SESSION A ASPECTS OF DESIGN

LECTURE A4 - VERTICAL ALIGNMENT – GRADIENTS & CURVES PRESENTER: CD SCOTT

1 INTRODUCTION

The vertical alignment comprises a combination of grades and vertical curves. In order to produce an acceptable alignment it is thus necessary to consider each of these elements individually and then also the interaction between them

2 GRADIENTS

Gradients are quoted in percentage form as the ratio between height gained and the horizontal distance in which the height gain occurs. The percentage format thus represents the height gain in metres over a 100 metre distance. A positive gradient is associated with an increase in height, and a negative gradient with a decrease, with distance taken in the direction of increasing stake value.

Gradients have an adverse effect on vehicle performance in terms of maximum attainable speed. The maximum speed attainable is a function of the power/mass ratio of the vehicle. The speed differential between a heavily loaded truck and a passenger car is greater on a steep gradient than it is on a level section and this increase in speed differential increases the possibility of collision. Overseas experience indicates that collision frequency increases sharply, if truck speed reduces by 15 km/h. For South African conditions, a reduction of 20 km/h in truck speed is taken as being representative of intolerable conditions. If it is considered that truck speeds on average are about 17 km/h lower than passenger car speeds, a reduction of 20 km/h actually represents a total speed differential of 37 km/h.

The greater impedance offered by the slower vehicles is exacerbated by the fact that any vehicle's ability to accelerate with a view to overtaking is reduced on gradients. Overtaking hence requires a longer distance, ie a longer gap in the opposing stream in the case of two-lane roads. There is thus a distinct possibility of there being a drop in the level of service offered by the road on a gradient. A bottle neck results, reducing the capacity of the road as a whole.

Gradients also require more power from the vehicle's engine in order to maintain a constant speed with a consequent increase in fuel usage and user cost. It has been suggested that a one metre increase in height is equivalent to 25 metres travel on a level road, i.e. a road can be 25 metres longer to eliminate a one metre climb and still generate the same road user cost.

The designer should seek to use the lowest value of gradient possible without generating major earthworks in the form of high fills or deep cuts.

2.1 Range of usable gradients

Maximum allowable gradients vary with the application. On a road with a mobility function serving high-speed long-distance travel, maximum gradients should not exceed 5 % and, in the case of freeways, a maximum of 4 % is often applied. Residential streets on the other hand have been built to gradients of as much as 20 % and some developers have offered spirited argument in favour of gradients of 25 % which is rapidly approaching the steepest gradient that a passenger car can actually climb. They do not offer any advice on construction techniques for roads at this order of gradient and it is useful to bear in mind that a 12/14 ton roller cannot manage more than about 12 % and also tears the road up at the bottom of the hill in attempting to stop prior to the next pass.

The minimum gradient is determined by considerations of drainage. If storm water is allowed simply to spill over the side of a fill, there is no reason why a minimum of 0 % cannot be adopted because the camber or crossfall, usually selected as being 2%, is sufficient to provide adequate provision for removing water from the road surface. If the road is to be kerbed and channelled, a minimum gradient of the order of 0,5 %, is required to ensure that water can flow along the channel without flooding back onto the roadway. An alternative is to grade the channel separately to ensure that it, at least, has a 0,5 % gradient even though the road gradient is less than this. The problem with this alternative is that kerb inlets have to spaced relatively close to each other to prevent there being too great a height difference between channel and road edge.

Table A4.1: Maximum gradients

Design Speed (km/h)	Topography		
	Flat	Rolling	Mountainous
60	6	7	8
80	5	6	7
100	4	5	6
120	3	4	5

gradients adopted for rural design are shown in the table above. The values selected are fairly arbitrary and stem from experience of what is reasonably easily obtainable in practice without indulging in excessively high construction costs.

The question most frequently asked is: How does one differentiate between flat, rolling or mountainous terrain? And the answer is to be found in truck performance. If a truck can maintain a fairly steady speed, the topography is described as flat. If truck speed reductions by 20 km/h are frequent or of extended duration, the topography is described as rolling. Trucks operating at crawl speed either at frequent intervals or over extended distances cause the topography to qualify for the appellation 'mountainous'.

The irony of the description lies in the fact that the topography is described in terms of the gradeline that is imposed on it and not its appearance. If a designer manages to achieve gradients that are consistently at a value of 3 % or less, does one then say that the topography is flat? Not really. The clue lies in the fact that the construction costs incurred are also involved in deciding how the topography should be described. Values of maximum gradient given in the table serve purely as guidelines. The optimisation of the design of a particular road section requires that the whole-life economy of the road be taken into account and this includes not only the initial construction costs but also road user costs incurred over the design life of the facility.

