INDIANA'S SAFETY MANAGEMENT SYSTEM SOFTWARE PACKAGE (SMSS) – A REVIEW

Godfrey Lamptey
Engineer, C3TS, 2520 NW 97th Ave., # 200, Miami FL, 33172. godfrey1@c3ts.com

Ashish Jain Samdariya
Graduate Student, School of Civil Engineering, Purdue University,
West Lafayette IN, USA, e-mail: ashish.samdariya@gmail.com

Samuel Labi
Assistant Professor of Civil Engineering, School of Civil Engineering, Purdue University,
West Lafayette IN, USA, e-mail: labi@purdue.edu

Kumares C. Sinha
Olson Distinguished Professor, School of Civil Engineering, Purdue University,
West Lafayette IN, USA, e-mail: sinha@ecn.purdue.edu.

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ABSTRACT

At the current time, most of the current safety analysis tools allow for the evaluation of safety enhancements for specific projects individually. Thus, the integration of safety management on existing road network into the transportation planning process still remains an issue. This paper reviews a framework and analysis tool that addresses this issue. The framework identifies current and future potential candidate locations within a selected road network over a specified analysis period and selects a set of alternative safety improvement projects based on identified roadway deficiencies and predominant crash patterns for each location. The framework also determines current and future safety investment physical and monetary needs, and enables development of a multi-year investment strategy for safety improvements for a given funding level over a specified analysis period. Furthermore, the impact of different funding levels on system-wide safety is investigated to determine the appropriate level of safety investment to meet the required safety goals established by the highway agency. The paper uses a case study to demonstrate the application of the framework.

Keywords: safety management, safety planning.

INTRODUCTION

Transportation facilities are critical for economic development because they help in safely moving people, goods, services and raw materials. As such, transportation agencies develop plans to ensure that the infrastructure provide highest levels of operational service (safety, mobility, etc.) in the most cost-effective manner and within available resources. The core of any transportation planning process is the establishment of a work plan over a period of time. The work plan specifies, for each facility in the network, what type of work should be done and its expected cost and efficacy.

Plans often include long-range capital improvement projects (new construction, expansions, etc.). The work plan takes cognizance of budgetary constraints and shows the consequences of the work plan in terms of overall network benefits and costs. Therefore, a transportation plan is typically accompanied by a financial plan that not only involves the cash flows associated with the needed physical improvements but also validates the feasibility of the transportation plan. Also, plans often include a programming component that adds the temporal dimension – a schedule that specifies when each work should be carried out. Transportation planning and programming are typically accomplished using tools such as ranking, prioritization, or optimization – the goal typically is to select the work types, facilities, and timings such that some network-level utility is maximized. Such utility, in the context of a safety management system, for example, could be a system-wide reduction in fatal crashes per dollar of safety investment. Ideally, agencies should have an overall plan that includes all component management systems for a given transportation mode. For example, for highway transportation, an overall plan is the sum of plans from the constituent management systems (pavement, bridges, safety, congestion, etc.) as well as plans from other special programs.

At the current time, most agency transportation plans do not include safety management mostly because of the lack of framework for network-wide safety management. As such, safety investments in many agencies are based on a case-by-base approach: safety problems are addressed as and when they occur, and when emergency funding can be made available for such enhancements. This leads to delay in resolving safety problems when they occur, inconsistencies in the manner of resolving such problems, and difficulty of carrying out trade-off and sensitivity analyses with respect to funding levels and also across competing facilities.

At certain countries, legislation has been passed to ensure that transportation agencies explicitly incorporate safety planning in the long-range planning process in a proactive manner. This has been mostly in the highway transportation mode. In the United States, for example, the Transportation Equity Act for the 21st Century (TEA-21) required agencies to include safety as a priority in their transportation planning programs in a more comprehensive and system-wide context.

This paper reviews a framework with which transportation agencies can incorporate safety in their transportation planning processes in a proactive, comprehensive, and system-wide manner, for any mode of transportation (Lamptey et al., 2010). First, a general framework is presented for identifying candidate facilities in the network for safety enhancement, identifying (for each candidate facility), the alternative safety enhancement projects on the basis of historical deficiencies and predominant accident patterns at that facility, and determining, for each facility in the network, whether safety enhancements are needed, the type and cost of enhancement to be carried out, and in which year the work is needed. Thus, the framework determines the overall safety funding requirements and develops a multi-year safety investment strategy, which candidate facilities should receive safety enhancement if the safety budget is limited, and assessing the impact of different budgetary levels on network-wide safety. The paper then uses a case study in highway transportation to apply the framework and therefore to demonstrate how safety can be incorporated proactively in the network-level transportation planning process.

