Since it is logical to assume that a four-lane highway will have higher design speeds than will a two-lane highway, the Δ-values for a four-lane highway are given for speeds equal to or greater than 80 km/h (50 mph) and, similarly, the Δ-values for six-lane highways are given for design speeds equal to or greater than 100 km/h (62 mph). This analysis leads to the following conclusions.

1. The Δ-values between the profiles of the edges and the centerline of a two-lane pavement are lower than the values suggested by AASHO (1). The exact relation is shown in Figure 3. The use of lower Δ-values gives a more gradual superelevation runoff, and the identity in length with that of the spiral may result in a rather simplified design.
2. For multilane highways, the Δ-values suggested here are higher than the AASHO values at lower speeds but not at speeds above 100 km/h (62 mph) on four-lane highways and 120 km/h (75 mph) on six-lane highways.

MAXIMUM RADIUS FOR NECESSARY USE OF SPIRALS

The need for transition curves is most pronounced on sharper curves. On curves having larger radii there is less need for the use of spirals.

Several criteria have been suggested for the use of spirals. One method designates a single degree of curve that is applicable to all design speeds. Another method suggests the use of spiral curves when p, computed by Equation 1 with C = 0.6 m/s^3 (2 ft/s^3), is greater than 0.3 m (1 ft). The method given in the NUTI Geometric Design Notes (4) suggests that the spiral be used on curves that require a superelevation rate of 0.03 or more

The following assumptions suggest another criterion for the introduction of spiral curves. A gently curving alignment that requires little centrifugal-acceleration resistance should not require spirals.

The minimum amount of centrifugal acceleration for the introduction of spiral transition curves is 0.4 m/s^2 (1.3 ft/s^2). The criterion for the maximum radii that will require use of a spiral is

$$V^2/R_c = 0.4 \qquad (5)$$

where R_c = maximum radius for necessary use of spiral transition (meters) and V = design speed (kilometers per hour). The values calculated by Equation 5 can be read directly from Figure 4, which shows that the centrifugal force varies hyperbolically with speed and radii.

The centrifigual-force criterion has two advantages. First, this criterion is based on the actual force that is imposed on the traveling vehicle. Second, this criterion agrees with the assumption, given by Spindler (7), that the safest and most comfortable situation is that in which the side-friction factor and the superelevation equally resist the centrifugal acceleration; i.e., the ratio of e to (e + f) should be 0.5.

CONCLUSIONS

A model for the relation between the rate of change of centrifugal acceleration on a spiral transition curve and the design speed is presented. The model has two regions and decreases linearly. The resulting spirals and their properties are discussed. The practical reasons of safety and uniformity were used as a guideline to the suggestion that the maximum relative slope between the edges of the pavement and the centerline should be greater than that recommended by AASHO. An identity between the superelevation runoff and the spiral lengths is assumed. The criterion of the maximum radius for the use of spiral transition curves is also discussed.

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New Concepts in Design-Speed Application

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The design-speed concept, as presently applied, does not preclude inconsistencies in highway alignment. The basic problem, particularly in the range of design speeds below 90 km/h (55 mph), is the tendency on the part of the driver to continually accelerate and decelerate. A secondary problem is the speed differential between automobiles and trucks. To overcome these weaknesses in current practice, a new concept in the definition and application of design speed is presented. The overall object is to meet driver expectations and to comply with his or her inherent characteristics to achieve operational consistency and improve driving comfort and safety. The principle used in the updated design-speed approach is the 15-km/h (10-mph) rule, which during periods of free-flow conditions, entails three considerations: (a) A reduction in design speed

should be avoided if possible, but if it is required, it should be no more than 15 km/h (10 mph); (b) within a given design speed, potential automobile speeds along the highway normally should vary no more than 15 km/h (10 mph); and (c) potential truck speeds generally should be no more than 15 km/h (10 mph) lower than automobile speeds on common lanes. The tool to accomplish these goals is a speed-profile technique. The potential automobile and truck speeds are plotted along the proposed highway improvement, taking into account the joint configuration of the horizontal and vertical alignments and the individual curvatures and gradients. The procedure is applicable to design of new facilities, but is even more useful for determining corrective measures to upgrade existing facilities.

The convenience and economy that a highway offers are related to the speed and safety of operation on it, and the speed that can be maintained is a direct function of the quality of the highway and the amount of traffic that it handles. Because of this, attempts to relate the potential speeds on the highway to its various geometric elements have been important for many decades, which has resulted in the introduction of the concept of highway design that is referred to as the design speed.

The application of this concept has served well, but in recent years a better understanding of the complexities associated with the driving task and the multitude of related human factors has shown the need to expand and improve on it.

The object of this paper is to present a new concept of the definition and application of design speed. The function of this concept in the design and redesign of highways will be to better meet driver expectations and to comply with his or her inherent characteristics. The results presented are intended to achieve operational consistency and improve driving comfort and safety through a more uniform and balanced design of highway alignment.

CONCEPT OF DESIGN SPEED

The concept of design speed was introduced during the 1930s, and its application was embraced in the 1940s. Two publications (1, 2) on highway geometrics had an important role in instituting this design guide, which with minor modification has been adhered to in the 1954, 1957, 1965, and 1973 American Association of Highway Officials (AASHO) Geometric Design Policies (3, 4, 5, 6). However, recent knowledge of traffic operations and driver characteristics has made it evident that the concept and its applications should be updated.

One problem in the use of design speed as it is applied today is that, primarily at lower speeds, the changing alignment causes variations in operating speeds; i.e., the horizontal curves that control the design speed along the highway cause the driver to increase speed on the flatter portions of the alignment and then require him or her to decrease speed on the sharper or controlling curves.

Another problem is that the design speed sometimes is lower than the driver's expectation and judgment of what the logical speed should be. The design speed must appear to be reasonable to the driver, whose sensitivity and judgment of a logical speed are very keen. He or she expects a high design speed in open country and flat terrain but recognizes, even if only inadvertently, the difficulty of the situation in mountainous terrain or in highly urbanized or built-up areas. Therefore, a speed that more nearly meets the driver's natural tendency must be used. On many highways, the elimination of some of the sharper curves to increase the design speed would make a more consistent and safer design. On others, the configuration of the alignment can be arranged to produce a more uniform speed if some curves of appropriate degree are introduced and others are nominally and compatibly sharpened.

The object is not only a logical and acceptable design speed but also one that produces a relatively uniform operating speed. This is fully met where high design speeds are used, but at low and intermediate design speeds, the portions of relatively flat alignments interspersed between the controlling portions tend to produce increases in operating speed that may exceed the design speed by substantial amounts.

