TRANSPORT and ROAD
RESEARCH LABORATORY
Department of the Environment
TRRL REPORT LR 469

THE DESIGN AND PHASING OF HORIZONTAL AND VERTICAL ALIGNMENTS : PROGRAM JANUS

by

A B Baker, BSc, CEng, MICE

(on loan from Highway Engineering Computer Branch,
Department of the Environment)

In this report imperial units have been retained because the work was carried out in these units in accordance with the design standards applicable at the time.

Construction Planning Division
Highways Department
Transport and Road Research Laboratory
Crowthorne, Berkshire
1972

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ABSTRACT

The Report outlines some of the factors which influence the geometric design of rural roads, with emphasis on the vertical alignment, and describes the geometric design standards currently recommended for Motorways in the United Kingdom. It discusses the phasing of the vertical alignment with the horizontal alignment required to present a visually pleasing design and to avoid the creation of hazards. The concept of phasing is extended to include the total separation of the vertical and horizontal curves, the phasing of one end only, or the phasing of both ends of the curves, depending on the type of mis-phasing and the radii of the curves. Critical values of radius at which phasing is required are determined by the engineer. The Report states a set of phasing rules which have been formulated and describes a computer program that adjusts a vertical alignment so as to phase it with the horizontal alignment according to these rules.

1. INTRODUCTION

Computers are being used increasingly to assist highway designers in work which is laborious and time-consuming. The British Integrated Program System for Highway Design[1] (BIPS) has been developed to perform many design calculations including those for the geometry of horizontal and vertical alignments and for cross-sections, superelevation, earth-work quantities and setting-out. In addition, because of the speed of operation of computers, design procedures can now be employed which were not possible formerly.

A series of programs currently being developed at the Transport and Road Research Laboratory will design a vertical alignment with lowest cost of earth-works given a horizontal alignment, ground levels, constraints, and unit costs of earth-works[2]. The series includes programs for checking and linearising ground-cross-section levels[3], for generating a vertical alignment from the ground data[4], and for checking its feasibility. Further programs adjust this alignment so that the vertical curves are phased with the curves of the horizontal alignment (as described in this Report), modify the vertical alignment so that the cost of earth-works is a minimum[5], and optimise the mass-haul strategy.

The present Report outlines the bases on which alignments are prepared, and describes the constraints which have to be met by the engineer. The phasing of the vertical alignment with the horizontal alignment so as to achieve a visually pleasing design and to avoid the creation of hazards is discussed. Rules for the attainment of satisfactory phasing are developed, their effect being modified by criteria determined by the engineer. A computer program is described that carries out automatically the whole process of adjusting a vertical alignment so as to phase it with a horizontal alignment in accordance with these rules. Finally some suggestions are made concerning possible improvements to the rules and the way in which they are applied.

2. DESIGN OF THE HORIZONTAL ALIGNMENT

A road is constructed to provide a line of communication between two or more places. The requirements of potential users determine the general location and direction of the route, which must be as short as practical. Land values, the location of urban development, areas of difficult engineering terrain, the location of suitable crossing points over natural obstacles such as rivers and escarpments, and construction costs are other factors that influence the choice of route.

These factors occur mainly in plan and are largely independent of the vertical alignment. The first step in designing a new road is therefore to prepare a trial horizontal alignment in accordance with given geometric standards and with only limited consideration of the vertical alignment. This is followed by the design of the vertical alignment to suit that particular horizontal alignment.

A change in the horizontal alignment will present the engineer with a different ground longitudinal section. It is therefore usual to make an estimate of the cost of constructing a road along a number of different horizontal alignments, each with its corresponding vertical alignment. This procedure leads to an estimated lowest cost for the provision of a road between the given points.

The horizontal alignment is usually made up of straight lines and circular arcs linked by transition curves. It is defined by the Intersection Points of the straight lines (called I.Ps) and the end points of the associated curves, which may include transitions.

3. DESIGN OF THE VERTICAL ALIGNMENT

The vertical alignment is designed to fit the ground longitudinal section along the predetermined horizontal alignment. It must obey level controls and geometric standards of design, and phase with the horizontal alignment (see Section 5 later) whilst incurring the lowest construction costs. Vehicle-operating costs are taken into consideration but are not used in design calculations, due to a lack of knowledge about the effects of gradients.

The vertical alignment is usually made up of straight lines linked by parabolic curves. The straight lines are extended to intersect at I.Ps. The parabolic curves which are fitted to the straight lines in the vicinities of the I.Ps may be replaced by circular arcs with insignificant change of profile. The vertical alignment is therefore defined by the chainages and levels of I.Ps and by the radii or curve lengths of the circular arcs. The spacing of I.Ps is an indication of the amount of undulation of the road and some typical densities are shown in Table 1.

Design of the vertical alignment is subject to various constraints, outlined below, which have to be applied at all stages of the phasing process.

4. CONSTRAINTS ON ALIGNMENT DESIGN

4.1 Geometric design standards

The numerical standards given in the following paragraphs are those for rural motorways[6]. For other roads the figures may vary but the principles are similar.

4.1.1 Horizontal alignment

4.1.1.1 Horizontal curves. These take the form of circular arcs. They may be described in terms of radii or degree of curvature. The degree of curvature is defined as the central angle subtended by an arc 100 feet long. The absolute minimum radius of curvature in motorway work is 1,500 feet, but this radius is used only if unavoidable in junction layouts. The normal minimum radius is 2,800 feet, which is approximately a 2-degree curve.

4.1.1.2 Transition curves. For a design speed of 70 mile/h transition curves are always provided in cases where the circular-arc radius is 5,000 feet (1-degree curvature) or less, and, wherever possible, for radii up to 10,000 feet. The transition curve is usually a clothoid of the form $LR = A^2$ where R is the instantaneous radius at a point distance L along the curve and A is a constant depending on the design speed and the allowable rate of change of radial acceleration.

4.1.2 Vertical alignment

4.1.2.1 Radius of curvature. The normal minimum radii of curvature for summit and valley curves are 50,000 feet and 25,000 feet respectively.

4.1.2.2 Length of vertical curve. The length of a vertical curve is normally not less than 1,000 feet.

If departure from these standards is unavoidable the sight distance on summit curves must not fall below the minimum of 950 feet. This distance is measured between objects 3 ft 6 ins high on the centre line of the carriageway.

4.1.2.3 Maximum gradient. A longitudinal gradient of 3 per cent is the normal maximum for motorways in rural areas.

A gradient of 4 per cent may have to be accepted in hilly country in order to reduce the amount of earthworks and also to reduce the total length of the road by avoiding detours from the direct line.

4.1.2.4 Minimum gradient. A minimum gradient of 0.4 per cent is sometimes specified to ensure the free drainage of surface water.

4.1.2.5 Fixed end gradients. If the proposed road is to be contiguous with an existing or previously designed road it will be necessary for the gradients at one end or both ends of the new road to match the existing gradients. In this case the entry or exit gradient, or both, may be fixed at appropriate values determined by the engineer. These values are not governed by the maximum and minimum gradients set for the remainder of the road.

4.2 Level-control points

Level-control points are located on the vertical alignment where the level of the road surface is subject to restrictions. These restrictions usually occur where the road crosses an obstacle such as a river, a railway or another road. There are four types of level-control point, defined as follows:–

4.2.1 Lower level-control point. This fixes the lowest permissible level for the road surface. Such a control point could occur where the road crosses a waterway.

4.2.2 Upper level-control point. This fixes the highest permissible level for the road surface. It may occur when the proposed road is crossed by another road.

4.2.3 Gated control point. A gated control point defines upper and lower limits of level between which the road surface may pass.

4.2.4 Fixed level-control point. This is also known as a tie point and is a single fixed level through which the road surface must pass. It may be considered as a special case of a pair of gated control points that are coincident.