EXISTING SOFTWARE PACKAGES FOR SAFETY MANAGEMENT

A safety management system should not only provide basic safety data at highway facilities but also must serve as a decision support tool that agencies can use in their tasks of selecting cost-effective highway safety strategies and projects. There are a number of existing software packages and databases that satisfy part of this mission. The Highway Safety Information System (HSIS) is an information system that contains data on crashes, roadway inventory, traffic, curve/grade, intersection and interchanges. HSIS helps users to analyze various safety related issues, and design models to predict future accidents. The *SafetyAnalystTM* is for site-specific highway safety improvements that involve physical modifications to the highway system. This tool determines accident pattern, frequency and percentage of particular accident type system wide. *SafetyAnalystTM* has the following functions: network screening to identify site for safety improvement; diagnosis to ascertain the nature of accident pattern at the site; countermeasure selection; economic analysis between various alternatives; ranking of sites and projects, and a before-and-after evaluation of the safety countermeasure. The Interchange Safety Analysis Tool (ISAT) is a spreadsheet tool that assesses the safety of interchanges and adjacent roadway segments and intersections which is basically geometric design and traffic control features. Its primary output is crash prediction. ISAT also predicts the safety performance of design alternatives. The Comprehensive Highway Safety Improvement Model (CHSIM) has functions that are similar to Safety Analyst. The Interactive Highway Safety Design Model (IHSDM) evaluates safety and operational effects of highway geometric designs. This tool diagnoses potential safety and operational issues, and estimates expected safety performance. At the current time, it seems that none of these packages carry out direct optimization to establish, for a given budgetary constraint, the optimal set of safety projects at a network level and the consequences of departures from the optimal solution in terms of safety performance. Indiana's SMSS addresses this gap.

ANAYTICAL FRAMEWORK

The overall framework for the study is presented in Figure 1.

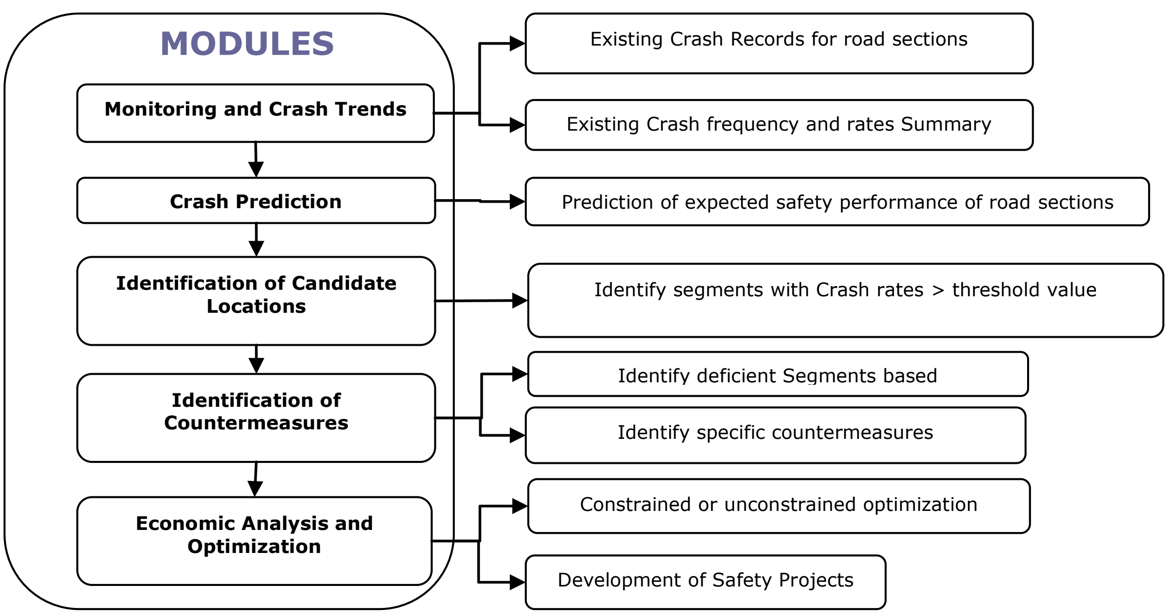

Figure 1 Analytical Framework for Safety Management System

Figure 1 involves the following steps:

1. Definition of analysis period and selection of the network or sub-network of interest,
2. Estimation of expected accident frequency in each year of the analysis period,
3. Selection of facilities deserving some safety enhancement in each year of the analysis period,
4. Identification of alternative safety enhancement treatment (projects) at each candidate facility,
5. Estimation of the cost and safety benefits of each safety enhancement project,
6. Identifying, for each facility, work needed and year of work, given budgetary constraints.

Figure 2 presents the conceptual algorithm used in this paper for the network-level safety planning and programming in the software package.

