UCI-ITS-WP-85-5

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July 1985

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NEW STOCHASTIC APPROACH TO GEOMETRIC DESIGN OF HIGHWAYS

by
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This paper addresses deficiencies found in the current practice of highway geometric design and presents an alternative approach which achieves more meaningful and cost effective design. Current design practice suffers from vague definition of the design speed concept, is very inflexible, is insensitive to traffic volume and composition, does not explicitly consider cost factors, and is very costly. These deficiencies are primarily attributed to the deterministic approach utilized by current design practice. While all factors involved in the geometric design process (i.e., speed, friction, reaction time, etc.) are stochastic in nature and are fully distributed among the road users, the current approach relies on a single arbitrarily chosen value to represent each factor.

This paper presents an alternative approach to geometric design of highways. This approach is fully sensitive to the real conditions of the design problem at hand (i.e., the traffic volume and composition), because it incorporates the stochastic nature of the various factors involved into the design process. The proposed approach also achieves an optimal, or a cost-effective, design which takes into account all the cost elements associated with the highway. An empirical example of horizontal curve design is presented to demonstrate the advantages of the proposed approach.

1.0 INTRODUCTION

This paper addresses the deficiencies found in the current practice of geometric design of highways, and presents an alternative approach which achieves more meaningful and cost effective design.

Current geometric design practice is heavily based on design standards, and uses the following design process. First, the highway section to be designed is classified into one of the highway types (i.e. freeway, arterial, local, etc.); then, a design speed is selected for the highway. Based on the highway type and the design speed, design values for the various highway elements are selected from a set of predefined design standards, usually in the form of a "cook book"[1, 2, 3]

The current practice has two major attributes. First, the design process is very simple and enables rapid training of highway engineers. Second, this practice supports the so-called "consistent" design. That is, a freeway designed for 100 km/h in one state will always have the same design values for the highway elements. Thus, the highway design can meet the expectations of the road users.

The above practice, however, has been recently subjected to increased criticism. First, it has become evident that current practice is very rigid, and does not allow the designer to exercise his/her own judgment in cases where it is felt that deviations from the standards are required and can be justified[4]. Second, current practice is not sensitive to important factors such as traffic volume, construction costs and traffic composition. That is, once the highway type and the design speed are selected, the minimum design value of a horizontal curve, for example, is fixed, regardless of the volume of traffic that will use the road, and regardless of the costs associated with implementing the design standard. Thus, an arterial road designed for 80 km/h and serving a very low traffic volume in a mountainous terrain will have the same minimum design value as a horizontal curve in a highway which serves high traffic volume on a level terrain.

Third, because the design standards are not flexible and may not be easily changed, they tend to rely mainly on safety considerations. In many situations, this results in very costly standards[5]. For example, in selecting a design value (i.e., a standard) for a vertical curve, the relevant input values are the driver's reaction/perception time, the travel speed, the friction factor and the driver's eye height. For the determination of the design standard, safe values for all of the above are taken. Thus, for example, a reaction/perception time of 2.5 seconds is considered, as it covers a high percentile of the population.

Another criticism focuses on the concept of the design speed, which is the basis of current design practice. The design speed is defined as the speed of the 85-percentile driver in the speed distribution. However, it is not always clear to which distribution it is applied as there is a tangent speed distribution, a curve speed distribution, and car and truck speed distribution. As a result, there has recently been a tendency to replace the design speed concept with the concept of consistent design[6,7]. The current practice of consistent design also addresses the 85-perecentile driver by attempting to control the maximum value of the speed change that the 85-percentile driver experiences. However, it is shown[8] that the 85-percentile driver in the speed distribution found in a tangent highway section is not the same 85-percentile driver in a curve speed distribution. Moreover, theoretically, it is possible that the speed distributions on a tangent section and on a following curve will be identical, implying a "consistent" design, yet, all drivers may experience some speed changes.

The concept of design speed is criticized by other studies, which claim that it is irrelevant in some specific cases, and particularly irrelevant in the case of a horizontal curve[9,10]. In this case, the determination of the "design speed value" for a curve with a given radius and superelevation rate is based on the value of the maximum superelevation rate. Thus, the same horizontal curve (i.e. the same radius and superelevation rate) may have various "design speed" values, based on various values of the maximum superelevation rates.

