QUANTIFYING SAFETY AND MANAGING THE ROADSIDE ENVIRONMENT

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ABSTRACT

The objective of roadside safety management is to maximize the safety return for the resources invested. Before safety can be maximized, it must be measured. A technique for measuring and defining safety is discussed in the following paper. This method systematically adds the risk associated with each hazard along a roadway and compute a safety scale that quantifies the "safeness" of the roadway. A conditional probability model that describes the probabilities of encroaching, becoming involved in an accident given that an encroachment occurs, and sustaining a severe or fatal injury given that a reported accident occurs is presented. An automated implementation of this quantification technique for managing roadside safety will be described. Implementation issues related to gathering data, developing encroachment, collision and severity models will also be presented.

INTRODUCTION

The Federal Highway Administration is advocating a management approach to highway operations problems like pavement and bridge deterioration and most recently safety and congestion (*1*). Safety management is a more systematic and effective means of allocating scarce resources to reduce injury and property damage. Although safety management involves much more, one important aspect is to "identify, investigate, set priorities and correct hazardous . . . locations and features (*2*)."

Managing safety implies that it can be observed, measured, and optimized. Safety, however, is not currently defined in quantifiable terms that the can be used to compare competing alternatives. Safety is usually accounted for by satisfying the minimum AASHTO criteria (*3*) or the appropriate State standards. The designer makes the assumption that exceeding all the individual AASHTO criteria makes the design safe enough.

Highway designers must balance many constraints in formulating acceptable designs. While safety is important, it is frequently over-looked in part because relationships between design elements and safety are not well understood. A systematic software approach, would benefit designers by standardizing the process of optimizing safety and focusing research on areas that are of immediate and practical use in the field.

ROADWAY DESIGN

Safety often competes with other aspects of design like right-of-way acquisition, environmental protection, and congestion relief. Safety imposes additional, though not primary, constraints on the design process.

Typically, no one person in a Department of Transportation (DOT) is involved with a single safety project from beginning to end. The accident statistics group identifies problems, the regional safety engineer gathers information and proposes alternatives, the planning division makes programming and funding decisions, the drafts-person or the junior engineer prepares detailed drawings and specifications and the construction division monitors the actual construction project. Some groups may have to make important design decisions with only partially complete information since the design process is distributed.

Safety improvement projects are usually initiated to address a specific problem at a specific site. In many States safety problems are identified yearly when the State's statistics office generates a list of high accident locations. A high accident location is identified as a site where the actual accident rate is higher than some critical rate. Critical rates are developed for various functional classifications of roadways and intersections. These locations are then ranked by their equivalent property-damage-only (EPDO) cost (*4*). This list represents the DOT's safety improvement priorities.

Each region in the state receives a list of high accident locations within their jurisdiction. The regional engineer obtains accident reports and the as-built drawings (if they exist) and then draws collision diagrams to assess if the accidents are all related by a common cause. The regional engineer may gather traffic data and survey the site as well as visit it to observe first hand how the r oad segment functions. Based on these observations and the engineer's analysis of the problem, a recommendation for resolving the safety problem is formulated. If the recommendation is straightforward, like installing signing, removing a fixed object, or installing a guardrail, the regional maintenance staff will usually correct the problem immediately. If the

