however, the major conflicts seem to have been resolved. The design meets nearly all the minimum standards for an Interstate highway; there are few deviations from safety standards, and the consensus is that the highway can be built without major permanent environmental, visual, or recreational impacts.

Since FHWA and DOT have indicated agreement with the conclusions of the design team, the CAC, and the state highway commission, by issuing design approval, the project has proceeded into final design, with construction anticipated at a pace that will complete one of the last gaps in the 68 400-km (42 500-mile) Interstate system by 1986. In addition, the Glenwood Canyon 20-km (13-mile) segment should, when completed, be a testimonial to the inspired blending of engineering with nature.

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Methodology for Evaluating Geometric Design Consistency

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This paper presents a methodology for evaluating and improving the geometric design consistency of rural nonfreeway highways. The methodology is based on driver behavior principles, a sound conceptual approach, and empirical evidence collected during a recent Federal Highway Administration-sponsored research project. Factors that contribute to potential geometric inconsistencies include basic feature type, design attributes, sight distance, separation distance, operating speed, and driver familiarity. The methodology may be applied to proposed or existing two-lane and four-lane highways in flat or rolling terrain. Design speeds may range from 80 km/h (50 mph) to 129 km/h (80 mph). The basic objectives of geometric design and application procedures are presented to aid the engineer in the design or evaluation of a design for geometric consistency.

The basic goal of the highway design engineer has always been to design a facility that will satisfy expected transportation needs safely, efficiently, and in a cost-effective manner. To satisfy public demand for better facilities, design engineers developed a vast highway system that reflects the needs, technology, and resources of the times. Design standards progressively changed to accommodate increasingly greater traffic volumes, increased speeds, larger trucks, and higher safety standards.

From 1920 to 1970, when most of the rural highway system was built, the evolutionary development process has had a major effect on rural driving experience and resulting driving behavior. During the earlier portion of this period, drivers had little experience with any long-distance, high-speed driving on rural highways. A high percentage of all roads were low-design and poorly coordinated. Drivers expected bad roads. World War II and the following 15 years also continued this variation in driving experience as highway conditions and vehicle performances continued to change rapidly. The driving experience of the 1960s stabilized to a great degree and motorists undoubtedly began to expect good roads everywhere. Perhaps the Interstate highway system created this illusion.

THE PROBLEM

Highway design engineers should recognize that existing high-design rural highways have produced a built-in set of high-design standards that cannot be safely ignored. Major changes in design speed, cross section, or alignment standards between adjacent sections along a rural highway may not be expected by today's motorist. Abrupt geometric changes may be so inconsistent with the driver's basic expectations that delayed driving responses and incorrect decisions may occur and result in unsafe driving (1).

The following sections present a methodology for evaluating the highway geometric design consistency of existing or proposed rural, nonfreeway highway facilities. Design concepts and procedures cover a wide range of design situations. Sound engineering evaluation and judgment still will be required to apply the methodology routinely to specific real-world design problems.

CONCEPTUAL MODEL

Certain driving tasks must be performed by a motorist in order to safely and comfortably follow a preselected route to the destination. The driver must control the vehicle in a manner that tracks a safe path along the highway at a safe speed for the conditions at hand (1). The driver continually updates vehicle control actions as new information is obtained from the driving environment. This information is handled in a decision-making process, and these decisions are translated into control actions (i.e., appropriate speed and path). The roadway itself serves as the primary source for information inputs to the driver and correspondingly imposes work-load requirements on the driver.

Driver Work Load

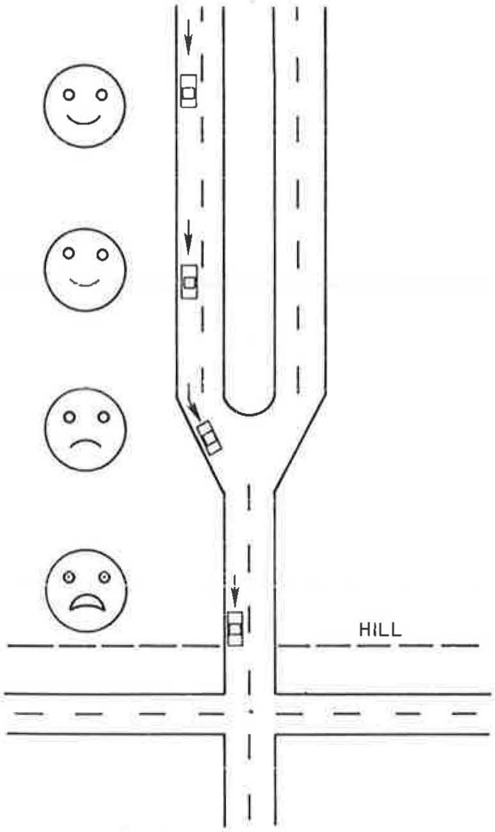
Driver work load is the time rate at which drivers must perform a given amount of work or driving tasks. Driver work load increases with increasing geometric complexity of those highway features perceived as potentially hazardous situations in the driving environment. Driver work load also increases with speed and reductions in sight distance for a given level of work to be performed over a section of highway. In addition, driver work load may increase dramatically for those motorists who are surprised by the unexpected occurrence or complexity of a set of geometric features. These motorists will require more time and mental effort to decide on an appropriate speed and path.