2.2 Length of gradient

There are no hard and fast rules about the maximum length of a grade, but it should be borne in mind that headlights can be a major nuisance even when as far away as four kilometres as discussed previously.

The critical length of a grade is determined by the distance required to cause a truck's speed to reduce by a specified amount which, as stated above, in South African practice has been taken to be 20 km/h. If the length of grade exceeds this critical length and it is not possible to amend the gradeline for whatever reason, consideration of a climbing lane may be justified.

Critical lengths of grade, as given in TRH 17 : Geometric design of rural roads, are shown in the table below.

Table A4.2: Critical length of grade

Gradient (%)	Length of grade (m)
3	400
4	300
5	240
6	200
7	170
8	150

Sometimes, designers attempt to get around the problem of critical length of grade by stepping the gradeline. This is also offered as relief to heavy vehicles at crawl speed on steep gradients. In practice, this is an exercise in futility. The former Transvaal Roads Department in constructing timber haul-roads in the then Eastern Transvaal essayed stepped gradelines merely to find that loaded trucks would simply maintain the crawl speed dictated by the steeper gradient rather than go through the process of working their way up and down through the gears.

There is an argument in favour of a minimum length of grade and this is purely to do with the aesthetics of successive curves as discussed later.

3 CLIMBING LANES

3.1 Operation of climbing lanes

The literature abounds with different names for these auxiliary lanes such as truck lanes, crawler lanes and even passing lanes. South African practice has adopted the term 'climbing lane' and it must be pointed out that the passing lane is a totally different animal. The distinction is however relatively subtle.

It has already been pointed out that a gradient of any magnitude can lead to a reduction in passenger car speed by virtue of the impedance offered by slower-moving vehicles and hence to a drop in level of service. The climbing lane, by removing the slower vehicles from the traffic stream, causes the Level of Service (LOS) on the climbing section to be brought up to match that of the level sections on either side of it.

The passing lane, on the other hand, is a platoon dispersal device typically provided on relatively level sections of the road. It increases passing opportunities so that the overall capacity of the road is increased. To use an extreme case by way of illustration, a four-lane road could be described as a two lane road with continuous passing lanes on either side.

3.2 Warrants

Warrants for climbing lanes are legion. These fall into natural categories such as:
Truck speed reduction by a given amount ie 20 km/h
Truck speed reduction to a specified crawl speed
An increase in speed differential to amount greater than some specified value
Either of the above in association with a specified traffic volume with, sometimes, an added distinction in terms of a specified percentage of trucks in the traffic stream
Economic analysis

TRH 17 provides a warrant based on traffic volumes and related to the percentage of trucks in the traffic stream as given below:

The first four types of warrant are purely operational in nature and do not consider the cost of creating a road environment or the cost of operating in it. In a time of heavily reduced funding available for road construction, these are luxuries that can be ill-afforded and economic analysis is thus favoured. CSIR has derived a package, ANDOG (Analysis of delay on grades), which is a partial form of economic analysis insofar it relates the value of time savings accruing to the road user over the design life of the road to the cost of achieving them. CLIM, also available from CSIR, considers an extended section of the road by means of a macro-simulation model and allows for selection of various sites for the provision of climbing lanes and also for different lengths of lane. The traffic volume and composition in the design hour is used and the model provides the reduction of delay achieved by whatever selection has been made by the designer. The recommended approach is to use both packages, starting with CLIM to establish the optimum location of climbing lanes and then to follow this up with ANDOG to establish which individual climbing lanes meet up with economic criteria.

Table A4.3: Traffic volume warrants for climbing lanes

Gradient (%)	Traffic volume in design hour (veh/h)	
	5 % trucks	10 % trucks
4	632	486
6	468	316
8	383	243
10	324	198

3.3 Design of climbing lanes

The climbing lane should have the same width as the adjacent through lane, which could be 3,1 or 3,4 or 3,7 m wide. The width of through lane is however predicated on traffic volumes and it is unlikely that a volume so low that a 3,1 m lane width would be adequate would actually qualify for the provision of a climbing lane, truck speeds notwithstanding. Climbing lanes should thus be either 3,4 or 3,7 m wide. Because they would tend to be built in areas where construction costs would, on the grounds of the ruggedness of the terrain, tend to be high the width of the climbing lane could be reduced to 300 mm less than the through lane width on the grounds of relatively low lane occupancy and speed.

