Safety Factors for Road Design: Can They Be Estimated?

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When asked to state the safety of a particular design, highway engineers are at a loss to give a single meaningful measure, as is possible in structural or geotechnical engineering. The question of a meaningful road safety design measure led to a method to estimate the margin of safety and safety index for isolated highway components. The method uses the basic highway alignment design equations and, on the assumption that the variables are independent, normal, and random, the expected value of the mean and variance are estimated and the margin of safety and safety index are derived. The proposed measures of road geometric design safety are the margin of safety and safety index. The variables included in the safety measures represent the characteristics of driver, vehicle, and road surface. Calculations based on preliminary information indicate that the safety index is the most meaningful safety measure for road design. A general method to specify the design parameter's value is also proposed. This method is based on factors that represent the strategic importance of a road, the number of road users, the type of vehicles, the quality of the drivers, the expected environmental conditions, the terrain, and the general standard of design or construction. These factors are all found implicitly in current design procedures. The apparent advantage of the proposed method is that the designer must explicitly specify the importance of the modifying factors. Research is required to make the method useful. The research must clearly develop the mean, variance, and distribution of the variables used in the basic geometric design equations. Further information will eventually be needed on the interaction of the variables, to remove the independence requirement and to permit an estimate of the road system reliability over a specified road link.

Many Canadian authors, including Navin (*1*), Hauer (*2*), and Hutchinson (*3*), have criticized the current road geometric design procedures for failing to meet the established operational safety standards for certain vehicles. In particular, a problem appears to be developing around the differing highway geometric demands for cars and large trucks.

The road geometric design standards by the Roads and Transportation Association of Canada (RTAC) (*4*) or AASHTO (*5*) and operational standards such as *Uniform Traffic Control Devices for Canada* (*6*) and the ITE Handbook (*7*) all work on the implicit assumption that if the published standards have been correctly applied, the road has an adequate margin of safety. This assumption is also accepted by the courts when ruling on the designer's liability for vehicular accidents where road geometry or operation is suspected. One method by which meaningful measures of road safety may be estimated will be outlined.

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The basic assumption is that all the variables used to estimate the design parameters in the elementary geometric design components are independent, normal, random variables. For example, when estimating the stopping sight distance design parameter, speed, perception-reaction time, and coefficient of friction are independent, normal, random variables. The published values of these variables are used in conjunction with expected value methods to obtain estimates of the mean and variance of the design parameters. The expected values are in turn used to calculate measures of road safety.

DEFINITIONS

The fundamental ideas behind the proposed method are those found in limit states design, as used by structural engineers. This approach requires the designer to think of the demand D_0 by driver-vehicle systems for a particular highway design parameter and also of the supply S_0 of this parameter provided by the current highway design standard. The general arrangement for such a system is shown in Figure 1. The driver-vehicle system demand is some random distribution about the mean value of D_0 and that supplied by the highway is the value S_0. In this example, when the supply S_0 is exceeded by the demand D_0 the system is considered to have failed. Failure is thus defined by the engineer or appropriate standard and need not actually result in an accident. A few additional definitions that will be used require explanation.

The simplest measure of safety is the central factor of safety [SF(Central)], which is defined as the ratio of the average

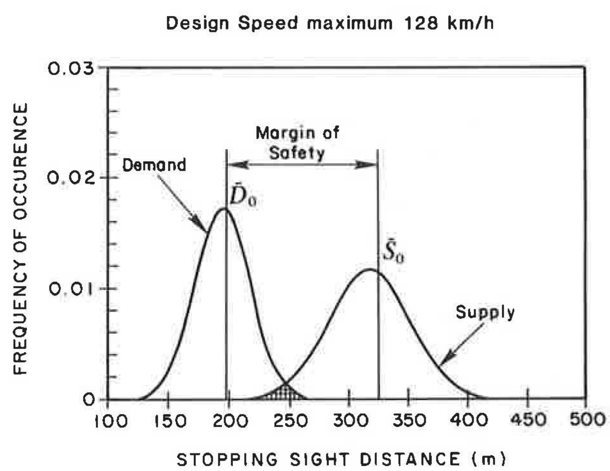

FIGURE 1 Stopping sight distance.

supply $\bar{S}_0$ and the average demand $\bar{D}_0$ (*8*). This value, given in Equation 1, is rarely used.

$$\text{SF(Central)} = \bar{S}_0/\bar{D}_0 \tag{1}$$

The most common measure is the conventional factor of safety. The ratio of the average demand is increased and the supply is reduced, by some multiple of the standard deviation. This approach implies that designers are uncertain about the exact values and allow for more demand and less supply of the parameter, as seen in Equation 2.

$$\text{SF(Conventional)} = \frac{\bar{S}_0 - k\sigma_{S_0}}{\bar{D} + k\sigma_{D_0}} \tag{2}$$

where k is any multiple of the standard deviation (σ).