This undesirable feature must be overcome. The communicative aspects of alignment design that interact with driver responses—the control and guidance of the vehicle and the pattern of operating speeds—are related to the configuration and composition of the longitudinal alignment. Thus, to compensate for the driver's physical and emotional states, to meet his or her expectations, and to comply with his or her inherent characteristics, it is necessary to achieve operational consistency and improve driving comfort and safety by the application of the appropriate design speed. Accordingly, this new concept of design speed recognizes the inadvertent increase in speed of drivers but limits it to a maximum of 15 km/h (10 mph). Design-speed designations remain the same [50, 65, 80, 95, 110, or 125 km/h (30, 40, 50, 60, 70, or 80 mph)], but, for speeds of less than 100 km/h, recognize a potential overdriving speed of 15 km/h; for example, a design speed of 50 km/h (30 mph) means a design-speed range of 50 to 65 km/h (30 to 40 mph), a design speed designated for 65 km/h (40 mph) means a design-speed range of 65 to 80 km/h (40 to 50 mph), and so on. This principle is summarized below.

1. Within a given design speed, the potential average automobile speeds should not vary more than 15 km/h (10 mph).
2. When a reduction in design speed is necessary, it should normally be no more than 15 km/h (10 mph).
3. On common lanes, potential average truck speeds should generally be no more than 15 km/h (10 mph) lower than average automobile speeds.

This device makes the composition of the highway a function of the design speed. What the driver sees and the message conveyed by the highway should induce a response on the part of the driver that encourages him or her to operate at a reasonably consistent speed. The physical makeup of the alignment should prevent or discourage increases in speed to more than 15 km/h (10 mph) beyond the designated design speed.

The basic concept of design speed, except for details of application, has the same general meaning and objectives today as it did nearly 40 years ago. The design speed primarily determines the quality of the highway and provides a consistent design. Once the design speed is selected in accordance with the driver's fundamental expectations and in conformity with the basic controls of the type of terrain, the extent of man-made features, and economic limitations, it is unhampered by other constraints, such as the constantly changing conditions on a highway caused by the effects of weather variations; differences in size, weight, and power of vehicles; the wide variation of behavior within the driving population; variations in traffic volumes during different periods of the day; and speed-limit restraints.

These constraints can have significant and sometimes dramatic effects on traffic operating speeds. However, they have no relation to the design of the highway after the design speed has been selected. Even the current imposition of the general 88-km/h (55-mph) speed limit on U.S. highways does not and should not have any effect on the selection of the design speed or the quality of the highway and the standards to which it should be designed. The highway and its basic configuration, which reflects its quality, will last for 30 years or more, but the speed limit, the form of energy used, and the type of vehicle employed can readily change in that period.

What actually happens is that the relative high quality of the highway provides a significant safety factor. A higher quality highway will have more leeway to handle various overloads and inconsistencies. The better design with a given number of lanes can carry the traffic at a higher level of service and with a larger margin of safety for minimizing hazardous maneuvers and accidents. Also, the larger the difference is between the design speed and the average speed of operation or the speed limit, the safer the operation of the highway will be; e.g., a highway that has a design speed of 110 km/h (70 mph) and a speed limit of 80 km/h (50 mph) is safer than a highway that has a design speed of 80 km/h (50 mph) and a speed limit of 80 km/h (50 mph).

This approach leads to the following reformulated definition: Design speed is a representative potential operating speed that is determined by the design and correlation of the physical (geometric) features of a highway. It is indicative of a nearly consistent maximum or near-maximum speed that a driver could safely maintain on the highway in ideal weather and with low traffic (free-flow) conditions and serves as an index or measure of the geometric quality of the highway.

The 15-km/h (10-mph) incremental speed value is based on several facts. Experience has shown that a driver can cope reasonably well with a 15-km/h (10-mph) speed adjustment in most circumstances. There is also evidence that variations from the average speed cause a definite increase in accident involvement (8). Also, there is a sharp rise in the ratio of the number of accidents occurring as the speed reduction of trucks (the difference between the average speed of trucks and the average speed of automobiles) increases relative to the number of accidents occurring when there is no speed reduction (i.e., trucks and automobiles can maintain the same speed). This is tabulated below (1 km/h = 0.6 mph).

Speed Reduction (km/h)	Ratio of Accidents	Speed Reduction (km/h)	Ratio of Accidents
8	2	24	8.9
16	3.7	32	15.9

This new definition requires a tool to regulate the design so as to maintain the necessary consistency and quality of the alignment. The speed profile (Figure 1), which charts potential automobile and truck speeds, can provide the necessary insight.

The application of the new design-speed concept also requires that, at the point at which potential speed increases occur, appropriately higher sight distances and increased superelevation on curves must be provided. Thus, the design will be fully sensitive to the way in which the driver operates. Moreover, should a change in design speed become necessary, the justification for the introduction of a reduced design speed should be obvious and psychologically acceptable to the driver.

DEVELOPMENT OF SPEED-PROFILE TECHNIQUE

The application of the design-speed concept requires that the speed profile be developed and analyzed for every project. On an existing facility, speed measurements (mean, average, or any percentile) at close intervals along the highway can be plotted against distance. Separate measurements and plots can be made for different classifications of vehicles; e.g., vehicles with passenger-automobile characteristics can represent one group and large trucks (dual-tired) can represent a second group and other subdivisions can be considered in special cases.

However, the use of the direct-measurement technique for every existing highway designated for improvement would be too time-consuming and expensive. Moreover, there are no completely appropriate or practical procedures available for the prediction of speed versus distance relations for determining or evaluating the operational characteristics on proposed improvements on old highways, or in the design of new ones. Some previous attempts to formulate such techniques have been reported by Leisch and others (10) and by Baluch (11).

The method for determining speed profiles given here has been devised from limited data, extensions of minimal research in vehicle operations, empirical speed relations, and experience judgments. However, despite the lack of direct research on some aspects of the problem, the results are believed to be sufficiently accurate for their purpose, can be effectively used immediately, and will serve as the essential tool for designing highway improvements directed toward optimizing operations and improving safety.

Speed-Profile Components

Speed profiles for a given type of highway may represent different conditions, such as speed measure (mean, average, or 85th percentile), traffic-volume condition (free-flow or specific traffic volumes), different types of vehicles, or intersection or interchange conditions along the route.

The type of speed profile developed here, particularly as it relates to the design speed, represents a basic set of conditions that allows the most direct way to evaluate and optimize the uninterrupted flow (geometric) characteristics of the highway. It applies to any type or classification of highway, but is normally used for rural or suburban highways on portions where there are no intersection or interchange problems.

The basic characteristics of the speed profile given here are predicated on the following assumptions:

1. Low volumes (free-flow conditions);
2. Average (running) traffic speeds;
3. Favorable roadway conditions such as daylight and good weather;
4. Top average speeds representative of freely moving vehicles (automobiles and trucks) on relatively straight open sections of roads, outside the influence of any other geometric constraints;
5. Average (running) speeds that agree with the low-volume relations of average running speed to design speed on horizontal curves;
6. Separate average (running) speeds for automobiles and for trucks plotted in juxtaposition [average truck speeds on or near level grades are assumed to be 8 km/h (5 mph) below average automobile speeds] (other values may be used as appropriate);
7. Truck selected to be representative for a particular highway (average weight to power ratio of 200 assumed) (other values may be used as appropriate);
8. Deceleration and acceleration for automobiles predicated primarily on and extrapolated from 1965 AASHO Geometric Design Policy (5); and
9. Deceleration and acceleration for trucks compiled from 1965 Highway Capacity Manual, 1965 AASHO Geometric Design Policy, and 1972 Federal Highway Administration Dynamic Design for Safety and (5, 10, 14).