The shoulders adjacent to climbing lanes should have the same width as the shoulders preceding and following the climbing lane section but the argument in respect of lane width applies equally, with a minimum width of 1,0 m still being considered acceptable.

Tapers 100 m in length are considered adequate, representing a taper rate of a little less than 1:30. This value can be compared to the roughly 1:15 acceptable for off-ramp tapers and the 1:50 applied to on-ramps, bearing in mind that speeds on the latter are likely to be substantially higher than those found in the vicinity of climbing lanes.

Impeding vehicles should be clear of the through flow from the time that their speed has dropped below an acceptable margin until the acceptable margin has once again been achieved. In South African practice, a truck speed profile will indicate the points between which the truck speed has reduced by 20 km/h or more. The full climbing lane should be available between these two points so that the tapers should be located beyond them. A final control on the location of terminals is sight distance. If, because of sight distance, there is a barrier line at the point at which the speed reduction restriction falls away, the lane should be extended to the point at which the marking ends and the taper should end 100 m beyond this point.

Two possible terminal treatments are offered by TRH 17. Current opinion is that the second alternative, requiring the slower moving vehicle to merge with the faster stream is preferred. The argument offered is that an unsuccessful attempt to merge will cause the vehicle to end on the shoulder whereas, with Alternative 1 where the faster vehicle is required to merge, an unsuccessful merge would cause the vehicle to run out of space altogether and end up in the opposing lane.

4 VERTICAL CURVES

The theory behind vertical curvature is discussed in the following lecture and the principal point of interest now is the selection of vertical curves and their relationship with the grades that define them.

A table is offered, relating the rate of vertical curvature, as expressed by the value of K, to stopping sight distance. Using the same relationship, K-values compatible with passing sight distance could also be calculated. It is however not unlikely that the earthworks that such a basis of selection could cause could be prohibitive. Bearing in mind that the designer has to match two objectives, being safety and operational efficiency, within the limitations of economic constraints, it may be possible to provide a greater length of passing sight distance over the length of the route as a whole by reducing the length of the vertical curve and hence increasing the length of the straight grades on either side of the crest, simultaneously reducing construction costs. Obviously, the dedicated designer would explore all options to derive the optimum solution.

4.1 Length of vertical curves

In contrast to the horizontal curve, there is no upper limit to the length of a vertical curve. The road builder simply follows levels as given him by a row of pegs and, whether those pegs describe a curve or a grade is a matter of indifference. The only practical problem with the long curve relates to the extended level section that may occur at the top of a crest curve or at the lowest point on a sag. If the road is kerbed and the stormwater drainage inadequate, the latter can be particularly devastating to the unwary driver.

In the rural environment, the problem occasioned by the crest curve is overcome by independently grading the side drains. The side drain would commence at the highest point of the curve with a zero depth and have a longitudinal slope of 1:200 if unpaved (1:300 if paved). This slope continues until it intercepts the line of the channel invert as fixed by the required channel depth and centre line height. Sag curves are accommodated by edge drains and chutes.

Where the algebraic difference between successive gradients is very small, the intervening minimum vertical curve can become short. If the difference in gradient is less than 0,5 %, the vertical curve can be and often is omitted.

In the case where the adjacent grades are long and the curve a sag, the appearance of a kink (the dreaded broken plank effect) can result and a minimum length of curve should be adopted for purely aesthetic reasons. For freeways, a minimum length of 240 m is recommended. The minimum lengths offered below apply to all roads other than freeways.

Table A4.4: Minimum lengths of vertical curves

Design Speed (km/h)	**Length of curve (m)**
40	60
60	100
80	140
100	180
120	220
140	260

4.2 Successive curves

The problem of interaction between successive curves as discussed in the case of the horizontal alignment also occurs in the vertical alignment. Reference here is to the broken back curve and the reverse curve.

A broken-back sag curve is a convenient but unsightly solution to the problem of crossing a water course above a specified minimum height above ground level. The broken-back crest curve is never ever seen in its entirety and the aesthetic problem does not really arise. However, the crest followed by a short grade followed by a second crest unnecessarily reduces the amount of passing sight available.

A far more common occurrence is the crest closely followed by a sag or vice versa. Without a short length of intervening straight grade, and a length of 60 to 80 metres is usually adequate, the gradeline appears discontinuous. The sag immediately following a crest creates the impression that the road drops into a hole before climbing up again. A crest immediately following a sag looks like a bump. The straight grade is never seen as such and the allusion of one curve smoothly flowing into another is created.