Skeleton Procedure for Evaluation of Highway Safety Improvements on a Road Network

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A systems approach to evaluation of safety improvements is described. The initial stage of the process is the identification of problem locations within the road network. This stage attempts to reduce the size of the problem and to make it solvable within a reasonable cost. The next stage consists of suggestions for improvement and an evaluation of their cost-effectiveness. This second stage is based on the definition of three standard design levels. The allocation process is defined as a mathematical programming problem, which ensures the optimal solution.

A method is presented for the allocation of a budget to a road network with the aim of minimizing the number of accidents. The emphasis is on the development of practical techniques based on an existing data base and relatively inexpensive implementation.

Sophisticated models based on extensive information and a large amount of data are often inoperable because of the nonavailability of relevant data. In addition, the allocation process itself is generally expensive and consumes a large portion of the available safety funds. The allocation procedure, therefore, is rarely applied. It is reasonable to assume furthermore that the procedure would not in any case be efficient because of high management and implementation costs.

The problem of the allocation of resources to ensure safety possesses some unique distinguishing features, as follows:

1. The size of the problem: The road network is composed of thousands of stretches of road and intersections that are potential sites for engineering improvement.
2. Multiplicity of alternatives: Because there are multiple reasons for road accidents, it is difficult to point to a specific solution. Therefore, there are a number of solutions for each location, distinguished by cost and effectiveness. The alternative solutions for each location are mutually exclusive, because the different locations are independent. The combination of mutually exclusive and independent solutions demands a sophisticated allocation procedure. For a particular budget, however, a specific combination of second-best solutions may be more efficient than the best alternative for each site.
3. Routine processes: Because of the dynamic nat re of road use and environmental characteristics, a periodic review of the condition of the network is necessary. The socioeconomic changes in the vicinity of the highway cause changes in the exposure to road accidents, and thus there is need for relatively frequent routine allocations.

As a result of these three characteristics, the danger exists that the procedure for the allocation of funds will become too expensive; the allocation process itself may consume a large part of the budget and rarely will be carried out.

The following paragraphs describe the impact of engineering improvements on the prevention of road accidents. To reduce the size of the problem, a method is evolved that provides a preliminary definition of "black spots" (stretches of road on which the number of accidents is high relative to the daily traffic) and suggests a quick and efficient evaluation of the effectiveness of the engineering projects. Finally, a budget-allocation model is presented.

ENGINEERING IMPROVEMENTS AS A TOOL FOR REDUCTION OF ROAD ACCIDENTS

Local engineering improvements are aimed at removing the black spots and bringing these locations to the general safety level of the entire infrastructure and in general at creating comfortable and uniform driving conditions throughout the network. The simplification of problems faced by drivers will help them to maneuver their vehicles in such a manner as to avoid accidents.

Driving on any stretch of road presents various problems, caused by the particular geometrical characteristics, traffic flow, traffic control system, weather, sight conditions, etc. Changes in the geometrical structure of the road, such as the existence of a curve, oblige drivers to maneuver their vehicles in a certain way in order to avoid an accident. The greater the radius of the curve, the less complicated the maneuvering is that is demanded and the greater are the chances of successful performance.

When the driver is faced with making a decision, a certain probability exists that an accident will be avoided; the probability is influenced by the complexity of the problem. The simpler the problem, the higher the probability--it may reasonably be assumed--that the driver will act according to an accident-preventive policy. Thus, Blumenthal (1) posited the event of an accident as a problem of faulty coordination between the level of performance of the driver and the performance demands of the road network.

Figure 1 (1) presents schematically the performance level of the driver and the performance demands of the road network as a function of time. The performance level of the driver varies because of such factors as fatigue, lack of attention, and illness. The demands of the network vary according to various levels of design, types of roadway, rates of traffic flow, etc. When the performance level of the driver is not compatible with the performance demands of the network, an accident occurs.

