

# DETERMINATION OF LONGITUDINAL GRADES ON RURAL ROADS

*A. Polus, Technion - Israel Institute of Technology*

*J. Craus, Technion - Israel Institute of Technology*

*M. Livneh, Technion - Israel Institute of Technology*

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## ABSTRACT

The design of vertical alignments of highways is controlled by several factors, such as terrain, design speed and traffic characteristics. Two issues usually govern the design process: (1) the maximum grade allowed and (2) the maximum desirable length of grade. In current practice, the first parameter is determined arbitrarily and the second is then calculated by speed reduction criteria, depending on the design speed and the slope. The paper discusses some of the deficiencies of current practice and reviews some of the acceptable design values.

In the proposed procedure, grade and length are treated as a single design element. Any practical grade can be associated with any design speed value. It is suggested that for low design speeds, any moderate grade and length combinations are adequate; for steeper grades, high design speeds require shorter lengths of grades. Furthermore, any feasible slope can be allowed for any design speed; however, the length must be checked for certain design limitations.

The appropriate length of grade is derived from an operational criterion based on the speed difference between trucks and passenger cars. Additionally, the length must be checked for design uniformity to prevent, for example, very short sections with steep grades on an otherwise moderate and continuous vertical alignment.

The proposed approach for determining slopes along a vertical alignment also deals with the approach grade, prior to a specific grade that needs to be designed. This allows a determination of the initial speed of cars and trucks on the grade and more accurate calculation of their relative speed difference, toward the end of the grade. If this speed difference is kept low, an integrated, more consistent and safer design is achieved.

## INTRODUCTION

In hilly and mountainous terrain, the overall location and alignment of a road are influenced largely by the vertical alignment. Known as the road profile, this alignment is determined by two main parameters: the maximum allowable slope and the maximum length of grade which are typically constant for a given terrain. The selection of an optimal combination of length and slope values for designing a specific road is dependent on several considerations and parameters, the most important of which are (1) the performance characteristics of trucks on grades;

(2) the desired safety level; (3) expected level of service and the predicted volume vs. the capacity of a specific grade; and (4) construction costs. The capacity of longitudinal slopes is greatly reduced, compared to a level approach section prior to the upgrade slope. This reduction is very significant, reaching 50% - 60% or more and therefore necessitating that the reduction in capacity be evaluated very carefully in order to ensure sufficient upgrade capacity and reasonable delays. If this analysis results in insufficient capacity or unreasonable delays, it will be necessary to resolve the capacity issue by adding a climbing lane on the upgrade and, also at times, on the down grade.

The above considerations and their relative importance change with different road projects and among countries. It is commonly agreed, however, that all four parameters should be considered seriously and evaluated when determining the vertical alignment.

The purpose of this study was to review existing guidelines for the design of a vertical alignment and to propose a new approach that could lead to greater design flexibility while preserving and enhancing performance, safety and capacity. A simulation program for the performance of trucks on grades was developed, and some of the proposed recommendations are based on values derived from that program.

## LITERATURE REVIEW

The maximum slope currently permitted by various standards is dependent on the design speed. For example, AASHTO (1990) in the U.S. recommends the maximum slopes shown in Table 1 for urban and rural freeways for design speeds of 50, 60 and 70 mph.

For local roads and streets, AASHTO's values for maximum grades are considerably higher. For low design speeds of 20 and 30 mph, for example, the maximum grades may be as high as 16 and 14 percent (in mountainous terrain), respectively.

Other countries or individual states in the U.S. or provinces in Canada use different standards. Saskatchewan in Canada, for example, recommends 3% to 5% as maximum freeway slopes. Australia recommends a range of 5% (desirable maximum) to an absolute maximum of 7% for a speed of 100 km/h (approximately 63 mph). Japan recommends for the same speed a range of 3% to 6%. In Israel, the guidelines of the Public Works Department (1994) propose the rates for slopes as presented in Table 2.

