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AUTOMATIC GENERATION OF THE HIGHWAY VERTICAL ALIGNMENT: PROGRAM VENUS

by

R Robinson BSc PhD MIHE

Access and Mobility Division
Transport Operations Department
Transport and Road Research Laboratory
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ABSTRACT

As part of the development of the Highway Optimization Program System, a method has been produced for the automatic design of the vertical alignment of a highway, and a computer program (VENUS) has been written to implement this. The method smooths the ground along the centre line of the road to produce a longitudinal profile similar to the required vertical alignment, and then fits the profile with tangent lines and parabolic curves. The alignment is then modified to obey geometric design standards and constraints on level by adjusting the position of the curves. When all the constraints are obeyed, the alignment is refined further to improve its fit to the ground.

VENUS can be used to produce alignments as a preliminary to optimization or as the basis for conventional design. It has been tested on several hundred kilometres of road and has also been used successfully in the design of a railway. The vertical alignments generated automatically tend to contain more vertical curves than those designed manually to the same geometric standards. This should reduce the earthworks quantities and hence the construction cost of the road scheme.

The program VENUS is written in FORTRAN and is available from the Department of the Environment. It is used routinely by Road Construction Units of the Department.

1. INTRODUCTION

A study of the application of computer technique to highway design is being carried out at the Transport and Road Research Laboratory[1]. The study has included the development of a computer program (MINERVA)[2] for optimizing the vertical alignment of a highway whose horizontal alignment is fixed. This program minimizes earthworks costs and height-dependent costs of side roads and structures. The optimization technique requires an initial vertical alignment on which to operate and the object of the investigation which this Report describes was to find a method of generating this initial vertical alignment automatically from the ground longitudinal section.

As part of the investigation, a computer program has been developed which can be used to design vertical alignments that are not just simulations of the engineer's manual designs, but which usually lead to cheaper designs. These designs often contain a larger number of curves than those produced manually because more undulations in the ground are picked out and followed since the problems of satisfying constraints and the extra calculations that would have been required for such an alignment are no longer prohibitive with an automatic method. The program derives such a number of undulations that the vertical alignment follows the ground closely and hence reduces earthworks costs whilst still obeying the same standards of geometric design and constraints on level that the engineer has imposed.

The title of the computer program is 'VENUS' (Vertical alignment design by estimating the number of undulations) and it was developed as part of the Highway Optimization Program System[1]. This system of computer programs is included in the British Integrated Program System for Highway Design [3,4].

This report describes the method used by program VENUS to generate highway vertical alignments and also discusses the use, availability and performance of the program. The detailed development of the program is described elsewhere[5].

2. THE CONVENTIONAL VERTICAL ALIGNMENT

2.1 Choice of alignment type

A road alignment is usually designed in two planes: horizontal and vertical. The horizontal alignment consists traditionally of arcs of circles and straight lines joined by transition curves, which are usually clothoidal[6] although other types of design, such as that based on polynomial curves[7], have also been considered.

The vertical alignment of a road consists conventionally of parabolic curves and straight lines which are called tangent lines. These tangent lines meet at intersection points (Fig. 1). As the instantaneous radii of the parabolic curves are large compared with their lengths, they can be approximated by circular arcs whose radii and curvatures are constant over the lengths considered[8]. In this case, the vertical alignment can be defined completely in terms of the chainage and level of the intersection points together with the length, or the radius, or the rate of change of gradient (curvature) of each of its vertical curves.

Polynomials[7] and, more recently, cubic splines[9] have also been used for vertical alignment design. However, the conventional type of alignment, consisting of a sequence of low-order polynomials (straights and parabolas), has the advantages that the alignment is in a form with which the engineer is familiar and is very simple to handle computationally. In addition, modifications can be made to any curve in the alignment without, in general, affecting the position of other curves some distance away. There are also many existing computer programs, such as the British Integrated Program System for Highway Design[3, 4], for carrying out the detailed design based on such an alignment and program VENUS forms part of the Highway Optimization Program System[1] which is also based on conventional design. Hence, there were good reasons for not departing from an attempt to produce a conventional alignment in this investigation.

2.2 Constraints

2.2.1 Geometric design standards. In the vertical plane the road is constrained by specified standards of geometric design[10]. A maximum gradient is imposed so that heavy vehicles can maintain reasonable speeds up hills. This reduces congestion in these regions and will also reduce vehicle operating costs. A minimum gradient may be imposed to assist drainage so that the road is kept clear of standing surface water.

A minimum radius of vertical curvature is adopted on sag curves so that the road can be illuminated over an adequate visibility distance by headlights and so that centripetal acceleration does not rise above an acceptable limit. A larger minimum radius is usually needed on summit curves so that adequate visibility distances can be maintained. Thus, the minimum radii are usually different for summit and sag curves. The length of vertical curves is also subjected to a minimum value to ensure that the road takes on a 'flowing' alignment. To ensure continuity of the alignment, vertical curves must be of such a length that they do not overlap each other (Fig. 2).

2.2.2 Control points. The level of the road may need to be constrained at places where it crosses rivers, railways, other roads, etc. and where, for instance, it has to be kept above the water table. At any point on the alignment, the level of the road may be required to

- (i) be fixed,
- (ii) be not lower than a given limit,
- (iii) be not higher than a given limit,
- (iv) lie between two limits.

Each of these cases is a special example of (iv). Case (i) is represented by two limits which are coincident. For case (ii), the lower limit is given and the upper limit is not defined and, for case (iii) the upper limit is given and the lower limit is not defined.

If the road under consideration is to link to existing or previously designed roads at its extremities, the initial and final road levels and the entry and exit gradients must be fixed.

3. THE DESIGN PROCESS

3.1 Basic requirements of design

The aim of the work to be described is to design the vertical alignment of a road by considering only the section through the ground along the horizontal alignment and the constraints to which the vertical alignment is subjected. The vertical alignment to be designed should be of conventional type as described in Section 2.

The highway engineer designs the horizontal and vertical alignments of a road to a large extent separately, but each with the needs of the other in mind. Geographical and statutory considerations lead to the horizontal alignment being 'fixed' at a certain stage in design, after which it is still permissible to alter the vertical alignment. Also, the horizontal alignment is always designed before the vertical alignment to provide the ground levels on which the design of the vertical alignment must be based.

The aim of the highway engineer when designing the vertical alignment is to obtain a smooth line which will allow traffic to flow freely and safely and, at the same time, will have a low construction cost. In hilly terrain, these aspects of the design are incompatible as the smoother is the vertical alignment, the heavier will be the construction cost. In practice, on a fixed horizontal alignment within the range of choice normally open to the engineer, the marginal cost of earthworks due to change in alignment is much greater than the marginal cost of land acquisition, pavement, drainage or traffic[1]. The principal design objective is therefore to minimize earthworks costs by fitting the alignment as closely to the ground as the constraints allow.

The maximum number of curves that a vertical alignment can contain is one curve for each undulation in the ground. Such an alignment would have negligible earthworks costs but would contain absurd gradients and vertical curvatures and would not provide a safe or economical route for traffic. In order to reduce these gradients and curvatures, the total number of vertical curves must be reduced and this requires that cuttings are built through hills and that valleys are filled. Limiting values for the gradients and curvatures of a road of a given class and design speed are laid down by the Department of the Environment[10] and minimum earthworks costs will be obtained when the alignment contains the maximum number of curves required to fit the alignment as closely as possible to the ground whilst still obeying all of these standards of geometric design.

The existence of level-control points often requires that, at these points, the vertical alignment must deviate from the line that it would have taken had they not been present. This, in turn, often requires that the alignment contains curves additional to those required merely to fit the ground.

Thus, the optimum number of vertical curves is the maximum number that can be fitted to the ground and still obey level-control points and geometric design standards.

3.2 Smoothing

In order to devise a method of generating vertical alignments automatically, the engineer's manual design process was examined and the possibility of its direct adaptation to the computer was studied. Unfortunately, few engineers appear to design vertical alignments in precisely the same way. Engineers rely to a large extent on their experience and their 'engineering judgement'. They get a 'feel' for the design of an alignment and, clearly, this is very difficult to simulate. However, it was possible to identify an underlying philosophy of the manual method and the automatic method to be described is based on this.

The basic concept is that the vertical alignment of a road is essentially a 'smoothing' of the ground longitudinal section. Material must be cut from the tops of hills and used to fill the valleys so that a profile is obtained which obeys the various standards of geometric design and level constraints. From an economic point of view, it is desirable that the volume of material obtained from cuttings should be about the same as the volume of material required for the embankments. If there is an excess of cut material, it must be disposed-of off the line of the road in what are known as 'spoil' tips. Similarly, if there is insufficient cut material for use in the embankments, extra material must be brought in to the site of the road from pits and quarries. This material is known as 'borrow'. Both borrowing and spoiling are expensive operations and engineers usually attempt to minimize and to balance cut and fill volumes as this will lead to a minimum cost.

