3 Design Form

3.1 General

Road design is traditionally a manual technique in which the problem is considered separately in three views, ie.

- plan,
- longitudinal profile, and
- cross section.

This approach is the result of the semi-graphical techniques usually employed and it produces satisfactory results when carried out by an experienced designer. It can also produce poor results if the designer considers each view independently of the other two without an appreciation of the interrelation between the various views.

The conscientious use of the appropriate design standards and charts will not automatically guarantee a satisfactory road design. Drivers see the road as a constantly changing three-dimensional picture and designers need to appreciate this fact because driver behaviour is largely determined by the appearance of the road. Unless the road appears to the driver as the designer intended it to the design will be unsatisfactory, and possibly unsafe.

During all stages of design the form of the road must be considered as a three-dimensional structure which should not only be safe, functional, economical but also aesthetically pleasing.

A more pleasing overall road design is achieved if the horizontal and vertical curves are kept in phase so where possible, vertical curves should be contained within horizontal curves to:

- enhance the appearance of sag curves by reducing the three-dimensional rate of change of direction, and
- improve the safety of crest curves by indicating the direction of curvature before the road disappears over the crest.

3.2 The Driver's View

The driver sees a foreshortened and thus distorted view of the road ahead. Even when the horizontal and vertical alignments each comply with the appropriate design standards unfavourable combinations of horizontal and vertical curves can result in apparent discontinuities in the a road alignment. Such combinations can mask a change in horizontal alignment or easily conceal a significant hazard from a drivers view.

Only the consideration of the road as a three-dimensional entity can reveal such deficiencies and good design practice requires the elimination of all such avoidable hazards, even though some extra expense may be incurred at times. The removal of such a hazard is however not the only benefit, the improved safety and performance potential usually means an enhanced amenity.

Because a driver's view is constantly changing the duration of their view of successive elements of the road alignment will also vary. Features situated in a long sag curve will normally remain in view for a considerable length of time while features at, or near, an abrupt crest or on a tight horizontal curve, will be only be in view briefly. Important features such as intersections are therefore best located on long sag curves and objectionable or peripheral features are less offensive or noticeable if they are located near crests or tight curves.

Visual driver cues from peripheral areas must also be considered. While the designer can view the whole road layout and is aware of all changes in its alignment, a driver will only see part of the alignment at any one time. This restricted view can be further limited at night or by poor visibility. The designer must therefore provide the driver with as many clues as possible as to what lies ahead while ensuring that the roadside conditions do not convey messages which are ambiguous or misleading.

The smooth curving face of a cutting can indicate the corresponding horizontal curvature of the road but a fill area, or a crest can give no sense of position if there is no visual background of fixed objects. A driver will not expect a horizontal curve if the sole cues come from a line of service poles or trees which continue straight on, or from a deceptive gap in a line of trees on the outside of the curve. A crest should not obscure a potential hazard such as a narrow bridge, a railway level crossing or a horizontal curve which requires a significant speed reduction.

3.3 Fitting the Road to the Terrain

The speed environment of a road is influenced partly by the nature of the terrain and partly by the horizontal alignment. If similar indications are given by both these factors the road will provide a consistent level of driver expectancy and safety.

A road with both its horizontal and vertical curvature carefully designed to conform with the terrain will result in a structure having the desirable aesthetic quality of being in harmony with the land form.

Perfect harmony is however not always possible and designers must consider what matters are beyond their control and make full allowance for the influence of these on drivers.

It is possible to build a high quality road in adverse terrain and this will produce a high speed environment. It is however very unlikely that a road in flat or gently rolling terrain will ever contain enough small radii curves to produce a low speed environment. Design speeds will always be high in the latter case, because of the terrain, and the vertical alignment must therefore provide the sight distances required for these speeds.

Where a high speed section of road join into a more constrained section the transition must be gradual, ie. not a sudden change of geometric standard.

