LECTURE A2 - TANGENTS & CURVES **PRESENTER: CD SCOTT**

1 INTRODUCTION

A road alignment comprises a continuous combination of tangents and curves in both the horizontal and vertical planes and the quality of the road is largely dependent in the standard and inter-relationship of these parameters. The better the alignment, the higher the safety and carrying capacity of the road for a particular operating speed.

A straight flat alignment is the "highest" standard of alignment that can be achieved as it represents an infinitely high design speed. However, it overlooks one of the restraints imposed on design being the frailty of the driver in the sense that monotony is followed by boredom and a driver asleep at the wheel. A high standard is hence not necessarily safe.

This lecture explores the concept of quality of design and relates it specifically to the horizontal alignment of the road.

The process of determining horizontal alignment involves fitting tangents to the overall topography of the terrain being traversed with due cognisance being taken of other restraints as discussed previously and then connecting these tangents by curves of an appropriate radius.

Various suggestions have been made from time to time that a road would be aesthetically more pleasing if the reverse process were to be followed, namely fitting curves to the topography and then linking them with relatively short tangents. The latter is referred to as curvilinear alignment. Reference has been made, in the same context, to higher order polynomials being used to define the curves selected. Such suggestions are totally impractical because they are so blinded by the beauty of what a road can be that they forget what the road should do. And more specifically what the road should not do and that is to confuse the driver with a wide radius that suddenly winds up on him because a spiral looks so pretty from the air. Furthermore, they also overlook the fact that these very complex curves may look effective on paper but are not readily transferred from the drawing board to the ground.

2 TANGENTS

As in the tale of Goldilocks, a tangent should not be too much or too little. It should be just right. The geometric aspects of a tangent that are of concern are thus principally its length and its bearing.

A tangent that is too long is, as suggested above, monotonous and correspondingly likely to introduce boredom and reduce safety. A tangent that is too short, on the other hand, will not allow sufficient distance in which to introduce the superelevation required for the next curve. Furthermore, when tangents are very short, i.e. curves follow each other in quick succession, the associated safety record is also not good. What then is actually meant by such fine qualitative words as "too long" and "too short"? American studies have shown that when the distance between successive curves is such that superelevation development is represented by a continuous rollover from one side of the road to the other the crash rate is high. Seeing that this research is old (thirty years plus) the actual values are, at this stage, of no consequence. When the distance from the end of one curve to the commencement of the next curve is of the order of twenty kilometres the crash rate is at about the same value as for continuous curvature. In between these two values, the collision rate declines and then increases in a nearly symmetrical parabolic fashion bottoming out at about twelve kilometres.

It would almost appear as though drivers have to be given something to do, or something different to look at, at about five-minute intervals to keep them awake so they stay on the road. On the other hand, if they get given too much to do every five minutes they get confused and have difficulty in staying on the road. While this may sound facetious, it would appear that tangents should, desirably be of the order of, say, eight to twelve kilometres long.

The minimum length of straight must allow for the run-off of the superelevation of the preceding curve followed by the development of that for the following curve. This distance should actually be calculated during detailed design but, as a rough rule of thumb, a tangent length of less than 200 m is likely to be a problem.

A tangent with a bearing that is East-West will present the driver with a major challenge at sunrise and sunset, with a beautiful golden glowing orb tastefully perched on the centreline of the road and blinding him. Avoiding this problem can tax the skill of the designer but an attempt has to be made to limit the distance over which the driver is effectively blinded. Various combinations of bearing and gradient can cause the same situation to arise at different times of day. The 6 % gradient and the bearing of 95^0 on the exit from Ladybrand in the direction of Bloemfontein means that few local drivers commence their journey at about four o'clock in the afternoon.

Where the topography is flat, a long tangent can also be a problem in night driving. A driver is very aware of approaching lights for as much as two minutes before the vehicles actually pass each other and in the second of the two minutes reference can be made to dazzle which becomes increasingly severe. Two vehicles approaching each other, when they are both travelling at say 120 km/h, are as much as eight kilometres apart at the commencement of the two-minute period referred to and are still four kilometres apart at the onset of dazzle! During the last fifteen seconds, at the commencement of which the two vehicles are still a kilometre apart, the drivers can only really guide their vehicles by concentrating on their left road edge at a point which will not be much more than about fifty metres in advance of their present position. At 120 km/h, a vehicle requires a stopping distance of 200 metres.