Extending this idea of uncertainty further, a finite chance exists that the demand will exceed supply; for example, the stopping sight distance required by the driver-vehicle system exceeds that provided by the highway design. The reasons why the demand exceeded supply are not important at this point, but this event may occur, and its occurrence is ascribed to random events rather than gross human error. Ang and Tang (*9*) give the method for deriving the expected value and variance of a design parameter and the derivation of measures of safety. The first measure is the margin of safety M, which is the difference between the expected value of the supply and the expected value of the demand, given in Equation 3. The ratio of the margin of safety and the combined variance, expressed in Equation 4, is defined as the reliability index or safety index (β).

$$M = E\langle S_0\rangle - E\langle D_0\rangle \tag{3}$$

$$\beta = \frac{M}{\sqrt{\text{Var}(S_0) + \text{Var}(D_0)}} \tag{4}$$

The chance of failure given by the safety index may be evaluated by normal probability methods if the variables in the basic equation are a linear combination. If they are not, then the correct chance of failure must be estimated by methods given by Ang and Tang (*9*).

To be accepted, the derived equations must have variables that are easily obtained and useful to both the road designer and road operator. Also, the minimum number of variables should be included in any parameter to keep them reasonably simple. The parameters should be easily understood both by the engineer and nonengineer. Finally, system elements such as road characteristics, driver behavior, and vehicle capabilities must be explicitly considered.

EARLY RESEARCH

The pioneering work by Moyer and Berry (*10*) on marking highway curves with safe speed indications gives the clearest insight into how early highway engineers thought about relative safety. Moyer and Berry (*10*) summarized the research, "The safe speed has largely been determined on the basis of retaining control of the car on the curve." The safe speed on a curve was defined by a 10-degree ball bank reading. They continued, "The general acceptance of this value is rather surprising because it is, after all, an arbitrary value at which the driver of a car senses some discomfort and where the hazard of skidding off the curve becomes apparent." The authors also took driver's attitude into consideration by recommending "14 degrees for speeds below 20 mph, 12 degrees for speeds of 25 and 30 mph, and 10 degrees for speeds of 35 mph and higher." The corresponding friction factors were 0.21, 0.18, and 0.15, for 20 mph, 25 to 30 mph, and 35 mph or higher, respectively. Satisfactory speed levels were indicated by acceptance by "a percentile value of 85 percent for curves of 30 mph or less and 90 percent for curves with speeds of 35 mph." Moyer and Berry (*10*) gave suggestions for rough roads and nighttime speeds. "The only condition in which the ball bank angle of 10 degrees or higher will not indicate the safe daylight speed is when the surfaces are slippery when wet, or ice or snow covered."

Moyer and Berry (*10*) addressed the relative safety of their recommendation.

> While it is true that friction values are lower on wet surfaces than on dry surfaces, . . . there is still a large margin of safety on wet surfaces properly constructed and maintained if the low value of $f = 0.1$ at a ball bank reading of 10 degrees is used . . . .

Further,

> asphalt, concrete and similar types with a gritty surface texture or sandpaper finish provide a wide margin of safety against skidding for speeds with a ball bank value of 10 degrees. . . . This analysis shows that drivers can drive safely at the posted speed on properly constructed and maintained surfaces when wet and even when covered with snow free from ice.

Figure 2 supports these statements by showing the coefficient of friction versus speed, tire conditions, and road surface type. Moyer and Berry (*10*) did not estimate the margin of safety. The method presented here will show how such estimates may be made.

The development of the AASHTO vertical curve design standard contrasts with the pragmatic research of Moyer and Berry (*10*). An excellent summary of the history of stopping sight distance in the United States is given by Hall and Turner (*11*). Neuman (*12*) gives the following overview of the AASHTO policy.

> The minimum sight distance available should be sufficiently long to enable a vehicle traveling at or near the likely top speed to stop before reaching an object in its path. While greater length is desirable, sight distance at every point along the highway should be at least that required for a below-average operator or vehicle to stop.

Vertical curve design reduces to simply determining the driver's eye height and the height of an obstacle on the road, given a budget and a driver's reaction time. The U.S. standard, used in 1940 and adopted in 1954, was an object of 4 in. and an eye height of 4 ft 6 in. Increasing the object from 0 to 4 in. reduced the length of the vertical curve by 40 percent, but above the 4-in. object height, little economic gain was derived. During the 1950s, the driver's eye height dropped,

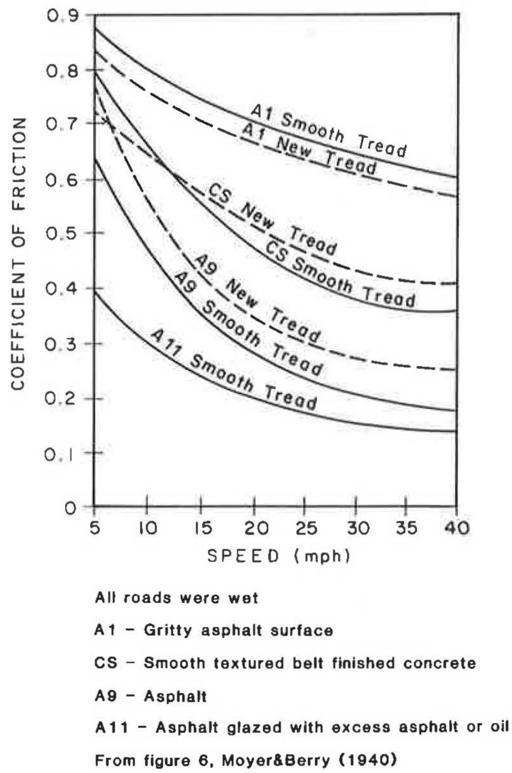

FIGURE 2 Effect of surface texture and surface condition on coefficient of friction for new and smooth-tread tires.

so the 1965 AASHTO Blue Book specified an object height of 6 in. and a driver's eye height of 3 ft 9 in.

