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PREDICTION OF PAVEMENT PERFORMANCE AND THE DESIGN OF OVERLAYS

by

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ABSTRACT

The deflection of a flexible road pavement under a heavy wheel load moving at creep speed can be used to predict the future structural performance of the pavement and to design the strengthening of it by overlaying with bituminous materials. Equipment and procedures for its use as standardised for the measurement of deflection in the United Kingdom are described in TRRL Laboratory Reports LR 834 and LR 835.

The present report describes the adjustment of measured deflections to standard values suitable for design purposes and their use, together with the appropriate traffic data, for the prediction of remaining pavement life and for the design of overlay thickness. The technique sometimes requires information from cores and trial holes to allow the appropriate decisions for a particular pavement to be made.

Matching practical strengthening measures to the variation in structural strength, as reflected by deflection measurements, along the length of any road requires a statistical approach. Methods of analysing deflection data are presented and procedures recommended for both manual and computer processing.

1. INTRODUCTION

Structural deterioration under traffic takes place to some extent in all road pavements although in well designed ones its development is a very slow and seasonal process. As the great majority of flexible roads continue to serve as load-carrying arteries for much longer periods than the conventional design lives of between 10 and 20 years, the periodic strengthening of all flexible roads, and not just those which are poorly designed or constructed, must therefore be considered as inevitable.

An increasing proportion of the network of major roads built in the last two decades will require strengthening in the years ahead; this is additional to the periodic strengthening required to improve the older and largely undesigned road network and to maintain it at structural standards appropriate to today's heavier traffic. It is therefore important that the considerable expenditure on strengthening of roads should be made as effective as possible by the use of a suitable method for designing strengthening measures.

In the past, strengthening has normally been carried out after considerable damage to the materials in the pavement evident at the road surface, has taken place. Because materials thus damaged can contribute little structurally to the overlaid pavement the thickness of overlay required is generally considerable; alternatively reconstruction of the roadbase and surfacing is necessary. Such solutions are generally more expensive than if a thinner overlay is applied before major surface deterioration is apparent and before the structural integrity of the pavement is seriously impaired, that is, when the road is in a critical and not a failed condition.

A system for the design of strengthening measures should therefore be capable of two functions:—

a) to predict the remaining life of a pavement under traffic so that strengthening by overlaying can be timed to coincide with the onset of critical conditions

b) to design the thickness of overlay required to extend the life of a road to carry any given traffic and to indicate lengths of road which have deteriorated sufficiently to require partial or total reconstruction.

Essential to a design method is some form of measurement of the structural condition of the road; the procedure must be sufficiently rapid and convenient to enable closely spaced measurements to be made over long lengths of road in a practically short time. Because roads in need of strengthening typically show considerable variations in structural condition along their length, the spacing of the measurements affects the design method and its accuracy.

The design method described in this Report characterises the structural condition of the pavement in terms of the deflection of its surface under a loaded dual wheel moving at creep speed; the measurement is made using either the Deflection Beam or the Deflectograph. These two pieces of equipment, as standardised for use in the United Kingdom, are described in LR 834[1]. Laboratory Report LR 835[2] considers preferred operating procedures for both when used to carry out a deflection survey along a length of road and indicates the way in which these procedures are a consequence of the design of the equipment and of pavement conditions.

Systematic measurements have been made with the Deflection Beam over a 20-year period on more than three hundred sections of pavement in the numerous full-scale road experiments built by the Laboratory. These have led to the development of deflection histories relating the deflection of pavements at a standard pavement temperature to their structural deterioration under traffic characterised in terms of cumulative standard axles[3]. Well-defined relations between deflection and critical life have been established for pavements incorporating the main types of roadbase. As the experiment sections deteriorated towards failure a number were overlaid and their subsequent performance monitored in a similar manner in order to provide information on the performance of strengthened pavements.

Information obtained primarily from the Alconbury Hill experiment and described in LR 375[4], formed the basis of the Laboratory's tentative method of design published in LR 571[5]. The considerable amount of additional performance data that has since accrued from other experimental roads[6] is associated with more detailed measurements of traffic loading from the dynamic weighbridges[7]. Pilot-scale testing has also increased the knowledge available on the reduction of deflection brought about by overlays of different types and thickness. The information has been consolidated into a more detailed design method which, when taken in conjunction with LR 834 and LR 835, supersedes that given in LR 571.

The method described in this report has six elements. The first five, listed below, describe very briefly how deflection measurements should be made, what corrections need to be made on the raw data and how the results are used.

1) Measurement of the deflection of the pavement under dual wheels loaded to 3175 kg moving at creep speed.

2) Estimation of past traffic carried by the pavement and of the traffic to be carried during its future design life.

3) Adjustment of measured deflection values to standard deflections which are then used for the following purposes.

4) Prediction of the unexpired life of the pavement up to the onset of critical conditions in it.

5) Design of the thickness of overlay required to extend the life of the pavement under traffic for a given period.

The sixth element is concerned with matching practical strengthening measures to the variation in structural strength, as reflected by deflection measurements along the length of the road; this requires a statistical approach.

Methods of analysing deflection data for this purpose are presented, primarily for data obtained with the Deflectograph; the methods are however equally suitable for the analysis of Deflection Beam measurements. Procedures are recommended for both manual and computer processing.

2. MEASUREMENT OF DEFLECTION

Deflections suitable for use in the method are obtained either with a Deflection Beam and loaded lorry or a Deflectograph; descriptions of the equipment, including suitable weights and dimensions, are given in LR 834. Necessary ancillary equipment for temperature measurement is also described. Testing and calibration procedures for use with both types of equipment are described in LR 835. This report also quantifies the effects of test-vehicle speed and loading on the measured deflections. The way in which high and low temperatures and temperature gradients within the bituminous layers impose restrictions on deflection testing is considered. Other information required for the purpose of interpreting a deflection survey is described and methods of obtaining it specified.

3. ESTIMATION OF TRAFFIC AND ITS DAMAGING EFFECT

In order to estimate the remaining life of a pavement information is required about the traffic carried since its construction, or since the most recent resurfacing or strengthening. For the design of an overlay, estimation of the future traffic during its design life is also required.

Cumulative traffic causing structural damage to a pavement is expressed in terms of equivalent standard axles of 8175 kg as defined in Road Note 29[3]: this design parameter is related to the number of commercial vehicles using the left-hand lane of the road and to the axle loading of these vehicles.

3.1 Estimation of the cumulative total of commercial vehicles

Future traffic has been estimated by means of the charts presented in both Road Note 29 and LR 571: these relate cumulative future traffic to the present total daily flow of commercial traffic in one direction during the design life and the expected growth rate during that period. Past traffic has been estimated indirectly using the same charts.

Growth of commercial traffic nationally is now lower than in the past and further charts are required to meet some future design requirements. Two nomograms in Figures 1 and 2 have therefore been devised for the direct prediction of both future and past traffic; both nomograms require the same design inputs as the charts they replace. Estimation can be made for a wide range of growth rates, down to one of zero, and in estimating past traffic it is also possible to use different growth rates for different periods during the life of the road.

Operation of the nomograms is described in Appendix 1.

For roads constructed in the last forty years the traffic carried since construction or since the last major strengthening can be estimated with sufficient accuracy using the nomograph for past traffic. On older country roads which have been maintained by little more than surface dressing over the years, traffic of measurable damaging power is likely to have been negligible prior to 1939. In the absence of detailed data on average growth rate of 4 per cent per annum over the past 40 years is recommended but for a predominantly agricultural area the growth rate would probably not have exceeded 2 per cent.

3.2 Estimation of the damaging effect of commercial vehicles

Weighbridges installed in the road surface at the Laboratory's full-scale road experiments have been used to classify the axle weights of the commercial traffic. From these data the cumulative number of equivalent standard axles has been computed using the procedure detailed in Road Note 29 and this information has been used to characterise the lives of pavements in terms of traffic in the development of the design method presented in this Report.

On public roads no details of axle loads will normally be available. Road Note 29 therefore gives guidance as to the average number of standard axles equivalent to the passage of one commercial vehicle to be expected on different categories of road.

Recent evidence from the weighbridges on the full-scale road experiments and particularly from other weighbridges installed in heavily trafficked motorways indicates that some increases in the standard axle equivalences per commercial vehicle are taking place. In estimating past traffic the consequences of using the factors given in Road Note 29 will not be significant except for the most heavily trafficked roads which have been opened in the last few years. Future traffic estimates will, of course, be more seriously affected. Revised damage factors for future traffic in terms of standard-axles/commercial-vehicle have now been issued by the Department of Transport in Technical Memorandum H6/78. Past and present traffic will be considered in a further Memorandum.

Uncertainty in relation to future growth in commercial traffic, both in terms of numbers of axles and their weight, inevitably limit the accuracy of any method of estimating the remaining life of a pavement and of designing any overlay that may be required. Nevertheless the range of damage factors measured on a given category of road is such that the use of damage factors alone for design may result in substantial unnecessary errors. Given that the traffic pattern on an existing road is normally well established, direct measurement of axle weights using a simple portable weighbridge is recommended whenever possible. Reliable equipment has been developed by the Laboratory[8] and digital output is now available.

4. CORRECTION OF MEASURED DEFLECTION VALUES TO STANDARD DEFLECTION VALUES

4.1 Standard deflection

For any given measured deflection value the standard deflection value is the equivalent Deflection Beam deflection value measured at a pavement temperature of 20°C, 40mm below the surface.

Where the measurement is made with a Deflectograph it is necessary to convert the measured value initially to an equivalent Deflection Beam deflection at the same pavement temperature, and then to correct this value to a deflection equivalent to that obtaining at a pavement temperature of 20°C. Where the measurement is made with a Deflection Beam it is necessary only to correct for temperature.

4.2 Correction of Deflectograph deflections to equivalent Deflection Beam deflections

The correlation between the deflection measured with the Deflectograph and that measured with the Deflection Beam is given in Figure 3. The relation is based on experimental evidence collected from pavements containing crushed stone, cement-bound and bituminous-bound roadbases constructed on a wide range of subgrade types with CBR strengths of between 2.5 and 15 per cent. Pavements with rolled asphalt, bitumen macadam and tarmacadam surfacings have been included.

The relation is well defined and relatively insensitive to the temperature of the pavement within the range 10–30°C when deflection testing is normally carried out. There is some evidence that at temperatures significantly below 10°C the relation is more variable and that, on very weak pavements (the dotted length of the relation shown in Figure 3), the effect of temperature is more important. Under these conditions, or when operating on pavements based on subgrades outside the CBR strength limits given above, it may be necessary for the user to derive separate correlation curves for his specific conditions.

The correction of Deflectograph deflection to equivalent Deflection Beam deflection should be carried out prior to temperature correction.

4.3 Correction of deflection values for the effects of temperature to standard deflections

4.3.1 Temperature correction charts. The stiffness of the bituminous layers of the pavement will change with temperature; the magnitude of pavement deflection will therefore also change with temperature, the size of the change depending on the proportion of the pavement's structural stiffness that is derived from bituminous materials.

Broadly linear relations between deflection and pavement temperature have been established for the wide range of pavement types and subgrade conditions noted above. Pavement temperature is characterised by measurements at a depth of 40mm below the pavement surface as described in Section 7 of LR 835. The information is presented in Figures 4 to 9 as temperature correction charts for the adjustment of deflections measured within a specified working range of temperatures to equivalent values at the standard temperature of 20°C.

4.3.2 Selection of the appropriate chart. Each chart relates to a different range of thickness of bituminous material. Where the thickness of bituminous layers is less than about 195mm it is necessary to define the proportion which is composed of dense material, ie dense coated macadam or rolled asphalt, as indicated on Figures 4 to 6. For the greater thicknesses considered in Figures 7 to 9 this distinction is not necessary, except in the special case of some old roads where coated materials having aggregates of a single size were laid, often in very considerable thicknesses. Only half the thickness of single-sized material should be used for calculating the total thickness of bituminous material present in these pavements.

In some roads, particularly those that have been built up over the years and that are therefore undesigned, bituminous materials may be present in layers separated from each other by other types of road material. Where the layers of bituminous material are in good condition and within 200mm of the road surface their thicknesses should be aggregated for the purpose of temperature correction; material whose upper surface is at a greater depth should be ignored as should bituminous layers lying beneath cement-bound materials. A pavement layer composed of multiple surface dressings should also be ignored unless it is greater than 25mm thick.

Where there has been extensive stripping of the binder from the aggregate in bituminous materials the thickness of stripped material should be considered as being unaffected by temperature when selecting the appropriate correction chart.

A pavement having the pattern of interconnecting and well developed cracks shown in Plate 1 is, in general, less susceptible to the effects of temperature than one which is substantially uncracked. Where there is evidence of such cracking, either from visual inspection or from cores or trial holes, Table 1 should be used to select the appropriate correction chart.

TABLE 1

Selection of appropriate temperature correction chart for severely cracked pavements

Total thickness of bituminous material in the pavement mm	Thickness of dense bituminous material in the pavement mm	Use temperature correction chart for	
		Thickness of bituminous material mm	Thickness of dense bituminous material mm
>324	–	275–324 (8)[A]	–
275–324	–	195–274 (7)	–
195–274	–	Either	
		75–195 (6)	if ⩾75
		or	
		137–195 (5)	if <75
75–195	⩾75	137–195 (5)	
137–195	<75	135 (4)[B]	<75
<137	<75	135 (4)[C]	<75

A Figures in brackets indicate Figure number in this Report

B The solid lines on Figure 4 should be used

C The dashed lines on Figure 4 should be used

4.3.3 Temperature limits for deflection testing. The relations between deflection and temperature in the charts should *not* be extrapolated beyond the temperature limits shown on the charts; the reasons for the restrictions are given in Section 7 of LR 835.

The measurement of pavement temperature at only shallow depth has been adopted for reasons of speed and convenience. Where considerable temperature gradients are present in bituminous layers of a pavement which are thicker than about 175mm the normal relations between deflection and temperature are distorted. However by restricting the deflection testing on such pavements to conditions when the rate of change of temperature at 40mm depth is less than 2½°C per hour the gradients are limited sufficiently to allow the normal temperature correction procedure to be applied.

4.3.4 Effect of very weak and very strong subgrades. The use of the temperature correction charts may lead to inaccurate estimates of standard deflection when pavements known to be sited on either very strong or very weak foundations are tested at temperatures close to the extremes of the working range. In these cases check measurements of deflection at another temperature are advisable.

5. ASSESSMENT OF THE REMAINING LIFE OF AN EXISTING PAVEMENT

Deflection histories were developed for pavements containing the main types of roadbase in common use. The majority of the observations were made on the Laboratory's full-scale road experiments which combined a wide range of thicknesses of granular, bituminous and cement-bound roadbase with surfacings predominantly of rolled asphalt, but also including a considerable number of sections of coated macadam. The experiments were constructed on subgrades in the weak-to-medium category with the majority having CBR strengths in the range 2.5 to 15 per cent. Additional information was also obtained from a number of other roads whose construction was of particular interest.

Deflections measured in the first few months after opening to traffic can change considerably as they reflect the effects on granular road materials of traffic compaction and, in some cases, cementing action and also the possible changes in subgrade moisture conditions after the disturbance caused by the construction of the road. Surveys made during this period can be a useful guide to the uniformity of strength of a road but are not a reliable guide to future performance[2].

Thereafter the histories showed that standard deflections in spring and autumn increased slowly but continually with increasing time and traffic (in terms of the cumulative number of equivalent or standard axles of 8175 kg): the trend continued at least up to the onset of critical conditions which, on roads constructed to reasonable specification, was shown to correspond broadly to damage visible at the road surface as described in Table 2.

Further deterioration towards a failure was less predictable and this is reflected in the associated deflection behaviour[6].

TABLE 2

Classification of the condition of the road surface

Classification	Code	Visible evidence
Sound	1	No cracking. Rutting under a 2m straightedge less than 5mm.
	2	No cracking. Rutting from 5mm to 9mm.
Critical	3	No cracking. Rutting from 10mm to 19mm.
	4	Cracking confined to a single crack or extending over less than half of the width of the wheel path. Rutting 19mm or less.
Failed	5	Interconnected multiple cracking extending over the greater part of the width of the wheel path. Rutting 19mm or less.
	6	No cracking. Rutting 20mm or greater.
	7	Cracking confined to a single crack or extending over less than half of the width of the wheel path. Rutting 20mm or greater.
	8	Interconnected multiple cracking extending over the greater part of the width of the wheel path. Rutting 20mm or greater.

5.1 Deflection-performance charts

The information relating to trend of deflection change up to the onset of critical conditions has been consolidated into four performance charts given in Figures 10 to 13. The trend lines of deflection lead to four envelope curves defining different levels of probability that the critical life of the pavement will be achieved. The life expectancy of a pavement is determined by following the deflection trend line from a point defined by the present level of deflection and the past traffic (in standard axles) to the envelope of the selected probability level. Deflections are in terms of measurements made with the Deflection Beam at the standard temperature of 20°C.

The chart for cement-bound roadbases requires further comments. In roadbases of medium-to-high strength the transverse cracks which form at the time of construction tend to propagate to the road surface. Any cracks that reach the surface are ultimately the source of major structural deterioration, both around the crack and along the wheelpaths; after the initial appearance of such cracks a further life of at least 5×10^6 standard axles can normally be expected before deterioration to a critical condition takes place.

The timing of the appearance of these cracks is influenced by the thickness of bituminous cover present. Under a 100mm surfacing the cracks may have appeared and developed to a critical condition after about 10×10^6 standard axles irrespective of the great stiffness of much of the pavement away from the cracks; this is shown as a dotted branch of the critical curve in Figure 13. When a bituminous upper roadbase is added to give a total thickness of 150mm, propagation of cracks is slower and the resulting critical life should be about 20×10^6 standard axles. Only when bituminous cover in excess of about 175mm is present can the normal critical curve be used with confidence; even so, cracks may be expected to appear after some very large number of applied standard axles.

It should however be emphasised that the dotted branches apply only when transverse cracks have actually appeared at the earliest likely times quoted in the previous paragraph; in many roads propagation does not happen and longer critical lives are appropriate.

Two types of cement-bound construction have been shown to give much shorter lives for a given deflection than indicated by Figure 13. The more important type contains cement-bound materials constructed in more than one layer, either as two roadbase layers or as a roadbase and a sub-base. When structural weakness, built into the top layer during construction, results in progressive deterioration of the upper layers of the road while the lower cement-bound layer remains intact, the associated deflections are kept relatively low by the presence of the undamaged lower cemented layer. The other type involves weak cemented materials whose aggregate grading has little mechanical stability. The inevitable early cracking of such a material leads to disintegration of the fragmented base although low deflections in early life are possible.

Failure in either type of construction cannot be anticipated at an early stage in the life of the road by conventional deflection testing unless information about the weak material is known.

5.1.1 Selection of the appropriate chart. Different charts are required for pavements with roadbases of granular, cement-bound and bituminous-bound materials; a distinction is also made between granular bases which develop some form of cementing action and those which do not. The type and thickness of granular sub-base does not have a significant effect on the deflection performance relations. These performance relations are valid for pavements surfaced with the bituminous materials in common use provided that the upper limits for traffic recommended for them in Road Note 29 are not exceeded, either at the time of the measurement or during any predicted remaining life.

Because individual road pavements can contain roadbase and sub-base materials that belong to several or all of the categories which relate to the four deflection-performance charts, further guidance may be necessary in choosing the appropriate design chart; this is particularly likely in the case of undesigned roads.

A pavement is classified as having a *cement-bound roadbase* if more than 100mm of such material is present even if located beneath a considerable thickness of bituminous surfacing and roadbase material. If the construction of the road is identified by coring evidence alone, it is advisable to inspect the cylindrical faces of the core holes for signs of cemented material because weakly cemented material in the core itself is often broken down. A pavement is classified as having a *bituminous-bound roadbase* when more than 150mm of bituminous materials are present, providing that there is not more than 100mm of cement-bound material also present. The bituminous layers can be separated by intervening layers of granular materials.

When there is evidence of stripping of the binder from the aggregate in bituminous materials the thickness of stripped material should be discounted. A bituminous layer composed of multiple surface dressings should be ignored unless it is greater than 25mm thick.

A pavement is classified as having a *granular roadbase with natural cementing action* when more than 150mm of this type of material is present; any associated cement-bound layers should be less than 100mm thick; any bituminous layers should be less than 150mm thick. Where there is doubt as to cementing action such action should be assumed; more conservative results are then obtained.

A pavement is classified as having a *granular roadbase without cementing action* when more than 150mm of this type of material is present, given the above provisos regarding the presence of other materials.

5.2 The relation between deflection and the visual condition of the pavement surface

The condition of the road surface as classified in Table 2 would be expected to correlate in a broad sense with the relation of the deflection traffic co-ordinates of the pavement to the appropriate critical curves in the deflection performance charts in Figures 10 to 13. However, there are a number of cases where this will not be so.

a) Extensive deterioration of the road surface is sometimes observed on a pavement whose deflection is low in relation to critical conditions: this will normally indicate premature failure solely of the surfacing, which may be inappropriate for the needs of traffic, out of specification, or both.

b) Lower-than-normal deflections, measured towards the end of a period of weather of sufficiently prolonged heat to reduce moisture contents in the subgrade soil, can also give the impression of a pavement of greater strength than its surface condition warrants. Repeat measurements under normal conditions are advisable.

c) Where relatively high deflections are associated with a pavement whose surface condition is good the cause may be a deterioration in subgrade strength brought about by a recent increase in the moisture content. The increase may be the result of thawing at the end of a prolonged period of cold weather during which the zero isotherm penetrates deep into the pavement, and possibly the subgrade also. Experience in the severe winter of 1963 indicated that normal subgrade conditions are restored by the late spring when re-testing will give representative results.

d) Relatively recent adverse changes in the drainage conditions of the area immediately around the road may also be the cause of high deflections. Timely measures to correct drainage faults before the pavement is permanently damaged may obviate the need to strengthen or reduce the thickness of overlay required. Irrespective of the condition of the road surface, the engineer should always look for any correlation between high deflections and signs of adverse drainage conditions, as overcoming pavement weakness which is caused by poor drainage by overlaying will normally be more expensive than improving the drainage itself.

e) Untypically high deflections may also be obtained during hot summer conditions when testing is not recommended. Deflection measurements in the preferred spring and autumn testing periods will not reflect this temporary weakening and should be used to check on the validity of any summer measurements.

When a gross mismatch occurs between deflection level and the visual condition of the pavement surface the engineer should check that there are no mistakes in the measurement and analysis of the deflection results or in the estimation of traffic.

6. DESIGN OF THE OVERLAY

6.1 The function of an overlay

The deflection of a flexible pavement can be reduced, and the structural strength increased, by the addition of bituminous overlay. The reduction of deflection will depend on the thickness of the overlay, its elastic properties and the deflection of the existing pavement.

The Engineer requires to know the thickness of overlay necessary to extend the life of a pavement by a given amount. He will then decide if the use of this thickness is practicable or whether it will be preferable to reconstruct the pavement. This decision will depend partly on economics and partly on such factors as levels and bridge clearances. On a multi-lane highway it may be cheaper to reconstruct the nearside lane than to apply a thick overlay to the whole carriageway width.

When high deflection levels on an existing pavement are primarily a result of poor drainage the application of a thick overlay may not produce the cheapest solution. Improvement of the drainage will reduce the deflection of the existing pavement which will then require a thinner overlay to achieve the same extension of life.

6.2 Derivation of the method of overlay design

A number of the Laboratory's full-scale road experiments have been overlaid with rolled asphalt, normally at a stage when a number of the individual experimental sections were approaching failure. Systematic measurements of deflection have been made before and after the application of the overlay, and deflection histories of the overlaid pavements have been developed.

The information essential to an overlay design method, ie the reduction in deflection brought about by an overlay of any given thickness and the deflection levels measured on the overlaid pavement required to give any given extension of pavement life, were obtained from these and other studies which are described in LR 832.