3 CURVATURE

The process of locating the alignment as a series of tangents tends to cause curves to be remote from each other so that each curve is an independent feature. As the terrain becomes more rugged, tangent lengths diminish until successive curves can no longer be dealt with in isolation. As a point of departure, the isolated curve shall be considered first.

3.1 Isolated curves

3.1.1 Minimum radii of curvature

In selecting curve radii, the principal control is the minimum radius that can be traversed in safety at the design speed. Travelling on a circular path generates a centrifugal force on the vehicle which has to be counteracted by a centripetal force. The latter is generated by means of the side friction between the vehicle's tyres and the road surface augmented by superelevation, which adds a component of the vehicle weight to centripetal force.

The centrifugal force to be overcome is a function of curve radius and speed. The calculation of minimum radius is thus aimed at determining the maximum centripetal force that can be generated by side friction and superelevation and then selecting a radius which will ensure that this is not exceeded at the design speed of the road.

Minimum radii for design speeds are thus dependent on whatever rate of superelevation is adopted by the road authority concerned. Rural authorities are inclined towards adopting higher values of maximum superelevation and opt for values of 10 %. Urban authorities are restricted in their choice of maximum rate of superelevation by other constraints such as the need for property access to the street and the presence of successive intersections in quick succession and may have to accept values of 4 % or 6 % with the former preferred.

3.1.2 Length of curve

As stated earlier, a standard in the geometric sense is not a quality of excellence and is, in this case, a minimum or a maximum to be used only in the most stringent of circumstances. In general, the deviation angle of a curve should be as low as possible to ensure that the road is directional, ie deviates only slightly from the shortest route between origin and destination, and should also be absorbed in the flattest possible radius so that passing opportunities are not unduly restricted.

TABLE A2.1: MINIMUM RADII OF HORIZONTAL CURVATURE			
Design Speed (km/h)	**Minimum Radius (m) for e_{max} of**		
	4 %	**6 %**	**10 %**
50	100	90	80
60	150	135	110
70	205	185	160
80	280	255	210
90	380	340	270
100	465	420	350
110	These design speeds are not normally encountered in urban situations		430
120			530
130			640
140			760

Not only is a kink unsightly but it can also lead to somewhat erratic behaviour because the driver may perceive too late that he is entering a curve and ultimately follow a path which has a lower radius than that actually selected by the designer. If the selected radius is also the minimum, the driver may find himself in a situation more exciting than he had bargained for.

A minimum length of curve often recommended is of the order of 300 m. If space is limited, this can be reduced to 150 m and for small deflection angles, i.e. less than 5^0, the length should be increased from 150 m by 30 m for each 1^0 reduction in deflection angle below 5^0. If the deflection angle is 2^0, it follows that the curve length should be 240 m and the radius thus about 7 000 m.

A long curve, particularly if it is at near-minimum radius as would be found in a hairpin or horseshoe bend, will cause tracking problems. These problems are suffered by vehicles travelling at speeds markedly different from the design speed of the road. The truck with a high load, when at crawl speed on a curve with a superelevation of 10 % (or, as previously was the case, a maximum of 12 %) could quite easily drop its load all over the road surface. The high-speed vehicle will almost certainly not follow a smooth circular path and a series of corrections will introduce localised radii which could prove to be sub-minimum to the consternation of the driver concerned.

A practical problem with the long curve is that, when left-handed, a trailing vehicle has to move out into the path of oncoming traffic in order to see whether overtaking is safe. This practice is, of itself, unsafe and means that passing opportunity is restricted over the length of the curve. Passing opportunity is also restricted by virtue of the fact that the overtaking vehicle has to traverse an outside curve which is a longer path than when overtaking on a tangent. Of course, the right-handed curve eases the problem of seeing oncoming traffic and the overtaking manoeuvre itself.

In general, the length of a curve should preferably not exceed 1 000 m.

3.2 Successive curves

Curves are considered successive when they can no longer be considered in isolation. The interaction between curves is both visual and operational. Visual interaction arises from a driver on one curve being able to see the following curve at close range. Operational interaction refers to the fact that the development of superelevation is impeded by the run-off of superelevation of the preceding curve.