**TABLE 1 AASHTO (1990) Maximum Grades for Urban and Rural Freeways**

	DESIGN SPEED (mph) = 50	DESIGN SPEED (mph) = 60	DESIGN SPEED (mph) = 70
TERRAIN	GRADES (percentage)		
Level	4	3	3
Rolling	5	4	4
Mountainous	6	6	5

In addition to the main consideration of cars' performance on grades, the maximum slope is also determined by economic considerations. Urban or suburban freeways, with large volumes of traffic, may justify higher construction costs than two-lane rural highways with very low volumes. The latter may require higher maximum slopes to make the construction more economical, by reducing earth-works, reducing hauling, etc.

Maximum grade in itself is only a partial design criterion. To achieve a quality balanced design, it is necessary to consider the length of the grade. Most standards do not explicitly limit the length of slopes, but suggest that it is desirable to limit the length of sections with maximum slopes. AASHTO (1990) proposes limiting the maximum length to that which will not exceed the "critical length of grade." The critical length is that which will cause a typical loaded truck (300 pound/horsepower) to "operate without an unreasonable reduction in speed" (AASHTO, 1990). A reduction of 10 mph is recommended, the reason being the significant increase in accident involvement rate at higher speed reductions.

**LIMITATIONS OF CURRENT DESIGN APPROACH**

A review of the literature shows that the control of the vertical alignment according to most design standards should be conducted in a two-step process: First is an arbitrary selection of the maximum grade, based on a certain design speed and terrain type. In most design standards, the determination of the maximum grade is generally recommended without a theoretical basis. The recommendation is based on general engineering judgment representing local conditions; however, it is not based on analytical calculations of the performance of trucks on grades. Second, an analytical selection is made of the maximum length allowed for a given grade. The limitation of length is proposed only for the maximum allowable grades, because steeper grades are not permitted even for small lengths.

The separate selection of the maximum grade and the maximum length and the lack of a theoretical basis for the former leads to inconsistencies between standards. For example, it is possible to find that some design standards (for example AASHTO, 1990) at 80 kph (50 mph), allow use of 9% slope at a length of less than 150 meters (500 ft.). Another standard (for example the South African TRH 17, 1984), will not even allow a more moderate slope of about 8% at the same design speed. Additionally, it may be found (for example AASHTO, 1990) that a moderate slope of 3% is unlimited in length (for passenger cars and recreational vehicles) while the same slope is restricted to 400 meters (1300 ft.) in TRH 17 (1984); also in the Scottish standards (1968), the same 3% slope is limited to 500 meters (1600 ft.).

All this leads to inconsistencies among standards and the lack of a common guideline for highway engineering projects.

**PROPOSED CONCEPT**

Because of the inconsistencies and limitations of the existing methods for determining the maximum grade and its maximum length based on the design speed, a new concept is proposed. This concept is based on the following principles:

- combining both grade magnitude and length to a single design element (i.e., joining the two parameters into one);
- determining the combined design control according to the performance characteristics of both cars and trucks;
- adhering to stringent safety considerations, in order to be consistent on grades, as well as on level sections, along the entire alignment.

The most important practical implication of these principles is that it will be possible to use any grade when designing a vertical alignment for any design speed. While steep grades could be used for short distances, moderate slopes could be designed for longer lengths, and very low grades could be unlimited in length.

**TABLE 2 Israel's (1994) Maximum Grades for Rural Freeways and Highways**

	DESIGN SPEED (kph)							
	50	60	70	80	90	100	110	120
	MAXIMUM GRADES (percentage)							
FREEWAY						5	4	3
MAJOR ROAD				6	6	5	5	
REGIONAL ROAD			8	7	7	6		
LOCAL ROAD	12	10	9	8				

There are three reasonable criteria for determining the maximum grade-length combination: first, the delay caused by trucks to passenger cars; second, the drop in truck speeds; third, the speed difference between cars and trucks along grades.

For this study, a simulation program was developed, based on the theoretical developments for speeds on grades given by Kobett and St. John (1978). The following are the main parameters that were used as input for the simulation program: (1) grade values; (2) hourly volumes, in each direction; (3) percentage of trucks in the traffic stream; (4) performance characteristics and parameters of the trucks and cars (weight to horsepower ratio, acceleration, etc.); (5) initial speed at the entry to the upgrade; and (6) the critical gap needed for passing on two-lane upgrades.