Driver Expectancy

Driver expectancy relates to the readiness of the driver to perform routine driving tasks in a particular manner in response to perceived situations and circumstances in the driving environment. Driver expectancy is primarily a function of the driver's memory and driving experience. The past experience that is relevant to the present task of driving a given section of highway is (a) the driver's immediate memory of the prior roadway and (b) long-term driving experience with similar facilities.

Driver performance is directly affected by driver

Figure 1. Example of compound geometric inconsistency.



expectancy. Driver performance tends to be error-free when an expectancy set is met. When an expectancy is violated, longer response times and incorrect driver behavior usually result (1).

Geometric Inconsistency

A geometric inconsistency in rural highway design is defined as a geometric feature or combination of adjacent features that have such unexpectedly high driver work load that motorists may be surprised and possibly drive in an unsafe manner. The unfamiliar motorist is more likely to be surprised by geometric feature inconsistencies.

The concept of a geometric inconsistency is illustrated through the use of an extreme example in Figure 1. An unfamiliar driver is traveling along an apparently well-designed four-lane divided rural highway. Suddenly and unexpectedly, the median ends and the road narrows to two lanes near the crest of a hill. The driver was performing at a low work-load level but, suddenly, the demand created from oncoming traffic, traffic to the left, and maneuvering to a new lane at a lower speed is much higher. The driver begins to respond to this new information and task loading since it demands a greater amount of work. As the driver crests the hill, he or she encounters an unexpected intersection, which may overtax the motorist's capabilities to deal with the situation.

PROCEDURES FOR ENSURING DESIGN CONSISTENCY

The goal of this federally sponsored research was to develop procedures for ensuring geometric design consistency by the development of a generalized methodology applicable to all rural nonfreeway facilities. Due to the necessary reliance on subjective ratings, expert opinion, and limited empirical evidence, the procedures presented should be interpreted as being a methodology for evaluating the geometric consistency of rural highways. The methodology approaches the evaluation from the viewpoint of designing the geometric features, such as lane drops, intersections, or curves so that unfamiliar motorists should be able to perform successfully the resulting driving tasks based on driver expectancy considerations described earlier. The influence of traffic control devices is not specifically considered.

Criticality Factors

The probability that a particular geometric feature may be inconsistent in a particular situation depends on numerous factors. The more influential factors that relate to the feature itself include the following:

1. Type,
2. Relative frequency of occurrence,
3. Basic operational complexity and criticality in the driving task, and
4. Overall accident experience in general.

Other important design variables that will affect the apparent criticality of a feature include (a) time available, (b) sight distance to the feature, (c) separation distance between features, (d) operating speed, and (e) prior roadway design features. Driver familiarity, traffic, topography, and roadside environment effects, among other factors, also will influence the resulting criticality of the individual geometric feature.

Criticality and Work-Load Ratings

Average criticality ratings were developed for nine basic geometric features by using a seven-point rating scale developed for identification of hazardous locations based on driver expectancy considerations (2). In this seven-point rating scale, 0 is no problem and 6 is a critical problem situation. A group of 21 highway design engineers and research engineers who have expertise in highway design, traffic engineering, and human factors rated each of the features. Each feature was assumed to be located along a high-quality rural highway. Average operating speed was 93 km/h (58 mph) and the sight distance to the feature was 244 m (800 ft). Some unfamiliar motorists drove the route. The engineers were asked to rate the nine basic geometric features, projected one at a time in schematic on a screen, according to their judgment of the average criticality of the feature (2). Engineers from Arkansas, Georgia, Illinois, Oklahoma, and Texas, in addition to the Texas Transportation Institute, were represented in the rating session.

The results of the rating session are presented in Table 1. The nine basic features are rank ordered from worst to best case. Ratings of different designs within a given feature category also were made as shown. Ratings for mediocre two-lane roads and undivided four-lane highways were determined from the basic ratings and other study results (3). In all studies made, divided highway transitions, lane drops, and intersections scored relatively high (more critical). Shoulder-width reductions, alignment changes, and lane-width reductions rated lower (less critical).

These criticality ratings were then used as anchor points on the criticality scale for each feature from which further study was conducted to estimate the range of probable criticality ratings for various specific cases that might exist. These calculated expectancy criticality scores were defined as work-load ratings and are used to evaluate the geometric design consistency of rural highways.

General Design Objectives

The following set of recommended general geometric design objectives, if thoroughly understood and practiced by design engineers, would eliminate many of the geometric feature inconsistencies that otherwise might appear in routine design.

Table 1. Summary of geometric feature ratings for average conditions on various classes of rural nonfreeway highway conditions.