In flat terrain a long straight road might appear to be the most appropriate design but elsewhere it is good design practice to avoid excessive lengths of straight road. A gentle curvilinear design helps keep the operating conditions *"under control"* and can often allow a far more sympathetic fitting of the road to the terrain. The increased flexibility of this type of approach also enables:

- more pleasing designs to be produced at no extra cost, eg. economies in earthworks can be achieved by fitting the road more closely to the terrain, and
- safety to be enhanced through drivers being made more aware of their speed, allowing them to make better assessments of distances and the speeds of other vehicles.

A curvilinear alignment can also be used in flat country as an alternative to a straight alignment but a driver's estimation of the speed of oncoming vehicles is not significantly improved if curve radii greater than 5,000 m are used.

Curvilinear design is most applicable to divided roads with their less stringent sight distance requirements but the principles can be very successfully applied to single carriageway roads, provided care is taken to ensure adequate overtaking opportunities are available. Very large radius curves can provide overtaking opportunities and still retain some of the benefits of curving alignment.

If the topography is such that the natural curvature does not provide overtaking sight distance, artificially introduced long straights can produce an alignment that lacks harmony with the terrain, or requires heavy earthworks. In such cases a harmonious curving alignment with the provision of passing lanes may produce an economical, as well as an aesthetically pleasing, solution.

3.4 Aesthetic Considerations

Aesthetic features which should be considered during roading design work are:

- A sag vertical curve should be located within a horizontal curve rather than on a straight section of road close to the start of a horizontal curve.
- A short vertical curve within a long horizontal curve produces a poor visual effect.
- A short section of straight grade between adjacent sag or crest vertical curves also produces a poor visual effect.
- A disjointed visual effect occurs where the start of a horizontal curve is obscured by the crest of a vertical while the continuation of the road is also visible in the distance.
- A long sag curve provides visual continuity and, where practicable, is very much preferable to a short sag curve.
- A horizontal curve at the end of a long straight can appear to be much sharper than it is in reality. The largest radius that is economically possible should be used in these situations.

3.5 Safety Considerations

Safety factors that should be considered during road design work include:

- Drivers react mainly to the perceived radii of a road's horizontal curvature but they will not often react and reduce speed when sight distance is restricted by vertical curvature. When a horizontal curve is combined with a vertical curve the horizontal curve must always start before the vertical curve, because this gives a safe road design which alerts drivers to the presence a horizontal curve. The reverse situation often produces and unsafe condition, a horizontal curve hidden by a vertical curve can surprise drivers by its sudden appearance.
- Designs speed for the horizontal and vertical alignment of a road should be, at least, the same. Desirably, the vertical alignment should have a design speed 10 to 15 km/h greater than the horizontal alignment.
- Where overtaking sight distance is provided on a section of road it should, where practicable, be in both the horizontal and vertical planes simultaneously.
- Sharp horizontal curves should not be introduced at, or near the top of, a crest vertical curve because drivers, especially at night, may not perceive the change in the alignment.
- The provision of sharp reverse horizontal curves within the length of a crest vertical curve is undesirable. The crest obscures the reverse alignment.
- The location of a crest vertical curve, or a sharp horizontal curve, at or near an intersection or railway level crossing, is undesirable.
- Pavement narrowing, transitions between divided and undivided roads and the introduction of traffic islands and median noses should not be combined with horizontal or vertical curves unless the appropriate driver eye height to zero object height sight distance is available.
- **Drainage:** Where a superelevation transition is combined with a vertical curve and/or a vertical grade the finished road surface needs to be contoured to check stormwater runoff paths. This is to ensure undesirable cross pavement flows and surface water ponds are avoided. Also, a long crest vertical curve should be avoided where there is the possibility of a level grade occurring on the top of the curve.

3.6 Horizontal Alignment

3.6.1 Minimum Standards

The mechanical use of minimum design standards will generally produce safe roads that have a satisfactory traffic operational performance. The resulting alignments will often have an aesthetically poor appearance and the use of higher design standards should be considered wherever it is economically possible, as a matter of good design practice. Aesthetic considerations are most important when the road alignment is visible to drivers for some distance ahead, ie. usually in easy terrain conditions. In hilly and mountainous conditions aesthetic considerations still have some relevance but safety and economic considerations are likely to assume greater importance.