4.2.5 Density of level-control points. The number of level-control points per mile depends on the location of the road. In rural areas an average of 1½ to 2 per mile may be expected, whereas in urban areas the average may be as high as 3 or 4. Table 1 shows the density of the level-control points on some typical rural major road contracts.

5. PHASING OF THE VERTICAL ALIGNMENT WITH THE HORIZONTAL ALIGNMENT

Phasing of the vertical and horizontal curves of a road implies their co-ordination so that the line of the road appears to a driver to flow smoothly, avoiding the creation of hazards and visual defects. It is particularly important in the design of high-speed roads such as motorways on which a vehicle driver must be able to anticipate changes in both horizontal and vertical alignment well within his safe stopping distance. It becomes more important with small radius curves than with large. Much has been written on the subject. Papers by Summers[7] in 1938 and Koester[8] in 1940 appreciated that the problem is three-dimensional and that horizontal alignment and vertical alignment must be considered in combination. More recent papers by Cardell and Howarth[9], Boyce[10], Aldington[11], Spencer[12], Department of Scientific and Industrial Research[13], Abbot[14], White[15], Smith and Fogo[16], and the American Association of State Highway Officials[17] have emphasised the importance of the elimination of ambiguity and obscurity and the eradication of visual defects such as kinked curb lines and illusory summits and valleys.

5.1 Defects in the alignment due to misphasing

Defects may arise if an alignment is misphased. A defect is defined as any undesirable feature of such magnitude as to require correction. Defects may be purely visual and do no more than present the driver with an aesthetically displeasing impression of the road. Such defects often occur on valley curves. Examples are shown in Figs. 1 (a) – (d) and in Plate 1. When these defects are severe they may create a psychological obstacle and cause some drivers to reduce speed unnecessarily. In other cases the defects may endanger the safety of the user by concealing hazards on the road ahead. A sharp bend hidden by a summit curve is an example of this kind of defect.

5.2 Types of misphasing and corresponding corrective action

Although the references given above all agree that defects are possible when horizontal and vertical curves are misphased, there is very little guidance on what constitutes misphasing or a defect. There is common recognition that defects are most likely to occur with sharp curves but no quantitative definition of critical "sharpness". There is no guidance on how to avoid defects. In the past this has been a matter for the judgement of the engineer but when the design is to be carried out by computer it is necessary to formulate precise rules.

When the horizontal and vertical curves are adequately separated or when they are coincident no phasing problem occurs and no corrective action is required. Defects may therefore be corrected and phasing achieved either by separating the curves or by adjusting their lengths so that vertical and horizontal curves begin at a common chainage and end at a common chainage. In some cases, depending on the curvature, it is sufficient if only one end of each of the curves is at a common chainage.

Cases of misphasing fall into four types. These are described below and the necessary corrective action for each type is set out in Fig. 2.

5.2.1 Insufficient separation between the curves. If there is insufficient separation between the ends of the horizontal and vertical curves a false reverse curve may appear on the outside kerb-line at the beginning of the horizontal curve, or on the inside kerb-line at the end of the horizontal curve. This is a visual defect. It is illustrated in Figs. 1 (a) and 1 (b).

Correction consists of increasing the separation between the curves.

5.2.2 The vertical curve overlaps one end of the horizontal curve. If a vertical summit curve overlaps either the beginning or the end of a horizontal curve a driver's perception of the change of direction at the start of the horizontal curve may be delayed because his sight distance is reduced by the vertical curve. This defect is hazardous. The position of the crest is important because vehicles tend to increase speed on the down gradient following the highest point of the summit curve, and the danger due to an unexpected change of direction is consequently greater. If a vertical valley curve overlaps a horizontal curve an apparent kink similar to that described in Section 5.2.1 may be produced. This visual defect is illustrated in Fig. 1(c).

The defect may be corrected in both cases by completely separating the curves. If this is uneconomic the curves must be adjusted so that they are coincident at both ends if the horizontal curve is of short radius, or they need be coincident at only one end if the horizontal curve is of longer radius.

5.2.3 Both ends of the vertical curve lie on the horizontal curve. If both ends of a summit curve lie on a sharp horizontal curve the radius of the horizontal curve may appear to the driver to decrease abruptly over the length of the summit curve. If the vertical curve is a valley curve the radius of the horizontal curve may appear to increase. Two examples of such a visual defect are illustrated in Fig. 1 (d) and Plate 2. The corrective action is to make both ends of the curves coincident or to separate them.

5.2.4 The vertical curve overlaps both ends of the horizontal curve. If a vertical summit curve overlaps both ends of a sharp horizontal curve a hazard may be created because a vehicle has to undergo a sudden change of direction during passage of the vertical curve while sight distance is reduced.

The corrective action is to make both ends of the curves coincident. If the horizontal curve is less sharp then a hazard may still be created if the crest occurs off the horizontal curve because the change of direction at the beginning of the horizontal curve will then occur on a down grade (for traffic in one direction) where vehicles may be increasing speed.

The corrective action is to make the curves coincident at one end so as to bring the crest on to the horizontal curve.

No action is necessary if a vertical curve that has no crest is combined with a gentle horizontal curve.

If the vertical curve is a valley curve an illusory crest or dip, depending on the "hand" of the horizontal curve, will appear in the road alignment.

The corrective action is to make both ends of the curves coincident or to separate them.

5.3 The economic penalty due to phasing.

The phasing of vertical curves restricts their movement in fitting to the ground so that the engineer is prevented from obtaining the lowest-cost design. Therefore phasing is usually bought at the cost of extra earthworks and the engineer must decide at what point it becomes uneconomic. He will normally accept curves that have to be phased for reasons of safety. In cases when the advantage due to phasing is aesthetic the designer will have to balance the costs of trial alignments against their elegance.

To date few valid comparisons have been made, but experience has indicated that the cost varies widely between schemes. Changes in the costs of earthworks due to phasing on optimised alignments have ranged from virtually zero to almost double.

6. THE PHASING PROGRAM : PROGRAM JANUS

6.1 General description

The program is one of a series which designs an optimal vertical alignment for a fixed horizontal alignment. The phasing operations are carried out on the vertical curves, which may be moved both longitudinally and vertically.

The phasing program takes each vertical curve with each horizontal curve in turn and classifies the combination with respect to the rules of phasing set out in Section 5 and Fig. 2. As the phasing status of each pair of curves is determined the appropriate corrective action is taken, followed by adjustments of intersection-point levels where necessary so that the alignment complies with geometric standards and level-control points.

The action required to correct misphasing depends on the radii of curvature of both the horizontal and vertical curve (see Fig. 2). The program recognises four ranges of severity of curvature for horizontal curves and two ranges for vertical curves. The ranges of severity and also the minimum separation distance between horizontal and vertical curves are set by the engineer and included in the data presented to the computer. The engineer thus retains control over the final configuration of the vertical alignment.

6.2 The phasing program

The outline flow diagram is given in Fig. 3.

6.2.1 Input. All input is on cards, the following items of data being included:—

(i) Job identification

Run number, date, jobname and other descriptive information desired by the engineer.

(ii) Units of measurement

The units may be imperial or metric.

(iii) Vertical alignment

Chainages and levels of I.Ps of vertical curves and curve lengths or radii of curvature or rates of changes of percentage gradient. The chainages and levels of the beginning and end points of the job and fixed gradients at these points, if specified, are also included. These data will normally be supplied by the engineer.

(iv) Level-control points

Chainages and levels of level-control points.

(v) Geometric design standards for the vertical alignment.

Maximum and minimum gradients.
Minimum radii of curvature for summit and valley curves.
Minimum length of vertical curve.

(vi) Exceptions to geometric design standards.

Details of modified design standards which the engineer may wish to apply to any vertical curve.

(vii) Limits on movement of curves.

If the engineer requires particular vertical curves to remain fixed in position longitudinally during the operation of the phasing program, he must specify fixed tangent-point barriers.

(viii) Horizontal alignment.