Three possible forms of interactive curves have to be considered. The first is the case where a curve is followed by a curve in the opposite direction and referred to as a reverse (or S) curve. The second case has the following curve in the same direction as the first and known as the broken-back curve. A compound curve has the successive curves of differing radius in the same direction, as with the broken-back, but does not have intervening tangents.

3.2.1 The reverse curve

The reverse curve, if correctly designed, can be visually pleasing. The ideal is to have the two radii and angles of deviation identical. This is the true S-curve, seldom achieved in practice. The change in superelevation should be a smooth continuum from the maximum value in the one direction to the maximum appropriate for the other and achieved by the rotation of the two road edges relative to the centreline. Apart from any visual appeal that this has, it also has the eminently practical effect of reducing the distance over which the road could be totally flat, hence creating a drainage problem.

Another problem to avoid is an abrupt reversal in alignment. No vehicle can instantaneously change from a circular path in one direction to a path in the reverse direction and a short length of tangent between the two straights is required to serve as a transitional area. This tangent is also required to accommodate the superelevation transition.

3.2.2 The broken-back curve

The broken-back is, visually, a disaster. Furthermore, it does not match driver expectations, which are that successive curves should be in opposite directions. Finally, it creates the impression that the designer was not terribly sure as to how far round the total change of direction should have been. The broken-back can lead to operational problems, especially for drivers who are attempting to follow a reasonably continuous circular path only to encounter a section of their path that may be unsuperelevated.

This potentially dramatic situation can be alleviated to a certain extent by having a cross-fall towards the inside of the curve instead of a normal camber. The cross fall also has the effect of avoiding the flat spot which is an inevitable feature of superelevation development. In mountainous terrain, the alternative single curve may generate excessive earthworks so that the broken-back cannot always be avoided.

A distance of about 150 m between curves does however serve to reduce the broken-backed appearance to some extent. And the epithet "broken-back" is usually not employed if the distance between curves is 500 m or more.

3.2.3 Compound curves

Compound curves afford flexibility in fitting the road to topographic and other controls. The simplicity with which such curves can be used may tempt the designer to use these curves without restraint. Drivers do not, however, expect the radius of a curve to change and seemingly also have difficulty in perceiving that the radius has, in fact, changed. Mention has also been made of the reluctance of drivers to change speed once on a curve so that these curves should be avoided if possible.

The one area where the application of compound curvature is legitimate is on interchange loops because the driver expects to exit from one road at its operating speed and then to decelerate to some minimum value on the loop before accelerating to the operating speed of the road to be entered. Large differences in successive radii of curvature should, however, be avoided and it has been found that a ratio of 1:2 between successive radii should not be exceeded if erratic behaviour is to be avoided. The length of the individual successive curves must also be sufficient to ensure that the driver has been afforded a reasonable opportunity to achieve the speed appropriate to the next radius encountered. Compound curves will be discussed in more detail in the lecture dealing with interchanges.

In the best of engineering traditions, the compound curve is, in fact, a compromise and serves in the role which should, more properly, be undertaken by a spiral curve. Spiral curves are, however, generally considered, and quite rightly so, to be a nuisance to set out and even to draw on plan. The only spiral curve that a designer is likely to want in his repertoire of geometric design devices is the transition curve. This curve is used to introduce superelevation on tight radius circular curves and the appellation "transition" refers to the fact that it serves as a transition from a tangent (otherwise a circular curve of infinite radius) to a circular curve.

4 Sight distance and horizontal curvature

Sight distance is the prime parameter in the consideration of vertical curvature and is also of major importance in the siting of intersections but plays a much lesser role in consideration of the horizontal alignment. It cannot however be overlooked.

The need for consideration of sight distance arises in the case of a horizontal curve that is in cut. Sight distance is normally measured along the centreline of the road and, if this convention were to apply also to horizontal curves, the driver on the inside of the curve would automatically have less sight distance than he requires. This problem is overcome by measuring sight distance in this case along the centreline of the inner lane as illustrated in Figure A4.1. The driver's line of sight is, of course shorter than this but it is the distance travelled that is of consequence and this can be approximated by measurement at the indicated point on the cross-section. If the added complication of a steep downgrade is considered, it may be found that the sight distance actually provided is hopelessly inadequate. Could it not be that this situation prevails on many of our mountain passes?