3.6.2 Horizontal Curves in Easy Terrain

Providing a road with an alignment that is in harmony with the terrain does not usually present too many problems in difficult country, and drivers readily appreciate the reasons for such restrictions. In easy terrain however, there are usually no obvious alignment restraints and designer's must therefore ensure that the road's geometry does not appear forced or unnatural. For this reason, curve radii considerably greater than the minimum specified in Tables 3.1 may be justified in flat terrain and arc lengths of at least 500 m required to ensure that curves with small deflection angles do not appear as kinks.

Speed (km/h)	Radius (m)
100	1100
110	1400
120	1600
130	1900

Table 3.1: Desirable Minimum Radius for Horizontal Curves

Long straights may be acceptable in level terrain because the artificial introduction of curves may result in an alignment that appears to have been *'forced'* onto the terrain. Where possible, isolated curves should be avoided in flat terrain, even if a fully curvilinear alignment is not employed.

Several curves in succession, from time to time, can however add a welcome variation to a journey in otherwise featureless terrain, the terrain rarely so flat that some legitimate curvature cannot be introduced. The gradual introduction of successively tightening curves should be used as a method of alerting drivers to a transition from easy terrain to more restricted conditions.

3.6.3 Compound Curves

The use of compound curves should generally be avoided unless the radii are very large, because drivers will have difficulty in detecting the change of curvature. Compound curves may however be considered where:

- the topography, or some other control, eg. a bridge, makes the use of a single-radius curve impracticable,
- a compound curve can replace an otherwise *'broken-back'* horizontal curve, or
- the use of a simple curve would result in excessive cost.

Where compound curve is necessary:

(a) The smaller radius should be at least two-thirds the larger radius when the smaller radius is 300 m or less.

(b) The design speed for the larger radii of a compound curve should not be more than 10 km/h greater than the design speed of the smaller radii.

(c) Individual curve superelevation rates must be adjusted so that if the smaller radii curve is negotiated at the design speed of the larger radii curve its side friction demand will not be more than 20% to 25% greater than that of the larger radii curve.

(d) The total arc length of a compound curve should be not less than 150 m and the total curve length must be sufficient to provide a significant arc length for each radius used.

Where these conditions cannot be met a spiral transition will need to be used between successive circular arcs.

3.6.4 Reverse Curves

A free-flowing alignment which fits naturally to the terrain will usually incorporate some reversed horizontal curvature. This type of alignment is generally very suited to rolling type terrain. The design must satisfy the appropriate dynamic requirements and ensure that:

- the curves have correctly related radii, and
- they are sufficiently well separated to allow a pleasing warping of the superelevation development.

3.6.5 Similar Curves

Alignments containing two horizontal curves in the same direction and joined by a short straight should generally be avoided, because they can form a *'broken back'* alignment. It is virtually impossible to provide the correct amount of superelevation throughout both curves and equally difficult to produce a visually pleasing vertical alignment for the edges of the road pavement. In practical terms, there is a maximum length of *'short'* straight which does not produce a visual or physical complication and there is a minimum length of *'long'* straight which will provide an effective separation of similar curves.

The maximum length of a *'short'* straight is equivalent to about 2 seconds of travel time, ie. a length of $0.6V_d$ metres, where V_d is the design speed in km/h. In most cases, a single curve with a slightly larger radius can, and should, be used.

Short straights of this length do not allow reversion to two-way crossfall between the curves and some improvement to appearance and safety can result if the one-way crossfall on the straight not reduced to normal crossfall but is only reduced to reverse normal camber.

The minimum length of a *'long'* straight between similar curves should allow for normal crossfall to be regained, and then maintained, for a distance equivalent to about 4 seconds of travel time at design speed, ie. a length of about $3V_d$ to $4V_d$ metres. Although this will produce a visually pleasing road layout longer straights should be used wherever possible.

