Models for Evaluating the Consistency of Highway Alignment

ABISHAI POLUS AND DORON DAGAN

In this paper, a study on the consistency of highway alignment is summarized. The emphasis is on horizontal alignments, but the models presented can be converted for evaluating vertical alignments as well. The objective was to develop tools that could be adopted by designers and decision makers for evaluating different alignment alternatives for design consistency. From a set of theoretical road sections that were developed, 23 roads were selected and systematically divided into six groups, based on their overall alignment features. The consistency of these roads was rated on the basis of previous research and engineering judgment and then compared with the rating obtained from each of three groups of models that were constructed: geometric, spectral, and compound (spectral-geometric). The spectral model correlated best with the consistency rating of the 23 theoretical roads; however, some reservations were voiced for using this model with highways on level terrain. The geometric and compound models were also shown to be valid for analysis of highway consistency.

Many engineers argue that the design of highways and roads is an art combined with an engineering process. The conceptual design goal is to produce a cost-effective design that results in a safe, efficient, and aesthetic highway. Sometimes, however, the concern with minimizing construction costs is viewed as the principal factor governing design. It is becoming evident, though, that other factors have an important influence upon the long-term quality of the facility in terms of travel safety, travel cost, and travel comfort.

The consistency of highway alignment is treated in this paper. The emphasis of this study was on horizontal alignment, but the models presented can be converted for evaluating vertical alignment as well. The objective was to develop tools that could adopted by designers and decision makers when they try to evaluate different alignment alternatives and to compare design consistency. Such an evaluation is particularly important when various designs have similar costs and potentially similar safety merits; the consistency analysis then becomes an additional dimension of the evaluation process. The procedures and models of geometric design consistency evaluated in this study are applicable to all rural two-lane highway facilities.

The major theme of this paper is the use of spectral analysis to evaluate highway consistency. The theoretical background of spectral analysis is briefly discussed, followed by the development of potential measures of consistency. These measures are evaluated against the proposed spectral model, and conclusions related to highway design consistency are drawn.

A. Polus, Department of Civil Engineering, Transportation Research Institute, Technion, Israel Institute of Technology, Haifa 32000, Israel. D. Dagan, Goodkind and Odea, 1190 Dixwell Ave., Hamden, Conn. 06514.

A relatively small number of studies have addressed the issue of geometric design consistency. Of these, only a few treated this subject directly; the others developed measures of overall geometric alignment or traffic performance such as operating speed or reliability that are related to design consistency.

Glennon and Harwood (1) argued that design consistency has always been recognized as the underlying principle in highway design. They suggested, however, that there is a general lack of explicit criteria for the contiguous combination of basic design elements or for the longitudinal variation of horizontal or vertical alignment. Without these explicit criteria, designers will continue to build inconsistent geometric details into highways. Glennon and Harwood further suggested that the concept of driver expectancy is wholly embodied in the general definition of design consistency; if driver expectancy is met, driver performance will tend to be error free.

Another study of highway consistency, which was based on a study conducted by Messer et al. (2), was published by Messer (3) who presented a methodology based on driver behavior principles associated with work load—potential ratings for different geometric features. For example, because sharper curves are generally more troublesome, the driver's workload increases with the degree of curvature (decreased radius) and with the deflection angle. Messer also suggested that excessively long curves are accident prone and are to be discouraged. Similarly, he advanced some general design recommendations that treated vertical alignment, intersections, divided highway transitions, and lane drops.

Leisch and Leisch (4) posited that the design speed concept, as presently applied, does not preclude inconsistencies in highway alignment. This application creates, they claimed, both a speed differential between automobiles and trucks and a tendency on the part of the driver continually to accelerate and decelerate. They proposed an updated design speed approach based on the speed profile technique, which compares the potential speed of automobiles and trucks along a defined highway section.

Earlier, AASHO developed the *Driver Expectancy Checklist (5)*, in which design consistency was a major parameter. Specifically, the results of the AASHO study pointed strongly to the fact that good driver communication, and therefore good design consistency, are achieved only by proper coordination among all roadway and terrain features.

Another concept of consistency was introduced by Polus and Schofer (6), who suggested that reliability is an indication of the operational consistency of a freeway facility over a period of time. Consistency was assessed by comparing daily perfor-

mance measures, and a method of predicting the complete distribution of the measure of performance was offered.

Several overall geometric design measures and their relation to safety level were presented by Polus (7), who used three horizontal measures. One such measure is the average curvature, defined as the ratio between the sum of deflection angles between each two consecutive tangents and the length of the section. The second measure is the ratio of the minimum to the maximum radius of an alignment, which is a measure of its horizontal consistency in terms of the use of similar horizontal radii along the road. The third measure is the average radius, which provides the relationship with the design speed; this measure may also provide information to drivers, who tend to build up an expectation of what the upcoming roadway will be like, based on their immediate previous driving experience.

McLean (8), in a study in Australia, divided each road on which curves were studied into sections of relatively uniform character, based on overall alignment factors such as topography, cross section, and adjacent land use. He concluded that above all, drivers expect consistency in alignment standards and that designers are provided with little quantitative information as to how this might be achieved.