6.2.1 Reduction in deflection. The reduction in deflection was found to be a function only of the thickness of the overlay and of the deflection of the pavement before overlaying. Within the limits of experimental error it was independent of the type and thickness of pavement (except in that these parameters were reflected in the deflection of the pavement) and of subgrade strength over a wide range.

6.2.2 Overlay performance. Although the amount of information on the performance of overlaid pavements is at present less extensive than that available from new pavements, the deflection histories of both types of pavement prove to be generally similar.

The lives achieved by overlaid pavements with granular bases (cementing) are similar to those for original pavements of similar deflection, measured in the early life of the road; the trend-lines of deflection are however somewhat flatter in the case of overlaid pavements. Although few of the overlaid pavements containing bituminous and cement-bound bases have as yet reached a critical condition, their deflection trends are consistent with those for new construction and suggest that the lives of the overlaid pavements will be at least equal to those of new construction.

6.3 The overlay design charts

The overlay design procedure is contained in design charts based on the information described in Section 6.2.2. The charts given in Figures 14 to 21 specify the thickness of rolled-asphalt overlay required to strengthen a pavement of given deflection in order to achieve a desired extension of life, expressed in standard axles. In defining the thickness of overlay required, the charts take into account any remaining life in the original pavement. Where the wearing course of the existing pavement is badly cracked it would normally be replaced before overlaying in order to prevent crack propagation in the overlay material.

Separate overlay design charts are not required for the weak cement-bound materials, whose anomalous deflection behaviour has been discussed in Section 5.1, because reconstruction, involving removal of the weak material, is an essential prerequisite for strengthening. Early information as to the state of any lower cemented layer is however important in determining the depth of reconstruction required, and experience on motorways suggests that deflections of less than about 24 x 10^{-2}mm are consistent with a largely uncracked lower cemented layer.

Different probabilities can be assigned to the assessment of the remaining life of an existing pavement and to design of the extension of its life by overlaying. In order to reduce the number of design charts required, the design procedure has therefore been confined to the two levels of probability judged to be of most interest, ie 0.50 and 0.90.

6.3.1 Selection of the appropriate design chart. The criteria listed in Section 5.1.1 for the selection of the appropriate deflection-performance chart apply.

6.4 Overlaying with coated macadam

The design charts are for overlays using rolled-asphalt materials only. In order to widen their scope to cover dense and open-textured macadams, some information has been obtained about the reduction in deflection coated macadams achieve and their performance as overlays. Their overlay performance is accepted as being at least equal to their behaviour in new roads, and reductions in deflection have been studied on experiments constructed in the Laboratory grounds and on normal roads.

Thicknesses of overlays in coated macadam can be obtained by using the design charts in Figures 14 to 21 to design in terms of rolled asphalt; these thicknesses are then converted to equivalent thicknesses of coated macadam using the multiplication factors given in Table 3. At present it is recommended that overlays in these materials should be limited to 100 mm thickness, ie wearing course and basecourse materials only.

TABLE 3

Overlay thicknesses for coated macadams in relation to the requirements for rolled asphalt

Material	Thickness factor
Rolled asphalt	1
Dense coated macadam containing 100 pen or B54 binder	1
Dense coated macadam containing 200 pen or B50 binder	1.3
Open-textured macadam	2

Open-textured macadams would normally be recommended only for overlaying roads carrying traffic of intensities lower than those for which the overlay design charts are primarily intended. A thickness factor is however quoted in the table in order to give some basis for estimating factors required for intermediate coated macadam materials.

6.5 Minimum recommended thickness of overlay

The design charts recommend a minimum thickness of 40mm of rolled-asphalt overlay. This is desirable because of the difficulty of predicting the performance of thinner overlays (performance is nominally highly sensitive to small changes in the thickness of very thin overlays) and because of the uncertain observed performance of thin overlays, often associated with construction problems. The limitation should certainly be adhered to on important roads.

On lightly trafficked roads, where open-textured macadams are likely to be used, the implied minimum recommended thickness of 80mm can be waived; thus the design life for a 40mm open-textured macadam carpet can be extrapolated using the appropriate overlay design chart and a rolled-asphalt overlay of 20mm thickness.

6.6 Definition of material thickness

The overlay will normally be applied to a pavement which is rutted to some extent. The design thickness of overlay should not include the depth of any rut. Where the ruts are wide, signifying structural deterioration in several or all pavement layers, the shoulders of the rut should define the datum for the overlay. Narrow ruts generally indicate a deformed wearing course which may be removed before overlaying is carried out. When it remains in place the overlay datum should be that of the road surfacing away from the ruts.

7. SUMMARY OF THE INFORMATION REQUIRED FOR THE USE OF THE METHOD

A summary of the required information is given below.

7.1 Measurements

a) The deflection of the existing pavement measured either by the Deflection Beam or the Deflectograph.

b) The temperature of the pavement at a depth of 40mm below the road surface.

7.2 Traffic

a) The cumulative number of standard axles carried by the existing road since construction or since its last major structural maintenance.

b) An estimate of the future traffic expected during the desired life of the overlay.

7.3 The pavement

Information to identify the type and condition of the pavement for the purpose of selecting the appropriate charts for:

a) correcting measured deflections to standard values at 20^{o}C

b) estimating the remaining life of the pavement

c) designing any overlay required.

7.4 The subgrade

a) A broad classification of subgrade strength to determine whether it lies in the range of CBR values between 2.5 and 15 per cent.

b) Information regarding cut and fill and other factors relevant to the drainage conditions under and near the road.

7.5 The overlay

The type of material to be used.

8. AN EXAMPLE OF THE USE OF THE DESIGN CHARTS

The design charts estimate the remaining life of a pavement of a given deflection and the overlay required to achieve a desired extension of the life.

A road with the characteristics listed below has carried 3 x 10^6 standard axles. It is required to design strengthening measures for a length of road having deflections of 25, 45 and 80 x 10^{-2} in order to obtain a future life of 10 x 10^6 standard axles, with a 0.50 probability of achieving at least the design life.

TABLE 4

Pavement details

Road layer	Thickness (mm)	Details
Surfacing	100	Rolled asphalt
Roadbase	200	Crushed rock with a natural cementing action
Sub-base	200	Type 1 crushed rock
Subgrade	–	CBR strength = 6%

The appropriate design charts are Figures 10 and 14.

For this example they are reproduced as Figures 22 and 23.

8.1 Determination of remaining life

This is shown by first plotting the deflection/standard axle co-ordinates on the deflection/performance chart (Figure 22). Providing that the points lie below the critical curve, the trend lines from the points to the critical curve can be drawn and the remaining lives read off.

A deflection of 25 x 10^{-2}mm gives a remaining life of 19 x 10^6 standard axles which is greater than the desired overlay design life; no action is necessary but the result can be used for timing a future deflection survey when the road will be closer to critical conditions. The remaining life for a deflection of 45 x 10^{-2}mm is only 3 x 10^6 standard axles and an overlay is therefore required to achieve the design life.

The deflection of 80 x 10^{-2}mm lies above the critical conditions curve for a pavement which has carried 3 x 10^6 standard axles. The pavement is structurally weak and strengthening action is required now. If the surfacing is badly cracked it should be replaced before an overlay is applied.

Also shown on Figure 22 is the maximum deflection on the existing pavement that will give a 0.50 probability of achieving the design life without overlaying. The value of 29 x 10^{-2}mm in the example is obtained by constructing the trend line of deflection backwards from the intersection of the critical curve with the abscissa of 13 x 10^6 standard axles, representing the total traffic on the pavement to the end of the design life. The maximum deflection value for which no overlay is required (the Deflection requiring zero overlay or DOO) is of importance in the analysis of data from an actual road and is used in the analysis presented in Appendix 2.

8.2 Design of overlay thickness

The overlay thicknesses required for deflections of 45 and 80 x 10^{-2}mm are obtained by plotting these values, in association with the desired life of 10 x 10^6 standard axles, on the appropriate overlay design chart (Figure 23).

A deflection of 45 x 10^{-2}mm requires less than the 40mm minimum thickness of overlay. A 40mm overlay should result in a future life of about 12.5 x 10^6 standard axles.

A deflection of 80 x 10^{-2}mm requires an overlay of 120mm. In this example the position of the deflection/traffic co-ordinate in relation to the critical condition curve indicates that the road could be already badly damaged and in need of total or partial reconstruction. The reconstruction measures adopted will depend on whether the weakness is in the pavement, in the subgrade, or in both. Where considerable lengths of road are involved it will normally be necessary to use trial holes and coring to obtain this information. An alternative is to apply a thick overlay on the damaged pavement; in practice level restrictions often preclude this solution.

For a better understanding of the procedures used in Appendix 2 of this report, it should be noted that, if a shorter design life were adopted of say, 7.0 x 10^6 standard axles, the overlay thickness of 120mm would be sufficient for existing deflection levels up to 98 x 10^{-2}mm (as shown by moving C to C′ in Figure 23).

9. DEFLECTION ANALYSIS FOR THE DESIGN OF PRACTICAL STRENGTHENING MEASURES

Deflections measured in a survey of structural strength along the length of a road typically show considerable variation: the variation reflects differences in subgrade strength, in the type of pavement and in its structural condition. Surveys on roads in need of structural strengthening are characterised by high deflection levels associated with a greater-than-normal variation in deflection. In contrast, the ideal strengthened road should be one whose deflections are as constant as possible so that future structural deterioration takes place relatively uniformly along its length; future strengthening can then be carried out with maximum economy by means of a relatively thin overlay. Because of the normal variation of deflection, it is not practicable to match this variation in deflection by strengthening measures which are exactly appropriate at all points along the length of the road.

However, the closely spaced output of deflection measurements from the Deflectograph (and also recommended for the Deflection Beam) can be used in a statistical analysis to give practical engineering recommendations that can eliminate the risks of localised early failure in the strengthened pavement as well as that of general overdesign of overlay thickness.

Three methods of analysis are described, two suitable for the analogue forms of output from deflection surveys and the third using profiles of deflection drawn by computer. The application of these methods to an actual deflection survey is considered in Appendix 2.

9.1 Design criteria for the methods

The innate variability of deflections along the length of any road makes it inevitable that any economic and practicable strengthening recommendations will lead to some proportion of the strengthened road reaching a critical condition before the design life of the road is achieved; a greater proportion will be overdesigned and in a small proportion the degree of overdesign will be considerable. The same picture will be true for estimating the remaining life of an original pavement. The methods presented require the specification of the proportion of the road that can be allowed to become critical within its design life and the earliest time at which critical conditions in any part of the road can be permitted.

The proportion and time selected will depend on such factors as traffic intensity and the disruption likely to be caused by minor repair work prior to a subsequent major strengthening contract.

It is not practical or economic to impose any limitation on the concomitant gross overdesign of short lengths of road.

The design inputs can be summarised as:—

1. The desired design life in standard axles
2. The probability of achieving that design life
3. The proportion of the length of strengthened road that may reach a critical condition during the design life
4. The earliest point in the design life at which any of this proportion may reach a critical condition.

9.2 Types of data output

Output from a Deflectograph can be in one of two forms: records of each complete measurement cycle taken on a pen-chart recorder, or peak deflections digitised during the actual survey (see LR 834). Subsequent digitisation of the peak readings from the analogue output is also sometimes carried out.

Deflection Beam readings are normally recorded on sheets designed for manual analysis of the results or, alternatively, on sheets designed for direct punching of the results for computer analysis. The relevant record sheets are shown in LR 835.

9.3 Presentation of deflection output

The analysis procedures are based on a graphical representation of deflection results in the form of a deflection profile in which deflections are plotted as ordinates on a horizontal scale representing the position of the measurements along the road.

For most purposes the output characterises about 12m of road and is obtained either by taking the mean of three successive deflection readings measured by the Deflectograph or, by two or more measurements by the Deflection Beam at the 12m spacing. This spacing is considered to be the minimum necessary to represent the structural condition of the road. The process of taking means increases the confidence in the result obtained by the Deflectograph; by so doing undue emphasis on isolated high or low values, which may be in error, is avoided.

An individual wheel-path in a traffic lane may not contain all the highest deflection values corresponding to the greatest structural weakness. Combining the deflection results from the two wheel-paths of a traffic lane is therefore desirable to the design of strengthening measures.

The characteristic initial mode of deterioration of high-strength cement-bound roadbases is the formation of relatively widely spaced cracks, both transversely and also in the wheel-paths, longitudinally. Detection of these cracks and the high deflection values that are associated with them is important in deciding on strengthening measures. It is therefore recommended that at least two deflection surveys are carried out on pavements with such roadbases so that the chance of locating the cracks is increased. Where the Deflectograph is used, the analysis of the results should be carried out on individual deflection values, rather than the means-of-three, and the remedial treatment from each analysis combined in such a way as to produce the greater requirement at any point.

9.4 Analysis of deflection data

9.4.1 Manual analysis, Method 1. (Described in detail in Section 5 of Appendix 2). In this method the original output, uncorrected for temperature, is used and lengths of road are selected which have a reasonably uniform level of measured deflection.

The deflection of each length is characterised by a single value only, which is then used for design purposes. The deflection profiles of the individual wheel-paths have to be combined manually. Provided that reasonably long lengths of road can be identified, this method is, given practice, a relatively rapid analysis procedure; the difference between actual recommendations obtained and the optimum one does, however, increase as the design lengths increase. Its major disadvantage is that the subjective element in the procedure, the choice of lengths of reasonably constant deflection, is made at the beginning of the analysis; subsequent changes in the lengths adopted require a complete re-analysis to be made. Because of the non-linear relation which exists between overlay thickness and deflection, selection of lengths on the basis of deflection rather than on required overlay thickness will rarely give an optimal strengthening solution.

The method. is,however, recommended for the analysis of roads that are generally in good condition and for which overlays, where required, are thin; in these circumstances the deflection profiles are usually more uniform and inaccuracies introduced by a poor initial selection of lengths are minimised.

9.4.2 Manual analysis, Method 2. (Described in detail in Section 6 of Appendix 2). In this method, which also uses the original chart output, the measured deflection scale is converted into a standard deflection scale on the analogue chart output. Standard deflection levels corresponding to various overlay thicknesses can then be plotted directly on to the measured deflection profile. The analysis of the profile is then similar to the analysis procedure for computer-drawn profiles described below except that, where it is necessary to combine the deflection results of the two wheel-paths and to take mean-of-three values, these stages must be carried out manually as in the previous method.

Method 2 is more time-consuming than Method 1 but is the more accurate of the two. The method is recommended for use where early and substantial strengthening measures are required.

9.4.3 Analysis of computer-drawn deflection profiles. (Described in detail in Section 7 of Appendix 2).

The DEFLEC computer program developed at the Laboratory can be used to process

a) digitised tapes from either of the two digital systems currently carried in Deflectographs,

b) digitised tapes produced from analogue output of Deflectographs after surveying,

c) data punched on cards from surveys carried out with the Deflection Beam.

DEFLEC can be used to produce the graphical presentation; it can display the maximum deflection requiring zero overlay (DOO) and up to four deflection levels corresponding to different overlay thicknesses required for a desired design life.

The program can output mean-of-three deflection values and combine the deflection results from the two wheel-paths when required. The method of analysis recommended is based on the same approach as that used in the manual analysis Method 2 but, because of the automatic processing capability described above, is considerably quicker to carry out than the latter method and also has greater flexibility.

It has the added advantage of being able to ensure that the development of the "allowable" critical conditions during the design life is randomly spaced along the road and not concentrated sufficiently to bring about localised early failure.

9.5 Comparison of the results obtained by the three methods of analysis

The strengthening recommendations designed by the methods described above for the length of road used to illustrate these methods are compared in Figure 24. The solutions assume that there are no practical restrictions on overlay thickness and that relative costs have not been taken into account in influencing the choice between reconstructing or overlaying badly damaged areas of high deflection. In the engineering solutions presented, transitional lengths of 100m between overlays of different thickness have been assumed; in practice this length may be much shorter particularly where the change in thickness is small.

The different methods give very close agreement on the thickness and position of overlays recommended, with the analysis using the mean-of-three computer-drawn profile giving, as expected, the minimum requirements. The good agreement of the results obtained by the manual analysis Method 1 was, however, obtained only at the expense of the very considerable labour involved in dividing up the road into relatively short sections for analysis.

The volume of overlay material required by each of the solutions is shown in Table 5; the extent of the possible savings in material which result from the use of the computer-drawn profile of means-of-three readings are obvious. Because the lengths selected in manual analysis Method 1 are shorter than those which, for convenience, would be likely to be used in practice, the quoted volumes of material required by this method represent an underestimate. At the other extreme, if the total length had been considered for an overlay of one thickness, 114 m^3 of material would be required: if two separate lengths are identified 84 m^3 would still be necessary.

TABLE 5

Quantity of overlay material required for the strengthening solutions presented in Appendix 2

Method	Volume of overlay per metre width of carriageway, m^3	
	Recommended requirement	Engineering solution
Manual Method 1	60	72
Manual Method 2	64	75
Computer output, individual values	62	73
Computer output, mean-of-three values	54	64

All solutions include the option to reconstruct lengths rather than increase overlay thickness.

10. THE SPACING OF DEFLECTION BEAM MEASUREMENTS

The distance selected between test points when the Deflection Beam is used will depend mainly on the purpose of the survey and on the visual condition of the road surface. On an apparently sound length of road, measurements should be made at about 25m intervals but, where the road shows visual signs of deterioration or the deflection measurements are sufficiently high or variable to suggest that deterioration is likely to be taking place, the test points should be placed more closely together; a spacing of about 12m in the nearside wheel-path is suitable in most circumstances, ie approximately at the spacing of the mean-of-three deflections measured by the Deflectograph. In addition measurements should also be taken in the offside wheel-path whenever there is evidence of deterioration there.

The importance of closely spaced measurements is discussed in Appendix 3 of this Report and in an OECD report on road strengthening[9].

11. THE USE OF THE METHOD

It is beyond the scope of this report to consider the way in which the method described should be implemented on the road system of the United Kingdom: implementation is in any case at present restricted by the limited resources available for deflection testing.

It is however, important to stress that the present use of the method which is primarily for designing strengthening measures for roads that are already damaged, does not exploit the full potential of the method for anticipating future maintenance requirements by regular deflection surveys on the road network. Surveys of major roads on a five-yearly cycle, with more frequent measurements on roads shown to be approaching critical conditions, is a practical possibility and would be of considerable assistance in forward planning and in minimising maintenance expenditure.

12. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Pavement Design Division (Head of Division: Mr N W Lister) of the Highways Department of TRRL.

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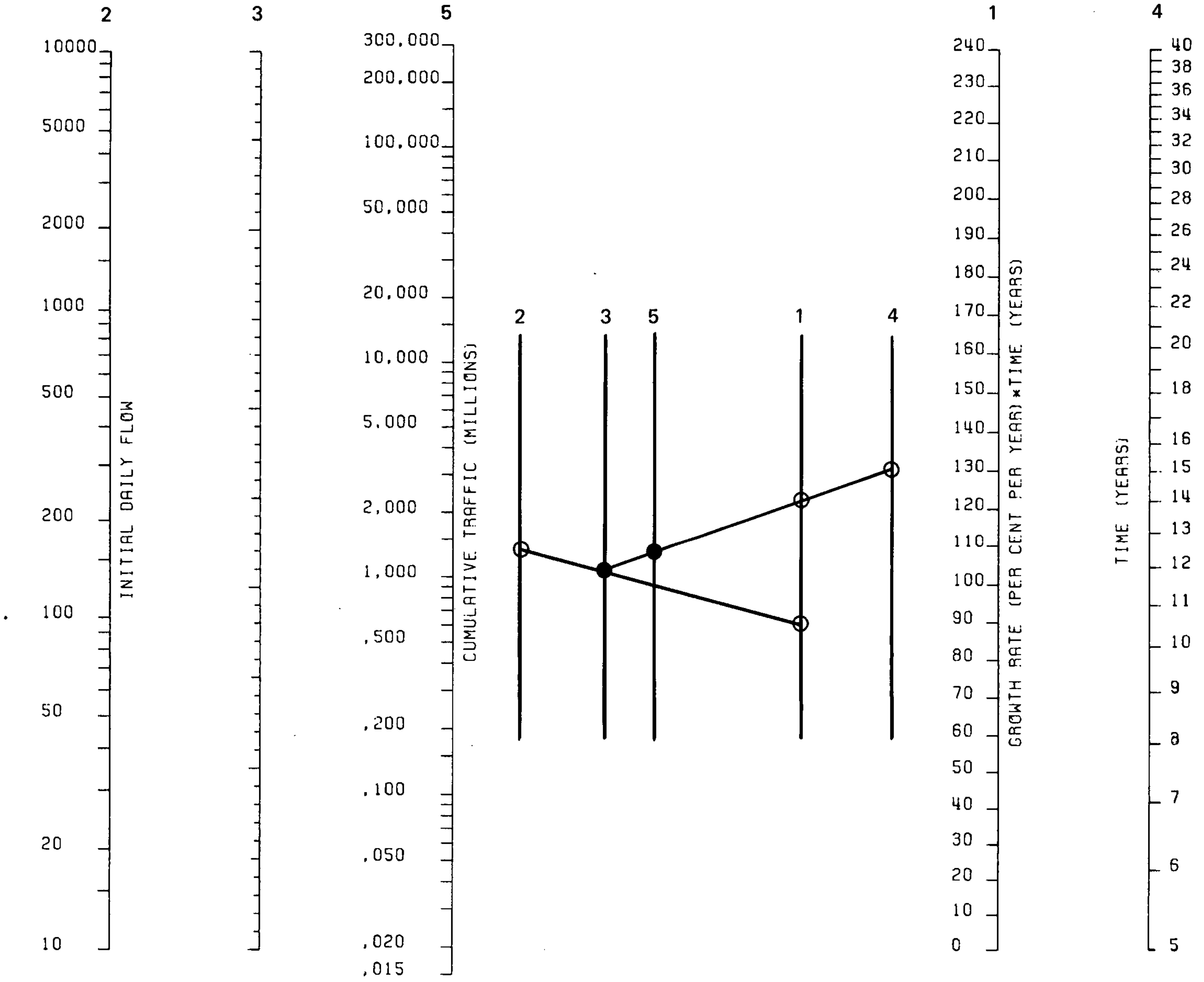


Fig. 1 NOMOGRAM FOR FORWARD ESTIMATION OF CUMULATIVE ONE-WAY TRAFFIC IN THE LEFT HAND LANE (COMMERCIAL VEHICLES)

