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GOODS VEHICLE MANOEUVRES: A COMPUTER SIMULATION AND ITS APPLICATION TO ROUNDABOUT DESIGN

by

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ABSTRACT

Computer program TRACK has been developed to simulate multiple manoeuvres at walking speed by rigid and articulated goods vehicles so that the space required for such manoeuvres can be determined. Its accuracy depends mainly on the precision with which the necessary physical quantities can be prescribed, including, usually, the minimum turning radius under the relevant conditions. TRACK is also sufficiently accurate for the study of vehicle paths in highway situations where speeds are higher than walking pace but still relatively low. Its application to the design of a small roundabout is described. It has also been used extensively in examining standard layouts for priority junctions.

1. INTRODUCTION

When an operator of a goods vehicle has to judge whether his vehicle can be turned round in a single sweep within a given area he can usually judge this correctly from the figure for the minimum turning-circle diameter provided by the manufacturer. In addition guidance is available on the amount by which the rear wheels cut in relative to the paths of the front ones from a previous TRRL report[1]. However the information from these sources is of little assistance when multiple manoeuvres have to be considered or even simple ones when allowance has to be made for the distance travelled whilst the driver is altering the steering.

In response to many requests from inside the Department of Transport and from different sectors of industry, a computer simulation has been developed which is capable of solving a wide range of problems involving a series of manoeuvres made at very low speed (walking pace) and can also be used for highway situations in which sharp turns have to be made at relatively low speeds (up to 20 km/h at least).

The version of computer program TRACK described in outline in this report was written in Fortran IV and applied to rigid vehicles and articulated combinations. As used at TRRL, it provides a plot of successive positions of selected parts of the vehicle so as to indicate the swept area as well as a numerical output. An example of such a plot is given in Figure 1: this shows the swept path for an articulated petrol tanker at a service station.

2. BASIS OF THE COMPUTER SIMULATION

The simulation process involves several stages. First a vehicle to be modelled is selected. This is a direct representation of the vehicle under consideration only in the case of simple vehicles; otherwise it is an equivalent vehicle with fewer axles. Then the 'modelled vehicle' is represented by a 'spine vehicle' by replacing the wheels at the opposite ends of axles by single wheels at the centres of the axles. The tracks of the wheels of the spine vehicle are generated as a series of very short straight lines and the tracks of the different parts of the real vehicle deduced from those of the wheels of the spine vehicle. The heart of the simulation is the algorithm for generating the wheel tracks of a two-wheeled vehicle.

2.1 *Simulation of the motion of a bicycle*

The basis of the computer model is most easily explained by considering, first, the low-speed motion of a bicycle with its frame vertical. When the cycle is moved with the steer angle (between the planes of the frame and the front wheel) held constant, the paths of the wheels are concentric circles, the front wheel path having the greater radius (see Figure 2a). The centre of rotation is the intersection of the axes of the front and rear wheels.

The basis of the computer algorithm, as applied to this bicycle, is illustrated in Figure 2b. The front wheel is moved in a series of equal but very short straight steps so that its circular path is represented by a regular polygon. On each occasion, the rear wheel is assumed to move along the line joining the new position of the front wheel to the old position of the rear wheel. Thus the path of the rear wheel is also represented by a regular polygon. More complex paths are represented by allowing the angle of steer to be changed between steps. For reversing a negative step size is specified.

After the first version of TRACK was in use, it was learned that Green[2] had adopted a slightly different algorithm which is essentially a computer representation of the manual graphical procedure of Schneider[3], described in English by Hill[4]. Green's algorithm gives a little more accuracy at the expense of some extra complexity. However, as discussed in Section 2.3, the accuracy of TRACK is already much higher than that of measurements of the physical data required to use it.

2.2 *Concept of a 'spine' vehicle*

2.2.1 The 'spine' vehicle for a two-axle rigid vehicle: In the model, the calculations for a two-axle rigid vehicle are based on those for an equivalent 'spine' vehicle taking the form of a bicycle with wheels at the positions of the centres of the axles of the real vehicle. This hypothetical bicycle is moved in steps as described in Section 2.1, the positions of its wheels being calculated on each occasion. After each cycle of 10 steps the program calculates the corresponding positions of the corners of the real vehicle.

The correct steering angle has to be assigned to the bicycle to enable the motion of the real vehicle to be simulated. If it is desired to make some part of the real vehicle move in some feasible direction the steering angle of the spine vehicle is easily calculated. However for studying manoeuvres in a confined space it is necessary to know the maximum steering angle which can be assigned to the bicycle. If the minimum turning circle of some part of the real vehicle (eg a front wheel) is known or can be measured,the equivalent steering lock for the bicycle can be calculated. If on the other hand the steering locks of the two front wheels of the real vehicle are measured, it is likely that they will give rise to two slightly different estimates for the steering lock of the bicycle. This is because the usual Ackermann steering system does not give perfect compatibility of the inside and outside steering angles and there may, in addition, be some error in the adjustment of the mechanism. Theoretical considerations suggest that the cotangent of the steering angle of the spine vehicle should equal the mean of the cotangents of the two estimates and this is in line with the results of practical tests with empty vehicles. The effect of load is discussed in Section 2.3.

2.2.2 The 'spine' vehicle for other rigid vehicles: However many axles a rigid vehicle has the spine vehicle to represent it is still taken to be a bicycle. The group of front (steered) axles has therefore first to be replaced by a single effective front axle and the group of rear axles by a single effective rear axle. Thus when the real vehicle under consideration has more than two axles the vehicle which is modelled is an equivalent two-axle vehicle which would give the same body path. The methods by which the real vehicle is replaced by the vehicle modelled are discussed in the following paragraphs.

If a rigid vehicle has two or more steered axles at the front the steering mechanism is designed to turn the individual wheels through different, but mutually compatible, angles. Therefore in modelling movements of the vehicle which are known to be feasible only one of the front axles need be represented (the front axle if the front wheel tracks of the real and modelled vehicles are required to be the same).

If the tightest possible turns have to be considered and the minimum turning radius for any part of the vehicle is known, the steering lock for the spine vehicle is easily calculated. If it is necessary to rely on measurements of maximum steering angles, measurements should be made at all the steered wheels, separate estimates made for the steering lock of the equivalent bicycle and these 'averaged' by the method explained in Section 2.2.1.

If there are two or more unsteered rear axles these have to be replaced by a single effective rear axle. Tests indicate that a close approximation to the observed turning behaviour is obtained if this effective axle is assumed to be at the mid-point of the assembly. However any rear axle of the self-steering type can be ignored entirely in forward motion; if it is locked for reversing it then becomes an additional unsteered axle.

2.2.3 The 'spine' vehicle for an articulated combination: For an articulated combination the spine vehicle is a bicycle towing a single-wheel trailer. The tractor, being a rigid vehicle, is replaced by a bicycle on the lines discussed in Sections 2.2.1 and 2.2.2 above. An equivalent single axle is determined for the axle assembly of the trailer as described for the rear axles of a rigid vehicle in Section 2.2.2 and this is represented by a single wheel in the spine vehicle. The motion of the spine vehicle for an articulated combination which has been circulating long enough for a steady condition to have been reached is described in Figure 2c.

In the computer representation the bicycle part of the spine vehicle is moved as already described and the position of the coupling between bicycle and trailer computed after each step. The motion of the wheel of the trailer of the spine vehicle is determined from the motion of the coupling using the same algorithm as for the rear wheel of the bicycle. After every ten-step cycle the position of the corners of the tractor and trailer are also determined.

2.3 *Accuracy of simulation*

The simulation process comprises a number of separate modelling assumptions each involving some degree of approximation. First consider low-speed (walking-pace) manoeuvres on firm, non-slippery surfaces: manoeuvres at higher speeds on more slippery surfaces are discussed later in this section.

The different modelling stages include:

(a) the replacement of multiple front (steered) and rear (unsteered) axles by single 'effective' axles,

(b) basing the motion of the actual vehicles on 'spine' vehicle representations of the model vehicles derived from (a),

(c) application of the basic computer algorithm (a dual application in the case of articulated vehicles) which includes the representation of curved paths by a series of straight lines.

Since the methods of simulation which have been developed can be applied in a number of different ways and in a number of different circumstances, it is not possible to quote a single figure for accuracy. With the usual step size of 0.01m the paths of two-axle vehicles making simple manoeuvres can be simulated to an accuracy of about 0.01m provided that, if turns on full lock are involved, minimum turning circles have been accurately measured under the same circumstances. If, on the other hand, it is necessary to rely on measured values of steering lock, errors of the order of about 0.1m can arise. For complex vehicles errors can rise to about 0.5m when steering locks have to be measured.

Minimum turning circles are usually measured with unladen vehicles on dry surfaces: with a full load and on wet surfaces slightly greater values are obtained. Theoretical considerations indicate that the differences would be greatest for vehicles with multiple unsteered axles. The results of a limited series of track experiments suggest that minimum turning radii for such vehicles can be increased by 0.5m when a full load is applied and a further 1.0m when the surface is wetted (even for a surface with a reasonable skid resistance). However, for vehicles with single unsteered axles,the effect of load was found to be negligible and wetting increased minimum turning radii by only 0.1m.

It is concluded that, for most applications relating to low-speed manoeuvres, the accuracy of the output of program TRACK is limited by the accuracy of the physical data needed to run the program rather than by the approximations in the program.

Theoretical analysis has indicated that TRACK is also useful for tight highway situations in which somewhat higher speeds arise, such as the small roundabouts to be discussed in Section 4. Consider the case of a fully-laden, 5.5m wheelbase, 16 ton GVW, rigid lorry starting from rest and then executing at increasing speed, a circular path of radius 11m (at centre of the front axle) on a wet, slippery surface. Between 0 km/h and 17 km/h (about the greatest speed for a long vehicle at a small roundabout) the radius of turn (at the centre of the rear axle) increases by about 0.22m. The cut-in of the rear wheels relative to the front is reduced or, in other words, the width of the swept path is reduced. Provided that full steering lock is not required at low speed and the steering angle can be increased to bring the front of the vehicle back on to its original path the vehicle will be able to continue to circulate within its original swept path. Thus if TRACK indicates that a vehicle can negotiate a small roundabout (or other tight roadway situation) at walking pace, it is likely to be able to do so at the somewhat higher speeds normal in such situations subject to the proviso concerning steering lock.

3. OUTLINE DESCRIPTION OF COMPUTER PROGRAM

3.1 *A simplified flow chart*

Figure 3 is a simplified flow chart to indicate the main operations performed by the program which has been designed to enable composite manoeuvres to be simulated. Provision is made for up to eight separate phases and tests are included to indicate when each phase should be terminated and the next begun.

Section A is primarily concerned with the definition of the vehicle and the manoeuvres. Three main types of information have to be fed in to the computer:

(1) Vehicle characteristics and initial co-ordinates for the spine vehicle.

(2) A specification of the steering routine to be used in each separate phase of the composite manoeuvre (assembled in an array called PATH).

(3) Criteria to determine when each phase should terminate and the next begin. (These consist mainly of limiting values of various angles and spatial co-ordinates associated with the vehicle assembled in an array called TEST.)

All input information is also printed out for record purposes.

Section B contains an arrangement to select from the array PATH a definition of the steering routine to be used in the particular phase reached, together with the values of the necessary parameters. In addition Section B makes provision for the values of all the relevant vehicle angles and co-ordinates to be printed out at the beginning of each phase and within phases after every 100 stepping movements. If the computer is coupled to a suitable X-Y plotter an outline plot of the vehicle is also produced: in the remainder of this description such a plotter will be assumed to be in use.

Section C contains the basic algorithm outlined in Section 2.1. The steer angle is revised as called for by the chosen steering routine, the front wheel of the spine vehicle is moved one step and the rear wheel made to follow according to the algorithm. These three operations are repeated nine times to give a cycle of 10 steps, after which the full range of angles and co-ordinates for the actual vehicle are calculated.

In section D these angles and co-ordinates are tested against the limits set out in the array TEST. The results of these tests determine whether the computer returns to section B to begin a further cycle of steps or whether it moves on to the next phase of the manoeuvre. When all the phases have been completed the final angles and co-ordinates of the vehicle are printed out and the final position of the vehicle plotted.

The description of the program is amplified and a fuller flow chart provided in the Appendix. For convenience the sub-division into sections A-D has been retained.

3.2 *Steering routines*

At the time of the work described in later parts of this report four steering routines were available.