Speed Values and Related Factors

The speed profile is represented by the average (running) speed of traffic during free-flow conditions. Its basic inputs evolve from a set of average speeds for free-flow, near-level highway conditions on tangent sections and horizontal curves.

Top Average Speed of Highway

Every highway or homogeneous section of one has what may be termed its top average speed that depends on the environment, the type of highway, the length of trips made on it, regional effects, and possibly speed limits and other restrictions. This relates to conditions of freely moving vehicles and indicates a driver's (average) desired speed under ideal traffic, roadway, and weather conditions on near-level and straight sections of road that are sufficiently removed from any constraining effects. Many such measurements have been recorded (12). The composite average speeds on main rural highways have increased from 80 km/h (50 mph) for automobiles and 72 km/h (45 mph) for trucks in 1951 to 100 km/h (62 mph) for automobiles and 92 km/h (57 mph) for trucks in 1972. [The recent constraint of the 88.5-km/h (55-mph) national speed limit has changed these relations somewhat.] The top average speeds for various types of vehicles and highways are summarized below (1 km/h = 0.62 mph).

	Avg Speed (km/h)		
Type of Highway	Automobiles	Trucks	All
Rural Interstate	107	96	104
Rural primary	94	87	93
Rural secondary	86	80	85
Urban Interstate	93	85	91
Urban primary	70	66	69
Urban secondary	64	62	64

Measurements of top average speeds of this kind should be a prerequisite to the reconstruction of old highways and an important input to the speed profile. In the design of new highways, measurements made on similar highways in the general corridor or region should be used. The values given below (or similarly derived values) are representative of low-volume, free-flowing conditions on open, near-level, and straight highways and may be used as a guide to top average speeds in the absence of specific data (1 km/h = 0.62 mph).

	Top Average Speed (km/h)	
Type of Facility	Favorable Highway Quality	Moderate Highway Quality
Rural highway		
Interstate	100	95
Primary—main	95	90
Primary—intermediate	90	80
Secondary	80	70
Urban highway		
Interstate	95	90
Arterial—main	80	70
Arterial—intermediate	70	65
Secondary—feeder	65	55

Speed on Curves

The curves that control the design speed (i.e., the maximum degree of curvature or the minimum radius for a given design speed) have been related, by actual measurements, to a set of corresponding average running speeds, as shown below (5) (1 km/h = 0.62 mph).

Design Speed (km/h)	Average Running Speed (km/h)	Design Speed (km/h)	Average Running Speed (km/h)
50	46	95	82
65	58	110	92
80	70	125	100

This basic relation between the design speed and average running speed is assumed to be applicable even where a flatter curvature is encountered so long as the design-speed designation is maintained. The problem arises when a driver is encouraged by a sufficiently long or inviting section of more gentle alignment to increase speed momentarily, even though he or she may reduce the speed to normal further along the road. In such a case, the operating speed (the average running speed) disrupts the above relation, which indicates that an equivalent higher design speed had been achieved temporarily. The proposed speed profile and the application of the 15-km/h (10-mph) rule would reveal this problem and provide the insight to adjust the design and possibly smooth out the differences.

For speed-profile purposes, what average speeds should be assigned to individual alignment curves? Figure 2 [adapted from the 1965 AASHO Geometric Design Policy (5)] shows the relations among the degree of curvature, the radius of the curve, and the average (maximum) speed that can be driven on it. The data given in this figure assume that the driver has no other constraints and that the approach speed to the curve is equal to or higher than the tabular value, although the actual average speed on the curve may be less because of the composition of the alignment and the type of highway. Lower speeds, and their numerical values in developing the speed profile, will automatically be determined by the driver's process of applying the required decelerations and accelerations.

Figure 2 can be used to establish the points on the initial plot of the speed profile.

Truck Speeds

Large trucks generally operate at lower speeds than do automobiles. On open highways and level grades the difference in average speeds is usually small, and it may be nearly the same when there are speed-limit controls. However, the overall average difference on main highways is approximately 8 km/h (5 mph) (12). The general averages under ideal conditions are that truck speeds are about 8 to 11 km/h (5 to 7 mph) lower than automobile speeds on high-quality facilities and 5 to 8 km/h (3 to 5 mph) lower on lower order facilities. The speed differences between the two types of vehicles are further reduced in less favorable traffic and highway conditions.

In developing the speed profile the 8-km/h (5-mph) speed difference should be applied uniformly along the speed profile under normal circumstances. This pertains to all near-level sections of roads, regardless of their horizontal alignment, although slightly different values could be used where justified by specific data.

On gradients, the speed differential between trucks and automobiles becomes significantly greater.

Speed-Change Characteristics

To maintain his or her desired speed a driver frequently accelerates, although at a moderate rate, after a deceleration that was caused by constraints or possible inconsistencies in the horizontal or vertical alignment of the highway. Because of the differences in the mechanical and operational characteristics of automobiles and trucks and in the drivers of each, the speed variations between the two types of vehicles differ drastically. Automobile speed changes are influenced largely by horizontal curvature, but truck speeds are affected by both horizontal and vertical alignment. Horizontal curvatures have the same basic constraints on both automobiles and trucks. Roadway gradients, on the other hand, have little effect on automobiles but cause trucks to have unusually high rates of deceleration and extremely low speeds on steep, sustained upgrades. Upward gradients of up to 4 and even 5 percent have little if any decelerating effect on the speed of automobiles; i.e., automobiles normally have no problem in maintaining constant-speed operation on such grades, and downward gradients of 3 or more percent have an accelerating effect on automobiles.

Because of these differences, the speeds of each type of vehicle must be analyzed separately. The driver characteristics of both the automobile driver and the truck operator also have a part in negotiating horizontal curves. In the case of the automobile, it is the driver characteristics, rather than the vehicle characteristics, that determine the speed, but in the case of truck operations, it is primarily the mechanical characteristics of the vehicle that determine the speed. This is an important fundamental difference that must be considered in determining decelerations and accelerations on a roadway occupied by both kinds of vehicles.

Sight distance seems to have little effect on the speed that drivers use on the highway. This is unfortunate since sight distance has a significant effect on safety. Drivers apparently are not able to properly judge the speeds that should be associated with sight restrictions and do not change speeds appropriately. Thus, the amount of sight distance or the lack of appropriate sight distance is not an element in the construction of the speed profile. However, extra sight distance should be provided on sections of highway that the speed profile shows to be high-speed operations.

Automobile Deceleration and Acceleration

The main limitations on the speed of automobiles are the horizontal curves. There is little information available on the deceleration and acceleration of vehicles as affected by changes in horizontal alignment of highways. Thus, in the absence of specific information that could be applied directly, a set of empirical rates based on the extension of values associated with intersection and interchange conditions in the AASHO Geometric Design Policies (5, 6) were developed.

Deceleration rates, which are equivalent to slowing

Figure 1. Example of speed profile.