The above deficiencies are primarily attributed to the deterministic approach adopted by the current design practice. While all the factors involved in the geometric design process (i.e. speed, friction, reaction time, etc.) are stochastic in nature and are fully distributed among the road users, the current approach relies on a single arbitrarily chosen value to represent each factor. Because of the design process, once such a single deterministic value is chosen, the designer is not able to use an alternative value. In some circumstances, failure to account for the stochastic nature of the design process is likely to lead to poor design. That is, in some cases the single values which are chosen from the distributions may under-represent the road user population, resulting in under-design of the highway section. In other cases, the single values may over-represent the population, and the highway section will be over-designed.

In summary, current design practice suffers from vague definition of the design speed concept, is insensitive to traffic volume and composition, does not explicitly consider cost factors, and is very costly. Also, due to its deterministic point of view, this practice is inflexible and may result in poor design. These problems were recognized by the design community, and several ad-hoc solutions were proposed. In order to overcome the high cost problems, design standards were developed for cases such as low-volume roads[11], low-cost roads, and developing countries[12]. These are mainly efforts to justify, on a theoretical basis, standards which are lower than usual. However, all of these ad-hoc solutions still use the current design practice: classification of the road; selection of a design speed value; and application of a set of deterministic design standards. Hence, once a set of design standards is selected, the designer can not adjust the design to meet the specific local conditions.

This paper presents an alternative approach to the geometric design of highways. This approach is fully sensitive to the real conditions of the design problem at hand, that is the traffic volume and composition, by utilizing the stochastic nature of the various factors involved in the design process. The proposed approach also achieves an optimal, or cost-effective, design which takes into account all the cost elements associated with the highway. Hence, the design which results from this approach is more meaningful, and allows the designer to analyze the implications of each design alternative.

The next section presents the proposed approach along with an empirical example. The differences between the current and proposed approach are demonstrated. The potential for future development of the proposed approach is discussed in the last section.

2.0 THE PROPOSED APPROACH

The first stage in the proposed approach is determination of the real conditions of the specific site which will be designed. This means that information about the estimated traffic volume, the composition of traffic, the drivers' performance and the vehicles' characteristics should be available. Relevant information includes: driver reaction/perception times, speed distributions at various highway locations, vehicle dimensions, and characteristics such as friction factors. It is understood that precise information for the specific site may not be available, especially for new highway sections. However, based on empirical studies, one may assume a reasonable distribution shape for the relevant factors. (Note that this is the case with the current approach, which also assumes the values of the relevant parameters for new highways, based on empirical studies.)

The major difference, however, between the two approaches is that while the current approach relies on a single deterministic value for each parameter, the proposed approach utilizes the full distribution shape of the parameter values. For example, in order to determine the design value (i.e. the standard) of a sight distance for design speed, V, of 80 km/h, the current approach assumes that the reaction/perception time, t, is 2.5 seconds, the friction factor value, f, is 0.5, and thus, the sight distance, S, is given by the relationship:

$$S = Vt + V^2/(2gf)\,, \tag{1}$$

where g is the gravity constant. In the proposed approach, however, we need to know the full shape of the distribution value of the travel speed, the reaction/perception time and the friction factor. Based on many empirical studies, it is possible to estimate these distributions when observations are not available. Usually, the various parameters may be assumed to have a normal distribution. Note, however, that the various distributions are not independent, as many relevant factors are highly correlated with travel speed. For example, the friction factor value decreases with an increase in travel speed, and the perception/reaction time may also decrease with increased speed.