Geometric Feature	Two-Lane High	Two-Lane Mediocre	Four-Lane Divided	Four-Lane Undivided
Bridge				
Narrow width, no shoulder	5.4	5.4	5.4	5.4
Full width, no shoulder	2.5	2.5	2.5	2.5
Full width, with shoulders[a]	1.0	1.0	1.0	1.0
Divided highway transition				
4-lane to 2-lane			4.0	
4-lane to 4-lane			1.8	
Lane drop (4-2 lanes)				3.9
Intersection				
Unchannelized	3.7	2.8	2.4	2.1
Channelized	3.3	2.5	2.1	2.4
Railroad grade crossing	3.7	3.7	3.7	3.7
Shoulder-width change				
Full drop	3.2	2.4	2.1	2.1
Reduction	1.6	1.2	1.0	1.0
Alignment				
Reverse horizontal curve	3.1	2.3	2.0	2.0
Horizontal curve	2.3	1.7	1.5	1.5
Crest vertical curve	1.9	1.4	1.2	1.2
Lane-width reduction	3.1	2.3	2.0	2.0
Crossroad overpass	1.3	1.0	0.8	0.8
Level tangent section[a]	0.0	0.0	0.0	0.0

Notes: Ratings of two-lane mediocre road (i.e., surface treatment pavement without paved shoulders) and all four-lane highways are usually assumed to equal 0.75 and 0.65 of two-lane high-design highway ratings.
Value system: 0 = no problem, 6 = big problem.

[a]Assumed.

Design to Give the Driver What Is Expected

The approaching road conditions, including the geometric design and resulting traffic operations, should be designed to be expected by the driver. Drivers tend to build up an expectation of what the upcoming roadway will be like based on their previous driving experiences. Some geometric features basically are unexpected at any location because of their limited frequency of use in rural highway design. Other features, such as horizontal curves and intersections, may have rare or unusual design attributes or operational demands that are unexpected. A 95 percentile horizontal curvature level (e.g., a 6° curve) is one example of a common feature (a horizontal curve) with an uncommon attribute.

Avoid Creating Compound Features

A compound geometric feature is one that contains two or more of the basic geometric features listed in Table 1 at the same location or in close proximity to one another. Close proximity is defined as a separation distance between the centers of the adjacent features of 457 m (1500 ft) or less. This distance may be reduced to 305 m (1000 ft) where 85 percentile speeds are less than 80 km/h (50 mph) or the compound feature is composed of two of the lower-valued basic features (less critical, i.e., less than 2.0) listed in Table 1. Tangent sections are excluded from compound feature analysis.

The designer should separate features by the proximity distance to provide the unfamiliar motorist time to recover from the experience of driving the first unexpected feature before being required to begin perceiving a subsequent surprise feature. The time a motorist needs to recover, perceive, and react to a subsequent unexpected feature is estimated to range from 5 to 10 s or more. Since the viewing (and maneuvering distance) to the next feature is also in the same range (5-10 s), an overall separation time of 10-20 s is desired.

Provide Feature Visibility in Proportion to Criticality of Work-Load Rating

The designer should seek to provide as much sight distance as is practicable on roadways that approach geometric features. The greater the work-load rating (i.e., the more unexpected and complex the feature is), the greater the sight distance needed. Adequate sight distance and feature visibility provide the time unfamiliar drivers will need to correct false expectations, decide on the appropriate speed and path, and make the required traffic maneuver.

The effective design speed from which sight distances would be determined is calculated from the following formula:

$$V_e = V_0 + 8W \quad W \geq 2 \qquad (1)$$

where

V_e = effective design speed (km/h),
V_0 = original design speed (km/h), and
W = work-load potential rating in Table 1 ($W \geq 2$).

Thus, a geometric feature that has a work-load rating of 2.0 would need a sight distance given by a design speed effectively 16 km/h (10 mph) greater than the existing original design speed of the highway. The 85 percentile vehicle operating speed ($V_{85\%}$) on the approach prior to the feature should also be estimated. The higher speed value of V_0 or $V_{85\%}$ should be used to determine the needed sight distance from standard sight-distance design tables.

Provide Adequate Transitions

In addition to providing adequate visibility and separating basic geometric features in new construction to reduce driver work load and to improve traffic safety, adequate transitions also should be provided in all improvement programs and new designs to improve traffic operations. These transitions are desired for those geometric features that require vehicle path adjustments to achieve safe vehicle control. Common geometric features that need an acceptable transition include the following:

1. Lane drops,
2. Lane-width reductions,
3. Shoulder drops (greater than 50 percent reduction), and
4. Divisional channelization at divided highway transitions and channelized intersections.

The transition for the feature may be developed by using a straight taper transition in the departure direction along the roadway that goes from the higher-standard design to the lower-standard cross section. A similar transition in the opposite direction may be provided for symmetry if desired. The longitudinal transition taper ratio should not be less than the design speed to one or the latest recommendation of the Manual on Uniform Traffic Control Devices (MUTCD) (4).