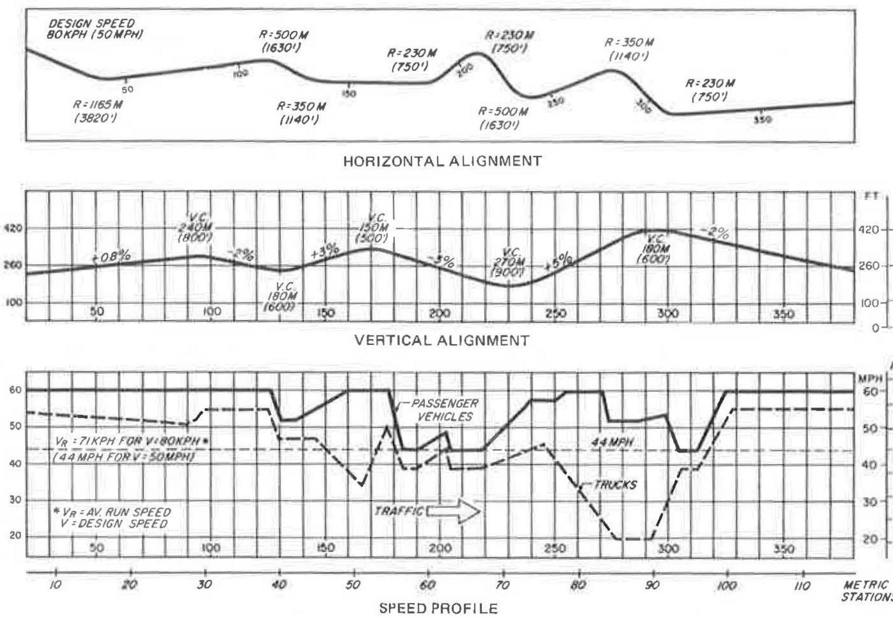


Figure 2. Speed versus curvature relations.

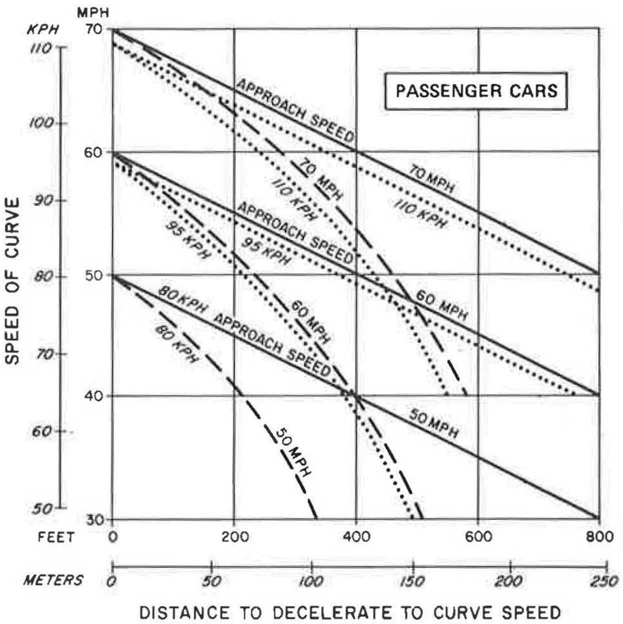
V- DESIGN SPEED, KPH	50			65			80			95			110		125
CORRESPONDING AVERAGE RUNNING SPEED, KPH													92	96	100
										82	86	90	92	96	100
							70	74	78	82	86	90	92 •	→	
				58	62	66	70	74	78	82	86 •	→			
	46	50	54	58	62	66	70	74	78 •	→					
D_M- MAX. DEGREE OF CURVE *	21.0	17.8	14.4	11.9	10.4	8.9	7.5	6.8	5.9	5.1	4.6	4.0	3.7	3.2	2.7
R_M- MIN. RADIUS, METERS	80	95	120	145	165	195	230	255	290	340	375	425	465	540	650

Note: 1 km/h = 0.62 mph; 1 m = 3.28 ft.

* $D_m = 1718.8734 \div R_m$ (BASED ON CENTRAL ANGLE SUBTENDING 30-METER ARC)

•→ FOR A DESIGNATED OR ESTIMATED DESIGN SPEED, ANY LARGER RADII BEYOND THE ARROW ARE ASSUMED TO HAVE THE SAME AVERAGE RUNNING SPEED AS AT THE ARROW.

Figure 3. Deceleration of automobiles approaching a curve that limits the speed.



Deceleration for required speed reduction of *25 KPH* (15 MPH) or less (based on deceleration in gear)

Deceleration for required speed reduction of *30 KPH* (20 MPH) or more (based on "light" braking)

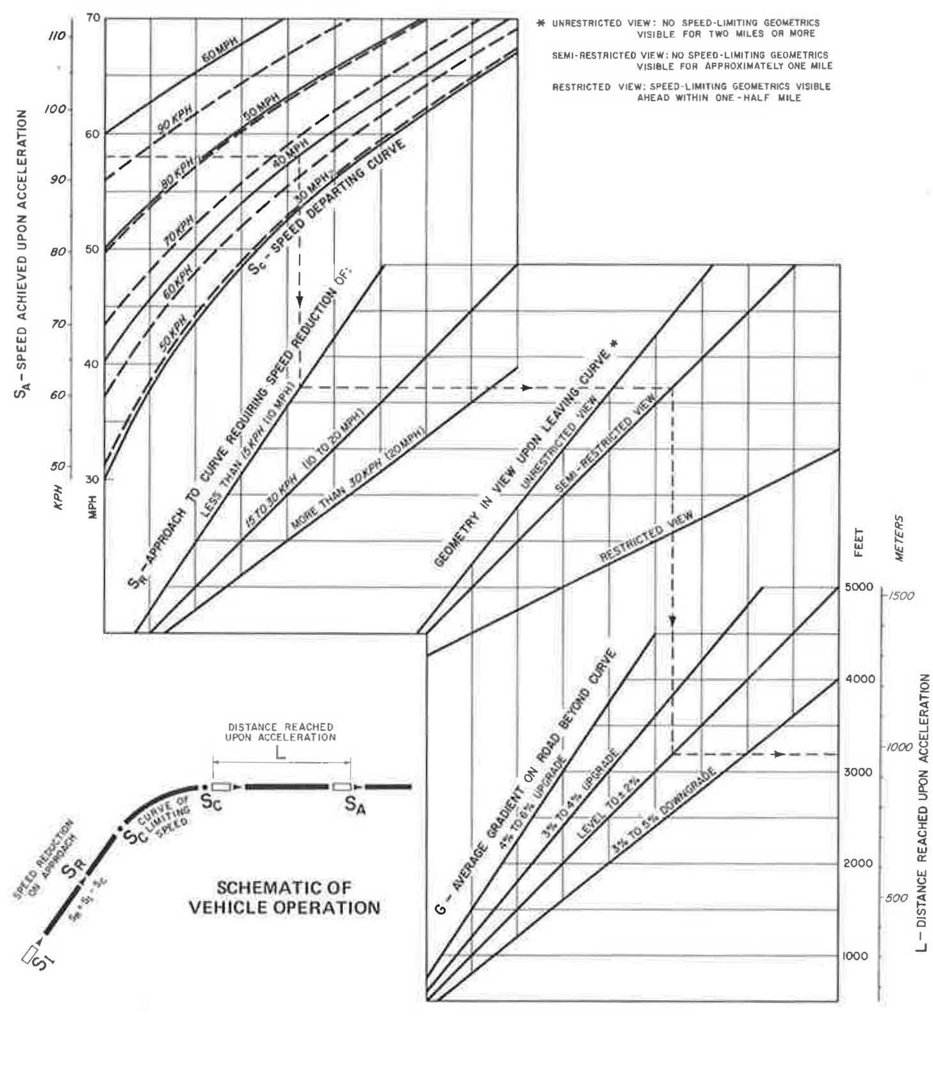
the vehicle in gear, and leisurely rates of deceleration for small and high reductions in speed respectively for approaching horizontal curves have been assumed as shown in Figure 3. The combination of Figures 2 and 3 (5) can be used directly in the development of speed profiles as the vehicle approaches and negotiates a horizontal curve.