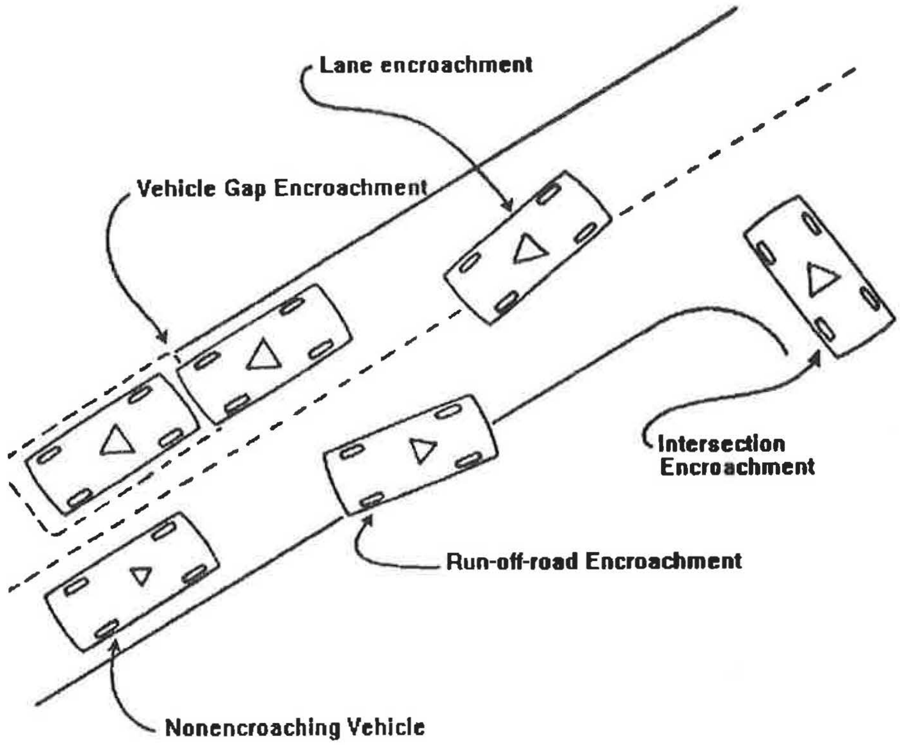

FIGURE 1 Encroachment scenarios (6).

improvement involves extensive site work or a change in the geometrics, the regional engineer recommends a course of action to the program development staff. The regional engineer's recommendations about the most appropriate solution is usually accepted at higher management levels since the engineer at the site is best able to gather data and observe the real performance of the roadway.

The program development office schedules construction projects and coordinates funding. When a funding mechanism is identified and the project is scheduled, the program development office prepares a functional specification for the project and sends it to the design division, initiating the detailed design phase. When the detailed specifications and drawings are complete they are checked before the final design is delivered to the construction division for the preparation of bid documents. The construction process is monitored and inspected by the construction division.

Regional and district engineers are responsible for making most of the important design decisions in safety improvement projects. The detailed designers, while enjoying great flexibility in designing new construction, usually do not make basic design decisions in improvement projects.

The regional engineer has the ability to gather complete data, analyze the problem and suggest solutions. These solutions are rarely changed since the on-site engineer has the best perspective of the real problem. The regional engineer, however, has the fewest resources in terms of technology transfer, staff support and time to work on any one project. An interactive assessment tool could provide the regional engineer with the means to make better design decisions more quickly. Providing an interactive highway safety assessment model to those who must be responsible for making design decisions has the potential to greatly improve both the quality and consistency of the roadway designs.

QUANTIFYING SAFETY

Safety Scale: S

Accidents are discrete random events that are caused by the combined interaction of highway, driver, and vehicle characteristics. The Poisson distribution can be used to estimate the probability of observing an accident during a fixed period, say one year.

$$P(X=x) = \frac{e^{-\lambda}\lambda^{x}}{x!} \quad (1)$$

The Poisson distribution is a good candidate for predicting accident events since it is intended for modeling events that are (1) discrete and (2) a function of many normally distributed random variables. Accidents fit both these criteria well.