In this model, the significance of engineering improvements in the road infrastructure is reflected in an equivalent lowering of the performance demands. As a result, the gap grows between the performance level of the driver and the performance demands of the network, and the probability of road accidents lessens. In other words, engineering improvements in the road are designed to simplify the problems faced by the driver and to reduce the risk that the performance level of the driver will be less than the level required to meet the demands of the network.

The road network can be improved at various levels. On the one hand, it is possible to increase the number of motorways, interchanges, bypasses, etc. On the other hand, a lower level of improvements may be made, such as antiskid treatment, painting, and increasing the sight distance.

PRINCIPLES OF ALLOCATION METHOD

The method for allocating safety resources advanced in this paper is derived from that stage in the decisionmaking process at which the size of the safety budget for investment in the infrastructure is being decided. The question asked at this time concerns the location and content of the changes. Figure 2 demonstrates the basic structure of this method. Four steps are distinguished.

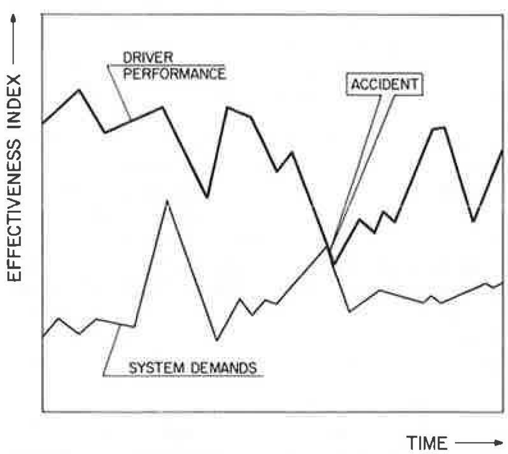
Step A: Safety Control of Road Network

The first step involves the preparation of a list of the black spots (short stretches of roadway and crossroads) where alternative engineering improvements may be suggested. This step is intended to decrease the dimension of the problem and to concentrate only on those elements that are thought to be worthwhile.

Step B: Alternative Projects for Improvement

From surveys undertaken at the sites of the black spots listed in step A, alternative projects are then devised for each site.

Figure 1. Hypothetical description of local failure of the system.



Step C: Definition of Cost and Benefit of Each Project

At this stage, an evaluation is made of the cost of the project and of the estimated safety benefit to be expected by a reduction in accidents.

Step D: Decision on Specific Projects to be Undertaken

Within the defined budget, a primary list of projects is prepared. The allocation of funds for these various projects is based on mathematical programming.

These four steps will now be discussed in detail.

SAFETY CONTROL OF ROAD NETWORK

The safety control of the road network is intended to identify the problem locations for which, at a later stage, the value of investment in safety means has to be examined. The immediate concentration on those elements in the road where safety benefits are most likely to be attained simplifies the problem of fund allocation, makes the entire procedure less costly, and enables routine, periodic inspection of the network. There is no doubt that a systematic, detailed scanning of the entire network, the compilation of a list of alternative programs for the network, and the allocation of funds over the entire network would ultimately lead to a more successful final allocation. In other words, an allocating system without safety control, i.e., without initial selection of black spots, would produce a greater reduction in accidents within a predetermined budget.

Figure 3 illustrates two hypothetical curves of the reduction in accidents as a function of the size of the budget. Curve A is derived from a combination of the investments without safety control, curve B with safety control. To the extent that the safety control is successful, the gap between the curves will decrease. The convexity of the curves demonstrates the decreasing marginal reduction in accidents with the increase in investment. This feature is caused by the fact that road accidents are not dispersed homogeneously throughout the road network.

Within the budget of C_1, a reduction of n_1 accidents will be produced when safety control is

Figure 2. Schematic diagram of allocation process.