Good transitions should be provided at the job terminals, even if plans exist to continue with the improved design in the near future. Plans can change rapidly and unexpectedly. The new project may not be finished for years. The transition requirements from a multilane divided highway to a two-lane highway without paved shoulders are large. It would appear unreasonable to continue these improvement programs to some arbitrarily selected location, such as at a major intersection located on the crest of a hill, then use a temporary reverse horizontal curve throughout the transition zone to connect the roadways, and finally expect motorists to negotiate the resulting compound feature safely until funds can be obtained to complete the work.

Provide Forgiving Roadside

When the previously recommended design objectives and practices are not feasible or cannot be implemented

Table 2. Work-load potential ratings (R_C) of horizontal curves.

Degree of Curvature (D°)	Deflection Angle (Δ°)				
	10	20	40	80	120
1	0.5	1.0	2.1	4.1	6.2
2	1.2	1.5	2.0	3.0	4.1
3	2.1	2.3	2.6	3.3	4.0
4	3.1	3.2	3.5	4.0	4.5
5	4.0	4.1	4.3	4.7	5.2
6	5.0	5.1	5.3	5.6	6.0
7	6.0	6.1	6.2	6.5	6.8
8	7.0	7.0	7.1	7.4	7.7

Note: All ratings are for two-lane, high-design highways. Ratings for two-lane mediocre roads (i.e., surface treatment pavement without paved shoulders) equal 0.75 of rating shown. Ratings for all four-lane highways equal 0.65 of rating shown.

effectively, the problem feature should be designed to have especially forgiving roadsides for possible errant vehicle operations. Estimate the more probable path guidance errors that might be made by drivers when exposed to the geometric feature susceptible to expectancy violations. Allow for these potential driver-control errors in design by providing clear recovery areas sufficient in space, slope, and surface stabilization to permit safe recovery of vehicle control. Paved shoulders may be an appropriate recovery addition for some situations. Hazardous roadside obstacles should be removed, relocated, or softened in areas where severely out-of-control vehicles might travel. One may wish to review the latest roadside safety literature, especially the American Assocation of State Highway and Transportation Officials' (AASHTO's) Yellow Book (5), before selecting a specific forgiving roadside design.

SPECIFIC FEATURE RATINGS AND DESIGN PROCEDURES

The following section presents material critical to the geometric consistency evaluation of specific geometric features and procedures for designing consistent features. The material is more technically detailed to more specifically identify trade-offs that exist among the related design variables.

Each geometric feature will have a set of estimated work-load potential ratings provided. These ratings serve three purposes. The ratings identify the estimated driver work load for the primary design variable; the ratings can be used to estimate the sight distance needed if an individual feature is being designed (in lieu of the average values presented in Table 1); and the ratings will be used in the roadway system-evaluation procedures to be described later in this paper.

The limits of these design and evaluation aids must be recognized by the user. The design-speed range is from 80 to 129 km/h (50-80 mph). Topography can be flat or rolling. Low speeds and mountainous terrain are not included because driver expectancy and driving experience are greatly different from those on routine rural highways.

Horizontal Alignment

Research and the literature review have shown that sharper curves are generally more troublesome to drivers. Accident rates were reported to increase significantly on curves greater than 8° (6). These curves were observed in this research study to be very rare curves in the normal rural highway driving experience (3). The most frequently used curve in design was noted to be about 2°. Illinois noted that excessively long curves are accident prone and are to be discouraged. The frequency of horizontal-curve central deflection angles (Δ°) was also measured. A central deflection angle of 20° was found to be about the average angle (3). An average horizontal curve was assumed to be a 3° curve with a 20° deflection angle. A work-load potential rating of 2.3 for an average horizontal curve had been previously established (Table 1) for a two-lane high-design road. Other work-load potential ratings (R_C) were estimated over the ranges of degree curvature based on the relative magnitude of side-force levels expected from the results of other operational speed studies reported earlier. Excessively long curves were rated proportionally higher. The resulting work-load potential ratings for a wide range of horizontal curve conditions are presented in Table 2.

AASHTO design procedures regarding horizontal alignment (7) (and in combination with vertical alignment) address several objectives, including geometric consistency of alignment. Selected procedures imply driver expectancy considerations. Aesthetic qualities are also reflected.

In addition to the AASHTO general horizontal alignment design procedures, the following horizontal alignment design procedures are recommended to maintain consistent geometrics:

1. The maximum increase in curvature between horizontal curves should not exceed 3° and
2. Horizontal curves that exceed 3° should be avoided in compound geometric features.

Vertical Alignment

The primary effect of vertical alignment on driver expectancy of criticality of geometric features is in the restriction to sight distance. Sight distance impacts were judged on an average basis during the evaluation of basic geometric features. Secondary effects are the unexpected frequency and duration of limitations on passing over a section of two-lane highway. Approximations of these passing limitations are provided. The impact of grade is believed to be negligible in flat and rolling topography. Speed losses are approximately regained on the downhill side, and little overall speed increase would be expected. Speed differentials between automobiles and trucks that exceed 16-24 km/h (10-15 mph) may create operational conflicts and unsafe driving practices. These differences estimated between vehicle speed profiles may be evaluated by using Leisch's method (8). No specific rating is provided for this situation. Sag vertical curves do not appear to contribute significantly to potential geometric inconsistencies when designed to prevailing operating speeds.