3.3 The manual design process

To design a vertical alignment manually, the engineer plots a longitudinal section of the ground along the proposed centre-line of the road and an initial vertical alignment is super-imposed over the plot. Different engineers design this trial alignment in different ways. One typical method is to lay 'railway curves'* on the longitudinal section to represent the vertical alignment. The positions of the templates are adjusted so that the alignment fits the ground as well as possible and the curves are then drawn in and joined up with tangent lines to locate the intersection points. Another method is to fit the tangent lines first and then to add in the vertical curves using published tables which relate visibility distance and rate of change of gradient at the intersection point to the minimum allowable length of curve[6]. When the trial alignment has been obtained, the engineer then makes minor adjustments to it to ensure that all the constraints are obeyed and also to reduce the area between the alignment and the ground to minimize the volumes of cut and fill. Both of these methods require the engineer to take an overall view and assessment of his drawing and to make decisions based on his judgement of the ground longitudinal section as a whole.

3.4 The automatic design process

Clearly, the computer cannot be programmed to emulate the manual design process and the following multi-stage procedure was developed in its stead.

First, some kind of smoothing of the ground profile is performed to produce a longitudinal profile with fewer undulations than that of the ground. The degree of the smoothing is controlled to produce a profile which approximates to the required vertical alignment and the type of smoothing is such that the areas corresponding to the cut and fill areas on the engineering drawing are approximately equal. This profile, known as the 'quasi vertical alignment', is then modified to obey all level-control points and, at this stage, approximates to the required vertical alignment.

Next, the quasi vertical alignment must be transformed into a series of parabolic curves and straight lines. Clearly, parabolic curves must be fitted to each summit curve and to each sag curve of the quasi vertical alignment and the position of these summit and sag curves must be determined. The points where the quasi vertical alignment changes from a summit curve to a sag curve are found by examining the changes in gradient of the alignment.

The alignment must then be converted to conventional form. The method which has been developed for doing this is based on that used for manual design and fits tangent lines to the quasi vertical alignment between the summit and sag curves. These tangent lines will meet at the intersection points of the required vertical alignment which is completed by inserting vertical curves of suitable length.

On some occasions, the ground is best fitted by two consecutive summit curves or two consecutive sag curves. A method has been developed for recognizing these situations and for fitting the required compound curves.

The preliminary vertical alignment derived in this way will fit the ground closely and obey most of the design constraints. However, the alignment will not necessarily obey all of the constraints and it must be modified to achieve this. Each vertical curve is specified uniquely by three parameters: intersection-point chainage, intersection-point level and curve length; the alignment can be modified by changing the values of any of these parameters for any of the vertical curves. The methods used for modifying these parameters to produce a feasible alignment (i.e. one that obeys all of the imposed constraints) are described in Section 5.

The production of the feasible vertical alignment may have reduced the quality of the fitting of the preliminary vertical alignment to the ground. Thus, an optimization technique is used to minimize the departure of the alignment from the ground whilst keeping all of the constraints obeyed. This has the effect of minimizing the volumes of cut and fill which is one of the aims of the design. Finally, a vertical alignment will have been produced which has all of the properties that are required.

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* Railway curves: a set of templates for arcs or spirals cut out in wood or celluloid, of different radii, used for drawing to scale the curves of railways[11].

A computer program (VENUS) has been written which uses this method of design to produce vertical alignments and this is described in Section 6. The program aims to minimize and to balance cut and fill, but takes no account of the possibly different costs for these operations, nor of the cost of borrow, spoil and haulage. The alignment produced by VENUS may be optimized with respect to cost by the use of a further program (MINERVA)[2] developed at the Transport and Road Research Laboratory.

4. THE PRELIMINARY ALIGNMENT

4.1 The quasi vertical alignment

A longitudinal profile which approximates to the required vertical alignment is generated by smoothing the ground longitudinal section. The method used is based on a technique developed at the Massachusetts Institute of Technology[12, 13].

The longitudinal section is divided into sections of convenient length defined by intervals of chainage known as "stations". These are shown in Fig. 3. Smoothing is carried out by calculating a weighted average of ground levels over a given range about each station in turn to generate a longitudinal profile which follows the dominant features of the ground.

As the road will be travelled in both directions, a symmetrical smoothing function is used so that points on either side of the station of interest have an equal effect on the smoothed level. To minimize the sudden influence of sharp features of the terrain, such as a cliff, on the vertical alignment but, at the same time to maintain the dominance of the station of interest, the function is weighted to be zero at the limits of the range of influence and increases to its maximum value at the station of interest. Thus, the smoothing function consists of an isosceles triangle (Fig. 3). For stations adjacent to the ends of the road, the smoothing function is gradually truncated and at each of the end points, consists of just half of the isosceles triangle. The severity of the smoothing is proportional to the range of influence of the smoothing function.

Experience of smoothing different ground longitudinal sections with functions of different range lengths showed that the use of triangular functions whose length in Fig. 3 was between 500 and 1000 metres produced profiles which were very similar to alignments designed manually[5]. These profiles do not consist of parabolic curves and straight lines but it was realized that by using such a profile as a starting point, conversion to conventional form without loss of too many characteristics should be possible.

Hence, the ground is smoothed in the way that has been described to produce a profile from which the final vertical alignment will be developed. This profile is known as the quasi vertical alignment. It is shown elsewhere[5] that the cut and fill areas given by this profile are approximately equal.

If the vertical alignment is to be capable of obeying level-control points, it must contain extra vertical curves over and above those generated by this method. These extra curves will allow the alignment to turn away from the ground and pass through the control points. Such a curve is inserted into the quasi alignment wherever it violates a level-control point and the alignment is adjusted to pass actually through that limit of the control point which is violated.

The difference in the level of the violated limit of the control point and the level of the quasi vertical alignment at the same chainage is found. The quasi alignment is then adjusted at stations on either side of the control point by a sinusoidally proportional amount so that the adjusted alignment passes through the limit of the control point in a smooth transition (Fig. 4).

4.2 Converting to conventional form

4.2.1 Locating the summit and sag curves. In order to convert the quasi vertical alignment to conventional form, the curved parts of the alignment must be replaced by parabolas and these joined by tangent lines. Consecutive summit and sag curved parabolas will normally be required and these will be fitted to appropriate sections of the quasi vertical alignment. The first task is therefore to find where the quasi vertical alignment changes from a summit curve to a sag curve so that parabolas of opposite curvature can be fitted between these points.

Such a point of inflection in the quasi vertical alignment will occur whenever the change in gradient of the alignment changes sign. Thus, the gradients between successive stations along the alignment are examined to locate these points.

If these points of inflection are too close together, it will be impossible to fit curves of a reasonable minimum length to the quasi alignment in this region. A method has been devised to reduce the number of points of inflection considered when these points are too close together. Thus:

(a) If two points of inflection are close together (Fig. 5), then neither is considered to be significant as, in this region, the overall curvature of the alignment is not changing.

(b) If three points of inflection are close together (Fig. 5), then the middle one is taken to be the most significant and assumed to represent adequately the major point of inflection in this part of the alignment.

Experience has shown that the design method described above tends to pick out more undulations in the ground than would a manual method and this leads to the generation of an alignment containing more vertical curves.

4.2.2 Forming the preliminary vertical alignment. Tangent lines are fitted to the quasi vertical alignment using the least-squares[14] method over a given range on either side of each point where a summit curve changes into a sag curve and vice versa. The points at which these tangent lines meet are the intersection points of the preliminary vertical alignment (Fig. 6). In order to produce a 'flowing' alignment, vertical curves should be as long as possible. To achieve this, curve lengths are fitted to the generated configuration of tangent lines in the following way. The differences in chainage between the current and preceding intersection point and the current and succeeding intersection point are calculated. The lesser of these values is taken to be the length of the curve which is fitted to the current pair of tangent lines. This is effectively the maximum length of curve which is certain not to overlap either the preceding or succeeding curve.

It has been found that, after points of inflection have been eliminated because they are too close together, the gradients of the quasi vertical alignment at the points of inflection may lead to an acute angle between consecutive tangent lines and the generated intersection point will fall outside the region between the inflection points. When curves are fitted, the curve in this region will have a negative length (Fig. 7). This problem could be overcome by fitting the tangent line through the coordinates of the points of inflection which have been eliminated. However, a simpler technique was found to be very effective and is used by the method. Thus, if a generated intersection point does not fall between the relevant inflection points, it is replaced by an intersection point whose chainage is the mean of the stations of the inflection points and whose level is the same as the level of the quasi vertical alignment at that mean chainage. New tangent lines are constructed to join the intersection points and curves of suitable length fitted to them in the same way as described earlier.

Occasionally, in a 'long' valley or hill section, the ground is best fitted using a compound curve.* In this case (see Fig. 8), the level of the road generated by the method just described will become very different from that of the quasi vertical alignment at the same station. If the difference in levels between the intersection point and the quasi vertical alignment at the same station becomes greater than a given value, the intersection point is replaced by two intersection points. These are at the intersections of the original tangent lines with a new line which is parallel to the line joining the two relevant points of inflection, and which passes through the highest point of the quasi vertical alignment for a summit curve, or the lowest point for a sag curve (Fig. 8).

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* A compound curve is a curve consisting of two or more arcs of different radii curving in the same direction and having a common tangent or transition curve where they meet.

5. THE FEASIBLE ALIGNMENT

5.1 Constraint obedience

The preliminary vertical alignment generated by the method described in Section 4 should fit the ground fairly closely. However, it will not necessarily obey geometric design standards or constraints on level or gradient.