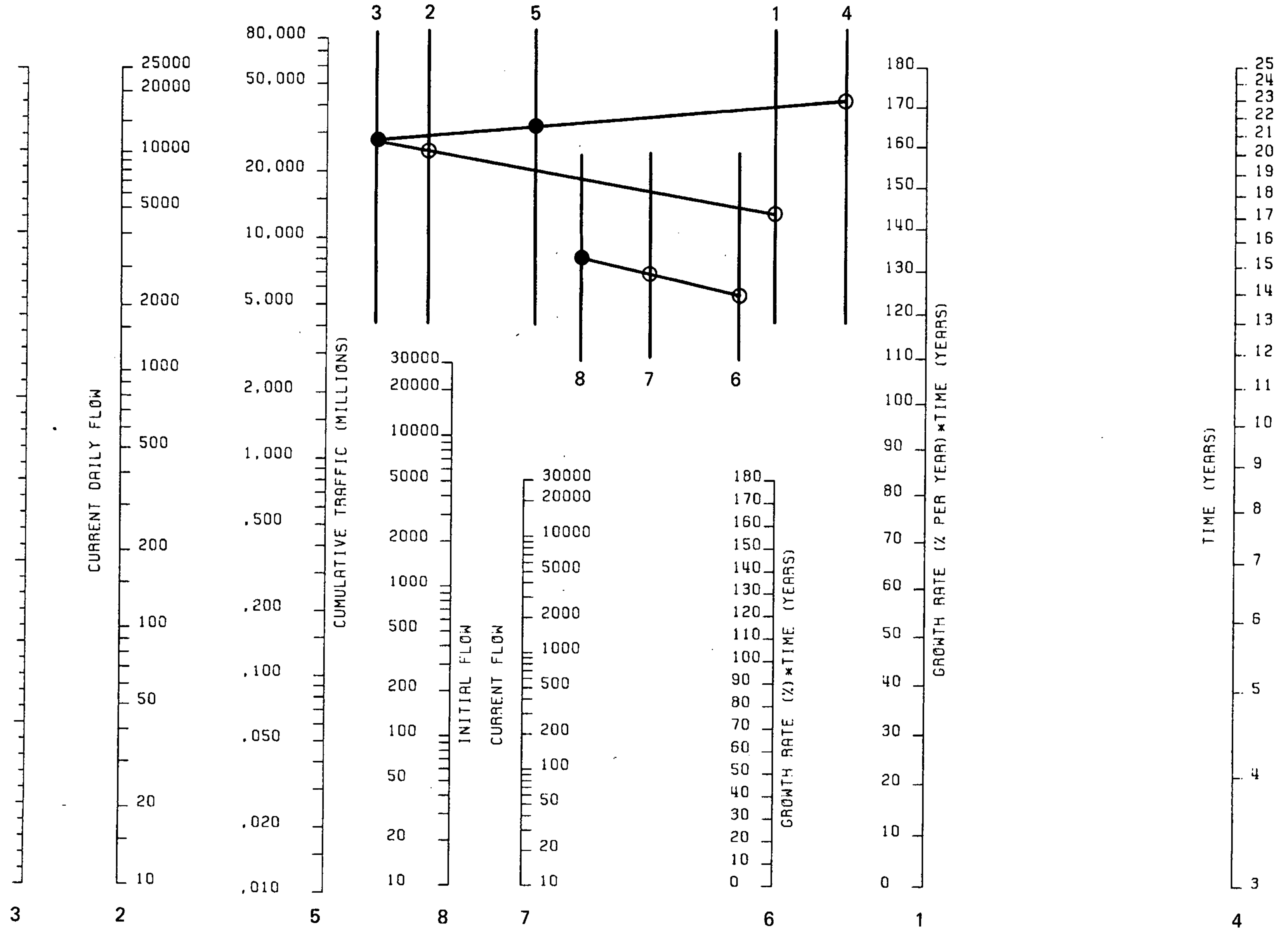


Fig. 2 NOMOGRAMS FOR BACKWARD ESTIMATION OF CUMULATIVE ONE-WAY TRAFFIC IN THE LEFT HAND LANE (COMMERCIAL VEHICLES)

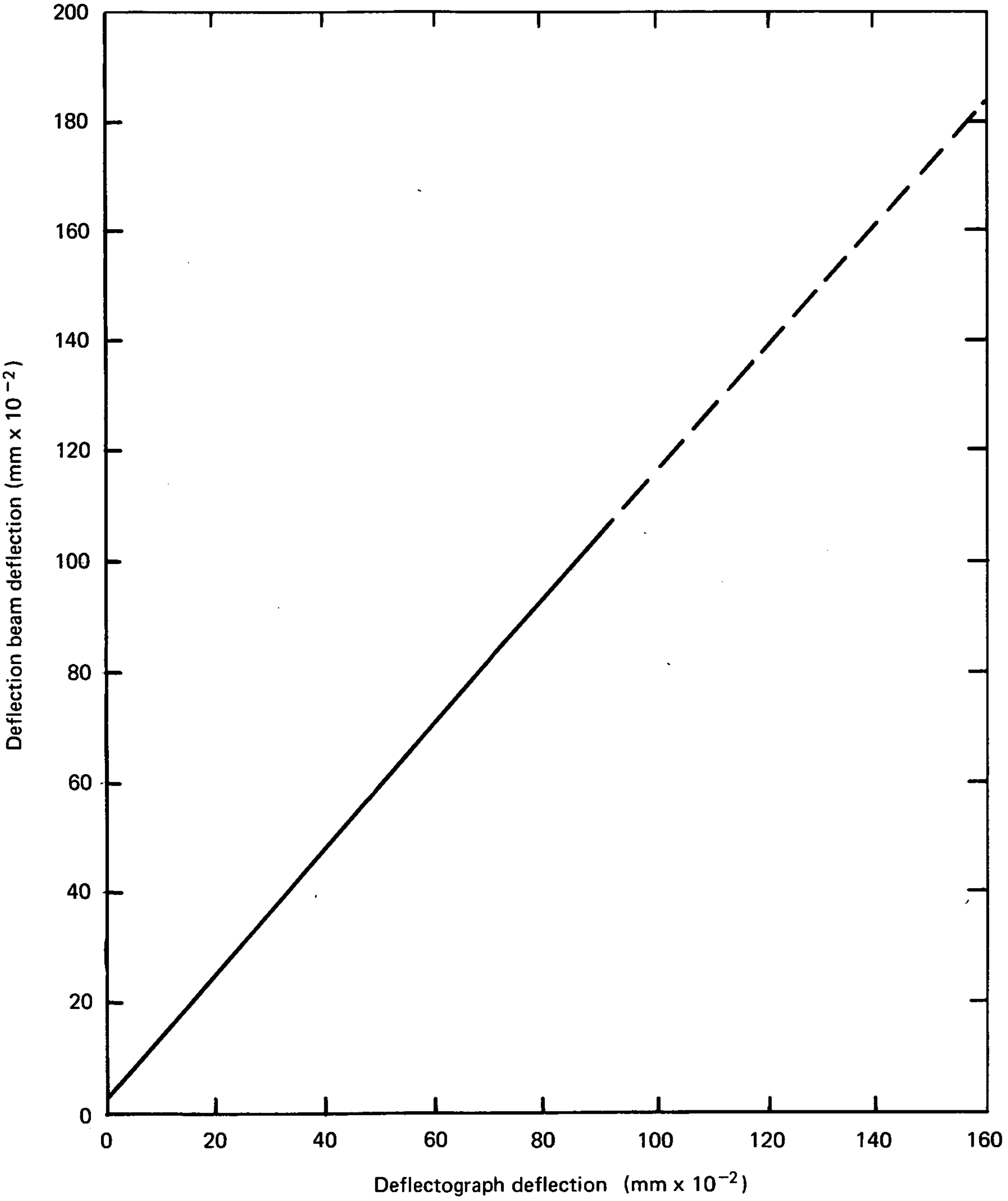


Fig. 3 CORRELATION BETWEEN DEFLECTION BEAM AND DEFLECTOGRAPH

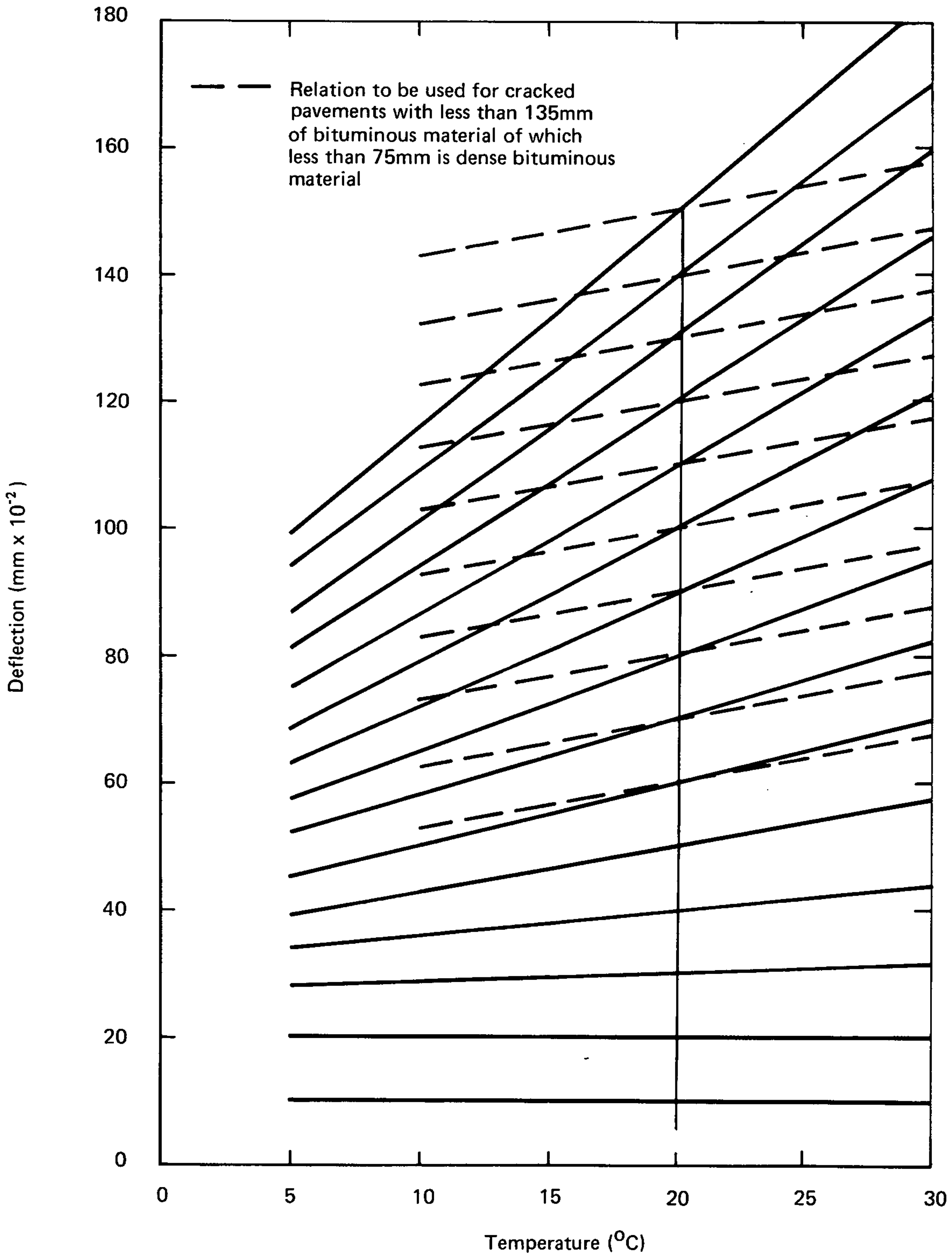


Fig. 4 RELATION BETWEEN DEFLECTION AND TEMPERATURE FOR PAVEMENTS WITH LESS THAN 135mm OF BITUMINOUS MATERIAL OF WHICH LESS THAN 75mm IS DENSE BITUMINOUS MATERIAL

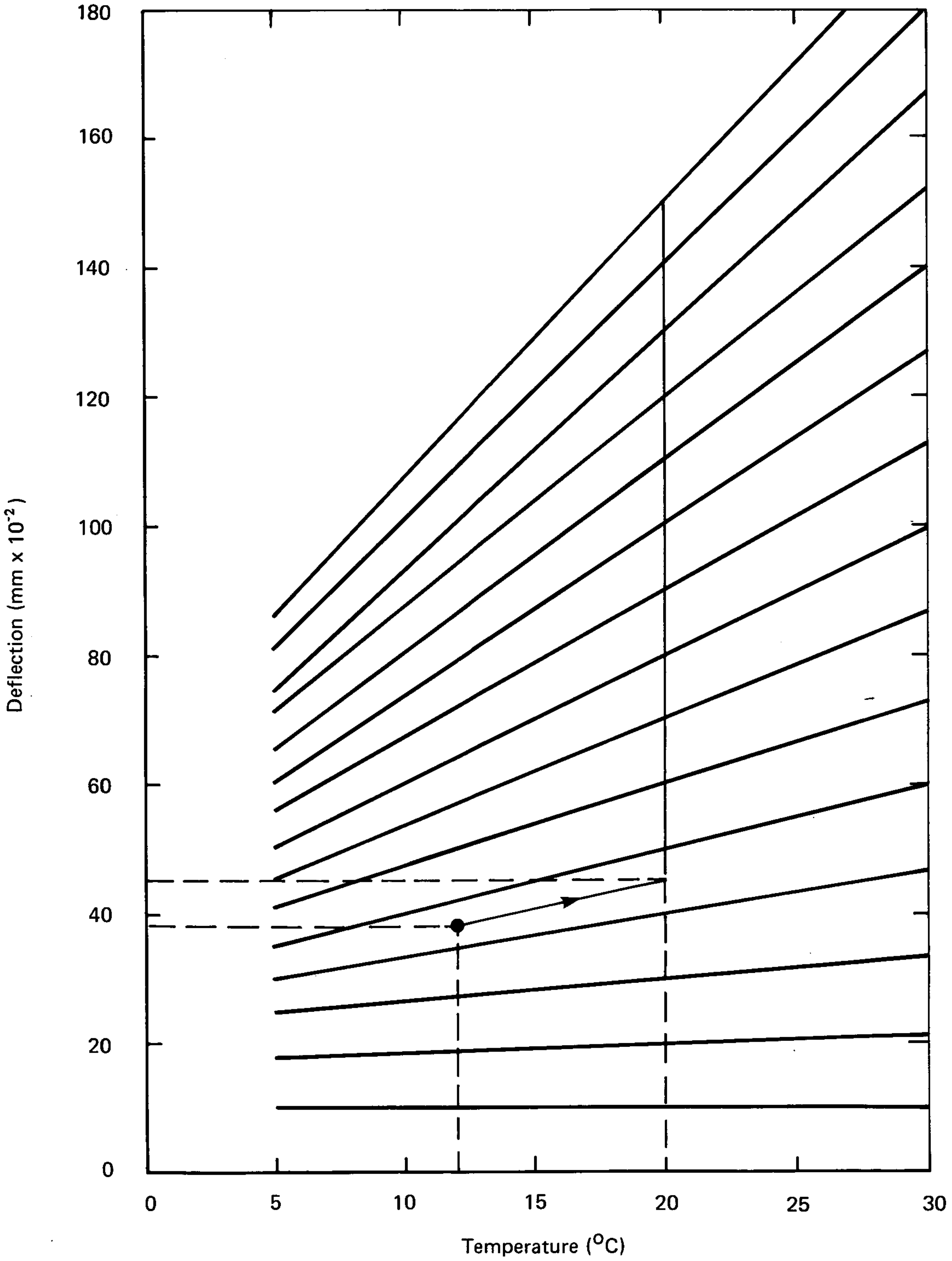


Fig. 5 RELATION BETWEEN DEFLECTION AND TEMPERATURE FOR PAVEMENTS WITH 135–195mm OF BITUMINOUS MATERIAL OF WHICH LESS THAN 75mm IS DENSE BITUMINOUS MATERIAL

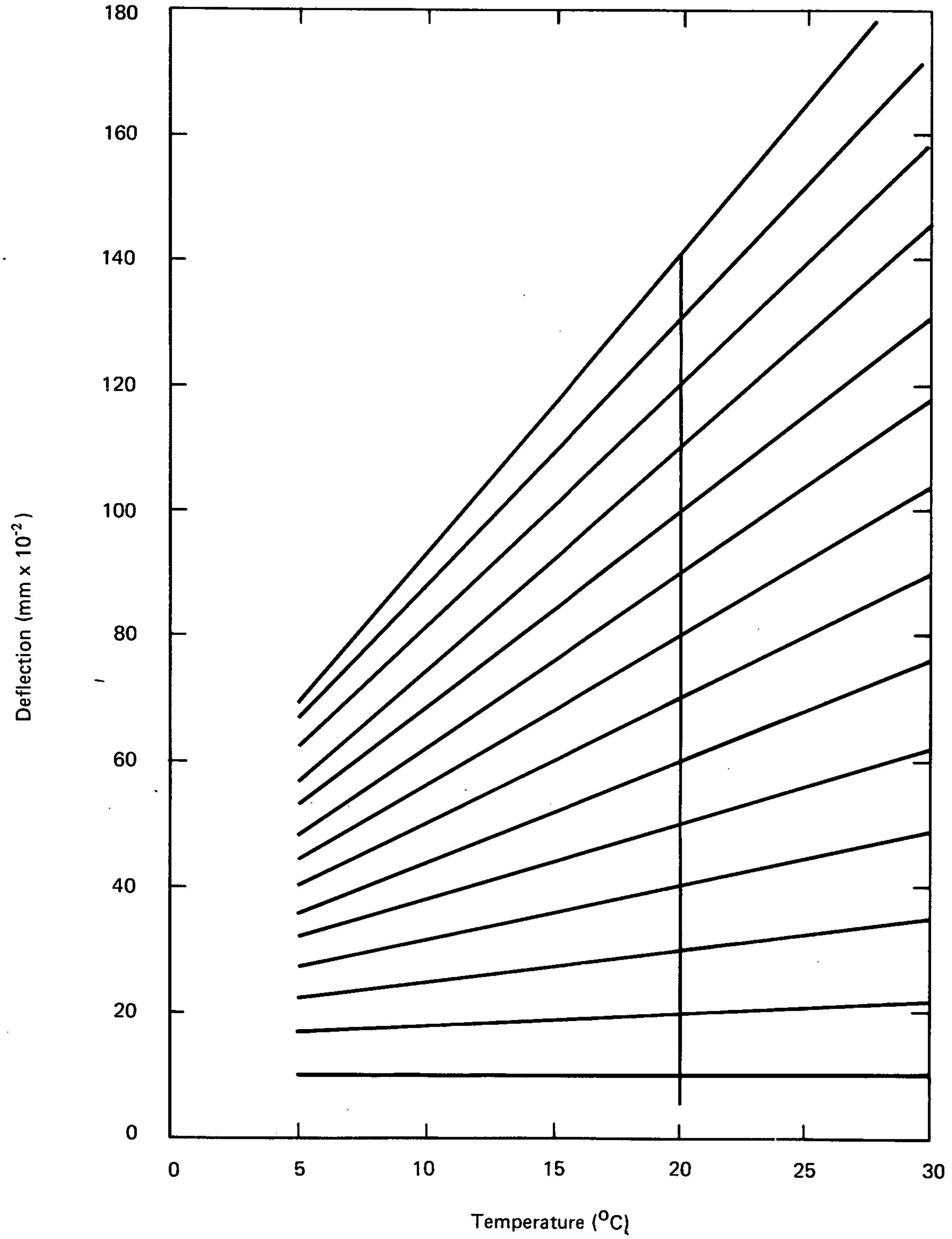


Fig. 6 RELATION BETWEEN DEFLECTION AND TEMPERATURE FOR PAVEMENTS WITH 75–195mm OF BITUMINOUS MATERIAL OF WHICH AT LEAST 75mm IS DENSE BITUMINOUS MATERIAL