The 1965 AASHTO committee thought the "standards adopted in 1954 were somewhat liberal." An object 7 in. high would give a stopping sight distance equal to that of the 1954 standard. The reduction of 1 in. was adopted, because it would be "wise to provide a factor of safety. . . ." In Canada, RTAC 1976 (*4*) recommends a maximum object height of 15 in. and a desirable object height of 6 in. with an eye height of 3 ft 5⁵⁄₁₆ in.

These two examples illustrate the concern that highway engineers have for highway safety and how they have developed design policies, constrained by budgets and the inability to estimate factors such as the margin of safety and a safety index for isolated components of a highway.

STOPPING SIGHT DISTANCE

Theory

Stopping sight distance is fundamental to all geometric design. To calculate the distance, suitable values as set by policy are assigned to the variables of Equation 5. This equation represents the stopping sight distance supplied by the highway as the sum of the driver's perception-reaction distance plus the vehicle's braking distance.

$$\mathrm{SSD}_H = V_H T + \frac{V_H^2}{2\alpha_x^H} \tag{5}$$

where

- SSD = stopping sight distance (m),
- V = velocity (m/sec),
- T = perception-reaction time (sec),
- α = deceleration rate (m/sec²),
- H = highway,
- x = longitudinal axis of highway,
- D = driver, and
- v = vehicle.

For the driver-vehicle system, which is assumed to have small random errors, the corresponding expected values of the mean and variance are

$$\mathrm{E}\langle\mathrm{SSD}_v\rangle = V_D T_D + \frac{V_D^2}{2\alpha_x^v} + \frac{V_D^2\left(\sigma^2_{\alpha_x^v}\right)}{2(\alpha_x^v)^3} + \frac{\sigma^2_{V_D}}{2\alpha_x^v} \tag{6}$$

$$\mathrm{Var}\langle\mathrm{SSD}_v\rangle = V_D^2\sigma_{TV}^2 + \frac{V_D^4\left(\sigma^2_{\alpha_x^v}\right)}{4(\alpha_x^v)^4} + \left(T_D^2 + 2\frac{V_D T_D}{\alpha_x^v} + \frac{V_D^2}{(\alpha_x^v)^2}\right)\sigma^2_{V_D} \tag{7}$$

where σ denotes the standard deviation of the corresponding distribution.

The stopping sight distance demanded by the driver-vehicle system depends on the speed V_D that the driver selects, his or her perception-reaction time T_D, and the stopping capabilities of the vehicle. No relationship is assumed between the driver's ability to brake the vehicle and the vehicle's ability to stop. This complexity may be included and will no doubt influence the numerical results, but adds little to the arguments being presented.

The general relationship between the stopping sight distance supplied by highway design and the distance demanded by the driver-vehicle system may be either a single value from the design manual or the actual value supplied after construction and changes over time with the quality of the road. A single design value has been assumed for simplicity of the arguments, even though most of the equations are derived for the more general case. Failure is defined as when the demanded stopping sight distance exceeds the distance supplied. To compare the supply and demand, the measures of interest are the margin of safety and the reliability or safety index, as previously defined.

The margin of safety for stopping sight distance is the difference between the stopping sight distance supplied by the highway and that demanded by the driver-vehicle system, given by the following equations:

$$M(\mathrm{SSD}) = E\langle\mathrm{SSD}_H\rangle - E\langle\mathrm{SSD}_v\rangle \tag{8}$$

$$\mathrm{Var}\langle M(\mathrm{SSD})\rangle = \mathrm{Var}\langle\mathrm{SSD}_H\rangle + \mathrm{Var}\langle\mathrm{SSD}_v\rangle \tag{9}$$

The safety index for stopping sight distance is as follows:

$$\beta\,(\mathrm{SSD}) = \frac{E\langle\mathrm{SSD}_H\rangle - E\langle\mathrm{SSD}_v\rangle}{\sqrt{\mathrm{Var}\,(\mathrm{SSD}_H) + \mathrm{Var}\,(\mathrm{SSD}_v)}} \tag{10}$$

If the AASHTO standard is used for the highway, then the safety index is as follows:

$$\beta\,(\mathrm{SSD}) = \frac{\mathrm{SSD}_H - E\langle \mathrm{SSD}_v \rangle}{\sqrt{\mathrm{Var}\,(\mathrm{SSD}_v)}} \tag{11}$$

The evaluation of the probability of failure from Equations 10 and 11 requires methods explained by Ang and Tang (*9*), because of the nonlinear combination of variables. The safety index used represents the situation in which the demand is random and the supply is fixed as a single value.

Estimated Values

The mean and standard deviation of the variables used in the stopping sight distance calculation are presented in Table 1. Few sources of good, basic data are available to precisely define the statistical nature of the variables. The graphical results for the lower AASHTO standard are shown in Figure 3. If these values are reasonable, the resulting margin of error and safety index are as follows:

- AASHTO high values (variance set to zero) compared to driver-vehicle system: SSD_H is 198 m, margin of safety is 61 m, safety index is 1.22, and chance of failure is about 1 in 10.
- AASHTO low values (variance set to zero) compared to driver-vehicle system: SSD_H is 160 m, margin of safety is 23 m, safety index is 0.42, and chances of failure are about 3 in 10.