It is usually possible to modify the preliminary vertical alignment so that all constraints are obeyed by manipulating the parameters of intersection-point chainage, intersection-point level and curve length which define the alignment. This is because in a conventional road alignment, a curve can be specified completely by these three parameters as was explained in Section 2.1. The position of individual curves in the alignment can be changed by varying any one of the three parameters associated with that curve.

In order to correct any curve overlaps or violations of the minimum curve length constraint, each vertical curve in the alignment is considered in turn. Whenever an overlap or minimum length violation is encountered, the curve in question is shunted longitundinally by varying the intersection-point chainage parameter (Fig. 9), or the curve is increased in length (Fig. 10). Cross-checking is necessary because satisfaction of one of the constraints can lead to violation of the other. These adjustments are independent of the curve's third parameter: the level of the intersection-point.

When all curve overlaps and minimum curve length violations have been eliminated, the intersection-point chainage and curve length parameters are held fixed while the intersection-point level parameters are varied to try and satisfy violated gradient, radius and level-control point constraints (Figs. 11, 12 and 13 respectively). Any such change to the intersection-point levels will not alter the chainage of intersection points or the lengths of curves and hence cannot upset the obedience of the minimum curve length and overlap constraints achieved earlier.

Usually, only one constraint on gradient, radius or level in the region of a particularly vertical curve can be corrected by this method, but sometimes violated constraints are complementary and the satisfaction of one will lead directly to the satisfaction of the other. For this method to produce a feasible alignment, there must be not more than one non-complementary violated constraint on gradient, radius or level associated with each vertical curve.

5.2 Penalty function method

If a feasible alignment is not produced by the above method, a further constraint-obedience technique is used. The magnitude of each constraint violation is multiplied by a weighting factor depending on the type of constraint and these weighted violations are added together to form a 'penalty function'. This function can then be minimized using an optimization technique with the intersection-point and curve length parameters as variables. Each variable is considered in turn and altered until a minimum of the function is located whilst keeping the remaining variables fixed. The method cycles through each of the variables until no further reduction in the function value can be achieved after a complete set of searches on all the variables. If a minimum of zero is obtained, a feasible alignment will have been produced.

The mathematical theory behind these constraint obedience techniques is discussed fully elsewhere[5].

5.3 The final vertical alignment

Experience has shown that the constraint obedience process tends to move the vertical alignment away from the ground. This results in an increase in earthworks volumes and a generated alignment which is far from optimal.

An indication of how closely the vertical alignment fits the ground can be obtained by considering the difference between the level of the ground and the level of the road along its whole length (Fig. 14). The fitting can be improved by minimizing the sum of these differences, taken without regard to sign, which has the effect of reducing the total volumes of cut and fill.

This minimization is carried out by varying the intersection-point and curve length parameters in the same way as in the penalty function method except that no change may be made to the value of any variable which will lead to a constraint being violated. At the conclusion of this minimization, the vertical alignment will fit the ground more closely than it did previously.

6. PROGRAM VENUS

6.1 Implementation

A computer program has been written using the method described to design the vertical alignment of a road. This program is named 'VENUS'. Using a ground longitudinal section, initial and final chainages and constraints given by the engineer as input, the program designs a vertical alignment which follows the undulations of the ground and obeys constraints. An example of the output from the program is shown in Fig. 15.

The program may also be used to process a manually produced alignment by amending it to obey constraints, or by improving its fit to the ground. The program will also plot the alignment on a CalComp graph plotter. Details of the processed alignment can be punched automatically onto cards for direct submission as data to subsequent programs of the Highway Optimization Program System, notably JANUS[15] which phases the horizontal and vertical alignments, and MINERVA[2] which optimizes earthworks costs.

The program is written in FORTRAN IV and requires a minimum of one card reader, one lineprinter with at least 120 print positions and an input sequential file containing ground data which has been generated by program PRELUDE[16] 75 K bytes of storage are required when the program segments are overlaid. The run time depends on the length of road and the number of stations defining the ground longitudinal section, the number of vertical curves and the number and 'tightness' of the level-control points. The run time has usually been between two and ten minutes on the ICL 4/70 computer at the Transport and Road Research Laboratory on which the program was developed, but in exceptional cases where the constraint obedience of a long alignment has proved difficult, the run time has risen to a maximum of 30 minutes.

A fully maintained version of program VENUS is available for use through the Highway Engineering Computer Branch of the Department of the Environment, Southwark Street, London SE1 and all queries concerning the program should be addressed to them[17]. The program forms part of the Highway Optimization Program System and the British Integrated Program System for Highway Design and these are available on magnetic tape for engineers in the United Kingdom at a nominal cost. Different versions of the program are available to run on a variety of computers, including the IBM 360 series, ICL 1900 series, CDC 6600, Univac 1108 and the ICL System 4.

6.2 Performance

In the majority of cases, VENUS works very well and is proving to be a valuable tool to assist the highway engineer in the route location problem. The program allows vertical alignments to be designed both quickly and cheaply. By removing much of the tedium from this part of the highway engineer's job, the program allows him to use his time to better effect.

VENUS has been used extensively by engineers in the testing of the Transport and Road Research Laboratory's Highway Optimization Program System. While the program was under development, it was used in the design of the following schemes:-

Abingdon by pass	13 km
Barnstaple by pass	11 km
Coventry-Leicester motorway	7 km
Dungannon by pass (Northern Ireland)	9 km
Exeter-Okehampton trunk road	27 km
M3 (Popham to Winchester by pass)	20 km
Maidstone-Ashford motorway	23 km
Newton Abbott by pass	7 km

Pontardulais by pass	14 km
Stoke-Derby motorway	14 km
Taunton by pass	12 km
Wellington by pass	18 km

A description of work on some of these schemes has been given by Withey[18, 19]. In addition, VENUS has been used to design part of an Italian autostrada and has been used during feasibility studies of over 100 km of road in both St. Lucia[20] and Honduras. A typical vertical alignment designed by the program is illustrated in Fig. 16.

It is also possible to use VENUS to design the vertical alignments of railways and the program has been used successfully by consultants designing a line in South America.

The vertical alignments generated follow closely the undulations in the ground and the method produces sufficient, but not too many, curves to fit the ground and obey the level-control points whilst still obeying the geometric design standards. Generally, the number of curves produced is greater than would have been used in a manual design for the same ground longitudinal section. For instance, where a long gradient has been fitted between a summit and a valley, the program has tended to break the gradient down into a series of curves. Also, long curves have been broken down into shorter ones which fit the ground better whilst still obeying the same standards of geometric desgin. This larger number of curves tends to lead to a lower earthworks cost for the road, as engineers have appreciated. The extra calculation which was prohibitive for manual design is now acceptable with an automatic method.

Occasionally, the alignments produced cannot be made to obey all of the imposed constraints. This may be due to the fact that, unlike the engineer, the program cannot make an overall assessment of an alignment, but can only look at one small part of it at a time; for instance, the program cannot decide to move two curves simultaneously. Alternatively, it is possible for the engineer to specify a set of constraints to which no feasible solution exists. The engineer must try and determine which of these two cases has occurred and either modify the alignment manually or re-examine the necessity for the constriants as appropriate.

VENUS is very useful for producing the vertical alignments for a design which is at the 'Preliminary Report' stage where less refinement is necessary. Alternative routes can be evaluated much more quickly than has previously been possible provided that adequate ground data are available.

VENUS forms part of the Highway Optimization Program System. Tests have shown that by using this System as an aid to highway design, reductions in the calculated cost of earthworks of between 15 and 20 per cent are possible[1, 2, 18, 19]. As earthworks contribute a large proportion of the cost of a highway, this represents a significant saving in the cost of a new scheme.

7. CONCLUSIONS

Program VENUS forms an integral part of the Highway Optimization Program System and the British Integrated Program System for Highway Design. It has been tested on several hundred kilometres of road of all classes and has also been used successfully in the design of a railway. It is now used by the Road Construction Units of the Department of the Environment and by consultants for obtaining a first vertical alignment for motorway and high standard trunk road designs.

The research has lead to a better understanding of the vertical alignment design process, which had previously been largely subjective and somewhat intuitive. Although the new method is basically heuristic, it has an underlying philosophy which also applies to the manual method. That is that the vertical alignment is essentially a smoothed version of the ground longitudinal section which it fits as closely as possible whilst, at the same time, taking account of constraints on level and standards of geometric design. As the degree of smoothing varies, so does the quality of the generated alignment, the number of vertical curves and the obedience of constraints.

The design method which has been developed generates vertical alignments which tend to contain more vertical curves than would be included by an engineer designing manually, whilst still obeying the same standards of design. This allows the alignments to follow the ground more closely and hence earthworks quantities are reduced. The resulting alignments should therefore be cheaper to construct than those designed manually.

In addition, the speed of operation of VENUS enables alternative routes to be evaluated much more quickly than has previously been possible which, in turn, gives the engineer the opportunity to consider more routes when choosing his alignment.

VENUS is used to generate the initial vertical alignment for the Highway Optimization Program System. This suite of programs reduces earthworks costs on average by between 15 and 20 per cent and this represents a significant saving in the construction cost of a new road scheme.