The second stage in the proposed approach is the determination of the relevant physical and/or behavioral relationships from which the design value may be calculated. In the current approach, these are the various design equations which relate design value with design speed, like the relationship in (1). As noted earlier, however, more than one relationship may determine the design value of a specific element. For example, one may design a horizontal curve to satisfy the dynamic forces acting upon the vehicle, and thus use the following relationship:

$$R = V^2/[g(e+f)] \tag{2}$$

where R is the curve radius, V is the travel speed, g is the gravity constant, e is the superelevation rate and f is the side friction factor. On the other hand, one may wish to have a consistent design such that:

$$\mathrm{Max}(V_t - V_c) = 15 \tag{3}$$

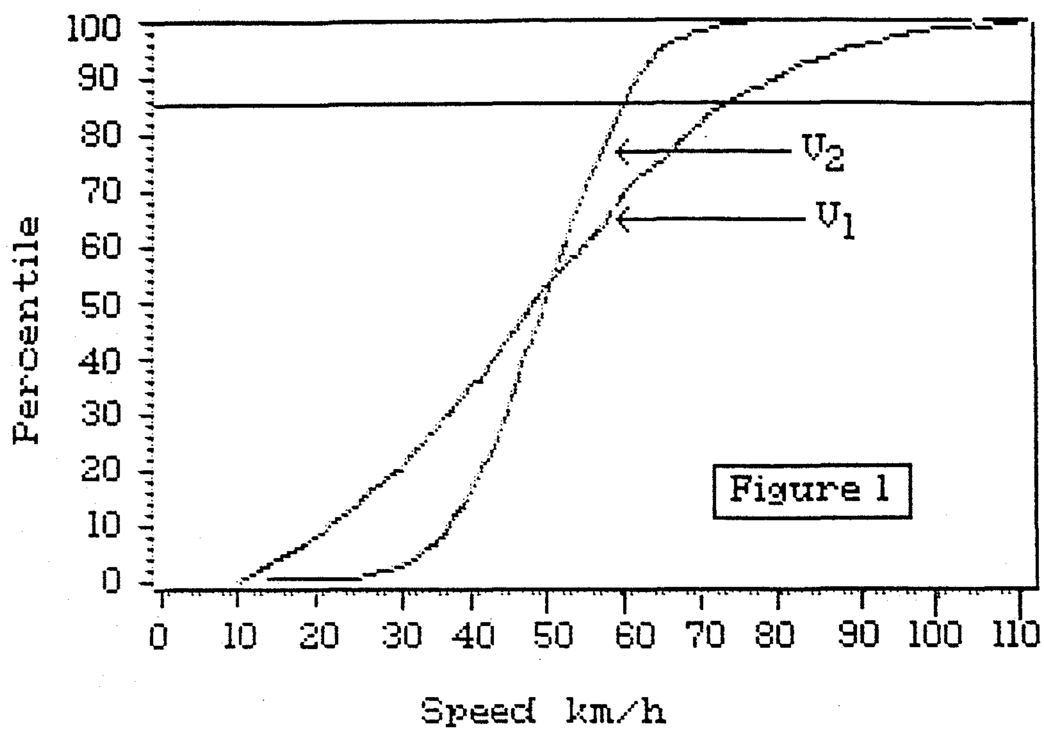
where V_t is the travel speed at the tangent section and V_c is the curve speed. The right hand side variables of the various relationships will be referred to here as the input parameters. Thus, the purpose of the first stage in the proposed approach is to determine the distributions of the input parameters. Once the input parameters are available, we can incorporate these distributions into the design relationships to get an output distribution for the left hand side parameter of the various relationships. In the current approach, the resultant left hand side parameter is the desired design value, or the standard. In the proposed approach, however, we get a full distribution of possible design values, from which we have to select only one. Thus, the left hand side variable in the proposed approach is referred to here as the intermediate variable, or the output value distribution.

Analytical determination of the distribution shape of the intermediate variable is not a simple task. Consider, for example, determination of the sight distance distribution using the relationship in (1). Assuming that all the input parameters are normally distributed (except the gravity constant g), it is almost impossible to find the distribution of a variable which results from a multiplication of normal distribution plus a square of normal distribution divided by normal distribution. Only in very simple relationships can a closed analytical solution be easily found, such as the case of climbing lane design, where the relevant relationship is the speed difference between cars and trucks. Assuming that both cars and trucks have a normal speed distribution along the highway, and assuming that their upgrade performance is also normally distributed, the speed difference between the cars and the trucks is also a random variable with normal distribution. (See [13] for a detailed example of applying the proposed approach to the case of climbing lane design.) In other cases, the functional relationships between the various parameters may be too complicated to allow closed analytical determination of the distribution of the intermediate variable. In these cases, application of a numerical approach to determine the distribution shape is suggested. A simulation process is a relatively simple approach which can yield the desired output distribution.