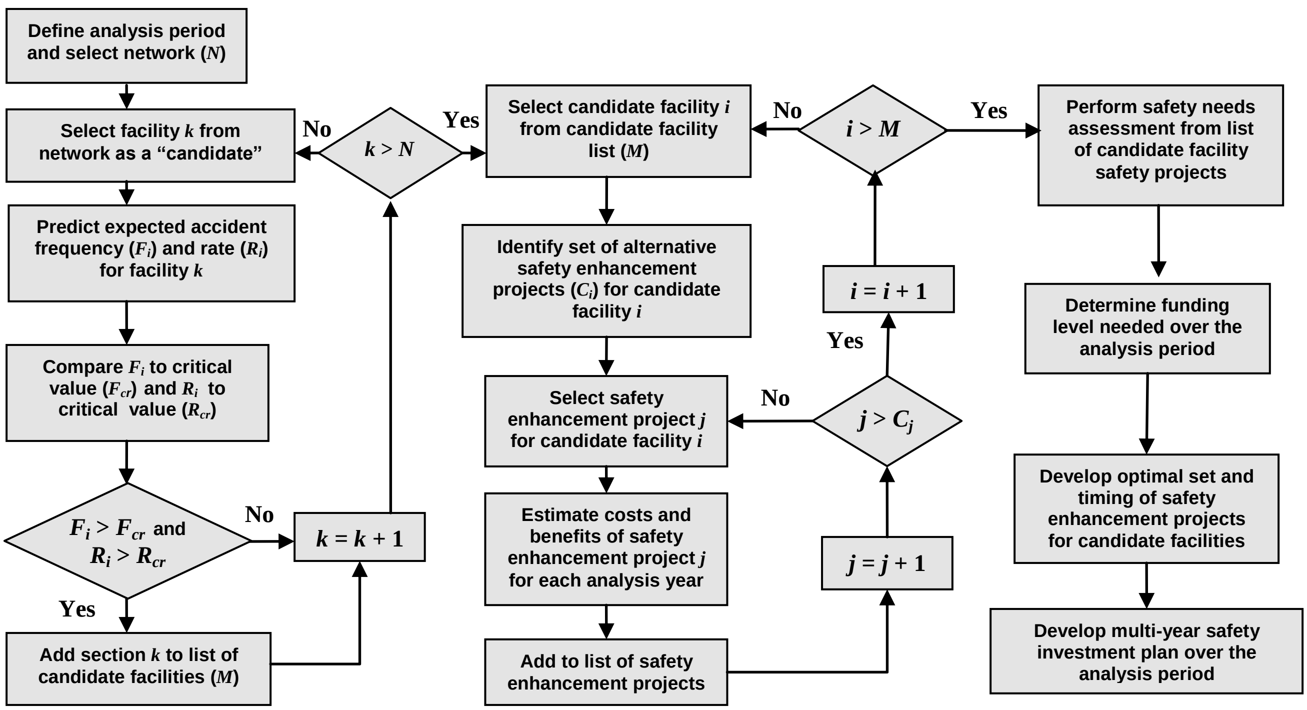

Figure 2. Conceptual Algorithm for network-level safety planning and programming

Step 1 - Definition of Analysis Period and Selection of the Network or Sub-network

The analysis period could a planning horizon that is either long-term (typically, 15-20 years) representing a long-range plan; or short-range (typically 3-5 years) representing safety funding renewal intervals. Network selection means defining, for the analysis, a sub-network of facilities (links, nodes, etc.) that are of specific interest due to some attribute(s) such as facility type, class, and jurisdiction.

Step 2 - Estimation of Expected Accident Frequency

The basic requirement for safety investment is to identify sections within the road network that need some safety intervention at the current or future time. The selection of these candidate locations requires knowledge of the safety performance (crash frequency and severity) of the road network over an analysis period. A considerable amount of research has been conducted on the prediction of expected safety performance of highway segments. Zegeer et al., (1991) developed a non-linear model to predict accidents on horizontal curves. Miaou et al., (1993) used the Poisson model form to predict accidents on road segments. More recently negative binomial models, a generalized form of the Poisson, have been used in crash modeling. Vogt and Bared (1998) developed the crash prediction models for two-lane rural highways using extended negative binomial regression analysis. The use of the Empirical Bayesian (EB) method in safety analysis has become widely accepted as the most unbiased estimate of the expected crash frequency. It is based on the recognition that historical crash counts are not the only indicator of safety performance. The EB method also automatically corrects for the regression-to-the-mean effect (Hauer, 2002).

For the present study, the crash prediction procedure for the analytical framework is based on the EB method outlined by Hauer et al.The EB estimate uses both historical crash record and expected crash frequency obtained from a multivariate safety performance function. This is implemented by using a weight factor that depends on the magnitude of historical crash record, and the reliability of safety performance functions. For the present paper, separate safety performance models were developed for fatal/injury and property damage only using negative binomial analysis of data extracted from Indiana's crash and roadway inventory databases. The functional forms of the models are shown in Table 1. The crash estimates obtained using the EB technique represents the expected crashes for the period where historical crash data is available. To obtain future crash estimates, AADT growth factors were used to convert the expected crash frequency for the before period to an expected crash frequencies for each year of the analysis period.

Step 3 – Identifying Candidate Locations for Safety Enhancement

In identifying facilities in the network that need some safety enhancement, it must be realized that some will need the intervention at the current time (that is, in the first year of the analysis period) while others may be safe at the current time but with traffic growth, become unsafe at some future year. As such, the identification of candidate locations is carried out not only for the initial year but also for each year of the analysis period. McGuigan (1981) introduced the concept of potential accident reduction (difference between observed accident count and expected accident frequency) as a method of identifying candidate locations. In a similar formulation, Persaud (1999) used the Expected Binomial estimate instead of the observed accident count. Arguing that a facility should be considered hazardous if the probability that the expected accident rate at the facility is greater than a specified critical value, Higle and Witkowski (1988) suggested using an EB estimate of accident rate. Hauer (1992) presented an EB method for identifying candidate facilities on the premise that a facility is hazardous if the probability of its expected accident frequency significantly exceeds a certain predefined critical accident frequency.

