Effect of Traffic and Geometric Measures on Highway Average Running Speed

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ABSTRACT

The objective of this study was to deal with two-lane rural highways and the effect of their geometry on flow characteristics. Several design measures that represent road geometrics and traffic were developed. The layout measures that were adopted as independent variables for the suggested models represented the horizontal and vertical alignments; they were the average curvature, average hilliness, and net gradient. The traffic parameters considered were the volume, density, and percentage of trunks, and directional distribution of traffic. Based on tests of several alternative functional forms, it is demonstrated that multiple linear-regression models may be used for prediction of the average running speed on two-lane rural highways. It is also demonstrated that either volume or density can serve as independent traffic parameters along with the percentage of trucks and directional distribution of traffic. The calibration of results of the models is presented and evaluated. Calculations of two-way rural highway capacity trends for level, hilly, and mountainous terrains indicate that the values obtained are less sensitive to percentage of trucks than are currently recognized capacity values. The suggested capacities are also higher than the current values, particularly for the upper percentage range of trucks.

The flow of traffic on two-lane rural highways is adversely affected by unfavorable geometric and topographic conditions, which results in nonuniform performance capabilities of vehicles and an overall reduction in traffic speed. These performance differences, particularly between loaded trucks and passenger vehicles, are most pronounced on grades and curved highways. Their influence on flow is twofold: first, the reduction in average running speed and capacity is significant; and second, the likelihood of traffic instabilities, accident potential, and delays is increased.

Considerable amounts of money are spent yearly on the construction of new two-lane rural highways and the improvement of existing ones. However, there is considerable lack of knowledge of the relationship between overall geometric measures and traffic-flow characteristics on two-lane rural roads. The speed/flow relationships and level-of-service parameters normally used for rural highways are those derived from the 1965 Highway Capacity Manual (HCM) (1), which makes no reference to specific geometric parameters.

A primary and a secondary objective were established for this study. The primary objective was to analyze speed characteristics of vehicles under various geometric and topographic conditions and to investigate the relationship of average running speeds to observed flows, densities, percentage of trucks, directional distribution of traffic, and road layout characteristics. The secondary objective was to derive average capacity trends for various horizontal and vertical highway layouts.

Several significant reports on rural highway speed/flow relationships, as related to highway geometrics, were the product of recent research. In England, Duncan (2) performed regression analysis and used several geometric parameters to find that the regressions explained about three-quarters of the between-sites variance of speed. He further found a marked flow effect, explained by differences in traffic behavior between the busy roads and the quieter ones, and generally pronounced effects of road hilliness and windingness. Farthing (3), also in England, performed similar research, although he concentrated on roads with steep gradients. He found that where there was a high proportion of heavy vehicles on steep gradients, regardless of type of road, speeds tended to be lower than those calculated by Duncan.

Both Farthing and Duncan found that the speed/flow relationship is a linear two-regime model. For low volumes, up to about 200 to 300 vehicles per hour per standard lane (depending on percentage of trucks, curvature, and hilliness), speed is not influenced by volume. For higher volumes, however, speed decreases linearly as volume increases.

Wahlgren, who conducted speed observations in Finland (4), considered several independent variables. Average curvature proved to be the most significant geometric feature in predicting average speed.

In India (5) a recent study evaluated the effect of horizontal curvature and sight distance on spot speeds of vehicles on curves of two-lane rural roads. Several regression models were calibrated and presented an increase of speed with an increase in curve radius and sight distance.

In North America, Edie (6) was the first to propose the idea of two-regime traffic-flow models. Other researchers also examined the validity of the non-congested-flow regime and the congested-flow regime; among them were Drake et al. (7) and Easa (8).

A recent Canadian study (9), which investigated capacities for two-lane rural highways, found that these capacities can far exceed the HCM limit of 2,000 vehicles per hour if the directional flows are balanced. Employing an alternative structure for describing ultimate capacities, based on single-lane analysis, the study revealed capacity values greater than 3,000 vehicles per hour. Research conducted in California (10) indicated unsatisfactory agreement between HCM truck equivalency factors for two-lane roads and factors obtained by simulation runs. This work concluded that the Manual may overestimate the adverse effects of trucks on steeper grades.