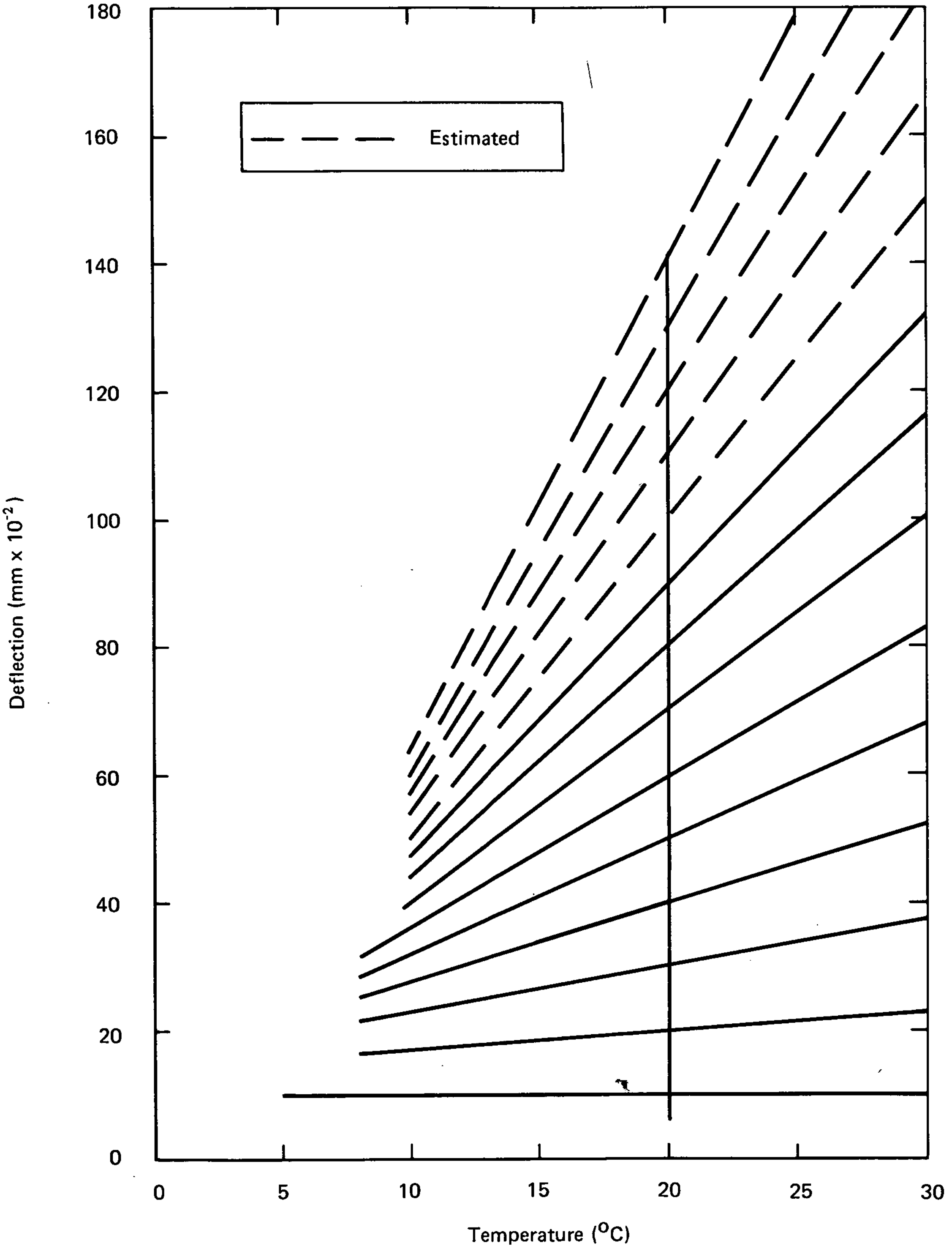


Fig. 7 RELATION BETWEEN DEFLECTION AND TEMPERATURE FOR PAVEMENTS WITH 195–274mm OF BITUMINOUS MATERIAL

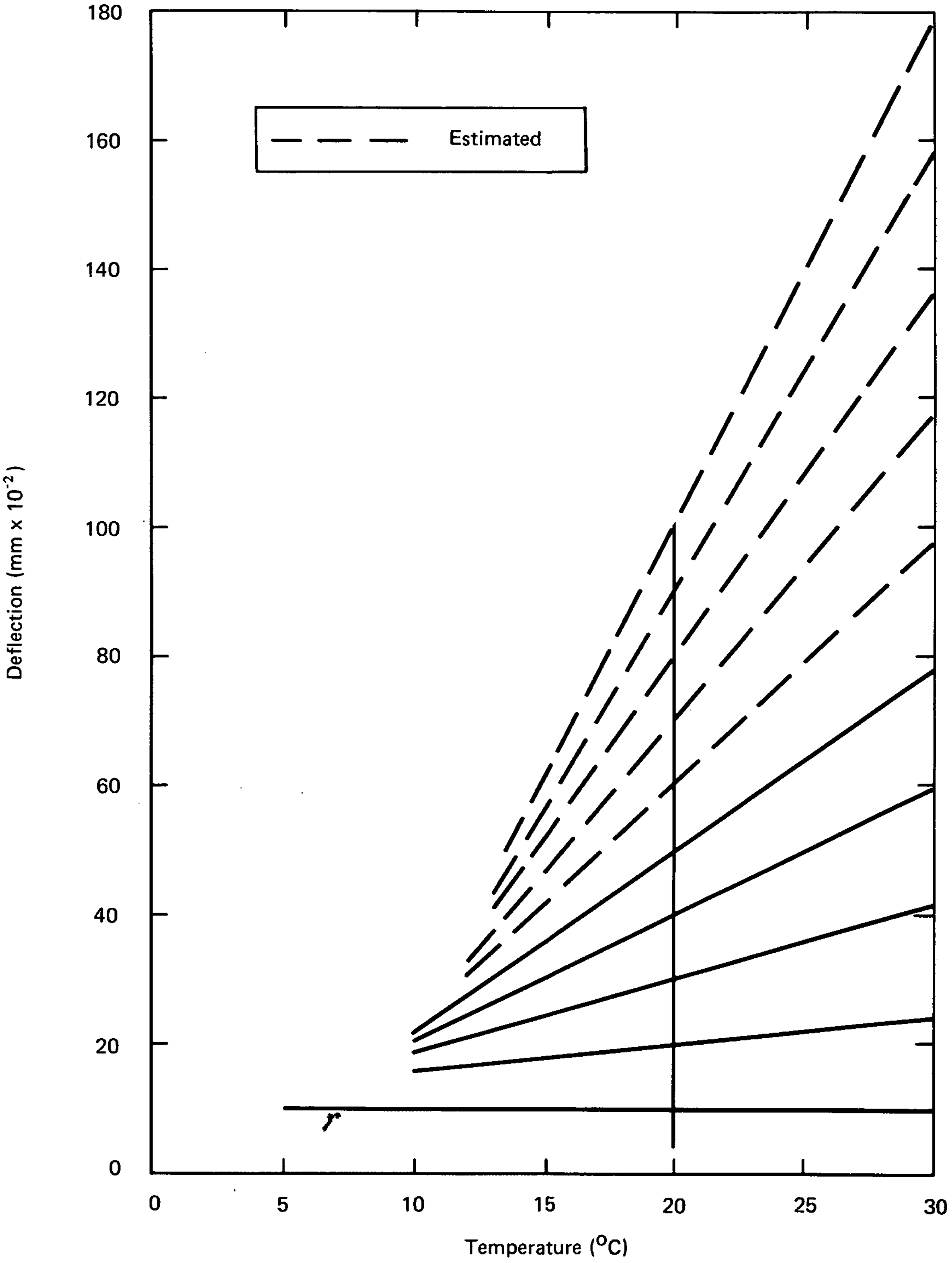


Fig. 8 RELATION BETWEEN DEFLECTION AND TEMPERATURE FOR PAVEMENTS WITH 275–324mm OF BITUMINOUS MATERIAL

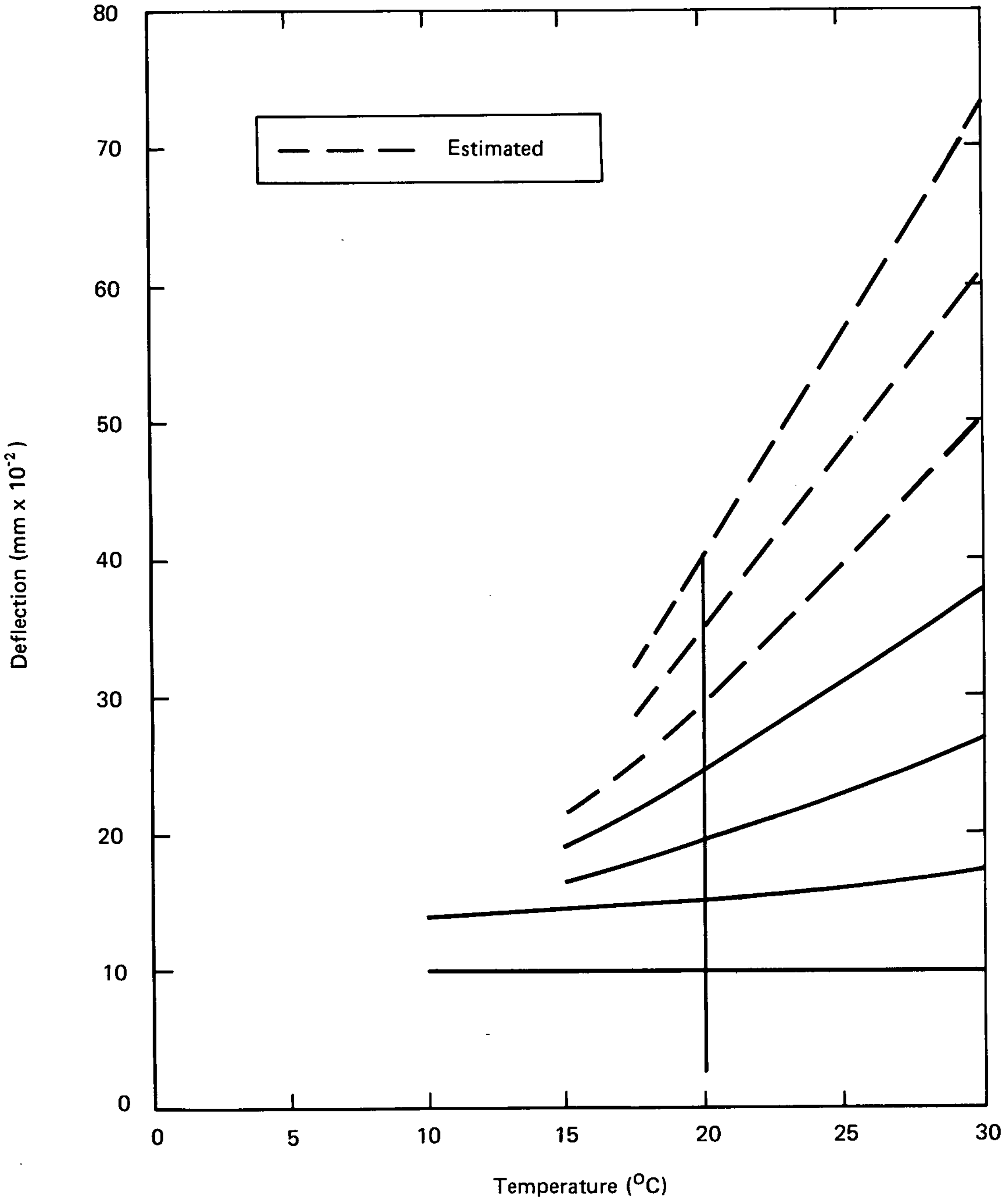


Fig. 9 RELATION BETWEEN DEFLECTION AND TEMPERATURE FOR PAVEMENTS WITH MORE THAN 324mm OF BITUMINOUS MATERIAL

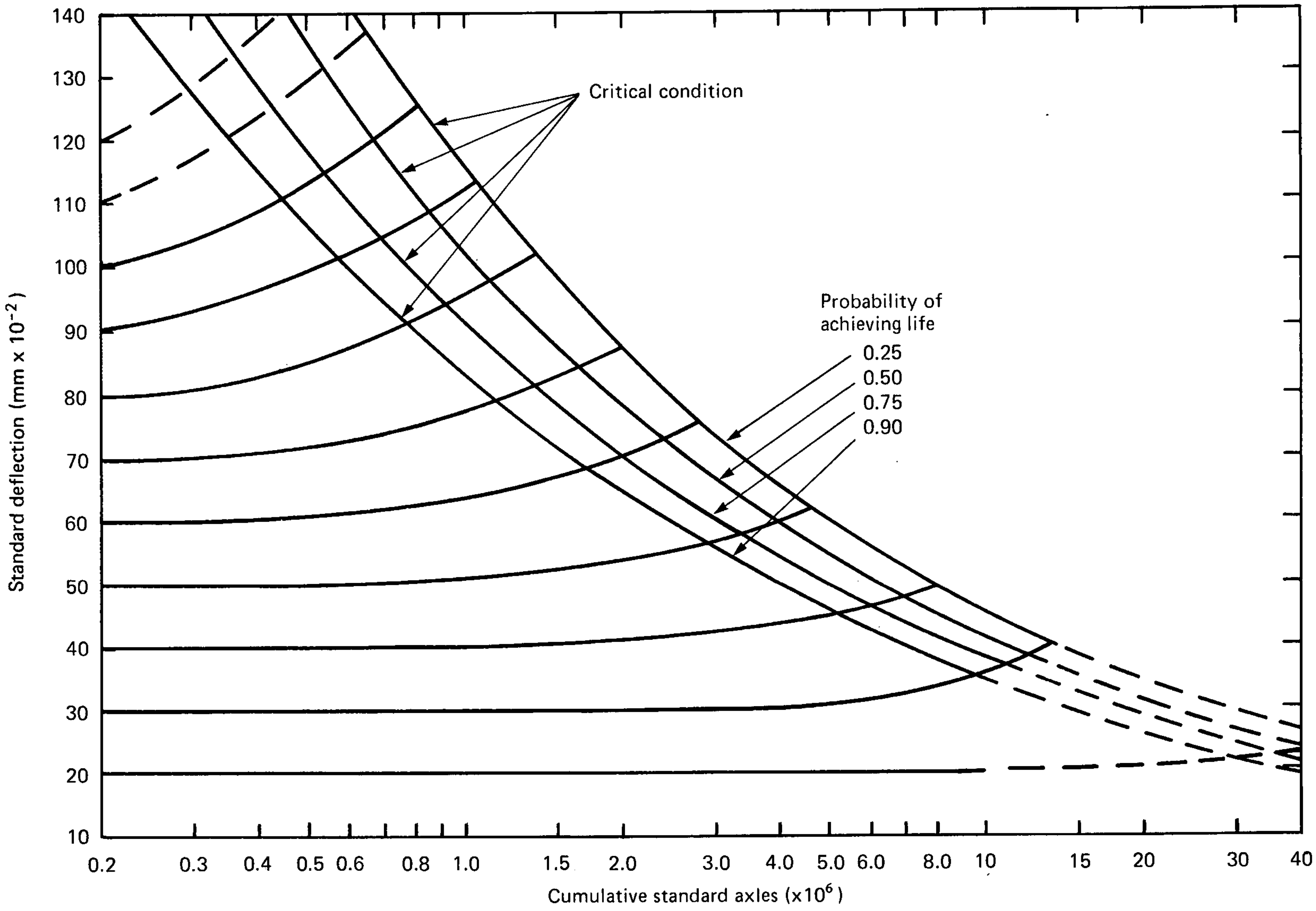


Fig. 10 RELATION BETWEEN STANDARD DEFLECTION AND LIFE FOR PAVEMENTS WITH GRANULAR ROAD BASES WHOSE AGGREGATES EXHIBIT A NATURAL CEMENTING ACTION

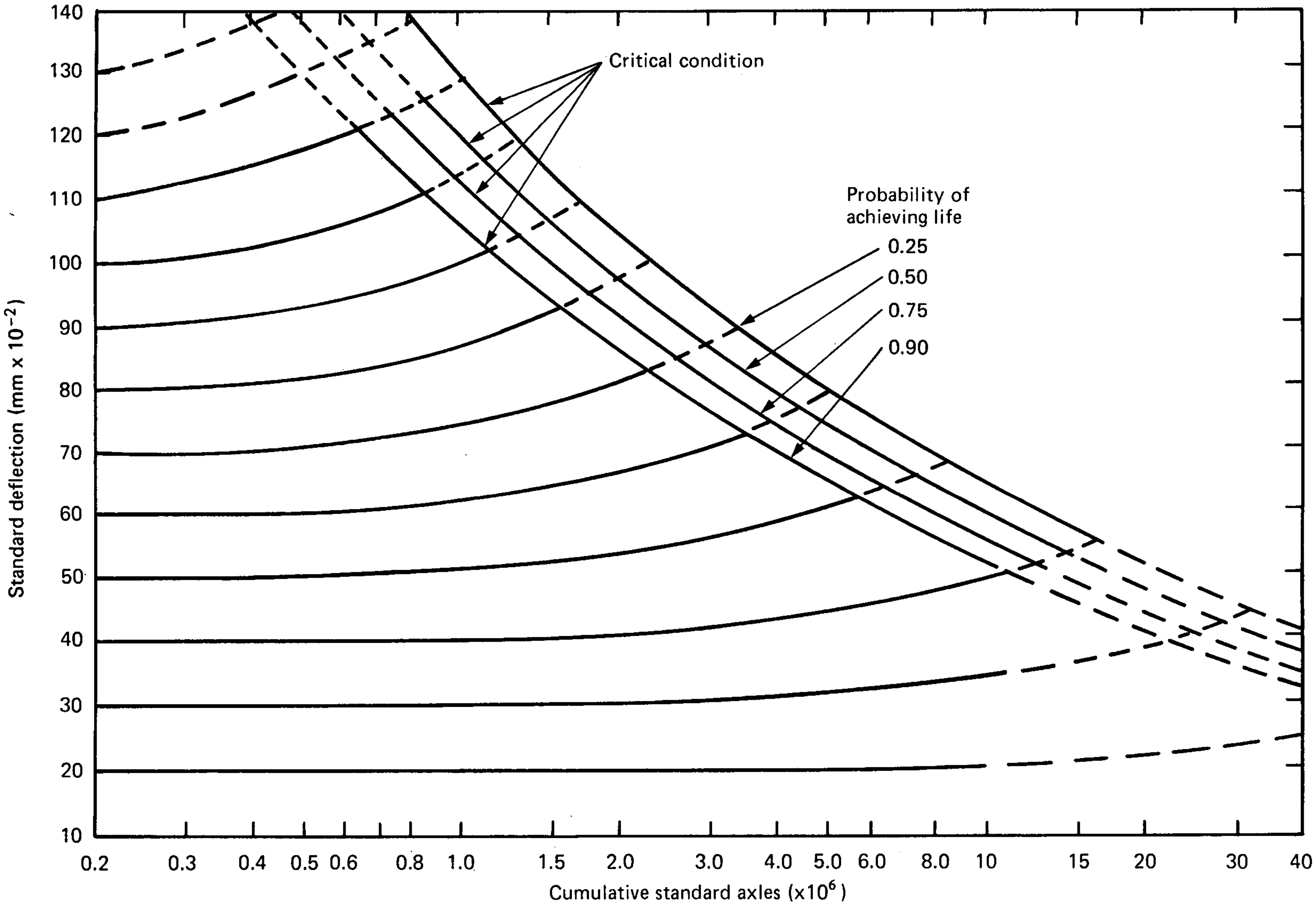


Fig. 11 RELATION BETWEEN STANDARD DEFLECTION AND LIFE FOR PAVEMENTS WITH NON-CEMENTING GRANULAR ROAD BASES

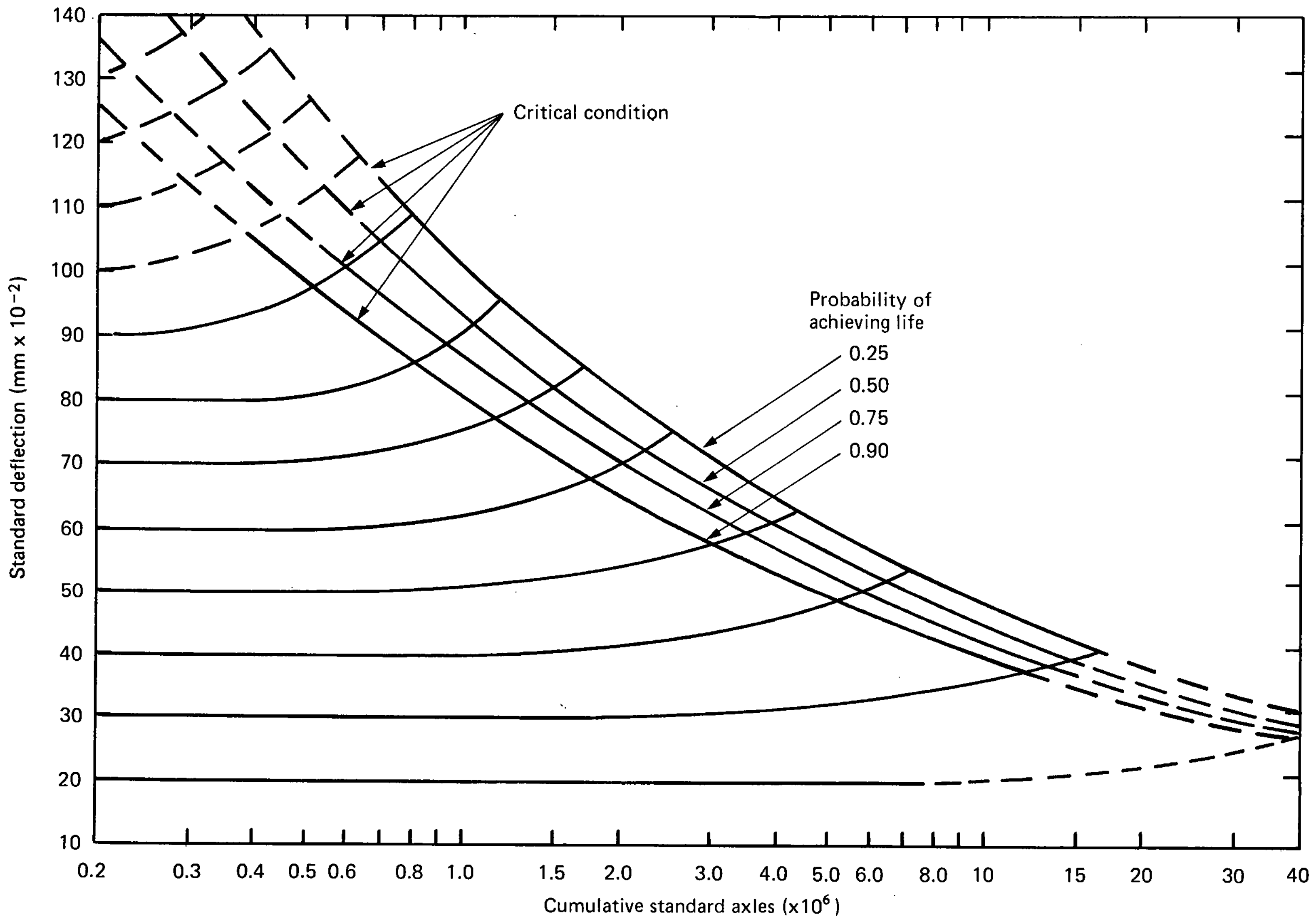


Fig. 12 RELATION BETWEEN STANDARD DEFLECTION AND LIFE FOR PAVEMENTS WITH BITUMINOUS ROAD BASES

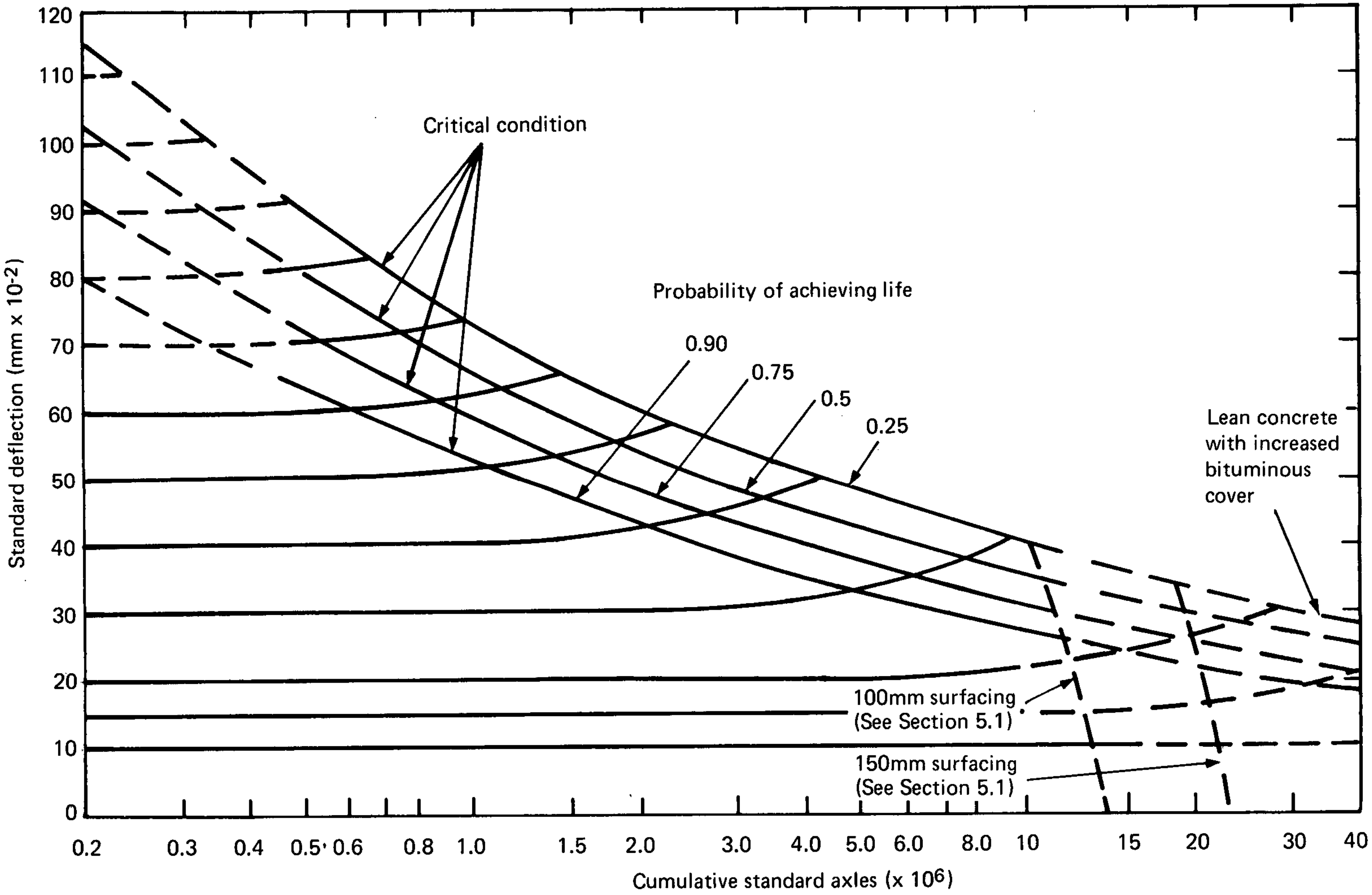


Fig. 13 RELATION BETWEEN STANDARD DEFLECTION AND LIFE FOR PAVEMENTS WITH CEMENT–BOUND ROAD BASES

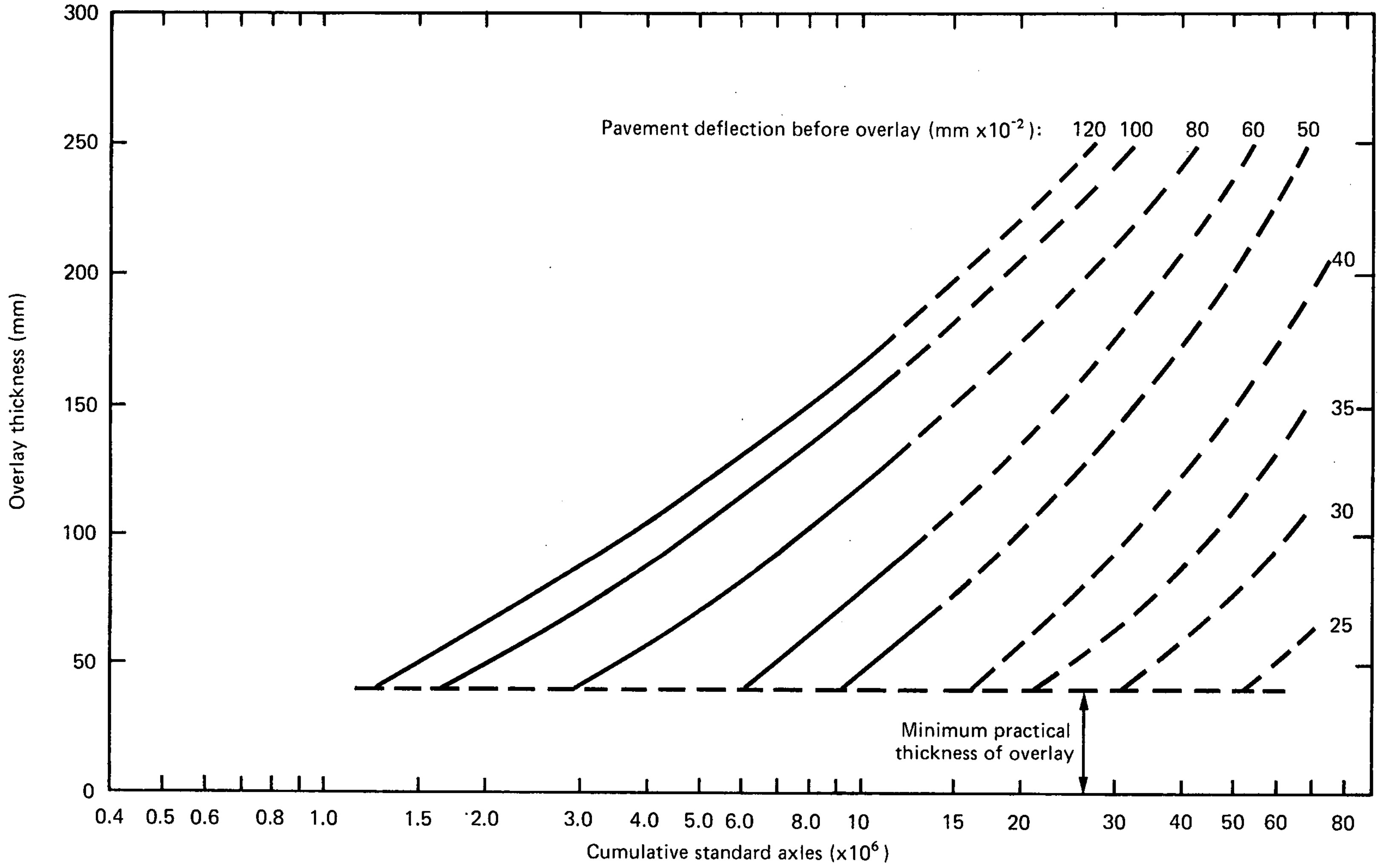


Fig. 14 OVERLAY DESIGN CHART FOR PAVEMENTS WITH GRANULAR ROAD BASES WHOSE AGGREGATES HAVE A NATURAL CEMENTING ACTION (0.50 PROBABILITY)