This study suggests limiting the relative difference between the speeds of cars and trucks to a predetermined threshold value,  $\Delta V_{cr}$  (see Figure 1). Therefore, the maximum length of any grade could be established at a point along the grade where the speed difference exceeds this threshold value. It is proposed that the maximum value of  $\Delta V_{cr}$  will be established within a range of between 25 and 35 kph (approx. 15 to 22 mph). The lower threshold value is adopted for high design speeds and for steep grades. This is justified for two main reasons: 1) at high design speeds, drivers expect a high level of service and also accident severity is increased; and 2) on steep grades the acceleration capability of passenger cars is limited.

The application of the critical speed difference between cars and trucks is used to determine the length of grade. If

the calculated speed difference is less than  $\Delta V_{cr}$ , the length of grade will not be limited. Usually this happens in level or hilly terrain, when slopes are moderate. Additionally, it could occur when the design speed is low and speeds are determined mainly by the horizontal alignment.

### SUGGESTED DESIGN VALUES

#### Unlimited Length of Slopes

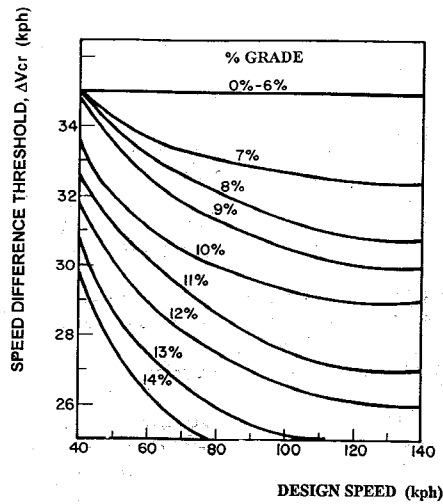
From the definition of the criteria discussed above and the philosophy behind them it is clear that there are two possible categories of slopes: (1) slopes which are unlimited in length, and (2) slopes that have a limited length, as obtained by the  $\Delta V_{cr}$  threshold.

For every design speed, it is possible to determine a "critical grade",  $G_{cr}$ , below which all grades will be unlimited in length and above which lengths will be limited. The values of  $G_{cr}$  are presented in Table 3 and in Figure 2.

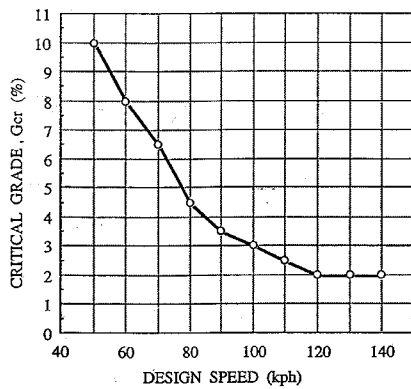
It is necessary to emphasize that the values in Table 3, which are based on the speed difference between cars and trucks, are relevant only for upgrades and not for down grades. When it is necessary to establish additional criteria, for example that trucks' speeds will not be less than a given value, the maximum allowable slope assumes a different value. Thus, a maximum slope of 5% is permitted for a design speed of 70 kph (approximately 45 mph), if the minimum speed of trucks does not fall below 30 kph (approximately 20 mph).

**TABLE 3 Suggested Values of Critical Grade ( $G_{cr}$ ) for Various Design Speeds**

DESIGN SPEED (kph)	50	60	70	80	90	100	110	120	130	140
CRITICAL GRADE (%)	10.0	8.0	6.5	4.5	3.5	3.0	2.5	2.0	2.0	2.0



**FIGURE 1 Values of  $\Delta V_{cr}$  for Various Design Speeds and Percent Grade**



**FIGURE 2 Change in Critical Grade with Design Speed**

### Limited Length of Slopes

When the slopes are steeper than the values of the “critical grades” presented in Table 3, it is necessary to limit their lengths. The criterion will be that the speed difference between cars and trucks is less than a given value. The length therefore will be dependent on the percentage of the slope, the design speed and the initial speed difference between heavy vehicles and cars. The initial speed difference depends largely on the slope of the approach grade, prior to the initial upgrade. The maximum lengths of slopes are given in Figure 3 through Figure 6, for approach grades of 0% (level road prior to the upgrade), 1%, 2% and 3%, respectively. It should be noted that it is impossible to utilize grades that are too short, because of the minimum requirements for the lengths of vertical curves. An empirical value of this minimum length (in meters) is suggested to be  $1 \cdot V_d$ , where  $V_d$  is the design speed in kph.