Failure has been defined as the driver-vehicle system's demanding a stopping sight distance greater than that prescribed by the highway design. Failure may or may not result in a serious physical outcome, depending on particular circumstances.

The distribution of margin of safety is the normal distribution, shown in Figure 4. The two values plotted are AASHTO low, which represents the highway supply, and the driver-vehicle system, which represents the demand. The margin of safety distribution $f(M)$ is as follows:

$$f(M) = \frac{1}{[2\pi\,\mathrm{Var}\,(M)]^{1/2}} \exp\left\{-\left[\frac{(M - \overline{M})^2}{2\,\mathrm{Var}\,(M)}\right]\right\} \tag{12}$$

TABLE 1 VALUES FOR STOPPING SIGHT DISTANCE (SSD) VARIABLES

Variable	Unit	Highway, AASHTO		Driver/Vehicle	
		High	Low		Source
V	km/h	95	85	80	AASHTO (5)
T	s	2.50	2.50	1.35	Olsen (13)
α_x	g	0.29	0.29	0.24	Navin (1)
σ_V	km/h	0	0	8.0	Olsen (13)
σ_T	s	0	0	0.18	Olsen (13)
σ_a	g	0	0	0.06	Navin (1)
SSD calculated	m	188	154	137	
SSD design	m	198	160		

The distribution of Figure 4 gives an indication of how an acceptable value of margin of safety might be estimated and then explained to those who set policies for acceptable safety index values.

HORIZONTAL CURVE

Theory

This analysis is similar to that for the stopping sight distance. The failure mode is assumed to be a vehicle rollover measured by the radius of turn. The highway's radius of curve is given by the following equation:

$$R_H = \frac{V_H^2}{\alpha_y^H} = \frac{V_H^2}{(e^H + f_y^H)g} \tag{13}$$

where

R_H = radius of curve (m),
V_H = highway design speed (m/sec),

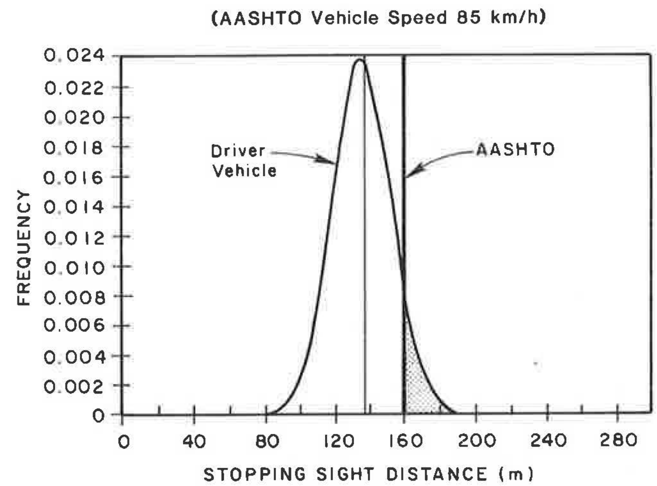

FIGURE 3 Stopping sight distance (SSD) distribution.

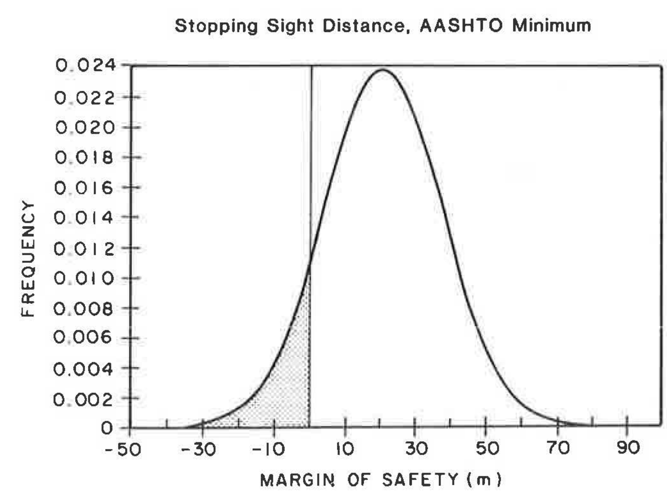

FIGURE 4 Margin of safety (*M*) distribution.

g = acceleration of gravity (9.8 m/sec²),
α_y^H = highway design lateral acceleration (m/sec²),
e^H = highway superelevation (m/m), and
f_y^H = highway lateral friction factor.

The expected radius demanded by the driver-vehicle system (R_D), assuming the vehicle velocity and rollover threshold acceleration are normally distributed, independent, random variables, is

$$E\langle R_D\rangle = \frac{V_D^2}{\alpha_y^v} + \frac{V_D^2\left(\sigma^2_{\alpha_y^v}\right)}{(\alpha_y^v} + \frac{\sigma^2_{VH}}{\alpha_y^v} \tag{14}$$

The variance is

$$\mathrm{Var}\langle R_D\rangle = \frac{V_D^4\left(\sigma^2_{\alpha_y^v}\right)}{(\alpha_y^v)^3} + 4\frac{V_D^2}{(\alpha_y^v)^2}\sigma^2_{V_D} \tag{15}$$

The margin of safety for radius is defined as the difference between the supply of the highway and the demand of the driver-vehicle system.

$$M(R) = R_H - E\langle R_D\rangle \tag{16}$$

The difference between the radii of turn is the suggested measure, even though this measure is not as intuitive as, for example, the stopping sight distance. The radius was selected because it is a physical design parameter that is easily related to the vehicle's velocity and threshold rollover acceleration. The lower the radius demanded by the driver-vehicle speed or stability, the safer the turning maneuver. Only when the radius demanded by the driver-vehicle system exceeds that provided by the highway should the curve fail insofar as the available radius has been exceeded.