Past work took some significant steps forward by introducing such concepts as driver expectancy, highway reliability, and driver workload, as well as some general design criteria that are functionally related to highway consistency. Nevertheless, despite these interesting consistency concepts, no overall measure or model for highway consistency has emerged. The goal of the study reported on in this paper was to develop potential models that could be used as tools for evaluating overall horizontal consistency of a highway section.

DEVELOPMENT OF THE MODELS

Before a model was constructed to evaluate the consistency of highway alignment, it was necessary to establish which road characteristics increase or decrease consistency. The following road features were found to violate highway consistency:

1. A horizontal curve at the end of a tangent. Raff (9) argued that a high rate of accidents could be found on roads with a sharp horizontal curve following a long tangent. Two reasons may be suggested for this phenomenon: first, drivers have difficulty in judging the needed reduction in speed after traveling on a long tangent section; second, driver alertness is reduced after a monotonous long section. For both these reasons, therefore, the accident rate increases.

2. Large variations in radii size. Drivers set their speeds to the curvature of the road. A curve of a much smaller than average radius violates their expectation, and therefore the consistency.

3. Inappropriate average radius of curves. A number of studies, among them Raff (9) and Smith et al. (10), showed the relationship of curvature and small radii to high accident rates. As may be expected, the larger the average radius, the less significant are the previous two features.

Three types of models were considered for the evaluation of consistency: first, a mathematical model based on a spectral analysis of the overall alignment; second, a model calculated by using the geometric parameters of the designed road; third, a compound model based on both the spectral components and the geometric parameters. An effort was made to construct models that had a positive relationship with the consistency of the road, that is, the greater the consistency of the highway, the greater the consistency parameter of the model.

The mathematical model selected uses spectral analysis (11), which is often used to describe cyclical physical phenomena, like the oscillations of sea waves or of electrical signals. Spectral analysis was recently used by Uzan et al. (12) to evaluate the roughness of airfield pavements on expansive clay. In that study, the longitudinal elevation profile of the pavement was represented as the superposition of a series of sinusoidal waves. In the highway model, an alignment is described using coordinates x and y in a two-dimensional Cartesian system. It may be assumed that these coordinates are y values in time x; alignments are then processed as time series by means of spectral analysis procedures. Because spectral analysis is used to detect cyclical data patterns, it was hypothesized that this method could be adapted to measure the amount of consistency of a horizontal alignment; that is, to determine whether an alignment consists of a repeating pattern, and is therefore consistent. The spectral model is based on an analysis of the data as a time series and on the transformation of the time series to a sum of geometric functions, using the Fourier transform.

A parameter I_{avg} of the average periodogram (11) is constructed with the mean square value equal to that of the deviation of the road alignment from its average line; therefore, it represents the average distance of the alignment from that line. A high I_{avg} value is obtained both when the average radius is large and when the variance among radii is small; that is, when all radii are large and similar in magnitude.

For the analysis of design consistency, it is possible to divide the roadway population into two major categories based on type of terrain and presence of physical constraints: (a) alignments located in mountainous or hilly terrain, where numerous constraints (e.g., location of bridges and side slopes of hillsides) exist; and (b) alignments on flat terrain with relatively few physical constraints. It may be assumed that in hilly or mountainous terrain (first category), the average distance from the straight line is associated with the average radius. A high I_{avg} value is obtained, therefore, when the average radius is large and all radii are of the same order of magnitude. This, then, can indicate high geometric consistency.

Although for these reasons I_{avg} can serve as a good model for consistency, its value may be rather large. In order to obtain values that are closer to one, the logarithm of I_{avg} is used as the spectral model for $S1$:

$$S1 = \log_{10}(I_{avg}) \tag{1}$$

The relationship between $S1$ and the consistency of various designs analyzed in the next section.

The geometric models that were developed are based on the following measures:

1. L_C, the ratio between the length of curves in a highway section and the total length of the same section. L_C is defined by the expression

$$L_C = \frac{l_C}{l_C + l_T} \tag{2}$$

where

L_C = relative length of curves in a highway section,

l_C = total length of curves (km), and

i_T = total length of tangents (km).

This measure is intended to evaluate the likelihood of the first highway consistency-violating characteristic. Low L_C values indicate high possibility of the existence of curves at the end of tangents, a consistency violation.

2. R_R, the ratio of minimum to maximum radius,

$$R_R = \frac{R_{min}}{R_{max}} \tag{3}$$

where R_{min} is the minimum radius of a highway section in meters and R_{max} is the maximum radius of a highway section in meters. This measure, previously presented by Polus *(7)*, indicates the variance of radii along the highway. It can easily be shown that as this ratio decreases, so does the geometric consistency of the section concerned.

3. R_D, the ratio of the average radius to the minimum radius for the design speed of the road section,

$$R_D = \frac{R_{avg}}{R_{VD}} \tag{4}$$

where R_{avg} is the average radius of a highway section and R_{VD} is the minimum radius for the highway's design speed. This measure gives the relative size of the radii on the highway in relation to the minimum radius for the design speed. As discussed, a small R_D value indicates a large likelihood that the two other measures L_C and R_R will affect consistency. Moreover, a large R_D value suggests that the road has an alignment that can be traveled at higher speed, with greater convenience and lesser work load, and therefore is of better consistency.