The main factors affecting the acceleration of a passenger automobile after encountering a constraint in the alignment are (a) the distance and degree of restrictiveness of the geometry in sight on departing a limiting curve and (b) the difference between the limited speed on the curve being departed and the speed on the road preceding the curve. A driver will accelerate faster on departing a limiting curve if the road ahead has an unrestricted geometry for a considerable distance than if another limiting curve is visible ahead. Also, the more a driver has decelerated in advance of the curve, the faster he or she will accelerate from the curve to regain the previous speed or a higher speed. This rationale and the correspondingly modified normal acceleration rates from the 1965 AASHO Geometric Design Policy (5) were used to develop the speed-change behavioral model given in Figure 4.

Truck Deceleration and Acceleration

The operational characteristics of large trucks are reasonably well documented with respect to gradeability, or speed variations along roadway profiles, but not with respect to changes in horizontal alignment, except for

Figure 4. Acceleration of automobiles departing a curve that limits the speed.



speeds on curves and top average speeds on open highways. Nevertheless, there is sufficient information to assemble a reasonable procedure for the development of their speed profiles.

The weight of the vehicle relative to its power is the most important effect on its speed and on the speed variations as they are influenced by the highway profile (13). Also, vehicles of the same weight to power ratio have similar operating characteristics. Therefore, a representative truck (for purposes of speed characteristics) was established for a given highway or class of highways. An approximately 85th percentile weight to power ratio of the truck population on a given class of highways can be taken as the criterion for a representative truck for design purposes. According to the 1965 Highway Capacity Manual (14), trucks having weight to power ratios of 325 and 200 are typical on two-lane and multilane modern highways respectively, although improvements in truck design continue to lead to lower weight to power ratios.

For purposes of analysis and demonstration in this paper, a typical truck is taken to have a weight to power ratio of 200. The deceleration and acceleration characteristics used to predict speed profiles are predicated on this vehicle.

The speed profile of a truck has two parts. First, the profile with respect to the horizontal alignment, assuming a level or near-level gradeline, must be developed and second, the profile with respect to the vertical alignment only, assuming no restrictions in the horizontal alignment, must be developed. The actual speed profile is then determined as a composite of the two parts.

For the horizontal control portion of the speed profile for trucks, two charts are used—the first for deceleration and the second for acceleration on a level or near-level gradient. Figure 5 [derived from the AASHO 1965 Geometric Design Policy (5) and Leisch and others (10)] can be used to estimate the deceleration of trucks on approaching a horizontal curve that limits the speed. These values were derived on the basis of a 50 percent increase in the deceleration distances for automobiles. This relation is extrapolated from data that indicate that the stopping distances required for trucks are approximately 1.5 to 2 times those for automobiles. This figure is entered at the left with the average speed representative of the curve and reads to the right to the speed of the truck on the approach to the curve and then downward to the distance required to decelerate between the two speeds.

Figure 6 [compiled from Figure 7 and Baluch (11)] can be used to determine the distances required for trucks to accelerate, on level or near-level grades, on departing a horizontal curve that had had a constraining effect on their speed. These relations were compiled from several sources of gradeability characteristics. The figure approximates the distance required for the representative truck to accelerate from the limiting speed

Figure 5. Deceleration of trucks approaching a curve that limits the speed.

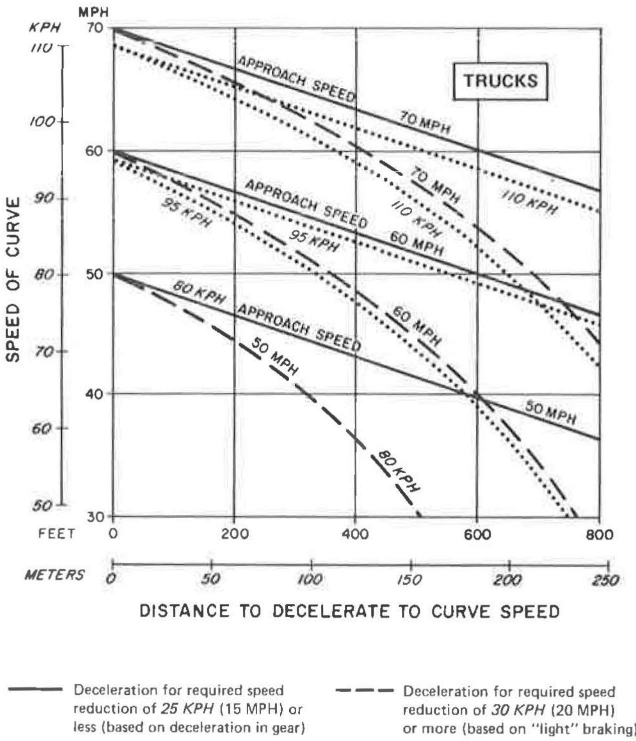
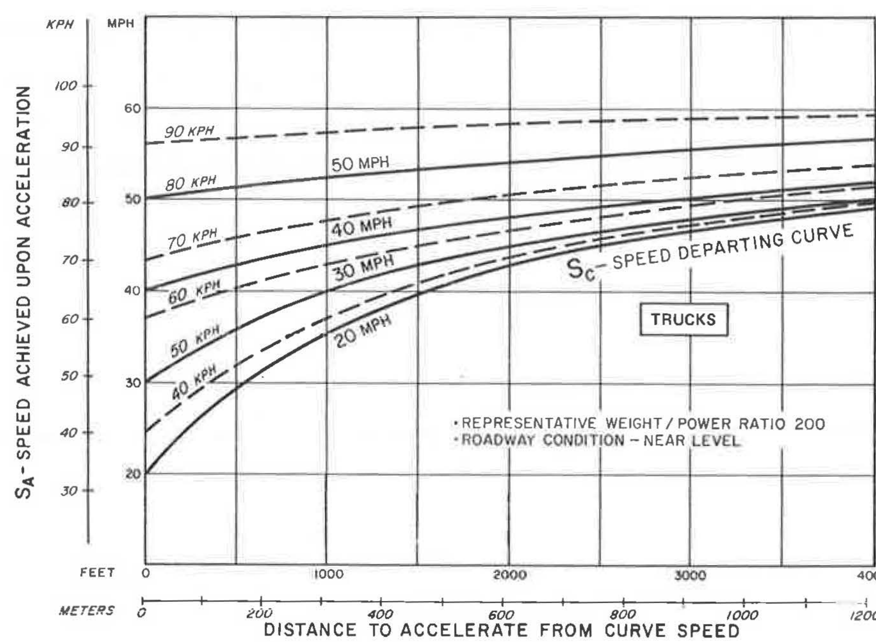


Figure 6. Acceleration of trucks departing a curve that limits the speed.



of the horizontal curve to a given speed beyond the curve.