From the above it can be seen that straight sections of road between similar curves which are in the range of 0.6V to 3V metres long will be visually and functionally unsatisfactory and should be avoided wherever possible. These straight length criteria may have to be used in constrained conditions but avoiding *'similar curve'* situations altogether will lead to more pleasing road designs.

Where a minimum length of straight can not be obtained the alignment must be altered to:

- increase the length of the straight, or
- eliminate the straight by the use of a compound curve which is either:
  - S transitional between the two main curves, or
  - S a long spiral curve.

3.7 Vertical Alignment

Much of the philosophy relating to horizontal alignment is equally applicable to vertical alignment. Even though the vertical scale is invariably much smaller than the horizontal scale a the incautious selection of vertical components can result in an alignment as unsightly as a poor horizontal design.

Some aspects of vertical design may warrant even closer attention to detail than similar aspects of horizontal design. Because driver behaviour is influenced mainly by horizontal alignment and terrain, drivers do not seem to respond to variations in vertical geometry. Vertical geometry cannot, therefore, be determined in isolation and must be related to the corresponding horizontal geometric features.

A vertical grading (profile) which has long tangents and generous vertical curves is much more preferable to one with numerous grade changes and short tangent sections. Hidden dips should be avoided, a design check of sight lines using a zero height object, ie. to the road surface will reveal such deficiencies. Road profiles should not include any minor humps or hollows which restrict sight lines when the horizontal alignment provides overtaking sight distance.

'Broken-back' profiles, which consists of two or more vertical curves in the same direction separated by a short length of straight grade, should be avoided. Such profiles are disjointed and look unsightly, especially in sag situations, and they should be replaced by a single, longer vertical curve. There is usually very little significant difference in the roadway levels and earthwork quantities between the two situations.

Reverse vertical curves can be designed to have common tangent points and this will produce a pleasing, flowing grade line which is more likely to be in harmony with the natural land form. If any of the component curves are designed for near limiting values of vertical acceleration the rate of change of vertical acceleration at the tangent points must be considered. The algebraic sum of the adjacent rates of vertical acceleration must remain within the acceptable limit of 0.1g if comfort criteria are to be maintained.

3.8 Combined Horizontal and Vertical Curvature

The most pleasing three dimensional result is achieved when the horizontal and vertical curvature are kept in phase, because this relates most closely to naturally occurring forms.

Where possible the following good design practice principles should be followed:

- Vertical curves should be contained within horizontal curves. This will enhance the road's appearance in sag curves by reducing the three-dimensional rate of change of direction, and improve the safety of crest curves by indicating the direction of curvature before the road disappears over a crest. The best visual appearance occurs when the scale of the vertical and horizontal movements are comparable, ie. a small movement in one direction should not be combined with a large movement in the other.

- Drainage structures in sag curves which are combined with horizontal curves require careful design to avoid a disjointed or kinky appearance. Culverts should not introduce adverse aesthetic effects when they are contained within fill embankments if they are made sufficiently long to accommodate the full road formation width.