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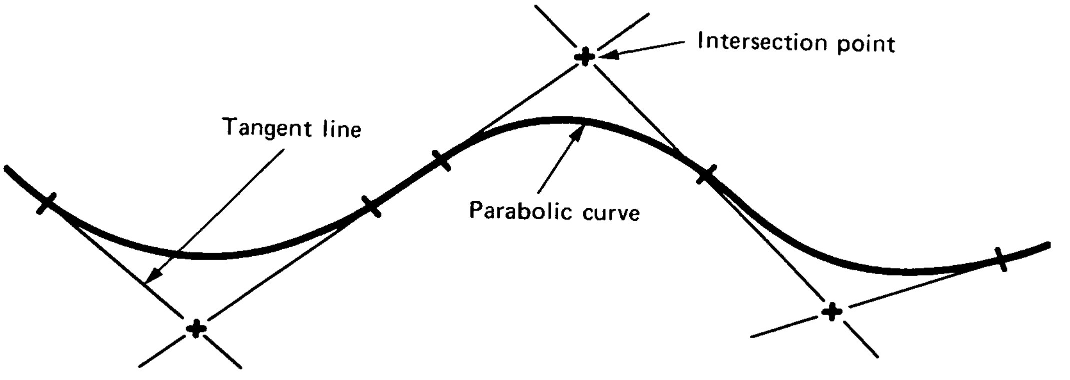