The work-load potential rating (R_V) for a given crest vertical curve can be determined from the table below by knowing the number of crest vertical curves in the prior 1500 m (5000 ft), including the one being analyzed.

No. of Crest Vertical Curves in Prior 1500	Work-Load Potential Rating (R_V)
≤ 2	1.9
≤ 3	3.0
≤ 4	4.0
≤ 5	5.0
>5	6.0

The vertical point of intersection (VPI) of the crest curve is used to determine the location of the curve. The work-load ratings were developed from the previously estimated average crest vertical-curve work-load potential rating of 1.9 (Table 1) and distributed to other conditions based on approximate probabilities of not being able to pass. For all multilane highways, assume the work load of a crest vertical curve is 1.2 regardless of the frequency.

AASHTO design procedures for providing aesthetics and consistency in vertical alignment design are recommended in general (7).

The following additional design consistency guidelines are offered based on the results obtained and observations made in this research.

1. Increase the design speed of a highway toward 113 km/h (70 mph) if few crest vertical curves exist and if the roadway is similar to local 113-km/h designs.

Table 3. Work-load potential ratings (R_i) for intersections.

Highway	Type of Approach to Intersection	Approach Stop or Yield Controlled	Approach Not Controlled: Crossroad Average Daily Traffic $\leq$100	<400	<1000	>1000
Two-lane high-design	Unchannelized	4.0	1.5	2.4	3.7	4.0
	Channelized	4.0	2.5	3.0	3.3	4.0
Four-lane undivided	Unchannelized	4.0	1.0	1.6	3.0	4.0
	Channelized	4.0	1.6	2.0	2.8	4.0
Four-lane divided	Unchannelized	4.0	0.6	1.2	2.7	4.0
	Channelized	4.0	0.5	1.0	2.5	4.0

Note: Mediocre two-lane road (i.e., surface treatment without paved shoulders) values equal 0.75 of two-lane high-design values.

2. Isolated crest vertical curves in flat topography will probably be driven at an apparent design speed of 113 km/h if the pavement surface quality and traffic volumes permit.

Intersections

Work-load potential ratings for channelized and unchannelized intersections located on high-design, two-lane facilities and on multilane highways are presented in Table 3. Only a few general classification parameters are used for practicality. Channelized intersections refer primarily to whether the approach has a protected left-turn bay. Stop- or yield-controlled approaches are treated separately from noncontrolled approaches.

It is difficult to design a major intersection in rural areas so that it will be expected. Stop-controlled intersection approaches on main highways are usually troublesome. When horizontal or vertical curvature is present, stop-controlled approaches are seldom satisfactory. Multiple or otherwise complex route numbers also create unexpected decision problems for motorists unfamiliar with a junction. No-passing zones and channelization may also confuse motorists.

The sight distance provided along the roadway that passes through the intersection should be increased above minimum required stopping sight distance in relation to the total work-load potential rating of all features within proximity distance or 457 m (1500 ft) of the center of the intersection. That is, sight distances for the resulting compound geometric feature should be provided to AASHTO requirements (7) for an adjusted design speed higher than the base design speed of the facility. The increased speed is calculated from the following formula:

$$V_a = V_0 + 8R_\Sigma \quad R_\Sigma \geq 2.0 \tag{2}$$

where

V_a = adjusted design speed (km/h),
V_0 = existing base design speed of roadway (km/h), and
R_Σ = sum of work-load ratings of all features within proximity distance 457 m (1500 ft) ($\geq$2.0).

At least 16-km/h (10-mph) increases in adjusted design speed are desired. No adjustment is needed if R_Σ is less than 2.0.

In general, horizontal curvature greater than 3° in intersections should be avoided on through roadways. Reverse curvature within the intersection area is also undesirable and should not be used on crest vertical curves.

Lane-Width Reductions

The criticality of lane-width reductions is primarily a function of vehicle lane placement, placement variability, and initial lane width. The average work-load potential rating of lane-width reductions was estimated to be 3.1. Evaluations of research on lane placement variability with horizontal curvature (9) and this research were used to develop the work-load potential ratings (R_ℓ) for two-lane high-design highways shown in the table below (1 m = 3.3 ft).

Reduction in Lane Width (m)	Work-Load Potential Ratings (R_ℓ) for Initial Lane Widths: 3.35 m	3.66 m	3.96 m
0.30	2.3	2.0	1.8
0.61	3.8	3.0	2.5
0.91	No good	No good	4.7

The ratings in the table were established for tangent alignment. Ratings on two-lane mediocre roads (i.e., surface treatment without paved shoulders) equal 0.75 of value shown. Ratings for all four-lane highways equal 0.65 of value shown. Average lane placement data suggest that vehicles drive closer to the edge of the pavement when traveling on the inside of the curve and drive farther from the edge when traveling on the outside.

