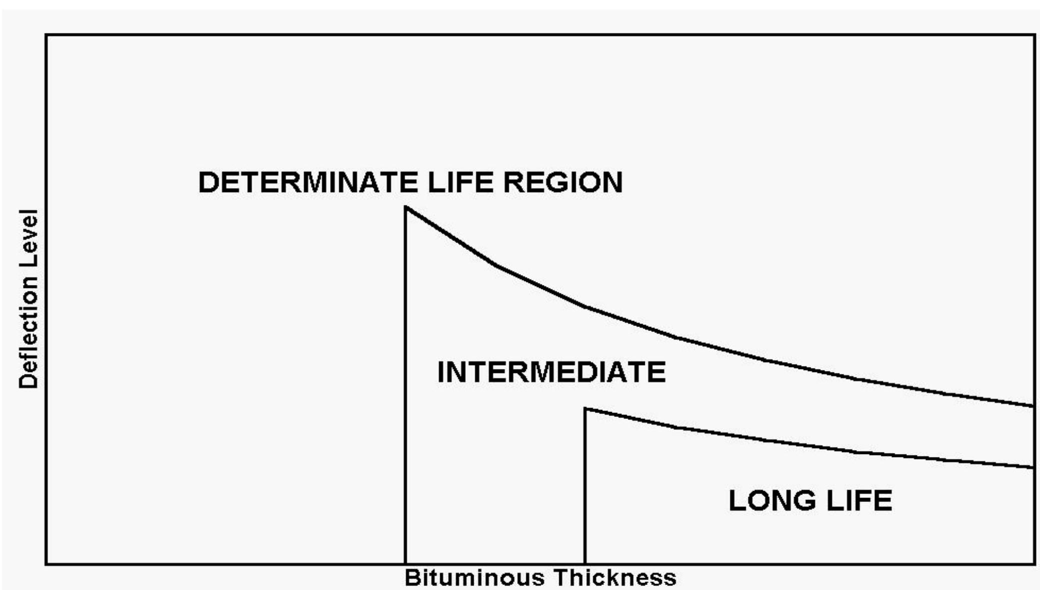

FIGURE 10 Provisional chart for preliminary identification of in-service long-life pavements.

fairly cautious criteria developed in conjunction with those creating long-life designs for new roads. The intermediate zone is bounded by a minimum thickness, the level below which rut rates increased significantly, and by a deflection/thickness curve.

Applying tentative criteria to a sample of the network suggests that around 80 percent of the fully flexible parts of the motorway network are long life. The proportion of the all-purpose trunk network that is long life is, as might be expected, rather lower. For fully flexible roads it is expected to be around 20 percent (mainly because of inadequate bituminous cover rather than high deflection levels). If these two figures are combined, this suggests that around 30 percent of the flexible pavements on the motorway and all purpose trunk road network may consist of long-life pavements.

It should be remembered, however, that long-life pavements do not mean infinite-life or non-maintenance pavements. Replacement of the surfacing layers will still be needed, sometimes to maintain skidding resistance or texture level and sometimes to replace cracked or rutted surface layers. Therefore, the recognition of the existence of long-life pavements will increase the proportion of the network in need of surface treatment, and a means of summarising its condition similar to that for structural condition will be required. This could be relatively easily generated on a simple level from traffic speed surveys, in particular, with the development of new techniques such as those embodied in the HARRIS vehicle shown in Figure 11 (*12*). Thus, surface condition parameters indicating potential structural deterioration such as rutting and cracking could be easily assessed, together with those parameters more related to the functional properties required of the pavement, such as longitudinal evenness and texture depth.

FIGURE 11 HARRIS survey system.

Scheme Selection

Current assessment procedures for assessing the structural needs of road pavements and scheme selection are set out in Volume 7 of the English Highways Agency's *Design Manual for Roads and Bridges* (*13*). The main features are illustrated in the flowchart in Figure 12. Although condition data are available from the High Speed Road Monitor (HRM) and CHART visual surveys, it is the results from deflectograph surveys that most strongly influence maintenance decisions.

The studies developing the concepts for long-life pavements have shown that, in the vast majority of cases on the trunk road network, the deterioration mechanisms encountered concern defects originating and propagating from the surface of the pavement downwards. This suggests that a more appropriate and reliable pavement assessment regime would be achieved by always first considering surface condition before structural condition. A new approach could integrate existing