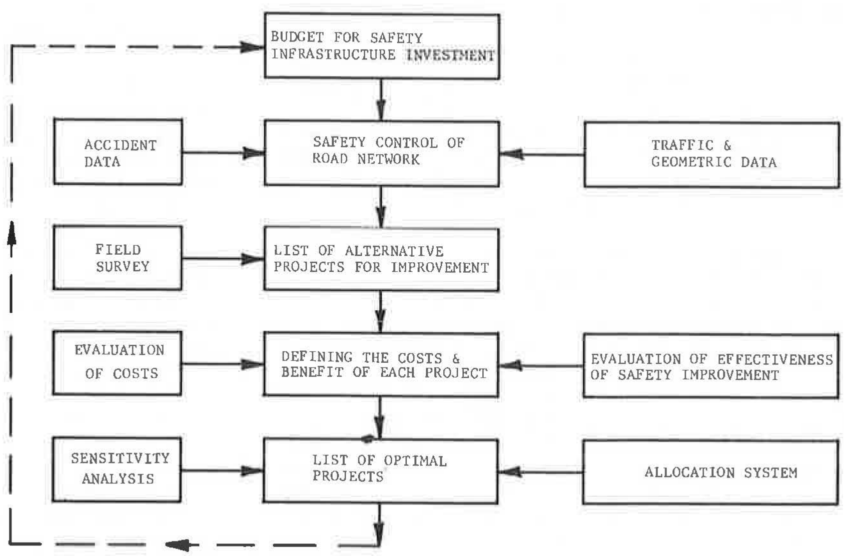
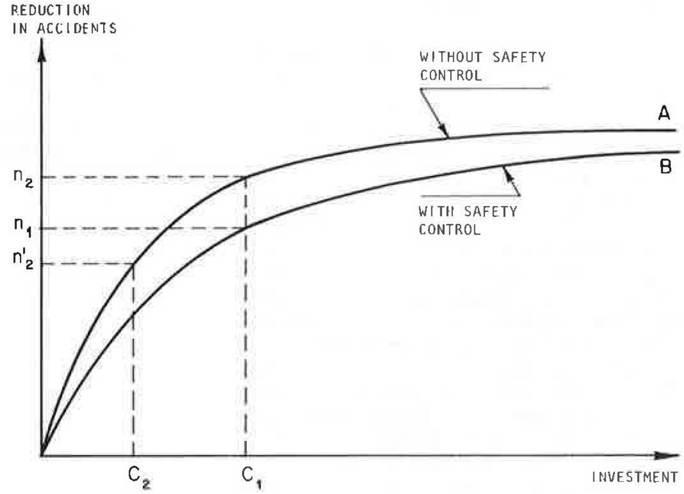


Figure 3. Accident-reduction curve with and without safety control.



carried out and n_2 accidents ($n_1 < n_2$) when no safety control is performed. As previously mentioned, however, the cost of compiling lists of alternative programs according to each system can be significant. If it is assumed that the additional cost of compiling a list of alternatives without safety control is $C_1 - C_2$ (Figure 3), this cost represents the planning expenses for large components of the network that will not be included in the final selection. If, therefore, C_1 represents a total budget with safety control, then C_2 ($C_2 < C_1$) will be designated as the actual investment without safety control. As a result, a budget of C_1 will help reduce n_1 accidents after safety control is applied and only n_2 accidents ($n_2 < n_1$) when safety control is not applied. This hypothetical example demonstrates the advantage of using safety control as a preliminary stage in the allocation process.

The exposure by safety control of those stretches and intersections where a high number of accidents occurs in relation to the number of opportunities for accidents does not explain the reasons for accidents at these black spots. This fact proves the lack of compatibility between the standards of the road and the traffic volume; in other words, there is an engineering deficiency in the road. The definition of the extent of noncompatibility between the demands of the road and the traffic volume cannot be made in absolute terms but only relative to the conditions existing throughout the road system during a specified period.

The identification of the black spots may be carried out in two stages:

1. Development of a model for estimating the potential for accidents and
2. Identification of those places where there is a gap between the actual number of accidents and the possible number of accidents as based on a probability model for accident occurrence at those locations.