Reduction in lane width must be carefully designed with good visibility of the pavement surface provided since all drivers will be exposed to the feature. Liberal transition tapering should be used to achieve the lane-width reduction. Paved shoulders may be substituted for the transition taper if the work-load potential rating is 2.0 or less. If the rating is greater than 2.0, transition tapering and all-weather stabilized shoulders should be provided to provide a forgiving roadside.

Divided-Highway Transitions and Lane Drops

The work-load potential ratings for lane drops and divided-highway transitions depend on the feature characteristics and direction of travel. Average ratings have been established as 1.8 for a four-lane to four-lane divided-highway transition (median drop), 4.0 for a four-lane to two-lane divided-highway transition (median and lane drop), and 3.9 for an undivided-highway four-lane to two-lane lane drop. No ratings are available for larger facilities. Observations indicate that short sections of divided-highway transitions, such as at a roadside park, and multilane passing sections would not surprise motorists when they terminate. A longer multilane facility might. This premise is reflected in the work-load potential ratings (R_t) for these features presented in Table 4.

Design procedures are presented by AASHTO for the design of divided highway transitions (7). The provision of a divided-highway transition on a horizontal curve that has a suitable alignment standard would provide satisfactory results. On long tangents, changes in median width cannot be effected readily except by reverse curves on one or both pavements.

The previous AASHTO design procedures generally seem satisfactory. The suitable alignment standard for a simple horizontal curve is probably about 3.0°. Reverse horizontal curvature of 2.0° or less should prove operationally satisfactory since this is approximately the most frequently used curve in highway design and motorists are accustomed to driving it.

Table 4. Divided highway transitions and lane drop work-load potential ratings (R_t).

Geometric Feature	Lane Direction		Work-Load Potential Ratings (R_T) for Prior Section Lengths		
	From	To	≤3.2 km	≤8.0 km	≥8.0 km
Divided-highway transition	4	2	3.0	3.3	4.0
	2	4	2.0	2.0	2.0
	4	4	1.0	1.5	1.8
Lane drop	4	2	2.5	3.0	3.9
	2	4	1.5	1.5	1.5

Note: 1 km = 0.62 mile.

The design need often arises to combine a divided highway transition with an intersection. This situation may have arisen due to a large drop in volume along a rural four-lane road as it intersects a state highway. This intersection most likely will be one that has high turning movement volumes (since the volume level drops significantly at this location). The intersection may also have some (and possibly significant) cross traffic. It follows that the divided highway's turning traffic will be slowing while the through traffic will be trying to maintain a constant speed. A large speed differential between vehicles and a high potential for traffic conflict will exist. In general, a high accident frequency can be expected.

The mixing of divided highway transitions or lane drops with intersections should be avoided. Unfamiliar motorists are never expecting this complex situation. If one must be constructed, no reduction in design speed should be permitted through the section, visibility should be maximized, only natural flowing horizontal alignment of 3° or less should be used, and paved shoulders should be maintained throughout the features.

Lane drops in rural highway design are typically a feature that results when a four-lane undivided roadway is reduced to a two-lane highway. Other lane-reduction features that should be considered as lane drops include the following:

1. Termination of passing (or truck climbing) lanes greater than 3.2 km (2 miles) long and
2. Termination of an intersection of a through or climbing lane.

In general, a lane drop should be considered as severe a potential geometric inconsistency as a divided highway transition (four-lane to two-lane), except for the likelihood that motorists may become entrapped by divisional channelization.

Lane drops designed according to AASHTO standards are satisfactory when not brought into combination with other geometric features. Several research reports discuss the options of which lane to drop and what pattern to use. Review of these documents is suggested for developing optimum design configurations. Stabilized shoulders should be maintained throughout the transition section.

EVALUATING GEOMETRIC DESIGN CONSISTENCY

The engineer may wish to evaluate either proposed designs or existing highways for geometric consistency. Routine safety reviews may have identified the existing highway as being accident prone. The evaluation process may consider only one problem geometric feature or an extended section of highway. The study procedure is directional in nature and treats one highway direction at a time. The analyst should begin by reviewing the features of the highway prior to the study area. To begin the evaluation, find the most featureless section of highway (e.g., level, tangent) approximately 2 km (1.25 miles) in advance of the study area. Estimate the driver work load of this section of roadway. With design plans in hand and photographs of the existing design (if available), begin the following evaluation procedure.

Identify Geometric Features

Use Table 1 as a guide in identifying the types of geometric features along the highway in the study area. Determine the following items for each feature:

1. Type,
2. Station,
3. Work-load potential rating (R_f),
4. 85 percentile speed [km/h (mph)],
5. Sight distance [m (ft)] to geometric feature, and
6. Separation distance [m (ft)] from last geometric feature.

Obtain Work-Load Potential Rating (R_f)

The basic work-load potential rating for the next geometric feature along the highway may be read directly from Table 1 to evaluate average conditions if this estimation level of accuracy is sufficient. Otherwise, determine the more specific work-load ratings for those features identified in the preceding tables. Note that vertical curvature initially must be considered separately on a systems basis to estimate the impacts of no-passing-zone restrictions.