Setting R_H as the single AASHTO value, the safety index for radius becomes

$$\beta\ (R) = \frac{R_H - E\langle R_D\rangle}{\sqrt{\mathrm{Var}\langle R_D\rangle}} \tag{17}$$

Equations 14 and 17 form the base of the remaining measures. These equations have factors that represent the highway design elements (H), the driver (D), and the vehicle (v). These are the elements considered important for both design and analysis.

Estimated Value

The failure of a driver-vehicle system on a highway curve may be either a rollover or a slide-out. Cars will usually slide out and trucks roll over. The rollover mode of failure is assumed. The values of the variables are from Moyer and Berry (*10*) for the original design decisions and from the University of Michigan Transportation Research Institute (*14*) and Navin (*1*) for modern tractor-trailer rollover.

Moyer and Berry, in discussing the margin of safety of their proposal to use a ball bank reading of 10 degrees, stated,

> As is evident . . . considerably higher friction values than 0.15 and higher speeds than that for a ball bank reading of 10 degrees are possible. . . . This is most evident on the sharper ones, such as the 61-ft and the 100-ft radius curves. On these curves, friction values close to 0.5 were developed at speeds almost double the safe speed based on a ball bank reading of 10 degrees. The ride at these speeds was far from comfortable and the limit of steering control was not far off; in fact, the path of the car was increasingly uncertain as the top speeds of these curves were approached.

Using the values of R, f_y, and V given by Moyer and Berry (*10*) in their Figure 5, the safety margins for the rollover failure mode are presented in Table 2. The very sharp curve (R = 18.6 m) has an estimated 2.6-m margin of safety at the recommended safe speed, and the slightly longer one has a 29.1-m margin of safety. At the limiting speed of the curves, the margin of safety is −0.9 m or more for the sharpest curve and 6.9 m for the longer. This simple analysis does not prove that the definition of margin of safety is correct, but it gives it some credibility on the basis of Moyer and Berry's (*10*) description of vehicle handling.

When the design speed is set at 95 km/hr with f_y equal to 0.12 and e_H equal to 0.06, and the operating speed is set at 85 km/hr (σ_v = 8.0 km/hr), and a vehicle's α_y^v equals 0.45 g (σ_α = 0.08g), the results shown in Figure 5 are determined.

If tractor-trailer rollover is the design criteria, the AASHTO design safe-speed radius of turn is 410 m and $E\langle R_{\text{veh}}\rangle$ is 116 m. The average margin of safety is 294 m and the chance of a random rollover failure is remote. Another method of calculating a more realistic failure probability of about 1 in 100,000 is given in Navin (*15*). Similar calculation for a car places β such that failure by rolling over is remote. These computations show how the process may be used to arrive at acceptable estimates of a safe curve. They do not necessarily represent actual margins of safety.

DECISION SIGHT DISTANCE

Theory

The decision sight distance is associated with high-speed roads where stopping is not permitted and decisions must be made while speeds are maintained. The failure mode in such circumstances is assumed to occur when the driver requires a distance greater than that provided by the highway. The fact that a failure may occur by technical definition does not

TABLE 2 ESTIMATED MARGIN OF SAFETY (M) ON A CURVE

		Curve 1		Curve 2	
Variable	Unit	Safe Speed	Driving Limit	Safe Speed	Driving Limit
f_y		0.14	0.46	0.14	0.48
V	m/s	5.4	8.9	11.2	17.9
R_v	m	22.2	17.1	90.1	67.9
R_H	m	18.6	18.7	61.1	61.0
M	m	2.6	-0.9	29.1	6.9
M/R_H	%	14	-5	48	11

necessarily mean that the physical result is an accident. The design relationship used to estimate decision sight distance is

$$DSD_H = (T_P + T_D + T_M)V_H \tag{18}$$

where

DSD = decision sight distance (m),
T_P = perception time (sec),
T_D = decision time (sec), and
T_M = maneuver time (sec).

The expected value and variance for the driver-vehicle system are given by the following equations:

$$E\langle DSD_D\rangle = (T_P + T_D + T_M)V_D \tag{19}$$

$$\mathrm{Var}\langle DSD_D\rangle = (\sigma^2_{TP} + \sigma^2_{TD} + \sigma^2_{TM})V^2_D + (T_P + T_D + T_M)^2\sigma^2_{VD} \tag{20}$$

Using Equations 3, 4, 19, and 20, the safety margin and safety index for decision sight distance are as follows:

$$M(DSD) = DSD_H - E\langle DSD_D\rangle \tag{21}$$

$$\beta\ (DSD) = \frac{DSD_H - E\langle DSD_D\rangle}{\sqrt{\mathrm{Var}\langle DSD_D\rangle}} \tag{22}$$

The safety index is easily computed in this case, because the variables in the basic equation are a linear combination and the normal probability tables may be used.