Stopping distance involves the capability of the driver to bring his vehicle safely to a standstill and is thus based on speed, driver reaction time and the desired rate of deceleration.
The only difference between stopping distance and stopping sight distance is that the latter brings the factors of eye height and object height into account. Stopping sight distance is the sum of two distances:

- ❑ the distance traversed by the vehicle from the instant the driver sights an obstruction to the instant the brakes are applied, and
- ❑ the distance required to stop the vehicle from the instant the brakes are applied

These are referred to as brake reaction distance and stopping distance, respectively.
These two components, using a reaction time of 2,5 seconds and a deceleration rate of 3,0 m/s^2, result in the relationship
These two components, using a reaction time of 2,5 seconds and a constant deceleration rate of 3,0 m/s^2, result in the relationship

Const Accel: $a = dv / dt = dv / dx . (dx / dt) = v . dv / dx$

$a.s \Leftarrow a. \mu dx = \mu v . dv = v^2 / 2 \,\big|\, v_0 \text{ to } v = \frac{1}{2} . (v^2 - v_0^2)$

$s = v_0^2 / 2.a$

SSD: $s = v.t + v^2 / 2.a$

$= \{V / 3,6\} . 2,5 + \{V / 3,6\} / (2 . 3) = V.(0,694 + V / 77,76)$

$= V.(0,694 + 0,013.V)$

where: s = stopping sight distance, m

V = initial speed, km/h

Stopping sight distances calculated using this equation are given in Table A2.1, rounded up for design purposes. Also shown in the table for general interest are the values of stopping sight distance adopted in the 2000 AASHTO Policy on the Geometric Design of Highways and Streets, the "Green Book 2000".

Table A2.2: Recommended stopping sight distances for design

Design Speed (km/h)	Stopping Sight Distance (m)		
	Calculated	Recommended for Design	Green Book 2000
30	32,5	35	35
40	48,6	50	50
50	67,2	70	65
60	88,4	90	85
70	112,3	110	105
80	138,7	140	130
90	167,8	170	160
100	199,4	200	185
110	233,6	230	220
120	270,5	270	250
130	309,9	310	285

In the measurement of stopping sight distance, the driver's eye height is taken as being at 1,05 m and the object height is as defined in Table A2.3.

Table A2.3: Object height design domain

Object Height (m)	Applicability
0,00	Risk of road washouts Pavement markings in critical locations
0,15	Risk of fallen trees or rocks Risk of log or construction debris fallen from truck Risk of fallen person
0,60	Vehicle tail or brake light
1,30	Passing sight distance for top of car Intersection sight distance