To date, the level of service is determined primarily by a volume-to-capacity ratio, although use of operating speed is suggested as well. Unfortunately, engineers often have to estimate this measure because an exact determination is impossible; level of service, therefore, is currently very much a one-dimensional concept.

DEVELOPMENT OF MEASURES AND DATA COLLECTION

The first step of this study was to develop design measures that represent road geometrics and layout and that may be directly related to average running speed. Several measures were considered. The first was a horizontal one--average curvature--which was used in the past (2,11,12). It is given as

$$\alpha = \sum_{i=1}^{n-1} \alpha_i/L \tag{1}$$

where

α = average curvature of a section (degree/km),
L = length of section (km),
α_i = external horizontal angle between i and i + 1 tangents (degree), and
n = number of tangents.

The second measure adopted represented the vertical alignment. This was the average hilliness, which was also previously used (2,12). It is given as

$$\beta = \sum_{i=1}^{m} \beta_i/L \tag{2}$$

where

β = average hilliness of a section (m/km),
L = length of section (km),
β_i = vertical distance between ith crest and following (i + 1)th sag or vice versa (m), and
m = number of successive crests and sags.

The effect of increased β may be an increase in speed variability and some reduction in average speed, particularly for heavy vehicles and low-powered passenger cars. Greater gradients on hilly and mountainous terrains, therefore, are likely to be associated with a reduction in average running speeds as well as some travel inconvenience.

Another geometric measure was the net gradient (γ), which was defined as

$$\gamma = h/L \tag{3}$$

where h is the vertical distance between the initial and final point of each section, and L is the length of the section.

These three simple measures of alignment were adopted because they are easier to obtain for existing highways and to estimate for new roads than are more complicated measures, such as sight-distance proportions and average highway speed. The latter measures, furthermore, were thought to be less likely to show significant effects unless the sample of roads could be significantly increased. One potential shortcoming of the suggested measures, however, is that they represent an average value and, as such, are not sensitive to the variability between highways with similar average values.

Several primary measures of traffic were considered for this study. The first was the hourly one-way traffic volume (Q) on the two-lane rural roads under investigation. Density (D) in vehicles per kilometer per lane was the second measure; it was derived independently of the traffic volume, although it was found later to be highly correlated with volume. Traffic composition ($\int$)--namely, the proportion of heavy vehicles expressed as a percentage of total flow--was a third measure, as it was considered a major factor influencing traffic flow, particularly on two-lane rural roads. Another measure was the directional distribution of traffic (ε). Finally, the average running speeds over a specified section of highways were measured, this being the summation of distances divided by the summation of running time.

The geometric and traffic data were collected on 16 two-lane, two-way highway sections in northern Israel. All sections varied in length, being between 1.0 and 3.4 km, and were at least 500 m removed from any intersection to avoid speed-change effects. The geometric data are given in Table 1: section length, average curvature, and average hilliness. The one-way flow data are illustrated in Figure 1. The data were collected with synchronized, timed videotape equipment at both ends of each section, so that the average running speed, volume, density, and percentage of trucks could be derived for successive intervals of 2.5 min. Each site was recorded for 90 to 120 min, and several hundred vehicles were observed at each. The highway geometrics were derived from detailed road maps of the Public Works Department of the Ministry of Housing. The speed limit on all highway sections in this study is 80 km/h. Because no other regulatory controls were located at the study sites, the speed limit was not considered an independent variable, and its effect on the average running speed was not evaluated; instead, more direct geometric measures were considered. The

TABLE 1 List of Sites and Geometric Data

Site Number	Site Name	Section Length (km)	Average Curvature (°/km)	Average Hilliness (m/km)	Net Gradient (m/km)	Lane Width (m)
1	Kiryat Ata	3.0	23.6	6.7	6.1	3.65
2	Yagur	2.2	32.9	0.0	0.0	3.65
3	Yokneam 1	2.0	4.9	7.5	5.7	3.60
4	Nazareth 1	2.2	47.8	16.3	16.3	3.65
5	Yokneam 2	1.3	11.3	10.4	2.9	3.60
6	Yokneam 3	3.4	7.3	8.4	4.4	3.60
7	Achihud	1.9	46.4	35.0	12.1	3.50
8	Sargel 1	2.0	0.0	1.0	0.0	3.50
9	Afula	2.0	0.0	14.1	11.9	3.50
10	Bat Shlomo 1	2.0	47.2	37.5	37.4	3.65
11	Sargel 2	1.0	0.0	0.0	0.0	3.50
12	Beit HaEmek	1.0	85.0	42.0	4.7	3.00
13	Beit Shean	1.4	14.5	23.4	21.2	3.50
14	Yagur 2	1.2	30.0	2.0	0.0	3.60
15	Bat Shlomo 2	2.1	30.8	29.0	28.7	3.65
16	Nazareth 2	2.0	0.0	14.1	14.1	3.65