If X is the number of fatal plus serious injury accidents (A+K) observed in one year along a one-mile segment of highway, λ would represent the yearly number of serious and fatal accidents per vehicle mile traveled per mile per year (i.e. the A+K accident rate) (λ=P(A+K) x ADT). P(A+K) is the probability that any one vehicle will become involved in an A+K accident while traversing the highway segment and the ADT is the average daily traffic. If the ADT of a particular road is 10,000 vpd and a safety analysis (described in the next section) predicts that any one vehicle has a probability of 1.42E-8 of becoming involved in an A+K accident, the Poisson distribution can be used to estimate the probability of observing no A+K accidents in one year (i.e.X=0):

$$P(X=0) = e^{-1.42(10)^{-8} \times 10{,}000} = 0.999858 \quad (2)$$

This quantity represents how "safe" the roadway is. The probability of *not* observing an A+K accident in a year of this segment of roadway would be 0.999858. A safety scale, S, can be defined as (*5*):

$$S = e^{P(A+K) \times ADT} \quad (3)$$

The safety scale defined in equation (3) provides a way to calculate a single number that represents the safety of the highway with respect to all possible accident scenarios. The scale is a number between 0 (an assured A+K accident during the year) and 1 (no chance of even one A+K accident). This scale is physically meaningful and can be compared with easily obtained gross accident statistics.

Gross national and state accident statistics can be used to see if the model predictions are reasonable. The safety scale determined for individual segments could be compared to the average values for each functional class and those that are too far below the mean could be targeted for improvement. The safety scale could be used to find locations with a high probability of an accident by identifying locations with a safety scale more than two or three standard deviations from the mean rate for that functional classification. This is similar to the way some States produce high accident lists now.

Calculating the probability of a single vehicle being involved in an A+K accident will be the most difficult part of the analysis task. The relationship between design variables and operational characteristics will be reflected in this probability.

Risk Model: P(A+K)

A number of studies have proposed techniques to estimate the number or severity of specific types of accidents (*6*) (*7*) (*8*). Perhaps the most widely used technique involves using Baysian conditional probabilities to estimate the expected number of accidents (*9*). The expected number of hazardous accidents is the product of three conditional probabilities. A hazard index was developed by Glennon of the form (6):

$$E(I)_i = E(E)_i \, P(C|E)_i \, P(I|C)_i \quad (4)$$

where,

- $E(I)_i$ = Expected number of injury accidents per year involving scenario i;
- $E(E)_i$ = Expected number of vehicle encroachments per mile per vehicle;
- $P(C|E)_i$ = Probability of a collision given an encroachment has occurred; and
- $P(I|C)_i$ = Probability of an injury accident given a collision has occurred.

Equation (4) estimates the number of injury accidents for a particular feature of a roadway, i. For example, a particular utility pole or segment of steep side slope could be expected to be involved in a certain number of injury accidents each year. Estimating the safety of a road segment would involve summing up the effects of all the potentially hazardous events in a roadway segment. Estimating the expected number of injury accidents for a feature would involve estimating the three probabilities for each hazardous scenario along the roadway.

Equation (4) predicts the expected number of accidents of a particular severity. The probability of a vehicle occupant being involved in an A+K accident involving hazard i while traversing the segment could be found by differentiating equation (4) with respect to the traffic volume. Since only the encroachment frequency is a function of the volume, the probability of experiencing an A+K accident involving a particular hazard is given by (*10*):

$$P(A+K)_i = P(E)_i \; P(C|E)_i \; P(A+K|C)_i \qquad (5)$$

The probability of experiencing an injury accident on a road segment could be estimated by combining the $P(A+K)_i$ of each hazard where the subscript i denotes a particular scenario like running off the road and striking a tree or encroaching on another lane and side-swiping another vehicle.

Glennon's hazard model was developed specifically for run-off-road, fixed-object accidents. The model shown in equation (5), however, can be interpreted from a much more general point of view. Encroachment could be understood to mean any vehicle position that departs from the desired position as shown in Figure 1. Encroaching on another lane may result in leaving the roadway (passenger-side encroachment), side-swiping another vehicle, or striking another vehicle head-on (driver-side encroachment). Encroaching on the inter-vehicle gap (the space between vehicles in the same lane) may cause a rear-end collision. Encroaching into another lane in an intersection when the right-of-way is with the other travel lanes may cause an intersection accident. There are, therefore, several possible encroachment scenarios that must be addressed when using equation (5). The probability of an encroachment becoming an accident, P(C|E), likewise can be interpreted more generally. If a vehicle encroaches into another lane and there is no vehicle coming in the opposite direction, a collision will not occur. The severity index can also be used in a more general sense to describe the expected severity of any accident event on the roadway or roadside.

