Operational and Economic Considerations in an Evaluation of Geometric Design Alternatives

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Design measures, operational characteristics, and economic considerations applicable to the selection of geometric design alternatives are reviewed. The discussion is based on recent research of driver behavior and a hypothetical analysis of level of service as related to invested capital. Geometric design measures are closely related to operational characteristics as well as to economic considerations. Unless ample sight distance is provided throughout a facility, some variability of speeds may be expected. Driver workload is increased and performance is likely to deteriorate without sufficient sight distances. The relationship of speed characteristics on two-lane roads to overall geometric measures such as average curvature and hilliness and to traffic parameters such as volume and traffic composition was established. To increase safety and operational uniformity, consistent speeds should be the goal of designers. The magnitude of acceleration noise may be predicted by overall measures representing design consistency, such as the ratio between minimum and maximum radii or the ratio of the sum of lengths of curves to total section length. Predicted acceleration noise for different alternatives may serve as a potentially adequate measure for evaluating the merits of various designs. Based on a hypothetical logistic-type relationship between investment magnitude and level of service, suggestions were made for the level of service to be adopted for design purposes. Because of diminishing returns for a high level of service, an intermediate level of service may be desirable if purely economic considerations govern planners' decisions.

An objective approach to the development, analysis, and evaluation of geometric design alternatives has long been sought. This is true for the design of new roads as well as for the redesign or improvement of existing highways. One objective of engineers and planners is to identify and give priority to improving those geometric elements that are currently incompatible with modern standards and policies and that may produce the greatest potential benefit from their improvement. The benefits may be manifested in better safety of the improved facility or in better operational characteristics, that is, in a higher overall level of service.

Current geometric design of highways is based on different standards and policies, such as the United States (AASHTO) policy *(1)*, the Australian (NAASRA) policy *(2)*, and various European standards. There is an urgent need to consider and determine the adaptability of these standards to flow characteristics and the driving behavior of most drivers; the exact percentile has yet to be established. Furthermore, geometric design elements and standards, although developed from theoretical considerations, are greatly influenced by practical engineering judgment and rational analyses. It is, therefore, of interest to check the adaptability of standards and to investigate whether or not some correlation exists between certain highway alignments and smoothness and efficiency of operation.

Finally, there is a need to evaluate the economic aspects of the planned investment for the highway under consideration. The complexity involved in such an evaluation is increased by the large number of and often conflicting objectives postulated by various groups affected by the highway. Desired evaluation can include, for example, analysis of vehicle delay, vehicle speeds, energy consumption, and overall expected level of service.

The issue of design compatibility and selection of alternatives is rather complex and has at least four facets: (a) the question of the compatibility of existing standards with theoretical considerations of new-vehicle dynamics and performance characteristics; (b) the question of the sensitivity of the designed road to various traffic and flow conditions, such as different road volumes, traffic compositions, or capacity characteristics; (c) the variance in the use of standards by various designers and the confusion that emerges from the contest between minimum and desirable design; and (d) the overall relationship between the designed highway (the product) and the capital investment level (the resources input).

This paper attempts to assess some operational characteristics necessary for an evaluation of new roads as well as to address conceptually the fourth, or economic, facet of the selection among alternatives. The discussion is based on recent research of driver behavior and a hypothetical analysis of level of service as related to invested capital. Consideration is given to sight distance and its effect on highway design, speed characteristics on two-lane rural roads, the relationship between acceleration noise and geometry, and level of service and economics.

SIGHT DISTANCE CONSIDERATIONS

In considering plans, the highway designer has several objectives in mind, among which are a reduction in the number and severity of accidents and the provision of a smooth, efficient trip to all vehicles. A major element in determining the character of any two-lane rural highway and its potential for provid-

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ing a smooth, safe trip is the available sight distance, which is a basic element of geometric design having a direct bearing on the quality and cost of the road design.