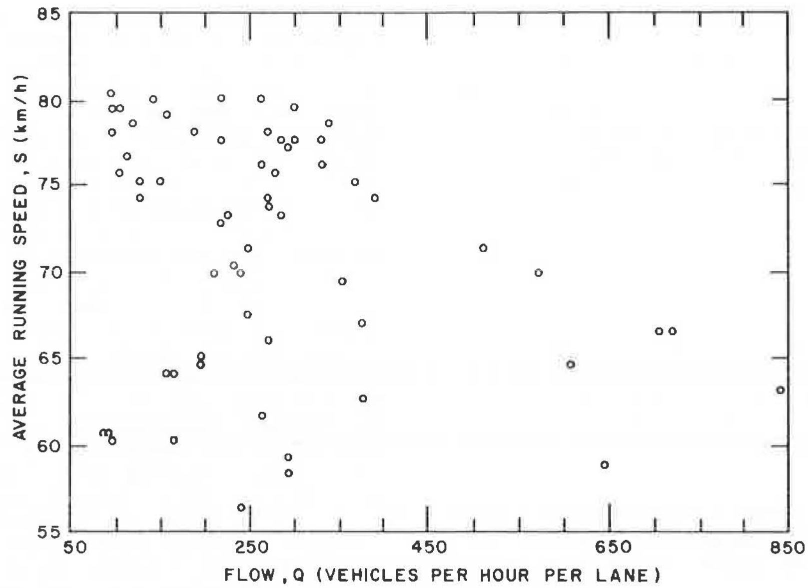

FIGURE 1 Observed average highway speed versus one-lane flow.

matrices, which included all data for all sites, were later encoded and stored in the main computer at Technion--Israel Institute of Technology for further analysis by using the Statistical Package for the Social Sciences (SPSS) program. The details of the data-collection process are discussed in a Transportation Research Institute report (13).

The correlation matrix between the parameters of the geometric and flow data is presented in Table 2, and it can be observed that most correlation coefficients are low. However, the correlation coefficient between the α and β parameters was found to be relatively high (0.785), which suggests that these two parameters may actually measure a combined geometric effect. This effect may be explained by hypothesizing that the horizontal alignment is actually in some proportion to the vertical alignment; for example, severe constraints in one alignment will naturally cause similar conditions in the other.

ANALYSIS OF DATA

The immediate purpose of the data analysis was to establish the effect of road layouts and flow on average running speed and to investigate the use of these effects in determining a level of service. The importance of the length of the sampling period was extensively investigated and discussed by Wright (14). In the present study, a 15-min base was chosen for averaging speeds and flows; this choice was made to extend the range of flows covered and at the same time to minimize the dangers in inferring whole-hour relations from short-period data.

Following is a discussion of several regression models based on observations of the relationships between the average running speed and a set of independent variables expected to explain the observed variability. The average curvature (α), average hilliness (β), and combined two-way flow (Q) each had a moderate negative correlation with average running speed (S). The effect of the percentage of trucks (ʃ) was also investigated, and it was concluded that a strong definite trend cannot be established. The effect of road width on average running speed was insignificant.

Following the initial analysis of the data, observation of graphical trends, and further investi-

TABLE 2 Correlation Coefficients of Geometric and Flow Data

	S	α	β	γ	ʃ	Q
S	1.000	0.584	0.537	0.220	0.198	-0.271
α		1.000	0.785	-0.232	0.048	-0.347
β			1.000	-0.644	0.119	-0.501
γ				1.000	0.057	0.163
ʃ					1.000	-0.207
Q						1.000

gation of other model forms, the general form of the regression model was established. Its formulation is given as

$$S = a_1 - a_2(\alpha) - a_3(\beta) - a_4(\gamma) - a_5(\int) - a_6(\epsilon) - a_7(Q) \quad (4)$$

where a_{1-7} are the regression coefficients.