To demonstrate the ideas presented so far, as well as to show the feasibility of applying a numerical approach, consider the following empirical example for the design of a horizontal curve. The relevant physical relationship which governs the curve design is given in (2) above, i.e:

$$R = V^2/[g(e+f)] \qquad (2)$$

In this example, the maximum superelevation rate which is used is 6%. The first input parameter required is the vehicles' speed distribution. For this example, we assume that the speed distribution can be approximated by the normal distribution with mean value of 50 km/h. As for the variance, we want to compare two different distributions: V_1, with standard deviation (S.D.) of 25 km/h (e.g. non-homogeneous traffic composition which may include slow trucks and fast cars), and V_2, with S.D. of only 10 km/h (e.g. more homogeneous traffic composition). Using these two speed distributions, a sample of 1,000 vehicles was randomly selected from each distribution. The resultant shapes of the two distributions are shown in Figure 1.



The next input parameter required is the side friction factor. The value of this factor is highly correlated with travel speed, as documented in many studies (i.e., $_{14}$). For this empirical example, it is assumed that the side friction factor is also normally distributed, with mean value given by:

$$f = 0.37*(0.0000214*V^2-0.0064*V+0.77) \qquad (4)$$

where f is the side friction factor and V is the travel speed in km/h. The above relationship is based on the empirical results reported by $_{14}$. The S.D. of the distribution is assumed to be 0.0555. For each vehicle in the random data set we can assign now a friction factor value, based on its speed, and using the relationship (4). Note that the relationship in (4) gives only the mean friction value for the vehicle. The actual friction value was randomly selected from a normal distribution where the mean value is given by (4) and the S.D. is 0.0555. The resultant shapes of the two friction factor distributions for V_1 and V_2 are presented in Figure 2.