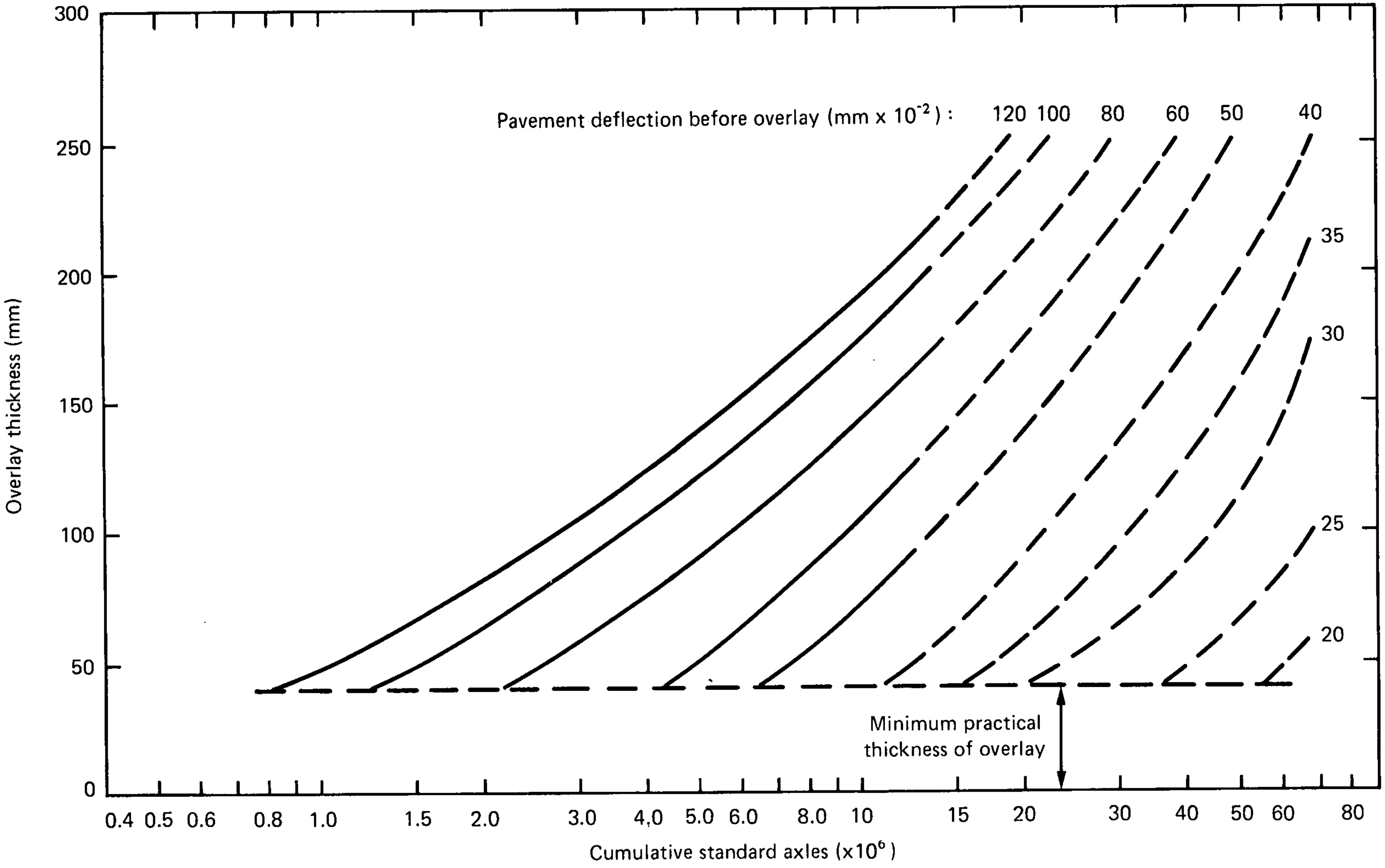


Fig. 15 OVERLAY DESIGN CHART FOR PAVEMENTS WITH GRANULAR ROAD BASES WHOSE AGGREGATES HAVE A NATURAL CEMENTING ACTION (0.90 PROBABILITY)

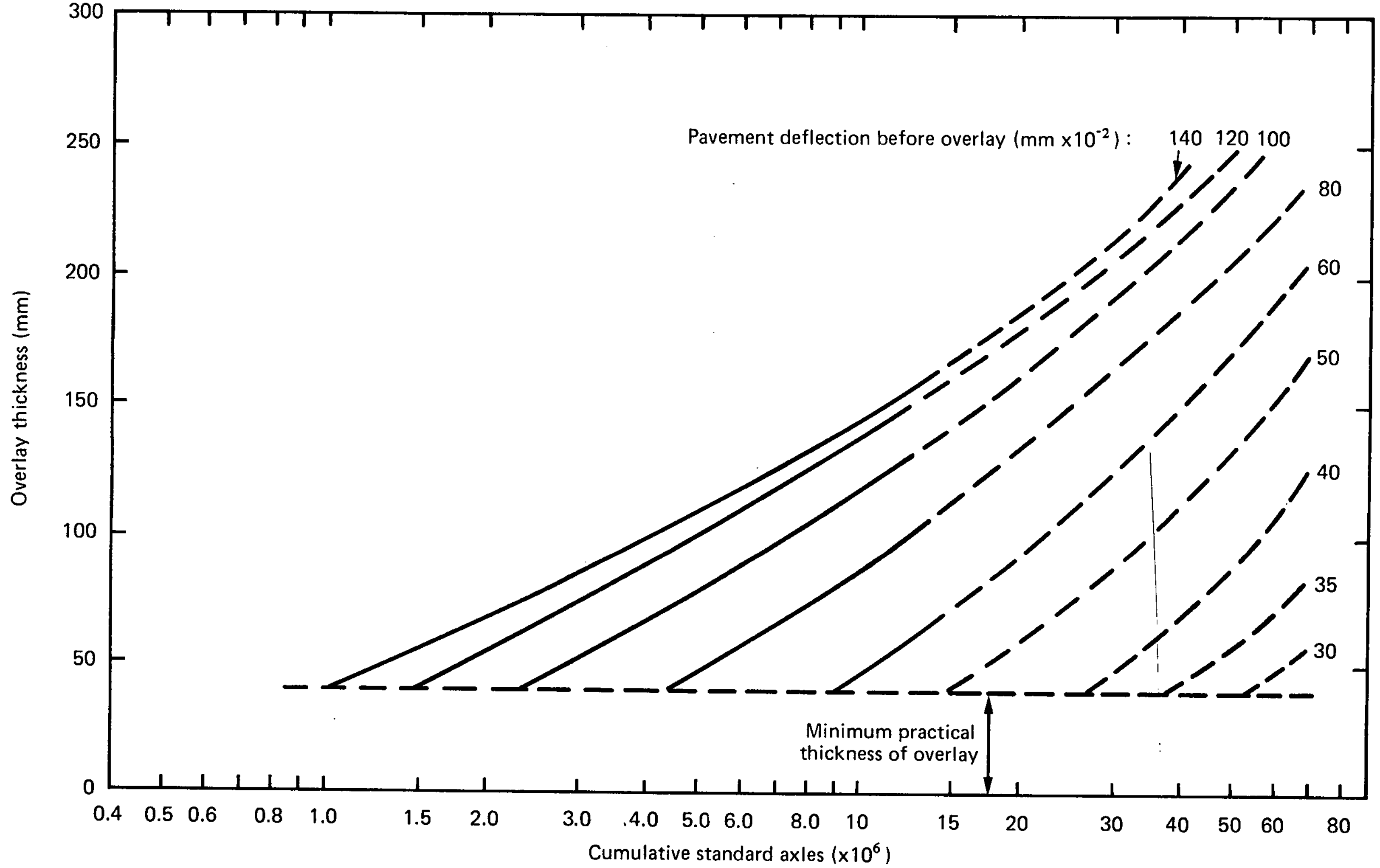


Fig. 16 OVERLAY DESIGN CHART FOR PAVEMENTS WITH NON-CEMENTING GRANULAR ROAD BASES (0.50 PROBABILITY)

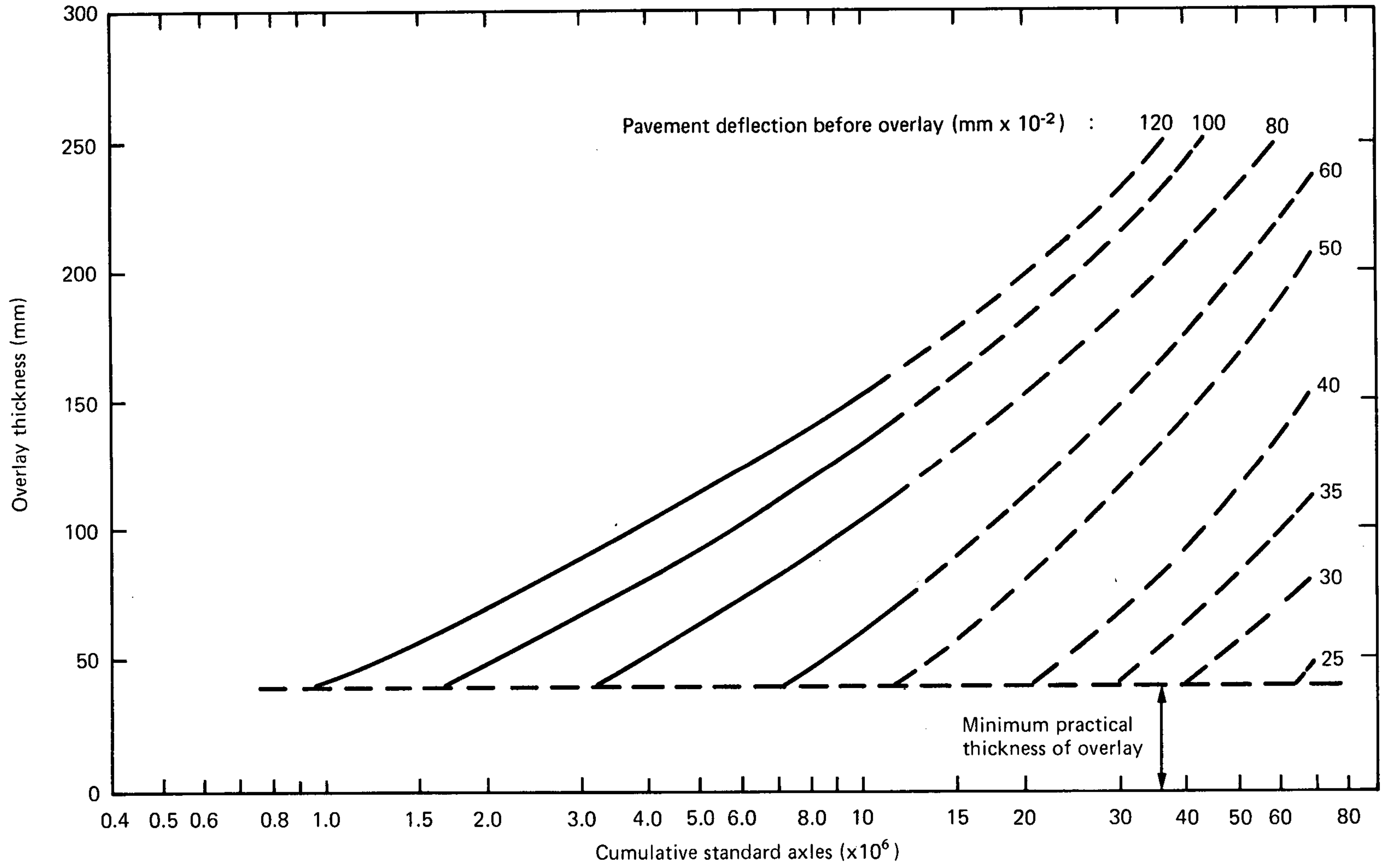


Fig. 17 OVERLAY DESIGN CHART FOR PAVEMENTS WITH NON-CEMENTING GRANULAR ROAD BASES (0.90 PROBABILITY)

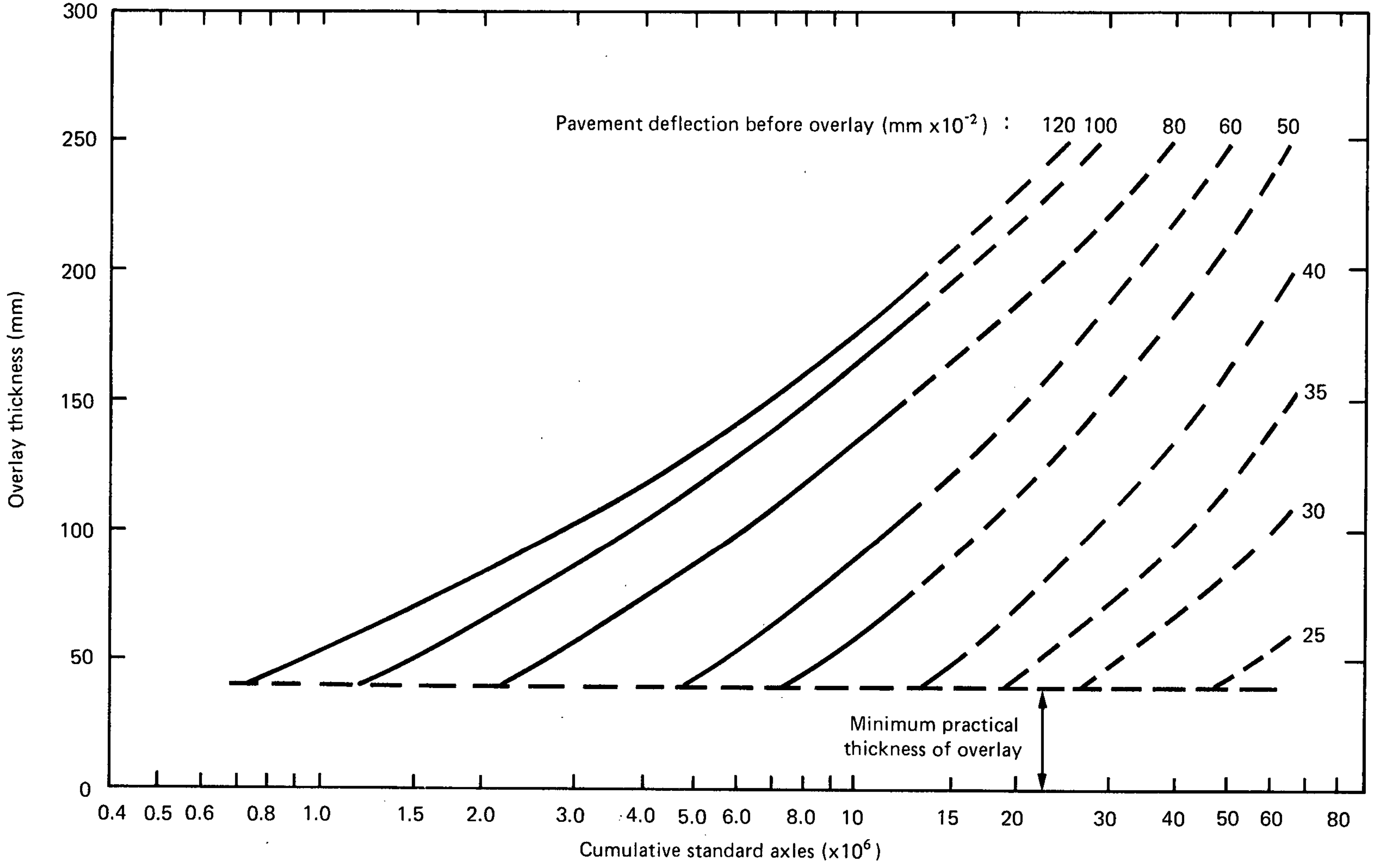


Fig. 18 OVERLAY DESIGN CHARTS FOR PAVEMENTS WITH BITUMINOUS ROAD BASES (0.50 PROBABILITY)

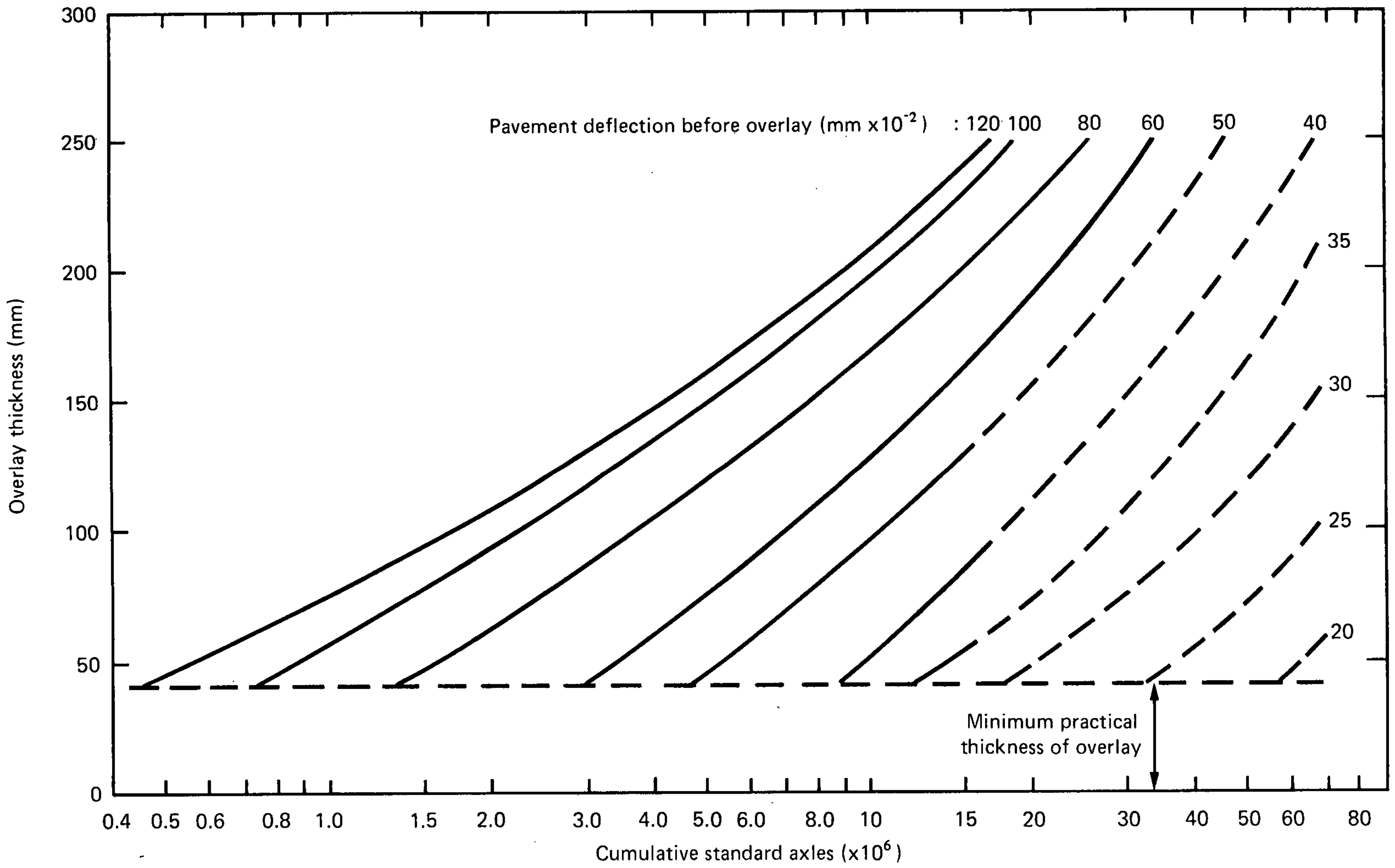


Fig. 19 OVERLAY DESIGN CHARTS FOR PAVEMENTS WITH BITUMINOUS ROAD BASES (0.90 PROBABILITY)