In one of these, thought of as the normal routine, the steer angle is held constant after an initial transition stage during which it is altered by a fixed amount between steps until the final value is reached. The steering increments should be chosen to be compatible with the rates at which drivers would make steering changes in situations of the type being considered. For example a steering movement from straight ahead to full lock can generally be made in the space of one metre's travel when manoeuvring very slowly in a very limited area but will take about 4m when entering a small roundabout at 15 km/h. This routine is given no code number and is used when no steering code is specified.

Steering code 66 makes the front wheel of the spine vehicle (corresponding to the mid-point of the steering axle of the vehicle modelled) enter a circular arc tangentially. Amongst the uses of this routine is the simulation of certain forms of right-angle and U turn.

Steering code 77 causes the outside front wheel of the vehicle modelled to follow a specified straight line. This routine has been used to simulate a vehicle straightening out alongside a raised kerb after a manoeuvre.

Steering code 88 is similar to code 77 but simpler to apply and can be used when a slightly lower degree of precision is acceptable. The front wheel of the spine vehicle is made to move in a specified direction.

By the choice of suitable steering parameters (angles and rates of change of angles) and suitable conditions for terminating phases quite complicated manoeuvres can be simulated using these four steering routines. However, it is easy to add further routines as the need arises.

3.3 *Criteria for terminating phases of a manoeuvre*

What has been referred to so far as the array TEST is strictly a combination of two separate arrays TEST 1 and TEST 2.

TEST 1 sets limits for the angles of orientation,with regard to chosen fixed axes on the ground,of the body and spine vehicle front wheel for a rigid vehicle. For an articulated combination the limits are for the orientation of the body and spine vehicle front wheel of the tractor, for the orientation of the trailer and for the angle of articulation between the two parts.

TEST 2 limits the movements of the vehicle modelled to a rectangular area on the ground with sides parallel to the reference axes.

The program being described was written so that the number of separate tests failed simultaneously is counted and when this exceeds some specified value the current phase of the manoeuvre is terminated.

Elsewhere in the program limits are set on the numbers of steps permitted during each phase of the manoeuvre and on the total number of steps for the whole manoeuvre. This feature is useful whilst the simulation of a complex manoeuvre is being developed but is not shown in the simplified flow chart.

4. USE OF COMPUTER PROGRAM 'TRACK' TO CHECK DESIGNS FOR SMALL ROUNDABOUTS

Although developed for the purpose of simulating slow vehicle manoeuvres in confined spaces, computer program TRACK has also been used to check the suitability of certain designs of roundabout for use by long vehicles. The applicability of the underlying theory to this case was discussed in Section 2.3.

4.1 *Design criteria*

Roundabouts of a wide range of sizes are used in different road situations. Whilst long vehicles can negotiate large roundabouts without difficulty they can only execute some manoeuvres (eg right turns) at very small roundabouts by allowing rear wheels to overrun the central island. Therefore, for the smallest roundabout – the mini-roundabout – raised kerbs are not used on the central island; instead a surface marking or slightly domed blister marker is employed. The problem, in the study to be described, was to find the smallest roundabout for which a central island marked out by kerbs with a normal upstand could reasonably be specified.

For the central island, 4m was assumed to be the minimum acceptable diameter. The problem was therefore reduced to finding the minimum satisfactory outside diameter for the roundabout (ie the minimum diameter for the so-called inscribed circle defined in Figure 4). In practice other factors, such as entry capacity and adequate deflection to reduce speed, would also have to be considered.

It was decided that, to be satisfactory, a roundabout design should allow long vehicles to make left turns, straight through movements, right turns and U turns without approaching within 1m of the central island or outside edge of the roundabout (except, of course, when entering and leaving the roundabout). The 1m strips left clear on the inside and outside would be required by cyclists overtaken by long vehicles.

The analysis was carried out for the symmetrical four-way design shown in Figure 4. The approach roads have a half-width of 3.75m widening to give an entry width of 7.5m. The entry and exit tapers start at the same distance from the centre of the roundabout, the former being 1:3 and the latter 1:6.

The assessments were carried out for three of the most extreme vehicles likely to be permitted by Motor Vehicles (Construction and Use) Regulations[5] in the near future.

4.2 *The design vehicles*

The design vehicles were chosen to be extreme examples (with regard to turning characteristics) of what may be described as the ordinary goods vehicles on the road, ie the more common types having widths and lengths under the normal maximum values specified in the Motor Vehicles (Construction and Use) Regulations[5]. The assumption is that any layout which the design vehicles can negotiate will be more easily negotiable by the great majority of the goods vehicles on the road. The design goods vehicles are of three types: a rigid vehicle, an articulated combination (a tractor drawing a semi-trailer, part of the weight of which is superimposed on the tractor), and a drawbar train (a rigid goods vehicle towing a trailer by means of a rigid drawbar). Trains incorporating more than one trailer have not been included, nor have extra-wide or extra-long vehicles.

For all three types of vehicle the Construction and Use maximum width is 2.5m and this has been assumed for the design vehicles.

For rigid goods vehicles the maximum length permitted by C and U Regulations is 11m but for public service vehicles (buses and coaches) it is 12m. For design purposes the 12m psv shown in Figure 5a has been used. The relatively short wheel base of such vehicles ensures a good turning circle between kerbs but long overhangs at front and rear make it necessary to check for clearance with items of street furniture including bollards on central refuges in the mouths of roads joining roundabouts.

For articulated combinations the maximum length in C and U Regulations was 15m at the time of the study but because of practical difficulties in assembling different tractor/trailer combinations, there was strong pressure for the limit to be raised to 15.5m.

The need for this change has since been endorsed by the Armitage Inquiry[6]. The articulated combination adopted for design purposes in this study was therefore the 15.5m combination shown in Figure 5b. The single axle of the semi-trailer, because of its proximity to the rear, gives rise to greater cut-in than is obtained with tandem-axle and tri-axle units.

Drawbar trains are, at present, much rarer than articulated combinations on British roads. They can be up to 18m long and are usually made up of two fairly equal units on the lines of the selected design vehicle shown in Figure 5c.

At the time of this study program TRACK had not been developed for use with drawbar trains and special arrangements had to be made to generate swept paths for the design drawbar train (see next section).

The minimum turning circles for the design vehicles are shown on Figures 5a-c and are close to the largest found for vehicles of these types.

4.3 *Use of TRACK to determine the minimum satisfactory inscribed diameter*

Attention was first concentrated on the left and U turns by the articulated vehicle as these were thought to be the most critical manoeuvres. The inscribed circle diameter was varied keeping the central island diameter constant (4m). With the roundabout layout corresponding to any given inscribed circle diameter a series of trials were necessary for both the left and U turns to determine whether these were possible with the desired clearances. This is because, even for such apparently simple manoeuvres, the sequence of movements which drivers have to make is really quite complex. This will be illustrated in the case of the left turn.

The computer simulation of the left turn involved six separate phases. In the first the vehicle entered from the right-hand lane, heading directly towards the central island as this appears to be the driving pattern habitually adopted at small roundabouts. In the second phase the tractor was steered to curve to the left so as to miss the central island. In the third phase the tractor wheels were maintained at 45^{o} to the axis of the entrance road. At a suitable point the fourth phase was initiated, the tractor being made to curve to the left until its body was parallel to the axis of the exit road. During the fifth phase the steering angle was gradually reduced until the front wheels were parallel to the axis of the exit road. In the final phase the steering angle was reduced progressively so as to allow the trailer to come gradually into line with the tractor as it proceeded along the exit road.

The maximum steering angle in phases two and four corresponded to a turning circle diameter of 15.5m between kerbs, which is a little greater than the minimum turning diameter of 15m assumed for this type of vehicle. In both cases the steering changes were made with a transition as described in Section 3.2.

For the U turn it was assumed that entry would be from the left-hand lane and that the tractor would circulate with the minimum clearance of 1m from the periphery until the exit was reached. This pattern of driving also required six phases of simulation.

Trials were made for roundabouts with inscribed circle diameters of 32m, 30m, 28m and 27m. It was concluded that 28m was the minimum diameter for these manoeuvres and this is the size of roundabout shown in Figure 4.

Next the suitability of such a roundabout for straight-through and right-turn movements by the articulated vehicle was assessed. In both cases no problems were encountered.

Figures 6a-d illustrate the four manoeuvres by the articulated vehicle at the 28m roundabout. The outline of the vehicle has been repeated at intervals of 1m to indicate the swept path.

The corresponding manoeuvres by the public service vehicle and the drawbar train were then simulated. In the case of the public service vehicle all the manoeuvres proved possible though the left turn was only just so. In the case of the drawbar train a temporarily extended computer program and some manual processing had to be employed to generate the swept paths: it was quite clear that all four manoeuvres could be accomplished more easily with the drawbar train than with the articulated combination. It was therefore concluded that a 28m inscribed diameter will satisfy the design criteria for all the design vehicles under the conditions to which their assumed minimum turning circles apply.

Since the assumed minimum turning circles were derived from published data they will refer to unladen vehicles on dry surfaces. Therefore consideration must be given to the effects of loads and wet surfaces on the minimum turning circles. For the design vehicles the effects would be small since none of the vehicles has multiple unsteered axles. Furthermore, these effects were adequately allowed for by the fact that the minimum turning radii actually used in the simulations were always greater than the design values. The margin was least for the articulated vehicle (0.5m) but still adequate.

Consideration has also been given to the possibility that some vehicles with multiple unsteered axles might have larger minimum turning circles on wet surfaces when loaded than the design vehicles. Though they have smaller radii when unladen and the surface is dry the combined effect of load and surface wetness is greatest for vehicles with multiple unsteered axles (see Section 2.3). However the latter effect does not appear to counter-balance the former.

It was concluded that the great majority of rigid commercial vehicles (including public service vehicles), articulated combinations and drawbar trains having normal widths and lengths (widths up to 2.5m and lengths up to 11m for rigid goods vehicles, 12m for rigid public service vehicles, 15.5m for articulated combinations and 18m for drawbar trains) can negotiate a roundabout with an inscribed circle diameter of 28m and a central island diameter of 4m without approaching within 1m of either margin (except when entering or leaving). Also this requirement can be satisfied whether the vehicles are unladen or laden or whether the road surface is dry or wet (but assuming a reasonable skidding resistance in the latter case). Any remaining vehicles of normal overall dimensions (as defined above) should be able to negotiate such a roundabout though without a 1m margin on each side.

4.4 *Experimental validation of results of computer simulations*

4.4.1 Articulated combinations: Trials with roundabout layouts were arranged on the TRRL test track to provide a practical check on the usefulness of the computer program for predicting the minimum roundabout dimensions for an articulated vehicle of precisely known characteristics. The main trials were with an unladen vehicle on a dry surface: there was no intention of checking the additional allowances required for vehicle load and surface wetness. These allowances were investigated in more general experiments (see Section 2.3) and their application to roundabout design considered outside the computer model (see Section 4.3).

A roundabout with the predicted minimum inscribed circle diameter of 28m was laid out using moveable surface markings and bollards. The main trials were made with an articulated vehicle having the same overall length as the design vehicle (15.5m) but having tandem axles on the trailer instead of the single axle assumed for the design vehicle. As a result, this test vehicle had an effective trailer wheelbase about 1m shorter than that of the design vehicle and so gave appreciably less cut-in when turning. Computer simulation indicated that with this vehicle and a roundabout of inscribed circle diameter 28m, a 1m clearance could be obtained externally and internally with a central island having a diameter of 7m. Consequently in the practical tests the central island of the roundabout was given a diameter of 7m instead of the 4m which formed the basis of the design exercise.

Time-lapse cine films were made from an overhead camera: a frame from one of these is shown in Plate 1. Illustrative photographs were also taken from ground level: Plate 2 was taken just before Plate 1 and shows the main test vehicle overtaking a cyclist within the roundabout. Plate 3 shows the same vehicle leaving the roundabout on completion of a U turn.

Observation at the time of the trials and subsequent examination of the cine films established that though the driver's path might vary slightly from that assumed in the simulation, a 1m clearance is possible on both sides of the vehicle during all four manoeuvres whilst still leaving sufficient margin to cover the small effects of loading and surface wetness which would arise in the case of the design vehicle. The trials vehicle would probably require a slightly greater allowance but with the proposed 4m central island (instead of the 7m test island) no difficulty would arise.