The accident potential at location i can be described in the following manner:

$$\lambda_i = f(X_i, \Theta) \quad (1)$$

where

λ_i = potential or expectation of accidents on stretch of road i,

$X_i = (X_{i1},\ldots,X_{im})$ = group of m independent variables describing stretch of road i, and

$\theta = (\theta_1,\ldots,\theta_m)$ = group of parameters of model.

The independent variables X_i are these: data on exposure (the number of vehicles per unit of time), data on the basic engineering characteristics (such as the number of lanes or stretch of road or intersection), and data on past accidents. Details of the models describing accident potential for the road network in Israel may be found in the last section.

The need to include the history of past accidents on the same stretch of road was treated with many reservations. The method of inclusion of the lag variable as an explanatory variable is accepted as an expression of dynamic models in economics. In this case, it became clear that the inclusion of the history of past accidents introduced an additional sensitivity into the model; that is, in addition to exposure and geometric structure, the model benefited from sensitivity to changes in the number of accidents from period to period. Empirically, the inclusion of the past accident history did not obscure the influence of exposure. Examination of the road section was then based on two lists of black spots, one without the past history and one with this explanatory variable. It became clear that the first list was a subgroup of the second.

Because the number of accidents on a stretch of road during a period of time is usually presumed to be Poisson distributed (2,3), it was impossible to use conventional regression methods in this case as a result of the dependence that existed between expectation and variance. It was necessary, therefore, to use the weighted least-squares method to achieve the best possible estimates that would be asymptotically normally distributed.

An intersection of stretch of road is declared a black spot when the following condition exists:

$$P[N(t) > Y_i | \lambda_i = f(X_i, \Theta)] = \sum_{n=Y_i}^{\infty} [\exp(-\lambda_i)\lambda_i^n/n!] < \alpha \quad (2)$$

where

α = level of significance,
$N(t)$ = number of accidents during (0,t), and
Y_i = number of accidents on stretch of road i.

ALTERNATIVES AND EVALUATION OF EFFECTIVENESS

Once the list of black spots has been prepared, a field survey is carried out to inspect the existing engineering problems of the road. Because of the fact that road accidents are a result of several factors, it is often difficult to isolate the specific faults that cause an accident. On the other hand, it is often discovered that such a wide range of engineering problems exists that the number of possibilities for improvement is very large indeed. For example, at one specific location the following improvements were found to be useful: lighting, improving skid resistance, new painting, and cutting back the shrubbery. Although there were four suggested improvements, the number of possible combinations of alternatives is $2^4 = 16$, which includes the do-nothing alternative. Evaluating the extent of effectiveness of these various improvements presents a problem. At the current state of the art, there are no reliable estimates that are useful for measuring the effectiveness of single improvements. It is even more difficult to evaluate the effectiveness of various combinations, because an interdependence is found among the individual improvements.

In order to simplify the process of identifying specific faults and to bypass most of the problems in that connection, three standards of road planning may be defined: initial (preparatory) planning, medium (secondary) planning, and the completed solution of the problem. For each group of standards, the necessary elements, as well as the required set of inputs to attain that standard, should be set out in detail. Thus, the engineering team sent out into the field needs only to fill out the routine forms containing the necessary improvements to reach each standard and does not have to initiate solutions of its own.

The effectiveness of each planning level is measured in accordance with the safety conditions existing at other locations on the road network where the standards already exist. This simple method, besides solving problems of planning and of estimating effectiveness, also solves most of the problems of costing. Because this method constitutes a modular view of planning, standard units of cost can be fixed for each modular unit, and thus initial costing evaluations can be derived without detailed planning of the project.

BUDGET ALLOCATION

Because of the complexity of the allocation problem, the use of accepted engineering economics techniques, such as cost-benefit and internal rate of return, might produce only a nonoptimal solution. The reason is that at every black spot, there are a number of substitutable alternatives distinguished by cost and effectiveness. It could happen that within the existing budget, the most effective combination of solutions over the road network will be such that the most worthwhile projects for a number of locations will be the second-best alternative or even the third best. In other words, a method based on the choice of the best alternatives for each location will not necessarily ensure that the final combination of investments will be optimal. Thus, it is necessary to use a more sophisticated technique of mathematical programming that will promise the systematic scanning of all possible alternatives.