The calibration results using the stepwise technique gave the following results, in which the variables are presented in order of their contribution to the explanation of speed variability (note that F values are in parentheses):

$$S = \underset{}{88.714} - \underset{(6.71)}{0.094.\alpha} - \underset{(12.18)}{0.282.\beta} - \underset{(4.03)}{0.069.\gamma} - \underset{(1.23)}{0.022.\int} - \underset{(2.89)}{3.981.\epsilon} - \underset{(56.47)}{0.270Q} \quad (5)$$

$r = 0.799$

The F values and the correlation coefficient (r) are defined in the statistical literature (15).

It is a widely held view that the speed/flow relationship is a closed parabola that ends up back at zero, having passed through capacity on the way. This study indicates a lack of curvature in the graph of speed against flow. It is believed that the lack of curvature is because the speed observations were of average running speeds and that the flow was counted and averaged for a relatively long period. This finding led to calibration of the speed model with data that fit the upper part of the normally assumed curved line, which is mainly calibrated by using spot speeds and short-period counts.

Similar regression analysis was done on the relationships between speed, density, and the geometric parameters. The following model was obtained for a prediction of average running speed:

$$S = 86.844 - \underset{(2.99)}{0.040.\alpha} - \underset{(114.80)}{0.399.\beta} - \underset{(12.64)}{0.198.\int} - \underset{(503.07)}{1.861.D} \quad (6)$$

$r = 0.798$

where D is the density in vehicles per kilometer.

Note the large influence of density on speed, a finding that has been documented many times in the past. Also, the insignificance of the α parameter at the 5 percent significance level is explained most probably by the presence of β in the same prediction model.

Further investigation of the graphical plots of data and correlation matrix lead to the calibration of a refined version of the model for a prediction of average running speed. This version is presented in Equation 7, in which all the insignificant variables (at the 5 percent significance level) have been excluded:

$$S = 85.510 - \underset{(293.5)}{0.0110.\beta^2} - \underset{(29.3)}{0.110.\int} - \underset{(532.3)}{1.761.D} \quad (7)$$

$r = 0.809$

Observation of Equation 7 indicates that the geometric measure used for speed prediction is the average hilliness, and the horizontal measure is not used at all in this model. However, as previously suggested, each of these two parameters may actually measure a combined geometric effect. Nevertheless, there are some cases where this correlation is not obvious; for instance, on flat terrain where the road alignment is constrained by small towns, rivers, and so forth. When considering such flat alignments, another model should be employed that uses the horizontal measure and excludes the vertical alignment measure:

$$S = 84.47 - \underset{(94.9)}{0.16\alpha} - \underset{(18.9)}{0.11.\int} - \underset{(324.4)}{1.68.D} \quad (8)$$

$r = 0.720$

Further investigation of the data indicates that the speed/flow relationship appears to behave somewhat differently in the low-flow range than in the moderate to high ranges: at low flows, speeds are not affected by an increase in flows; in dense traffic though, an increase in flow results in a decrease in speeds.

Based on tests of several alternative functional forms and visual observation of the speed/flow data, it was decided to calibrate a two-regime model for flows that are equal to or less than 200 vehicles per hour (one way) and for flows greater than 200 vehicles per hour. A recent Indian study (5) also analyzed free speeds on sections where the volume was less than 200 vehicles per hour. The best possible models that were obtained in terms of their correlation coefficient and other statistical parameters are presented as follows:

$$S = 90.485 - \underset{(2.52)}{0.010.\alpha} - \underset{(40.73)}{0.591.\beta} - \underset{(9.35)}{0.029.\gamma} - \underset{(5.47)}{0.231.\int} \quad Q \leq 200 \text{ vph} \quad (9)$$