Encroachment Probability: P(E)

The quantity E(E) in equation (4) is the expected number of vehicles that leave the roadway in a given period. The concept of encroachment has been used extensively for run-off-road accidents but it can be generalized to include encroachments into other lanes, intersections, or encroachment into the safe gap between vehicles. Encroachments initiate a sequence of events that sometimes result in an accident.

The probability of encroachment is the derivative of the frequency of encroachment with respect to the traffic volume (*11*). The *Roadside Design Guide* model for the expected number of encroachments is E(E)=0.0005ADT. The probability of encroachment, using this model, would therefore be:

$$P(E) = \frac{\delta E(E)}{\delta ADT} = 0.0005 \qquad (6)$$

A linear model relating the number of encroachments to the amount of exposure (traffic volume) implies that risk is constant, this is plainly not so.

All the models based on the Hutchinson-Kennedy data are functions of the traffic volume alone. Here are, however, other characteristics that are likely to play an important role in the probability of encroachment. Encroachments should be greater on roads with more curves and grades than on straight and level roads. Roads with narrow lanes and shoulders should have more encroachments than roads with wider lanes and shoulders. Travel speed should also play a role in the probability of encroaching. Vehicles travelling at higher speed should be more likely to leave their lane than slower moving traffic. A general encroachment model should include not only traffic volume but other characteristics of the roadway. The encroachment probability should be a function of a number of roadway characteristics. The following expression could be used to represent a general model for the probability of a vehicle encroaching:

$$P_j(E) = \prod_{k=1}^{l} a_k b_k^{c_k} \qquad (7)$$

The symbol $\prod$ indicates that each term is multiplied by the next. The values for a_k, b_k and c_k are characteristics of the roadway or constants. The values could come from statistical analyses or from experience. The important idea is that the encroachment is predicted by some finite set of measurable characteristics of the highway.

Collision Probability: P(C|E)

The term P(C|E) in equation (5) represents the probability that an encroachment will become an accident. Often the drivers of encroaching vehicles can regain control before actually striking a hazardous object, pedestrian or another vehicle. Other times a collision does occur but is not reported to the police presumably because the resulting accident was relatively minor. Some encroachments are intentional such as passing maneuvers and pulling over to the shoulder to change a tire. The term P(C|E) should be interpreted as the probability that an encroachment becomes a police reported accident.

The distance from the edge of the roadway to a hazardous roadside object has been shown to be an important factor in predicting whether a run-off-road encroachment progresses into an accident *(12)* *(6)* *(13)*. Glennon investigated several mathematical models for predicting the probability of an encroachment and selected an exponential model. An exponential model predicts that the greatest probability of striking an off-road object occurs when the object is at the edge of pavement. The probability decreases to zero at an offset distance of infinity so the farther away the object is the less likely a collision with a vehicle becomes. The exponential model is given by the expression:

$$P(C|E)=e^{-0.08224y} \qquad (8)$$

where y is the lateral distance from the edge of pavement to the hazard.

The probability that an encroachment will be transformed into an accident, then, is also a function of a set of roadside and roadway characteristics. The following general purpose expression, could be used to represent this conditional probability:

$$P_i(A|E)=\prod_{k=1}^{l} d_k e_k^{f_k} \qquad (9)$$

where d_k, e_k and f_k are characteristics of the roadside geometry and the position of the hazard or constants. Equation (8) can be represented in this form recognizing that $e^{-0.08224\,y} = 0.9211^y$. If equation (9) were used to represent Glennon's lateral encroachment model, $d_1=1.0$, $e_1=0.9211$ and $f_1=y$.