This value is therefore instituted as the minimum length of grade, because it has to contain two halves of both vertical curves, on each side of the slope. The minimum length line is shown in Figures 3, 4, 5 and 6.

Appropriate selection of the design speed is critical for the safe implementation of the lengths of grades derived from these figures. If the design speed is smaller than the actual speeds, the obtained length (according to the speed difference criterion) will be longer than the permitted length. This means that the actual speed difference between cars and trucks will be greater than the established criterion, thereby leading to a potential deterioration in safety levels and to increased delays.

### SUMMARY

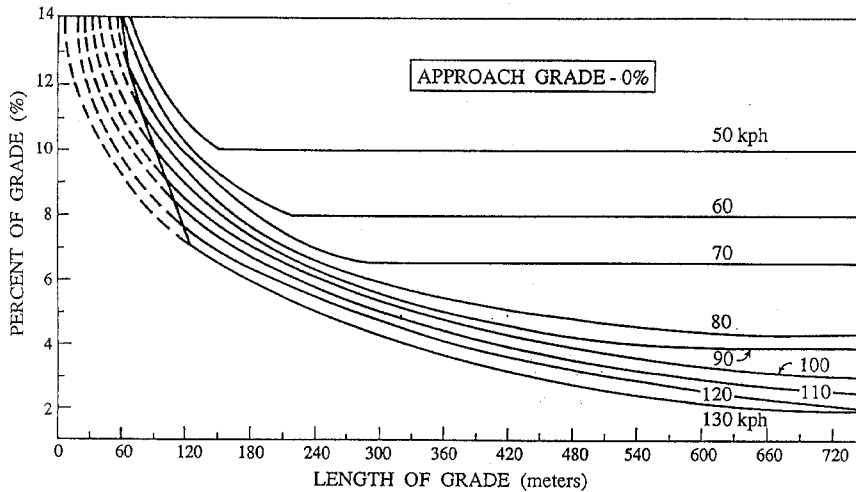
Design of vertical alignments, as commonly accepted in many guidelines, is actually controlled by two main

parameters: (1) maximum permitted grade and (2) maximum permitted length of each grade. The lack of a consistent theoretical basis for these parameters leads to differences between guidelines.

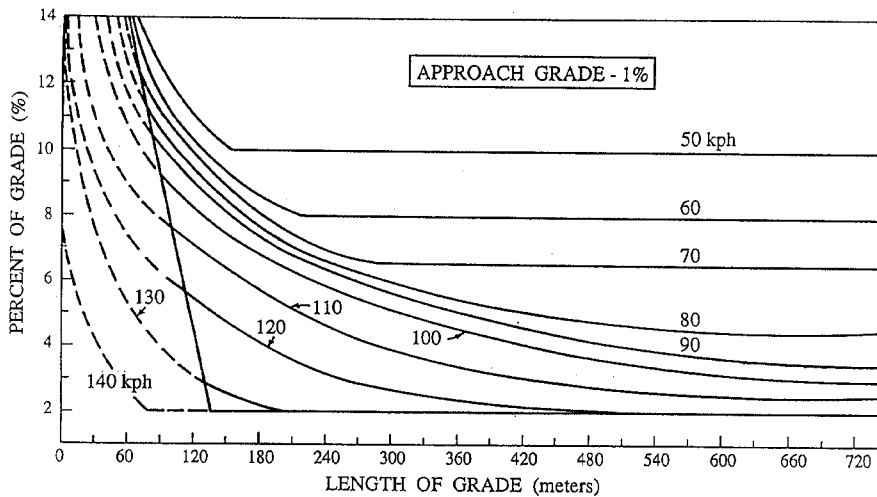
This work suggests using only one criterion for the design of slopes: A combination of length and slope, such that the maximum difference between the speed of cars and that of trucks should be less than a given threshold. This threshold depends on the design speed and on the rate of slope.

For every design speed, it is possible to determine a “critical grade”,  $G_{cr}$ , below which all grades will be unlimited in length and above which the lengths will be limited. Values of  $G_{cr}$  are presented in Table 3.