Estimated Value

The values from Table 3 and Equations 21 and 22 are used to produce the following results. The mean and variance of the various times are estimated from data spread throughout the ITE handbook (*7*). The safety margin and safety index are calculated using the decision sight distance recommended for design purposes.

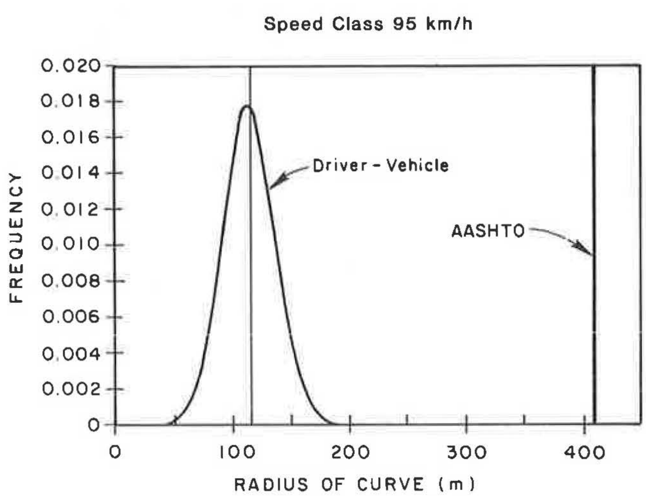

FIGURE 5 Radius (*R*) of horizontal curve.

TABLE 3 VALUES FOR DECISION SIGHT DISTANCE (DSD) VARIABLES

Variable	Unit	Highway, ITE		Driver/Vehicle	
		High	Low		Source
V	km/h	95	85	80	ITE(7)
T_P	s	3.0	2.0	2.5	ITE(7)
T_D	s	7.0	4.7	5.9	ITE(7)
T_H	s	4.5	4.5	4.5	ITE(7)
σ_V	km/h	0	0	10.0	Olsen (13)
σ_{TP}	s	0	0	2.0	McGee* (16)
σ_{Tn}	s	0	0	5.7	McGee (16)
σ_{TM}	s	0	0	1.7	McGee (16)
SSD calculated	m	382	296	287	
SSD design	m	389	305		

* Used ratio of mean to standard deviation from observed data, also used Triggs (17).

- ITE high values (variance set to zero) compared to driver-vehicle system: DSD_H is 389 m, margin of safety is 102 m, safety index is 1.38, and chances of failure are about 4 in 10.
- ITE low values (variance set to zero) compared to driver-vehicle system: DSD_H is 305 m, margin of safety is 18 m, safety index is 0.06, and chances of failure are about 5 in 10.

PASSING SIGHT DISTANCE

Theory

Passing sight distance is associated with the design of two-lane roads and helps determine their level of service. The determination of the passing sight distance is based on observation and calculated as follows:

$$PSD_H = (V - m)t_1 + {}^1\!/\!_2\alpha t_1^2 + {}^5\!/\!_3 V t_2 + d_3 \tag{23}$$

where

PSD = passing sight distance (m),
V = speed of passing vehicle (m/sec),
m = speed difference between vehicles (m/sec),
α = acceleration of passing vehicle (m/sec^2),
t_1 = preliminary delay time (sec),
t_2 = time that vehicle occupies passing lane (sec), and
d_3 = safety distance (m).

This formulation accounts for the preliminary delay distance when the faster vehicle must decide to pass the slower, the overtaking distance, a safety distance between the faster vehicle and the approaching vehicle, and the distance traveled by the approaching vehicle during much of the maneuver. Assuming all the variables are independent, random, normal variables results in the expected value and variance, as follows:

$$E\langle PSD_v\rangle = (V_v - m_D)t_1 + {}^1\!/\!_2\alpha t_1^2 + {}^5\!/\!_3 V_D t_2 + {}^1\!/\!_2\alpha\sigma^2_{t1} + d_3 \tag{24}$$

$$\mathrm{Var}\langle \mathrm{PSD}_D\rangle = (V_D - m_D + \alpha t_1)^2\sigma_{t1}^2 + (5/3 V_D)^2\sigma_{t2}^2 + (1/2 t_1^2)^2\sigma_\alpha^2 + t_1^2\sigma_{mD}^2 + (t_1 + 5/2 t_2)^2\sigma_{VD}^2 + \sigma_{d3}^2 \quad (25)$$

The margin of safety and safety index for passing sight distance are estimated by

$$M(\mathrm{PSD}) = \mathrm{PSD}_H - E\langle \mathrm{PSD}_D\rangle \quad (26)$$

$$\beta\ (\mathrm{PSD}) = \frac{\mathrm{PSD}_H - E\langle \mathrm{PSD}_D\rangle}{\sqrt{\mathrm{Var}\langle \mathrm{PSD}_D\rangle}} \quad (27)$$

The value of the safety index comes from a nonlinear combination of variables, and the probability of failure must be estimated by methods given by Ang and Tang (*9*).

Estimated Values

Values from Table 4 and Equations 24 through 27 are used to produce the following results. The mean and variance of the various times are estimated from data in Lay (*18*) and Hobbs and Richardson (*19*). The passing speed for design was set at the highway's design speed. The average for the passed vehicle was set lower. According to Hobbs and Richardson (*19*), the passing sight distance specified by design is able to accommodate 95 percent or more of all the passing operations. The safety margin and safety index are calculated using the passing sight distance recommended for design purposes.