TABLE 1 Severity indices for fixed objects on rural roads

Hazard	Percent, A+K
Traffic Signal Pole	17
Highway Sign	8
Luminaire Pole	10
Attenuator	12
Median Barrier	11
Utility Pole	12
Guardrail	15
Bridge Rail	14
Tree	24

Severity Probability: P(A+K|C)

The conditional probability P(A+K|C) in equation 6 is often called the severity index. It represents the likelihood of sustaining a severe or fatal injury given that an accident has occurred. Table 1 shows some severity indices obtained from the NASS CSS data. The percentage of A+K accidents for each type of fixed roadside objects was determined. The severities shown in Table 1 actually represent the average severity for all types of impact conditions, accidents scenarios and traffic conditions. The actual severity of an accident is a function of the characteristics of the particular collision, the site, and the object struck. The severity of a guardrail collision may be a function of impact speed, impact angle, appurtenance strength and the after-collision trajectory. The severity of a rollover on a steep side slope might be a function of the slope, the road grade, and the embankment height. Although the variables that could be used to predict injury are different for different accident types, there is some set of variables that affect the probability of sustaining a serious injury. A general expression for the probability of an accident becoming a serious injury accident could be expressed as:

$$P_i(A+K|C)=\prod_{k=1}^{l} g_k h_k^{i_k} \qquad (10)$$

where the P_i (A+K|C) is the probability of sustaining an injury in accident scenario i. The terms included in the severity model should be observable characteristics of the hazard. The model itself could be derived using in-depth accident data (as suggested by Mak (*14*) (*15*) and Glennon (*6*)), crash test data or, in the absence of either, using engineering judgement and intuition.

The objectives for developing a method for quantifying safety are to provide an unambiguous, systematic technique for assessing the safety of highway designs. The engineer will need to compare designs, prioritize hazardous situations and develop recommendations for most effectively improving the safety of a highway design. The method described in the previous sections accomplishes these goals. There are a number of models that would need to be developed for this method to be effective. The overall formulation provides a way to focus research efforts aimed at building these models in such a way that they all fit together and contribute to developing a larger, more general design methodology.

INTERACTIVE ASSESSMENT PROCEDURES

A computer software implementation is best suited to quantifying safety since a great deal of data must be stored and manipulated. A prototype software tool called the SafetyAdvisor is being developed to assist engineers in quantifying the safety of road segments and designs. Once the engineer knows how safe the segment is, a cost benefit analysis can help decide which alternative provides the most safety for the least cost.

There are at least three possible uses for an interactive safety assessment model: generating high-hazard location lists, checking final designs, and evaluating design alternatives. Hazardous locations are identified in generating a high-hazard location list; safety assessment would provide a proactive method for identifying sites with substandard performance. Safety assessment could also be made a part of the checking procedures to ensure that all projects have adequately addressed safety. Automated assessment could also be integrated into the detailed design phase as a means of comparing design alternatives. The following sections describe how the automated safety assessment tool could be used in the context of these three types of design and analysis activities.

High-Hazard Lists

Most States generate high-hazard-location lists based on accident rates observed during a three to five year period. Sites where there are no accidents are presumed safe until proven otherwise. Clearly, there are sites where the geometric, roadside and operational characteristics strongly suggest that an accident is likely to occur sometime in the future if the site is not improved. The DOT is forced to react to safety problems instead of correcting problems before a serious or fatal accident occurs.

An assessment procedure that does not rely solely on accident data would help identify problems before they become accident statistics. Instead of plotting clusters of accidents, the probablistic approach to quantifying safety could be used to plot all sites where there is, for example, better than 1 chance in 10 of a severe accident occurring in the next year. Resources could best be applied to these high probability sites regardless of whether an accident has occurred there yet or not.