Using these measures, five geometric models were developed:

$$G1 = L_C + R_R \tag{5}$$

$$G2 = L_C + R_R + {}^1/_4 R_D \tag{6}$$

$$G3 = L_C + R_R + {}^1/_3 R_D \tag{7}$$

$$G4 = L_C + R_R + {}^1/_2 R_D \tag{8}$$

$$G5 = L_C + R_R + R_D \tag{9}$$

The three measures defined in Equations 2–4 have a direct relationship with consistency, but only L_C and R_R have values ranging from 0 to 1.0; for this reason, these measures appear with a weight of one. Because R_D may have a value greater than 1.0, four models, G2 through G5, were constructed with various weighting factors for R_D.

Each measure of consistency used in the spectral and geometric models presented is sensitive to slightly different highway alignment characteristics. It was posited, therefore, that a compound model would provide a more reliable description of consistency.

The following compound models were introduced:

$$GS1 = S + L_C + R_R + R_D \tag{10}$$

$$GS2 = S + L_C + R_R + {}^1/_2 R_D \tag{11}$$

DEVELOPMENT OF THEORETICAL SAMPLE ROADS

In order to evaluate the various consistency models, 23 sample roads were selected for further analysis from a larger set that was generated to represent a large variety of design configurations. As illustrated in Figure 1, each theoretical road was composed of tangents and curves and constructed in such a manner as to reflect potential design inconsistencies. An effort was made to ensure uniformity in all the parameters not linked to consistency, as follows:

1. The length of all road sections was exactly 8,000 m (26,247 ft).
2. The distance between each horizontal (*X*) coordinate in all the roads was exactly 100 m (328 ft).
3. The design speed for all the roads was 80 km/hr (50 mph).

According to their geometric properties, the sample roads were divided into six groups as follows:

Group No.	Roads in Group	General Description of Road Geometry
1	1, 15, 17, 19	Curves of constant radius
2	6, 7, 8, 11, 15, 20, 21	Curves having a 1,000-m radius
3	1, 2, 5, 6, 7, k6, k8	Curves having a 500-m radius
4	2, 5, 6, 8, 16	Curves following a long tangent
5	4, 9, 12, 13, 14	Alternating curves and tangents
6	3, 10, 22, 23	Constant radii with varying tangents

The geometric and spectral characteristics of all 23 sample roads are presented by group in Table 1.

The sample roads were rated according to their expected consistency, based on the general recommendations stated earlier (i.e., driver expectancy and driver workload) and the following specific principles:

1. For roads consisting of curves with equal radii only (Group 1), the greater the radius of the curve, the greater is the consistency; for example, the consistency of Road 17 is greater than the consistency of Road 19.
2. For roads with different curves (Groups 2 and 3), the consistency is greater when the similarity among the curves is greater; for example, the consistency of Road 11 is greater than the consistency of Road 7. The consistency is greatest when all the radii are identical, as in Group 1.
3. Tangents situated between curves (Groups 5 and 6) decrease the consistency; for example, the consistency of Road 1 is greater than the consistency of Road 10.
4. When the road consists of curves and tangents, the longer the tangents, the less is the consistency; for example, the consistency of Road 22 is greater than the consistency of Road 23.
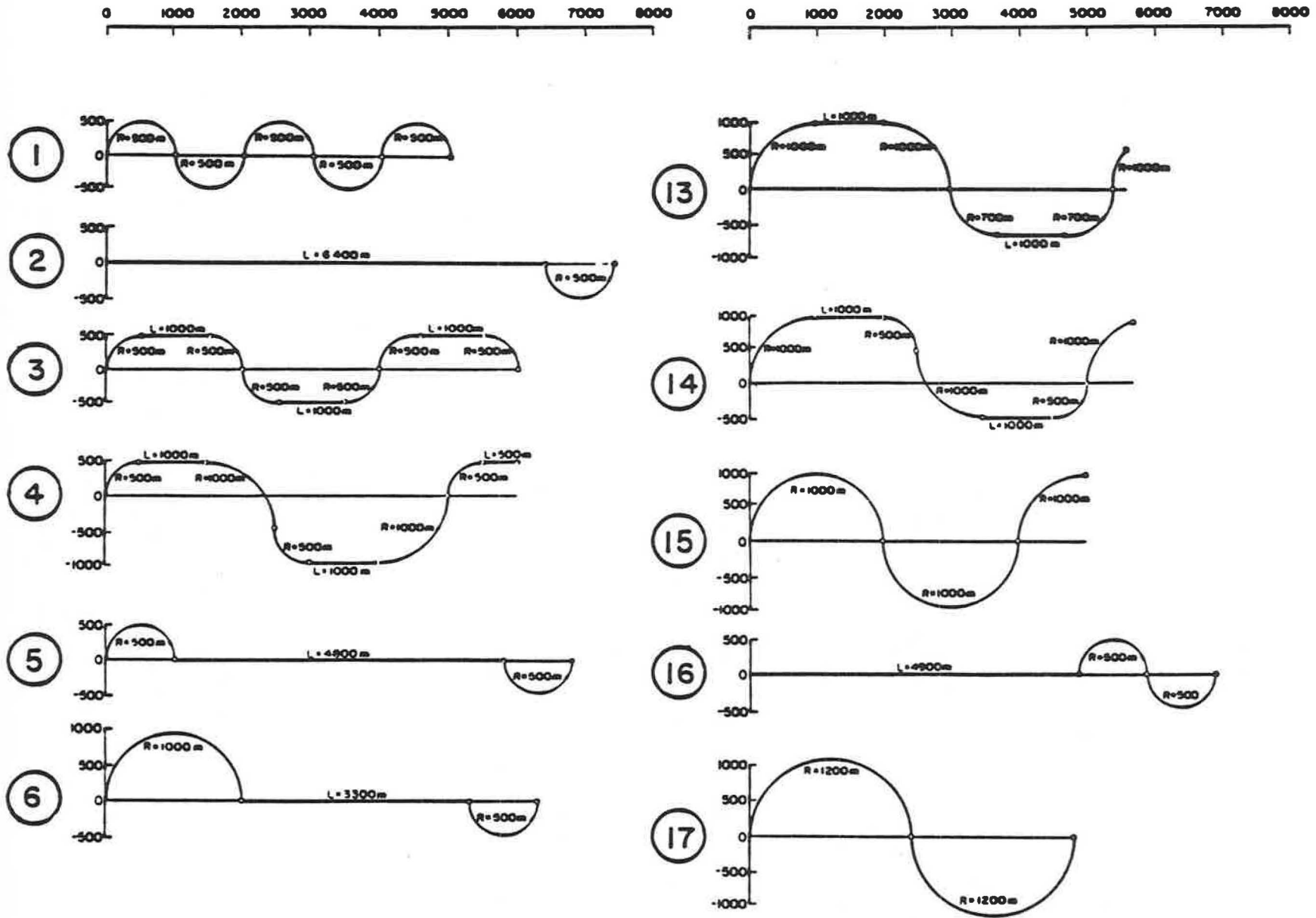
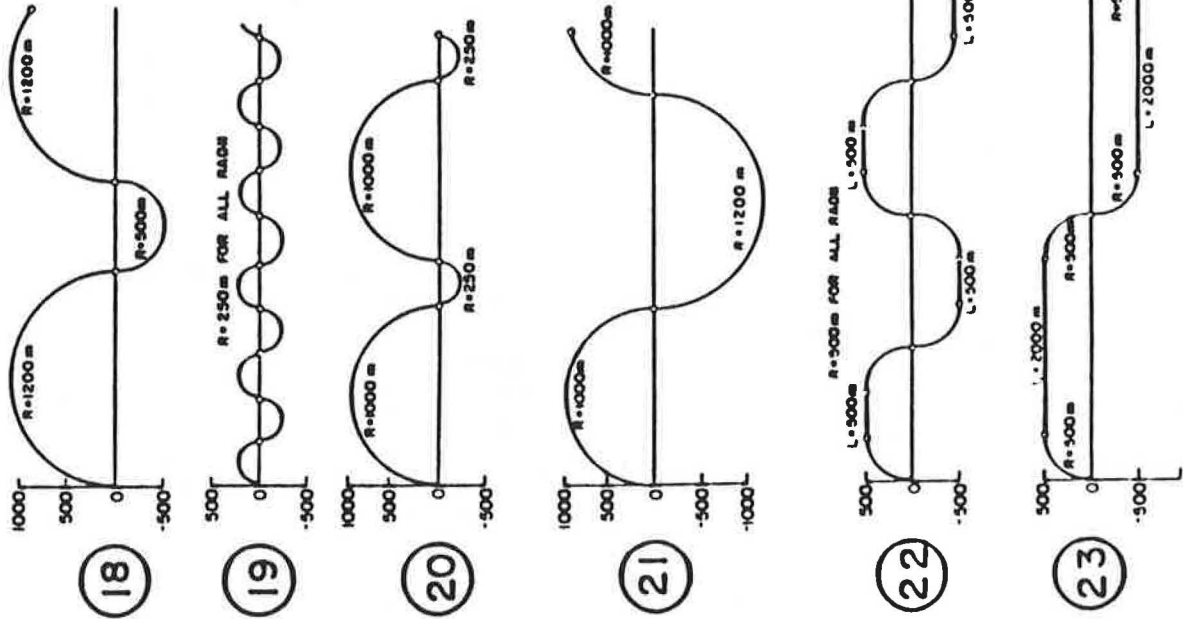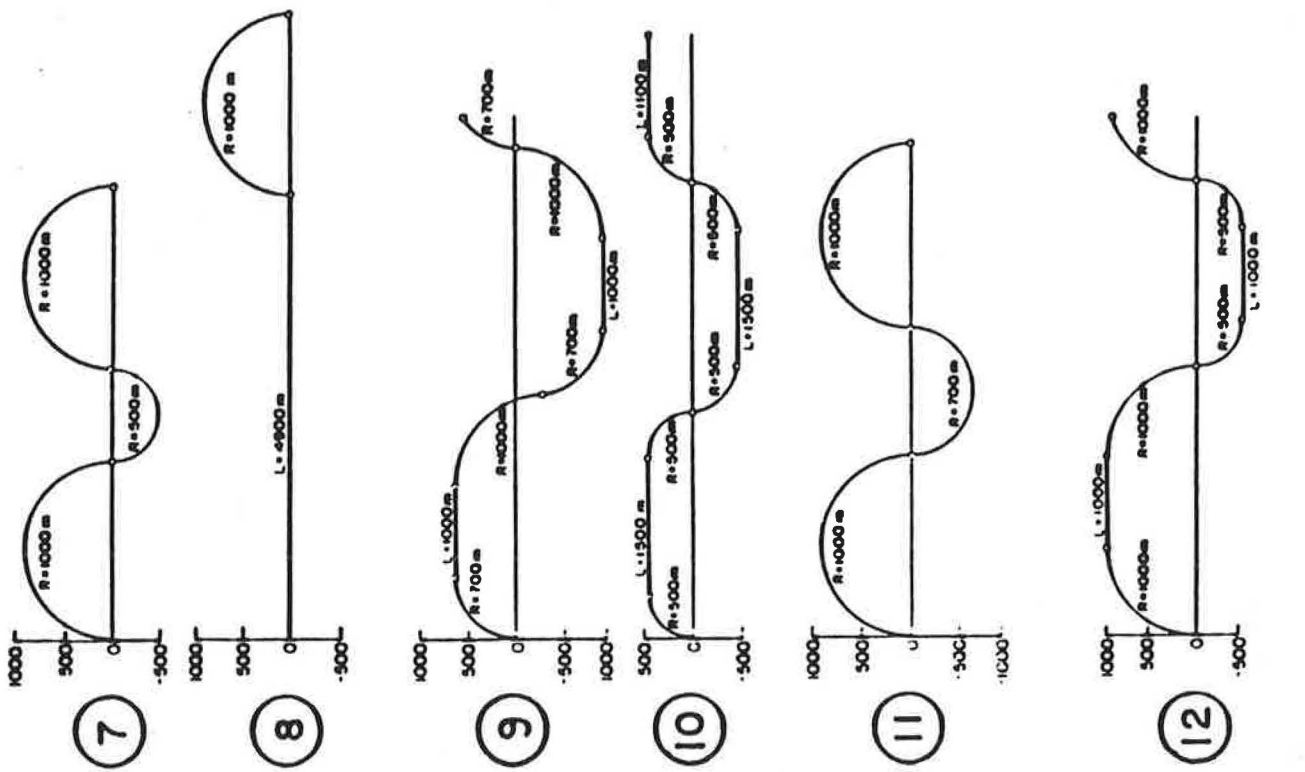FIGURE 1   The sample roads, each with different design configuration.