The framework described in present paper selects candidate facilities using both approaches – the expected accident frequency as well as the expected accident rate. The component of the framework that uses the expected accident frequency approach guarantees the selection of facilities with the highest potential benefit; and the component that uses the expected accident rate approach minimizes the bias of selecting facilities with high usage levels (and thus relatively low accident rates). The "accident density" is defined as the number of accidents divided by the facility's physical size, while the "accident rate" is defined as the number of accidents divided by the facility's usage level. A facility is selected as a candidate for safety enhancement if both expected accident frequency and accident rate obtained from the EB estimate exceed their respective critical values as shown:

$$F_{c(it)} = D_a.L_i + k(D_a.L_i)^{0.5} \quad -$$

$$R_{c(it)} = R_a + k.(R_a/VMT_{it})^{0.5} \quad -$$

Where: $F_{c(it)}$ = Threshold or critical crash frequency for road section *i* in year *t*
$R_{c(it)}$ = Threshold or critical crash rate for road section *i* in year *t*
D_a = Average crash density for similar road sections obtained from historical crash records
R_a = Average crash rate for similar road sections obtained from historical crash records
L_i = Length of road section *i*
VMT_{it} = Estimated Vehicle Miles Travelled (VMT) for road section *i* in year *t*
k = A constant representing the statistical significance of the estimate.
In place of these "critical" values, an agency may use safety thresholds established by the highway agency. The candidate facilities are then ranked on the basis of the ratio of expected and critical accident frequencies and the ratio of the expected and critical accident rates.

Step 4 - Identification of Safety Enhancement Projects

The framework next defines the alternative safety enhancement projects that can be considered to address the defects at each candidate facility. These enhancements, which vary from site to site, are based on the establishment of the presence of contributory accident factors whose elimination or modification are expected to translate to reduced accidents. Safety improvements programs can be categorized into three main groups based on the contributing factors: the facility characteristics, features of equipment that use the facility, attributes of the human operator, and the operating environment. In the present paper, the framework focuses only on the facility characteristics. Appropriate safety treatments can be identified on the basis of (i) known or predicted deficiencies of the facility with respect to its geometric features, construction and design standards, material type, etc., (ii) patterns of past or expected future accidents.

An accident pattern is described as being dominant at a given facility if its expected frequency significantly exceeds its critical accident frequency at that location. The framework assumes that the historical proportions of the accident patterns remain unchanged throughout the analysis period. Thus the expected frequency for the various accident patterns is obtained by distributing the expected accident frequency using default estimates of the historical proportions among the various accident patterns. The critical frequency for each accident pattern is given as:

$P_{c(ij)} = P_{aj} + \sigma_j$

Where $P_{c(ij)}$ = Threshold or critical frequency for accident pattern *j* for candidate facility *i*
P_{aj} = Expected average frequency for accident pattern *j* for similar facilities
σ_j = Standard deviation for expected average frequency of accident pattern *j* for similar facilities

Based on the identified roadway deficiencies and predominant crash pattern a set of alternative safety improvement projects is identified for each candidate location. For example, a rural two-lane section with predominant off-road collisions is assigned a safety improvement of "Install continuous rumble strips on right shoulder". By default, the "Do Nothing" alternative is added to the set of alternative safety improvement projects for each candidate location. The default set of alternative safety improvement projects for each roadway deficiency and predominant crash pattern (Table 2) does not represent the full range of safety improvement projects that can be implemented at a site due to limited available site specific conditions.

Step 5 - Computation of Cost and Benefits

The costs and benefits of each safety improvement project, over the analysis period, is determined. These projects can be implemented in any year within the analysis period provided that year equals or exceeds the "critical year" of that location, that is, the year when the location becomes hazardous.

Estimation of Project Costs

The cost of each safety enhancement treatment can be estimated from default unit construction cost, maintenance cost and salvage cost values. In cases where the service life of the safety improvement project exceeds the analysis period, then its value over the remaining service life is taken as a salvage value and discounted to the present year. The present worth of costs for safety enhancement treatment *j* at facility *i* in year *t*, PWC_{ijt} is estimated as follows:

$PWC_{ijt} = C_{ijt}\ [1/(1+r)^{t-1}] + M_{ijt}\ [\{(1+ r)^{p-t-1} -1\}/(r(1+r)^{p}] + S_{ijt}\ [1/(1+r)^{p}]$

Where C_{ijt} = Initial construction cost for safety enhancement treatment *j* at facility n *i* in year *t*

M_{ijt} = Annual maintenance cost for safety enhancement project *j* at facility *i* in year *t*