$r = 0.900$

$$S = 87.409 - \underset{(4.30)}{0.137.\alpha} - \underset{(8.20)}{0.191.\beta} - \underset{(3.69)}{0.072.\gamma} - \underset{(2.40)}{2.746.\epsilon} - \underset{(40.72)}{0.027.Q}$$

$$Q > 200 \text{ vph} \quad (10)$$

$r = 0.774$

When the one-regime model presented in Equation 5 was compared with the two-regime models (Equations 9 and 10), it did not appear to be substantially different. Thus, although the visual appearance of the data confirms the view that a two-regime model follows the data better, the one-regime model is likely to be sufficiently precise for practical applications where the model is to be used, and it will certainly be easier to use. It is interesting to note that the percentage of trucks appears as a significant (at the 5 percent level) independent variable in Equation 9, where the volume is low. One possible explanation for this is that passenger-car drivers, whose preferred speed is higher than average at low-volume situations, are forced along at lower speed as the proportion of heavy vehicles increases. When traffic becomes more dense, however, whether on level or hilly terrain, the speed is controlled primarily by volume and the geometric features of the highway. In this case truck percentage is no longer a significant parameter.

CAPACITY CONSIDERATIONS

In order to investigate the appropriateness of the models developed for practical applications, an attempt was made to determine capacity trends of typical two-lane rural highway sections. Toward this end, general definitions of terrain characteristics in terms of average curvature (α) and average hilliness (β) were adopted. These are presented in Table 3, which may be used for a determination of α and β on typical terrains.

To compute the capacity of a given section, a one-regime linear model was adopted. By using the models given by Equation 7 or Equation 8, capacity values for various terrains can be obtained by calculating the product of optimal density and speed. Hence volume capacities for various terrains and percentages of trucks can be obtained, and it is suggested to adopt the most conservative value,

TABLE 3 Suggested Guide to Determine Type of Terrain by Average Curvature and Average Hilliness

β, Average Hilliness (m/km)	Type of Terrain by α, Average Curvature (degrees/km)				
	0	25	50	80	120
0	L	L	-	-	-
10	L	L-H	L-H	H	-
30	-	L-H	H	H	H-M
50	-	H	H	H-M	M
80	-	-	H-M	M	M

Note: L = level, L-H = level-hilly, H = hilly, H-M = hilly-mountainous, and M = mountainous.

namely the lower value of the two models. Usually, the capacities given by Equation 7 will be lower, except for extremely flat terrain with winding roads (note the previous discussion), where the model given in Equation 8 should be used. This analysis is summarized and presented in Table 4 and Figures 2-4, and compared to capacity limits obtained by the conventional method of the HCM (1), and discussed in length in Chapter 10 therein. Specific values of α and β used in this comparison are shown in Figures 1-3, whereas for general purposes, average α and β values may be obtained from Table 3 for various terrain types. Usually in a design process, the data in Table 3 may serve as a general guide for initial analysis; however, once the alignment is determined, the exact α and β values for the highway section should be calculated before predicting its capacity.

TABLE 4 Suggested Capacities for Various Terrains and Comparison with Highway Capacity Manual Values

Trucks (%)	Two-Way Capacity (vehicles per hour)					
	Level Terrain		Hilly Terrain		Mountainous Terrain	
	Suggested	HCM	Suggested	HCM	Suggested	HCM
0	1,965	2,000	1,625	2,000	955	2,000
5	1,940	1,900	1,600	1,620	940	1,300
10	1,910	1,820	1,575	1,420	920	960
15	1,885	1,740	1,555	1,250	900	750
20	1,815	1,660	1,530	1,120	885	620

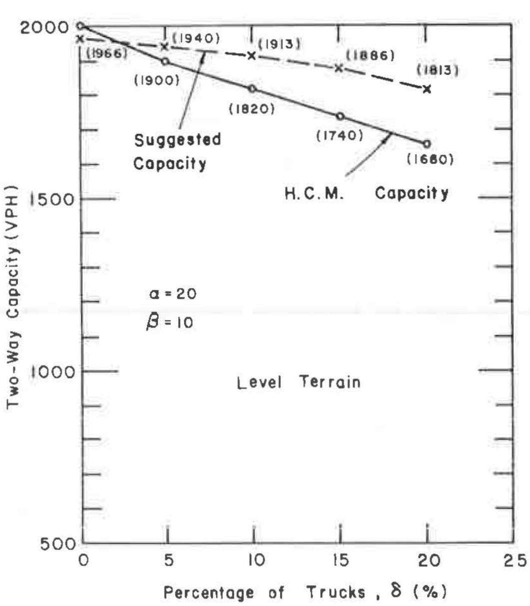

FIGURE 2 Two-way capacity versus percentage of trucks on level terrain.