Estimate 85 Percentile Speed

The 85 percentile speed ($V_{85\%}$) on the approach to the feature should be estimated. In essence, an 85 percentile operating speed profile is required along the highway for each direction of travel. Do not rely totally on the speed limit or design speed in estimating the 85 percentile speed. The 85 percentile speed is approximately 11 km/h (7 mph) above the estimated average speed. The allowable range of 85 percentile operating speeds is from 80 to 113 km/h (50-70 mph).

Determine Sight-Distance Factor

Estimate the maximum sight distance (S) to each feature by using the same measurement criteria as for safe stopping sight distance. Check both horizontal and vertical alignment restrictions. A motorist can be assumed to look through features to see other features downstream if they are visible. Use the midpoint (or obviously most critical location) of the feature for evaluation purposes, including the determination of separation distances. Having estimated the sight distance to the feature and the 85 percentile speed, read the sight-distance adjustment factor (S) from Figure 2. This factor adjusts rating values from average speed and sight distance levels to specific site conditions.

Determine Carry-Over Factor

Once the separation distance from the last feature and the V_{85} speed are known, determine the work-load carry-over factor (C) from Figure 3. This factor adjusts conditions from isolated conditions to specific circumstances. It accounts, in general, for driver memory loss, decision-sight-distance requirements, and average viewing distances (not sight distance) used in the driving task.

Calculate Feature Expectation Factor

The feature expectation factor (E) adjusts for the potential confirmation of driver expectancy where the prior feature is similar to the current feature. If the feature is similar to the prior feature, $E = 1.00 - C$. If the new feature is not similar to the last one, $E = 1.00$. Horizontal curves that have curvature more than 3° greater than the preceding horizontal curve may be considered not similar to the previous curve (3). Flatter curves are always similar when immediately following a sharper curve.

Figure 2. Sight distance factor (S) due to sight distance to next feature as related to 85 percentile speed.

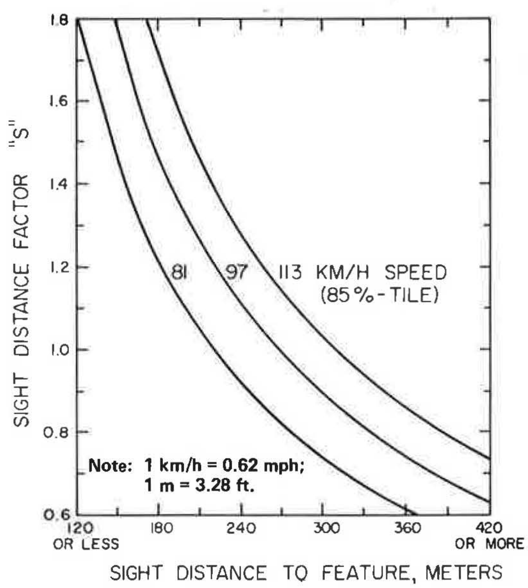
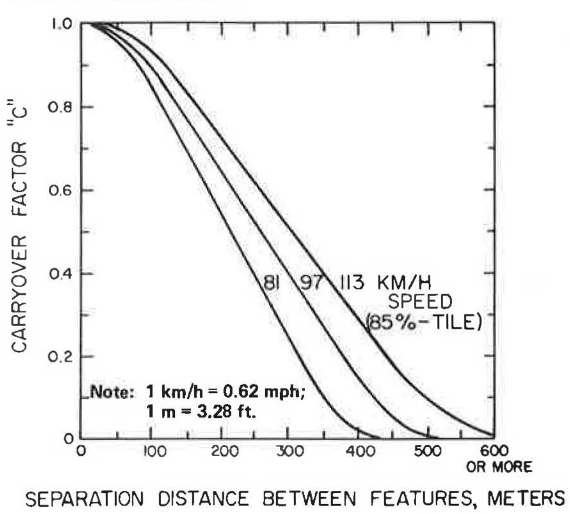


Figure 3. Carry-over factor (C) due to separation distance between features as related to 85 percentile speed.



Estimate Driver Unfamiliarity Factor

The higher the percentage of motorists unfamiliar with the highway (U), the higher the probability of drivers being surprised by relatively unusual geometric features. Use the table below as a guide for estimating U.

Classification System	Examples	Factor U
Rural principal arterial	Major U.S. highway, Interstate	1.0
Rural minor arterial	U.S. route, major state highway	0.8
Rural collector road	State highway, major farm-to-market road	0.6
Rural local road	Farm-to-market road, county road	0.4

Calculate Driver Work-Load Value

Evaluation of the potential for the geometric feature to be inconsistent by using these procedures is based on the calculated driver work-load value (WL_n). WL_n refers to the work-load value being calculated for the next feature, whereas WL_ℓ refers to the work-load value previously calculated for the last feature. The work-load value (WL_n) is determined from the following equation, which uses the previously described factors and the work-load value calculated in the last feature (WL_ℓ).

$$WL_n = U \cdot E \cdot S \cdot R_f + C \cdot WL_\ell \quad (3)$$

Estimate Level of Consistency of Feature

The previous factors have been combined to provide information that could indicate which unexpected geometric features are creating a problem. But at what value of work load can this conclusion be drawn? At present, this decision is subjective. However, in an effort to standardize the process and to allow relative comparisons, the criteria presented in the table below are suggested.