All sites with a safety scale more than two or three standard deviations away from the mean for that functional classification could be targeted for safety investigation and possible improvement. Assume the average P(A+K) for all roads in a region with the same functional classification is 2.43E-8 and the average safety scale is 0.84. If the safety assessment procedure predicts that another roadway has a safety scale of 0.71, the analyst can say that this roadway is less safe than the average roadway in its functional class. If the standard deviation of the safety scale on all the region's roads in this functional class is 0.06, this particular roadway would be more than two standard deviations below the average. This would indicate that this particular roadway is significantly worse than other similar roadways and it should probably be targeted for improvement.

Before a high hazard list can be generated in this way, a complete database of roadway, roadside and operational characteristics must be assembled. Currently there are only a handful of States with such databases. The emergence of State Safety Management Systems should increase the availability of this type of data, the computing resources required to assess every roadway in the state may also pose a serious problem. Because of the scarcity of data and the demands on computing time, generating high hazard lists using a non-accident-based assessment procedure is still probably far in the future.

Detailed Design

In contrast to generating high hazard location lists, an interactive design tool could be used immediately by designers to assess the safeness of design alternatives. The process for designing a roadway begins when the design staff is given a functional specification of the roadway and the initial tangent alignments. One of the

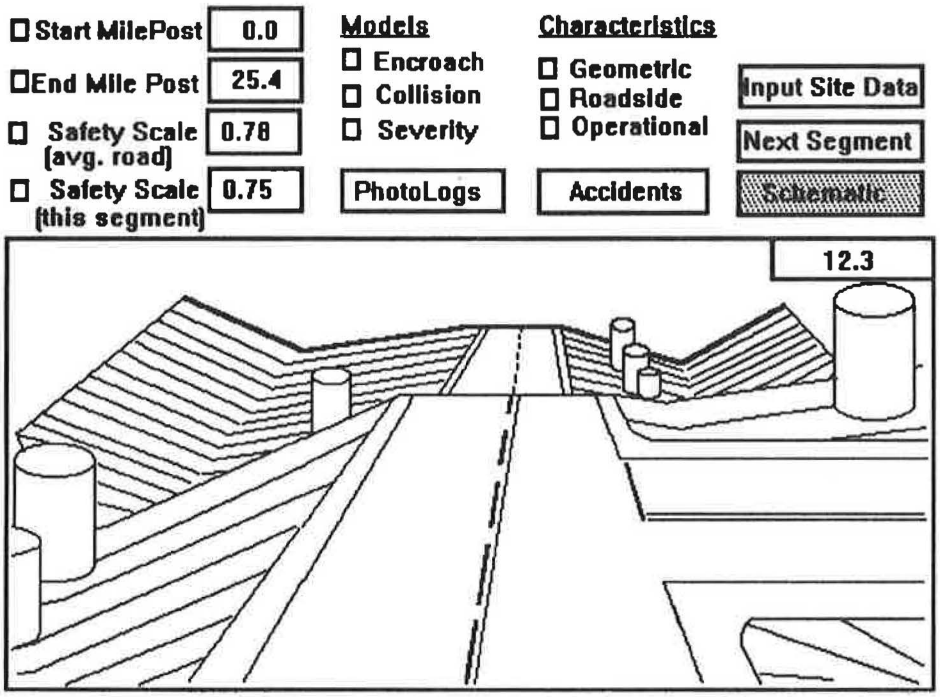

FIGURE 2 More detailed view of the assessment tool.

designers first activities is often to try and minimize the amount of right of way that must be taken and the amount of earth that must be moved. Both these tasks are performed largely with the aid of a CAD/CAE package. The preliminary designers primary tasks are to minimize right-of-way taking and minimize earth moving while satisfying the functional specifications and design guidelines. A safety assessment tool could be used at this stage to compare the relative safety of different horizontal and vertical alignments.

When the designer has found a possible alignment and grade, the safety assessment tool could be called, possibly from within the CAD/CAE software. Since the CAD/CAE program contains all that is known about the design at any stage, this information can be shared with the safety assessment tool. The horizontal and vertical alignments already stored in the CAD/CAE design package could be transported to the safety assessment tool directly.