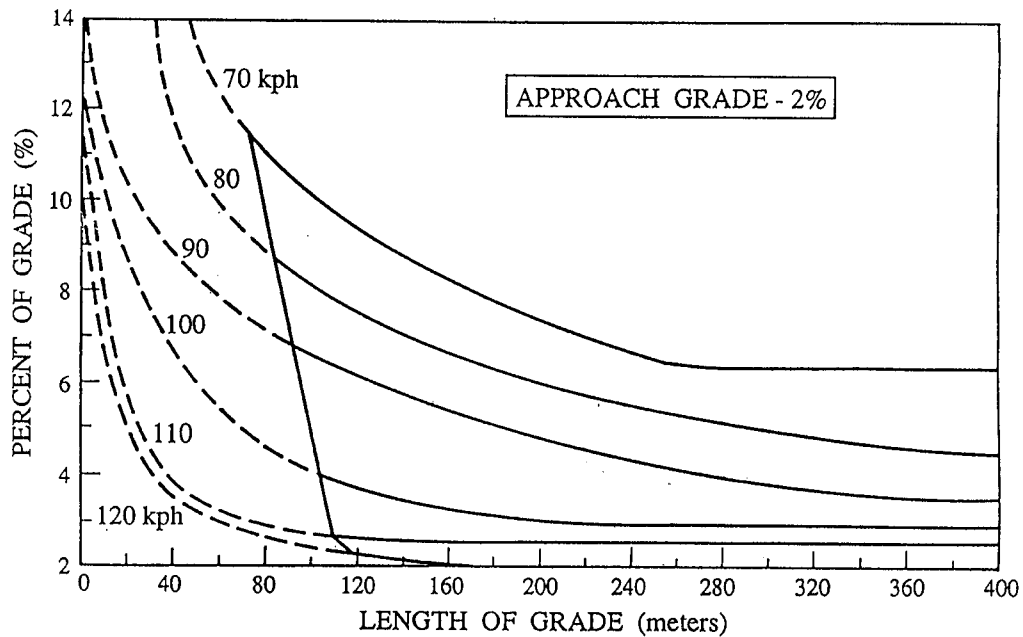
It is also suggested that the “maximum grade” term not be used. The use of any reasonable slope, depending on the terrain and other constraints (such as earthworks quantities etc.), is recommended, as is the establishment of its length by the speed difference criterion. Figures for various approach grades are provided to determine the allowable length.



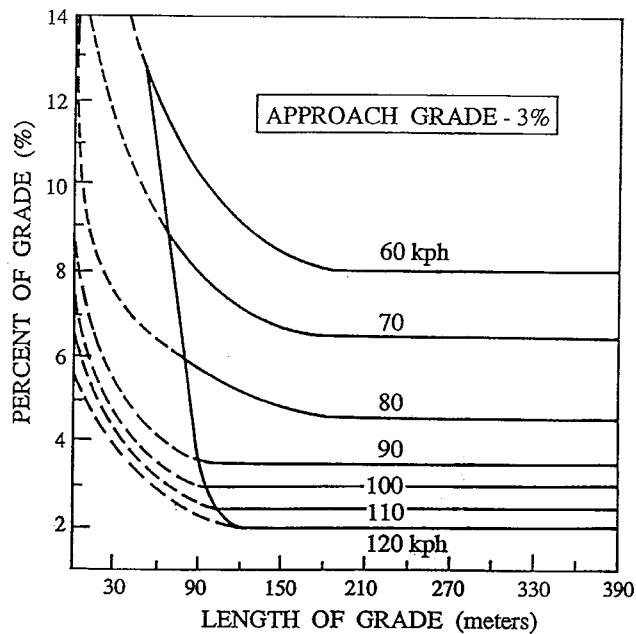
**FIGURE 3 Maximum Length of Grade for Various Design Speeds (Approach Grade = 0%)**



**FIGURE 4 Maximum Length of Grade for Various Design Speeds (Approach Grade = 1%)**



**FIGURE 5 Maximum Length of Grade for Various Design Speeds (Approach Grade = 2%)**



**FIGURE 6 Maximum Length of Grade for Various Design Speeds (Approach Grade = 3%)**

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