A review of various criteria that have been adopted by road planners shows some agreement among transportation engineers that minimum sight distances do not meet the requirements for efficient highway operation, and therefore greater distances should be allowed. Several sight distance parameters such as stopping sight distance and passing sight distance are common in highway design. The most recent (1984) policy of AASHTO *(1)* suggests that these distances are often inadequate when drivers must make complex decisions or when information is difficult to perceive. A decision sight distance, one considerably greater than a stopping sight distance, is suggested for use when an unexpected or otherwise difficult-to-perceive item of information or hazard may be encountered. On the other hand, there is no room for overdesign in general and in particular for a sight distance that would unjustifiably increase construction costs. As a general measure, it can be suggested that a consistent, greater-than-minimum sight distance should be sought for the entire highway section under evaluation. Geometric consistency in rural highway design may be defined as a combination of geometric features that are similar in size or magnitude and that meet driver expectations from the road.

Analysis of driver response to a limited sight distance situation was conducted by Polus et al. *(3)*. The data were gathered at six rural sites where the visibility was restricted by a vertical curve. The vertical curve with limited sight distance caused drivers to change their regular driving habits, that is, to reduce their average spot speeds significantly. Because at all sites the vertical curve followed a tangent section with an approaching grade that was about level, it was assumed that the curve was the only contributing factor to the observed response. Three forms of approach speed gradient were chosen as the best measures to represent the expected response; these were calculated against the appropriate actual sight distance at the six sites. In a typical resulting model that yielded the average speed reduction at all sites, an exponential dependence was assumed.

$$GRV = 0.36 + 15.59\, e^{-0.02(SD)} \quad (1)$$

where *GRV* is the maximum average approach speed gradient in percent and *SD* is the minimum sight distance in meters at the site.

The average approach speed gradient was defined as the percentile ratio of the approach speed minus the speed at the vertical curve divided by the approach speed. Equation 1 is presented graphically in Figure 1. Two distances are designated: one distance representing a desirable minimum sight distance, as suggested by AASHTO *(1)* for a design speed of 50 mph (80 km/hr); the second distance representing a suggested threshold, no-response sight distance, greater than which the maximum speed gradient approaches a constant value of about 0.5 percent attributable to regular oscillations of speeds. The threshold distance of 240 m (790 ft) is about twice the length of the lower limit suggested by AASHTO *(1)* as a minimum stopping sight distance, 122 m (400 ft); on the other hand, it is about equal to the AASHTO decision sight distance of 228 m (750 ft). In spite of the preliminary nature of the threshold conclusion, a desired uniform speed throughout a two-lane rural highway section will be available only if ample sight distance is consistently provided.

The stopping sight distance criterion suggested by AASHTO *(1)* appears to be rather short for its adaptation to overall designs; it should, therefore, be further evaluated, with particular reference to driver anticipation. The concept of anticipatory sight distance was introduced by Leisch *(4)*. Messer *(5)* further emphasized that driver performance was directly affected by driver expectation. Messer also suggested that driver performance tended to be error free when expectations from the road were met. In sum, where different design alternatives are compared, the scaling and recording of sight distances on all plans

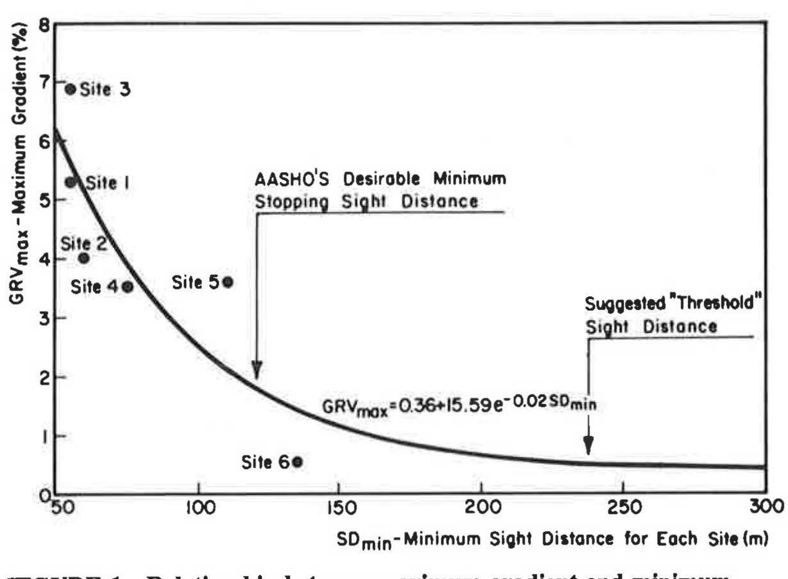

FIGURE 1 Relationship between maximum gradient and minimum sight distance for all sites.

should be conducted and criteria for above-minimum distances should be adopted for the selection process or for identification of inconsistent locations.