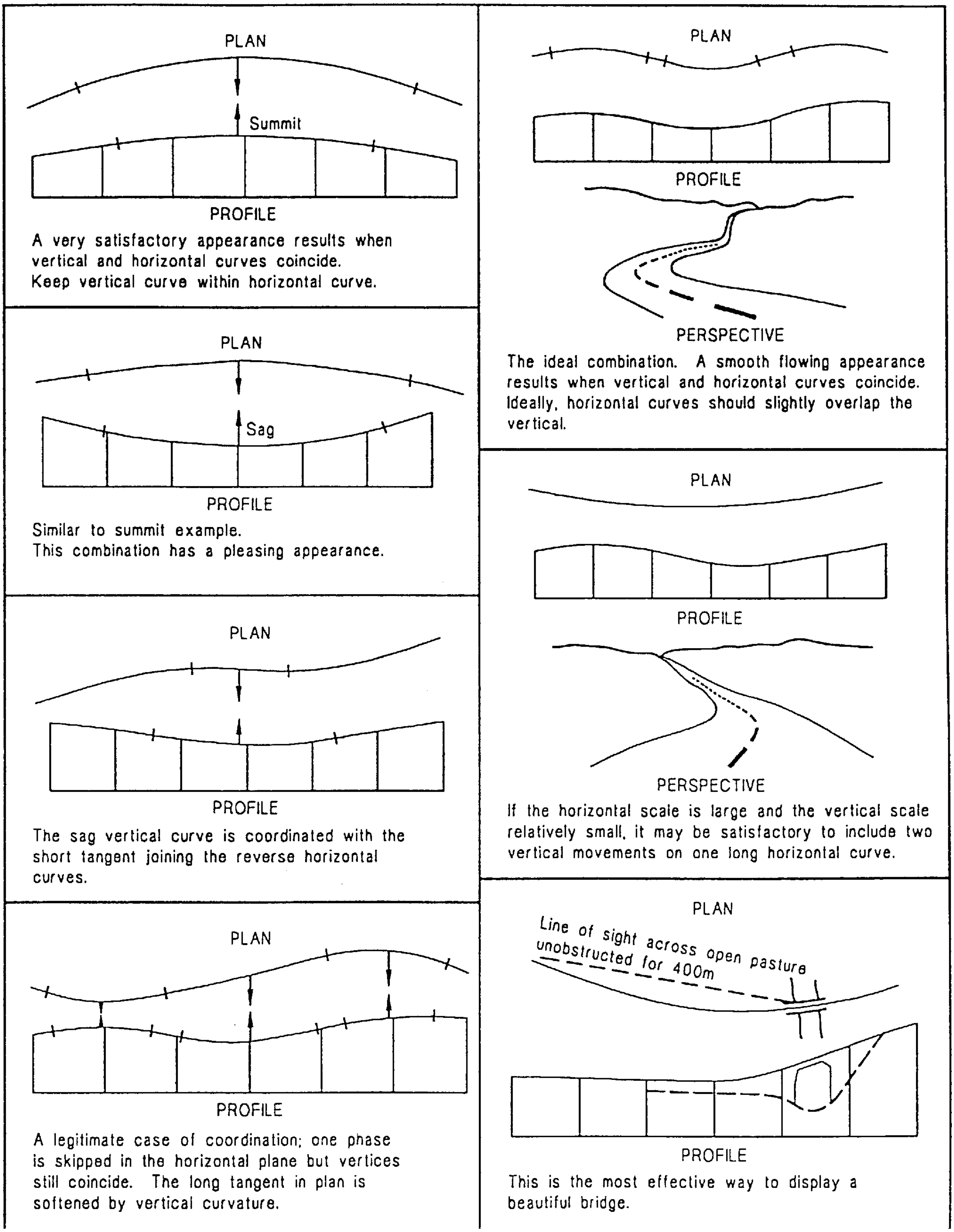
- Bridges built on combined horizontal and vertical curvature can present considerable aesthetic problems, especially if when reduced formation widths are used on the bridges. Particular care should be taken with the design of bridge kerbs and railings, as well as to the location and transitioning of approach guard rails. In general, the more generous the curvature the more pleasing and safe the resulting road alignment.

- Horizontal curves combined with crest vertical curves generally have less influence on the appearance of a road than those combined with sag vertical curves. However, their effect on safety can be much greater because a crest vertical can obscure the direction and severity of the horizontal curve. Minimum radius horizontal curves should therefore not be combined with crest vertical curves.

Figures 3.1 and 3.2 show examples of good and bad horizontal/vertical alignment coordination.