For the vertical control portion of the speed profile for trucks, the speed versus distance relations give the representative truck. The solid curves show the deceleration distances based on the truck entering an upgrade at a speed of 80 km/h (50 mph). However, a lower entering speed can be used to determine the speed reduction for any distance upgrade by shifting the horizontal axis and, for a higher entering speed, the curves have been extrapolated for grades of 2 percent or more, up to 95 km/h (60 mph). The addition of travel distances to the left of zero will give the total distances along the grade for the various speed changes. After a certain distance of upgrade travel, a minimum constant (crawl) speed is reached.

APPLICATION OF SPEED-PROFILE ANALYSIS AS BASIS FOR DESIGN

The various graphs (Figures 3 through 7), the tabulation in Figure 2, Table 2, and the 8-km/h (5-mph) speed differential between automobiles and trucks can be used for the direct determination of speed profiles for various highways.

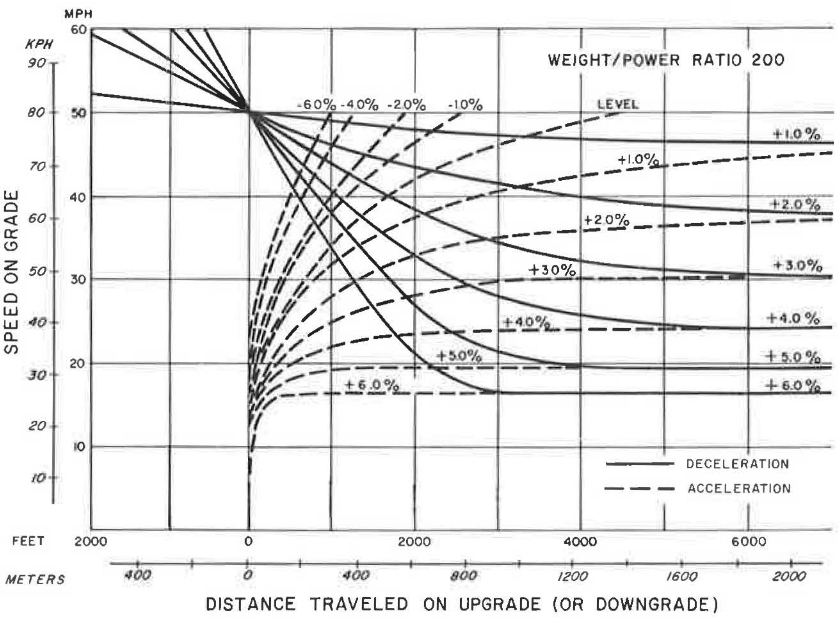


Figure 7. Speed versus distance relations for operation of trucks on grades.

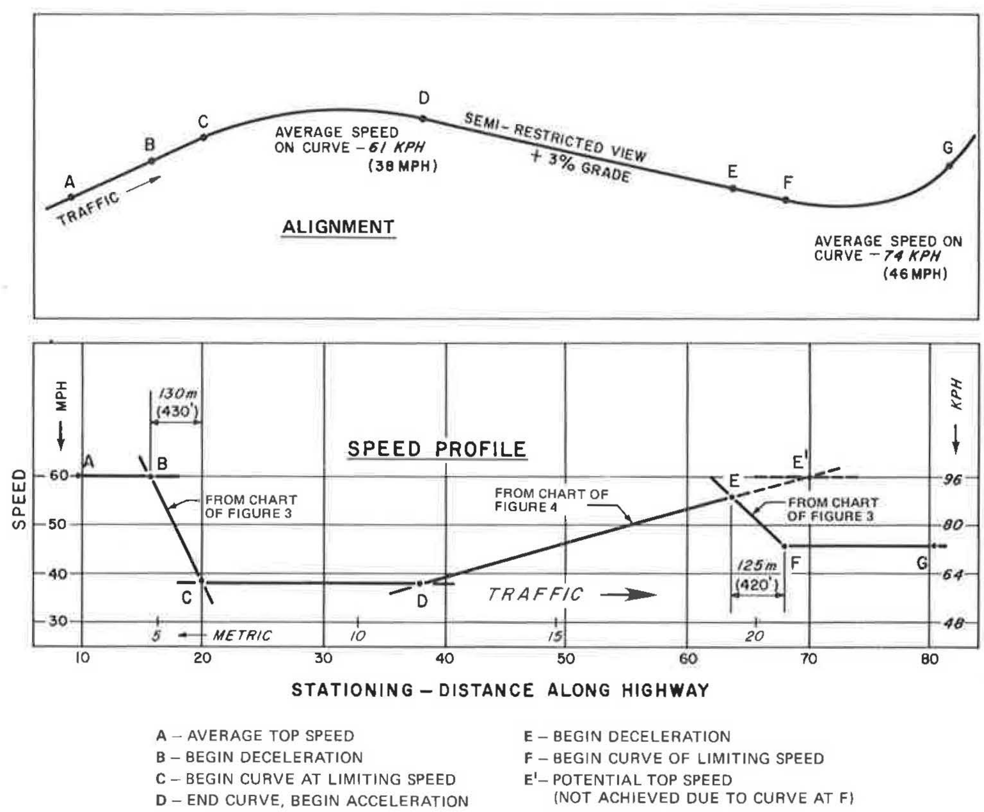


Figure 8. Development of speed profile for automobiles.

The speed profile provides a continuous plot of the average speeds of vehicles along the roadway in each direction of travel at times when the traffic is sufficiently light to represent the condition described as free flowing. By thus charting separate speed configurations, one for a representative automobile and the other for a representative truck, a complete (predicted) record of operating speeds along the course of a highway can be shown graphically. The form of and the associated variations within the speed profile, when plotted and displayed together with horizontal and vertical alignment of the highway, present a picture of the favorable and unfavorable operational characteristics that could not be seen by any other means.

The following illustrations are given to provide a better understanding of how the various charts and related material are used in constructing the speed profile. Figure 8 shows the construction of a speed profile for automobile operations on the indicated alignment. The points labeled A through G designate the principal controls that affect the profile. [The problem assumes that the top average speed is 95 to 96 km/h (60 mph) in agreement with Table 2, which applies to the conditions of the road at point A.] From Figure 2, the horizontal curve C to D (according to its radius) has an average speed of 61 km/h (38 mph). The deceleration approaching this curve at a speed reduction exceeding 30 km/h (20 mph) is 130 m (430 ft) (from Figure 3). The acceleration distance on leaving the curve at point D and driving toward the tentative point E′ is determined from

Figure 9. Use of speed versus distance relations for trucks (Figure 7).