The designer could experiment interactively with changing some of the alignment characteristics to see how the safety scale is affected. The safety scale would change in response to the user's moving the location of the crest. The user can alter the design in a truly interactive way; observing the effect of each design change on the safety scale.

After the user is satisfied with the safety of the design, the characteristics could be transferred back to the main CAD/CAE software to determine earth volumes, right-of-way encroachments, and mass haul distances. By iterating between the CAD/CAE software and the assessment tool, the user would balance safety with other design considerations.

The road need not be fully characterized to use the assessment tool. Other characteristics can be added in later stages of the design. The safety scale would not have any absolute meaning if the design is not complete but it still could be used to compare two alternative horizontal curves or grades. This type of interaction would allow the designer to explicitly examine the trade-off between, for example, flattening grade to improve safety and the cost of moving the additional earth.

Once the basic alignments have been determined the designer begins the detailed design phase. The designer might add intersections, cross-sectional geometry and fixed object locations. At each stage, the designer could obtain the characteristics of the segment from the CAD/CAE program, transport them to the assessment tool and explore the safety consequences of each design decision. Figure 2 shows an example of the Safety Advisor's user interface. The location of fixed objects (the cylinders in figure 2), an intersecting roadway and striping have been added to the design file. As the characteristics of the roadway become more complete, the safety scale assumes greater meaning.

While integrating the tool with CAD/CAE packages is helpful it is not absolutely necessary. The field or regional engineer could also use the assessment tool in evaluating improvements to existing highway segments. The regional engineer could investigate sites listed in the regional high hazard list. The regional engineer, rather than the CAD/CAE package, would gather all the required data to provide input to the interactive design model. Gathering the data may involve visiting the site to measure lane widths, traffic volumes, turning maneuvers, and the distribution of speeds. Most of this data would be required for a good manual analysis anyway so gathering it would not significantly increase the effort of the regional engineer. After collecting this data, the regional engineer could enter the field data into the computer using the assessment tool. The buttons under the label "Characteristics" would pop up text editors that could be used to enter, modify, or view the input data. The buttons under "Models" would not normally be used by a field engineer or designer since they facilitate changing the underlying probability models.

The entire package of computer-encoded site data used by the regional engineer or designer would then be forwarded to the program development staff. If the program development staff wishes to check the regional engineers work, or if a change is required to meet the
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requirements of a particular program, all the same information could be re-used to assess the effect on safety.

The program development staff could deliver the data files to the detailed design division with the more traditional advance planning material. If the detailed designer needs to check or change the basic design recommendations all the information that went into the decision at the regional and program development stages would be available in the computer data files. Finally, the design group would forward the final design drawings and specifications along with the safety assessment data to the construction group. An explicit safety assessment could be performed with the forwarded data. The data could then be added to a State-wide database of as-designed projects. Over time, this database would grow to include many of the most troublesome segments of roadway in the State. Eventually this database could be used to generate high hazard location lists as discussed in the last section.

The interactive design model serves several functions in this procedure. First, it provides a standardized way to evaluate the safety of various designs; each person who evaluates safety will obtain answers in the same way so they can be directly compared. They may disagree about the tradeoffs but at least there will be agreement on how safety was measured. Second, the software representation provides a way to transmit complete information up and down the decision making chain so that every contributor has all the information necessary for making the best decisions.

Checking Designs

Checking designs for completeness, conformance to specifications and safety is already an important part of the design process. Once a design has been substantially completed it is passed along to the construction group. Before bid documents are prepared the design is carefully checked to resolve as many potential problems as possible before construction begins.

An interactive assessment tool would be useful for design checkers as well as detail designers since it would allow the construction engineer to quickly assess how safe a particular design is. The data files used by the detailed designer could be passed along to the checker when the drawings are delivered. The checking staff
all could then ensure that all aspects of design are satisfactory.