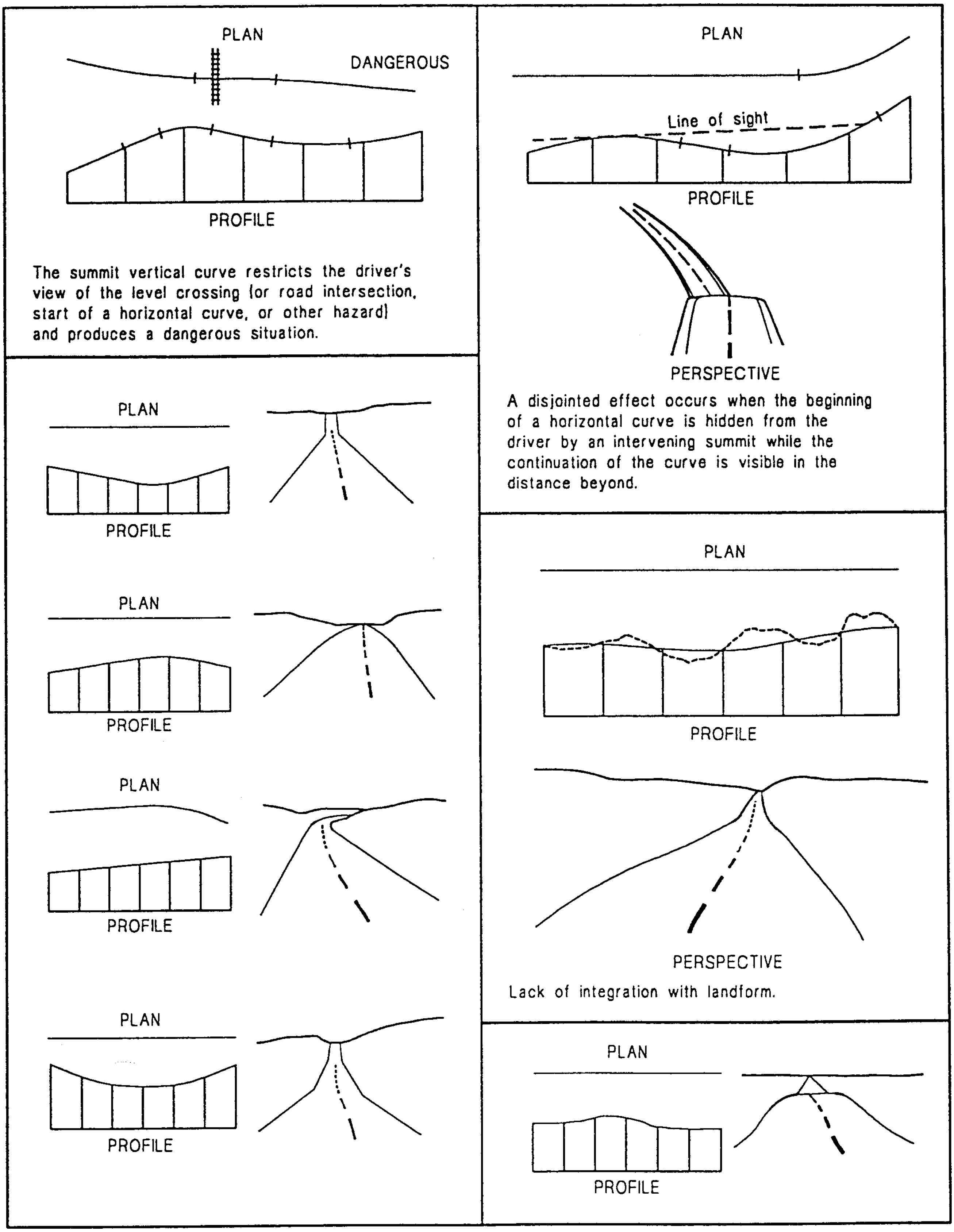
Figure 3.3 shows some typical examples of what can happen when the interaction of the horizontal and vertical alignment is not considered during road design work, particularly when a *"minimum"* standard vertical alignment is superimposed onto relatively unconstrained high standard horizontal alignment. A remedial measure is also shown for each problem

NOTE: ***These diagrams are not comprehensive and only demonstrate the general concepts that should, or should not, be followed in roading design work.***