Chainages of extremities of horizontal curves including transitions, and radii.

(ix) Phasing standards.

Limiting values of the four ranges of severity for horizontal radius of curvature and the two ranges of severity for vertical radius of curvature. Minimum curve separation. These are set by the engineer.

(x) Exceptions to phasing standards.

Details of modified phasing standards which the engineer may wish to apply to any horizontal curve.

6.2.2 Operation of the program. The program first reads all the details of input listed in Paragraph 6.2.1 above and makes tests on the validity of each section of the data as it is read. If an apparent error is found a message is printed immediately and the reading and testing of data is continued if possible, the program being terminated at the end of the data input. If no errors are found in the data the program proceeds to calculate the complete vertical alignment from the I.P. chainages, levels and curve lengths to give values of radii, rates of change of per-cent gradient, per-cent gradients and chainages of ends of curves. This configuration is tested to ensure that there are no overlapping vertical curves and that the constraints of level-control points and geometric design standards, including exceptions, are not violated. If no violations are found the vertical alignment is feasible and is used in the program. In the event of any constraints being violated, the intersection-point levels are varied in an attempt to find a new vertical alignment that obeys the contraints. This is often successful and the new vertical alignment is then accepted for use in the program. If unsuccessful the program prints a message that the alignment is infeasible and then stops. The phasing action consists of moving the initial tangent point or the final tangent point of the vertical curve, or both tangent points, horizontally through the minimum distance necessary to achieve acceptable phasing. The program examines the phasing of each vertical curve with each horizontal curve. The curves are considered in sequence and are described by their start and finish chainages and radii. When a misphasing as classified in Columns 1 and 2 of Fig. 2 is found, action is taken as shown in Columns 3 and 4 of Fig. 2. The new curve length is then checked against the standard minimum length of vertical curve for acceptance. If the curve is now too short, and the original action had been to fix both tangent points, nothing further can be done and an informative message is printed. If only one tangent point of the curve had been fixed the curve length is corrected by moving the other. This may cause the curve being adjusted to overlap the next curve on the vertical alignment. If so, adjustments are made to this curve and the series of checks are repeated until either no further curves are affected or no further adjustment is possible. In the latter case this is indicated in the output. Checks are made to ensure that no curves are moved outside the boundaries of the road length being considered. The chainages of one or more I.Ps will have been altered during this process of moving the vertical curves. Thus the gradients between the curves and also their radii may have been changed and the road may no longer obey the constraints. Adjustments are therefore made to the levels of the I.Ps so that all constraints are obeyed. If it proves impossible to find a feasible alignment the attempt to phase the current vertical curve is abandoned and a message is printed. This infeasible vertical alignment is erased and replaced by the alignment which existed before this last step was attempted. The program takes each vertical curve in turn and repeats the whole process until the last vertical curve has been dealt with. As the work proceeds some vertical-curve end-points take up positions in which either they are fixed or may be moved in only one direction without upsetting the phasing. This information is stored in the tangent-point barrier table for use by program MINERVA. The program then returns to the first vertical curve and makes a second pass along the entire road length, followed by a third and final pass. On the second and third passes the operation is governed by the tangent-point barriers originally set by the engineer together with any new ones generated during previous passes. Although program JANUS will normally be used prior to the optimisation program it can, if desired, be used as a check after optimisation or for the phasing of any alignments.

6.2.3 Output. The output is printed as shown in Fig. 4, and consists of the title of the job and the unit of measurement used followed by the details of the vertical alignment, a list of the level-control points, the geometric design standards, the exceptions to these standards, lists of the fixed tangent-point barriers and the horizontal alignment, the phasing standards and the exceptions to these standards.

The table showing the initial configuration of the vertical alignment gives the following details for each curve:—

Chainage and level of intersection point.

The length of curve.

Radius (signed as appropriate).

Rate of change of per-cent gradient.

Preceding and succeeding gradients.

Chainage of start of curve.

Chainage of end of curve.

A similar table, but showing the modified configuration, is then printed if the initial alignment had to be altered in order to obey constraints.

Messages giving information about phasing difficulties encountered at particular vertical curves together with details of the configuration of the vertical alignment at the end of each phasing pass are next printed. The tabular format of the intermediate vertical configuration is similar to that of the initial configuration with the exception that the rate of change of per-cent gradient is replaced by a phasing marker, which indicates the vertical curves that have been moved during each pass.

The final vertical alignment in the same format as the initial alignment is then printed followed by the tangent-point barrier table.

6.2.4 Implementation of the program. The program is written in FORTRAN IV, the total number of FORTRAN statements being approximately 2000. It was developed on an ICL System 4/70 computer and when overlaid occupies approximately 85k bytes of store in this machine. Average execution time for a 10-mile length of road is 15 seconds.

7. AN ILLUSTRATION OF THE OPERATION OF THE PROGRAM

A modified version of the Durham motorway Contracts I and II was used for testing because it utilised most of the facilities provided in the program. This scheme consisted of 12 miles of rural motorway which included seven horizontal curves, 15 vertical curves and 27 level-control points. The operation of the program on this scheme is described below and a diagrammatic representation of the stages followed in the development of the final alignment is given in Fig. 5.

The initial vertical alignment was based on an engineer's design that had reached an advanced stage and so could be expected to obey level-control points and geometric design standards. Manual phasing had also been carried out but the alignment was considered to be a valid test because mis-phasing by as little as 0.5 feet would be sufficient to actuate the program.

The phasing standards were as shown in Fig. 2. For the vertical alignment the geometric design standards for rural motorways[6] were applied with the following exceptions, which were set as a result of previous runs of program FEASBL[18].

Minimum valley-curve radius 29,000 ft at Curves Nos. 2 and 13

Minimum summit-curve radius 59,000 ft at Curve No. 3

Maximum gradient 3.1 per cent preceding Curves No. 3 and 13

Minimum gradient 0.4 per cent preceding Curves Nos. 7 and 8.

The list of level-control points is given in Table 2. The level-control point at Ch 53350 is an example of a fixed level-control point and those at Ch 18900 and Ch 30500 are gated level-control points.

Fig. 5 shows the initial unphased infeasible vertical alignment, the modified unphased vertical alignment, the phased vertical alignment and the horizontal alignment. The numbering of the vertical curves follows the convention used in the program which considers the start and finish chainages to be at I.Ps of curves with zero curve length. In this case they are numbered 1 and 17 respectively but are not shown in the Figure.

The program tested the initial alignment and found that two level-control points, at Ch 13950 and Ch 53350 were violated. This was corrected within the program by alteration of the levels of the I.Ps at Ch 13800 and Ch 53250. A new alignment was then calculated and is shown in Line 2 of the bar-chart in Fig. 5. Comparison of the two alignments shows that the radii of vertical curves Nos. 3, 4, 5, 12, 13 and 14 had been changed as had the gradients preceding curves Nos. 4 and 13.

The program then compared the new feasible vertical alignment with the horizontal alignment and listed the following cases of phasing defects.

(1) Vertical curve No. 2 and horizontal curve No. 1.

Vertical curve No. 2 was a valley curve and the misphasing was classified as Type III (ii) of Fig. 2. The action required was either to separate the curves or to make them exactly coincident. The program found that the latter solution would cause least movement of the vertical curve and that a feasible alignment could be generated. This action was then carried out.

(2) Vertical curve No. 3 and horizontal curve No. 2.

Vertical curve No. 3 was a summit curve and the misphasing was classified as Type II (ii) of Fig. 2. The program indicated that separation of the curves was the best solution but it also found that the alignment could not then be made feasible. The phasing of this curve was therefore abandoned.

(3). Vertical curve No. 8 and horizontal curve No. 3.

The vertical curve was a valley curve and misphasing was Type IV (ii) in Fig. 2. Exact coincidence of the curves was the best solution and a feasible alignment could be generated. This action was therefore taken.