Another articulated vehicle, loaded to 32 tons GVW and with a different driver happened to be available at the time of the trials. Although 15.2m in length overall this second vehicle had an effective trailer wheel base 1m less than the main test vehicle (for which the trials roundabout was set out) and 2m less than the design vehicle. This second trials vehicle is more representative of the general run of large articulated vehicles on the road than are the design and main test vehicles (which were deliberately chosen as extreme examples). The trials roundabout was very easily negotiated by this second (loaded) vehicle. Plate 4 shows it completing a left turn.

Finally the two drivers changed places so that each was driving an unfamiliar vehicle. After a few minutes practice each could negotiate the roundabout in a near optimum manner.

4.4.2 Rigid vehicles and drawbar trains: Although suitable rigid and drawbar vehicles were not available at the time of the roundabout trials on the test track, sufficient evidence has been obtained about their performance on other occasions.

The computer simulation of the movements of rigid vehicles is relatively simple and the accuracy of the computed paths for right-angle turns and complete circles by these have been validated experimentally on a number of occasions during the early development of the program.

Practical comparisons of the paths swept in right-angle and U turns by articulated and drawbar vehicles approximating to the design vehicles were made on a separate occasion. The rear cut-in of the drawbar train was found to be considerably less than that of the articulated combinations. Therefore with the roundabout design selected to be satisfactory for the articulated combination the design criteria would be more than satisfied for the design drawbar train.

5. DISCUSSION

Program TRACK enables the swept paths of rigid and articulated vehicles of precisely-known characteristics to be determined with negligible error (much less than ± 0.1m) when making feasible well-defined manoeuvres at low-speed (walking pace). If, as is often the case, turns on full steering lock are involved, the accuracy of the predictions is determined mainly by the accuracy with which the turning capability of the vehicle is known. If a minimum turning circle has been determined experimentally for the actual vehicle concerned under the appropriate conditions errors may still be negligible. However published information is usually for empty vehicles on firm dry surfaces and experiments have shown that, in the case of a lorry with multiple unsteered axles, the addition of a full load can add 0.5m to the minimum turning radius and wetting the surface can add a further 1.0m (even if the surface still has a reasonable skid resistance by highway standards). For vehicles with single unsteered axles the combined effect of loading and wetting appears to be only of the order of 0.1m. When it is necessary to deduce turning radii from measurements of maximum steering angles made with garage equipment errors of ± 0.5m can arise in the cases of vehicles with steered wheels on more than one axle.

Theoretical analysis has indicated that TRACK is also sufficiently accurate for the study of highway situations requiring sharp turns to be made. Under these conditions speeds, though still relatively low, are much higher than walking-pace and result in some degree of side slip at the tyre/road interface. TRACK has been used for the study of the widening required at sharp bends and its application to the design of small roundabouts has been discussed in Section 4. It has also been used by consulting engineers to Traffic Engineering Division of the Department of Transport to determine how to make provision for long vehicles at priority junctions.

Program TRACK can deal with quite complicated multiple manoeuvres but is capable of improvement and extension in a number of ways. Its extension to deal explicitly with drawbar trains has been discussed and additional steering routines would be an advantage for special purposes. A fully interactive program would be easier to use, especially by those with only slight knowledge of vehicle manoeuvring theory, and this is under consideration.

6. ACKNOWLEDGEMENTS

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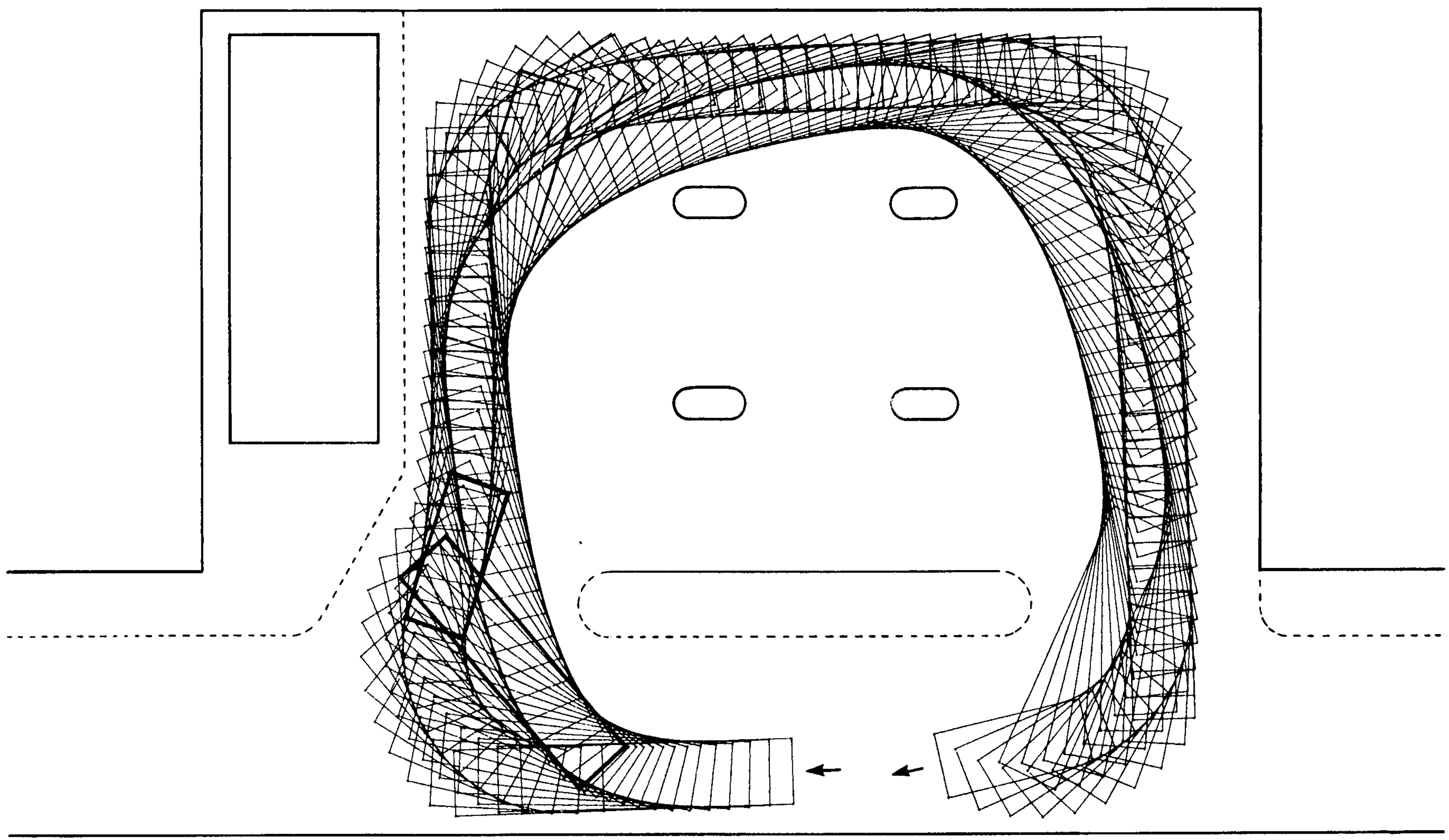
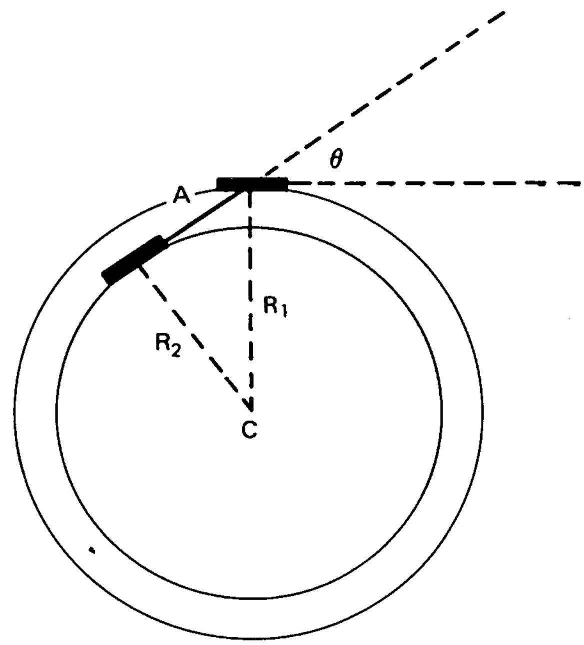


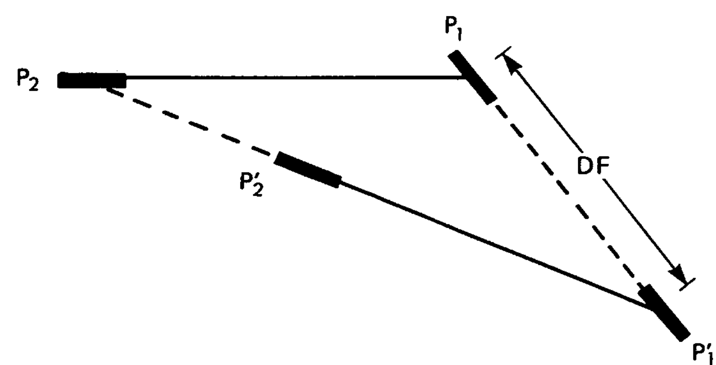
Fig. 1 Example of a plot produced by TRACK. Manoeuvres by an articulated petrol tanker at a service station



C is meeting point of extensions of axles of wheels
A is wheelbase (separation of axles of wheels)

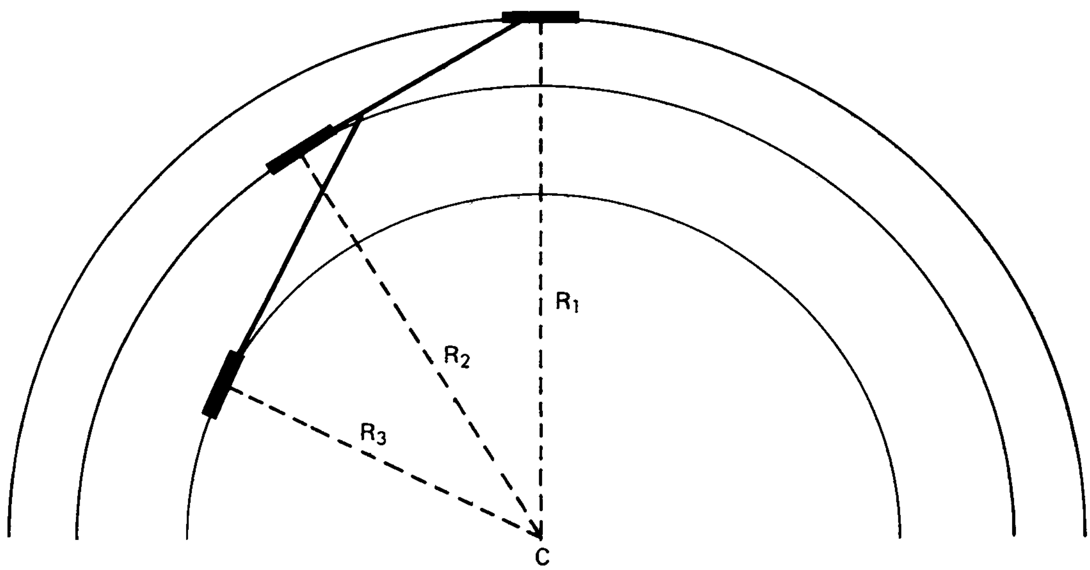
$R_1 = \dfrac{A}{\sin\theta}$ $\qquad$ $R_2 = \dfrac{A}{\tan\theta}$

Fig. 2(a) Wheel tracks of a bicycle moving with fixed angle of steer



Front wheel moves a short step, DF, from P_1 to P_1'
The rear wheel moves from P_2 to P_2' which is assumed to lie on P_1' P_2
The orientation of the front wheel is then adjusted to give the required angle of steer for the next step

Fig. 2(b) Basis of computer algorithm for two-wheeled vehicle



C is meeting point of extensions of all three axles $R_3 < R_2 < R_1$

Fig. 2(c) Steady-state motion of spine vehicle representing an articulated combination