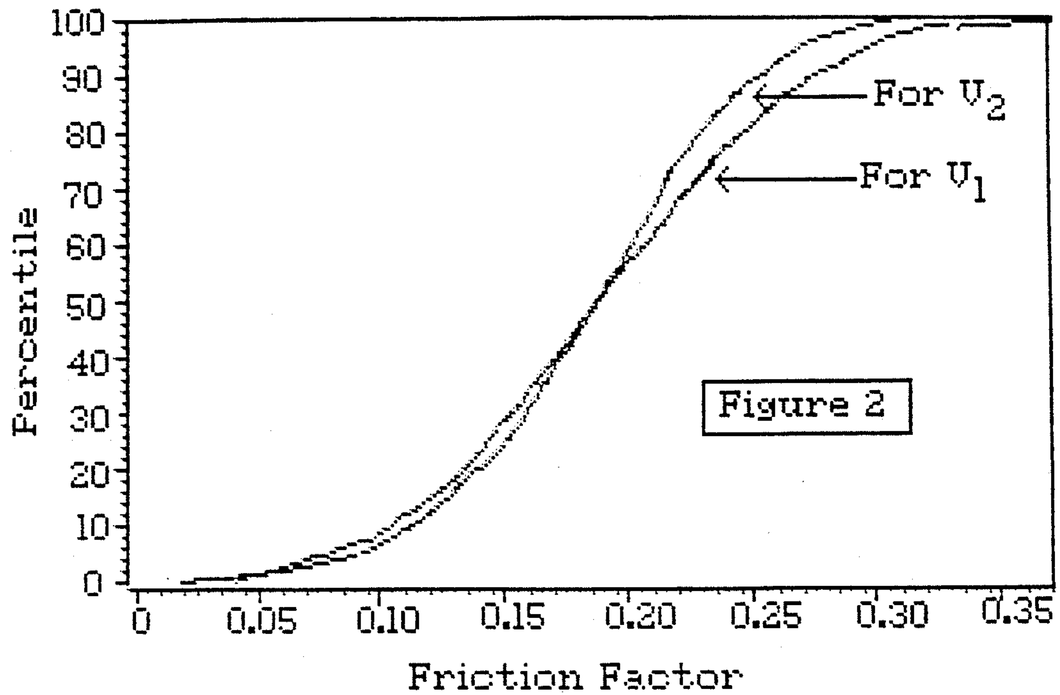


Figure 2 requires careful interpretation, as each percentile value means that the given percentile of the population has the given friction factor <u>or less</u>. However, in the geometric design process we want a certain percentile of the population to have <u>at least</u> a given amount of friction factor. Thus, if we want to select a friction factor value which covers 90% of the population, we need to select the value corresponding to the <u>10-percentile</u> in Figure 2.

As each vehicle in the sample has now been assigned both a travel speed and a friction factor, it is possible to calculate the minimum horizontal curve radius required by the vehicle, using equation (2). Since each vehicle has different speed and side friction factor, then each vehicle also requires a different minimum curve radius. Figure 3 presents the curve radius distribution for the two speed distributions as calculated for the sample data set. As can be expected, the wider speed distribution, V_1, results in a wider distribution of radii.

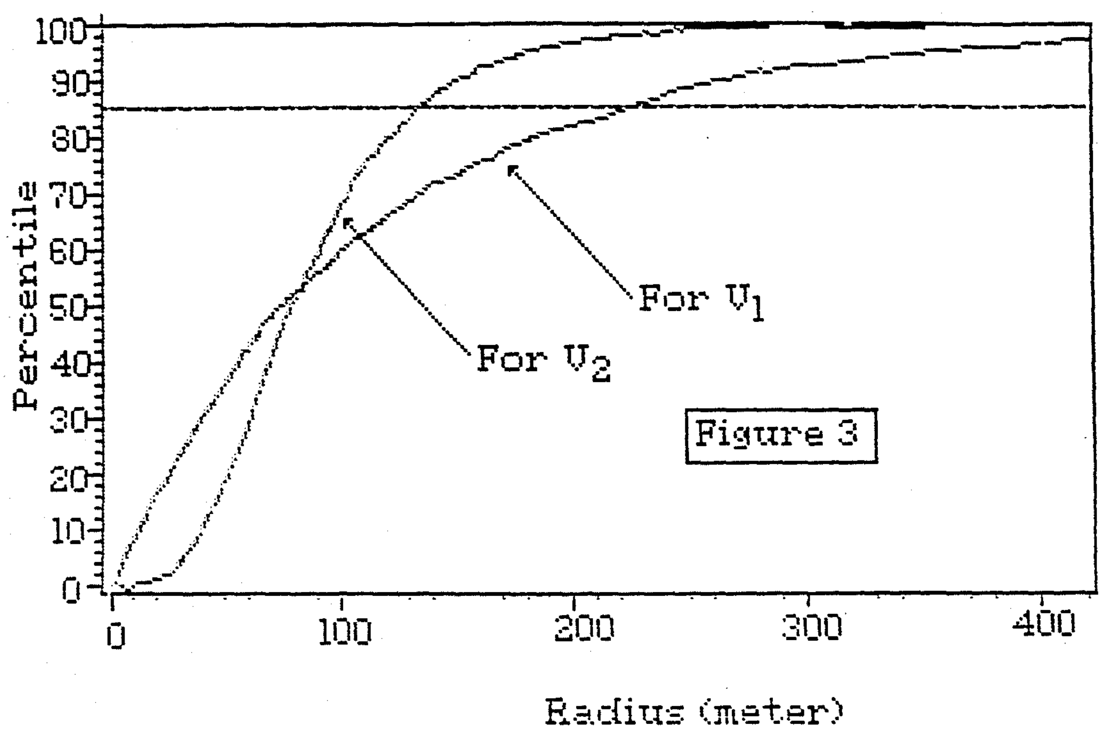


Figure 3

Figure 3 represents the output value distribution of the horizontal curve radius. As the curves in Figure 3 are in cumulative form, they have an intuitive meaning. For example, 90 percent of the drivers which belong to the narrow speed distribution may be satisfied with a curve radius of 151 meters, while a curve of 265 meters is required to satisfy 90% of the drivers which belong to the wider speed distribution.