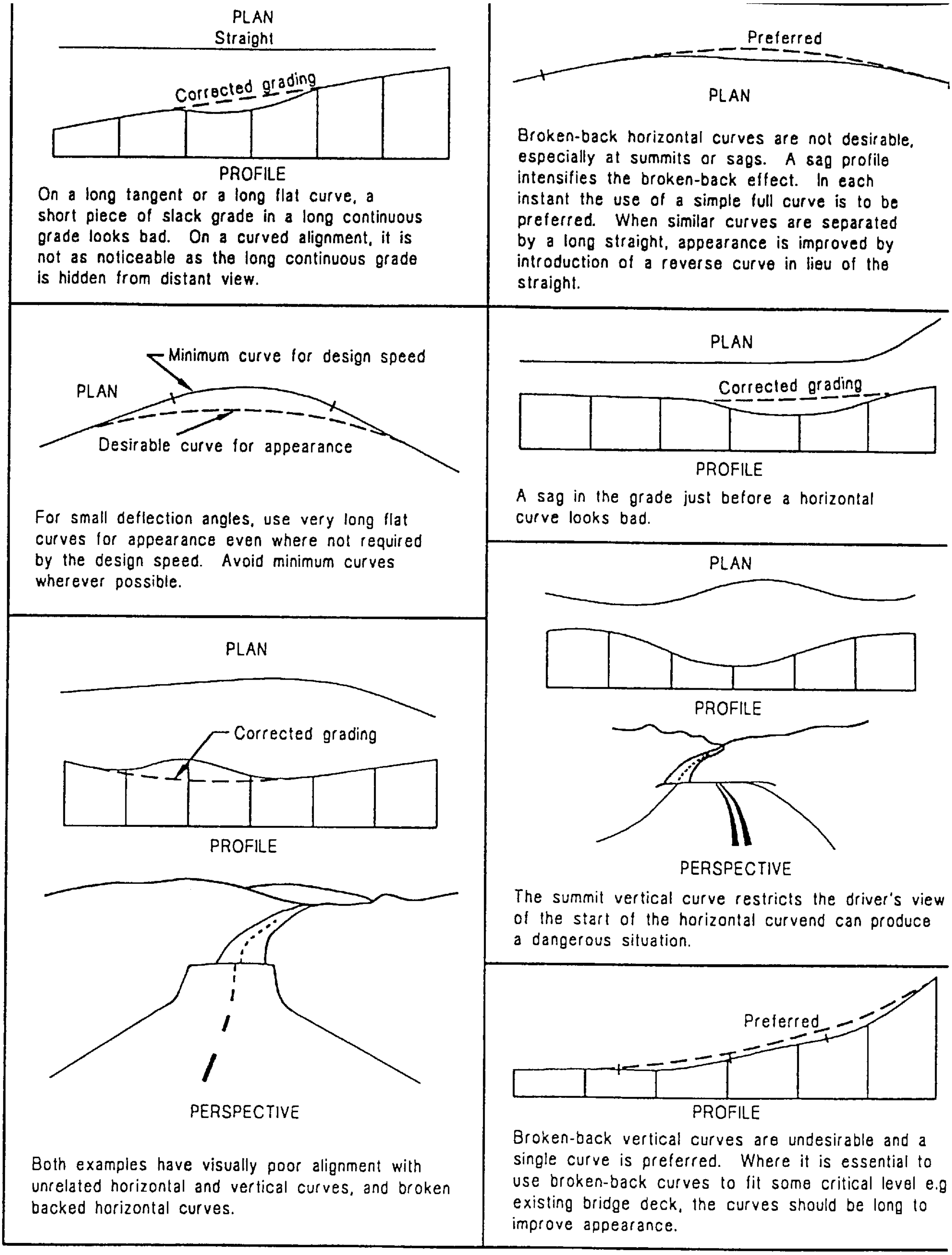
Source: Main Roads WA

Figure 3.1: Good Design Form



Source: Main Roads WA

Figure 3.2: Bad Design Form



Source: Main Roads WA

Figure 3.3 Poor Design Form and Correction Method

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