SPEED CHARACTERISTICS

The speed performance of vehicles on rural highways is needed for capacity calculations, for determination of lane requirements, and for such analyses as user costs in economic studies. Speed performance information, however, is rarely readily available in spite of its importance to highway design engineers.

Galin *(6)*, in presenting findings on speeds on two-lane rural roads, suggested that the speed of individual drivers depended on numerous factors such as type of vehicle, driver age, length of trip, volume and proportion of trucks, and environmental conditions such as type of area or weather. His results, however, were based on similar road geometries and, therefore, were inapplicable for comparing alternatives or predicting speeds for different geometries.

A study that dealt with two-lane rural highways and the effect of their geometry on flow characteristics was conducted recently in Israel *(7)*. Several design measures representing horizontal and vertical alignments that may be directly related to average running speed were developed. The first was a horizontal measure, average curvature *AC*, which was the sum of external horizontal angles at all tangents divided by the length of the section.

A second measure represented the vertical alignment, average hilliness *AH*, defined as the sum of the vertical distance between crests and following sags divided by the section length. Another vertical measure was the net gradient *NG*, the vertical distance between the initial and final points of each section divided by the section length.

Three major traffic measures were considered. The first measure was the hourly one-way traffic volume *VL*. The second measure was the traffic composition *TC*, that is, the proportion of heavy vehicles expressed as a percentage of total flow. The third measure was the directional distribution of the traffic *DD*. The dependent variable was the average running speed *S* (in km/hr) over specified highway sections, or the sum of distances for all vehicles divided by the sum of running times. Following the analysis of the data, several alternative functional models were developed for predicting average running speeds. A two-regime prediction model was developed for flows (one way) equal to or less than 200 vehicles per hour (vph) and greater than 200 vph, as follows:

$$S = 90.485 - 0.010(AC) - 0.591(AH) - 0.029(NG) - 0.231(TC) \quad (VL \leq 200 \text{ vph}) \qquad (2)$$

and

$$S = 87.409 - 0.137(AC) - 0.191(AH) - 0.072(NG) - 2.746(DD) - 0.027(VLO) \quad (VL > 200 \text{ vph}) \qquad (3)$$

This model was found to be sufficiently precise for the practical application of predicting running speeds based on geometric and flow parameters.

Aerde and Yagar *(8)*, in a study conducted in Ontario, Canada, suggested another model that assumed that the speed of vehicles on rural roads was dependent on the free speed (the speed during extremely low traffic densities); this speed was reduced with increase in number of cars, number of trucks, number of recreational vehicles, and number of opposing vehicles. The median free speed found on the Ontario roads investigated was about 56 mph (90 km/hr), which was similar to the free speed obtained in Equation 2.

The roadway alignment includes both the vertical profile consisting of grades and vertical curves and the horizontal alignment consisting of tangent sections and curves. Although most accidents occur on straight, level sections, accident rates are higher for curves and grades *(9)*. Previous research generally suggests that as the radius of a curve decreases accident rates increase *(10–12)*. Safety considerations have caused critical reviews of the applicability of the design speed concept to proper highway design *(13)*. Instead of design speed, a consistent horizontal speed value may be suggested, the criteria for which are preset to satisfy the nature of the terrain, drivers' expectations, and expected traffic conditions. For example, a preset value of 50–60 mph was previously suggested as a value at which the accident involvement rate on two-lane rural highways is small *(14–16)*; this range, therefore, may be adopted for the desired average running speed that should exist on a given two-lane rural road. The expected speeds should be predicted for the design features of a given alternative from the use of Equations 2 and 3 or similar models and evaluated for consistency against the preset criterion for the desired speed.