S_{ijt} = Salvage value for safety enhancement treatment *j* at location *i* in year *t*

r = Minimum attractive rate of return

n = Life span of the safety enhancement treatment *j*

t = Analysis year = 1, 2…..*p*

Estimation of the benefits of safety projects

The benefits associated with each safety enhancement treatment depend on the expected accident reduction which can be estimated using the accident reduction factor (ARF's) for that treatment. The benefits can be computed either in non monetary terms as the total accident reduction or as present worth of benefits from the accident reduced over the analysis period as follows:

$AR_{ijt} = N_{sit}\ .\ CRF_{sij}$, summed up over all *s*'s (s = 1, 2) and over all *t*'s (t = 1, ..., p)

$PWB_{ijt} = [(N_{sit}\ .\ CRF_{sij}\ .\ CC_{sit})/(1 + r)^{t-1}]$, summed up over all *s*'s (s = 1, 2) and over all *t*'s (t = 1, ..., p).

Where AR_{ijt} = Total accident reduction for safety enhancement treatment *j* at facility *i* in year *t*

PWB_{ijt} = Present worth of benefits for safety enhancement treatment *j* at facility *i* in year *t*

N_{sit} = Expected accident frequency of accident severity *s* at facility *i* in year *t*

ARF_{sij} = ARF for accident severity *s* associated with safety enhancement project *j* at facility *i*

AC_{sit} = Accident cost for severity *s* at location *i* in analysis year *t*

s = Accident severity level; r = Minimum attractive rate of return; n = Service life of the safety enhancement treatment *j*; t = Analysis year = 1, 2…..*p*

If a safety enhancement is deferred to a later year, the benefits are computed only in terms of the accident reduction between the implementation year and the end of the analysis period. Thus the penalty for deferring a specific safety enhancement treatment is implicit in the equations above.

Step 6 – Selecting Projects under Limited Funding

A transportation agency may have a network-wide budgetary limit for safety enhancing projects on the network. As such, a need often arises to establish the most suitable safety improvement program (collection of safety projects and associated years of implementation). There are many techniques in operations research literature that could be used to accomplish this task. Integer programming is deemed more efficient than dynamic programming and also simpler than incremental benefit cost ratio (Harwood et al., 2003). In the context of highway transportation mode, Kaji and Sinha (1980) developed a resource allocation methodology for highway safety improvements using integer programming.

In the current framework, the objective of the optimization is to maximize the total economic value for all the safety enhancement projects selected. A "project" can be defined as a safety enhancement treatment at a facility. The economic value (E_{ijt}) of a safety enhancement treatment *j* at location *i* at analysis year *t* is evaluated using any appropriate economic evaluation criterion such as:

Cost-effectiveness = $(CR_{ijt} \, . \, 1000)/PWC_{ijt}$ (7)

Net present value = $PWB_{ijt} – PWC_{ijt}$ (8)

Benefit cost ratio = PWB_{ijt} / PWC_{ijt} (9)

The optimization procedure considers the following alternative scenarios: unconstrained funding optimization, total budgeting optimization, and multi-year budgeting with carry-over of unspent budget.

Unconstrained Funding Optimization

This scenario is consistent with traditional safety needs assessment. There is no budgetary constraint however only one safety improvement project can be implemented at each candidate location. The funding needs can be determined using the following integer programming equation.

Maximize ($x_{ijt} \, . \, E_{ijt}$) summed up over all t's ($t = 1, ..., p$), j's ($j = 1, ..., m$), i's ($i = 1, ..., h$)

Subject to $x_{ijt} = 1$ summed up over all t's ($t = 1, ..., p$), and j's ($j = 1, ..., m$)

$x_{ijt} = 0$ if $t \neq y_i$

$x_{ijt} = 0, 1$

Where h = Number of candidate locations within selected network; m = Number of alternative safety enhancement treatments at facility i; t = Analysis year = 1, 2, … p; y_i = Year when facility i becomes hazardous (critical year); E_{ijt} = Economic value of safety enhancement treatment j at facility i in year t;

$x_{ijt} = 1$ if safety enhancement treatment j is implemented at facility i in year t.

Total Budgeting Constrained Optimization

"Total budgeting" represents the situation where a given budget is specified for the entire analysis period and there are no constraints as to the amount that can be spent in a particular year. For this scenario, the constraint is the total funding available for the entire analysis period. The optimal allocation of the funding can be obtained by solving the following integer programming equation:
Maximize ($x_{ijt} \, . \, E_{ijt}$) summed up over all t's ($t = 1, ..., p$), j's ($j = 1, ..., m$), i's ($i = 1, ..., h$)
Subject to
$(x_{ijt} \, . \, C_{ijt} + (p – t) \, x_{ijt}.M_{ijt}) \leq B$
$x_{ijt} = 1$ summed up over all t's ($t = 1, ..., p$), and j's ($j = 1, ..., m$)
$x_{ijt} = 0$ if $t < y_i$
$x_{ijt} = 0, 1$
Where M_{ijt} = Annual maintenance cost of safety enhancement treatment j at location i in year t
C_{ijt} = Initial capital cost of safety enhancement treatment j at location i in year t
B = Total budget for analysis period. Other symbols have their usual meanings.