According to McFarland and others (4), an optimal solution can be reached by either integer or dynamic programming. In this study, it was decided to adopt an integer-programming solution. The advantages of using integer programming were the availability of appropriate computer software and the special structure of the problem, which promised an almost-integer solution by using linear programming. The linear-programming (LP) solution enables us to conduct sensitivity tests.

Mathematically, the safety-fund allocation problem can be stated as follows:

$$\text{Min} \sum_{i=1}^{N} \sum_{j=0}^{N_i} b_{ij} X_{ij} \qquad (3)$$

Subject to:

$$\sum_{i=1}^{N} \sum_{j=0}^{N_i} C_{ij} X_{ij} \leqslant C \qquad (4)$$

$$\sum_{j=0}^{N_i} X_{ij} = 1, \quad i = 1, \ldots, N \qquad (5)$$

$$X_{ij} \geqslant 0 \text{ for all } i, j \qquad (6)$$

$$X_{ij} = 0, 1 \text{ for all } i, j \qquad (7)$$

where

b_{ij} = number of accidents at location i after implementation of project j,
C_{ij} = cost of project i at location j,
C = size of budget,
X_{ij} = decision variable regarding implementation of project j at i,
X_{i0} = do-nothing alternative,
N = number of locations, and
N_i = number of projects at i.

Constraints 4, 5, and 6 by themselves constitute an LP problem, whereas constraint 7 turns the problem into one of integer programming. The constraint matrix is shown in Figure 4. This structure of the problem promises the possibility of exclusion of constraint 7; despite that, the optimal solution to the LP problem (5-7) will be almost integer. According to Lasdon (5), any basic feasible solution of a linear program has the following property: at least N - 1 of the indices i have one X_{ij} positive (and hence unity).

In addition, it is possible to arrive at a solution by using algorithms of generalized upper bounding to reduce the magnitude of the problem. As a result, for some locations there will be no integer solution; instead, the solution will have a linear combination of two alternatives. In fact, at location i it is usually possible to define a revised project within a certain budget framework,

$$\sum_{j=1}^{n_i} C_{ij} X_{ij}$$

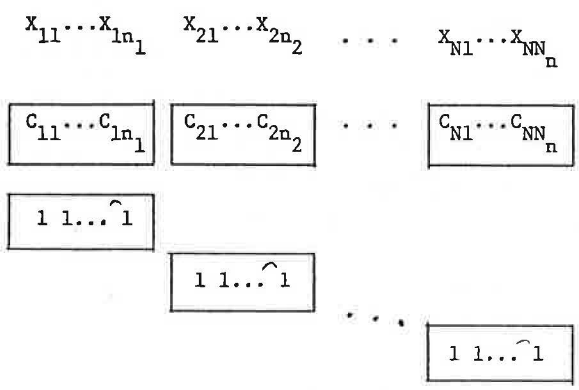
which will correspond to accidents represented by

$$\sum_{j=1}^{n_i} b_{ij} X_{ij}$$

Of course, it is always possible to add constraint 7 and to search for the integer solution; however, this has three drawbacks:

1. The problem becomes complex; the process may consume much computer time.
2. Usually, as will be shown in the example given below, not all the budget will be exploited in the integer solution, so that the general reduction in the number of accidents by means of the integer solution may be less than in the approximate LP solution.

Figure 4. Constraint matrix.



3. Most of the sensitivity tests that are possible by means of the LP solution are impossible by means of the integer solution.

CASE STUDY

The following limited example was worked out in order to test the practicability of the procedures suggested. It shows the advantage of solving the problems as an LP problem rather than searching for the integer solution. The case study also illustrates the superiority of both of those methods over the traditional methods used in engineering economics.