Driver Expectation	Level of Consistency	Work-Load Value, (WL_n)
No problem	A	≤1
expected	B	≤2
Small surprises	C	≤3
possible	D	≤4
	E	≤6
Big problem possible	F	>6

One may conclude that a $WL_n > 6$ is defined as an apparent geometric inconsistency. Thus use the above table to estimate the level of consistency (LOC_n) of the geometric feature given the calculated work-load value.

The designer would use this procedure to minimize both the absolute level of geometric work-load values and also the jump between features. Ways to improve the level of consistency include the following:

1. Improve geometrics,
2. Increase spacing between features, and
3. Increase sight distance to the feature.

CASE STUDY

The following brief case study is presented to illustrate the basic methodology of applying the geometric design consistency procedures to an existing highway. Few, if any, modifications are necessary to apply the procedures to a proposed new design. The basic differences are that a specific problem site may not have been identified based on accident statistics and that estimates of operational variables rather than field measurements would be required. In the case study evaluated, a complete set of calculation results will be provided. Subsequent level-of-consistency evaluations will be presented.

A few years ago, an existing two-lane, primary highway was improved to a four-lane divided facility for 2.4 km (1.5 miles) to expedite the construction of a new railroad bridge overpass. The northern terminus of the four-lane section is located on a rather featureless stretch of the highway. However, the southbound terminus is just beyond the crest of a 97-km/h (60-mph) vertical curve. Other geometric features found along the four-lane divided section include a bridge and a flat, horizontal curve. The three-year accident history indicates that seven accidents have occurred in the southbound direction at the southern divided-highway transition. The average daily traffic (ADT) along the highway is 5200 vehicles/day. The 85 percentile vehicle speeds in the four-lane section vary between 100 km/h (62 mph) and 105 km/h (65 mph), depending on the vertical alignment.

The southbound direction only will be evaluated for consistency. A drive through in the southbound direction

Table 5. Evaluation of geometric consistency of divided-highway transition case study.

Feature	Divided-Highway Transition, Two-Lanes to Four-Lanes	Bridge, Full Width, No Shoulders	Horizontal Curve $2^\circ, 15^\circ$	Railroad Bridge Overpass	Crest Vertical Curve	Divided-Highway Transition, Four-Lanes to Two-Lanes
	Calculations of Geometric Features in Southbound Direction of State-16					
Station	701+10	727+90	734+90	740+00	776+50	780+00
R_f	2.0	2.5	0.9	0.8	1.2	3.0
V_{85} (km/h)	105	105	105	105	100	100
Sight distance (m)	600	321	606	545	909	144
Separation distance (m)	636	812	212	155	1106	106
R_f	2.0	2.5	0.9	0.8	1.2	3.0
S	0.69	0.90	0.69	0.69	0.69	1.80
E	1.00	1.00	1.00	1.00	1.00	1.00
U	0.80	0.80	0.80	0.80	0.80	0.80
C	0.00	0.00	0.68	0.73	0.00	0.90
WL_ℓ	0.0	1.1	1.8	1.7	1.7	0.7
WL_n	1.1	1.8	1.7	1.7	0.7	5.0
LOC_n	B	B	B	B	A	E

Note: 1 m = 3.3 ft; 1 km/h = 0.62 mph.

would suggest that conditions are good except near the southbound terminus of the four-lane section where the crest vertical curve severely limits the sight distance to the divided highway transition for the existing operating speeds. The route is classified as a rural minor arterial since it is a major state highway and, therefore, the U factor is 0.8.

Table 5 presents a summary of the initial geometric feature data, resulting calculations, and level-of-consistency evaluations. The calculations solve the work-load equation. Level-of-consistency evaluations are determined based on the criteria presented in the preceding table. As indicated in the last line in Table 5, the four-lane roadway is very consistent (i.e., the level of consistency is B, B, B, B, A, E) over much of the four-lane section except at the southern (last) divided-highway transition. To solve this problem the divided-highway transition should be moved farther away from the crest of the vertical curve until the sight distance is again unrestricted.

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Abridgment

Use of Total Benefit Analysis for Optimizing Lane Width, Shoulder Width, and Shoulder Surface Type on Two-Lane Rural Highways

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The relationships between safety and design for lane width, shoulder width, shoulder surface type, and accidents have been developed. The objective of this paper is to demonstrate how these and other relationships may be employed to obtain optimal design specifications for lane width, shoulder width, and shoulder surface type. A manual procedure is presented for basic design problems. As the complexity of the problem increases, some computerized optimization procedure, such as dynamic programming, is recommended.