- ITE high values (variance set to zero) compared to driver-vehicle system: PSD_H is 640 m, margin of safety is 102 m, safety index is 1.28, and chance of failure is about 1 in 10.
- ITE low values (variance set to zero) compared to driver-vehicle system: PSD_H is 305 m, margin of safety is −233 m, and safety index has a value of −4.07, which implies that it is inadequate about 99 times out of 100.

TABLE 4 VALUES FOR PASSING SIGHT DISTANCE (PSD) VARIABLES

Variable	Unit	Highway		Driver/Vehicle	
		High	Low		Source
V	km/h	95	88	80	Hobbs (19)
m	km/h	16	16	16	Hobbs (19)
α	g	0.19	0.19	0.15	Hobbs (19)
t_1	s	4.3	4.3	4.3	Hobbs (19)
t_2	s	10.7	10.7	10.0	Rockwell (20)
d_3	m	76	76	76	
σ_V	km/h	0	0	8.0	Olsen (13)
σ_m	km/h	0	0	4.0	estimated*
σ_α	g	0	0	0.04	estimated
σ_{t_1}	s	0	0	1.0	estimated
σ_{t_2}	s	0	0	1.0	estimated
σ_{d_3}	m	0	0	20	estimated
PSD calculated	m	671	616	538	rounded
PSD design	m	640	305		

* The estimated values come from a general reading through the Human Factors literature, Rockwell (20). The low value is used for pavement markings. Additional information may be found in Ohene (21).

VERTICAL CURVE

Theory

The design of vertical curves is based on stopping sight distance as determined by eye and object height for crest curves and headlight beam for sag curves. The following formulation is for crest curves with the stopping sight distance shorter than the length of the vertical curve; the curvature is estimated by the factor K_H, given as

$$K_H = \frac{(\mathrm{SSD}_H)^2}{100F^2} \quad (28)$$

where

$F = (2h_1)^{1/2} + (2h_2)^{1/2}$,
h_1 = eye height (m), and
h_2 = object height (m).

Given that all the variables are normal, independent, and random, the expected value and variance are as follows:

$$E\langle K_D\rangle = \frac{S_D^2}{100}F^{-2} + \frac{2}{100}F^{-2}\sigma_{sD}^2 + \frac{S_D^2}{100}F^{-3}[3F^{-1}(2h_1)^{-1/4} + 2(2h_1)^{3/2}]\sigma_{h1}^2 + \frac{S_D^2}{100}F^{-3}[3F^{-3}(2h_2)^{-1/4} + 2(2h_2)^{-3/2}]\sigma_{h2}^2 \quad (29)$$

$$\mathrm{Var}\langle K_D\rangle = \left[\frac{S_D^2}{100}F^{-3}(2h_1)^{-1/2}\right]^2\sigma_{h1}^2 + \left[\frac{S_D^2}{100}F^{-3}(2h_2)^{-1/2}\right]^2\sigma_{h2}^2 + \left[2\frac{S_D^2}{100}F^{-2}\right]^2\sigma_{sD}^2 \quad (30)$$

The margin of safety for the crest vertical curve is

$$M(K) = K_H - E\langle K_D\rangle \quad (31)$$

The following safety index must be evaluated by the methods given by Ang and Tang (*9*), because the basic relationship is not a linear combination of variables.

$$\beta\ (k) = \frac{K_H - E\langle K_D\rangle}{\sqrt{\mathrm{Var}\langle K_D\rangle}} \quad (32)$$

Estimated Value

The values from Table 5 and Equations 29 through 32 are used to produce the following results. The mean and variance

TABLE 5 VALUES FOR VERTICAL CREST CURVE VARIABLES

Variable	Unit	Highway		Driver/Vehicle	
		High	Low		Source
S	m	eqn 5	eqn 5	eqn 6	
h_1	m	1.07	1.07	1.07	AASHTO (5)
h_2	m	0.15	0.15	0.15	AASHTO (5)
σ_s	m	0	0	eqn 7	
σ_{h1}	m	0	0	0.007	ITE'65 (22)
σ_{h2}	m	0	0	0.01	estimated*
K calculated	m	88	61	47.2	
K design	m	95	58		

*The estimated values come from a general reading of the driver, Chapter 3, Figure 3.6 of the Traffic Engineering Handbook, Washington, D.C., 1965 (22).

eye height are estimated from data from ITE (*22*). The safety margin and safety index are calculated using the stopping sight distance recommended for design purposes.

- AASHTO high values (variance set to zero) compared to the driver-vehicle system: K_H is 95, margin of safety is 48, safety index is 2.72, and chances of failure are about 3 in 1,000.
- AASHTO low values (variance set to zero) compared to driver-vehicle system: K_H is 58, margin of safety is 11, safety index is 0.49, and chances of failure are about 3 in 10.

The margin of safety in this context is not as intuitive as that for stopping sight distance, but the safety index when stated as a chance of failure is easily understood.

RESULTS

The preceding calculations are summarized in Table 6. The standard design parameter values supplied by the highway are given in the first column. The expected demands by the driver-vehicle system are in the second column. The difference between the highway and driver-vehicle system is the margin of safety. An estimate of the safety index for the isolated components is given in the last column (chance of failure).