SUMMARY

Establishing systematic and quantifiable design procedures would help standardize the quality of designs on a variety of roadways. The safety implications of various changes in the design can be compared to determine which alternative results in the largest improvement in safety. Once the "safest" design is found, a cost effectiveness analysis can be used to determine which design provides the biggest improvement per unit cost.

The most serious drawback to this procedure is the need to obtain and manipulate a great deal of data about the geometric, operational and safety characteristics of the highway. A data-intensive procedure such as this would be impossible to implement as a manual technique. The amount of data and computations required makes this technique ideally suited to computer implementation. A software tool that accomplishes this process would provide a very powerful facility for the designer to explore a variety of designs quickly and in great detail.

A software tool was described that could be integrated into the typical design process currently used in many State DOT. This automated tool features an easy-to-use graphical interface and facilities for updating the probablistic models. This type of software could be integrated with other CAD/CAE tools in wide use among highway designers. The software would provide a standardized framework for performing and disseminating research on hazardous scenarios.

Highway designers must balance many constraints in formulating acceptable designs. While safety is important, it is frequently overlooked in part because the relationships between design elements are not well understood. A systematic approach would benefit designers by standardizing the process of optimizing safety. Providing a systematic means of quantifying and assessing the safety of highway designs will improve the safety performance of the nation's highways and roadways.

REFERENCES

1. Samuel K. Skinner. *Moving America: New Directions, New Opportunities*. U.S. Department of Transportation, February 1990.

2. FHWA. *Management approach to highway safety* (draft). Memorandum to FHWA Division Offices, November 19, 1990.

3. AASHTO. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington, D.C. 1984.

4. James L. Pline. *Traffic Engineering Handbook.* Prentice Hall, Inc., fourth edition, 1992.

5. Malcolm H. Ray, *Conceptual Requirements for an Interactive Highway Design Model*, Unpublished report, Federal Highway Administration, USDOT, Washington, D.C., June, 1992.

6. John C. Glennon. *Roadside Safety Improvement Programs on Freeways.* Report 148. National Cooperative Highway Research Program, Washington, D.C., 1974.

7. King K. Mak, Hayes E. Ross and C. Eugene Buth, *Severity Measures for Roadside Objects and Features*, FHWA Report No. FHWA-RD-86-019, Federal Highway Administration, April, 1986.

8. Charles V. Zegeer, J. Hummer, L. Herf, D. Reinfurt, and William Hunter. *Safety cost-effectiveness of incremental changes in cross-section design - informational guide*. Report Number FHWA-RD-87-094, Federal Highway Administration, December 1987.

9. John C. Glennon, *Roadside Safety Improvement Programs on Freeways*, NCHRP Report 148, National Cooperative Highway Research Program, Washington, D.C., 1974.

10. Malcolm H. Ray and Lori A. Troxel, *Safety Assessment of Highway Designs*, Proceeding of the 2nd Conference on Highway Safety on Two Continents, Vag och-Trafik Institutet, Linkoping, Sweden, VTI Rapport 372A, pp. 44-53, September, 1991.

11. D. Mahalel. *A note on accident risk*. Transportation Research Record, 1068, 1986.

12. Damian Kulash and Robert Skinner, *Special Report 214: Designing Safer Roads*. Transportation Research Board, Washington, D.C., 1987.

13. King K. Mak and Robert L. Mason. *Accident analysis - breakaway and nonbreakaway poles including sign and light standards along highways*. National Highway Traffic Safety Administration, Washington, D.C., August 1980.

14. King K. Mak, T. Chira-Chavala and Barbara A. Hilger, *Automated analysis of high accident locations*, Transportation Research Record 1068, Transportation Research Board, Washington, D.C., 1986.

15. T. Chira-Chavala and King K. Mak, *Identification of accident factors on highway segments: a method and applications*, Transportation Research Record 1068, Transportation Research Board, Washington, D.C., 1986.