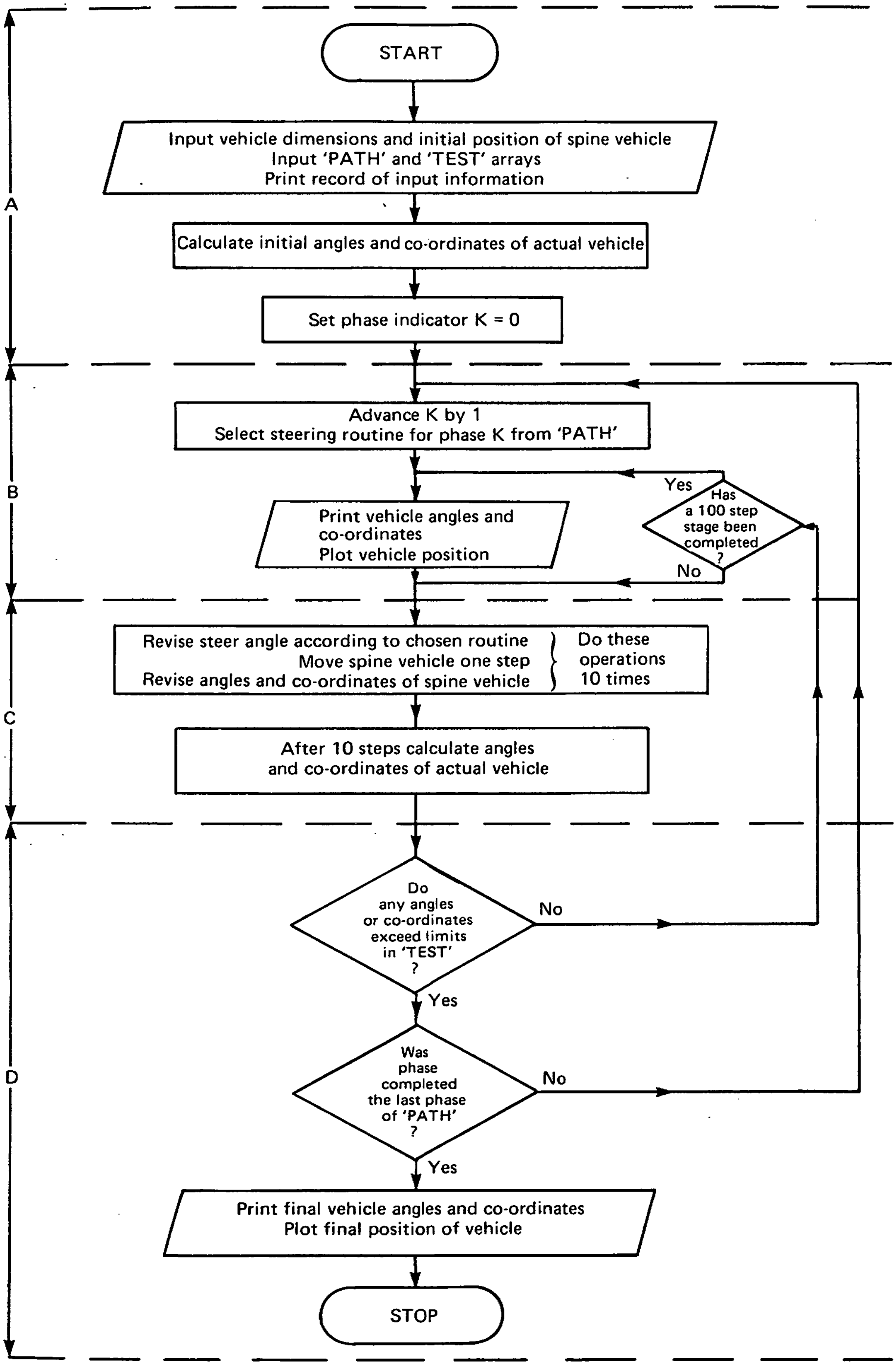


Fig. 3 Simplified flow chart for program TRACK

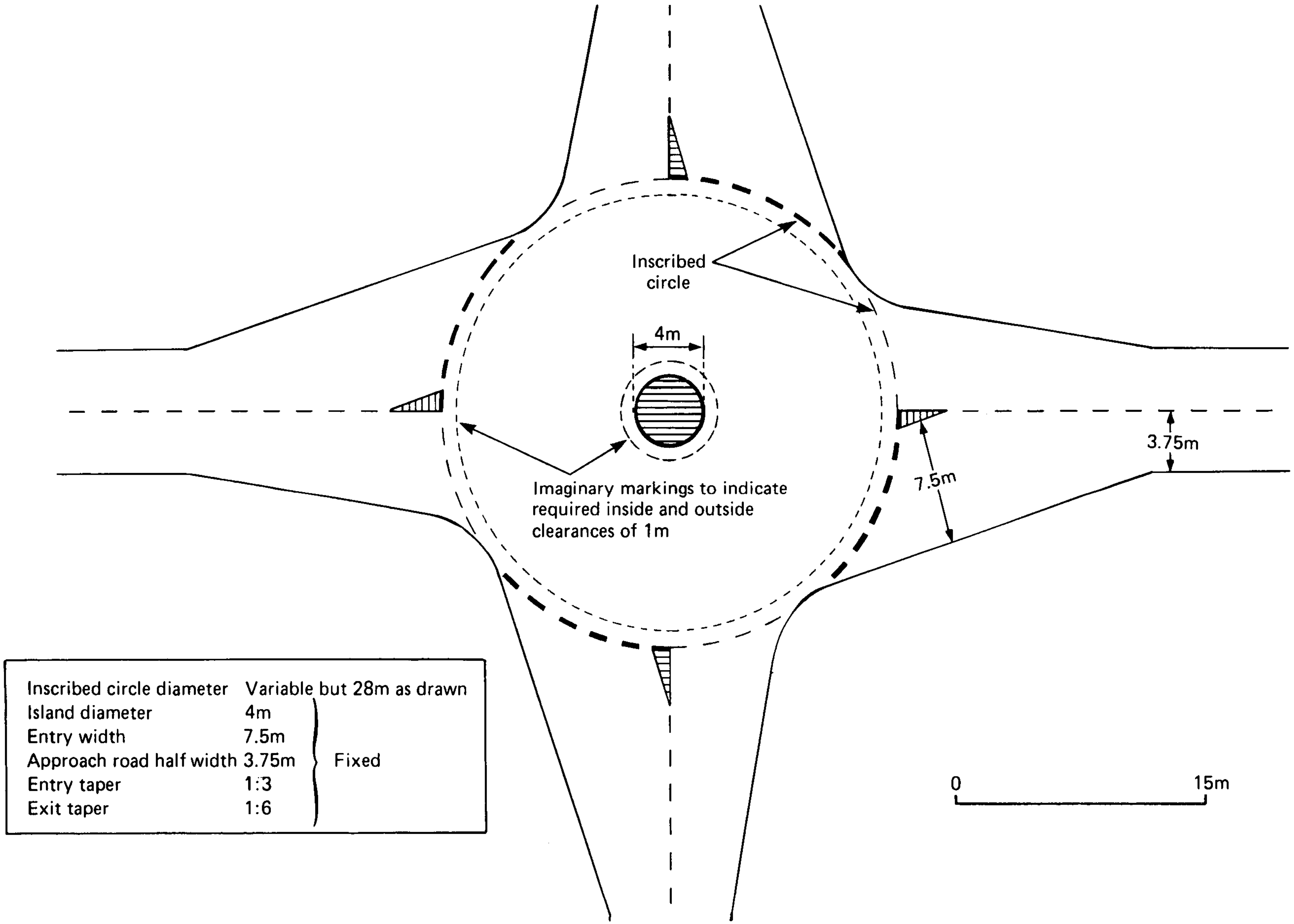
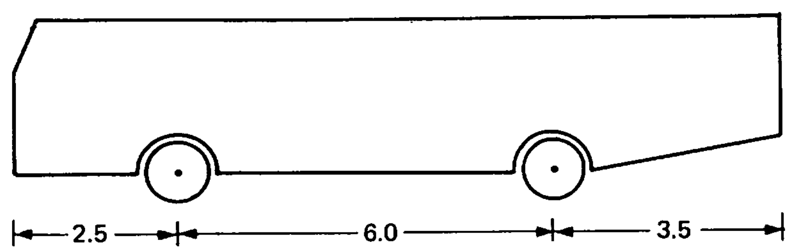
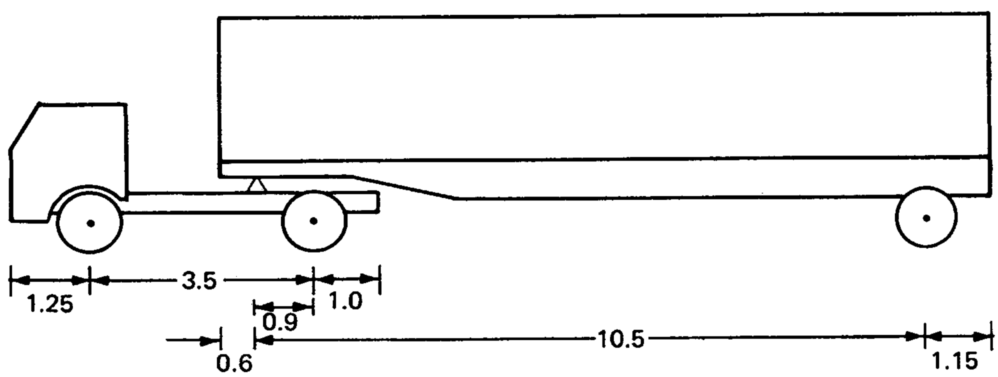


Fig. 4 Roundabout layouts assessed using computer program TRACK



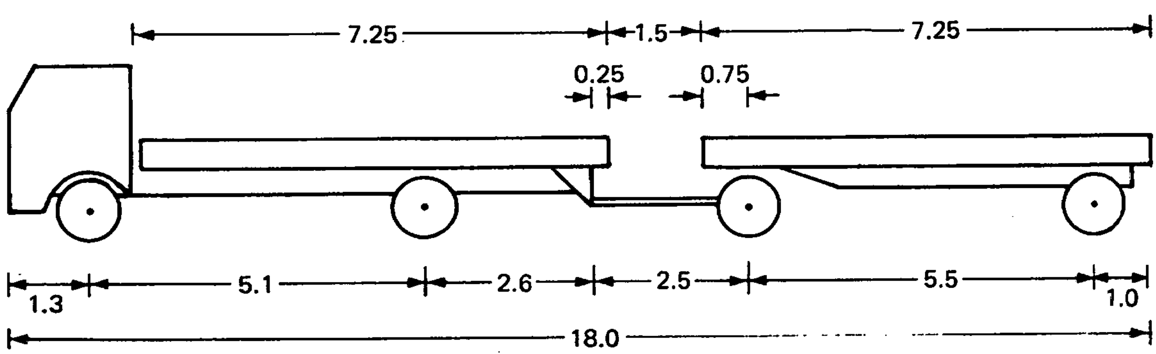
Assumed minimum turning diameter 21m *

(a) RIGID PUBLIC SERVICE VEHICLE



Assumed minimum turning diameter of tractor 15m *

(b) ARTICULATED COMBINATION



Assumed minimum turning diameter of rigid towing vehicle 20m *

(c) DRAWBAR TRAIN

All dimensions in metres

Fig. 5 The design vehicles for the roundabout study (* Refers to turning between kerbs)