The equations above show the objective function of the integer program, the constraints on the total expenditure (initial capital and annual maintenance cost) in terms of the budgetary limit for the analysis period; the constraint on the number of safety improvement project (including do-nothing project) for each candidate location; and the requirement that at least one safety enhancement treatment (including the Do-Nothing alternative) should be implemented in each year of the analysis period.

Multi-Year budgeting with carry-over of unspent budget

Multi-year budgeting with carry-over of unspent budget represents the situation where an annual budget is specified for each year of the analysis period however any unspent budget can be transferred to the next year. The optimal funding allocation of the funding can be obtained as follows.

Maximize (x_{ijt} . E_{ijt}) summed up over all t's (t = 1, ..., p), j's (j = 1, ..., m), i's (i = 1, ..., h)
Subject to
(x_{ijt} . C_{ijt} + (p – t) $x_{ijt}.M_{ijt}$) summed up over all t's (t = 1, ..., p), j's (j = 1, ..., m), i's (i = 1, ..., h)
+ (t –k)$x_{ijk}.M_{ijt}$ summed up over all k's (k = 1, ..., t–1),
≤ B_{ijt} summed up over all t's (t = 1, ..., p), for all t.
x_{ijt} = 1 summed up over all t's (t = 1, ..., p), and j's (j = 1, ..., m)
x_{ijt} ≥ 1 summed up over all j's (j = 1, ..., m), and i's (i = 1, ..., h)
$x_{ijt} = 0$ if $t < y_i$
x_{ijt} = 0, 1
Where M_{ijt} = Annual maintenance cost of safety enhancement treatment j at location i in year t
C_{ijt} = Initial capital cost of safety enhancement treatment j at location i in year t
B = Total budget for analysis period. Other symbols have their usual meanings.
Symbols have their usual meanings

The above equations show the objective function of the decision model and the constraints on annual expenditure (initial capital and annual maintenance cost), and the annual budget limit plus any excess funds carried over from the previous year.

For any of the above integer programs, the optimal solution is the set of safety enhancement projects (facilities and treatments needed), and for each project, the implementation years and associated costs and benefits, subject to the given constraints. Constituent projects of the optimal solution are then prioritized on the basis of their implementation year and critical values. For example, if the optimal solution shows that safety improvement projects A and B are to be implemented in the same year, the project with the higher critical value is assigned a higher rank.

DESCRIPTION OF SAFETY MANAGEMENT SOFTWARE

A safety management system software package, (SMSS) described in Lamptey et al. (2004), was applied to implement, for highway transportation the framework described in the preceding section. SMSS, which is a stand-alone program using Microsoft Visual Basic.Net platform, uses the OptiMax 2000® component library from Maximal software for the optimization routines which allows Mathematical Programming Language (MPL) models to be integrated seamlessly and directly into object-oriented programming languages such as Visual Basic.

SMSS includes inventory and crash databases of the Indiana state highway network from 1997 to 2000. Any subset of the network can be selected for developing the safety plan. Each of the six procedures described in the planning framework constitute a module in the software and are executed in that order. The results from any module are used as input for the subsequent module. Also, each module can be executed independently. The software includes updatable default values of geometric standards, crash costs, average crash frequencies and rates, safety improvement projects and crash reduction factors for treatments at various highway functional classes.

The software selects alternative safety improvement projects for each candidate location and performs economic evaluations using Benefit-Cost Ratio (BCR), Cost Effectiveness (CE) or Net Present Value (NPV). Integer optimization is then carried using the CPLEX® Solver included in the OptiMax component library to select the optimal mix and timing of safety improvement projects for the candidate locations.

CASE STUDY

The framework and software were applied to a selected network of non-interstate road sections in Tippecanoe County in Indiana for a five year analysis period (2004 to 2008) to determine the current and future safety funding needs in the county. A multi-year safety investment strategy (what should be done, where, and when) was also developed for a given budget ceiling.

Description of Data and Analysis

The crash prediction procedure for the analytical framework is based on the EB method outlined by Hauer et al. (2002). Safety performance models were developed for fatal/injury and property damage only using negative binomial analysis of the data (Table 1).

Table 1. Safety Performance Functions for Crash Prediction.

Location	Safety Performance Functions	Overdispersion factor
Rural two-lane segments	$a_{IF} = 0.208 \times L \times Q^{0.604}$ $a_{PD} = 0.712 \times L \times Q^{0.592}$ $a_T = 0.922 \times L \times Q^{0.598}$	0.420 0.430 0.427
Rural multi-lane segments	$a_{IF} = 0.107 \times L \times Q^{0.814}$ $a_{PD} = 0.634 \times L \times Q^{0.615}$ $a_T = 0.737 \times L \times Q^{0.654}$	0.451 0.484 0.473
Urban two-lane segments	$a_{IF} = 0.105 \times L \times Q^{1.080}$ $a_{PD} = 0.603 \times L \times Q^{0.896}$ $a_T = 0.733 \times L \times Q^{0.917}$	1.253 1.349 1.459
Urban multi-lane segments	$a_{IF} = 0.674 \times L \times Q^{0.435}$ $a_{PD} = 2.028 \times L \times Q^{0.460}$ $a_T = 2.641 \times L \times Q^{0.458}$	1.588 1.946 2.095

a_{IF} = Annual Fatal and Injury crash frequency, a_{PD} = Annual PDO crash frequency, a_T = Annual Total crash frequency, Q = AADT for roadway segment, in thousand veh/day; L = Roadway segment length, in miles.