FIGURE 1 *continued.*

TABLE 1   SPECTRAL AND GEOMETRIC PARAMETERS OF
SAMPLE THEORETICAL ROADS

INFORMATION			SPECTRAL AND GEOMETRIC PARAMETERS				
1	2	3	4	5	6	7	8
ROAD GROUP	ROAD NUMBER	CONSISTENCY RATING	AVERAGE I	LENGTH RATIO	RADIUS RATIO	AVERAGE RADIUS	RATIO TO DESIGN R.
1	19	1.0	755	1.00	1.00	250	1.00
	1	2.0	3,063	1.00	1.00	500	2.00
	15	3.0	12,465	1.00	1.00	1,000	4.00
	17	4.0	17,780	1.00	1.00	1,200	4.30
2	8	1.0	2,802	0.39	1.00	1,000	4.00
	6	2.0	3,880	0.59	0.50	750	3.00
	20	3.0	3,788	1.00	0.25	625	2.50
	7	4.0	5,265	1.00	0.50	833	3.33
	11	5.0	7,472	1.00	0.70	900	3.60
	21	6.0	14,984	1.00	0.83	1,100	4.40
	15	7.0	12,465	1.00	1.00	1,000	4.00
3	2	1.0	383	0.20	1.00	500	2.00
	16	2.0	916	0.39	1.00	500	2.00
	5	3.0	942	0.39	1.00	500	2.00
	6	4.0	3,880	0.59	0.50	750	3.00
	18	5.0	6,618	1.00	0.42	967	3.87
	7	6.0	5,265	1.00	0.50	833	3.33
	1	7.0	3,063	1.00	1.00	500	2.00
4	2	1.0	383	0.20	1.00	500	2.00
	16	2.0	916	0.39	1.00	500	2.00
	5	3.0	942	0.39	1.00	500	2.00
	8	4.0	2,802	0.39	1.00	1,000	4.00
	6	5.0	3,380	0.59	0.50	750	3.00
5	12	1.0	7,770	0.75	0.50	750	3.00
	14	2.0	8,030	0.75	0.50	750	3.00
	4	3.0	8,550	0.75	0.50	750	3.00
	13	4.0	10,609	0.75	0.70	850	3.40
	9	5.0	10,610	0.75	0.70	850	3.40
6	22	1.0	3,741	0.66	1.00	500	2.00
	3	2.0	3,554	0.63	1.00	500	2.00
	10	3.0	4,007	0.49	1.00	500	2.00
	23	4.0	4,171	0.39	1.00	500	2.00