ACCELERATION NOISE AND HIGHWAY GEOMETRY

Another measure that may be applicable to the selection of alternative geometric designs is the acceleration noise *AN* that drivers experience on a given highway. This parameter, which represents the variability of acceleration values over a specified section of highway, is defined as follows:

$$AN = (1/T)\left\{ \sum_{i=1}^{n} [a_i(t_i)]^2 \cdot \Delta t_i \right\}^{1/2} \qquad (4)$$

where

$a_i(t_i)$ = acceleration at time Δt_i,
Δt_i = time interval at t_i,
T = total time in motion, and
n = number of time intervals.

The concept of acceleration noise was developed as a result of car-following studies. Jones and Potts *(17)* suggested that this parameter was related to safety and alignment of roads. It was reasonably assumed that drivers attempt to maintain a uniform speed when traveling along a well-designed, consistent roadway.

A study of the relationship between acceleration noise and several overall geometric measures was conducted on 17 roadway sections, each having a length of exactly 2.5 km (1.56 mi), in northern Israel. The acceleration noise data were collected with the aid of a computerized data logger called "Traffic

Engineering Logger" (TEL), which was installed on a traveling vehicle and collected speed and distance information every 1/8th sec. This information was later converted to acceleration and acceleration noise. Acceleration noise data and consistency-oriented geometric measures developed for this study are presented in Table 1. The following overall geometric parameters were used:

LR = ratio of sum of lengths of curves to total section length,
RR = ratio of minimum to maximum radius,
RA = average radius of section (m), and
RD = ratio between average radius and minimum radius for the design speed.

LR represents the relative length of highway that is not straight, and, therefore, the built-in indirectness (obliquity) of the alignment. *RR*, the ratio of minimum to maximum radius, provides an absolute measure of design consistency. *RA*, the average radius, an absolute measure of curvature, is related to speed and safety. *RD* is defined as the ratio of the average radius to the minimum radius for the design speed because a measure of curvature relative to the minimum curvature for a given design speed is appropriate in evaluating design qualities and potential speed and acceleration variabilities.

Before any models were constructed to predict acceleration noise, a check of correlation coefficients was made. Because all coefficients were revealed to be relatively small except for the correlation between the average radius *RA* and the ratio *RD* of average radius to minimum radius for the specific design speed of the road, it was decided to include only one of the latter two parameters in the prediction model.

Two typical models obtained by the stepwise multiple regression technique follow:

$$AN = 0.551 - 8.08 \cdot 10^{-5} \cdot RA \quad (5)$$

$$R^2 = 0.322$$

$$F = 7.14$$

where *AN* is the average acceleration noise in meters per second squared; and

$$AN = 0.893 - 7.05 \cdot 10^{-5} \cdot RA - 0.25RR - 0.57LR \quad (6)$$

$$R^2 = 0.418$$

$$F = 3.11$$

From Equation 5, the average radius *RA* alone can explain about 32 percent of the observed variability in acceleration noise; further, the larger the average radius, the smaller the acceleration noise. The ratio of minimum to maximum radius *RR*, which appears in Equation 6, adds about 2 percent to the explained variability and leads to a reduction in acceleration noise when it increases. That is, when the difference between the maximum and minimum radii is small, acceleration noise is reduced more than when the difference is large. This variable is directly related to design consistency. The third independent parameter is *LR*, the sum of lengths of the curves in proportion