(4) Vertical curve No. 12 and horizontal curve No. 6

The vertical curve was a valley curve and the misphasing was Type II (ii). The program indicated that coincidence of the initial tangent points of the curves was required and that a feasible alignment could be generated. This action was taken.

(5) Vertical curve No. 14 and horizontal curve No. 7.

The vertical curve was a valley curve and the misphasing was Type II (ii). The action taken was the same as Case 4 above.

The unphased and phased feasible alignments are shown on Lines 2 and 3 of the bar-chart in Fig. 5.

On completion of the phasing the program printed a list of tangent-point barriers for the four curves that had been moved. This is shown in Table 3.

Examination of Fig. 5 shows that the phasing rules were correctly implemented with the exception of one case when a feasible alignment could not be achieved. This was detected and noted in the output. In accordance with the phasing standards vertical curves of radius greater than 100,000 feet were ignored (Curves No. 7 and 15). It will be noticed that in the phased alignment vertical curves No. 8 and 9 had radii of 111,423 feet and 101,085 feet respectively. This occurred as a result of the adjustments necessary for the regeneration of a feasible alignment following a phasing cycle.

8. FURTHER WORK

Application of phasing will always limit the longitudinal movement of one or both ends of some vertical curves. This will restrict the freedom of the optimisation program so that the cost of the optimised profile will be greater than it would have been had the optimisation been unrestricted. This increase in cost is the cost of phasing. It follows that any relaxation of the restriction imposed by phasing will decrease this cost.

In the present version of the program, phasing is effected by fixing one or both ends of some vertical curves or by setting up tangent-point barriers, which allow curve ends to move in one direction only. In all these cases the ends of horizontal curves are the reference points for determining the position of the ends of the vertical curves. An improvement in the result of the optimisation program would be achieved if some relaxation of the definition of the reference point was allowed, for example if it was permitted to be within some given distance of the end of the horizontal curve instead of precisely at the point.

Further investigation should therefore be directed to determining the amount of relaxation of the phasing rules that can be permitted before the magnitude of the defects becomes unacceptable. In the first instance consideration should be given to allowing the reference point to move anywhere within the length of the transition curve in the case of the sharper horizontal curves and a length of one hundred feet on either side of the tangent points of less sharp curves. An alternative way of using transition curves might be to limit the freedom of movement of the reference point to that part of the curve that has a radius greater than a given value. This approximate phasing is expected to give rise to two problems. Firstly it will be difficult to define curve separation. Secondly, if the vertical curves are allowed some horizontal movement while remaining phased, it will be easier to make the vertical alignment obey the constraints but the program will be much more complex and will take longer to run.

When phasing is to be carried out by computer the machine must be given a set of precise rules to which it should work. This Report has defined such a set of rules but, to allow a measure of control over their effect on the alignment, the values of the associated numerical standards are left to the discretion of the engineer. It is expected that experience with the program will indicate values that will normally give an acceptable alignment at reasonable cost and will also suggest improvements to the set of rules.

It is essential that improvements indicated by experience are incorporated in the program so that when optimisation of the horizontal alignment as well as the vertical alignment is carried out by computer it will be possible to produce a phased alignment entirely automatically. Work on the subject of phasing that has been carried out in the past has been hampered because of the difficulty of visualizing or drawing the effects of different approaches to phasing. The introduction of a perspective drawing program into the British Integrated Program System for Highway Design[1] will now enable engineers to see clearly the effects of changes in their designs. The expense of using the program may be offset by savings due to dispensing with phasing where it can be seen to be unnecessary, thereby allowing more freedom to the optimisation program.

9. ACKNOWLEDGEMENTS

Permission to make use of the data from the Durham Motorway was given by Mr. W.H.B. Cotton, C.B.E., M.Sc., F.I.C.E., F.I.Mun.E., F.I.H.E., County Surveyor at the time, and is gratefully acknowledged. Thanks are also due to the engineers on his staff for their assistance in the study.

The work was carried out in the Construction Planning Division of the Highways Department of the Transport and Road Research Laboratory.

10. REFERENCES

1. MINISTRY OF TRANSPORT, COUNTY SURVEYOR'S SOCIETY and ASSOCIATION OF CONSULTING ENGINEERS. British Integrated Program System for Highway Design. Part II. London, 1970. (Ministry of Transport, County Surveyors' Society and Association of Consulting Engineers).

2. DEPARTMENT OF THE ENVIRONMENT, ROAD RESEARCH LABORATORY. Road Research 1970. Annual Report of the Road Research Laboratory, London, 1971 (HM Stationery Office), pp. 22-3.

3. CHARD, M.E. Ground data processing before optimization of the vertical alignment: program PRELUDE. Department of the Environment, TRRL Report LR 459. Crowthorne, 1972 (Transport and Road Research Laboratory).

4. ROBINSON, R. A computer method for designing the vertical alignment of a road: program VENUS I. Department of the Environment, TRRL Report LR 457. Crowthorne, 1972 (Transport and Road Research Laboratory).

5. DAVIES, H.E.H. Optimizing highway vertical alignments to minimize construction costs: program MINERVA. Department of the Environment, TRRL Report LR 463. Crowthorne, 1972 (Transport and Road Research Laboratory).

6. MINISTRY OF TRANSPORT. Layout of roads in rural areas. London, 1968 (HM Stationery Office).

7. SUMMERS, B.S. Visibility on new roads: its treatment in three dimensions. J. Inst. Mun. Engrs, 1938, 65 (9), 501 – 16.

8. KOESTER, H. Experience gained in setting out the National Motors Roads. Die Strasse, 1940, 7 (15/16), 317 – 32. Translated by G.N. Gibson.

9. CARDELL, J.E. and H. HOWARTH. Principles and practice of road location with particular reference to major roads outside built-up areas. Inst. Civ. Engrs. Paper No. 22. London, 1947 (Institution of Civil Engineers).

10. BOYCE, E.C. Road location and design with special reference to motor roads. London, 1947 (Public Works and Transport Congress and Exhibition), p. 259.

11. ALDINGTON, H.E. The design and layout of motorways. J. Inst. Highw. Engrs, 1948, 1, (2). 5–35.

12. SPENCER, W.H. The co-ordination of horizontal and vertical alignments of high-speed roads. Inst. Civ. Engrs Road Paper No. 27, 1949 (Institution of Civil Engineers).

13. DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH, ROAD RESEARCH LABORATORY. German motor roads : 1946. Department of Scientific and Industrial Research, Road Research Technical Paper No. 8. London, 1964 (HM Stationery Office).

14. ABBOTT, R.A. Road alignment. J. Inst. Highw. Engrs, 1950, 1, (11), 6–32.

15. WHITE, R. Aesthetics of road alignment. Proc. Inst. Mun. Engrs, 1958, 85, (4), 121–7.

16. SMITH, R.L. and R.D. FOGO. Some visual aspects of highway design. Highway Research Record No. 172. Washington, D.C., 1967 (National Research Council).

17. AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS. A policy on the geometric design of rural highways. Washington, D.C., 1965 (American Association of State Highway Officials).

18. ROBINSON, R. Feasibility checking by computer of the vertical alignment of a new road. Department of the Environment, RRL Report LR 399. Crowthorne, 1971 (Road Research Laboratory).