Using these models and the observed crash records, the EB estimate of the expected safety performance of a location was then computed as follows:

$$\varepsilon_i = \omega_i a_i + (1 - \omega_i) x_i$$

$$\omega_i = 1/[1 + a_i/\alpha L_i)$$

Where: ε_i = EB estimate of crash frequency, ω_i = Weight factor, a_i = Expected annual crash frequency on road section i from safety performance function, a = Overdispersion factor of safety performance function, x_i = Number of observed crashes on road section i.

The crash estimates obtained from Equation (1) represents the expected crashes for the period where historical crash data is available. To obtain future crash estimates, AADT growth factors were used to convert the expected crash frequency for the before period to an expected crash frequencies for each year of the analysis period. The data for the analysis consist of 40 urban and rural non interstate roadway sections in Tippecanoe County. The reference points and length of each section is defined by township and city boundaries. Each road section is divided into a number of homogeneous segments. The historical crash records are stored by section while roadway and geometric characteristics are defined for each homogeneous segment. Using the EB method described in Step 2 the expected crash frequency for each roadway section for each year of the analysis period was computed from a sum of expected crash frequency on the homogeneous segment within the roadway sections.

A number of roadway sections were identified (Step 3 of the framework) as candidate facilities that deserve some safety enhancement during the analysis period. Table 2 summarizes the characteristics of these sections. Identification of alternative safety projects and computation of the benefits and costs associated with the implementation of these safety improvement projects in each year of the analysis period were done as described in Steps 4 and 5 of the framework. The optimization step was carried out using three different economic evaluation criteria separately.

Table 2. Characteristics of Candidate Locations.

Section ID	Functional Class	# Lanes	Length	Average AADT (1997 – 2000)	Average Crash Rate/MVMT (1997-2000)	Average Crash Frequency/Mile (1997-2000)	Critical Value	Critical Year
79-S-025-0-01	UOPA	4	2.4	19458	6.78	48.13	8.789	2004
79-S-026-0-01	UOPA	2	7.22	28362	4.13	42.73	7.532	2004
79-S-038-0-01	UOPA	2	1.75	23286	3.70	31.43	5.352	2004
79-U-052-0-01	UOPA	4	10.44	27924	2.86	29.17	5.238	2004
79-S-043-0-01	ROPA	2	6.78	6187	3.76	8.48	4.729	2004
79-S-025-0-02	ROPA	2	9.25	9425	2.28	7.84	3.848	2004
79-U-231-0-02	ROPA	2	6.58	8921	2.26	7.37	3.585	2004
79-U-231-0-01	UOPA	2	7.98	14741	2.53	13.60	2.968	2004
79-S-126-0-01	Urban Collector	2	1.09	3610	0.70	0.92	2.471	2006
79-S-225-0-01	Rural Major Collector	2	3.25	1408	5.09	2.62	2.471	2007

UOPA – Urban Other Principal Arterial; ROPA – Rural Other Principal Arterial

Identification of Safety Enhancement Projects

For each candidate location, the factors considered in selecting an appropriate safety project are:

Deficient Roadway Geometric Features

The geometric features considered include right and left shoulder width, lane width, median width, access control, pavement friction, horizontal alignment and vertical alignment. A roadway geometric feature at a given candidate location is considered deficient if its value at the location is less than the recommended design value obtained from the Indiana Road Design Manual.

Expected Predominant Crash Pattern

Crash patterns considered are rear-end, head-on and opposite direction side-swipe, same direction side-swipe, off-road and night crashes. A crash pattern is identified as predominant if its expected frequency at a given location significantly exceeds its critical crash frequency at that location. The framework assumes that the historical proportions of the crash patterns remains unchanged throughout the analysis period. Thus the expected frequency for the various crash patterns is obtained by distributing the expected crash frequency using default estimates of the historical proportions among the various crash patterns. The critical frequency for each crash pattern is given as:

$P_{c(ij)} = P_{aj} + \sigma_j$

Where $P_{c(ij)}$ = Threshold or critical frequency for crash pattern *j* for candidate location *i*; P_{aj} = Expected average frequency for crash pattern *j* for similar road sections; σ_j = Standard deviation of expected average frequency of crash pattern *j* for similar road sections

Based on the identified roadway deficiencies and predominant crash pattern a set of alternative safety improvement projects is identified for each candidate location. For example, a rural two-lane section with predominant off-road collisions is assigned a safety improvement of “Install continuous rumble strips on right shoulder”. By default, the “Do Nothing” alternative is added to the set of alternative safety improvement projects for each candidate location. The default set of alternative safety improvement projects for each roadway deficiency and predominant crash pattern (Table 2) does not represent the full range of safety improvement projects that can be implemented at a site due to limited available site specific conditions.