Fifteen locations were selected on the interurban network in Israel: 10 stretches of road, 4 black spots, and 1 intersection. At each location, different levels of improvement were defined. The number of accidents for the do-nothing alternative was taken as the expected number of accidents over the coming 20 years, on the assumption that no improvements would be carried out. The number of accidents for each level of improvement was estimated for the same 20-year period. If the life of an improvement was less than 20 years, it was assumed that at the end of its life the level of accidents would return to the do-nothing level.

Figure 5 shows the improvements in the number of accidents under different budget levels. Both an integer and a continuous solution for the LP problem are presented and compared. As expected, the LP solution presents higher benefits than does the integer solution. In most cases, a scheme for improvement can be defined that will be equivalent to a linear combination of two levels of improvement, as determined by the continuous LP solution. Figure 5 also presents the results obtained by the cost-effectiveness solution. As can be seen, allocation by the cost-effectiveness method is inferior to that by the mathematical-programming solution.

SUMMARY AND DISCUSSION

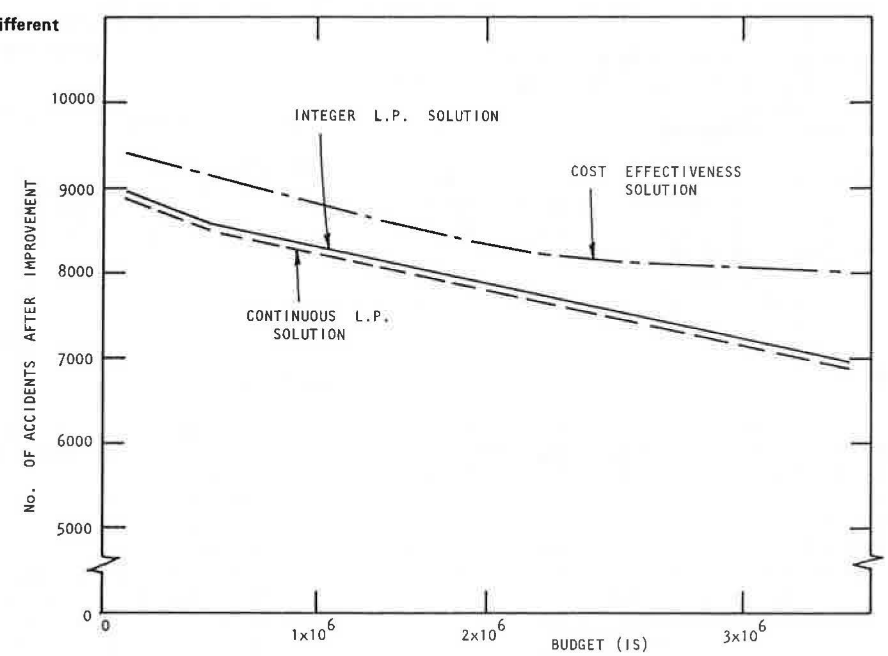
This paper has described a systems approach to the solution of the problem of allocation of safety resources for black spots. Special attention was given to a level of applicability within limited means of management costs, background data, and labor time to reach a decision based on the allocation of the safety budget. From this point of view, the model should be classified as a skeleton model, because it is based on practical information and provides input for a more-detailed planning process in the future.

The extent of the problem arising from the size of the road network initially demands concentration on problem locations within the network. This process is performed by constructing a model of accident potential and by isolating stretches of road and intersections where significant differences exist between the accident potential and the actual number of past accidents.

The next stage in the process is the suggestion of improvements and an evaluation of their cost and effectiveness. In order to perform this stage efficiently, three levels of design standards were defined. The field team was asked only to designate the necessary improvements to bring the black spots to the level of each of these standards. The effectiveness of these improvements is measured by comparing the safety conditions with conditions existing at other locations where these standards already exist.