TABLE 1

Density of intersection points and level-control points on typical rural major road contracts

Contract		Contract Length (ft)	Number of level-control points						Number of intersection points	
			Lower	Upper	Gated	Fixed	Total	C.Ps /mile	Total	I.Ps / mile
A1 (M)	Durham Nos. 1 and 2	63100	16	3	3	3	25	2.1	15	1.3
A1 (M)	Durham Nos. 3 and 4	55600	7	3	–	6	16	1.5	15	1.4
A1 (M)	Darlington By-pass	53500	17	3	2	2	24	2.4	13	1.3
M3	Turners Wood – Kitsmead Lane	73500	12	9	2	3	26	1.9	17	1.2
M6	Carnforth – Farleton	42700	9	2	–	2	13	1.6	11	1.4
M6	Farleton – Killington	40700	1	1	–	2	4	0.5	9	1.2
M6	Tebay – Thrimby	51000	5	–	1	2	8	0.8	8	0.8
A108	Sunderland By-pass	56900	6	7	1	2	16	1.5	12	1.1

TABLE 2

Level-control points

No.	Chainage (ft)	Lower Level (ft)	Upper Level (ft)
1	3750	197.00	
2	3950	238.43	
3	4700		268.00
4	13950	249.33	
5	14800	264.90	
6	18900	238.00	244.00
7	21000	243.00	
8	29800	247.85	
9	30500	254.40	280.00
10	31900	283.43	
11	33300	307.77	
12	34000		330.00
13	36400	291.50	
14	36900	260.00	
15	37200	268.00	
16	40600	341.00	
17	42300	390.10	
18	48100		440.10
19	50700	370.57	
20	51700	327.00	
21	52400	292.00	
22	53350	300.45	300.45
23	54800	310.23	
24	56550	269.00	
25	59000	284.14	
26	61500	280.00	
27	62700	277.00	

TABLE 3

Tangent-point barriers

Vertical-curve number	Start of curve (ft)		End of curve (ft)	
	Lower limit	Upper limit	Lower limit	Upper limit
2	2300.00	2300.00	3380.00	3380.00
8	28380.00	28380.00	31326.00	31326.00
12	46988.00	46988.00		
14	54285.00	54285.00		

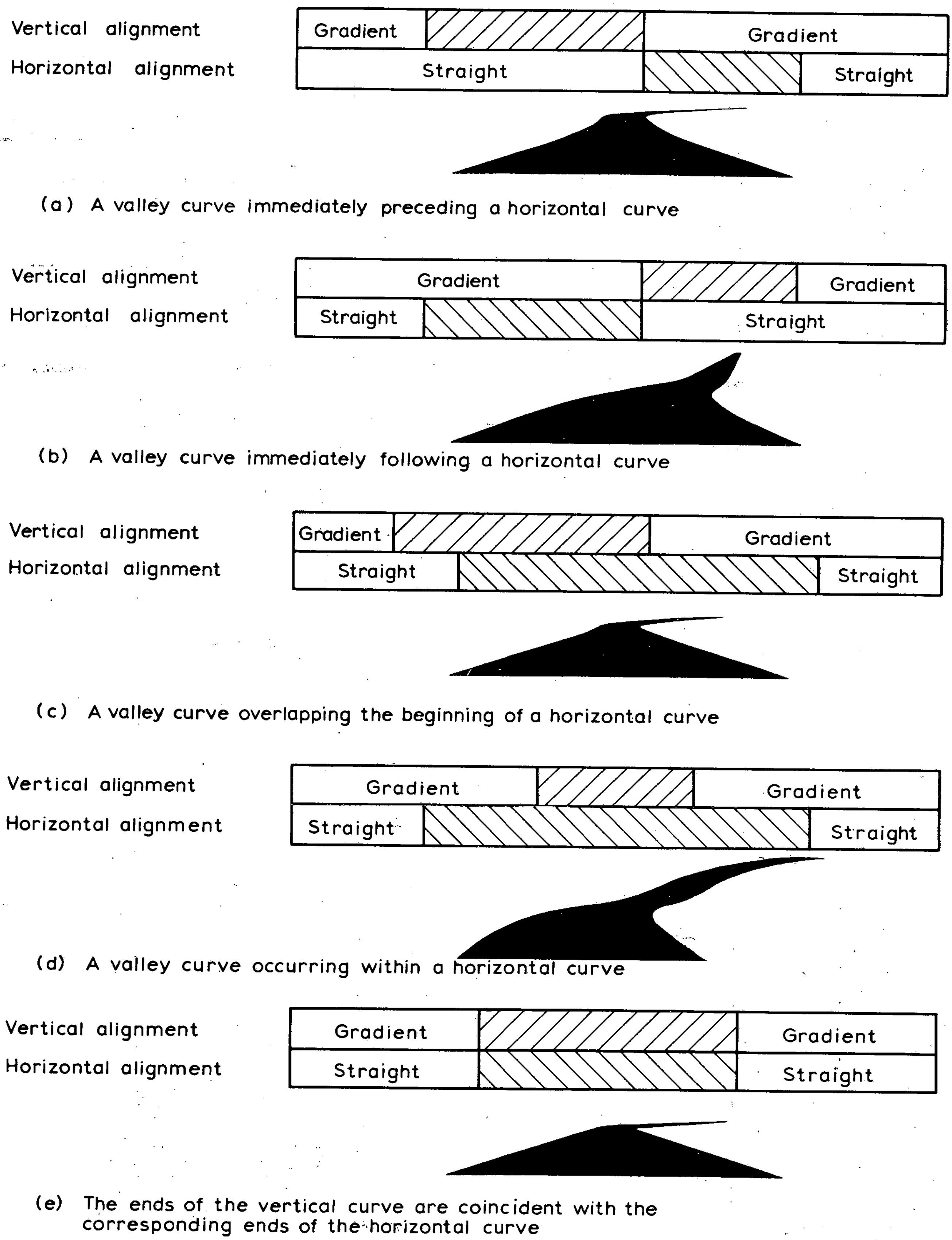
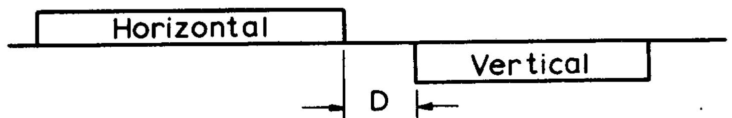
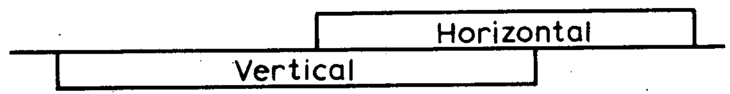
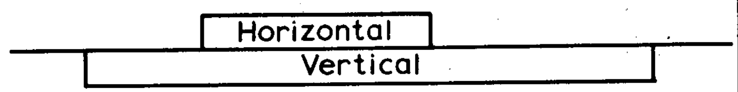
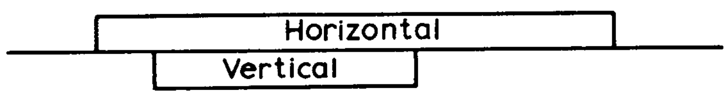


Fig. 1. DIAGRAMMATIC REPRESENTATIONS OF SOME COMBINATIONS OF HORIZONTAL AND VERTICAL CURVES
(After Abbott)

	(1) Type of misphasing		(2) Critical values of horizontal radius	(3) Action: Summits	(4) Action: Valleys
I	 D Less than minimum recommended separation		≤ 22919 ft	A	A
II	 Vertical curve overlaps one end of horizontal curve	(i)	≤ 22919 ft, > 11459 ft — No crest / Crest	None / A or C +	A or C + / ——
		(ii)	≤ 11459 ft, > 5729 ft	A or C +	A or B +
		(iii)	≤ 5729 ft	A or B +	A or B +
III	 Vertical curve overlaps both ends of horizontal curve	(i)	≤ 22919 ft, > 11459 ft — No crest / Crest	None / A or C +	A or B + / ——
		(ii)	≤ 11459 ft, > 5729 ft	A or B +	A or B +
		(iii)	≤ 5729 ft	A or B +	A or B +
IV	 Both ends of vertical curve lie on horizontal curve	(i)	≤ 22919 ft, > 11459 ft	None	None
		(ii)	≤ 11459 ft, > 5729 ft	None	A or B +
		(iii)	≤ 5729 ft	A or B +	A or B +

Action A. Move one end of vertical curve to achieve minimum separation
Action B. Phase ends of vertical curve to ends of horizontal curve
Action C. Phase one end of vertical curve to one end of horizontal curve
+ In these cases the action taken is that which results in the least movement of the vertical curve