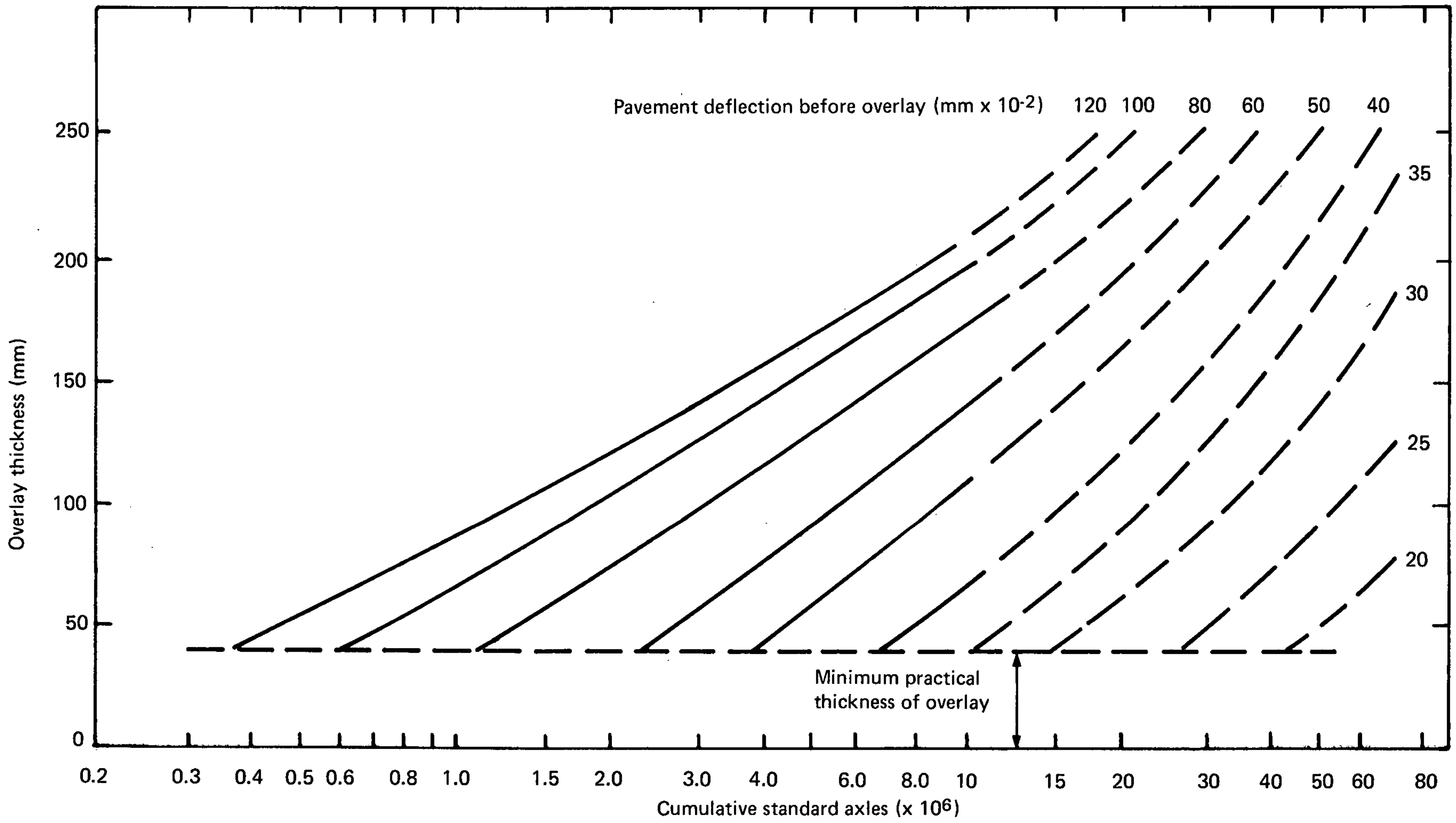


Fig. 20 OVERLAY DESIGN CHART FOR PAVEMENTS WITH CEMENT–BOUND ROAD BASES
(0.50 PROBABILITY)

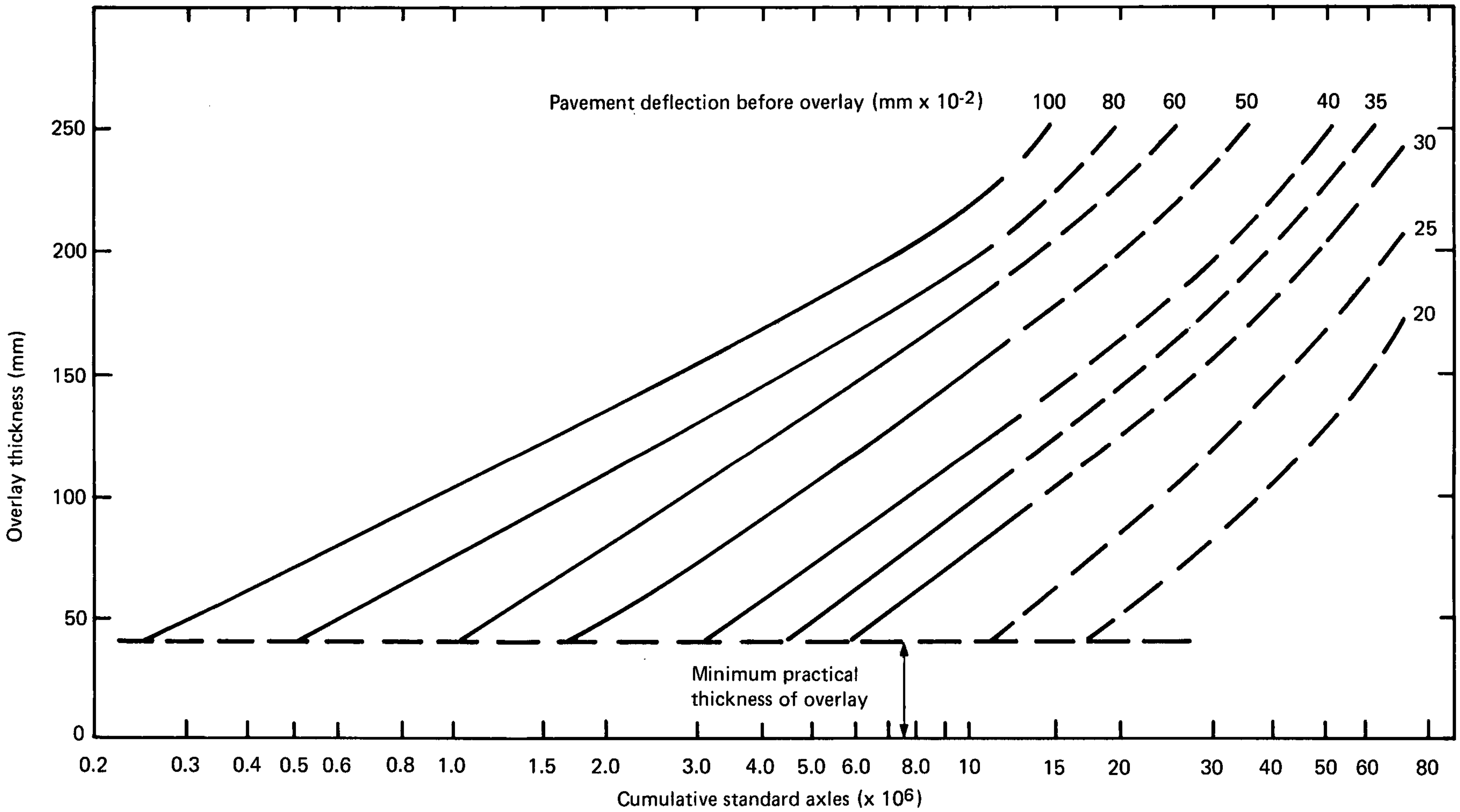


Fig. 21 OVERLAY DESIGN CHART FOR PAVEMENTS WITH CEMENT–BOUND ROAD BASES
(0.90 PROBABILITY)

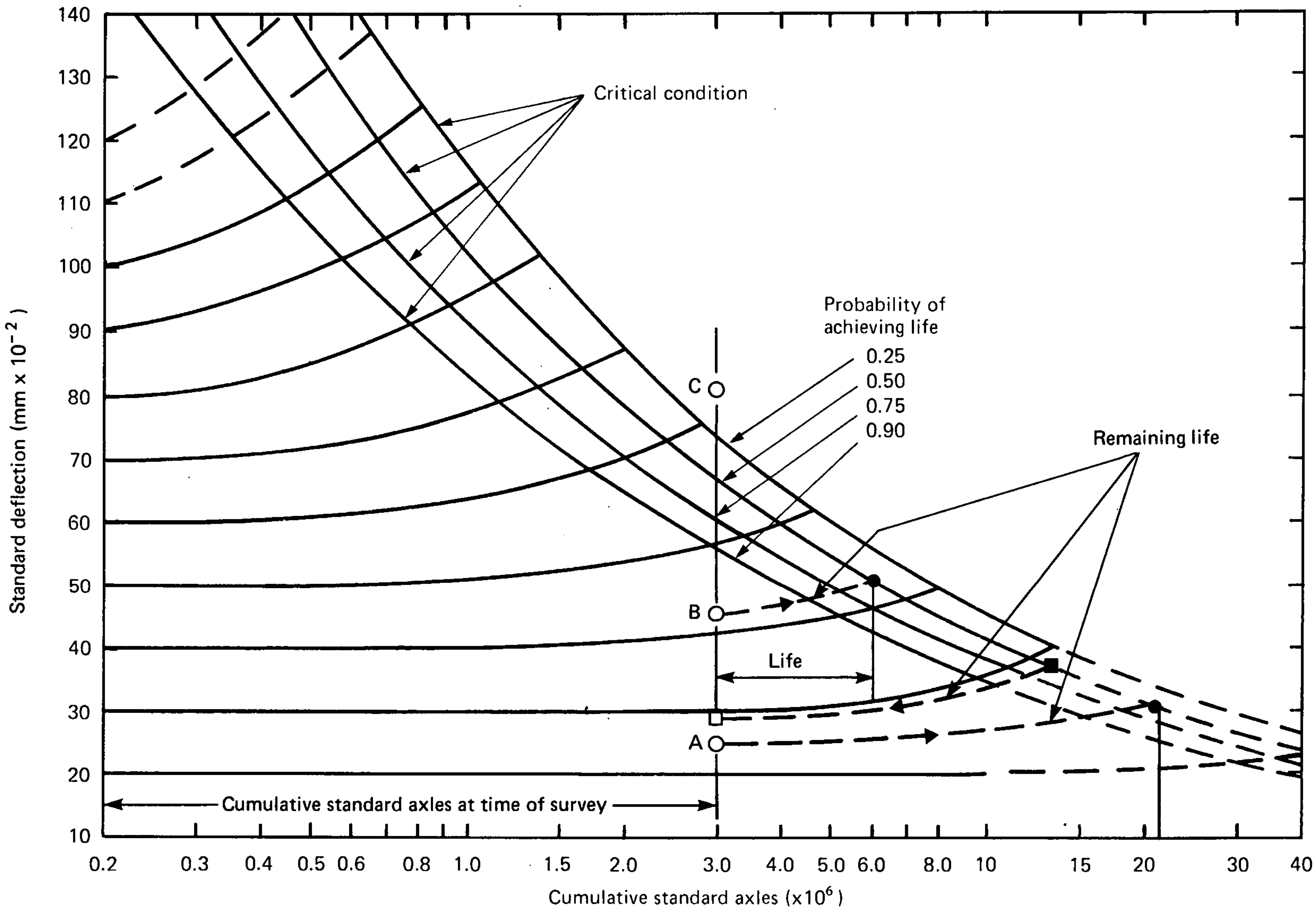


Fig. 22 RELATION BETWEEN STANDARD DEFLECTION AND LIFE FOR PAVEMENTS WITH GRANULAR ROAD BASES WHOSE AGGREGATES EXHIBIT A NATURAL CEMENTING ACTION – DESIGN EXAMPLE

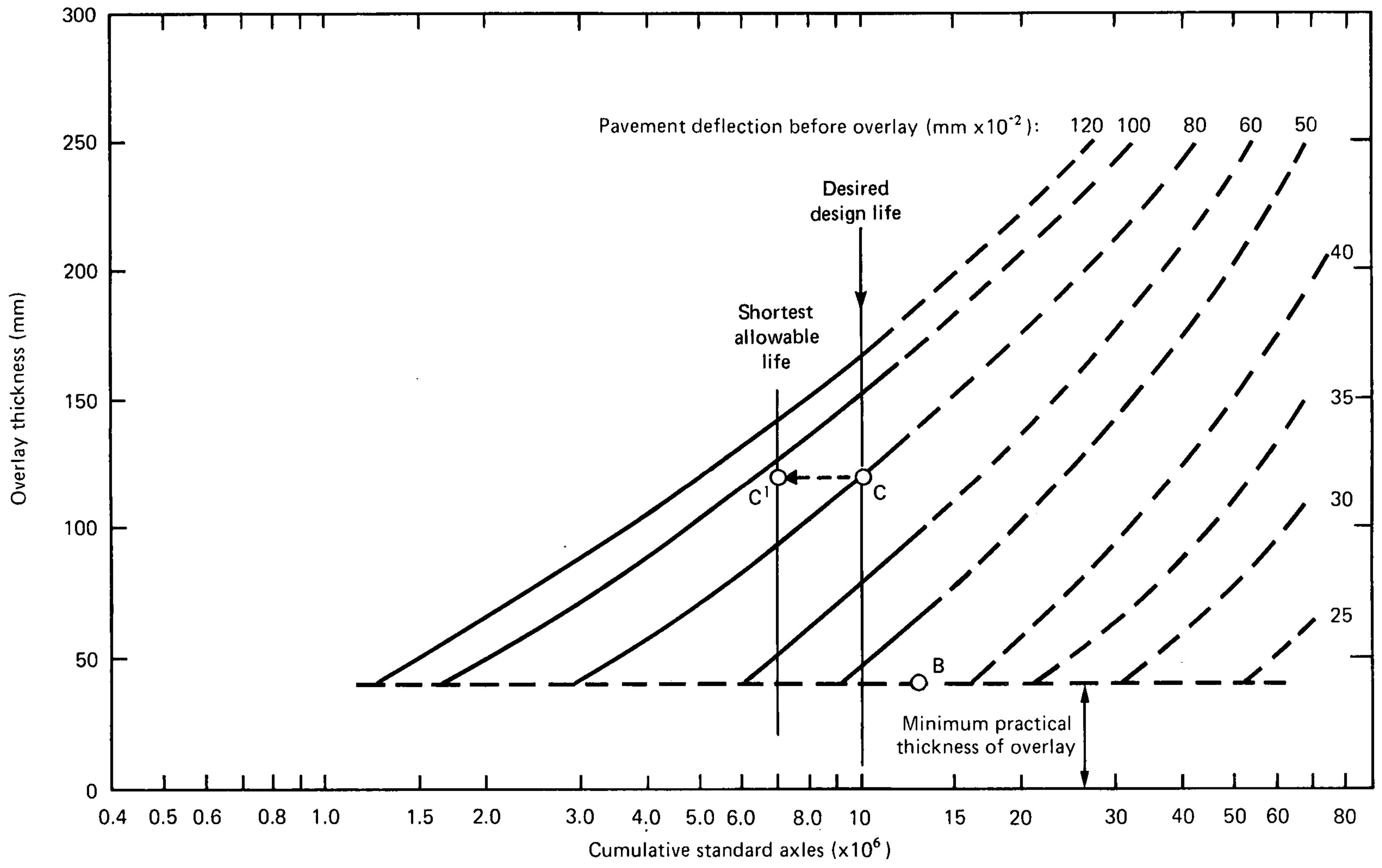
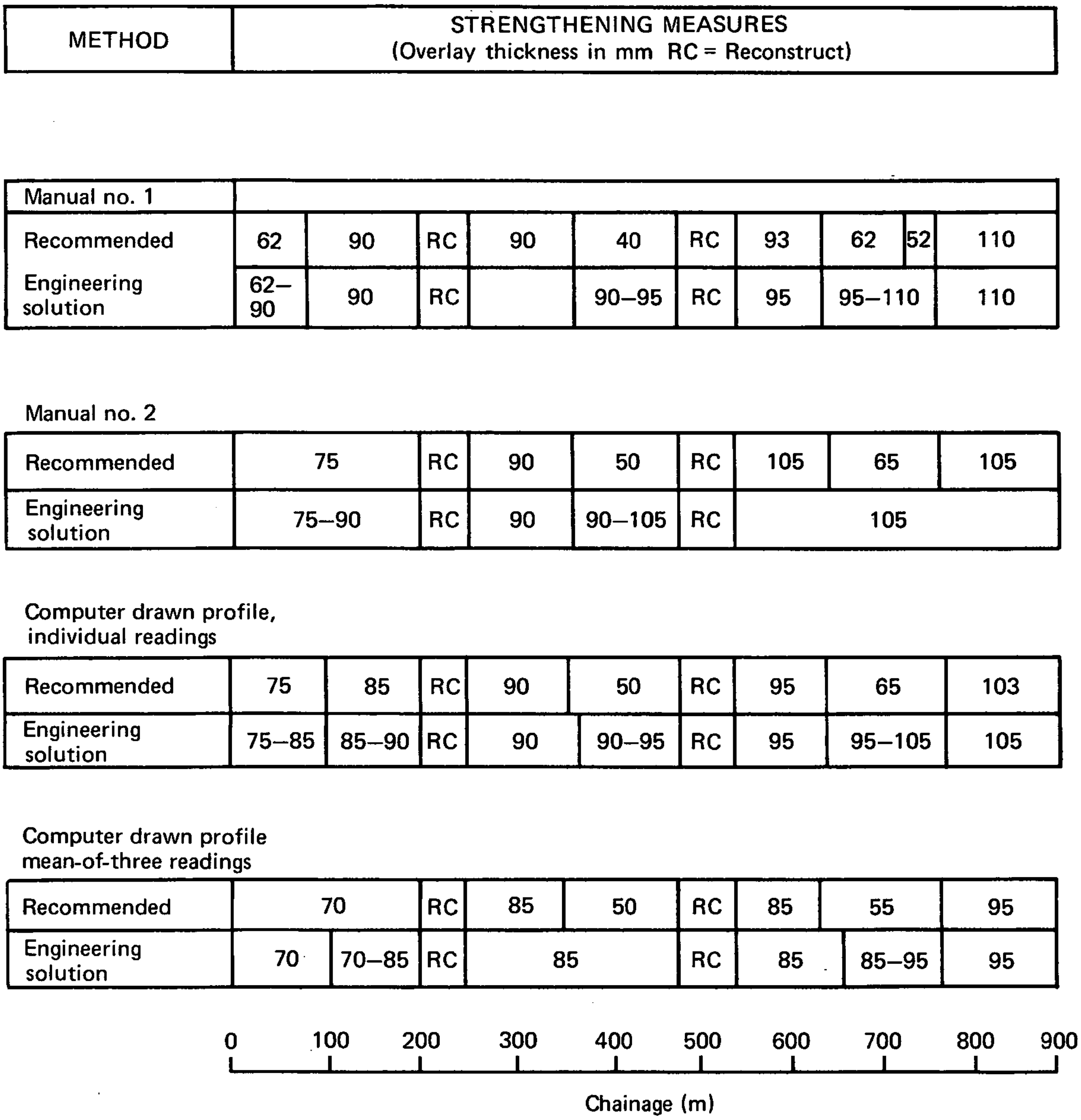


Fig. 23 OVERLAY DESIGN CHART FOR PAVEMENTS WITH GRANULAR ROAD BASES WHOSE AGGREGATES HAVE A NATURAL CEMENTING ACTION (0.50 PROBABILITY) – DESIGN EXAMPLE



METHOD	STRENGTHENING MEASURES (Overlay thickness in mm RC = Reconstruct)

Manual no. 1										
Recommended	62	90	RC	90	40	RC	93	62	52	110
Engineering solution	62–90	90	RC		90–95	RC	95	95–110		110

Manual no. 2

Recommended	75	RC	90	50	RC	105	65	105
Engineering solution	75–90	RC	90	90–105	RC	105		

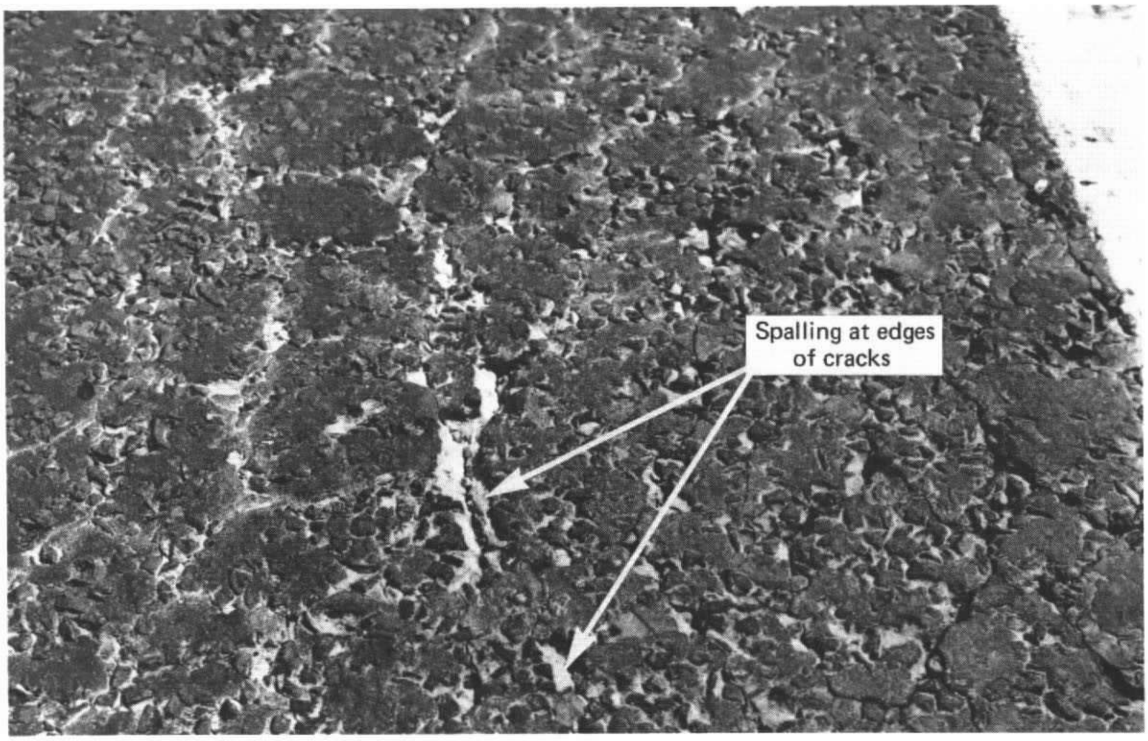
Computer drawn profile, individual readings

Recommended	75	85	RC	90	50	RC	95	65	103
Engineering solution	75–85	85–90	RC	90	90–95	RC	95	95–105	105

Computer drawn profile mean-of-three readings

Recommended	70		RC	85	50	RC	85	55	95
Engineering solution	70	70–85	RC	85		RC	85	85–95	95

Fig. 24 COMPARISON OF THE RECOMMENDATIONS DETERMINED BY THE THREE METHODS OF ANALYSIS



Neg. no. R1167/75/2

Approximate scale ← 200mm →

Plate 1 TYPICAL EXAMPLE OF AREA CRACKING

14. APPENDIX 1

NOMOGRAMS FOR THE ESTIMATION OF CUMULATIVE TRAFFIC

In order to estimate the remaining life of a pavement, information is required about the traffic carried since its construction or since the most recent resurfacing or strengthening. For the design of an overlay, estimation of the future traffic during its future desired life is also required. This Appendix describes the method of use of two nomograms for estimating the future and past traffic.

The method of use is indicated diagrammatically on each nomogram. The open circles on the scales in the diagrams represent data input values and the solid circles represent intermediate or final output values. The various scales on the diagrams and in the nomograms are numbered conformally.

14.1 The nomogram for future traffic

This is given in Figure 1 of the main Report. Proceed as follows:

(i) Identify the point on Scale 1 corresponding to the appropriate growth rate and design life.

(ii) Join this point with a straight line to the point in Scale 2 corresponding to the total (one direction) daily flow of commercial vehicles.

(iii) Determine the intersection of this line with Scale 3.

(iv) Join this intersection point to the point in Scale 4 corresponding to the desired design life.

(v) Read off the cumulative total of commercial vehicles in the left-hand lane (one direction only) at the intersection of this line with Scale 5.

14.2 The nomogram for past traffic

This is given in Figure 2 of the main Report. Proceed as follows:

(i) Join with a straight line the point on Scale 1 corresponding to the estimated growth rate and period of time concerned to the point on Scale 2 corresponding to the current total daily (one direction) flow of commercial vehicles.

(ii) Identify the intersection of this line with Scale 3.

(iii) Join this point with a straight line to the point on Scale 4 corresponding to the time period.

(iv) Read off the cumulative total of commercial vehicles in the left-hand lane (one direction only) at the intersection of this line with Scale 5.

If the total period is being sub-divided into, say two periods because of changes in either or both the growth rate or the conversion factors between commercial vehicles and standard axles, it is necessary to be able to estimate the flow at the start of the second period; the nomogram can then be re-entered to determine the total flow over the first period by taking this value as the new current daily flow. The subsidiary nomogram, Scales 6–8, is provided for this purpose. To use it:–

(i) Identify in Scale 6 the point corresponding to the growth rate and time, and join it to the point in Scale 7 corresponding to the current daily flow.

(ii) The initial flow is given by the intersection of this line (extended) with Scale 8.