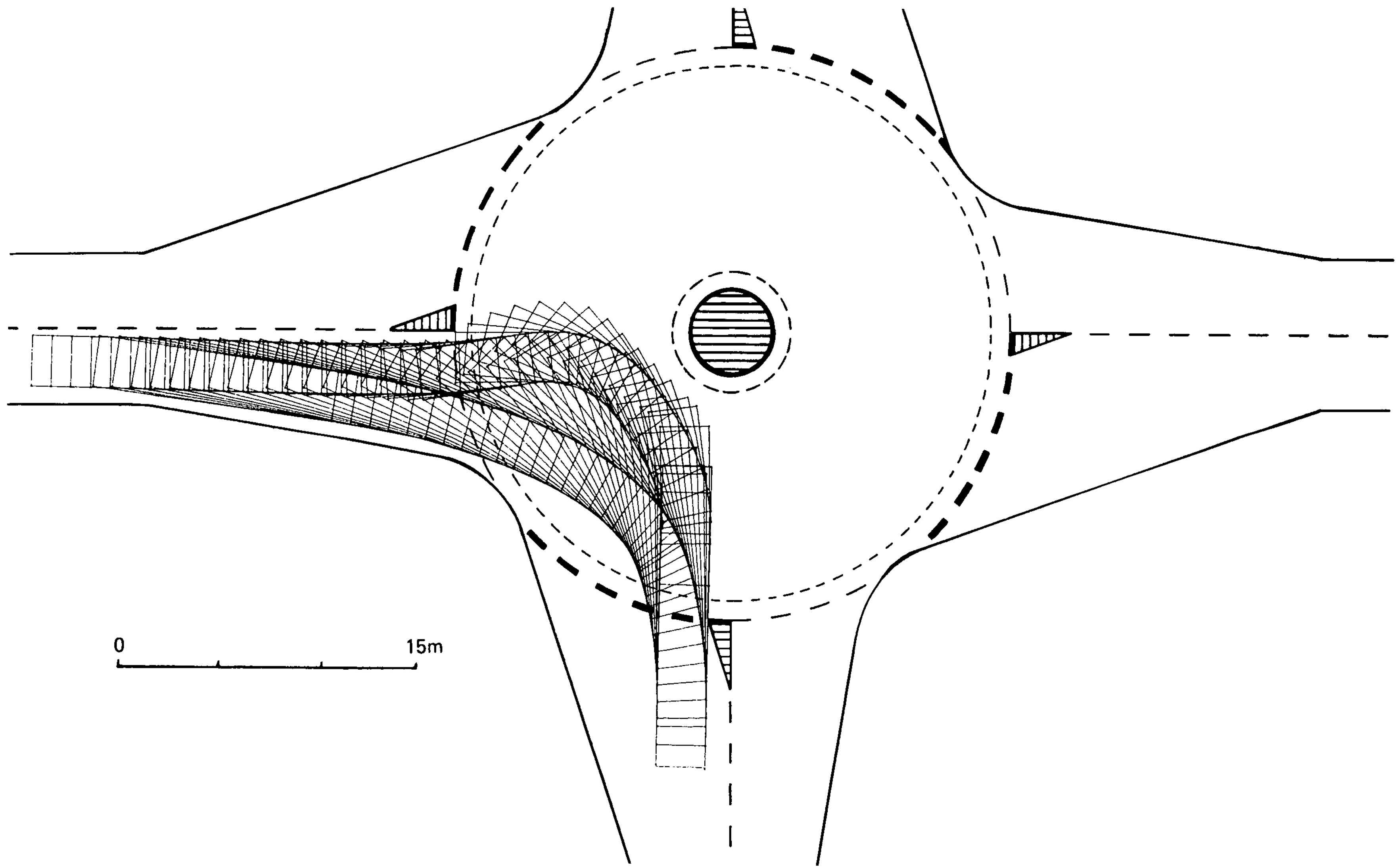


Fig. 6a Simulated left-turn by the design articulated combination at roundabout shown in Fig. 4

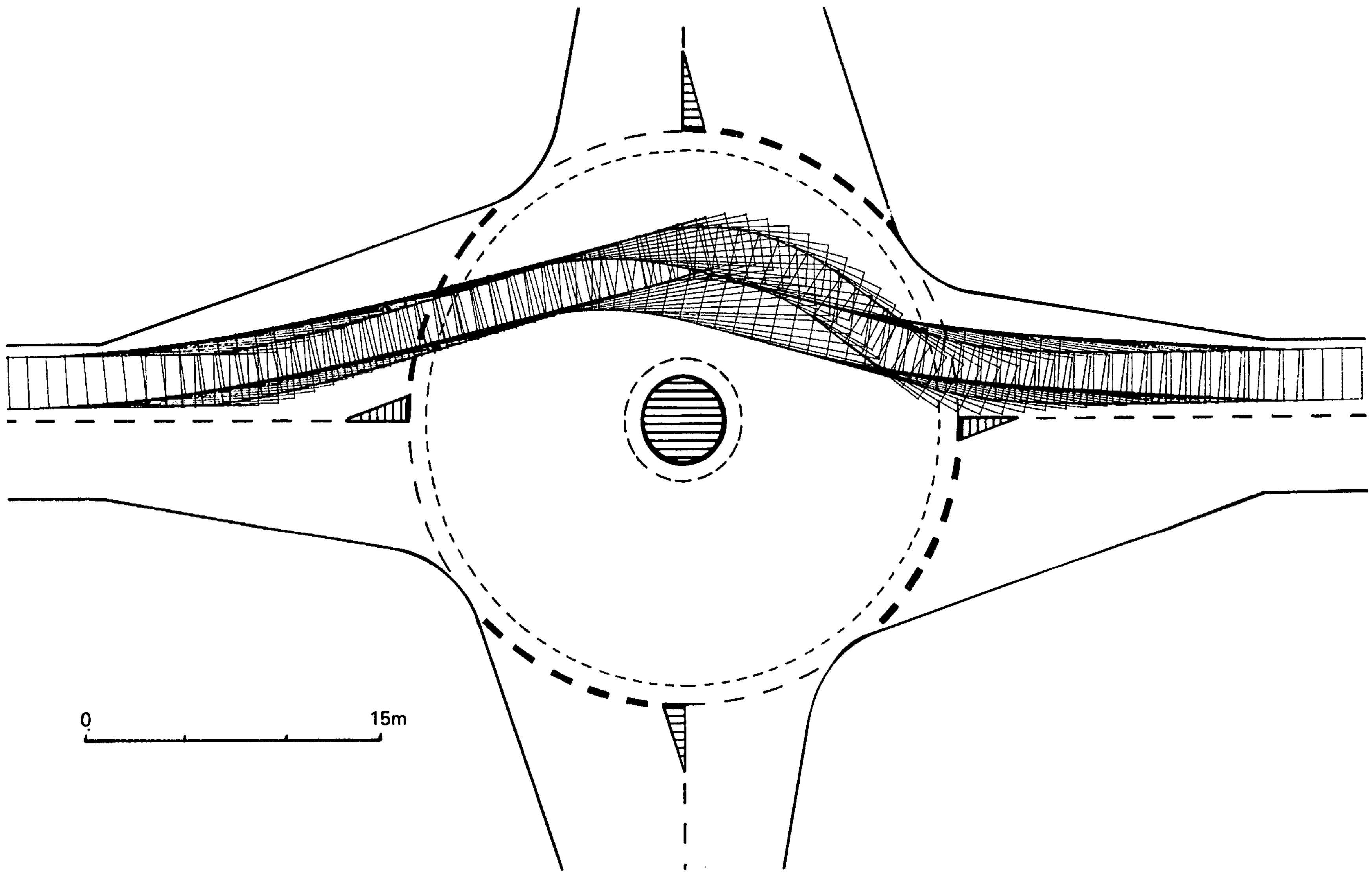


Fig. 6b Simulation of a straight through movement by the design articulated combination at roundabout shown in Fig. 4

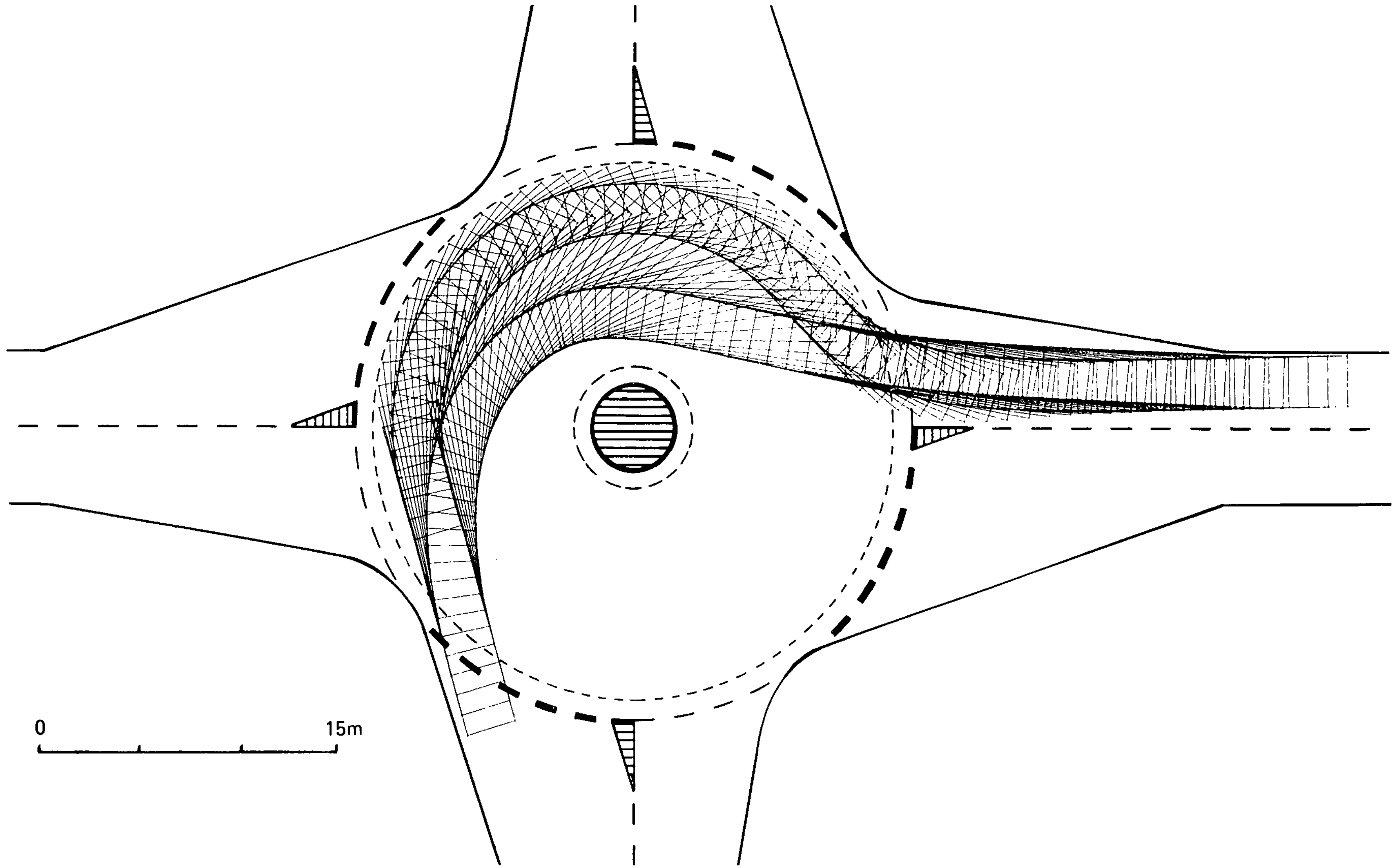


Fig. 6c Simulated right-turn by the design articulated combination at roundabout shown in Fig. 4