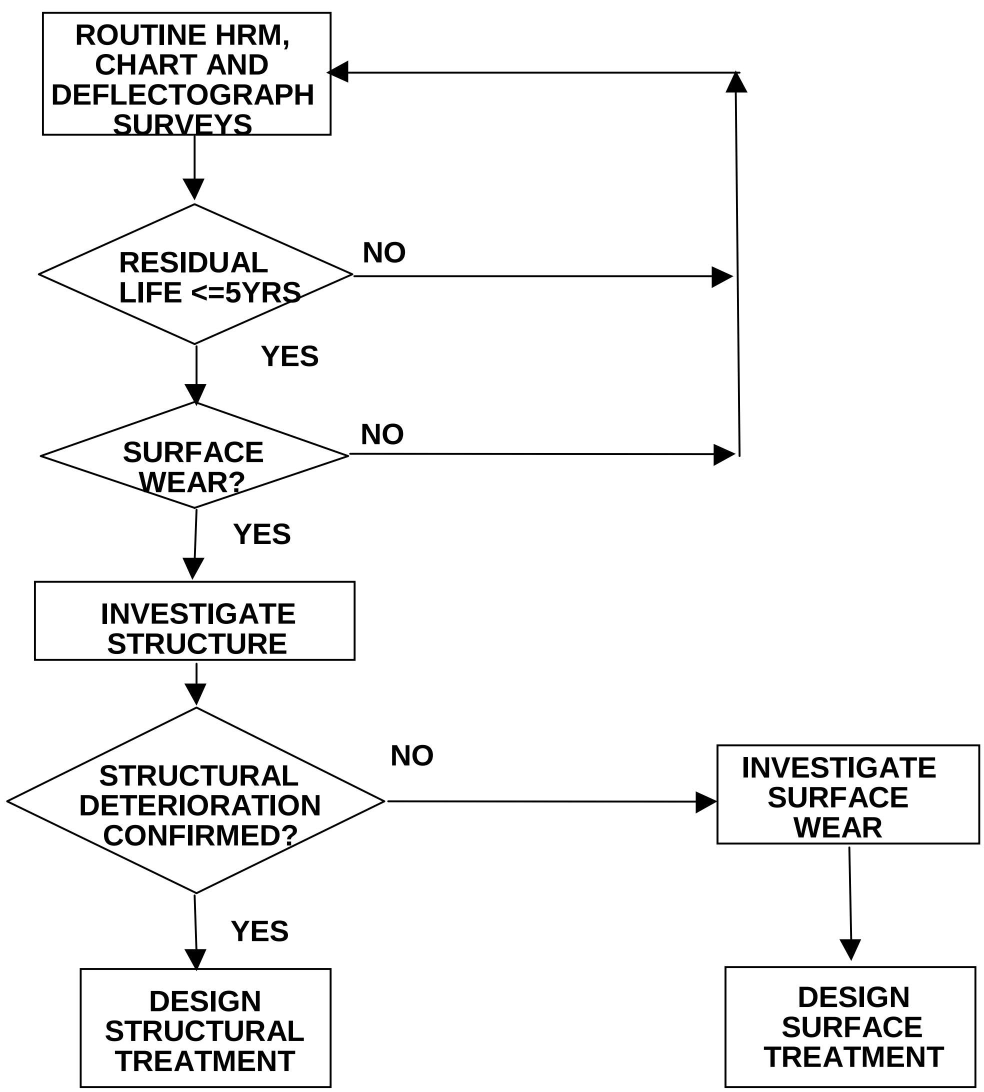

FIGURE 12 Current structural assessment procedure (HRM = high-speed road monitor).

procedures for assessing surface and structural maintenance and assume that no maintenance of any kind is required unless there is evidence of wear on the road surface. Much more reliance would be placed on the results of surface condition surveys that will, in future, mostly be carried out at traffic speed with little traffic disruption. However, routine deflection surveys would need to continue to support network structural assessments and maintenance decisions for all types of pavements, particularly the thinner ones.

Project Level Investigations

The initial aim of project level investigations will be to determine how far the surface deterioration extends into the pavement and, in particular, whether it is only in the surfacing. Details of the exact location and extent of rutting and pattern of cracking will be available from routine survey data. Cores taken on the cracks or at crack ends will determine the depth, direction and propagation of cracks. These cores should penetrate at least halfway into the base on fully flexible pavements to ensure that the full depth of cracking can be recorded. They will also provide evidence of which layers are affected by rutting and any loss of integrity of the materials, such as stripping of the binder. In future, on the basis of earlier TRL research, it may be possible to use ground penetrating radar systems to monitor such penetration nondestructively (*14*). If the cracking is found to penetrate into the structural layers of the pavement, a conventional thorough structural investigation will be necessary.

Treatment Selection

Acknowledgement of the existence of long-life pavements will, of course, affect the selection of suitable maintenance treatments. As was stated earlier, long-life pavements will not be of infinite life. However, as long as the pavement has been well constructed and the foundations remain sound, no structural treatment such as overlays or reconstruction should be necessary. The surface will deteriorate as for determinate life pavements. Accumulated deformation will cause rutting, which will need to be treated by replacement or by thin overlay before it becomes a safety hazard. Cracking may initiate at the surface, which will need treating by replacement before it penetrates into the structural components of the pavement. Skid resistance will deteriorate and initiate the necessary remedial surface treatment. If structural deterioration has occurred, on a determinate-life pavement, strengthening may need to be provided by overlays or reconstruction. However, it should be noted that it may be that only thin overlays are necessary to convert a determinate-life pavement into a long-life equivalent.