The main nomogram can then be re-entered for the earlier period with the "current flow" on Scale 2 set to this value. The process can be repeated to cover as many intervals as necessary, summing the contributions from each interval, after making any necessary adjustments for changes in the nature of the traffic. This procedure has in any case to be followed for lives of greater than 25 years.

15. APPENDIX 2

ANALYSIS OF DEFLECTION RESULTS FOR THE PRACTICAL DESIGN OF STRENGTHENING MEASURES

15.1 Introduction

Deflection surveys on roads in need of structural strengthening are characterised by high deflection levels and by large variations in deflection; it is not therefore practicable to match the variation in deflection by strengthening measures which are exactly appropriate at all points along the road.

The closely spaced output of deflection measurements from the Deflectograph (and also recommended for the Deflection Beam) can be made to overcome this problem by using a statistical procedure to give practical engineering recommendations which can eliminate the risk of localised early failure in the strengthened pavements and of general overdesign of overlay thickness.

This Appendix describes three methods of analysis, two suitable for the analogue forms of output from deflection surveys and the third using profiles of deflection drawn by computer.

15.2 Site details

In the following examples deflection measurements recorded during an actual Deflectograph survey have been used. The only changes that have been made to the original data are:

1. the deflection output is in vertical ordinates rather than the complete deflection bowl recommended in LR 835

2. a length of 880m is considered out of the total length of 1,200m actually surveyed

3. a spacing of precisely 4.0m between individual readings is assumed. (The actual value was 3.84m).

The reduction in length and change in form of output have been made because of restrictions on the space available for presentation in this Report. The change in spacing of the readings has been adopted to simplify the numerical computations in the example.

Events recorded during the survey have been omitted for the sake of clarity.

The pavement construction is the same as that specified in Section 8 of the main Report. The appropriate temperature-correction chart is, therefore, Figure 6 for a pavement with 75–195mm of bituminous material of which at least 75mm is dense bituminous material.

The pavement temperatures encountered during the survey varied between 30 and 28°C as shown on the measured deflection profile in Appendix 2, Figure 1.

15.3 Design criteria

The following design criteria have been adopted:

Desired design life = 10×10^6 standard axles

Probability of achieving at least the design life = 0.50

The proportion (p) of the strengthened pavement that can reach a critical condition during the design life = 15%

The earliest point in the design life at which this proportion p will approach a critical condition = 7×10^6 standard axles

The following design charts in the main Report are used:

1. Deflection/performance chart: Figure 10 for pavements with a granular roadbase whose aggregate exhibits a natural cementing action.
2. Overlay design chart: Figure 14 for pavements with a granular roadbase whose aggregate exhibits a natural cementing action and for which there is a 0.50 probability of achieving at least the future life.

In the examples, almost all the measured deflections exceed the maximum deflection requiring zero overlay (DOO) (see Figure 22 and Section 8 of the main Report). Strengthening is therefore considered for the total length analysed. The procedures outlined are however equally applicable for determining remaining lives in excess of the design life in cases where the DOO level is not exceeded.

15.4 Decision to use deflection results from individual wheel-paths or both wheel-paths combined

The deflection profiles obtained for the nearside and offside wheel-paths of the length of road used in the example are similar in general shape and magnitude. Strengthening measures appropriate to the combined wheel-paths or traffic lane have therefore been computed. Where there is a marked difference between the two profiles separate analysis of the wheel-paths may be more appropriate. Marked differences can be caused by such factors as nearside edge failure or recent trench reinstatement in either wheel-path. The most economic solution in the case of nearside edge failure may be reconstruction of that wheel-path followed by a thin overlay over the total width of the traffic lane. If a survey is taken soon after trench reinstatement, it is advisable to re-survey parts of the length after compaction under traffic has taken place.

Where the alignment of a road has, in the past, been improved, and in particular where a road has been widened, differences in the individual wheel-path deflection profiles may indicate that different road-base types exist. In this case separate analysis of the individual wheel paths will be necessary using the appropriate design charts in each case. The resulting maximum strengthening requirements are then appropriate. It is important to note that, in this case, if a cement-bound base is found in one wheel-path only, the lower deflection profile may produce the maximum strengthening requirements.

15.5 Manual analysis of deflection data, Method 1 – the selection of treatments on the basis of lengths of nominally constant levels of measured deflection

Lengths of road containing measured deflections uncorrected for the effects of temperature of a nominally constant magnitude are identified, and characterised by a single deflection level; this value only is then analysed for design. If long lengths of reasonably constant deflection can be identified this method provides a relatively rapid analysis procedure. However, as the lengths selected become larger, the discrepancy between the overlay solution obtained and the optimal solution increases.

The method is described step-by-step below. Appendix 2, Figure 1, details the method diagrammatically.

STEP 1. It is initially necessary to select lengths of nominally uniform deflection level. In selecting these lengths the following rules must be applied.

a) Change in temperature during the course of a deflection survey will act as a limit.

b) Changes in roadbase type requiring the application of different performance criteria will act as limits.

c) The lengths selected must be common to both wheel-paths.

Other physical attributes of the road, eg a junction or a node in the chart inspection procedure may also be chosen to act as limits to the selected lengths.

Having plotted these arbitrary length limits, lengths of nominally constant deflection level are then identified. In this example seven lengths have been selected with an average length of 125m. (It should be noted that with short lengths of this magnitude the method detailed in Appendix 2, Section 15.6 would be more appropriate.) The lengths selected have been chosen to permit a comparison of the recommended strengthening measures computed by the three methods presented.

STEP 2. This would normally be the stage at which the analysis criteria would be selected. In this case this has been covered in Appendix 2, Section 15.3.

STEP 3 The number of the deflection readings in each treatment length that may reach a critical condition during the design life of the strengthened pavement is calculated and taken into account in defining a single deflection value for the length.

The number of readings in each length that can approach a critical condition during the design life is given by (p x total number of readings in length) ie for Length 1 with p defined as equal to 15% we have 0.15 x 20 = 3.

The deflection level above which 15% of the readings lie is then calculated. For Length 1, three readings lie above 49 x 10^{-2}mm on the offside wheel-path (OSWP). The value of 49 x 10^{-2}mm is referred to as the 85th percentile value (100–15) per cent, and is taken to characterise the OSWP of Length 1. For the nearside wheel-path (NSWP) in Length 1 the 85th percentile value is 58 x 10^{-2}mm. A solid horizontal line is drawn on the profile at the 85th percentile level. For the wheel-path with the smaller 85th percentile value, both its own and the larger percentile value should be plotted. If there is a significant difference between these values the points raised in Section 4 of this Appendix should be considered.

The 85th percentile values for the OSWP and NSWP are shown for each length on Appendix 2, Figure 1, both as a solid horizontal line and as a numerical value.

STEP 4. The 85th percentile values must be corrected to standard deflections to make them compatible with the use of the design charts. This correction is made using Figures 3 and 6 in the main Report. For Length 1 the 85th percentile values of standard deflection for the OSWP and NSWP are 48 and 56 x 10^{-2}mm respectively. These values, together with the 85th percentile values of standard deflection for the other lengths, are shown in Appendix 2, Figure 1.

Note: in general use of the method it is necessary only to correct the larger percentile value for each length.

STEP 5. The appropriate overlay design chart, in this case Figure 14 in the main Report, is used to determine the overlay thickness required on the basis of the greater of the two standard 85th percentile values of each length. For Length 1, the NSWP deflection of 56 x 10^{-2}mm is the greater value and Figure 14 indicates that an overlay thickness of 62mm is required to achieve a future life of 10 x 10^6 standard axles.

STEP 6. The same overlay design chart is also used to establish the maximum deflection on the present pavement which, when strengthened by the overlay of 62mm thickness, would achieve a life of 7 x 10^6 standard axles, ie the life equal to the earliest point in the design life at which a part of the proportion p of the road can reach a critical condition. This procedure is detailed in the last paragraph of Section 8.2 in the main Report. For Length 1, an existing standard deflection level of 66 x 10^{-2}mm when strengthened with a 62mm overlay will have a future life of 7 x 10^6 standard axles. The deflection levels calculated by this procedure are standard deflections. They must now be corrected to equivalent Deflectograph deflections at the appropriate pavement temperature, using Figures 3 and 6 and reversing the normal adjustment procedure. These equivalent Deflectograph deflection levels are then plotted on the deflection profile as horizontal dashed lines. For Length 1 the equivalent deflection value is 70 x 10^{-2}mm: this is plotted on both wheel-path profiles.

STEP 7. Each length must now be checked to ensure that the measured deflections do not lie above the deflection limits represented by the dashed line. Where this occurs, ie Lengths 2, 4 and 6, the highest mean-of-three individual deflections around the deflection exceeding the level of the dashed line must be computed. The maximum of each pair of NSWP and OSWP values should be used in deriving this highest mean. This is most conveniently achieved by placing a cross (X) above the lower value of the two pairs on either side of the pair containing the value exceeding the dashed line. The maximum values are then clearly identified visually and the calculation can be carried out quickly. If it exceeds the level of the dashed line, the length over which the dashed line is exceeded should be allocated for reconstruction, or the overlay thickness increased until the level of the dashed line appropriate to the increased overlay thickness is equal to, or exceeds, the largest mean-of-three. If the mean-of-three value does not exceed the level of the dashed line, as is the case for Lengths 2 and 6, no further action is necessary and the following condition must be investigated.

The distribution of the lengths of road that will become critical in the final 3 x 10^6 standard axles of the design life must be reasonably uniformly distributed along the total length; this refers to the 15 per cent of the length of road whose deflections lie between the solid and dashed lines. Unless uniformity is achieved the pavement will have lengths within it where the deterioration is concentrated and these lengths will require substantial maintenance or restrengthening before the design life is reached. Compliance with this requirement can be checked by taking 100m lengths of the road with the start point advanced successively in 4m steps, and ensuring that not more than the specified proportion of the length that is allowed to reach a critical condition during the design life will do so. A spacing of the individual measurements of 4m has been assumed, and every 100m length of road will contain 25 readings in each wheel-path. Therefore in any 100m length of road not more than 4 (25 x 0.15) individual deflection values should lie in the region between the solid and the dashed lines.

In the example, Appendix 2, Figure 1, one value lies in this region for the first two 100m lengths in the OSWP considered, ie chainages 0–100m and 4–104m. The 100m length from 8–108m will contain 2 readings in this range, one from Length 1 and one from Length 2; this is still satisfactory and the analysis continues. More than 4 values in the region between the solid and dashed lines are encountered for the first time in the 100m length between chainage 132–232m; it occurs in the NSWP. The worst 100m length in this area is found in the NSWP for chainages 200–300m. For this length a calculation is then made of the total number of pairs of NSWP and OSWP values that contain at least one value which lies in the regions between the solid and dashed lines. This is most conveniently achieved by again placing a cross (X) above the lower value of any pair of readings that lie in this region, and counting the number of ordinates present in the region without an (X) beside them. The values recorded for the NSWP and OSWP at chainage 200 on Appendix 2, Figure 1, both lie in the specified region; the value in the NSWP is the lower and this is not included when counting the total number of readings lying between the solid and dashed lines.

For Chainage 200–300m there are 10 ordinate values left without a cross beside them. This would result in 40 per cent of the 100m length reaching a critical condition before the end of the design life; more than 70 per cent of the length between Chainages 200 and 250m would do so.

To avoid the continuous lengths of premature deterioration that would result if this condition were ignored, treatment can take one of two forms; the thickness of overlay can be increased, or part or all of the length can be allocated for reconstruction.

If it is decided to increase the overlay thickness it will be necessary to define the deflection level which is exceeded by not more than 4 values in any 100m length. This deflection level, for Chainages 200–300m, is represented by the chain-dashed line marked A in Appendix 2, Figure 1. The overlay thickness necessary for the desired design life is then calculated for this deflection level as if it were an 85th percentile value.

For Length 1 in Appendix 2, Figure 1, using Figure 14 from the main Report, an increased overlay thickness of 105mm is recommended.

If the area is allocated for reconstruction, the deflection values within the area to be reconstructed must be omitted from the analysis, and Steps 3 to 7 inclusive repeated. For example, for Length 2 the following data apply:

No of readings in length after removing those allocated for reconstruction	=	55
15% of this value	=	8

85th percentile value of deflection = 63×10^{-2}mm (NSWP)

Equivalent standard deflection, 85th percentile value = 61×10^{-2}mm

Overlay thickness required = 80mm

Level of dashed line = 74×10^{-2}mm

Do any means of three values exceed the level of the dashed line? = No

Do more than 4 values from both wheel-paths lie above 63×10^{-2}mm in any 100m length? = Yes

Between Chainages 254 and 354, five values in the NSWP and two values in the OSWP lie above 63×10^{-2}mm. Both the OSWP values correspond with values in the NSWP which also lie above the deflection level of 63×10^{-2}mm and for each pair the lower value has been omitted from the analysis by placing a cross (X) above it.

The level not exceeded by more than 4 values in any 100m length (Chain-dotted line B on Appendix 2, Figure 1) = 67×10^{-2}mm

This is exceeded by one value in the OSWP and two values in the NSWP. Two further values in the NSWP lie exactly on the line.

The equivalent standard deflection level = 66×10^{-2}mm

Overlay thickness required = 90mm

Level of dashed line = 79×10^{-2}mm

Do any mean-of-three values exceed the level of the dashed line? = No

A new overlay thickness of 90mm is therefore selected to achieve the design life of 10×10^6 standard axles and also to ensure that not more than 15 per cent of any length approaches a critical condition between 7×10^6 and 10×10^6 standard axles.

Similar procedures were applied to Lengths 4, 5 and 7. In Length 4 one mean-of-three exceeded the original dashed line. Two solutions were computed, one with an increased overlay thickness and one which included reconstruction of part of the length. In Lengths 5 and 7 no mean-of-three values exceeded the dashed line and the overlay thickness only was increased, there being no need to reconstruct.

The detailed recommendations obtained for strengthening either by means of overlay only, or with the option of reconstructing the most badly damaged lengths of road, are given in Appendix 2,

Figure 1. Corresponding engineering solutions are also shown, in which the need to limit the frequency with which overlay thickness can be changed along the road have been taken into account.

15.5.1 Discussion of manual analysis, Method 1. The method described above is undoubtedly lengthy but, although appearing complex, is reasonable, straightforward and can produce a rapid analysis procedure with practice. Its major disadvantage is that a choice must be made early in the procedure of the lengths over which a given strengthening requirement is to be determined, ie the subjective element in the procedure. Changes in the lengths adopted after this initial subjective choice require a complete re-analysis.

Further, the lengths are selected on the basis of measured deflection levels rather than the necessary overlay thickness requirements. This procedure will rarely give the most economic combination of overlay thicknesses because of the non-linear relation which exists between overlay thickness and deflection.

The procedure is best suited for the analysis of roads which are generally in good condition, which have a considerable remaining life, and for which overlays, where required, are thin. In these circumstances the deflection profiles obtained are usually more uniform, and inaccuracies introduced by a poor initial selection of lengths are minimised. If the method is used for analysis of deflection profiles of roads which require early and substantial strengthening (this is not recommended), it is important that the procedures outlined to ensure against early failure and against the development of lengths of concentrated critical areas during the design life are not omitted. If the 85th percentile values, determined only by Steps 1 to 4 are used to determine overlay requirements the earliest point in time at which critical conditions would occur are shown in Table 6.

TABLE 6

Comparison of the overlay requirements from application of Steps 1 to 4 of Method 1 with those from the complete method

Length (see Appendix 2 Figure 1)	Overlay thickness using Steps 1 to 4 of Method 1 mm	Recommended overlay thickness using complete Method 1 mm	Earliest life in standard axles at which critical conditions would occur using Steps 1 to 4 of Method 1 (mean-of-three deflection values)
1	62	62	8.1
2	92	105	6.0
3	40	40	>10
4	105	127	5.7
5	40	62	5.6
6	52	52	8.5
7	95	110	6.0

These results indicate that areas in three of the lengths will approach a critical condition earlier than specified. The agreement between the two procedures shown in this table is better than would occur if longer lengths, more appropriate to the use of the method, had been selected. For example, if the total length had been analysed as a single treatment length, a deflection level of 67 x 10^{-2}mm would have been calculated on the 85th percentile value. An overlay thickness of 90mm would have been recommended and lengths of the road would have approached a critical condition after only 4.9 x 10^6 standard axles. The areas which approach a critical condition during the design life would be concentrated into three principal areas.

When long lengths are used for analysis the method presented will overestimate the strengthening required. The overlay recommended for the total length on a single analysis would be equal to the greatest overlay thickness specified in the worked example, ie the 130mm overlay recommended for Length 4 would be allocated to the total length. If the two reconstruction areas had been identified for separate treatment, an overlay thickness of 110mm would have been selected.

Because of the convergence of the deflection/temperature relations (see Section 4.3.1 of the main Report), the accuracy of this method is reduced significantly when applied to all but the stiffest pavements tested at temperatures significantly below 20°C. This is discussed further in Appendix 2, Section 15.6.1.

As a result of considering the wheel-paths separately, it is possible to fail to identify areas in which a non-uniform development of critical conditions will occur in the traffic lane. For example, three values in each wheel-path lying between the solid and dashed lines will indicate acceptably uniform deterioration. However, unless at least two of the values in one wheel-path are paired with values in the other wheel-path, more than 4 values would result in the combined wheel-path. Although not a serious omission, it is a limitation to all methods in which the results for the wheel-paths are presented separately.

Finally, as a consequence of processing profiles of individual deflections the influence of isolated high values is usually overestimated. This leads to the computation of overlay recommendations greater than are actually required.

The strengthening recommendations computed by this method are compared with those obtained by the two following methods in Figure 24 of the main Report.

15.6 Manual analysis of deflection data, Method 2 – selection of treatments on the basis of constant overlay thickness

This method also uses the original output of measured deflections uncorrected for temperature. The recorded deflection scale is converted into a standard deflection scale on the analogue chart output and standard deflection levels corresponding to various overlay thicknesses can then be plotted directly on to the recorded deflection profile. The analysis of the profile is then similar to the procedure adopted for computer-drawn profiles described in Appendix 2, Section 15.7, except that, where it is necessary to combine the wheel-path results and to take means of values, this must be carried out manually as in Method 1 just described.

The method is presented below in detail. Appendix 2, Figure 2 illustrates the analytical procedure superimposed on the original deflection survey.

STEP 1. Figures 3 and 6 of the main Report are used to convert a range of standard deflection levels to equivalent Deflectograph values appropriate to the pavement temperatures measured during the survey: the values obtained are listed in Table 7.

TABLE 7

Conversion of standard deflections to Deflectograph deflections for use with manual analysis Method 2

Standard deflection	Equivalent deflection (mm x 10^{-2}) at pavement temperature of			Equivalent deflectograph deflection (mm x 10^{-2}) at pavement temperature of		
	30°C	29°C	28°C	30°C	29°C	28°C
0	0	0	0	0	0	0
10	10	10	10	6	6	6
20	22	21	21	17	16	16
30	35	34	34	28	27	27
40	49	48	47	40	39	39
50	62	61	60	51	51	50
60	76	75	73	64	63	61
70	90	88	86	76	74	72
80	104	102	99	88	86	83
90	118	115	111	100	97	95

The standard deflection scale can then be drawn at each temperature change, and lines of equal standard deflection level drawn between the scales. For clarity, on Appendix 2, Figure 2, the scales are shown only at the ends of the profile and lines of equal standard deflection level are omitted: the lines of equal standard deflection will be horizontal only if there is no temperature change. Over lengths where temperature changes occur the lines will slope down towards the lower temperature.

STEP 2. At this point the design criteria would normally be decided. In these examples however, this is covered in Appendix 2, Section 15.3.

STEP 3. To provide an initial estimate of strengthening requirements, overlay thicknesses are selected in 25mm steps. At this stage it is convenient to adopt practical overlay thicknesses; some but not all, will be modified by the additional analysis.

TABLE 8

Maximum deflections on the present pavement associated with various overlay thicknesses to achieve a desired life. Manual analysis Method 2

Overlay thickness mm	Maximum present level of deflection for life of 10 x 10^6 standard axles mm x 10^{-2}	Maximum present level of deflection for life of 7 x 10^6 standard axles mm x 10^{-2}
50	51	60
75	59	72
100	71	84
125	84	100

It is possible to determine the maximum levels of deflection on the existing pavement which can achieve the desired overlay life of 10 x 10^6 standard axles when associated with these thicknesses. Corresponding values of deflection to give lives of 7 x 10^6 standard axles, the earliest point at which the strengthened pavement can reach a critical condition can also be calculated. The values obtained are tabulated in Table 8.

These standard deflection levels are then plotted on the profile as shown in Appendix 2, Figure 2. The solid line represents a life of 10 x 10^6 standard axles with the overlay thickness indicated by the values written within the circles. The dashed lines represent a life of 7 x 10^6 standard axles with the overlay thickness indicated by the numbers written within the boxes. The two lowest lines represent the maximum deflection levels requiring zero overlay (DOO) consistent with a future life of 10 x 10^6 standard axles (solid line) and 7 x 10^6 standard axles (dashed line) calculated from Figure 10 of the main Report. The procedure for determining the levels is detailed in Section 8.1 of the main Report.

STEP 4. An initial estimate of strengthening requirements for each wheel-path is made using the overlay thickness lines. In making the estimate of initial requirements shown in Appendix 2, Figure 2, isolated single values that exceed the dashed line of the overlay thickness selected are ignored.

STEP 5. The initial requirements for the individual wheel-paths can now be combined in such a way that at each point, the greater overlay thickness requirement is chosen. In Appendix 2, Figure 2, this is labelled as "combined initial requirements".

STEP 6. It is now necessary to ensure that no areas exist where critical conditions will occur prematurely, ie before 7 x 10^6 standard axles and that the areas that will approach a critical condition during the final 3 x 10^6 standard axles of the design life are uniformly distributed along the length of the road. The procedures adopted are the same as those used for the manual analysis Method 1. Reference to Step 7 of Method 1 should be made for the detailed procedure. In summary, where a deflection value exceeds the level of the appropriate dashed line for the chosen overlay thickness, the maximum value of the mean-of-three individual deflections around the value exceeding the limit must be computed. A thicker overlay is required that will ensure a life of at least 7 x 10^6 standard axles when applied to a pavement whose deflection is equal to or greater than the measured mean-of-three value. Alternatively, the length represented by the three individual deflections whose mean exceeds the dashed line for the original overlay thickness can be allocated for reconstruction.

Where the mean-of-three values do not exceed the level of the dashed line appropriate to the originally selected overlay thickness, no further action is necessary. This was found to be the case for the initial requirements for both wheel-paths combined selected in Appendix 2, Figure 2. When this is so the initial requirements should be checked to ensure that they do not represent an overestimate of the strengthening requirements.

To ensure that a uniform distribution of deterioration occurs in areas that approach a critical condition during the final 3 x 10^6 standard axles of the design life, successive 100m lengths advanced in 4m steps along the road are checked to determine whether they include more than the specified proportion of such areas. As in the previous method this requires that not more than 4 deflection values in any 100m length lie between the solid and dashed lines for the overlay thickness selected. Where more than four values are found in either wheel-path the profiles of the two wheel-paths are compared. The lower of any pair of values in the nearside and offside wheel-paths lying between the two lines is ignored by placing a cross (X) against it, and the deflection level exceeded by a total of not more than 4 values from both wheel-paths determined. The chain-dotted lines labelled A to E in Appendix 2, Figure 2, indicate such levels.

The 100m length between Chainages 468 and 568m in Appendix 2, Figure 2, is the most complex to analyse. Deflection values that lie between the levels of the solid and dashed lines occur over lengths allocated to different overlay thicknesses, ie 125mm for Chainages 468 to 516m and 75mm for Chainages 516 to 568m. It is the maximum overlay thickness that will control the overall solution proposed. Therefore, in determining the detailed overlay thickness, it is desirable to keep to a minimum any increase in the overlay thickness above 125mm over the length 568 to 516m. Of the 4 deflection values which may lie between the solid and dashed lines of the increased overlay thickness, three, therefore, have been allowed to remain within the length 468–516m and only one value in the remaining length. Chain-dashed lines C and C^1 in Appendix 2, Figure 2, result from this procedure and indicate overlay thicknesses of 135 and 125m respectively for Chainages 468–516m and 516–568m. However, if Chainage 468–516m is allocated for reconstruction, all the offending deflection values in this length are removed. For the adjacent 100m length between 516 and 616m, 4 values now lie between the solid and dashed lines of the increased overlay thickness. The chain-dashed line C^{11} results, requiring only a 105mm overlay.