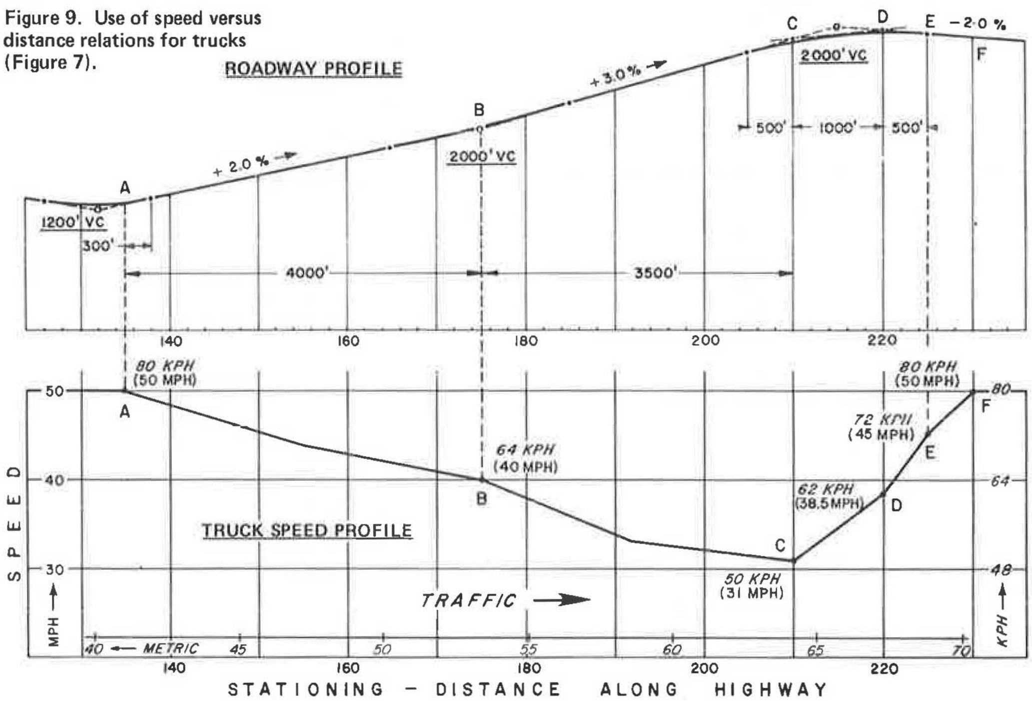


Figure 10. Development of speed profile for trucks.

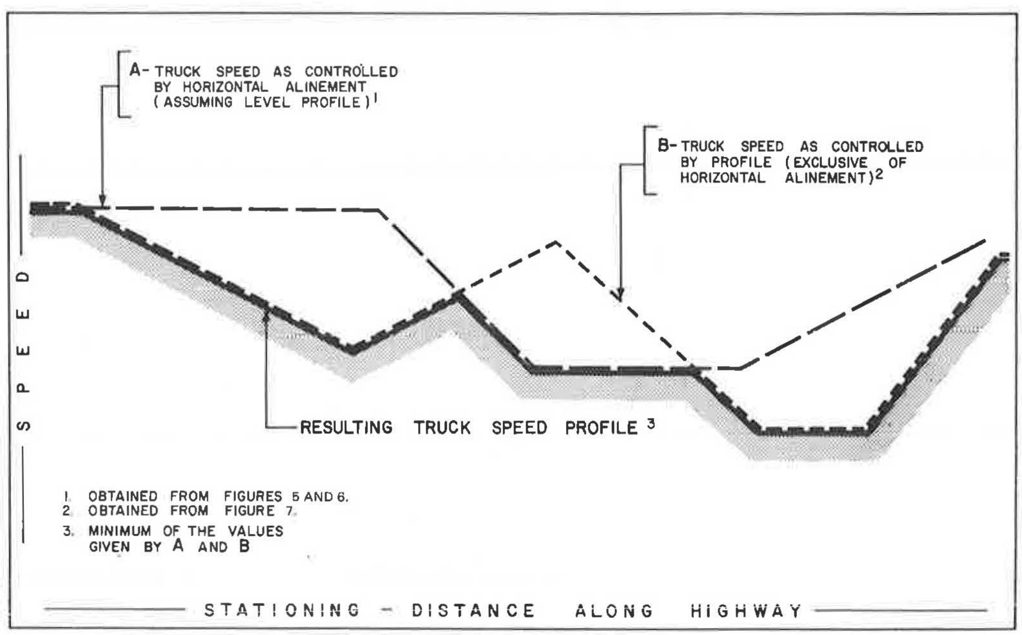


Figure 11. Application of speed profile.

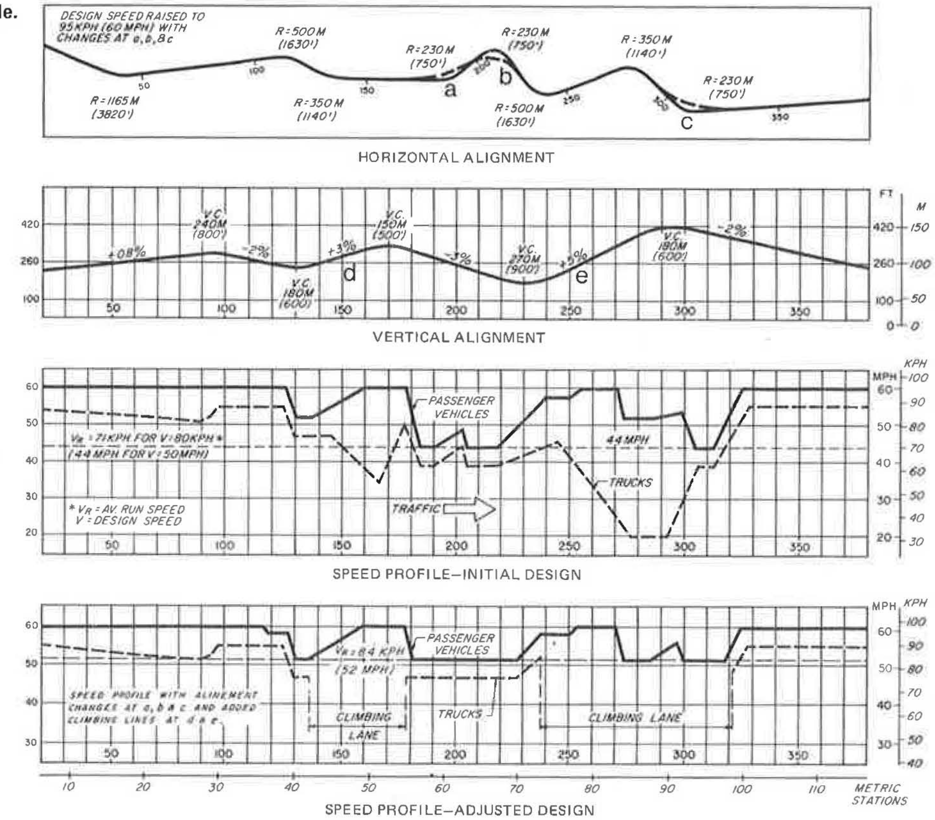


Figure 4. Point E, at which the vehicle begins to decelerate for the next horizontal curve, FG, is determined from Figure 3 by plotting in reverse the deceleration distance between the 74-km/h (48-mph) speed on the horizontal curve and a sufficiently high preselected hypothetical speed on the approach to form the intersection with the previous line. (Occasionally, a second attempt will be required to find the intersection point, if the first hypothetical speed assumed was incorrect.)