Fig. 1 CONVENTIONAL VERTICAL ALIGNMENT

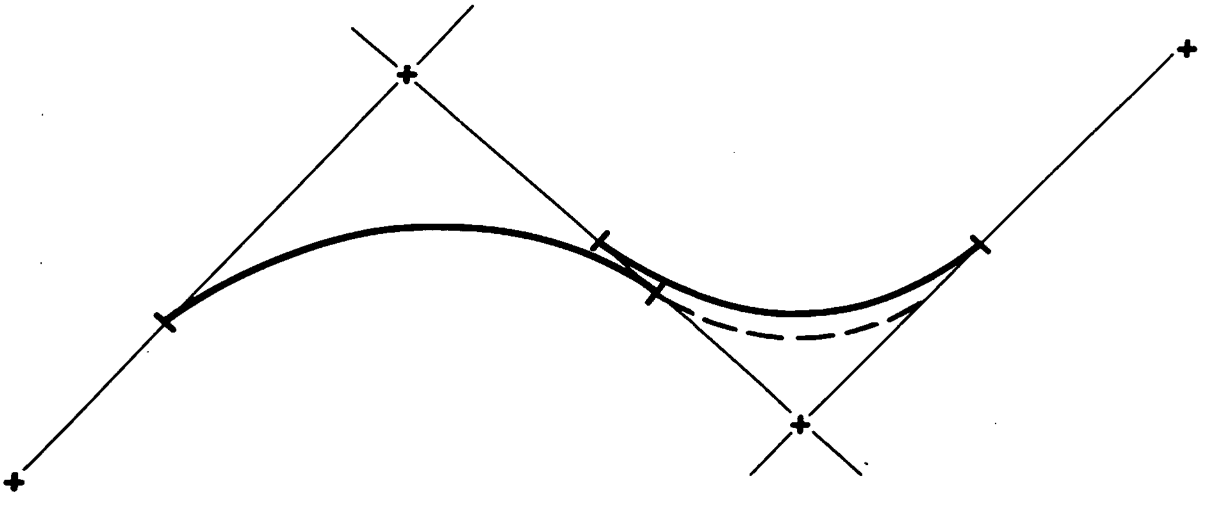


Fig. 2 OVERLAPPING CURVES

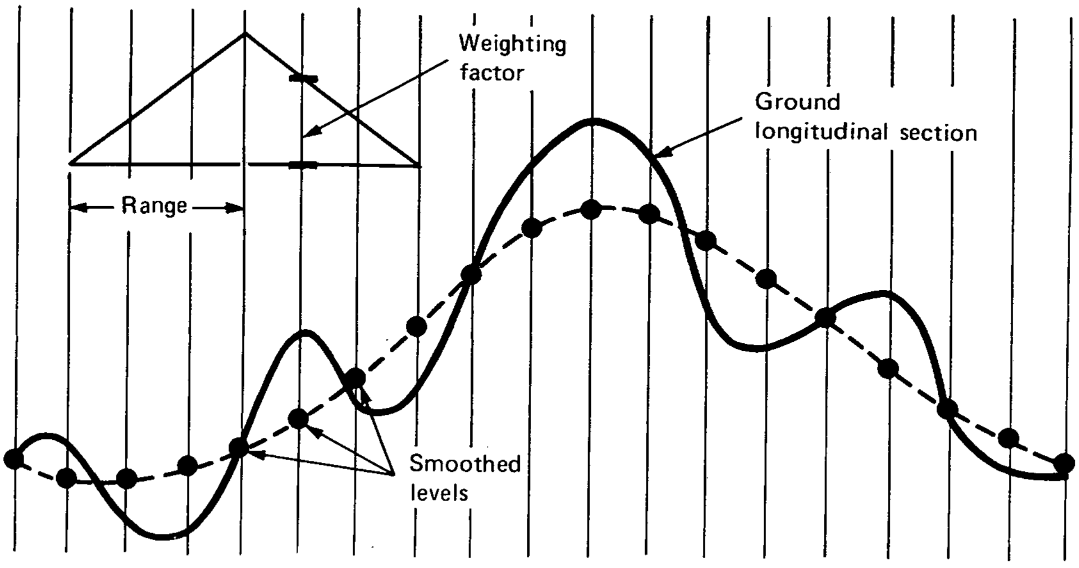


Fig. 3 THE SMOOTHING PROCESS

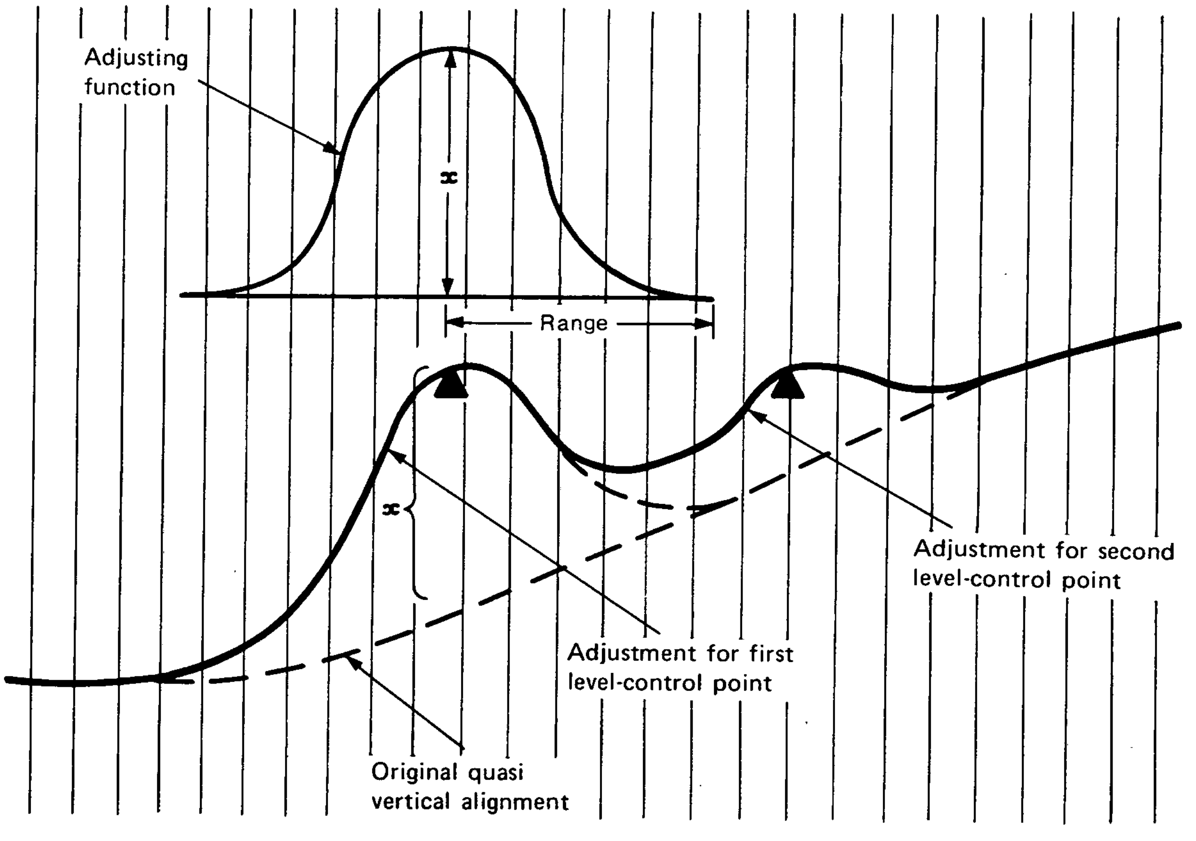


Fig. 4 ADJUSTMENT OF QUASI VERTICAL ALIGNMENT TO MEET LEVEL-CONTROL POINTS

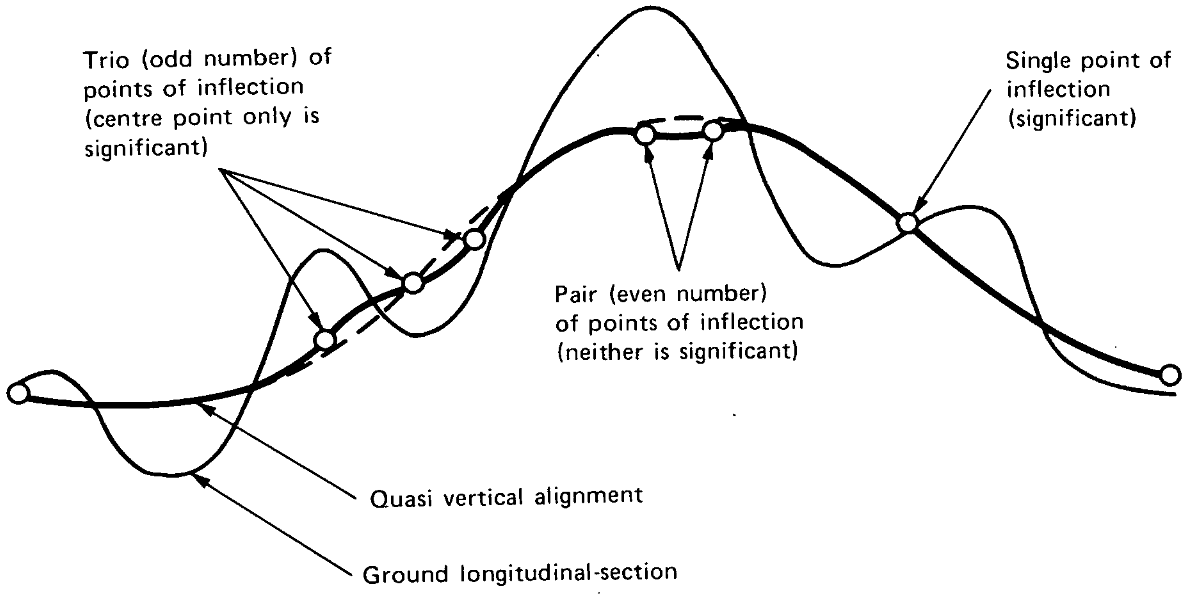


Fig. 5 POINTS OF INFLECTION

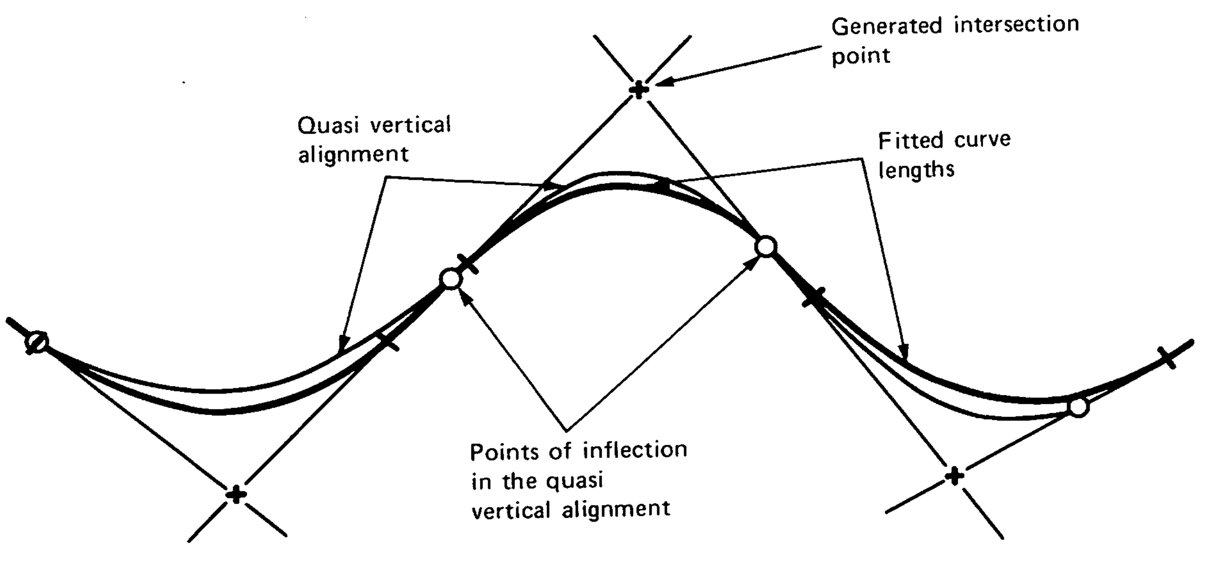


Fig. 6 FORMATION OF PRELIMINARY VERTICAL ALIGNMENT

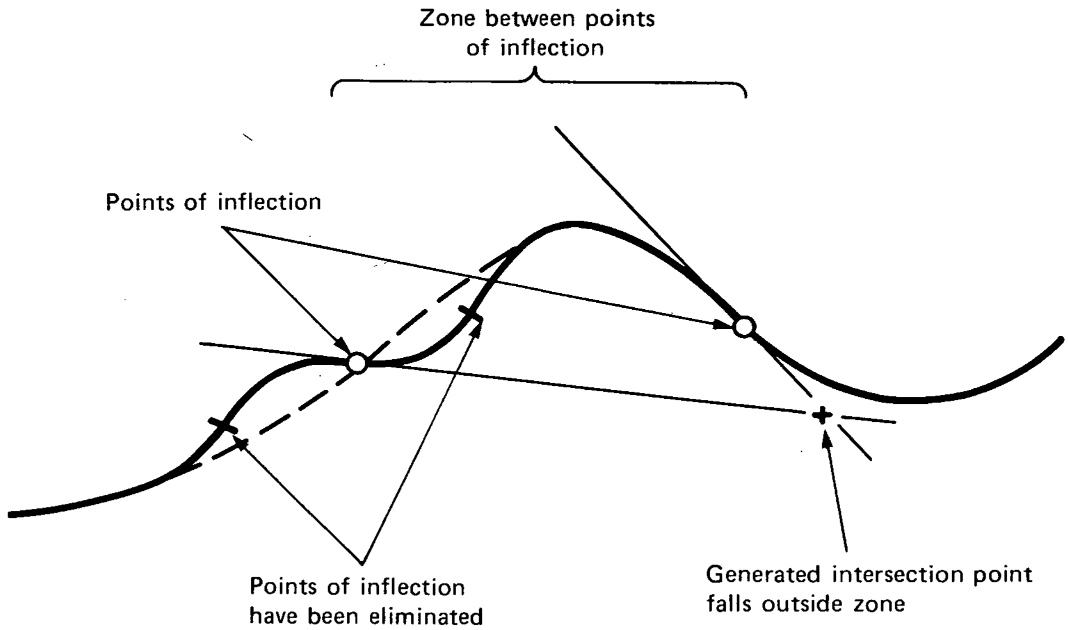


Fig. 7 ELIMINATION OF NEGATIVE CURVE LENGTHS

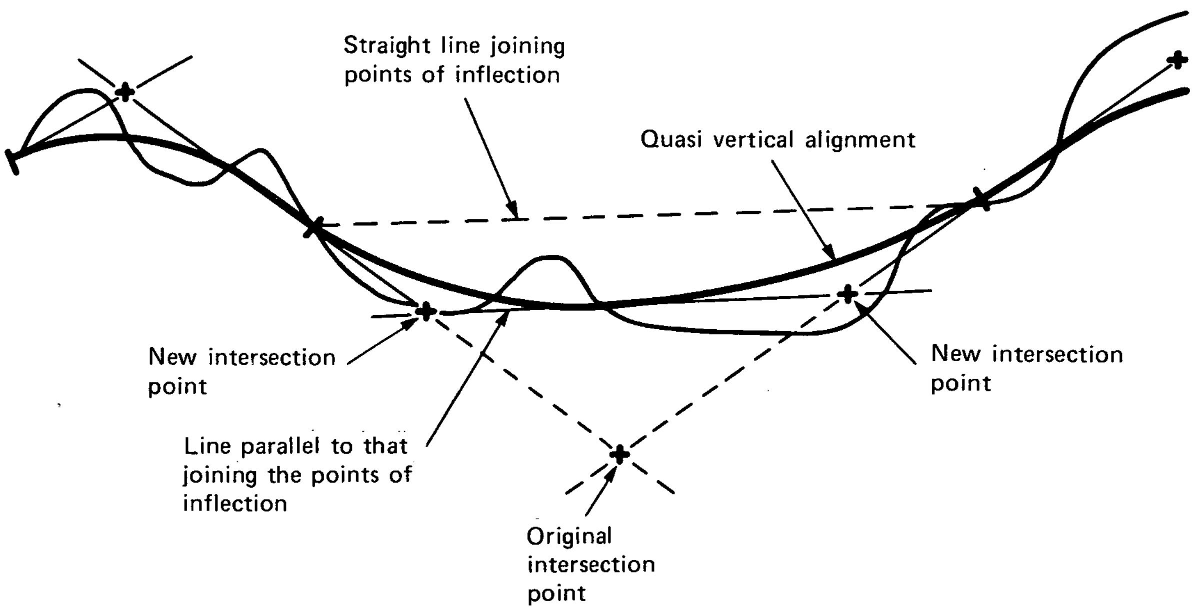


Fig. 8 FITTING A COMPOUND CURVE

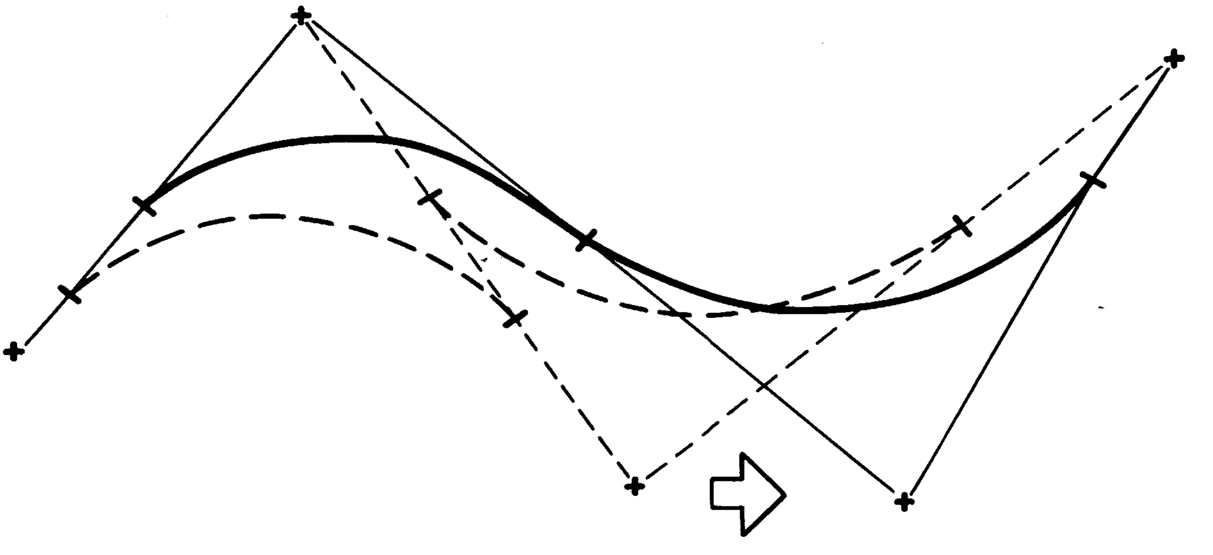


Fig. 9 CORRECTION OF CURVE OVERLAPS

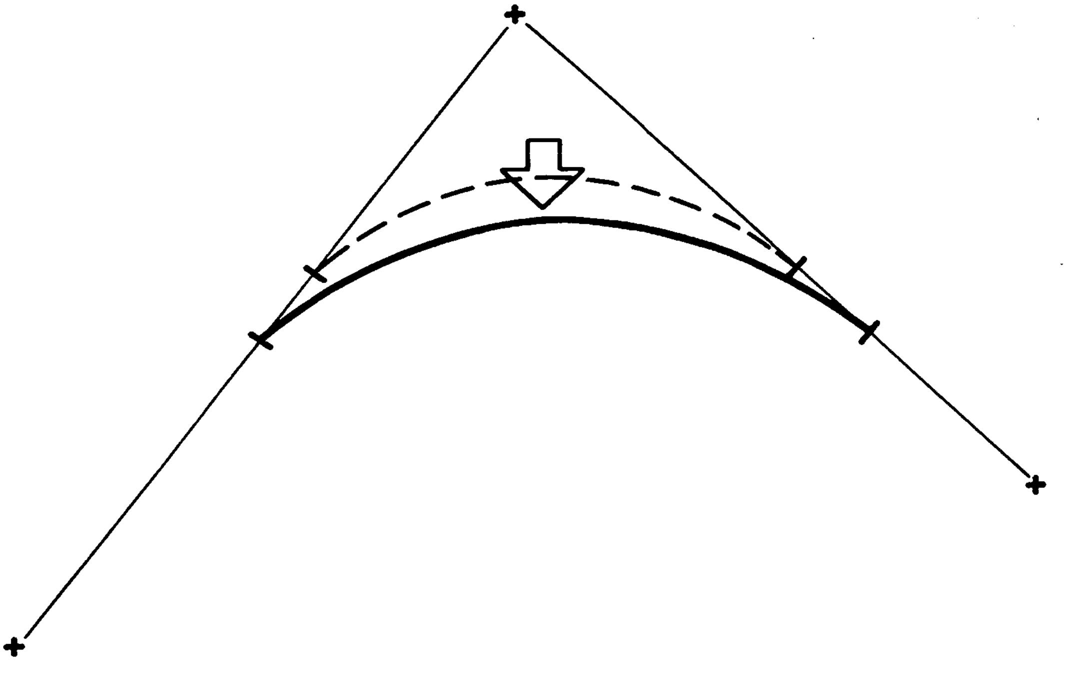


Fig. 10 CORRECTION OF MINIMUM CURVE LENGTH VIOLATIONS

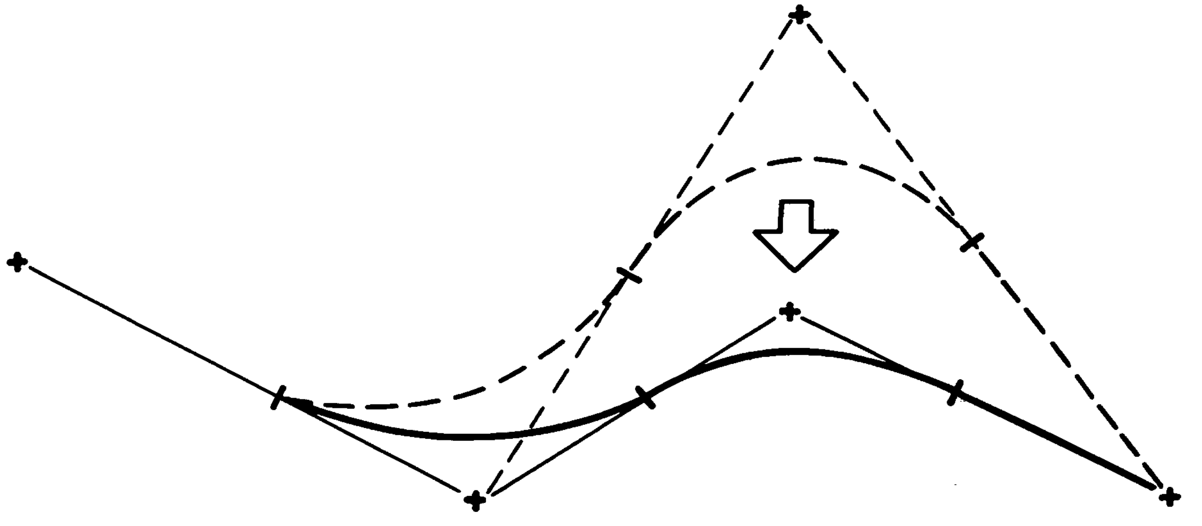


Fig. 11 CORRECTION OF VIOLATED MAXIMUM GRADIENT CONSTRAINT