The corresponding radii for 85% of the population are 134 and 222 meters, respectively.

At this point it may be useful to compare the radii distribition in Figure 3 with the design standard which can result from the current approach. As mentioned above, the design speed is usually the speed of the 85-percentile driver. Thus, the narrow speed distribution, V_2, results in a design speed of 60.2 km/h and the wider speed distribution, V_1, results in a 73.4 km/h design speed, according to the current approach. In order to calculate the value of the minimal radius (i.e. the standard) according to the current approach, we need to assign a single friction factor value to each design speed. For that purpose we use the relationship in (4) above, which gives the mean value of the friction factor. The mean values of the friction factors which result from this relationship are 0.153 and 0.171 for V_1 and V_2, respectively. However, for design we need "safe" values of the friction factor, rather than the mean value. As we assume that the standard deviation of the friction factor distribution is 0.0555, then approximately 85 percent of the population will be covered by a friction factor which is equal to the mean value minus one standard deviation, and approximately 90 percent of the population will be covered by the mean value minus 1.3 times the standard deviation. The friction values which cover 85 percent of the population are 0.0975 and 0.1155 for V_1 and V_2, and the corresponding values for 90 percent of the population are 0.0808 and 0.0989 for V_1 and V_2, respectively.

Incorporating the design speed value and the 85-percentile friction factor value into equation (2) yields curve radii of 269 m and 162 m for V_1 and V_2, respectively. The 90-percentile friction factor values yield radii of 301 m and 179 m for V_1 and V_2, respectively.

Having these radii and using Figure 3, we can now see what percentile of the road user population is covered by these radii. In the first case, where the 85-percentile values of the friction factor are used, the corresponding percentile of the population that is covered by the design standards are 90 percent and 93 percent for V_1 and V_2. In the second case, where the 90-percentile values of the friction factor are used, the percentile covered by the standards are 93 percent and 95 percent, respectively.

The above results show two things. First, the current approach is not consistent with respect to the percentile of the population that is covered by the standards. Thus, a design speed of 73 km/h and a friction factor which is appropriate for 85 percent of the population results in a standard which covers 90 percent of the population, while a design speed of 60 km/h with an 85-percentile friction factor results in a standard which covers 93 percent of the population. Secondly, the results show that by using the 85-percentile value of the speed distribution, and the 85-percentile value of the friction factor, one may derive a design standard which covers 93 percent of the population, and can be regarded as an over-design standard.

Having established the output value distribution, as shown in Figure 3, we now need to select only one value out of the distribution to implement at the site. In order to do so, this paper suggests two design criteria: the percentile criterion and the optimal cost criterion. The percentile criterion states simply that the selected single design value must satify the requirements of at least a certain percentage of the drivers. It is believed that there is no need to state a-priori the value of the minimum percentile. Examination of the shape of the output value distribution may lead to a reasonable selection of a design value. The percentile criterion has an intuitive safety implication, meaning that the higher the percentile value is, the safer the design is. However, it is obvious that there is no need to design the highway for the 100-percentile driver. Based on the output value distribution, the designer will know the implication of specific design alternatives. For example, if the curve radius is constrained to be only 100 meters, the designer will know that such a design will satisfy the requirements of only 60 percent of the drivers. In current design practice, however, the implications of deviation from the design standards are not known. Moreover, even the implications of the design standards are not known. That is, selecting the 85-percentile value from both the speed distribution and the side friction factor distribution do not mean that the derived standard will satisfy the requirements of the 85-percentile driver, as was shown above.