Another typical problem is the construction of the speed profile for trucks as controlled by the roadway profile by using Figure 7. An example of the development of a truck speed profile that is controlled by the vertical alignment of the roadway is shown in Figure 9. The technique for the use of Figure 7 by the progressive manipulation of horizontal and vertical projections has been discussed by Leisch (15). In applying the chart of Figure 7 to the roadway profile shown in the upper part of Figure 9, the accompanying truck speed profile was developed directly. It indicates a speed configuration that ranges from an 80-km/h (50-mph) approach to the minimum speed of 50 km/h (31 mph) on the roadway crest at point C and finally through an acceleration to a return to 80 km/h (50 mph) on the downgrade at point F.

The speed profile in Figure 9 is valid if there is no horizontal alignment constraint more severe than the vertical constraint. For this reason, truck speed profiles require the combination of the two effects. The most expedient way to do this is to plot two separate speed profiles for the truck: First, use only the horizontal controls (in effect assuming a near-level gradient) and, second, use only the vertical controls (in effect assuming a horizontally straight or nearly straight road).

The first (horizontally controlled) speed profile is developed in a manner similar to that demonstrated for the automobile (Figure 8). The primary differences are the use of average speeds 8 km/h (5 mph) lower than the corresponding automobile speeds for both the top average speed and the permissible average speed on horizontal curves and the deceleration and acceleration characteristics given in Figures 5 and 6.

The second (vertically controlled) speed profile is developed in the manner shown in Figure 9.

The final truck speed profile is then developed by the combination of the two as shown in Figure 10. The lower line of the combination, which is formed by superimposing the separate profiles, is the resultant truck speed profile and is highlighted by the shaded line.

An application of the speed profile to an actual problem involving an approximately 11-km (7-mile) section of highway is shown in Figure 11. The horizontal and vertical alignments of an existing highway (except for the dashed lines at points a, b, and c) are shown in the two upper blocks of the figure. The combination of the variable horizontal curvature based on the original design speed of 80 km/h (50 mph) and the undulating profile produces highly variable speeds as shown in the third block of the figure. This speed profile (shown for travel in one direction only) reveals the inconsistency of the design and its resulting operations. The speed profile for automobiles indicates variations that require a series of decelerations and accelerations, with changes in average speed of as much as 25 km/h (15 mph). The truck speed profile is even more erratic and shows critical variations not only in truck speeds, but also in the speed differential between automobiles and trucks.

The trouble spots can be easily found by examining the speed profile. The apparent problems are the inability of the alignment to achieve an appropriate design speed and consistent operation for automobiles and the effect of the combination of the horizontal and vertical alignments on truck operations. The lack of conformity to the 15-km/h (10-mph) rule is obvious, as are the locations of the relatively rapid changes in speed and those locations where the speed differential between automobiles and trucks exceeds 15 km/h (10 mph) [at several locations these differences are approximately 40 and 50 km/h (25 and 30 mph)].

Some situations are of particular concern. For example, between metric stations 43 and 50 (stations 140 and 165), trucks are rapidly decelerating, but automobiles are accelerating. Such a condition is very hazardous, particularly in a case such as this where the maximum speed differential between the two types of vehicles is nearly 45 km/h (28 mph). There is another undesirable situation between metric stations 91 and 93 (stations 300 and 305) where automobiles are decelerating to negotiate a horizontal curve, and trucks are continuing to accelerate on a downgrade.

These are some of the more obvious points of concern. A methodical study of the speed profile can provide a thorough insight into the operational characteristics of the highway and spot inconsistencies in the design and potentially hazardous locations. (Although it is ignored here, a plot of a sight-distance profile together with the speed profile can add to the perception of the problem and provide a more thorough diagnosis and evaluation.)

The use of the speed profile on an existing highway immediately shows the means for remedial measures. Any number of improvements can be suggested and depend largely on socioeconomic considerations. A rather minimal improvement that complies with the design principle of the 15-km/h (10-mph) rule is shown in the same figure. These improvements would be the realignment of the three horizontal curves (at a, b, and c) from a design speed of 80 km/h (50 mph) to a design speed of 95 km/h (60 mph) with a change in radius of from 230 to 350 m (750 to 1150 m) and the construction of truck-climbing lanes at locations d and e (approximately) metric stations 42 to 54 and 73 to 98 (stations 137 to 178 and 238 to 322).

The revised speed profile incorporating these improvements is shown in the bottom block of Figure 11. This profile shows compliance with the 15-km/h (10-mph) rule and that the design-speed designation has been changed from 80 to 95 km/h (50 to 60 mph), which provides a more consistent design and uniform operation. The speed variance of automobiles is within 15 km/h (10 mph), and truck speeds on common lanes are no more than 15 km/h (10 mph) lower than the speeds of automobiles. A similar speed profile was developed for travel in the opposite direction and showed the need for further profile adjustments.

SUMMARY

A key to consistent design and built-in operational uniformity for highways has been a goal of designers for the past half century. The principal guideline that has served as a common denominator in design has been expressed through the use of the design speed.

In this paper, the basic principle and intrinsic value of the design-speed concept as it has been used since the early 1940s is maintained as a general guideline, but the scope has been broadened to provide increased sensitivity toward design. The tool used for the updated design approach is the 15-km/h (10-mph) rule. During periods of free-flow conditions, when the design is most meaningful, this rule entails

1. Avoiding design-speed reductions along the highway except where the environment naturally and logically allows for them and maintaining these reductions at or below 15 km/h (10 mph),
2. Maintaining potential automobile speeds along the highway within a given design speed that should not vary more than 15 km/h (10 mph), and
3. Maintaining potential truck speeds at a value no more than 15 km/h (10 mph) lower than automobile speeds on common lanes.

The use of the new design-speed concept requires the application of a special tool—the plotting of a speed profile. The potential automobile and truck speeds are plotted along the proposed highway improvement, with separate plots for each direction, taking into account the joint configurations of the horizontal and vertical alignments and the individual curvatures and gradients.

A complete procedure for the development of speed profiles for free-flow conditions is described. The numerical values of speed and speed change for various conditions were derived from limited data, extensions of minimal research in vehicle operations, empirical speed relations, and experience judgments, but despite lack of direct research in some aspects of the problem, the results are believed to be reasonably accurate for their purposes and can be used effectively immediately.

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