The input of the allocation problem is a group of

Figure 5. Allocation results of three different methods.



black spots; at each spot, in addition to the do-nothing alternative, there exist at least three other alternatives (three design levels), which are mutually exclusive. Thus, the range of alternative solutions consists of a mixture of independent, mutually exclusive projects. The optimal solution can be found by solving it as a problem of integer programming. The structure of the constraint matrix creates a situation in which the solution of the problem by linear programming is almost integer; for practical purposes, this solution is usually sufficient.

The advantage of the allocation method advanced here shows itself when the allocation budgets are relatively small. This is due to the ability of the integer-programming method to systematically scan all possible solutions and to locate the best one. Some of the projects selected for the optimal solution are, however, second best. As the total budget grows, the advantages of this method decrease in comparison with the classical methods.

ESTIMATE OF ACCIDENT POTENTIAL

Models defining the accident potential of road sections and intersections were estimated for the road network in Israel. The estimating process and the final structure of these models are described in this section.

Road Sections

On road sections, the independent variables used in this study were traffic flows, number of accidents at a location in the period prior to that for which the expectation was being estimated, and the number of carriageways.

The model adopted for further study was of the following form:

$$E(Y_i) = \Theta_0 + \Theta_1 X_{i1} + \Theta_2 X_{i2} + \Theta_3 X_{i3} \quad i = 1, 2, \ldots \tag{8}$$

where

$E(Y_i)$ = expected number of accidents on section i during 1970-1972,
X_{i1} = average daily traffic flow on section i,
X_{i2} = past number of accidents on section i,
X_{i3} = dummy variable denoting whether section i is single or dual carriageway, and
$\theta_0, \theta_1, \theta_2, \theta_3$ = parameters of regression equation.

Information on the number of carriageways was included in the model by means of a dummy variable (X_{i3}); values of 0 were taken for single carriageways and 1 for dual carriageways. This variable was later found to be not statistically different for the two types of roads, and therefore it was omitted in the final model.

Intersections

The relationship between accidents and a number of variables was also studied at both urban and interurban intersections. The independent variables studied were (a) an index of traffic flows, (b) the number of accidents in the previous period, (c) the length of time the intersection had been signalized, (d) the number of conflict points, and (e) the town in which the intersection was located.

At the 202 urban intersections studied, the correlation between flow index and accidents was R = 0.74 and between past accidents (1967-1970) and accidents in the previous period (1971-1972), R = 0.87. No consistent relationship was found between accidents and signalization or number of conflict points, so these variables were therefore dropped from the final procedure. The dummy variable for the different towns also contributed very little and was also dropped. Because of different traffic characteristics, separate models were estimated for urban and interurban intersections.

The model finally adopted was of the following form:

$$E(Y_i) = \Theta_0 + \Theta_1 X_{i1} + \Theta_2 X_{i2} \tag{9}$$

where

$E(Y_i)$ = number of injury accidents in 1971-1972,
X_{i1} = number of injury accidents in 1967-1970,
X_{i2} = index of traffic flows, and
$\theta_0, \theta_1, \theta_2$ = constants.

Estimate of Model Parameters

The final models adopted were estimated by means of a multiple linear regression. The regression coefficients were calculated by a weighted least-squares method, as developed by Jorgensen (6) and Weber (7). In the case that a dependent variable was Poisson distributed, the expectation would be equal to the following variance:

$$\lambda_i = E(Y_i) = \mathrm{Var}\,(Y_i) \tag{10}$$

In such a case, the least-squares estimates obtained by the normal procedure were unbiased but not consistent.

The final formulas fitted to the different locations were as follows:

1. Road sections: In the final analysis, 1630 road sections were included, and the equation fitted was of the following form:

$$E(Y_i) = 0.023 + 4.225 \times 10^{-4} X_{i1} + 0.499 X_{i2} \tag{11}$$

The multiple correlation coefficient was R = 0.82.

2. Urban intersections: The final analysis included 202 urban intersections, and the equation fitted was

$$E(Y_i) = 0.507 + 0.514 X_{i1} + 2.724 \times 10^{-5} X_{i2} \tag{12}$$

The multiple correlation coefficient was R = 0.81.