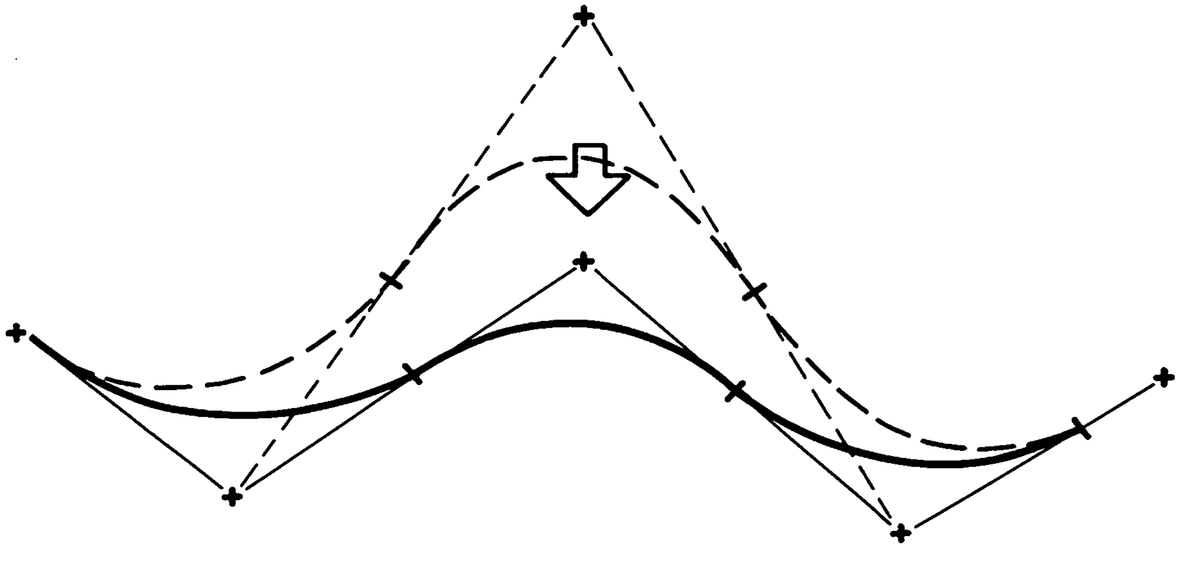


Fig. 12 CORRECTION OF VIOLATED RADIUS CONSTRAINT

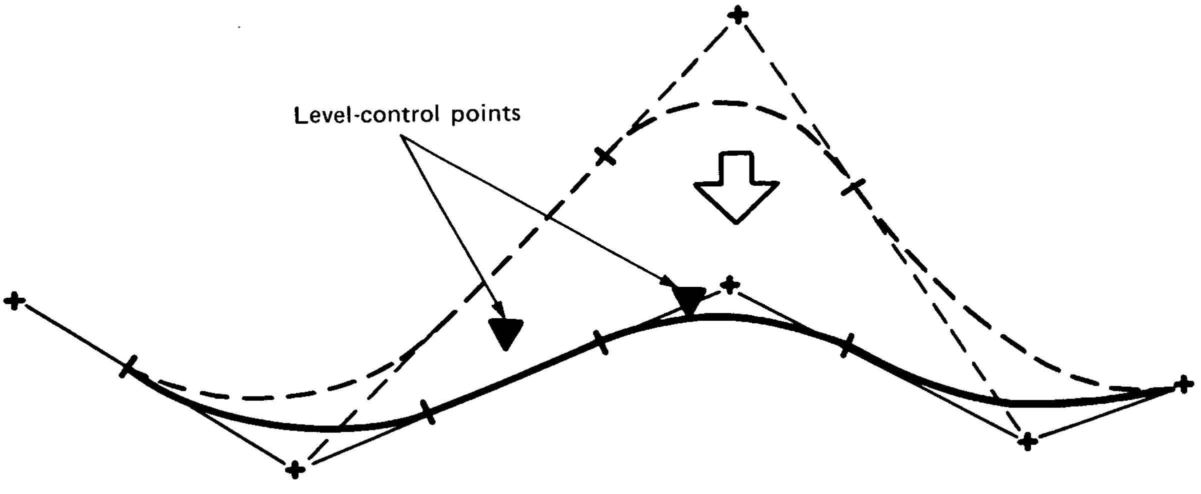


Fig. 13 CORRECTION OF VIOLATED LEVEL-CONTROL POINTS

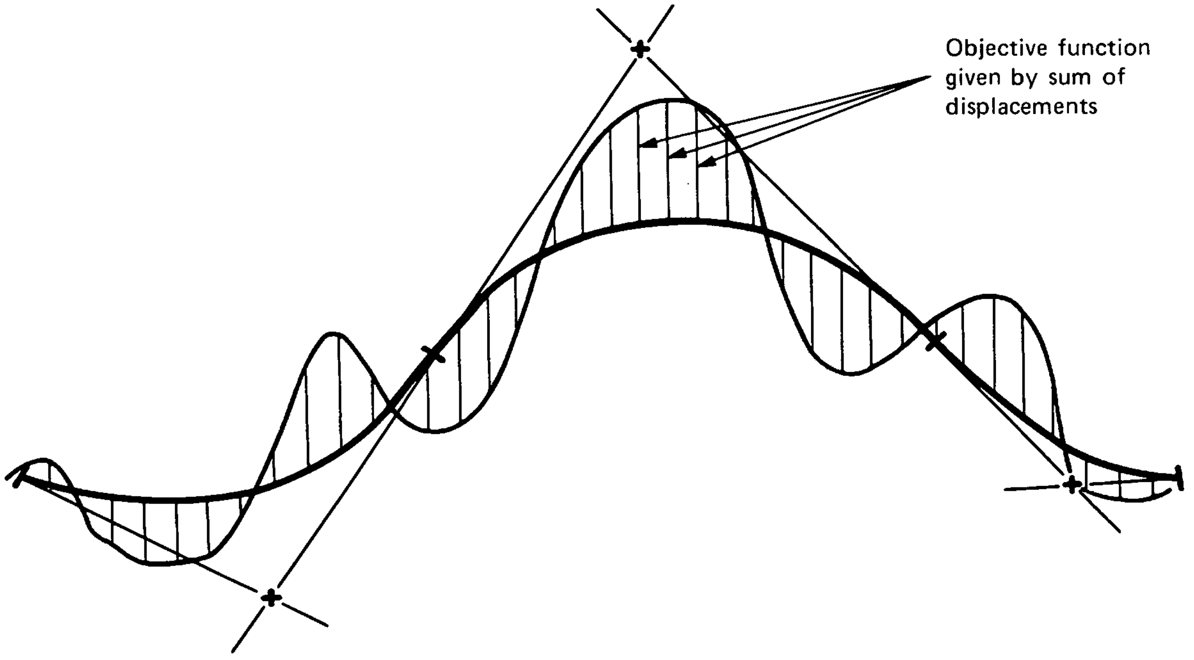


Fig. 14 FUNCTION USED TO FIT THE ROAD MORE CLOSELY TO THE GROUND

BRITISH INTEGRATED PROGRAM SYSTEM FOR HIGHWAY DESIGN
HIGHWAY OPTIMIZATION PROGRAM SYSTEM

V E N U S

(VERTICAL ALIGNMENT DESIGN)

TRANSPORT AND ROAD RESEARCH LABORATORY
DEPARTMENT OF THE ENVIRONMENT

SEPTEMBER 1972 VENUS RUN 1 - GENERATION OF VERTICAL ALIGNMENT

C9T9/ SIMULATED HIGHWAY DESIGN

GENERATION OF VERTICAL ALIGNMENT

FINAL VERTICAL ALIGNMENT

*****LENGTHS IN METRES

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
0.5000	3.0000	300.00	18000	9000

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