CONCLUDING REMARKS

This proposed design method suggests that, in future, the wearing course on fully flexible pavements is likely to be replaced at intervals, whereas the underlying layers will be regarded as permanent. Thus, maintenance costs would be generally limited to the wearing course to maintain safety and comfort for the road user.

Pavement deterioration caused by cracks propagating downwards from the surface has received relatively little attention from researchers. However, a better understanding of deterioration mechanisms in general will result in improved materials and construction practices that prevent or delay the onset of problems. The ultimate goal of pavement design is to develop a mechanistic method based on a fundamental understanding of the behaviour of road materials. Although this goal may be difficult to achieve, it should be pursued. A fully developed and validated analytical design method would aid economic planning and provide insight into the consequences of future changes in materials or vehicle characteristics.

The relationships developed between design inputs and design thicknesses are based on historical evidence. Therefore, there is a need to continually monitor factors that may affect pavement performance. For the future there are many changes expected, such as heavier lorries, air suspensions, increasing proportions of super-single tyres, and the development of innovative materials and construction practices. All of these will need careful monitoring so that designs can be adjusted as necessary to ensure that road pavements provide good value for money.

The overall conclusion is that well-constructed pavements built above a minimum strength are not likely to exhibit structural damage when subjected to very high levels of commercial traffic for a very long time, provided that deterioration originating in the asphalt surfacing as either rutting or surface initiated cracking is detected and remedied before it has a serious impact on the structural integrity of the road.

Existence of long-life pavements has increased the importance of reliable methods of assessment of surface condition, in particular the identification of surface cracks and their depth of propagation. The recent development of new traffic-speed equipment to identify surface cracks automatically will help with this, but further techniques still need to be developed.

The maintenance of in-service long-life pavements should be relatively simple and low cost if close monitoring of surface condition is employed and any loss of surface integrity rapidly repaired.

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REFERENCES

1. Powell, W. D., J. F. Potter, H. Mayhew, and M. E. Nunn. *Design of Bituminous Roads.* TRL Report LR 1132, Transport Research Laboratory, Crowthorne, U.K., 1984.
2. Nunn, M. E., A. Brown, D. Weston, and J. C. Nicholls. *Design of Long-Life Flexible Pavements for Heavy Traffic.* TRL Report 250, Transport Research Laboratory, Crowthorne, U.K., 1997.
3. Kennedy, C. K., and N. W. Lister. *Prediction of Pavement Performance and the Design of Overlays.* Report LR 833, Transport and Road Research Laboratory, Crowthorne, U.K., 1978.
4. Goddard, R. T. N., and W. D. Powell. Assessing the Condition of Bituminous Roads. *Journal of the Institution of Highways and Transportation,* Vol. 34, No. 5, London, U.K., 1987, pp. 26–32.
5. Thrower, E. N. *A Parametric Study of a Fatigue Prediction Model for Bituminous Road Pavements.* TRL Report LR 892, Transport Research Laboratory, Crowthorne, U.K., 1979.
6. Wu, F. *Assessment of Residual Life of Bituminous Layers for the Design of Pavement Strengthening.* Ph.D. thesis. University of Glamorgan, Wales, U.K., 1992.
7. Nunn, M. *A Question of Fatigue?* Symposium on Performance and Durability of Bituminous Materials, University of Leeds, U.K., 1994.

8. Schmorak, N., and A. Van Dommelen. *Analysis of the Structural Behaviour of Asphalt Concrete Pavements in SHRP-NL Test Sections.* International Conference on SHRP and Traffic Safety, Prague, Czechoslovakia, 1995.
9. Chaddock, B., and K. Pledge. *Accelerated and Field Curing of Asphalt Road base.* TRL Project Report PR87, Transport Research Laboratory, Crowthorne, U. K., 1994.
10. Ferne, B. W., and P. K. Roberts. *Deflectograph—The Way Forward for Structural Assessment*. Institution of Highways and Transportation, London, Oct. 1991, pp. 5–6.
11. Jordan, P. G., B. W. Ferne, and D. R. Cooper. *An Integrated System for the Evaluation of Road Pavements*. 6th International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Mich., 1987.
12. Ferne, B. W., L. G. Hawker, and J. Pynn. *A Practical System for Crack Image Collection and Automatic Identification*. 5th International Conference on the Bearing Capacity of Roads and Airfields, Trondheim, Norway, 1998.
13. *Design Manual for Roads and Bridges.* English Highways Agency, Norwich, U.K., 1974.
14. Hawker, L. G., and B. W. Ferne. Routine Assessment of the English Trunk Road Network. *Proc., Alan Brant Memorial Workshop*, Leamington Spa, U.K., April 1992, Institution of Highways and Transportation, London, 1992.