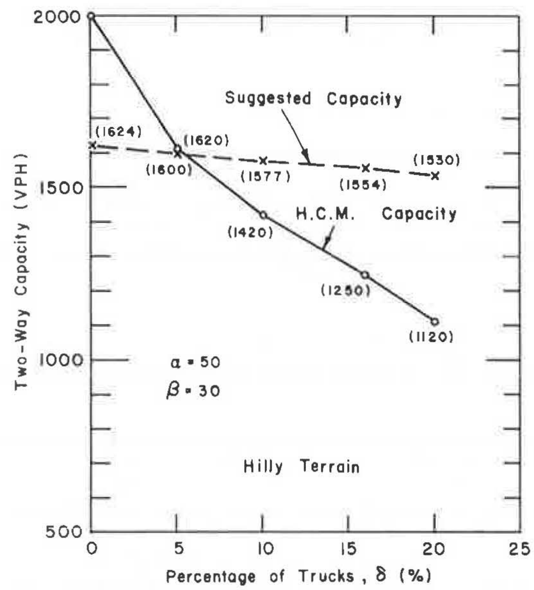

FIGURE 3 Two-way capacity versus percentage of trucks on hilly terrain.

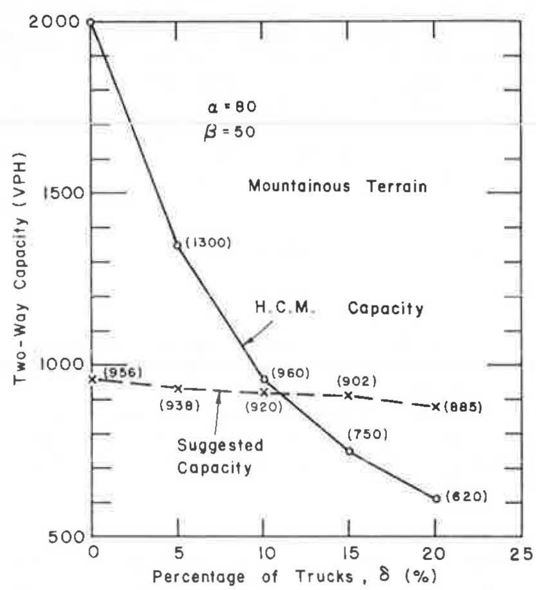

FIGURE 4 Two-way capacity versus percentage of trucks on mountainous terrain.

By observation of the capacity trends presented in Table 4, two important observations can be made. First, the two-way capacities given by the suggested model are lower than the HCM values for a low percentage of trucks, but higher for percentages greater than about 5 percent (level and hilly terrains) or about 10 percent (mountainous terrain). Second, the suggested model is less sensitive than the Manual's model to the percentage of trucks and, particularly, to the reduction of capacity with an increase in truck percentage. This is because of the moderate influence of ʃ on the average running speeds, which may be explained by the improved weight/power ratio in new trucks and the strict control of weight regulations. Another possible explanation is the high estimate of passenger-car equivalents given by the Manual, which has been documented in the past (10,16), and which results in an overestimation of the adverse effects of trucks on highway capacity.

CONCLUSIONS

This study presented several models for a prediction of average running speed on two-lane rural highways through overall geometric data and flow parameters. The layout characteristics considered were average curvature, average hilliness, and net gradient. The flow parameters were the two-way volume, traffic density, percentage of trucks, and directional distribution of traffic. A one-regime regression model, which was chosen from numerous models tested, enabled the prediction of average running speeds and densities and therefore permitted the calculation of two-way capacities for various terrain conditions and percentages of trucks. Finally, the suggested values obtained for rural highway capacity may be more realistic than currently accepted values because the suggested values more closely represent current flows on high-speed, modern, two-lane rural highways. However, it is suggested to use the capacities presented as general values that present a certain trend, rather than firm values, until further analysis of this issue is completed.

Further research is suggested on (a) rural highway speed/flow relationships at or close to roadway capacity, and (b) the effect of other geometric and flow parameters, such as consistency of horizontal and vertical design and superelevation, on average running speed and capacity.

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