Legend

Road number = number of road corresponding to Figure 1.
Average I = I_{AV}.
Length Ratio = L_C as defined in Equation (2).
Radius Ratio = R_D as defined in Equation (3).
Ratio to Design R = R_D as defined in Equation (4).

5. The consistency is lower when curves appear in pairs of equal radii, rather than in successively alternating radii; for example, the consistency of Road 14 is greater than the consistency of Road 12.

Because of the wide differences among the characteristics of Groups 1–6, no attempt was made to determine the relative consistency of all 23 roads. Instead, the roads within each group were simply presented in an ascending order of consistency as presented in Column 3 of Table 1. This order was established according to the guidelines and principles discussed.

The various models that were developed to evaluate road consistency were applied to the 23 theoretical roads. The resulting consistency values are presented in Table 2. Observation alone can tell that some correlation exists between Column 3 (the logical order) and the columns representing the various model ratings. At least, all the model ratings in Table 2 have desirably small values.

The level of correlation between all models and the logical order was calculated next to evaluate the suitability of these models for consistency analysis and to determine the best model.

CONSISTENCY ANALYSIS

To evaluate the various consistency models, a number of comparison tests were performed: (a) between ratings based on spectral models and those based on developed principles (logical rating); (b) between ratings based on geometric models and logical ratings; (c) between ratings based on compound (spectral-geometric) models and logical ratings. The correlation between ratings obtained by various models [e.g., logical rating $R(X_i)$ versus spectral rating $R(Y_i)$] was assessed with the Spearman rho test (13). This test is based on the statistic ρ, calculated as follows:

$$\rho = 1 - 6 \sum_{i=1}^{n} [R(X_i) - R(Y_i)]^2 / n(n^2 - 1)$$
$$= 1 - 6T/n(n^2 - 1) \qquad (12)$$

T is defined as

$$T = \sum_{i=1}^{n} [R(X_i) - R(Y_i)]^2 \qquad (13)$$

where

X_i, Y_i = values of two consistency models,
$R(X_i)$ = rating of roads given by first model,
$R(Y_i)$ = rating of roads given by second model, and
n = sample size.

The following hypotheses were tested:

H_0: the values of X_i and Y_i are mutually independent.
H_1: there is a tendency for the larger values of X and Y to be paired together.

Summary statistics of the three correlation analyses are presented in Table 3 for spectral versus logical models, geometric versus logical models, and compund versus logical models. For each of the six groups liste din Tables 1 and 2, the sum of the squares of the rank differences T was calculated. Using Equations 12 and 13, the corresponding ρ was also calculated. In some cases, the value was negative, thus showing that the two models had no correlation at all. With the use of the table of quantiles of the Spearman test statistic (13), the value of the significance level $(1 - \alpha)$ was determined on the basis of the value of ρ.