Vertical curves with radius greater than a critical value of 100 000 ft are not phased
Critical values of horizontal and vertical radius are decided by the engineer
Values in table are only suggestions

Metric equivalents	
100 000 ft.	30480 m
22 919 ft.	6980 m
11 459 ft.	3490 m
5 729 ft.	1740 m

Fig. 2. PHASING CRITERIA IN PROGRAM JANUS

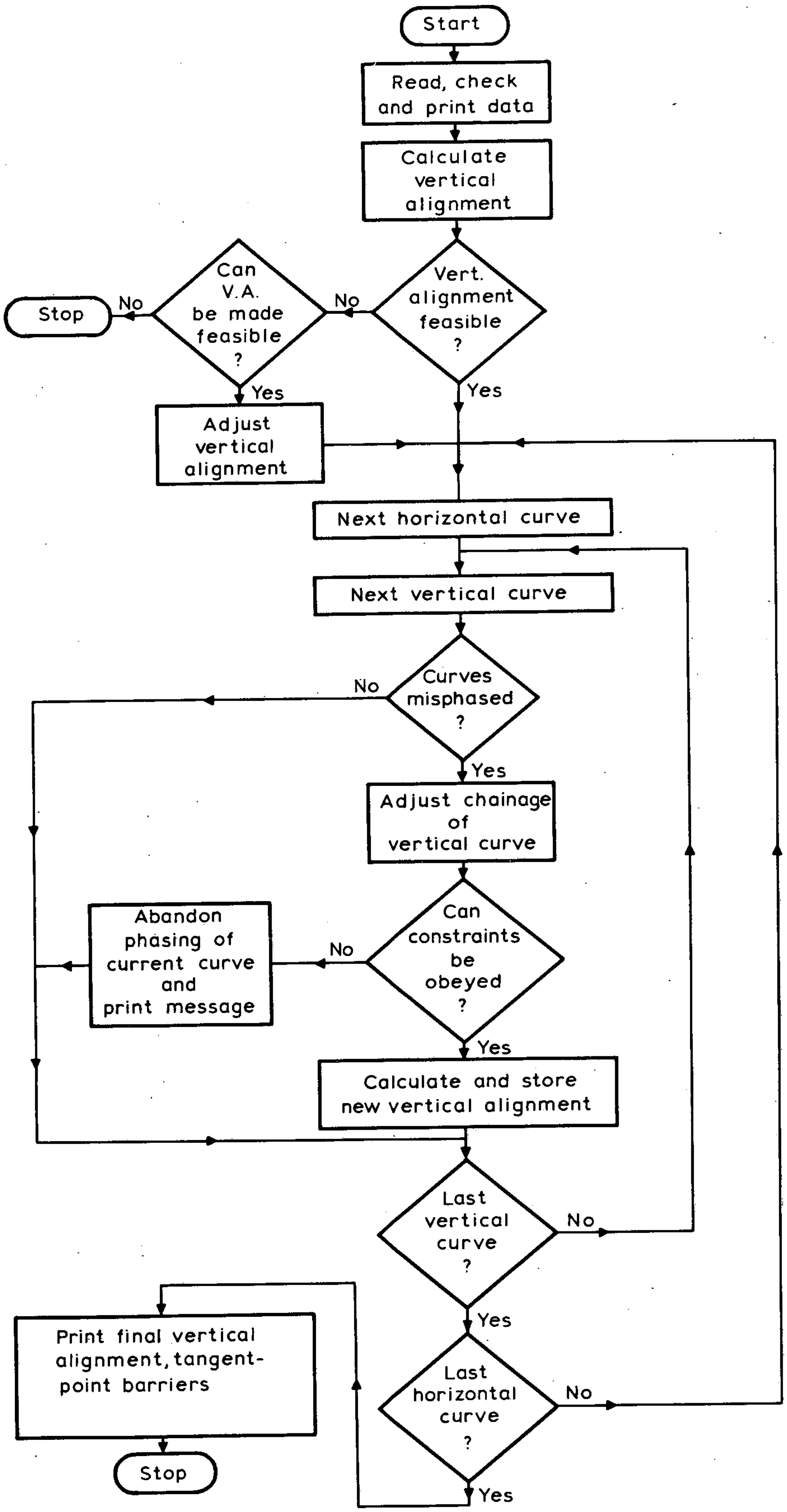


Fig. 3. OUTLINE FLOW DIAGRAM - PROGRAM JANUS

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                  BRITISH INTEGRATED PROGRAM SYSTEM FOR HIGHWAY DESIGN
                        HIGHWAY OPTIMIZATION PROGRAM SYSTEM

                                      J A N U S

                  (PHASING OF THE VERTICAL AND HORIZONTAL ALIGNMENTS)

                        TRANSPORT AND ROAD RESEARCH LABORATORY
                           DEPARTMENT OF THE ENVIRONMENT

RUN 1.  FEBRUARY 1972

                                     JANUS TEST.

SECTION 1.  INPUT DATA.
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                       * * * * * LENGTHS IN METRES * * * * *
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Fig. 4 EXAMPLE OF TYPICAL OUTPUT FROM PROGRAM JANUS

INITIAL VERTICAL ALIGNMENT

(FOR FEASIBILITY TEST OF INITIAL VERTICAL ALIGNMENT - SEE SECTION 2)

NO.	INTERSECTION CHAINAGE	POINT LEVEL	CURVE LENGTH	RADIUS (SAG CURVES NEG)	RATE OF CHANGE OF PER CENT GRADIENT	PER CENT GRADIENT	START OF CURVE	END OF CURVE
1	6800.0	45.32						
						-.9206		
2	7614.7	37.82	1290.59	-248027	.00040318		6969.40	8259.99
						-.4002		
3	9023.6	32.18	838.58	269999	.00037037		8604.31	9442.89
						-.7108		
4	9862.2	26.22	837.99	-75486	.00132475		9443.21	10281.19
						.3993		
5	10771.3	29.85	907.99	113638	.00087999		10317.31	11225.29
						-.3997		
6	12495.0	22.96	600.00	-59781	.00167277		12195.00	12795.00
						.6039		
7	13409.0	28.48	420.00	19992	.00500198		13199.00	13619.00
						-1.4969		
8	13892.0	21.25	540.00	-26047	.00383925		13622.00	14162.00
						.5763		
9	15740.0	31.90	507.50	19493	.00513010		15486.25	15993.75
						-2.0272		
10	16144.0	23.71	300.04	-12359	.00809127		15993.98	16294.02
						.4005		
11	17424.3	28.84	1198.81	149567	.00066860		16824.90	18023.70
						-.4011		
12	18623.1	24.03	996.91	-124356	.00080414		18124.65	19121.55
						.4006		
13	19200.0	26.34						

Fig. 4 Cont. 1)

F I X E D   E N D   G R A D I E N T S

ENTRY GRADIENT = -.9206 PER CENT
EXIT GRADIENT NOT FIXED.

