4. VERTICAL ALIGNMENT

COMPONENTS OF THE VERTICAL ALIGNMENT

4.1 The two major aspects of vertical alignment are vertical curvature, which is governed by sight distance and comfort criteria, and gradient which is related to vehicle performance and level of service.

4.2 Vertical curves are required to provide smooth transitions between consecutive gradients and the simple parabola is recommended for these. The parabola provides a constant rate of change of curvature, and hence visibility, along its length and has the form:

\[ y = \frac{GL}{200} \cdot \frac{x}{L} \cdot 2 \]

where
\( y = \) vertical distance from the tangent to the curve (metres)
\( x = \) horizontal distance from the start of the vertical curve (metres)
\( G = \) algebraic difference in gradients (%)
\( L = \) length of vertical curve (metres)

CREST CURVES

4.3 The minimum lengths of crest curves have been designed to provide sufficient sight distance during daylight conditions. Longer lengths would be needed to meet the same visibility requirements at night on unlit roads. Even on a level road, low meeting beam headlight illumination may not even show up small objects at the design stopping sight distances. However, it is considered that these longer lengths of curve are not justified as high objects and vehicle tail lights will be illuminated at the required stopping sight distances. Vehicles will be identified by the approaching illumination and drivers should be more alert at night and/or be travelling at reduced speed.

4.4 The greater sight distances required to provide safe overtaking opportunities are not easily provided on crest curves. If full overtaking sight distance cannot be obtained, the design should aim to reduce the length of crest curves to provide the minimum stopping sight distance, thus increasing overtaking opportunities on the gradients on either side of the curve.

4.5 Two conditions exist when considering minimum sight distance criteria on vertical curves. The first is where sight distance is less than the length of the vertical curve, and the second is where sight distance extends beyond the vertical curve. Consideration of the properties of the parabola results in the following relationships for minimum curve length to achieve the required sight distances:

For \( S < L \): 
\[ L_m = \frac{G \cdot S^2}{200 \left( h_1 + h_2 \right)^2} \]

For \( S > L \): 
\[ L_m = \frac{200 \left( h_1 + h_2 \right)^2}{G} \]

where
\( L_m = \) minimum length of vertical crest curve (metres)
\( S = \) required sight distance (metres)
\( G = \) algebraic difference in gradients (%)
\( h_1 = \) driver eye height (metres)
\( h_2 = \) object height (metres)

4.6 For \( S < L \), the most common situation in practice, \( L = K \cdot C \) where \( K \) is a constant for a given design speed.

4.7 Eye height \((h_1)\) has been taken as 1.05 metres, and object heights have been adopted of 0.2 metres above the road surface and to the road surface itself. The need to see the road surface is only applicable in particular circumstances such as a vertical curve on the approach to a ford or drift where a driver may have to stop because of the presence of surface water.

4.8 Two approaching vehicles on a single lane road require twice the distance in order to stop safely and avoid collision, and in this instance an object height of 0.2 metres above the road surface and to the road surface itself. The need to see the road surface is only applicable in particular circumstances such as a vertical curve on the approach to a ford or drift where a driver may have to stop because of the presence of surface water.

4.9 Charts of required lengths of vertical curves for safe stopping for an object on the road, safe overtaking and for meeting vehicles on a single lane, are shown in Figures 4.1, 4.2 and 4.3 respectively. Minimum values have been derived from considerations of appearance.

4.10 Sight distances have been based on the characteristics of car drivers as, although braking distances are greater with trucks, they will usually be travelling more slowly and the eye height of truck drivers is about 1.0 metre higher. Requirements are related to rates of deceleration available with an emergency stop. Skid resistance values are dependent
Algebraic difference in gradient (A)(%)  

Fig.4.1 Length of crest vertical curves for safe stopping sight distance
Fig. 4.2 Length of crest vertical curve for overtaking sight distance

Notes:
- Design speed .......... km/h
- Overtaking sight distance .......... m
- Vertical curvature (K) .......... m

Algebraic difference in gradient A (%)
on tyre, road surface conditions and speed, and vary substantially. The values for available longitudinal friction in this guide are given in Table 1.2. A reaction time of 2.0 seconds has been assumed. Drivers will react more quickly when alert and in a situation where action is expected and, in practice, reaction times normally vary from about 0.5 to 1.7 seconds.

### SAG CURVES

4.11 It has been assumed that adequate sight distance will be available on sag curves in daylight. However, at night, visibility is limited by the distance illuminated by the headlamp beams, and minimum sag curve length for this condition is given as:

For S\(<L\):

$$L_m = \frac{G.S^2}{200 h_1 + S \tan \theta}$$

For S\(>L\):

$$L_m = 2S - \frac{200 (h_1 + S \tan \theta)}{G}$$

where $h_1$ = headlight height (metres)
- $\theta$ = angle of upward divergence of headlight beam (degrees)

Appropriate values for $h_1$ and $\theta$ are 0.6 metres and 1.0 degrees respectively.
4.12 The use of these equations can lead to requirements for unrealistically long vertical curves as, especially at higher speeds, sight distances may be in excess of the effective range of the headlamp beam, particularly when low meeting beams are used. Thus, the only likely situation when the above equations should be considered for use is on the approaches to fords and drifts and other similar locations where flowing or standing water may be present on the road surface. Most of these structures occur on low speed road where headlamp illumination is more likely to reach the full sight distances.