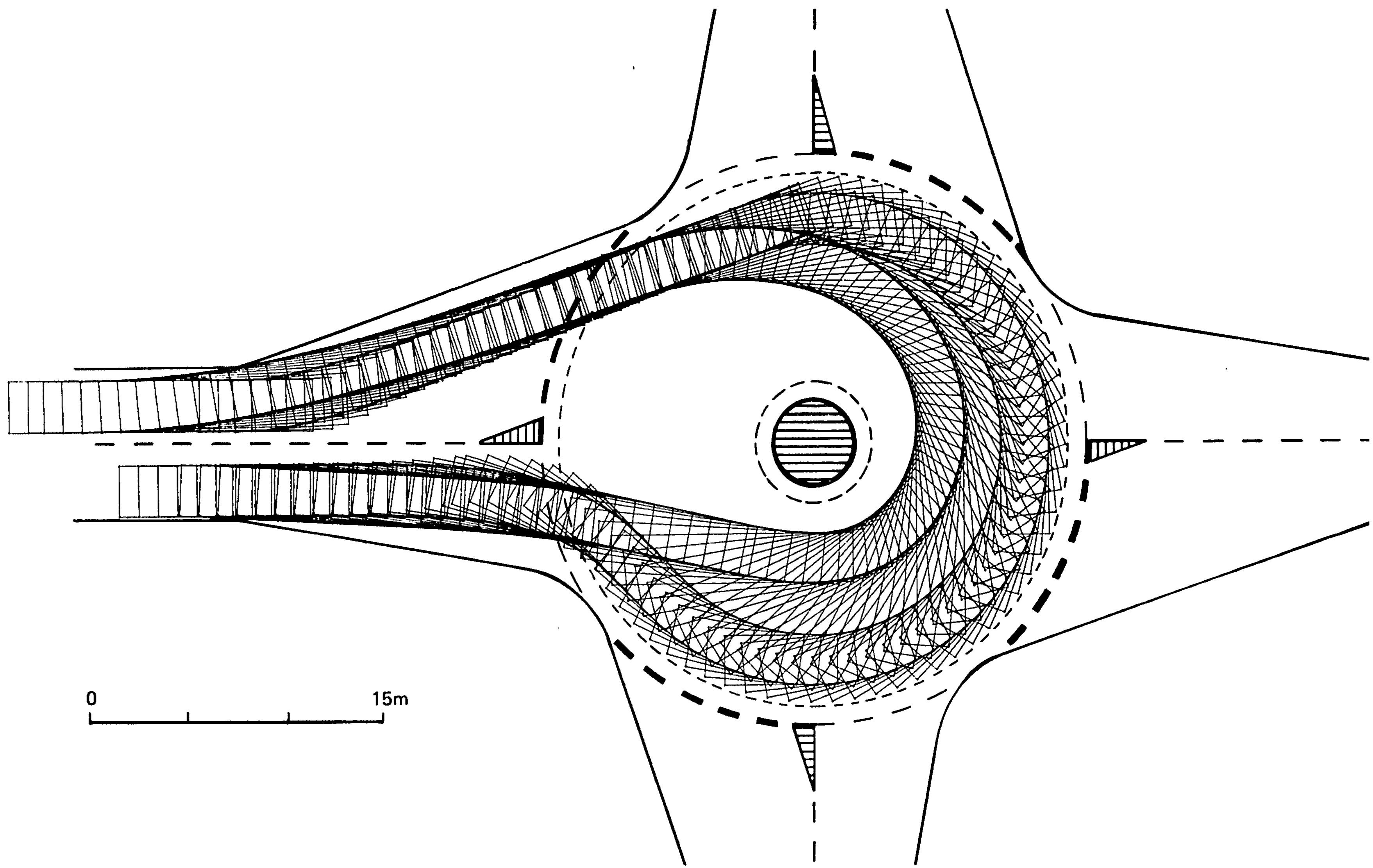
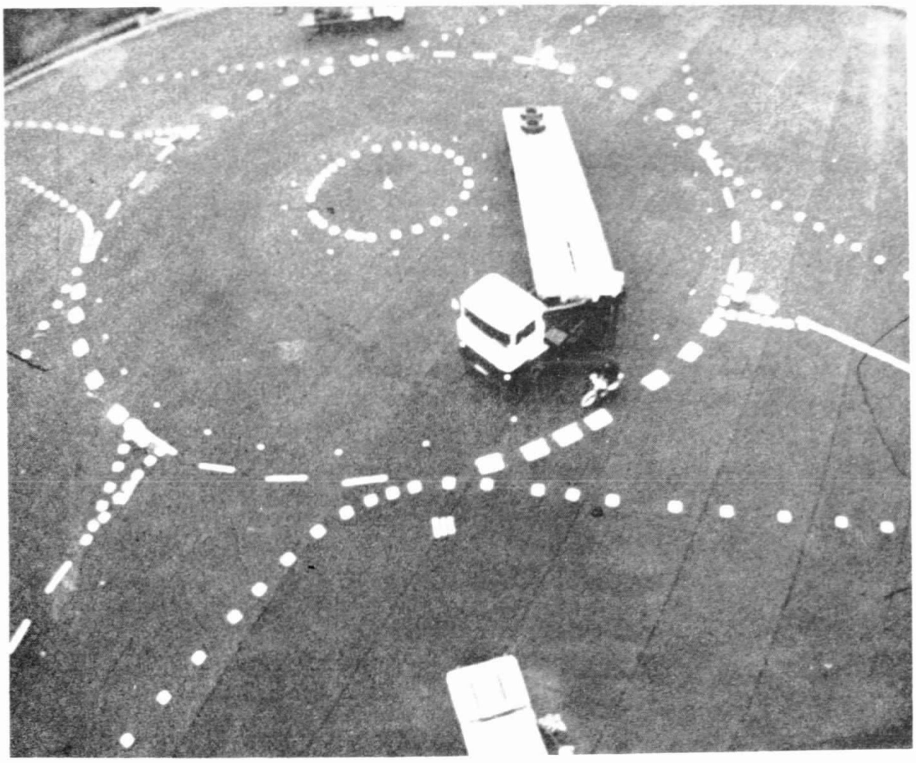


Fig. 6d Simulated U-turn by the design articulated combination at roundabout shown in Fig. 4

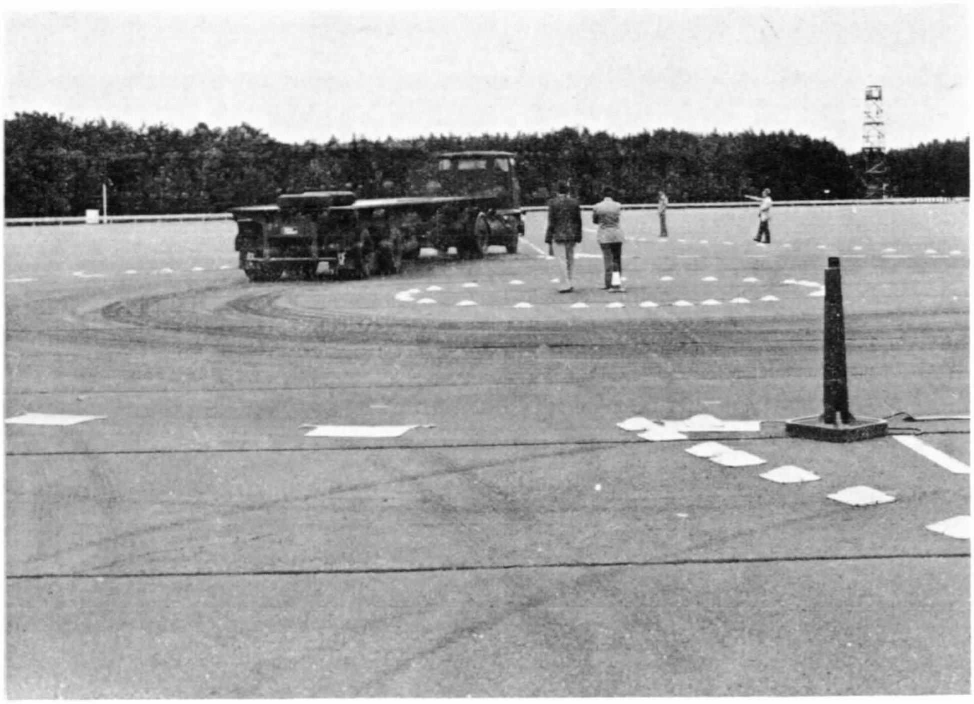


Neg. no. E38/80

Plate 1 View from overhead of 15.5m articulated combination passing cyclist within roundabout

Neg. no. CR 449/80/8

Plate 2 Photo taken at ground level a few seconds before Plate 1



Neg. no. CR 449/80/3

Plate 3 15.5m articulated combination completing a U-turn

Neg. no. CR 448/80/6

Plate 4 Fully loaded 32 ton GVW articulated combination 15.2m long completing a left turn

8. APPENDIX

Amplification of description of computer program TRACK

This appendix supplements the very brief description of the computer program TRACK given in the main text. A longer flow chart is given: whilst this covers the essential operations of the simulation process it does not fully cover the input and output routines.

8.1 *Detailed flow chart for program TRACK*

The flow chart given as Figure 7 is an amplification of the simplified flow chart given as Figure 3 retaining the same sub-divisions into sections A-D. For guidance on terminology and definitions of symbols see Section 8.2.

8.2 *Terms and symbols used in the full flow chart*

Dimensions and co-ordinates of the vehicle modelled. Reference should be made to Figure 8:

P1, P2 and P4 are centres of tractor front, tractor rear and trailer axles.
P3 is king pin.
P5–P12 are body corners.
P1–P12 have co-ordinates (X1, Y1) – (X12, Y12).
A1 is tractor wheel base.
A2 is king pin offset.
A3 is effective wheel base of trailer.
WT is overall front and rear track widths of tractor, both assumed to be the same as tractor body width.
WV is overall track width of trailer (assumed same as trailer body width).
ETF and ETB are front and rear overhangs of tractor.
EVF and EVB are front and rear overhangs of trailer.

Spine vehicle:

In the program being described the basic algorithm for the movement of the vehicle applies to a simplified representation of the vehicle to be modelled. This is referred to as the spine vehicle and consists of a bicycle in the case of a rigid vehicle and a bicycle towing a single-wheel trailer in the case of an articulated combination. For full details see Section 2.2. The positions of points on the vehicle modelled are then deduced from the position of the spine vehicle.

Angles and co-ordinates associated with the spine vehicle. Reference should be made to Figure 9:

Notes: (i) 'Forward' has the normal meaning in relation to parts of the vehicle.
(ii) Positive angles are anti-clockwise whilst negative angles are clockwise.

Points P1–P4 are as in Figure 8.
ET is angle of orientation of bicycle axis with respect to reference axes.
EV is angle of orientation of trailer axis with respect to reference axes.

EA is the angle of articulation (EA=EV–ET).

EF is angle of orientation of bicycle front wheel with respect to reference axes.

ES is steer angle (ES=EF–ET).

DS incremental change in ES between steps during a steering transition.

MES final or target value of ES during a steering transition.

Input information:

Dimensions of vehicle modelled – A1, A2, A3, ETF, ETB, WT, EVF, EVB, WV.

Initial position of spine vehicle – ET, EA, ES, X1, Y1.

NT – number of phases in composite manoeuvre.

NS – number of steps permitted for composite manoeuvre.

Array PATH – specification of manoeuvre phase by phase.

Arrays TEST 1 and TEST 2 – criteria for terminating phases.

Sub-divisions of the program:

Step – the smallest movement considered in the program.

Cycle – ten consecutive steps between calculations of the full range of vehicle angles and co-ordinates and the application of tests.

Stage – 100 steps (ie 10 cycles). Used to determine when vehicle position should be printed and plotted.

Phase – part of the complete manoeuvre executed with a single steering routine.

Counters referred to in detailed flow chart:

K – phase indicator.

IC – counts step movements in tens.

NNU – count of cycles within an individual phase.

NNP – count of cycles in tens for printing and plotting purposes.

NCOND – number of test conditions fulfilled in an application of the tests.

Steering routines:

Normal (no code) – ES is changed by DS between steps until equal to a specified value MES and stays constant thereafter.

Steering code 66 – causes front wheel of spine vehicle to enter a circular arc tangentially, the curvature of the arc being specified by DC (rate of change of EF in radians/step).

Steering code 77 – maintains a constant value of EFO, orientation angle of outside front wheel of vehicle modelled. ('Outside' refers here, to the convex side of the vehicle path).

Steering code 88 – maintains a constant value of EF, orientation angle of front wheel of spine vehicle.

Elements of array PATH (in order):

(1)	NU	–	number of cycles which will terminate phase (NNU $\geqslant$ NU).
(2)	NC	–	number of test conditions which will terminate phase (NCOND $\geqslant$ NC).
(3)	Steering routine code or MES (Value of ES required after a transition).		
(4)	100 (DC)	–	DC is rate of change of EF (radians/step) for code 66.
	EFO	–	required orientation of outside front wheel for code 77.
	EF	–	required orientation of spine vehicle front wheel for code 88.
(5)	DF	–	step size (length of step movements of spine vehicle front wheel).
(6)	DS	–	rate of change of steer angle (radians/step).

Elements of arrays TEST 1 and TEST 2:

TEST 1 sets maximum and minimum values for the following angles: ET, EA, EV, EF.

TEST 2 specifies limiting values for:

X(MAX)	–	maximum value X1–X12
X(MIN)	–	minimum value X1–X12
Y(MAX)	–	maximum value Y1–Y12
Y(MIN)	–	minimum value Y1–Y12

Additional symbols required when there is a steering transition with the normal steering routine:

DIFFT = $\sqrt{}$ (sin ES – sin MES)^2

Calculated using a provisionally altered value of ES:

DIFFL = $\sqrt{}$ (sin ES – sin MES)^2

Calculated using value of ES for previous step:

DIFT $\nless$ DIFFL indicates end of steering transition

ES is then held equal to MES and

IFLAG set to indicate this.

IFLAG – takes value 0 when ES $\neq$ MES

takes value 99 when ES = MES.

8.3 *Units*

Linear dimensions are in metres.

Angular dimensions are in radians.