TABLE 2   RESULTS OF THE VARIOUS CONSISTENCY MODELS

1	2	3	4	5	6	7	8	9	10	11
ROAD GROUP	ROAD NUMBER	CONSISTENCY RATING	S1	G1	G2	G3	G4	G5	GS1	GS2
1	19	1.0	2.88	2.00	2.25	2.33	2.50	3.00	5.88	5.38
	1	2.0	3.49	2.00	2.50	2.67	3.00	4.00	7.49	6.49
	15	3.0	4.10	2.00	3.00	3.33	4.00	6.00	10.10	8.10
	17	4.0	4.25	2.00	3.20	3.60	4.40	6.80	11.05	8.65
2	8	1.0	3.45	1.39	2.39	2.72	3.39	5.39	8.84	6.84
	6	2.0	3.59	1.09	1.84	2.09	2.59	4.09	7.68	6.18
	20	3.0	3.58	1.25	1.88	2.08	2.50	3.75	7.33	6.08
	7	4.0	3.72	1.50	2.33	2.61	3.17	4.83	8.55	6.89
	11	5.0	3.87	1.70	2.60	2.90	3.50	5.30	9.17	7.37
	21	6.0	4.18	1.83	2.93	3.30	4.03	6.23	10.41	8.21
	15	7.0	4.10	2.00	3.00	3.33	4.00	6.00	10.10	8.10
3	2	1.0	2.58	1.20	1.70	1.87	2.20	3.20	5.78	4.78
	16	2.0	2.96	1.39	1.89	2.06	2.39	3.39	6.35	5.35
	5	3.0	2.97	1.39	1.89	2.06	2.39	3.39	6.36	5.36
	6	4.0	3.59	1.09	1.84	2.09	2.59	4.09	7.68	6.18
	18	5.0	3.82	1.42	2.39	2.71	3.35	5.29	9.11	7.17
	7	6.0	3.72	1.50	2.33	2.61	3.17	4.83	8.55	6.89
	1	7.0	3.49	2.00	2.50	2.67	3.00	4.00	7.49	6.49
4	2	1.0	2.58	1.20	1.70	1.87	2.20	3.20	5.78	4.78
	16	2.0	2.96	1.39	1.89	2.06	2.39	3.39	6.35	5.35
	5	3.0	2.97	1.39	1.89	2.06	2.39	3.39	6.36	5.36
	8	4.0	3.45	1.39	2.39	2.72	3.39	5.39	8.84	6.84
	6	5.0	3.59	1.09	1.84	2.09	2.59	4.09	7.68	6.18
5	12	1.0	3.89	1.25	2.00	2.25	2.75	4.25	8.14	6.64
	14	2.0	3.90	1.25	2.00	2.25	2.75	4.25	8.15	6.65
	4	3.0	3.93	1.25	2.00	2.25	2.75	4.25	8.18	6.68
	13	4.0	4.03	1.45	2.30	2.58	3.15	4.85	8.88	7.18
	9	5.0	4.03	1.45	2.30	2.58	3.15	4.85	8.88	7.18
6	22	1.0	3.57	1.66	2.16	2.33	2.66	3.66	7.23	6.23
	3	2.0	3.55	1.63	2.13	2.30	2.63	3.63	7.18	6.18
	10	3.0	3.60	1.49	1.99	2.16	2.49	3.49	7.09	6.09
	23	4.0	3.62	1.38	1.88	2.05	2.38	3.38	7.00	6.00

Legend

Column 1 - 3, as defined in Table 2.
Column 4 = Spectral model as defined in Equation (1)
Column 5 - 9 = Geometric models as defined in Equations (5)-(9).
Columns 10 - 11 = Compound model as defined in Equations (10)-(11).

In order to better assess the various models, the average value of $(1 - \alpha)$ over all groups was calculated. The result, presented in Table 3, does not have a direct statistical significance, but it can show clearly which models have a better correlation with the logical rating. In addition, the number of road groups for which the models failed to correlate with the logical rating is shown. Based on these tests and analyses, several observations were made:

1. The $S1$ spectral model with a good $(1 - \alpha)$ value was the only model that had a high correlation with the logical rating for all road groups.

2. Of the geometric models, Models $G1$ and $G2$ had low correlations for Groups 3 and 2, respectively, and therefore were immediately rejected.

3. $G3$, $G4$, and $G5$ geometric models failed only for Group 6; all showed similar average values of $(1 - \alpha)$. Of these

TABLE 3 SUMMARY STATISTICS OF CORRELATIONS BETWEEN MODEL RATINGS

ROAD GROUP		S1/CR	G1/CR	G2/CR	G3/CR	G4/CR	G5/CR	GS1/CR	GS2/CR
1	T	0.00	5.00	0.00	0.00	0.00	0.00	0.00	0.00
	RHO	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00
	1-ALPHA	95.00	N.C.**	95.00	95.00	95.00	95.00	95.00	95.00
2	T	4.00	6.00	12.00	14.00	16.00	24.00	16.00	10.00
	RHO	0.93	0.89	0.79	0.75	0.71	0.57	0.71	0.82
	1-ALPHA	99.50	99.50	97.50	97.50	95.00	90.00	95.00	97.50
3	T	14.00	12.50	8.50	6.50	8.50	14.50	14.00	8.00
	RHO	0.75	0.78	0.85	0.88	0.85	0.74	0.75	0.86
	1-ALPHA	97.50	97.50	99.00	99.50	99.00	97.50	97.50	99.00
4	T	0.00	22.00	12.50	2.50	2.00	2.50	2.00	2.00
	RHO	1.00	-0.10	0.38	0.88	0.90	0.88	0.90	0.90
	1-ALPHA	99.00	N.C.	N.C.	95.00	99.00	95.00	99.00	99.00
5	T	0.00	2.50	2.50	2.50	2.50	2.50	0.50	0.50
	RHO	1.00	0.88	0.88	0.88	0.88	0.88	0.98	0.98
	1-ALPHA	99.00	95.00	95.00	95.00	95.00	95.00	99.00	99.00
6	T	2.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
	RHO	0.80	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
	1-ALPHA	95.00	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.
AVR. (1-ALPHA)		97.50	97.30	96.60	96.40	96.60	94.50	97.10	97.90
No. of FAILURES		0.00	3.00	2.00	1.00	1.00	1.00	1.00	1.00

* Rho and T are calculated from eqs. (12) and (13), respectively, for correlation tests of all models vs. the consistency rating (note symbol definitions in Table 3).

** N.C. - Ho cannot be rejected; no correlation was found.

models, G5 was the only one that did not have any preselected weighting parameters; therefore, it appeared to be preferable to the others.

4. Both GS1 and GS2 compound models showed a similar ability to evaluate consistency. GS1 is based on the G5 geometric model, and therefore may be preferable to GS2.