TABLE 1 VALUES OF AVERAGE ACCELERATION NOISE AND GEOMETRIC VARIABLES FOR 17 ROADWAY SECTIONS

Road No.	Independent Geometric Variables*				Acceleration Noise (m/sec^2)
	LR	RR	RA	RD	AN
1	0.30	0.13	870.00	3.48	0.28
2	0.41	0.33	557.14	2.23	0.37
3	0.62	0.71	566.67	2.27	0.21
4	0.54	0.25	960.00	3.84	0.22
5	0.58	0.13	842.86	3.37	0.36
6	0.51	0.16	697.17	3.87	0.38
7	0.56	0.23	445.21	2.47	0.48
8	0.34	0.15	153.57	0.85	0.95
9	0.44	0.29	182.69	1.01	0.79
10	0.56	0.23	445.21	2.47	0.74
11	0.51	0.16	697.17	3.87	0.70
12	0.31	1.00	2000.00	8.00	0.34
13	0.60	0.16	4625.00	18.50	0.23
14	0.20	1.00	4000.00	16.00	0.29
15	0.20	1.00	4000.00	16.00	0.23
16	0.60	0.16	4625.00	18.50	0.22
17	0.31	1.00	2000.00	8.00	0.35

to the total section length. This parameter, which provides a measure of the relative bendiness of the road, was found to explain an additional 8 percent of the observed variability in acceleration noise, and its contribution was also negative; that is, when *LR* increases, acceleration noise decreases, as would be expected.

The models presented in Equations 5 and 6, although having modest R^2 values, were significant at the 98 and 94 percent significance levels, respectively. Therefore, they can be adopted for a prediction of the expected acceleration noise of alternative designs of a roadway section. The acceleration noise, as explained, is a measure of the quality of the driving process, and therefore its estimation for various design alternatives is an essential step in the overall evaluation process.

LEVEL OF SERVICE AND ECONOMIC CONSIDERATIONS

Although basically developed from theoretical considerations, geometric design relationships are greatly influenced by practical and economic considerations. Because of the various opinions on unquantified traffic-flow situations, for example, vehicle paths on curves or exact passing distances, some variability exists in design standards. An objective approach to the evaluation of highway design alternatives should link geometric variables to user benefits and impacts and should include economic considerations, particularly as related to the resulting level of service to travelers.

The 1984 AASHTO policy *(1)* includes revised concepts on design vehicles, roadside safety features, and driver behavior. New design concepts and modified design criteria in this book are based mostly on safety-related studies and some operational research. Ranges of design values are provided for the design engineer, who is given flexibility in selecting the desired feature. Economic consequences and impacts of a flexible design process, however, are not taken into consideration.

A hypothetical relationship between highway capacity investment and vehicle level of service may assume the general shape shown in Figure 2. At Point I, relatively low-cost investments are introduced, such as signing, marking, or delineating; some slight change in vehicle level of service may be expected. At Point II, more capital investment is made, perhaps for improving drainage, resurfacing deteriorated roads, or improving road lighting at key locations; a further upgrading of the level of service is achieved. Shoulder resurfacing or widening is the next step up in potential level of service. At Point IV, consistency studies may lead to an improvement of horizontal curves by such actions as increasing radii, adjusting superelevation, or adding spirals. This improvement in turn may significantly increase average speed and, therefore, level of service. Investment actions represented at Point V, such as the improvement of vertical sight distances and radii, are usually relatively expensive, but are expected to increase speed uniformity significantly.

Added capacity projects, which are normally rather expensive, are shown at Points VI*a* and VI*b*. Two significant designs available on two-lane rural highways are these: (a) the addition of passing lanes at a preset frequency and (b) the expansion of overall capacity by constructing a four-lane highway. A high level of service may be expected initially; however, deterioration in level of service may be experienced over time. This is due to the time effect; that is, the greater attraction of vehicles to a better road (increased demand) and the resulting reduction in level of service. Deterioration can also be experienced because of the destruction or wearing of pavements over time.

The question arises as to the level of service that a public design agency may wish to adopt in selecting geometric design alternatives. The recommended limit of capital investment is usually provided by budget constraints. Still, various alternatives may yield two completely different levels of service for a similar investment. In this case, the selection of the preferred alternative according to the higher level of service obtained is obvious. In other instances, similar investments may result in the same level of service. This eventuality may lead, of course, to a more complicated selection situation, in which the planner has to designate the preferred alternative primarily with operational or environmental variables. If these are indifferent, a refined economic analysis may be desirable, with an in-depth evaluation of expected benefits. The exact location of the