Beside the intuitive meaning, the other advantage of the percentile criterion is that it is sensitive to the real conditions of the drivers' performance and the composition of the traffic. As can be seen from Figures 1 and 3, even when the mean travel speed is the same, more homogeneous traffic volumes (i.e. few vehicle types, homogeneous driver performance) result in lower design values. However, the percentile criterion still suffers from some of the problems mentioned in the previous section. It is not sensitive to the volume of traffic, and it is not sensitive to cost considerations. Implicitly, one can make the percentile criterion sensitive to volume by stating that the selected design value should satisfy the requirements of a given number of drivers. Thus, by knowing the total volume, the corresponding percentile value can be easily found. However, this is not a common design criterion.

Thus, in order to overcome the above problems, this paper suggests another design criterion, called the optimal cost criterion. Formally, we define an objective function which attains its optimal level by selecting an optimal design value. The objective function in this case is a total cost function with two components: road user cost and construction and maintenance cost. The idea underlying this criterion is very simple. Each possible design value results in a different road user cost and a different construction and maintenance cost, and hence, a different total cost. Out of all the possible design values, we will select the one that results in the minimum total cost. Similar approaches were used in past studies[11, 12] to help in the selection of a cost-effective design from various discrete alternatives. The uniqueness of the criterion proposed by this paper is that it accounts for the full range of all the possible values, and that it is linked with the actual distribution shape of the possible values. The importance of the second aspect will be explained shortly.

As noted above, the total cost function has two components. The road user cost component is composed from elements such as accident costs, vehicle operating costs, and drivers' value of time. These cost elements are dependent on both the selected design value and the full distribution shape of the intermediate values. For example, accident costs may be dependent on the difference between the design value required by each driver and the actual design value selected. The same applies to the fuel consumption cost, which is partially dependent upon the magnitude of the speed changes incurred by the drivers. These changes are a function of both the selected design value and the full distribution shape of the intermediate variable.

The other component of total cost is construction and maintenance cost. This component depends only on the selected design value, and has no connection with the intermediate value distribution.

Formally, the cost criterion may be defined as follows: Let X denote the desired optimal design value, x denote the intermediate variables, $f(x)$ denote the P.D.F. of x, $C(X,x)$ denote the road user cost component, and $I(X)$ denote the construction and maintenance cost component. The objective function can be written as:

$$\min_{X} \left[\int_{x} C(X,x)*f(x)d(x) + I(X)\right] \tag{5}$$

If desired, the objective function can be subjected to various design constraints. To demonstrate the concept of the optimal cost design, consider the problem of selecting an optimal design value for a vertical curve, denoted by R. Define r to be an intermediate variable, i.e., r is the curve radius required by each driver. For simplicity, assume that r has no distribution (i.e., all road users are identical). Note that this assumption is the one which is used by current design practice, i.e., all road users require the same design value. In other words, in this example we can define r to be the design standard. Define the road user cost to be the following:

$$C(R,r) = \begin{cases} N*b_1*(r-R)^2 & \text{for } R < r \\ 0 & \text{for } R > r \end{cases} \tag{6}$$

Assume that in this cost function, the only relevant element is the accident cost. Thus, when the selected design value, R, is smaller than the intermediate value r which is needed by the road users, accidents occur. If the selected design value, however, is equal or greater than r, accident costs are assumed to be zero. The non-linear cost function is supported by empirical studies[15] which relate the number of accidents to the curve radius. In the above cost function, b_1 is the accident parameter cost and N is the number of vehicles using the road. To simplify the presentation we define B_1 to be equal to $N*b_1$.

The construction and maintenance cost function is given by:

$$I(R) = b_2*r^2 \tag{7}$$

Here the construction cost is also represented by a non-linear function, as it is mainly associated with earth movement costs, which have a non-linear relationship with the curve radius. The b_2 parameter thus represents the earth movement costs. The total cost function is the sum of (6) and (7). It can be easily shown that for the case of $R > r$, the optimal design value is $R = r$. This means that if we do not want to consider the possibility that the selected design value can be smaller than the value needed by the road user, then the optimal design is to implement the exact value needed by the road users. However, if we are willing to consider the possibility of implementing a radius which may be smaller than the one needed by the road users, the objective function is:

$$\underset{R}{\mathrm{MIN}}[B_1(r-R)^2 + b_2 * R\ ]^2 \tag{8}$$

and the optimal solution is:

$$R_{opt} = r/[1+b_2/B_1)] \tag{9}$$

The conditions in (9) state that the optimal design value is related to the intermediate variable r by the ratio of the parameter of the road user cost to the construction cost parameter. Unless b_2 is equal to 0 or B_1 is infinite, the optimal design value R will be always be less than the intermediate value r. Recall that r is in fact the current design standard. Thus, implicitly, the current design practice neglects all the construction costs relative to the accident costs. This may be a reasonable assumption to make in level terrain, for example. However, in mountainous terrain, the cost of earth movement can become a very significant factor. Moreover, it is evident that current design practice does not wish to place an infinite value on accident costs and neglect construction costs.

This is because the deterministic values which are input into the current design process come from high (or safe) percentile values, but do not cover the 100-percentile driver.

The optimal cost criterion, however, does offer a mechanism for making a tradeoff between cost and level of safety. By selecting the appropriate values for the cost parameters, the designer and the policy maker can adjust the design to represent actual needs.

3.0 DISCUSSION

This paper presents a new approach to geometric design of highways. This approach utilizes a full distribution of input parameters, and attempts to achieve a cost effective design. The advantages of the proposed approach are the following:

- The design is sensitive to real local conditions such as traffic volume, vehicle composition, and driver performances.
- The resultant design is more meaningful and has intuitive interpretation.
- Cost effective design can be achieved.

However, there are still some methodological problems associated with the proposed approach. First, in order to be sensitive to local conditions, there is a need for the appropriate input value distributions. In some cases this may call for extensive data collection efforts. As many parameters may be correlated (e.g. speed and reaction time), such a data collection effort is not a simple task. Second, having established the appropriate input value distributions, there is a need for derivation of the relevant output value distribution. Analytical derivation of the output value distribution is always the preferred approach. However, for many highway design problems, the analytical derivation is a very complicated task, and a simulation process is suggested instead.

Another methodological problem is the construction of an appropriate cost function. First, there is a need for identification of all the relvant cost components. The conventional road user cost components are accident costs, vehicle operating costs and value of time. In some instances, some of these elements may not be relevant (e.g., value of time). Also, even when the total cost components are known, there is still a need to place monetary value on such elements as accidents and value of time, which is also not a simple task. As highways are designed for years of service, there is a need to forecast the value of the various parameters associated with the design process, such as future volumes and costs. As the proposed approach involves many factors, this may introduce some uncertainty into the design process, and as a result, the selected single design value may not be optimal or cost effective. A possible solution to this problem is to perform sensitivity analysis by varying the values of the various parameters. An example of such an analysis can be found in[14] for the case of climbing lane design.

Another methodological problem is the interdependency that may exist between the input variables and the selected design value. In the case of a horizontal curve, for example, it was found that drivers adjust their speed and lateral acceleration rate according to the curve radius[16]. The design process should be able to account for this phenomenon, as well. A related issue is the three dimensional aspect of the design. The methodology presented in this paper demonstrated the design process for a single highway element. However, highway elements are interrelated in a three dimensional system. An optimal design should take into account all the highway elements in the given section.

The last problem discussed here is the incorporation of the new approach into conventional "cook book" practice. On a day-to-day basis, it is not practical to conduct an extensive study each time that there is a need to design a highway section. Rather, it would be desirable to be able to upgrade the current design standards to include the features of the new approach. In this respect, it is suggested that the design standards should have more dimensions. Thus, for example, travel speed will be represented by its distribution parameters (i.e., the mean and the S.D.), and a design value will be presented for each percentile value to incorporate the percentile criterion. As for the optimal cost criterion, the design tables may have the speed distribution (i.e., mean and S.D.) as one input, and the traffic volume as another input, and a suggested optimal design value will be presented for each combination of speed distribution and traffic volume. Another practical possibility for the use of the proposed method is development of a set of integrated micro-computer programs that will be used in the design of highway elements. Such a program can be developed as an expert system which will assist the designer in the selection of an optimal geometric design.

To conclude, the proposed approach to geometric design of highways offers many advantages over current design practice, and results in more meaningful and cost-effective design.

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