L E V E L - C O N T R O L   P O I N T S

(FOR RELATION TO INITIAL ROAD LEVELS - SEE SECTION 2)

NO.	CHAINAGE	LOWER LIMIT	UPPER LIMIT
1	8800		33.10
2	10300	25.10	30.20
3	16644	25.40	

G E O M E T R I C   D E S I G N   S T A N D A R D S

MINIMUM PER CENT GRADIENT	MAXIMUM PER CENT GRADIENT	MINIMUM CURVE LENGTH	MINIMUM SUMMIT RADIUS	MINIMUM SAG RADIUS
.4000	3.0000	300.00	18000	9000

Fig. 4 (Cont. 2)

EXEMPTIONS FROM GEOMETRIC DESIGN STANDARDS

INTERSECTION POINT NO.	INTERSECTION POINT CHAINAGE	MINIMUM PER CENT GRADIENT	MAXIMUM PER CENT GRADIENT	MINIMUM CURVE LENGTH	MINIMUM SUMMIT RADIUS	MINIMUM SAG RADIUS
5	10771	.3900	-	-	-	-
6	12495	.3900	-	-	-	-
9	15740	-	-	500.00	-	-
10	16144	-	-	300.00	-	-
11	17424	-	2.5000	-	50000	-
12	18623	.3900	-	550.00	-	10000

FIXED TANGENT-POINT BARRIERS

NO.	INTERSECTION POINT	LHS LOWER CHAINAGE	LHS UPPER CHAINAGE	RHS LOWER CHAINAGE	RHS UPPER CHAINAGE
6	12495.0	-	-	12795.00	12795.00

HORIZONTAL ALIGNMENT

(RIGHT HAND CURVES NEG)

CURVE NO.	CHAINAGE OF START OF CURVE	CHAINAGE OF END OF CURVE	RADIUS
1	8740.20	10496.10	-2323
2	10496.10	12267.40	2204
3	12879.60	14028.40	-1581
4	14028.40	15654.80	-4231
5	15654.80	16307.30	-1549
6	16307.30	17862.00	1549

Fig. 4 (Cont. 3)

PHASING STANDARDS

HORIZONTAL RADIUS LIMITS			VERTICAL RADIUS LIMIT	MINIMUM CURVE SEPARATION
UPPER	MIDDLE	LOWER		
6896	3493	1746	30000	100

EXEMPTIONS FROM PHASING STANDARDS

CURVE NO.	HORIZONTAL RADIUS LIMITS			VERTICAL RADIUS LIMIT	MIMIMUM CURVE SEPARATION
	UPPER	MIDDLE	LOWER		
4	-	-	-	-	50

END OF DATA

Fig. 4 (Cont. 4)

SECTION 2. INPUT DATA ANALYSIS.

*****THERE ARE NO VIOLATIONS OF THE GEOMETRIC DESIGN STANDARDS OR LEVEL CONTROL POINTS.

SECTION 3. PHASING PROCESS.

VERTICAL CURVE NO. 7 OUT OF PHASE WITH HORIZONTAL CURVE NO. 3

VERTICAL CURVE NO. 8 OUT OF PHASE WITH HORIZONTAL CURVE NO. 3

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 4

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 5
AUTOMATIC PHASING OF CURVE NO. 9 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

VERTICAL CURVE NO. 10 OUT OF PHASE WITH HORIZONTAL CURVE NO. 5

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 6
AUTOMATIC PHASING OF CURVE NO. 9 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

VERTICAL CURVE NO. 10 OUT OF PHASE WITH HORIZONTAL CURVE NO. 6
AUTOMATIC PHASING OF CURVE NO. 10 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

Fig. 4 (Cont.5)

INTERMEDIATE VERTICAL ALIGNMENT

NO.	INTERSECTION CHAINAGE	POINT LEVEL	CURVE LENGTH	RADIUS (SAG CURVES NEG)	PER CENT GRADIENT	START OF CURVE	END OF CURVE	SUMMIT CHAINAGE	PHASING MARKER
1	6800.0	45.32							
					-.9206				
2	7614.7	37.82	1290.59	-248015		6969.40	8259.99		
					-.4002				
3	9023.6	32.18	838.58	269991		8604.31	9442.89		
					-.7108				
4	9862.2	26.22	837.99	-75486		9443.21	10281.19		
					.3993				
5	10771.3	29.85	907.99	113638		10317.31	11225.29	10771	
					-.3997				
6	12495.0	22.96	600.00	-61518		12195.00	12795.00		
					.5756				
7	13454.0	28.48	1148.80	86041		12879.60	14028.40	13375	1
					-.7596				
8	14278.4	22.22	300.00	-22720		14128.40	14428.40		2
					.5608				
9	16004.8	31.90	500.00	27329		15754.80	16254.80	15908	1
					-1.2687				
10	16557.3	24.89	300.00	-17402		16407.30	16707.30		2
					.4552				
11	17424.3	28.84	1198.81	140000		16824.90	18023.70	17462	
					-.4011				
12	18623.1	24.03	996.91	-124356		18124.65	19121.55		
					.4006				
13	19200.0	26.34							

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 5

AUTOMATIC PHASING OF CURVE NO. 9 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 6

AUTOMATIC PHASING OF CURVE NO. 9 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

VERTICAL CURVE NO. 10 OUT OF PHASE WITH HORIZONTAL CURVE NO. 6

AUTOMATIC PHASING OF CURVE NO. 10 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

Fig. 4 (Cont. 6)

INTERMEDIATE VERTICAL ALIGNMENT

NO.	INTERSECTION CHAINAGE	POINT LEVEL	CURVE LENGTH	RADIUS (SAG CURVES NEG)	PER CENT GRADIENT	START OF CURVE	END OF CURVE	SUMMIT CHAINAGE	PHASING MARKER
1	6800.0	45.32							
					-.9206				
2	7614.7	37.82	1290.59	-248015		6969.40	8259.99		
					-.4002				
3	9023.6	32.18	838.58	269991		8604.31	9442.89		
					-.7108				
4	9862.2	26.22	837.99	-75486		9443.21	10281.19		
					.3993				
5	10771.3	29.85	907.99	113638		10317.31	11225.29	10771	
					-.3997				
6	12495.0	22.96	600.00	-61518		12195.00	12795.00		
					.5756				
7	13454.0	28.48	1148.80	86041		12879.60	14028.40	13375	1
					-.7596				
8	14278.4	22.22	300.00	-22720		14128.40	14428.40		2
					.5608				
9	16004.8	31.90	500.00	27329		15754.80	16254.80	15908	1
					-1.2687				
10	16557.3	24.89	300.00	-17402		16407.30	16707.30		2
					.4552				
11	17424.3	28.84	1198.81	140000		16824.90	18023.70	17462	
					-.4011				
12	18623.1	24.03	996.91	-124356		18124.65	19121.55		
					.4006				
13	19200.0	26.34							

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 5

AUTOMATIC PHASING OF CURVE NO. 9 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

VERTICAL CURVE NO. 9 OUT OF PHASE WITH HORIZONTAL CURVE NO. 6

AUTOMATIC PHASING OF CURVE NO. 9 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

VERTICAL CURVE NO. 10 OUT OF PHASE WITH HORIZONTAL CURVE NO. 6

AUTOMATIC PHASING OF CURVE NO. 10 IS NOT ADVISABLE. PHASE MANUALLY AND FIX POSITION OF CURVE BY TANGENT-POINT BARRIERS.

Fig. 4 (Cont. 7)

I N T E R M E D I A T E   V E R T I C A L   A L I G N M E N T

NO.	INTERSECTION CHAINAGE	POINT LEVEL	CURVE LENGTH	RADIUS (SAG CURVES NEG)	PER CENT GRADIENT	START OF CURVE	END OF CURVE	SUMMIT CHAINAGE	PHASING MARKER
1	6800.0	45.32							
					-.9206				
2	7614.7	37.82	1290.59	-248015		6969.40	8259.99		
					-.4002				
3	9023.6	32.18	838.58	269991		8604.31	9442.89		
					-.7108				
4	9862.2	26.22	837.99	-75486		9443.21	10281.19		
					.3993				
5	10771.3	29.85	907.99	113638		10317.31	11225.29	10771	
					-.3997				
6	12495.0	22.96	600.00	-61518		12195.00	12795.00		
					.5756				
7	13454.0	28.48	1148.80	86041		12879.60	14028.40	13375	1
					-.7596				
8	14278.4	22.22	300.00	-22720		14128.40	14428.40		2
					.5608				
9	16004.8	31.90	500.00	27329		15754.80	16254.80	15908	1
					-1.2687				
10	16557.3	24.89	300.00	-17402		16407.30	16707.30		2
					.4552				
11	17424.3	28.84	1198.81	140000		16824.90	18023.70	17462	
					-.4011				
12	18623.1	24.03	996.91	-124356		18124.65	19121.55		
					.4006				
13	19200.0	26.34							

Fig. 4 (Cont. 8)

SECTION 4. FINAL ALIGNMENT ANALYSIS.