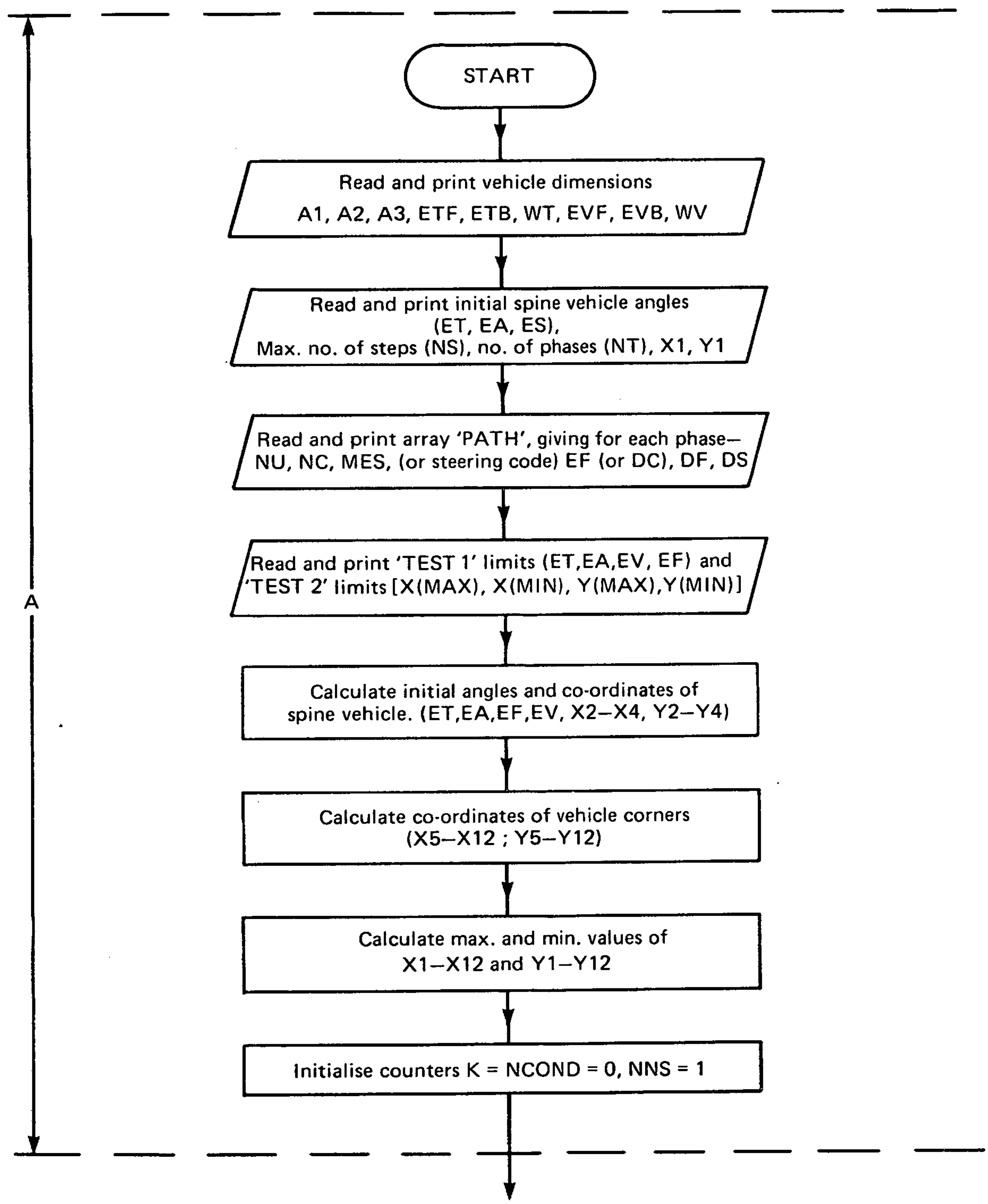


Fig. 7 Detailed flow chart for program TRACK

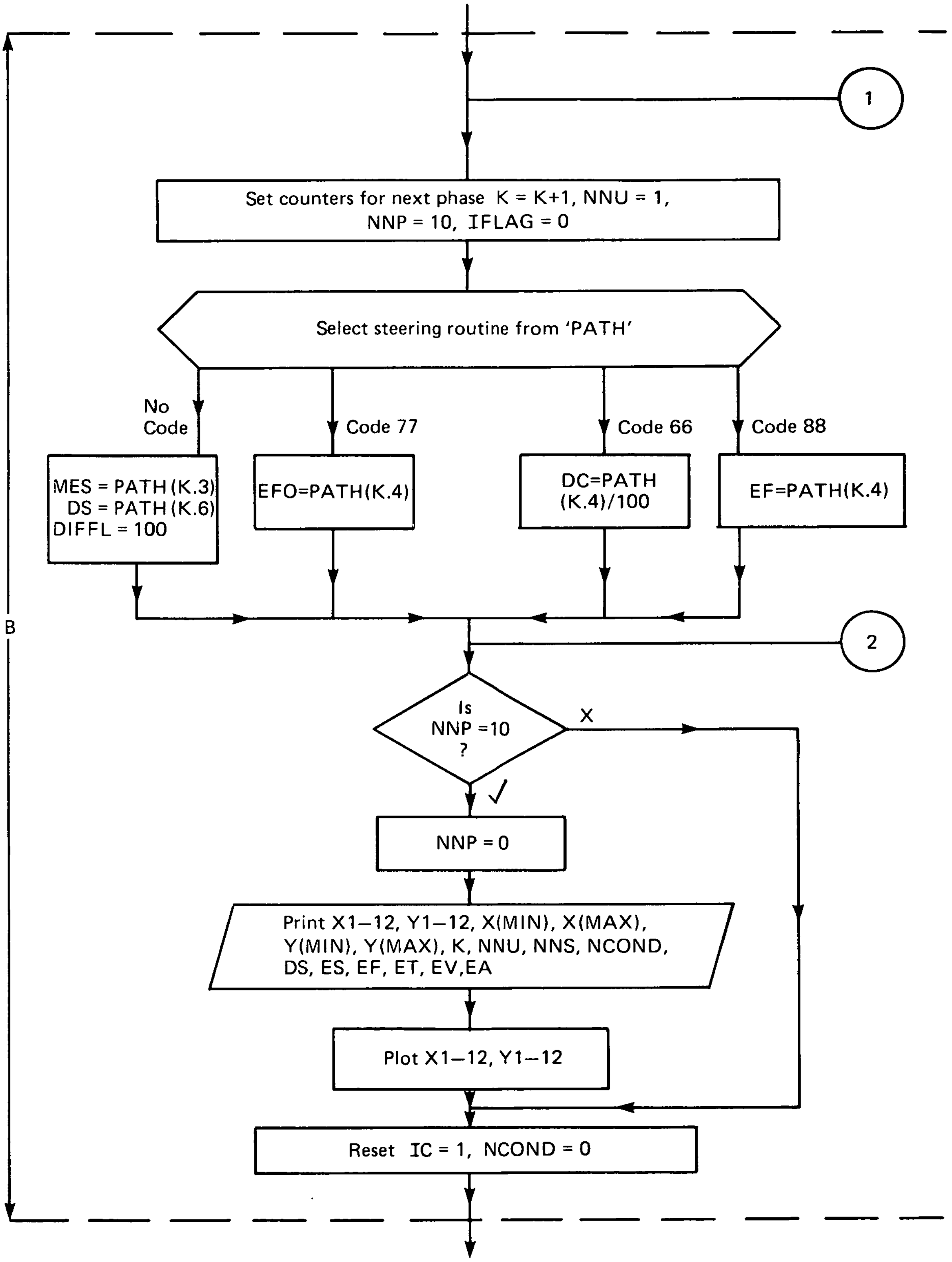
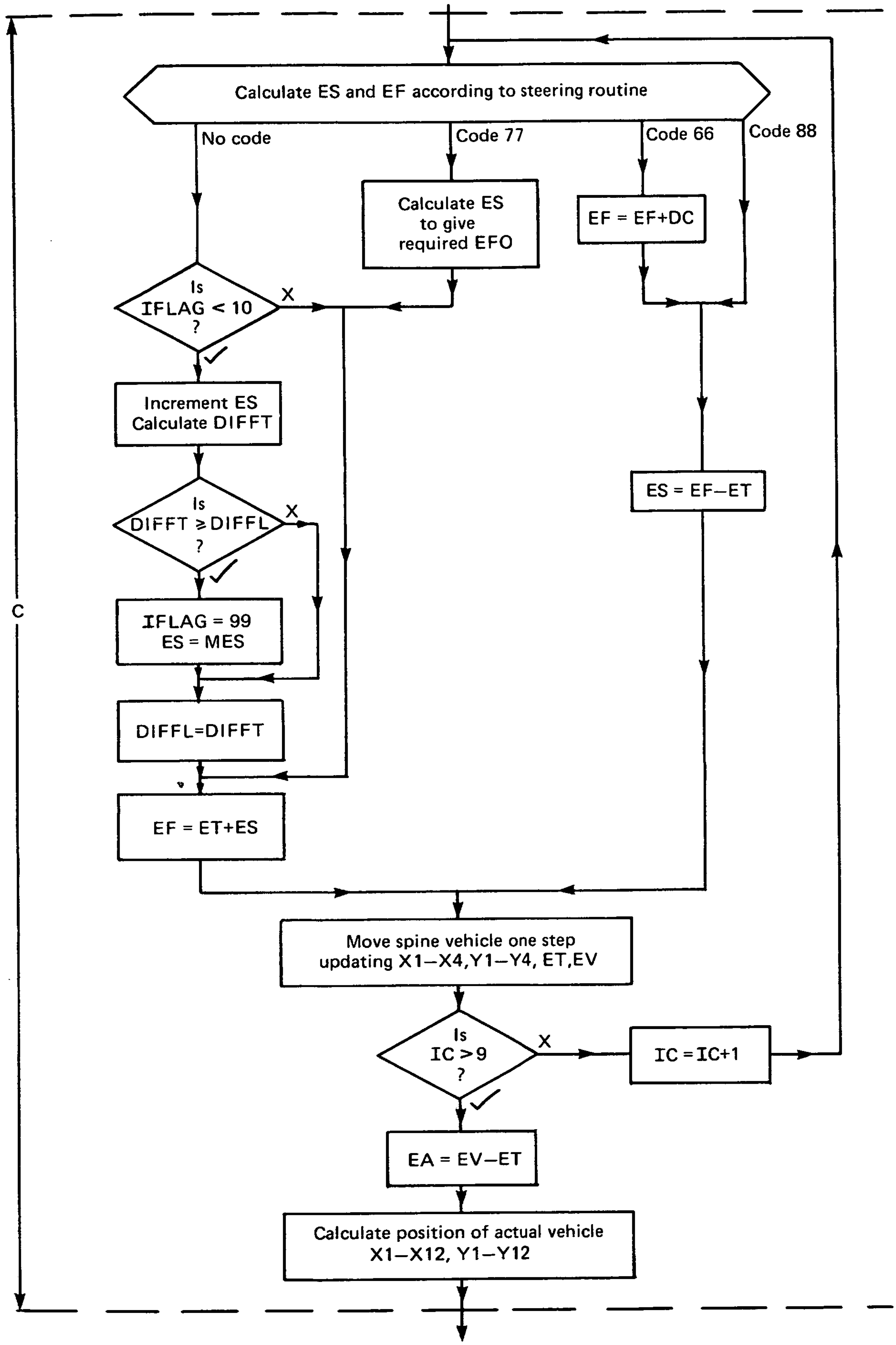

1
Set counters for next phase K = K+1, NNU = 1,
NNP = 10, IFLAG = 0
Select steering routine from 'PATH'
No Code
Code 77
Code 66
Code 88
MES = PATH (K.3)
DS = PATH (K.6)
DIFFL = 100
EFO=PATH(K.4)
DC=PATH (K.4)/100
EF=PATH(K.4)
B
2
Is NNP =10 ?
X
√
NNP = 0
Print X1—12, Y1—12, X(MIN), X(MAX), Y(MIN), Y(MAX), K, NNU, NNS, NCOND, DS, ES, EF, ET, EV,EA
Plot X1—12, Y1—12
Reset IC = 1, NCOND = 0

Fig. 7 (cont.)



Calculate ES and EF according to steering routine
No code
Code 77
Code 66
Code 88
Calculate ES to give required EFO
EF = EF+DC
Is IFLAG < 10 ?
X
Increment ES Calculate DIFFT
ES = EF–ET
Is DIFFT ≥ DIFFL ?
X
C
IFLAG = 99 ES = MES
DIFFL=DIFFT
EF = ET+ES
Move spine vehicle one step updating X1–X4,Y1–Y4, ET,EV
Is IC > 9 ?
X
IC = IC+1
EA = EV–ET
Calculate position of actual vehicle X1–X12, Y1–Y12

Fig. 7 (cont.)