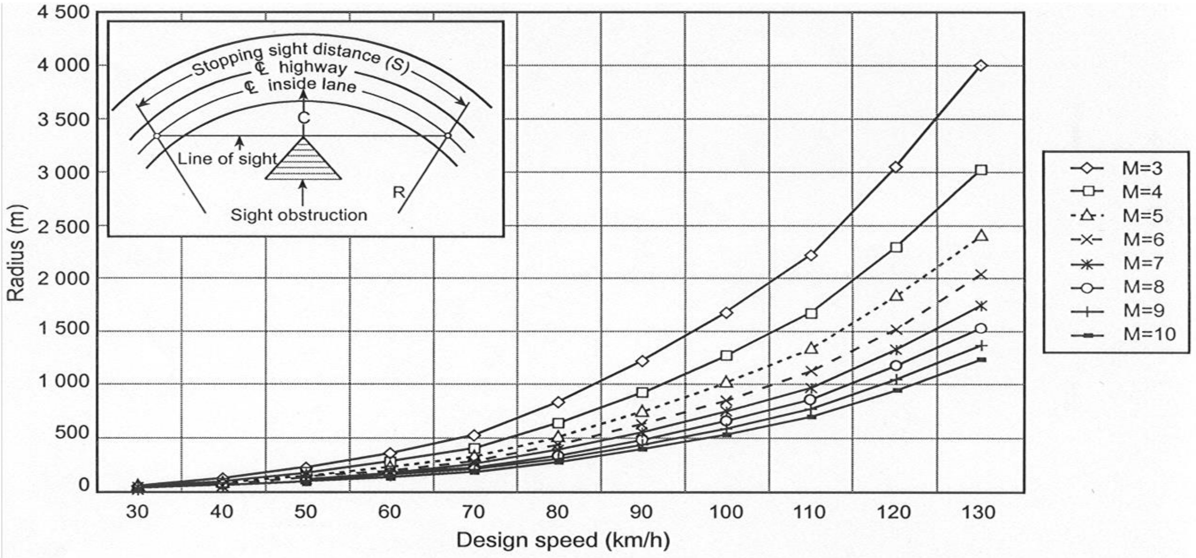

Figure A2.1: Minimum horizontal radius for stopping sight distance

These are the stopping distances that have to be borne in mind when designing a horizontal curve in cut.

The gradient has a marked effect on stopping distance requirements and this is illustrated in Figure A2.2, which is an expansion of the above table. The equation for stopping distance is amended to

$$s \quad = \quad 0{,}694.V + V^2 / 254.(f + G)$$

with G expressed as a decimal fraction, i.e. 6 % is quoted as 0,06, to allow for the effect of gradient. G is taken as being positive in the uphill direction.

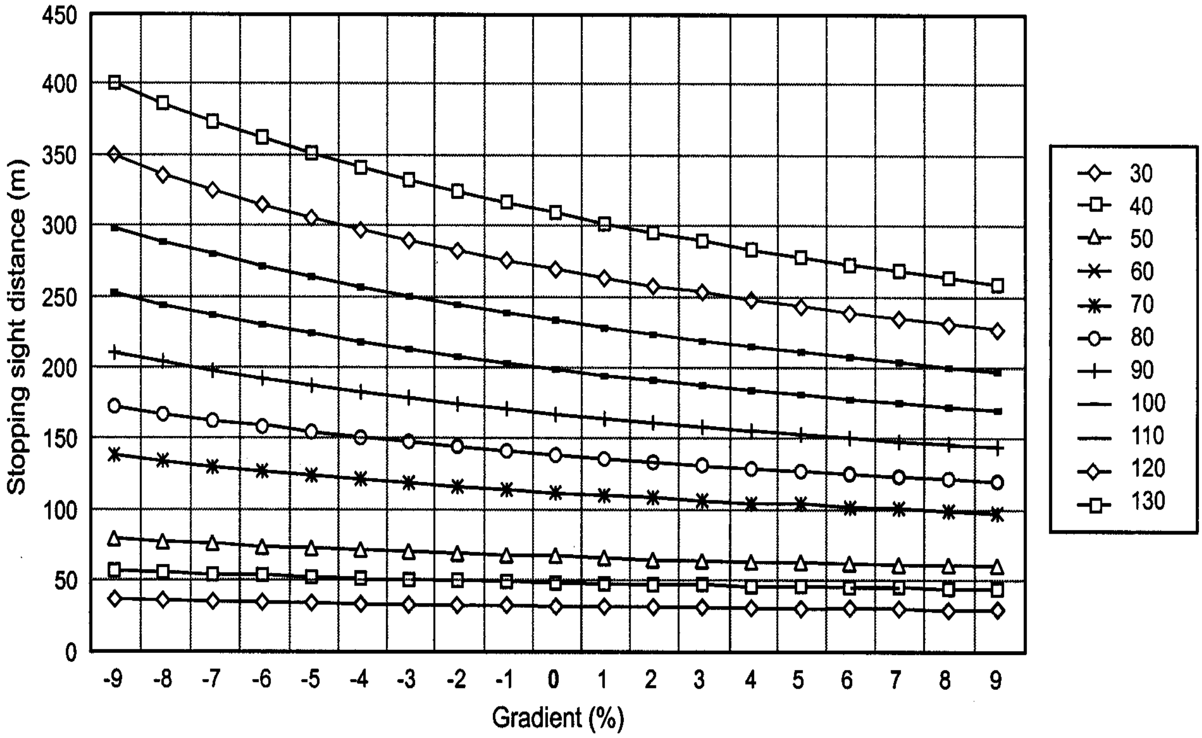

Figure A2.2: Stopping sight distance on gradients