3. Interurban intersections: There were 40 interurban intersections in the final analysis, and the equation fitted was

$$E(Y_i) = 2.546 + 0.514 X_{i1} + 1.330 \times 10^{-5} X_{i2} \tag{13}$$

The multiple correlation coefficient was R = 0.83.

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Evaluating Need for Accident-Reduction Experiments

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New traffic control devices or new applications of existing devices are frequently proposed as a means of facilitating the driving guidance and control process and thereby improving traffic safety. Before such changes can be approved at the national level, some research must be undertaken to evaluate the potential safety effectiveness of the new device. Safety effectiveness can be measured directly in terms of a reduction in accident rate or indirectly in terms of a change in an alternative measure of effectiveness. A requirement that accident data be collected before a new traffic control device standard or guideline is approved may itself be impractical and/or not cost-effective. A four-step methodology is presented for quantitatively addressing the need to undertake accident-reduction research experimentation. Statistical analysis and sampling requirements are developed first. This is followed by a determination of the minimum accident-rate reduction that would economically justify nationwide deployment of the new traffic control device treatment. The cost-effectiveness of alternative experimental designs is then evaluated. The final step is a trade-off analysis of the value of information to be derived versus the cost of obtaining the information. A case study application of the methodology is also presented.

New traffic control devices or new applications of existing devices are frequently proposed as a means of facilitating the driving guidance and control process and thereby improving traffic safety. Before such changes can be approved at the national level, some research must be undertaken to evaluate the potential safety effectiveness of the new device. In addition, the costs required to implement the new traffic control device treatment, under either an as-needed or an immediate-replacement policy, must be evaluated.

Safety effectiveness can be measured directly in terms of a reduction in accident rate or indirectly in terms of a change in an alternative measure of effectiveness. Examples of the latter include vehicle speed profiles, variance in lateral placement of vehicles within a roadway lane, driver head and/or eye movements, and various types of traffic conflicts as defined by procedures for traffic-conflicts analysis (1-3). Regardless of whether accident data or alternative measures of effectiveness are used, the principal issue is how much information is necessary to make a reasonably confident decision about potential safety cost-effectiveness.

A requirement that accident data be collected and evaluated before a new traffic control device standard or guideline is approved may itself be impractical and/or not cost-effective. If this is the case, then a decision about approval of the new traffic control device must be based on an evaluation of alternative measures of effectiveness. This would require an assumption about the true relationship between accident rate and the alternative measure. Because this is usually a qualitative judgement, there can be substantial differences of opinion about potential safety effectiveness and therefore a lack of necessary support for what may actually be a very cost-effective standard or guideline.

The purpose of this paper is to present a methodology for analytically addressing these issues. The methodology was developed during research on an experimental design for evaluating the safety benefits of railroad advance-warning signs (4). The results from that case study will be used to demonstrate the application of the methodology.

EVALUATION METHODOLOGY

The evaluation methodology is designed to address the following basic questions relative to proposed research experiments of the accident-reduction potential of a new traffic control device standard or guideline:

1. What are the sampling requirements based on a treatment-control comparison?
2. What is the critical, or minimum, accident-rate reduction that the experimental design should be capable of detecting?
3. What is the cost-effectiveness of alternative experimental designs?
4. What is the value of the information to be derived from the experiment?

The evaluation methodology is therefore presented as a four-step process.

STATISTICAL ANALYSIS AND SAMPLING REQUIREMENTS

It is assumed that a treatment-control comparison is to be used in the analysis of the experimental data, although this can be supplemented with a before-and-after analysis if desired. With a treatment-control type of design, one group of sites is selected to receive or be treated with the proposed new control device application. A second group of sites would be selected as a control or base against which measured changes in accident rate at the treatment sites can be compared.

The sampling scheme is composed of two parts. First, the selected population of study sites would be divided into k homogeneous sets, each composed of n similar sites (where n = 1, 2, 3, 4, 5, or larger). Then, from each of the k sets, one of the