NO.	INTERSECTION POINT CHAINAGE	INTERSECTION POINT LEVEL	CURVE LENGTH	RADIUS (SAG CURVES NEG.)	RATE OF CHANGE OF PER CENT GRADIENT	PER CENT GRADIENT
1	0.0	17.945				
						-0.5000
2	526.0	15.315	300.00	-14524	0.00688448	
						1.5653
3	889.6	21.007	427.31	18000	0.00555554	
						-0.8086
4	1789.4	13.732	300.00	-21498	0.00465129	
						0.5868
5	2726.5	19.232	300.00	22023	0.00454072	
						-0.7754
6	3071.9	16.553	390.88	-13378	0.00747449	
						2.1462
7	3544.2	26.689	322.27	19576	0.00510820	
						0.5000
8	5000.6	33.971	300.00	-15888	0.00629353	
						2.3881
9	5856.5	54.411	586.95	18000	0.00555552	
						-0.8728
10	6300.0	50.540				

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

ENTRY GRADIENT = -0.5000 PER CENT

EXIT GRADIENT IS NOT FIXED

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

NO.	CHAINAGE	LOWER LIMIT	UPPER LIMIT
1	858.0	19.590	
2	997.0	19.260	21.450
3	2764.0	18.290	
4	3064.0		18.000
5	6174.0	50.290	