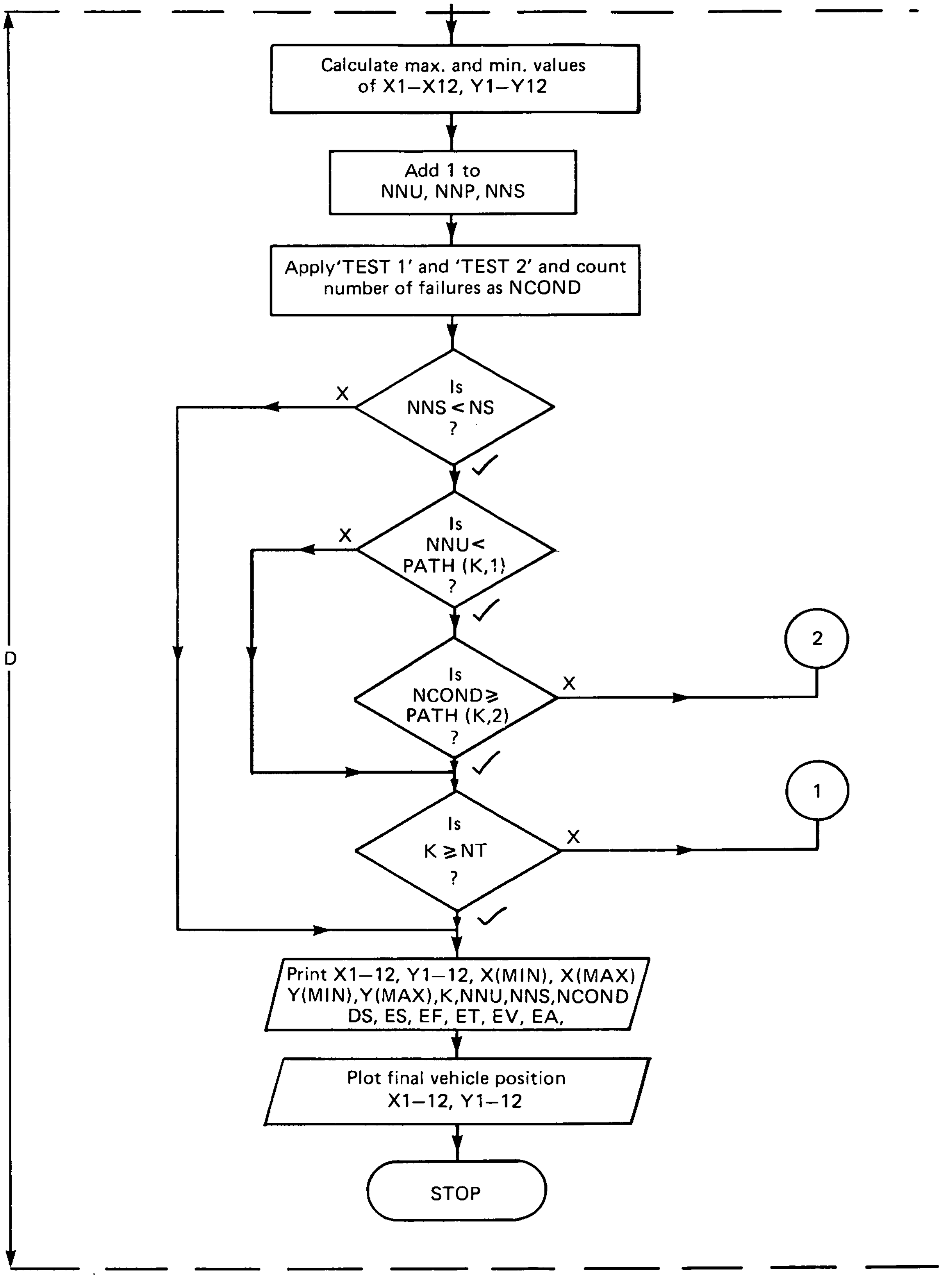

Calculate max. and min. values
of X1–X12, Y1–Y12
Add 1 to
NNU, NNP, NNS
Apply 'TEST 1' and 'TEST 2' and count
number of failures as NCOND
Is
NNS < NS
?
X
Is
NNU<
PATH (K,1)
?
X
Is
NCOND≥
PATH (K,2)
?
X
2
Is
K ≥ NT
?
X
1
D
Print X1–12, Y1–12, X(MIN), X(MAX)
Y(MIN),Y(MAX),K,NNU,NNS,NCOND
DS, ES, EF, ET, EV, EA,
Plot final vehicle position
X1–12, Y1–12
STOP

Fig. 7 (cont.)

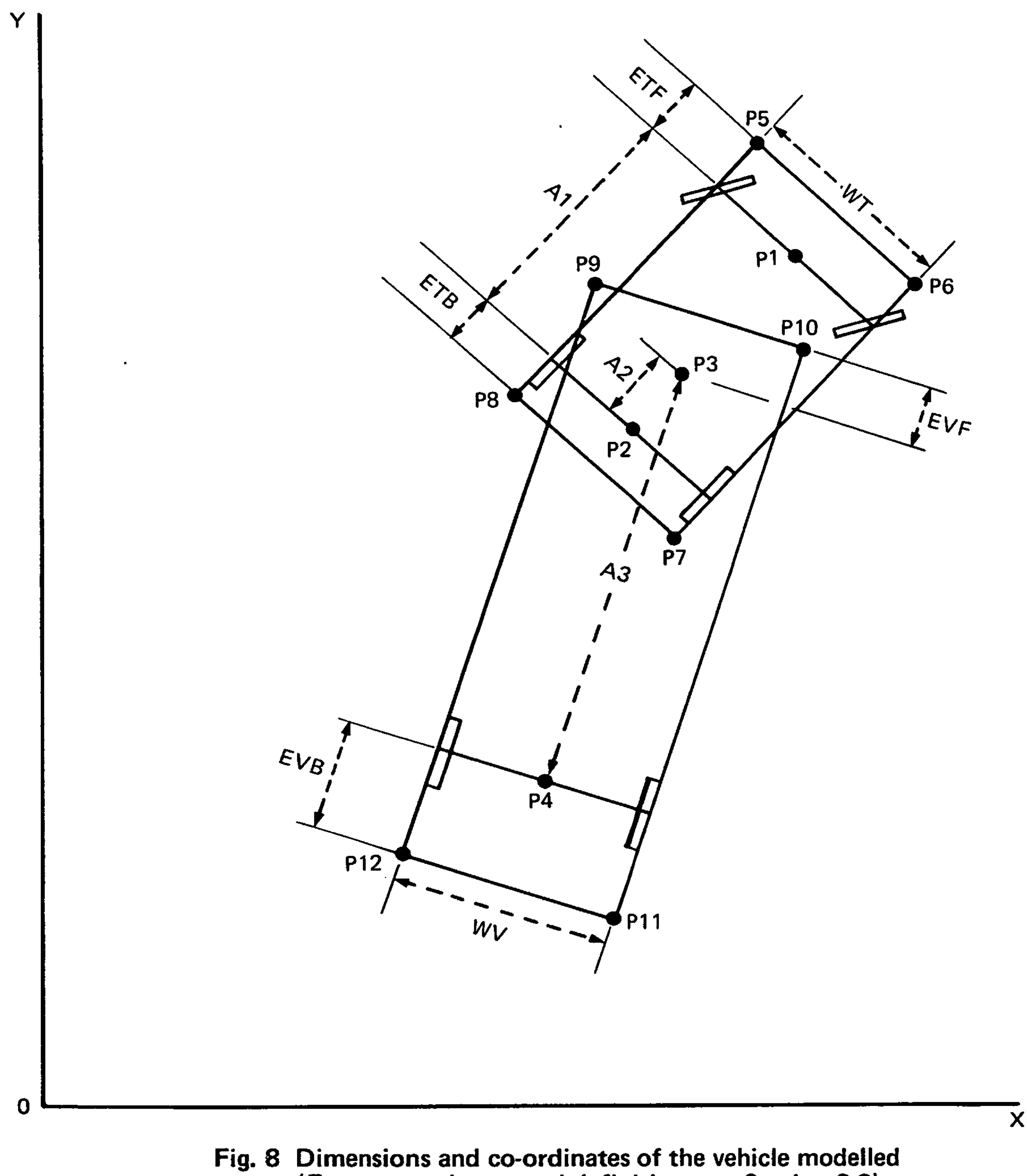


Fig. 8 Dimensions and co-ordinates of the vehicle modelled (For nomenclature and definitions see Section 8.2)

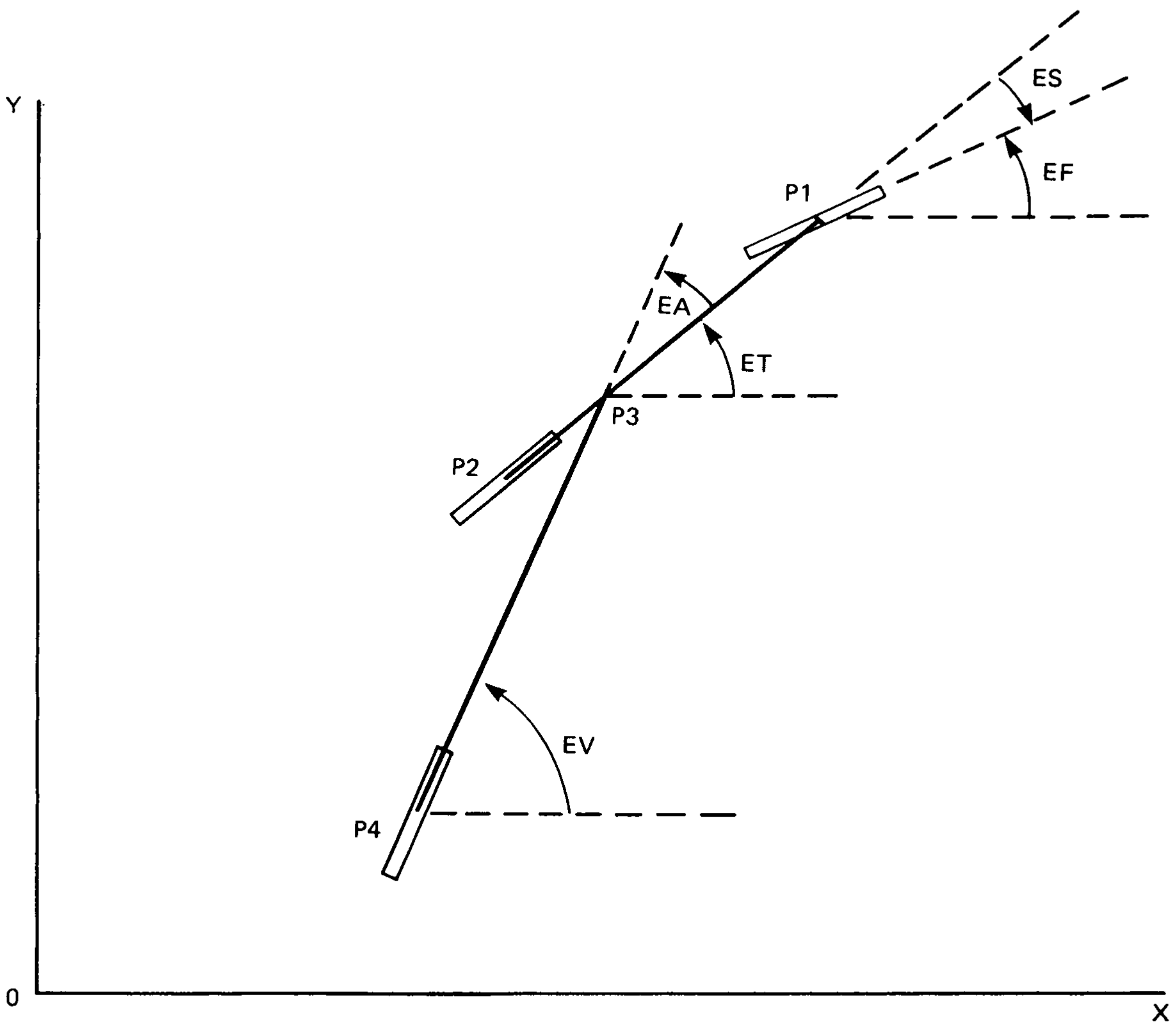


Fig. 9 Angles and co-ordinates associated with the spine vehicle (For nomenclature and conventions see Section 8.2)

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