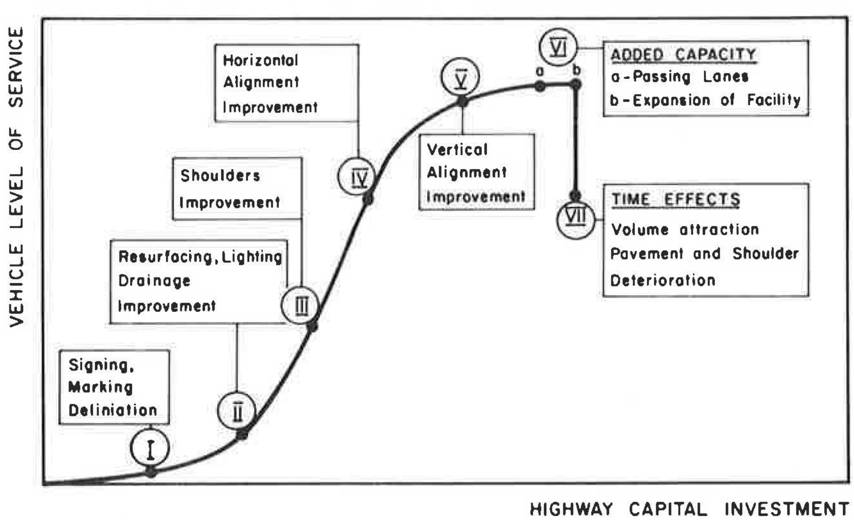

FIGURE 2 Potential change in vehicle level of service as related to capital investment.

alternative investment in relation to the logistic-type curve shown in Figure 2 is of importance. The flat portions, where the marginal level of service for an increased investment is small, are not usually recommended for selection.

Thomas and Schofer *(18)* suggested that because of the nature of transportation decisions, some basic requirements have to be satisfied in evaluation processes, such as a knowledge of all feasible solutions and their consequences and a precise definition of optimality. These requirements, however, cannot always be met.

Figure 2 shows that, for high and low levels of service, the investment needed to create a constant amount of change is higher than that needed for an intermediate level of service. This phenomenon was discussed by Brinkman and Smith *(19)* in their analysis of two-lane rural highway safety. They showed the diminishing returns for additional investments on present worth of benefits over a next-20-years curve. Improvement on a higher level of service situation usually yields lower monetary benefits, on a lower level-of-service situation, higher monetary benefits. Therefore, the selection of an alternative for implementation is also strongly dependent on the level of service of the facility concerned.

CONCLUSIONS

This paper has reviewed design measures, operational characteristics, and economic considerations that are applicable to the selection of geometric design alternatives. Geometric design measures are closely related to operational characteristics as well as to economic considerations. Sight distance was the first geometric measure discussed. Unless ample sight distance is provided throughout a facility, some variability of speeds may be expected, driver workload is increased, and performance is likely to deteriorate.

Speed characteristics on two-lane roads and their relationship to overall geometric measures, such as average curvature and hilliness, and to traffic parameters, such as volume and traffic composition, was established. It was suggested that a consistent speed should be the goal of designers in order to increase safety and operational uniformity.

Another operational measure typical of vehicle performance on a given highway is acceleration noise, which represents the variability of acceleration values over a specified highway section. It was shown that the magnitude of this measure may be predicted by overall measures representing design consistency, such as the ratio between minimum and maximum radii or the ratio of the sum of lengths of curves to total section length. The predicted acceleration noise for different alternatives may serve as a potential measure for evaluating the merits of various designs.

Finally, level of service and the economic implications of capital investment in highway design were discussed. Based on a hypothetical logistic-type relationship between investment magnitude and level of service, suggestions were made for the level of service to be adopted for design purposes. Because of diminishing returns for a high level of service, an intermediate level of service may be desirable if purely economic considerations govern decisions.

Part of the complexity of selecting among various well-designed alternatives for a specified highway was evaluated in this paper. Operational, economic, and geometric dimensions, it was shown, contribute significantly to this complexity; other dimensions, such as those related to environmental or social factors, were not discussed and should be further studied.

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