The margin of safety is a convenient safety measure for design parameters, such as stopping sight distance or radius of turn, but not for geometric elements such as vertical curvature, K. The safety index appears to be a more useful measure for comparative purposes. When stated as a probability of failure, the safety index is an effective measure. Failure is defined simply as the driver-vehicle system demand exceeding the highway's supply of a particular design parameter. In this case, the consequence of a failure may be speculated, and, given its probability, the risk may be estimated as the product of the consequence and its probability of occurrence. If all the consequences of failure are identical, then, to have a highway with uniform risk, the components would be designed to have an identical chance of failure.

Actually designing highways by a procedure that is similar to that used by structural engineers for buildings appears to be feasible. The procedure is simple in concept. If the mean, variance, and distribution of a particular driver-vehicle design parameter are known, this value can be increased to reflect

TABLE 6 HIGHWAY AND DRIVER-VEHICLE DESIGN PARAMETERS

Design Parameter		Unit	AASHTO or ITE	Driver Vehicle	Safety Margin	Safety Index	Chance of Failure
SSD	high	m	198	137	61	1.22	1:10
SSD	low	m	160	137	23	0.42	3:10
R	truck	m	410	116	294	55	remote
	car	m	410	79	331	--	remote
DSD	high	m	389	286	102	1.35	4:10
DSD	low	m	305	286	18	0.06	5:10
PSD	design	m	640	538	102	1.28	1:10
PSD	paint	m	305	538	-233	-4.07	99:100
K	desirable		95	47	48	2.72	3:1,000
(crest)	low		59	47	11	0.46	3:10

uncertainty and the importance of the road link. The procedure is summarized in the design Equation 33 for parameter P.

$$\phi P_H \geq SETDetd(P_{D/v}) \quad (33)$$

where

ϕ = performance factor,
S = highway system importance,
E = exposure factor,
T = traffic mix,
D = driver mix,
e = environmental factor,
t = terrain factor, and
d = desired design or construction standard.

The value of the parameter $P_{D/v}$ is taken from observation of the driver-vehicle system. Factors alter this observed value on the basis of the strategic importance of the road, the number of road users, the types of vehicle, the quality of drivers, expected environmental conditions, the terrain, and the overall design and construction standard required. The performance factor ϕ reduces the roads' supplied characteristics to some acceptable level. A general organization of the relationship between the demanded driver-vehicle parameter and the highway supply is shown in Figure 6. The highway supply may also be subject to changes experienced over time. Also, the driver-vehicle system demand need not be independent of the supply. Most of the factors are already implicitly considered in road design. The strength of the proposed procedure is that it requires the designer to explicitly specify the factors.

The problems that remain are (a) determining that there are advantages to explicitly defining the design parameter of a highway, and (b) actually developing the basic driver-vehicle system information and the factors by which it may be modified.

REQUIRED RESEARCH

The margin of safety and safety index for isolated geometric sections of a highway can be estimated. However, basic infor-

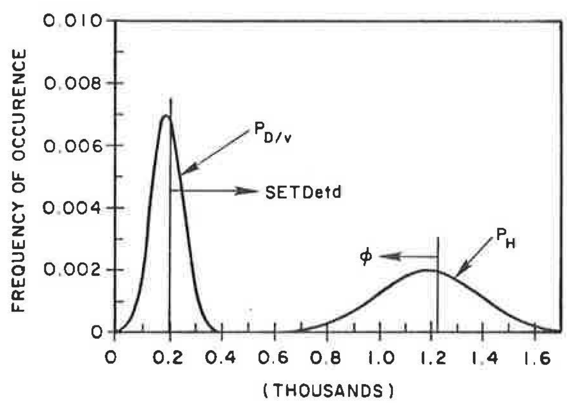

FIGURE 6 General highway design parameters (*P*).

mation on limits to various driver and vehicle performance measures is lacking. To correct this, detailed experiments and onsite observations must be undertaken to establish performance limits for normal operations, human tolerance, and vehicular road limits. Also, the statistical nature and interaction of phenomena such as operating speed, perception reaction time, vehicle deceleration rates, vehicle lateral acceleration rates, passing speeds, and others as indicated in the equations and as related to road geometry need to be studied.

In addition to these statistical distributions, consideration must be given to the appropriate values to use in the equations, as well as the acceptable safety margin and safety index for various types of roads. Finally, some method must be devised to convey the information on relative levels of safety to the various vehicle populations in operating conditions.

CONCLUSIONS

Early researchers such as Moyer and Berry (*10*) explicitly recognized the problems of margin of safety. Using the ball bank indicator, car driver reactions, and observations, they developed a procedure that provided, in their judgment, a reasonable margin of safety. Moyer and Berry and other researchers of the day were limited by instrumentation, in particular reliable accelerometers, and could not estimate the margin of safety. If they could have, they would no doubt have included variables representing the driver, the vehicle, and the road.

The margin of safety and safety index may be estimated using the methods outlined for all isolated geometric sections of a road. The equations also allow individuals or agencies to set, as a policy, the accepted chance of failure at an isolated component. Once such a policy is accepted, it is possible to calculate the correct design value, provided the demand function and supply variance are known.

Further research should be undertaken to explore the usefulness of these equations. The equations appear to hold some promise that a reasonable measure of safety may be estimated for isolated components of the road.

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