The conclusion based on this correlation analysis is that the three models S1, G5, and GS1 may be adopted for describing consistency of highway alignment.

The spectral model seems best suited for the task of road consistency analysis, but it has one drawback: a possible lack of computing facilities and programs needed for the calculation. Two tasks must be completed when evaluating the spectral model: (a) Conversion of the highway alignment into a set of Cartesian coordinates, which may prove to be somewhat complicated, particularly because alignments are not always readily converted (e.g., for spirals); and (b) Use of the special computer program such as SAS (14), which may not be available to all road engineers.

The geometric models are much easier to calculate because the parameters needed for the calculation of their measures are readily available from the overall highway alignments. Because consistency evaluation is similar with the geometric and spectral models, use of the former model (G5) would be advantageous whenever use of the spectral model S1 for evaluating road design consistency is not possible.

In order to test use of the geometric model further, correlation between rankings based on models G5 and S1 was evaluated for all 23 roads in the sample. The result of this rank correlation analysis is presented in Table 4, as is the correlation between geometric model G5 and compound model GS1. Both the S1 and GS1 ratings are highly correlated with the ratings of the G5 geometric model. It may be concluded, therefore, that the geometric model can be used to evaluate highway consistency whenever it is not possible or convenient to use the spectral or compound models. Furthermore, because the proper use of the spectral model for highways with long tangent sections is not established, it may be inferior to the geometric models in level terrain.

TABLE 4 COMPARISON OF RATINGS GIVEN BY A GEOMETRIC MODEL (G5) AND A SPECTRAL MODEL (S1)

ROAD NUMBER	G5	RATING G5	S1	RATING S1	GS1	RATING GS1	G5/S1	G5/GS1
1	4.00	10.0	3.49	6.0	7.49	10.0	16.00	0.00
2	3.20	2.0	2.58	1.0	5.78	1.0	1.00	1.00
3	3.63	7.0	3.55	7.0	7.18	7.0	0.00	0.00
4	4.25	13.0	3.93	18.0	8.18	14.0	25.00	1.00
5	3.39	4.5	2.97	4.0	6.36	4.0	0.25	0.25
6	4.09	11.0	3.59	10.0	7.68	11.0	1.00	0.00
7	4.83	15.0	3.72	13.0	8.55	15.0	4.00	0.00
8	5.39	20.0	3.45	5.0	8.84	16.0	225.00	16.00
9	4.85	16.5	4.03	20.0	8.88	18.0	12.25	2.25
10	3.49	6.0	3.60	11.0	7.09	6.0	25.00	0.00
11	5.30	19.0	3.87	15.0	9.17	20.0	16.00	1.00
12	4.25	13.0	3.89	16.0	8.14	12.0	9.00	1.00
13	4.85	16.5	4.03	19.0	8.88	17.0	6.25	0.25
14	4.25	13.0	3.90	17.0	8.15	13.0	16.00	0.00
15	6.00	21.0	4.10	21.0	10.10	21.0	0.00	0.00
16	3.39	4.5	2.96	3.0	6.35	3.0	2.25	2.25
17	6.80	23.0	4.25	23.0	11.05	23.0	0.00	0.00
18	5.29	18.0	3.82	14.0	9.11	19.0	16.00	1.00
19	3.00	1.0	2.88	2.0	5.88	2.0	1.00	1.00
20	3.75	9.0	3.58	9.0	7.33	9.0	0.00	0.00
21	6.23	22.0	4.18	22.0	10.41	22.0	0.00	0.00
22	3.66	8.0	3.57	8.0	7.23	8.0	0.00	0.00
23	3.38	3.0	3.62	12.0	7.00	5.0	81.00	4.00
						T	457.00	25.00
						RHO	0.77	0.99
						1 - ALPHA	99.30	99.30

CONCLUSIONS

In this paper, several models for evaluating highway alignment consistency were analyzed. The models developed were divided into three categories: geometric models, based on overall measures of alignment such as the ratio between minimum and maximum radii or relative length of curves; spectral models, based on time series spectral analysis of the highway alignments; and compound models, consisting of both spectral and geometric parameters.

The validity of all three types of models was established from an analysis of a sample of 23 theoretical roads selected from those composed for this study and divided into six groups. The following major conclusions were deduced:

1. The spectral model is valid for describing the amount of consistency in highway design; this model has the highest correlation with logical rating established from previous research and engineering judgment.

2. The geometric model may also describe the consistency of a given design; it may be adopted whenever computing facilities required by the spectral model are not readily available.

3. The compound model may also be adopted for the purpose of evaluating the amount of consistency of an alignment.

Assuming that the spectral and geometric models are equally accessible to planner or decision maker, the use of the spectral model is suggested for roads with curve and linear alignments, such as roads located in hilly or mountainous terrains. The geometric model may be adopted for roads on level terrains, where long tangents are typical.

Further research (such as cross-spectral analysis) is suggested on measures of consistency that equally represent both the horizontal and the vertical alignment and on the relationship between highway consistency and the accident history of real roads.

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