D E T A I L S O F F I N A L V E R T I C A L A L I G N M E N T

NO.	INTERSECTION CHAINAGE	POINT LEVEL	CURVE LENGTH	RADIUS (SAG CURVES NEG)	RATE OF CHANGE OF PER CENT GRADIENT	PER CENT GRADIENT	START OF CURVE	END OF CURVE
1	6800.0	45.32						
						-.9206		
2	7614.7	37.82	1290.59	-248015	.00040320		6969.40	8259.99
						-.4002		
3	9023.6	32.18	838.58	269991	.00037038		8604.31	9442.89
						-.7108		
4	9862.2	26.22	837.99	-75486	.00132475		9443.21	10281.19
						.3993		
5	10771.3	29.85	907.99	113638	.00087999		10317.31	11225.29
						-.3997		
6	12495.0	22.96	600.00	-61518	.00162554		12195.00	12795.00
						.5756		
7	13454.0	28.48	1148.80	86041	.00116224		12879.60	14028.40
						-.7596		
8	14278.4	22.22	300.00	-22720	.00440135		14128.40	14428.40
						.5608		
9	16004.8	31.90	500.00	27329	.00365913		15754.80	16254.80
						-1.2687		
10	16557.3	24.89	300.00	-17402	.00574657		16407.30	16707.30
						.4552		
11	17424.3	28.84	1198.81	140000	.00071429		16824.90	18023.70
						-.4011		
12	18623.1	24.03	996.91	-124356	.00080414		18124.65	19121.55
						.4006		
13	19200.0	26.34						

T A N G E N T - P O I N T B A R R I E R S

NO.	INTERSECTION POINT	LHS LOWER CHAINAGE	LHS UPPER CHAINAGE	RHS LOWER CHAINAGE	RHS UPPER CHAINAGE
6	12495.0	-	-	12795.00	12795.00
7	13454.0	12879.60	12879.60	14028.40	14028.40
8	14278.4	14128.40	-	-	-
9	16004.8	15754.80	-	-	-
10	16557.3	16407.30	-	-	-

Fig. 4 (Cont. 9)

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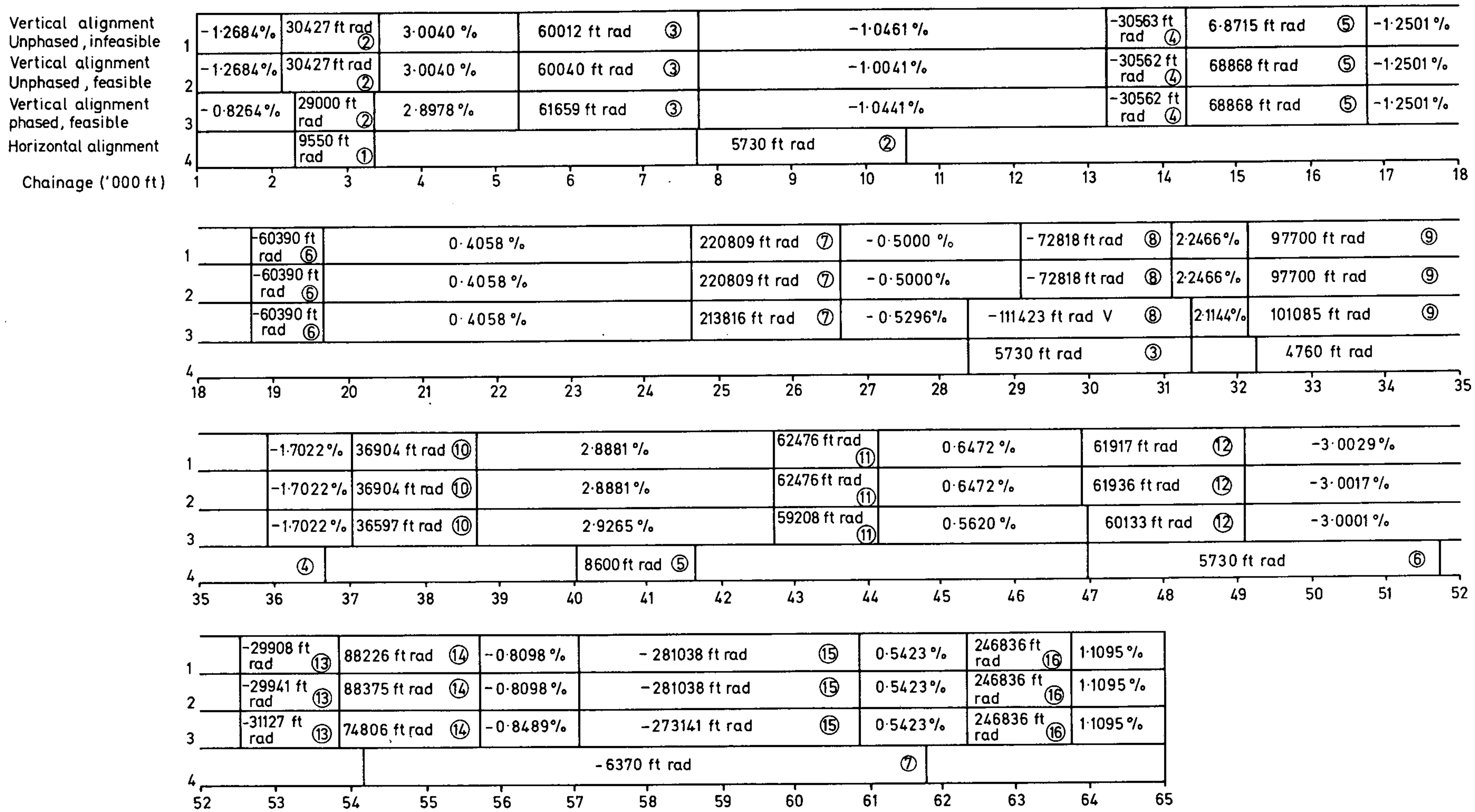

Notes :-

Vertical alignment
Positive radius indicates summit curve
Negative radius indicates valley curve
Positive percentage indicates uphill gradient
Negative percentage indicates downhill gradient

Horizontal alignment
Positive radius indicates left-hand curve
Negative radius indicates right-hand curve

Curve number shown thus ④

Fig. 5. DURHAM MOTORWAY. STAGES IN THE DEVELOPMENT OF THE PHASED, FEASIBLE ALIGNMENT

Neg No H302/72

PLATE 1

An example of misphasing. A valley curve overlapping
a right-hand horizontal curve
(Photograph by courtesy of R A Abbott)

Neg No B3253/69

PLATE 2

Misphasing. The apparent straightening of the horizontal curve is caused by a valley curve near the Lay-by

ABSTRACT

The design and phasing of horizontal and vertical alignments : program JANUS: A B BAKER, BSc, CEng, MICE: Department of the Environment, TRRL Report LR 469: Crowthorne, 1972 (Transport and Road Research Laboratory). The Report outlines some of the factors which influence the geometric design of rural roads, with emphasis on the vertical alignment, and describes the geometric design standards currently recommended for Motorways in the United Kingdom. It discusses the phasing of the vertical alignment with the horizontal alignment required to present a visually pleasing design and to avoid the creation of hazards. The concept of phasing is extended to include the total separation of the vertical and horizontal curves, the phasing of one end only, or the phasing of both ends of the curves, depending on the type of mis-phasing and the radii of the curves. Critical values of radius at which phasing is required are determined by the engineer. The Report states a set of phasing rules which have been formulated and describes a computer program that adjusts a vertical alignment so as to phase it with the horizontal alignment according to these rules.

ABSTRACT

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