4.13 It is recommended that, for most situations, sag curves are designed using the driver comfort criterion of vertical acceleration. The values used are given in Table 4.2 and the resulting curve length values are shown in Figure 4.4, with minimum length values for satisfactory appearance.

**TABLE 4.2 : MINIMUM LEVELS OF ACCEPTABLE VERTICAL ACCELERATION**

<table>
<thead>
<tr>
<th>Design speed km/h</th>
<th>120</th>
<th>100</th>
<th>85</th>
<th>70</th>
<th>60</th>
<th>50</th>
<th>40</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical acceleration</td>
<td>0.05</td>
<td>0.060</td>
<td>0.070</td>
<td>0.080</td>
<td>0.090</td>
<td>0.100</td>
<td>0.110</td>
<td></td>
</tr>
<tr>
<td>(Proportion of g in m/sec²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 4.4 Length of sag vertical curve for adequate riding comfort
4.14 Vehicle operations on gradients are complex and depend on a number of factors: severity and length of gradient; level and composition of traffic; the number of overtaking opportunities on the gradient and in its vicinity.

4.15 For very low levels of traffic flow with only a few four-wheel drive vehicles, the maximum traversable gradient is in excess of 20 per cent. Small commercial vehicles can usually negotiate an 18 per cent gradient, whilst two-wheel drive trucks can successfully tackle gradients of 15-16 per cent except when heavily laden. These performance considerations have formed the basic limiting criteria for gradient as shown in Table 1.1.

![Speed increases with climbing lanes](chart)

**Fig.4.5 Estimated speed increases with climbing lanes**

**Note:**

1) The above results are estimations based on simulation. Vehicle performance and driver characteristics will vary from country to country and the assumptions incorporated here should be considered as coarse approximations.

2) Climbing lanes on gradients of up to 100 metres in length were shown to have little effect.

3) Varying the percentage of heavy vehicles (HGV) from 20 percent to 40 percent has little effect on the mean speed reduction.

4) The above curves are based on directional flows of 200 vehicles per hour. For lower flows, the benefits of a climbing lane were small, although for higher flows of 400 to 600 vehicles per hour, the benefits were found to increase by about 25 percent on a 300 metre gradient, and by about 60 percent on a 600 metre long gradient.

5) The speed increases shown in the above Figure are values averaged over a 1.0 kilometer section of road which contains the gradient section.
4.16 Gradients of 10 per Cent or over will usually need to be paved to enable sufficient traction to be achieved, as well as for pavement maintenance reasons. There will often be considerable non-motorised movement on the lower Design Class roads and, whilst pedestrian and animal movements are possible on very steep inclines, some laden animal drawn carts may find steep grades difficult to traverse because of a lack of grip.

4.17 As traffic flows increase, the economic disbenefits of more severe gradients, measured as increased vehicle operating and travel time costs, are more likely to result in economic justification for reducing the severity and/or length of a gradient. On the higher Design Classes of road, the lower maximum recommended gradients (Table 1.1) reflect the economics, as well as the need to avoid the build up of local congestion. However, separate economic assessment of alternatives to long or severe gradients should be undertaken where possible or necessary. An estimation of vehicle operating cost savings may be made from relationships such as those incorporated in the TRRL road investment model (micro-RTIM2), or the World Bank’s highway design and maintenance standards model (HDM-I11).

CLIMBING LANES

4.18 A climbing lane may be introduced as a more cost effective alternative to reducing a gradient.

4.19 Benefits from the provision of a climbing lane accrue because faster vehicles are able to overtake more easily, resulting in shorter average journey times and reduced vehicle operating costs. Benefits will increase with increases in gradient, length of gradient, traffic flow, the proportion of trucks, and reductions in overtaking opportunities. The effect of a climbing lane in breaking up queues of vehicles held up by a slow moving truck will continue for some distance along the road.

4.20 The effects of a climbing lane on the mean operating speed of a traffic stream have been estimated with a simulation model and are given as Figure 4.5 for guidance. These mean speeds should be used with local values of travel time savings, appropriate vehicle operating costs savings, and the additional costs of construction, to estimate overall economic returns of the alternatives to enable the most cost-effective solution to be determined. With the generally low values of travel time found in developing countries and excluding accident considerations, climbing lanes are unlikely to be justified other than on a small proportion of Arterial roads with very high flows. In view of the uncertainties associated with simulation, local data should be used where available.

4.21 As climbing lanes will be used largely by trucks and buses, they must be a minimum of 3.0 metres in width. They must be clearly marked and, where possible, should end on level or downhill sections where speed differences between different classes of vehicle are lowest to allow safe and efficient merging manoeuvres.