*****VERTICAL ALIGNMENT IS FEASIBLE

Fig. 15 OUTPUT FROM VENUS

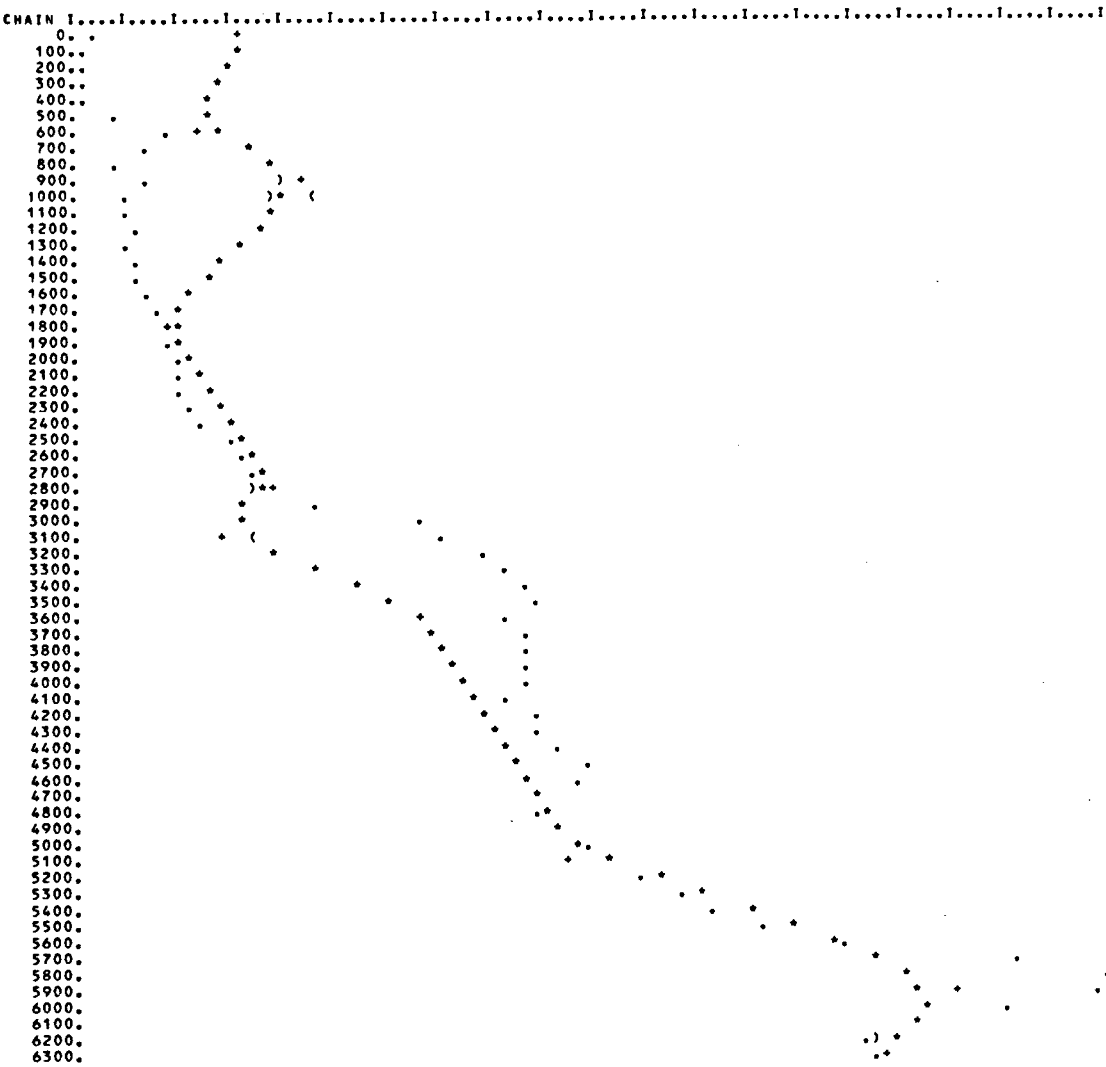
PLOT AND TABULATION OF
GROUND LONGITUDINAL SECTION
AND
VERTICAL ALIGNMENT

KEY

. GROUND LEVEL
* ROAD LEVEL
+ INTERSECTION POINT

O FIXED LEVEL-CONTROL POINT
) LOWER LIMIT OF LEVEL-CONTROL POINT
(UPPER LIMIT OF LEVEL-CONTROL POINT

1 INCH INTERVAL ON VERTICAL SCALE REPRESENTS 5.3 METRES



CHAIN	LEVEL GROUND	LEVEL ROA
0.	10.10	17.
100.	9.65	17.
200.	9.82	16.
300.	9.46	16.
400.	9.62	15.
500.	11.54	15.
600.	13.88	16.
700.	12.74	18.
800.	11.49	19.
900.	13.18	19.
1000.	11.72	19.
1100.	11.98	19.
1200.	12.27	18.
1300.	11.93	17.
1400.	12.32	16.
1500.	12.53	16.
1600.	12.93	15.
1700.	13.26	14.
1800.	13.78	14.
1900.	14.04	14.
2000.	14.29	14.
2100.	14.57	15.
2200.	14.77	16.
2300.	14.82	16.
2400.	15.40	17.
2500.	16.95	17.
2600.	17.84	18.
2700.	18.15	18.
2800.	18.47	18.
2900.	21.68	17.
3000.	26.58	17.
3100.	28.04	18.
3200.	30.02	19.
3300.	31.19	21.
3400.	31.94	23.
3500.	32.55	25.
3600.	31.15	26.
3700.	32.22	27.
3800.	32.19	27.
3900.	31.98	28.
4000.	32.02	28.
4100.	31.04	29.
4200.	32.84	29.
4300.	32.65	30.
4400.	33.88	30.
4500.	35.14	31.
4600.	34.58	31.
4700.	32.77	32.
4800.	32.35	32.
4900.	33.70	33.
5000.	35.44	34.
5100.	36.25	36.
5200.	37.81	38.
5300.	40.05	41.
5400.	41.46	43.
5500.	44.07	45.
5600.	48.32	48.
5700.	57.66	50.
5800.	62.09	51.
5900.	62.07	52.
6000.	57.00	52.
6100.	52.21	52.
6200.	49.45	51.
6300.	49.99	50.

C9T9/ SIMULATED HIGHWAY DESIGN - END OF RUN

Fig. 15 OUTPUT FROM VENUS (cont.)

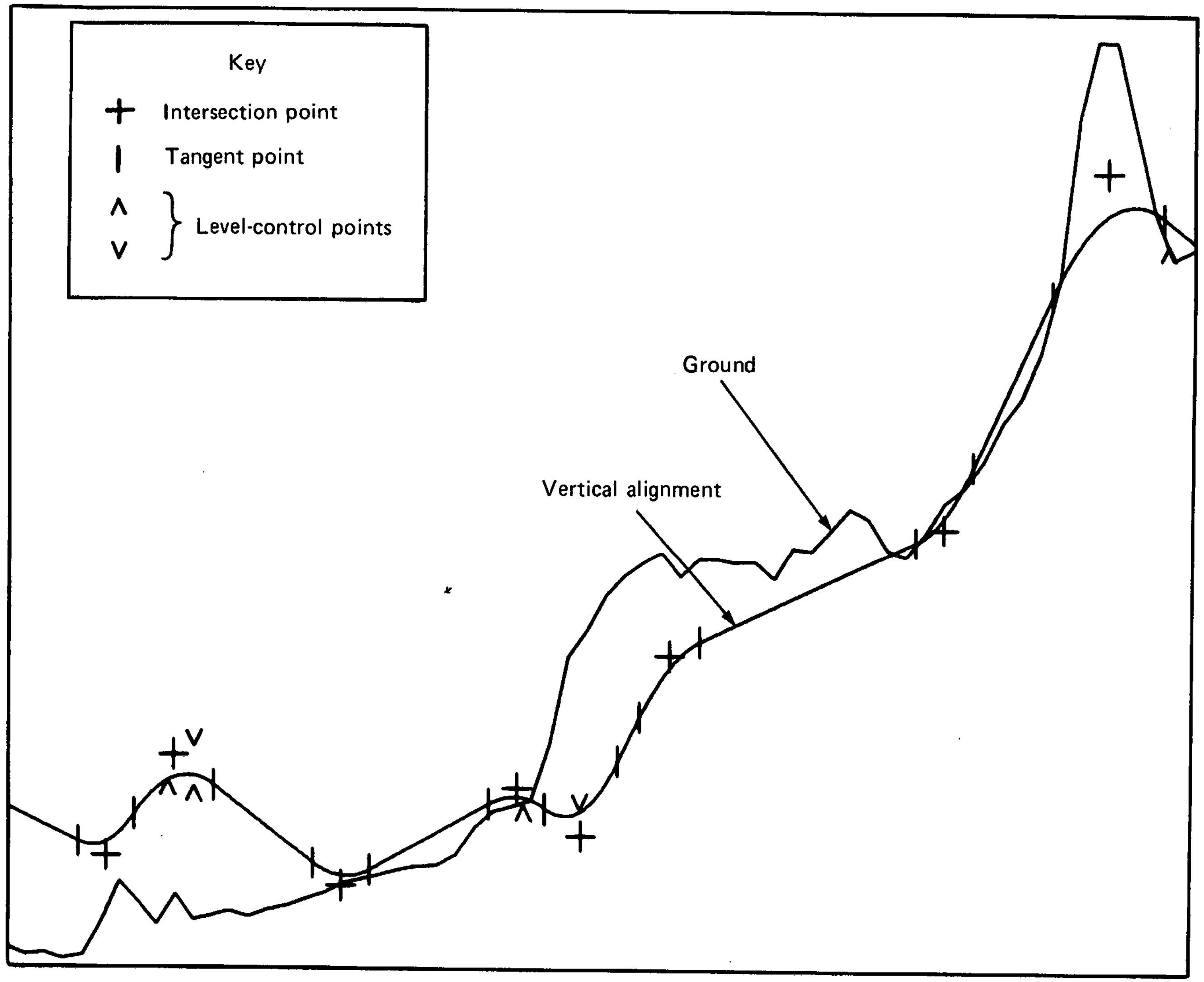


Fig. 16 TYPICAL ALIGNMENT GENERATED BY VENUS

(503) Dd209410 2M 4/76 HPLtd So'ton G1915
PRINTED IN ENGLAND

ABSTRACT

Automatic generation of the highway vertical alignment: program VENUS: R ROBINSON, BSc PhD MIHE: Department of the Environment, TRRL Report LR 700: Crowthorne, 1976 (Transport and Road Research Laboratory). As part of the development of the Highway Optimization Program System, a method has been produced for the automatic design of the vertical alignment of a highway, and a computer program (VENUS) has been written to implement this. The method smooths the ground along the centre line of the road to produce a longitudinal profile similar to the required vertical alignment, and then fits the profile with tangent lines and parabolic curves. The alignment is then modified to obey geometric design standards and constraints on level by adjusting the position of the curves. When all the constraints are obeyed, the alignment is refined further to improve its fit to the ground.

VENUS can be used to produce alignments as a preliminary to optimization or as the basis for conventional design. It has been tested on several hundred kilometres of road and has also been used successfully in the design of a railway. The vertical alignments generated automatifally tend to contain more vertical curves than those designed manually to the same geometric standards. This should reduce the earthworks quantities and hence the construction cost of the road scheme.

The program VENUS is written in FORTRAN and is available from the Department of the Environment. It is used routinely by Road Construction Units of the Department.

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