The detailed strengthening recommendations obtained are shown in Appendix 2, Figure 2; these are for strengthening by means of overlay only or with the option for reconstruction. Corresponding engineering solutions for strengthening are also given.

15.6.1 Discussion of manual analysis, Method 2. The method presented above, although rather more time-consuming to execute than the previous method, is more accurate and has the distinct advantage that treatment lengths are identified near the end of the procedure and on the basis of thickness requirements. This method of analysis is recommended for use in analysing deflection profiles that require the implementation of early and substantial strengthening measures and for which no computer drawn profile is available. Although the procedure is suitable for analysing profiles of roads which have long lives remaining the more rapid procedure of Method 1 is also adequate.

As in the case of Method 1, failure to comply with the restrictions on the earliest point in time at which critical conditions can occur, and on the uniformity of the distribution of lengths that can attain a critical condition during the design life of the strengthened road, can result in a significant underestimation of overlay requirements in these lengths. The magnitude of this underestimation can be gauged by comparing the "combined initial" and "combined detailed" recommendations shown in Appendix 2, Figure 2.

The accuracy of this method is reduced significantly when pavements are tested at temperatures significantly below 20°C, and is the result of the converging form of the deflection temperature relations on the temperature correction charts: only the very stiffest pavements are unaffected. The convergence leads to the compression of the vertical spacing of the standard deflection levels and increases the difficulty of identifying accurately percentile values visually. For example, values of deflection of 40 and 50 x 10^{-2}mm measured by Deflectograph on a pavement containing 275–324mm of bituminous material at a temperature of 15°C give standard deflection levels of 72 and 99 x 10^{-2}mm; the measured difference of 10 x 10^{-2}mm is increased to 27 x 10^{-2}mm in terms of the standard deflection values.

15.7 Analysis of computer-drawn profiles

The method of analysis recommended for computer-drawn profiles is based on the same approach as that used for the manual analysis, Method 2. There is, however, no need to construct a scale of standard deflection because the profile itself has been corrected to standard deflection values by the computer before plotting. The present DEFLEC programme* can display on the profile the maximum deflection requiring zero overlay (DOO) and up to four deflection levels corresponding to different overlay thicknesses required for a desired design life. Only the maximum present level of deflection that, for a given overlay thickness, will achieve a life equal to the earliest point in the design life at which critical conditions can occur (7×10^6 standard axles) has to be calculated and drawn manually.

Analysis can be carried out on individual deflections, of means-of-three deflections for individual wheel-paths, or for both wheel-paths combined. Except for deflection profiles obtained from pavements containing a cracked cement-bound roadbase, the mean-of-three profile is recommended for general use. An example of both individual and mean-of-three analysis is presented.

Appendix 2, Figure 3, illustrates the method applied to the same deflection profile used for the two manual methods.

Detailed instructions for the method of analysis of computer-drawn deflection profiles are not given here, except where the procedure departs from that given for the manual analysis, Method 2 in Appendix 2, Section 15.6 of this Report. The step-by-step procedure is given below, with appropriate cross reference.

STEP 1. As Step 2, Appendix 2, Section 15.6.

STEP 2. As Step 3, Appendix 2, Section 15.6 with the exception that only the level of the dashed lines for the overlay thickness chosen needs to be determined and drawn on the profile.

STEP 3. As Step 4, Appendix 2, Section 15.6

STEP 4. As Step 5, Appendix 2, Section 15.6.

STEP 5. The checking procedures detailed in Appendix 2, Section 15.5, Step 7, and Appendix 2, Section 15.6, Step 6 must be followed. In the present method,combination of the wheel-paths by computer and the use of a means-of-three analysis each reduces the work involved significantly. When both procedures are used this reduction is very considerable.

The overlay requirements calculated are presented in Appendix 2, Figures 3A and 3B.

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* A computer program for the analysis of deflection profiles to be published as part of a more comprehensive system for optimising strengthening recommendations.

15.7.1 Discussion of the method of analysis using computer-drawn deflection profiles.

This method is quicker to perform than manual analysis, Method 2. It requires a similar time to execute as the manual analysis Method 1, providing that only long lengths are considered in the manual method.

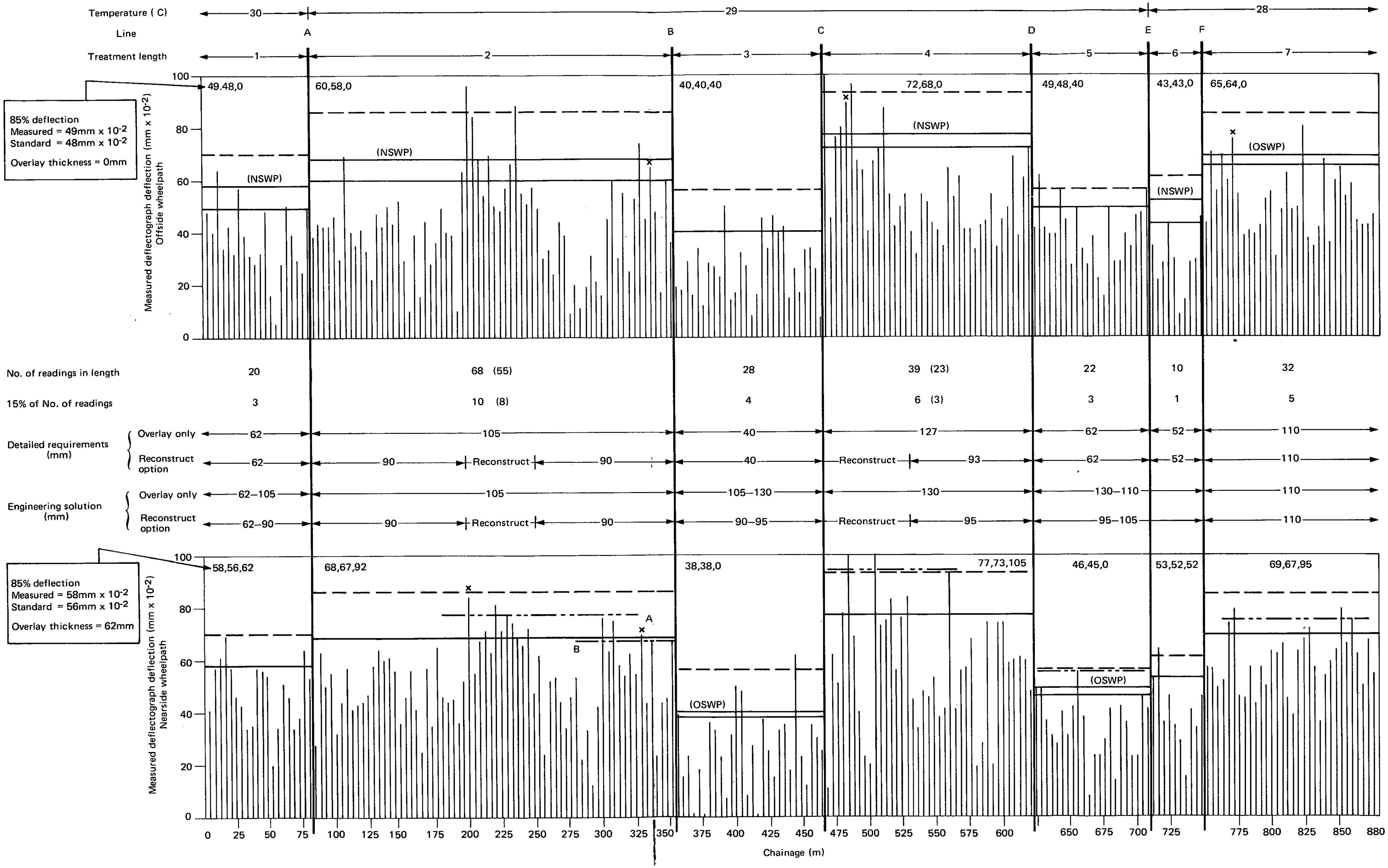
The superiority of the computer-based approach is greatest when applied to the results of both wheel-paths combined. This is the way which is most likely to be used because it eliminates the time-consuming manual procedure required where deflection levels are nearly equal in both wheel-paths.

The use of combined wheel-paths with means-of-three results plotted has the major advantage of reducing the uncertainty as to the true pavement deflection associated with using a single measured value.

The deflection profile to be expected after strengthening for the length of road analysed is shown in Appendix 2, Figure 3C. This profile has been constructed on the basis of the engineering solution using mean-of-three deflections and the lives of future life calculated from information built into the overlay design method described in the main Report.

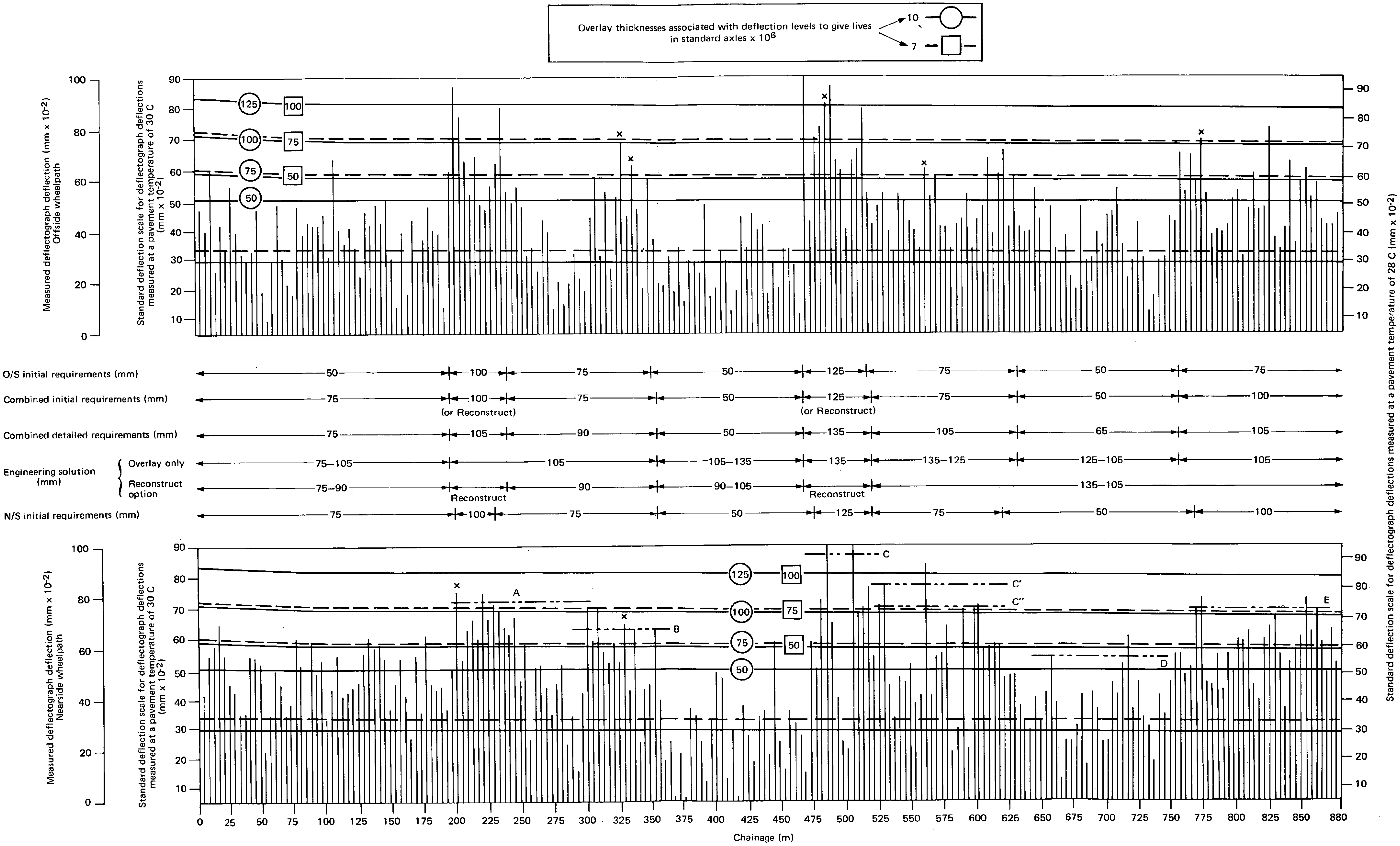
The profile shown in Appendix 2, Figure 3C, for the strengthened pavement is much closer to the ideal profile of constant deflection than that measured on the existing pavement. This will allow a more uniform overlay solution to be applied at the next major strengthening.

The length of road which will become critical during the design life of the overlay is 10 per cent of the total as compared with the 15 per cent allowed for in the design assumptions. This difference is the result of a slightly conservative bias built into the design procedure and of the changes made in turning the requirements dictated by the deflection profile into a practical engineering solution. The 10 per cent is reasonably evenly distributed along the total length.



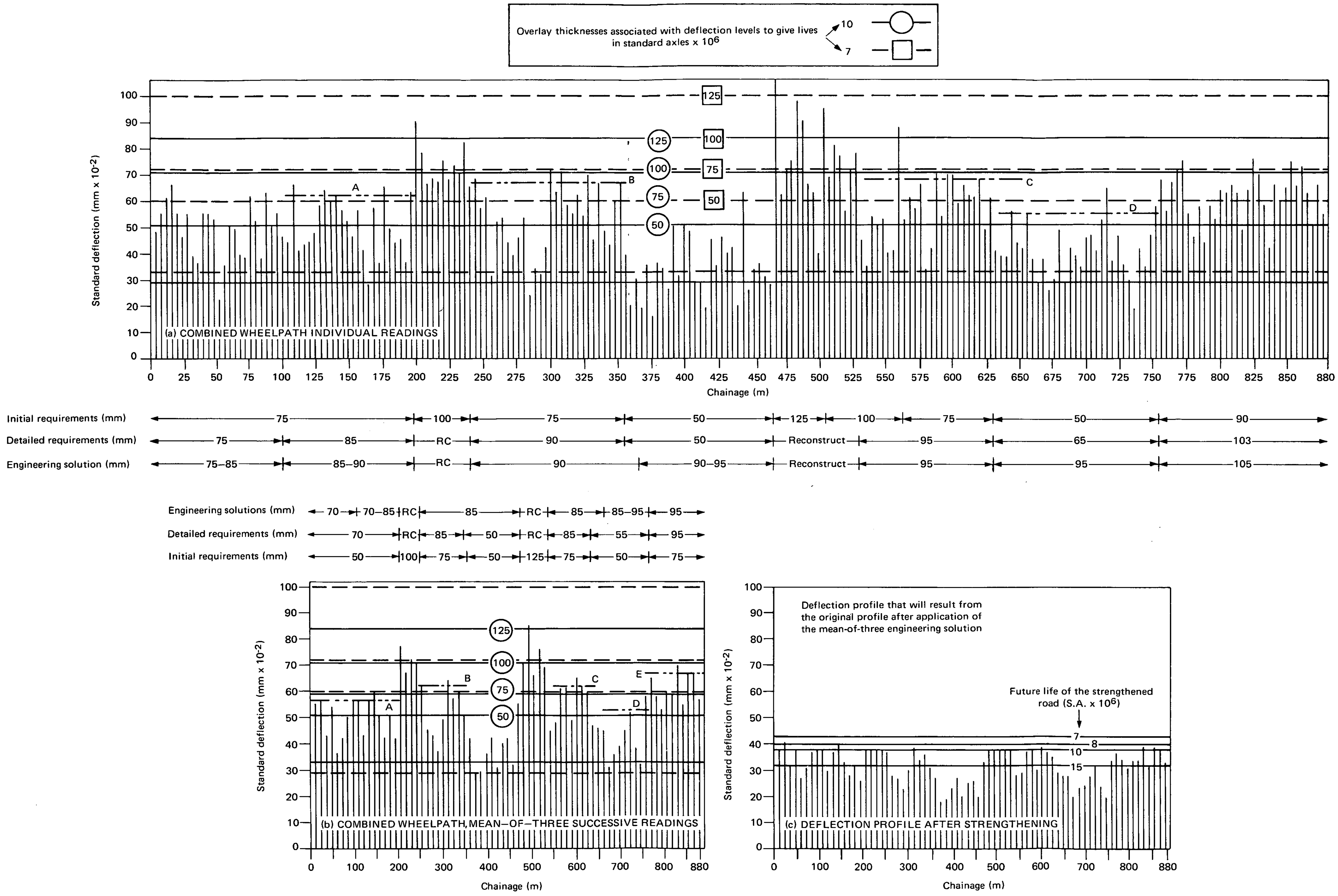
Note:- Details of the construction of the figure are given in Appendix 2, Section 4, of this report

Appendix 2 Fig. 1 MANUAL ANALYSIS OF DEFLECTION PROFILES, METHOD 1 : STRENGTHENING MEASURES DESIGNED BY A PROCEDURE IN WHICH THE ROAD IS DIVIDED INTO LENGTHS FOR DESIGN BY SELECTION ON THE BASIS OF REASONABLY CONSTANT DEFLECTION LEVELS



Note:- Details of the construction of the figure are given in Appendix 2, Section 5, of this report

Appendix 2 Fig. 2 MANUAL ANALYSIS OF DEFLECTION PROFILES, METHOD 2 : STRENGTHENING MEASURES DESIGNED BY A PROCEDURE WHICH DIVIDES THE ROAD INTO LENGTHS FOR DESIGN BY SELECTION ON THE BASIS OF CONSTANT OVERLAY THICKNESS



Note:- Details of the construction of the figure are given in Appendix 2, Section 6, of this report

Appendix 2 Fig. 3 ANALYSIS OF DEFLECTION PROFILES DRAWN BY COMPUTER

16. APPENDIX 3

THE EFFECT OF THE SPACING OF DEFLECTION BEAM MEASUREMENTS ON THE STRENGTHENING MEASURES RECOMMENDED

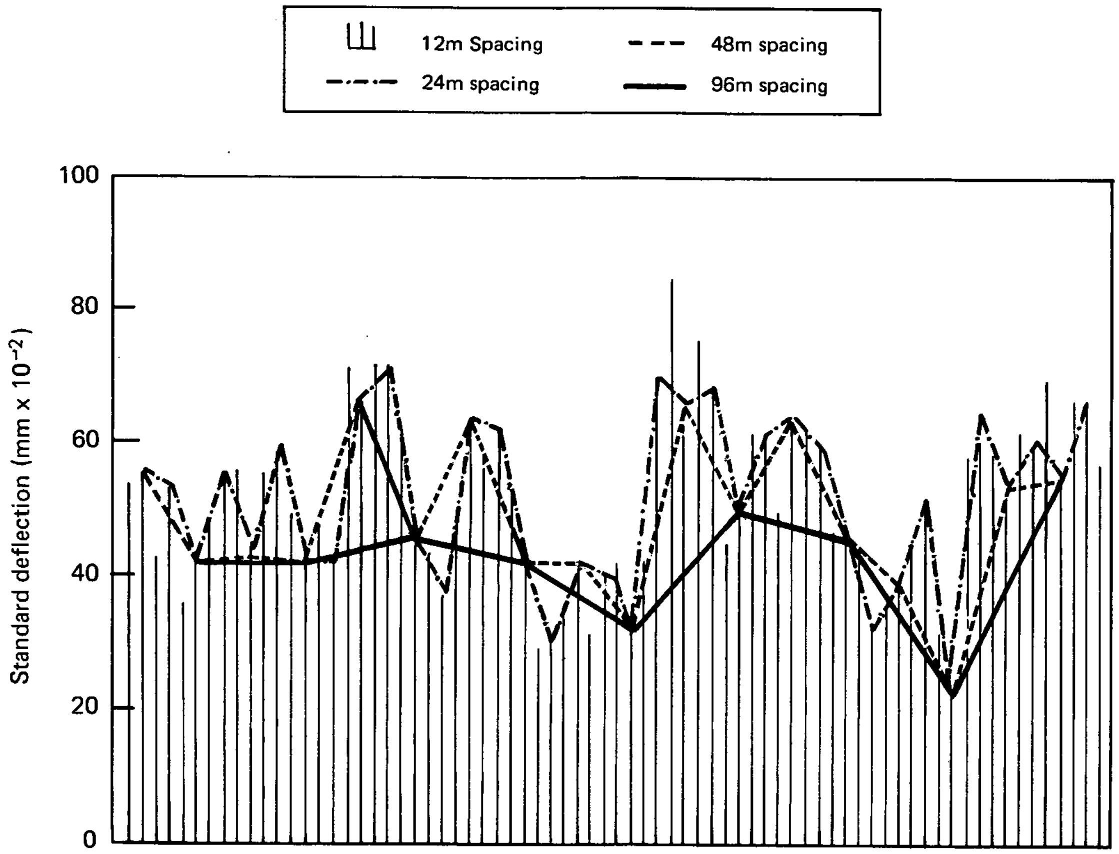
Deflection measurements made at intervals greater than the 12m recommended have the advantage that the structural strength of a greater length of road can be assessed in a given time. However, the information thus obtained on any given length is more limited and, in contrast to the mean-of-three measurements at 12m intervals normally used with the Deflectograph, does not give any indication of the variation in strength between the points of measurement.

The spacing of measurements influences the strengthening measures that are recommended. To illustrate this, the profile of means-of-three deflections for both wheel-paths combined given in Appendix 2, Figure 3B, has been used to compare strengthening measures based on measurements at intervals of 12, 24, 48 and 96m. Appendix 3, Figure 1, shows the resulting deflection profiles together with the associated thicknesses of overlays.

In designing the strengthening measures it has been assumed that the distribution of areas within the total length that can reach a critical condition during the design life is unimportant.

The strengthening requirements computed for the measurement spacings adopted are shown below the profile in Appendix 3, Figure 1. At a spacing of 24m the areas of highest deflection have been underestimated and thinner overlays than required would be recommended. The smoothing action of increasing the spacing above 24m rapidly reduced the strengthening requirement further, until at a spacing of 96m a 50mm overlay only is recommended.

It should be noted that closer agreement between the strengthening proposals can be found by a judicial selection of the starting point for each spacing. In practice, however, such a selection could not be made without having first taken the closely spaced results.



Deflection profile is the mean of three
deflectograph profile from Appendix 2 Fig 3B

Spacing of measurements	Strengthening recommendations (Overlay thickness in mm)											
12m	50	100		75		50	125		75		50	75
24m	50	75				50	75				50	75
48m	50		75		50			75		50		
96m	50											

Appendix 3 Fig.1 EFFECT OF SPACING OF DEFLECTION BEAM MEASUREMENTS ON STRENGTHENING PROPOSALS

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ABSTRACT

Prediction of pavement performance and the design of overlays: C K KENNEDY and N W LISTER: Department of the Environment Department of Transport, TRRL Laboratory Report 833: Crowthorne, 1978 (Transport and Road Research Laboratory). The deflection of a road pavement under a heavy wheel load moving at creep speed can be used to predict the future structural performance of the pavement and to design the strengthening of it by overlaying with bituminous materials. Equipment and procedures for its use as standardised for the measurement of deflection in the United Kingdom are described in TRRL Laboratory Reports LR 834 and LR 835.

The present report describes the adjustment of measured deflections to standard values suitable for design purposes and their use, together with the appropriate traffic data, for the prediction of remaining pavement life and for the design of overlay thickness. The technique sometimes requires information from cores and trial holes to allow the appropriate decisions for a particular pavement to be made.

Matching practical strengthening measures to the variation in structural strength, as reflected by deflection measurements, along the length of any road requires a statistical approach. Methods of analysing deflection data are presented and procedures recommended for both manual and computer processing.

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