Table 3 presents the default set of alternative safety improvement projects for each roadway deficiency and predominant crash pattern does not represent the full range of safety improvement projects that can be implemented at a site due to limited available site specific conditions.

Table 3. Default Safety Improvement Projects.

Road Environment Factor	**Recommended Safety Improvement Project**	
Roadway Deficiency	Left shoulder width	Widen left shoulder if less than design standard (2 ft or 4 ft)
	Right shoulder width	Install 6 ft right shoulder if not existent Widen right shoulder if less than design standard (2 ft or 4 ft)
	Lane width	Widen roadway lanes if less than design standard (1 ft or 2 ft)
	Median width	Widen roadway median width if less than design standard
	Access control	Change access control from none to partial control
	Horizontal alignment	Realignment of horizontal curves
	Vertical alignment	Realignment of vertical grades
	Off road	Install 6 ft outside shoulder if not existent Widen right shoulder if less than design standard (2 ft or 4 ft) Install guard rail Install rumble strips on outside shoulder
Predominant Crash Pattern	Head on or opposite direction side-swipe	Widen roadway lanes if less than design standard (1 ft or 2 ft) Install non mountable Median for two-lane road Install rumble strips on inside shoulder if present
	Same direction side-swipe	Install 6 ft right shoulder if not existent Widen right shoulder if less than design standard (2 ft or 4 ft) Widen roadway lanes if less than design standard (1 ft or 2 ft)
	Rear end	Improve pavement friction if less than design standard Install rumble strips in roadway pavement
	Night Crash	Install or improve pavement markings Install or improve roadway lightening

The accident reduction factors (CRF's) or accident modification factors (AMF's) were obtained from a variety of sources such as the Indiana Design Manual (INDOT, 2000), Tarko et al., (1999), Harwood et al., (2003) and Harwood (1993). The unit crash costs used for the present worth of benefits computation were updated from the 1994 estimates developed by Indiana Department of Transportation. The economic crash cost or the comprehensive crash costs estimates can be used. If a safety improvement project is deferred to a later year in the analysis period the benefits are computed only in terms of the crash reduction between the implementation year and the end of the analysis period. Thus the penalty for deferring a safety improvement is implicit in Equations shown in the formulation.

Needs Assessment and Constrained Optimization

First a needs assessment was carried out assuming no budgetary limit (results are shown in Table 4). Then a budget constraint of $500,000 was used for the total budgeting constrained optimization scenario (Table 5). In using this budgetary constraint, the optimization procedure selects improvements with lower costs and benefits or defer the implementation of some safety projects in order to satisfy the budgetary constraint. The results from the scenario represent the multi-year safety investment strategy for the analysis period and given budgetary constraint under each economic evaluation criteria.

From the results, it is seen that a total expenditure of $0.459M, $0.496M, and $0.455M is required for safety enhancements over the analysis period when BCR, CE and NPV, respectively, are used as the criterion for economic evaluation. These funding requirements represent significantly lower amounts (reductions of 82%, 80% and 84%, respectively) compared to the unconstrained needs assessments. Furthermore, the expected total benefits decreased by 79%, 11% and 13%, respectively, compared to the unconstrained needs assessments due to the budgetary constraint.

Table 4. Network-wide Consequences of Unconstrained Investment (Addressing all the Safety Needs)

Economic Evaluation Criteria	Year	Capital Cost	Maintenance Cost	Funding Requirement	Estimated Benefits	Length of Road Improvement (miles)	Total Crashes Saved	System-Wide Crash Rate/MVMT
Benefit-Cost Ratio	2004	$2,071,238	$0	$2,071,238	$3,422,033	47.25	258	1.173
	2005	$0	$100,643	$100,643	$3,422,033	0	258	1.171
	2006	$40,677	$100,643	$141,320	$3,422,392	0.12	258	1.184
	2007	$20,339	$102,677	$123,016	$3,424,772	0.06	258	1.193
	2008	$0	$103,694	$103,694	$3,424,772	0	258	1.185
	Total	**$2,132,254**	**$407,657**	**$2,539,911**	**$17,116,003**	**47.43**	**1290**	**-**
Cost Effectiveness	2004	$2,071,238	$0	$2,071,238	$3,422,033	47.25	258	1.173
	2005	$0	$100,643	$100,643	$3,422,033	0	258	1.171
	2006	$40,677	$100,643	$141,320	$3,422,392	0.12	258	1.184
	2007	$20,339	$102,677	$123,016	$3,424,772	0.06	258	1.193
	2008	$0	$103,694	$103,694	$3,424,772	0	258	1.185
	Total	**$2,132,254**	**$407,657**	**$2,539,911**	**$17,116,003**	**47.43**	**1290**	**-**
Net Present Value	2004	$2,362,992	$0	$2,362,992	$3,509,976	48.1	267	1.163
	2005	$0	$115,230	$115,230	$3,509,976	0	267	1.161
	2006	$0	$115,230	$115,230	$3,509,976	0	267	1.174
	2007	$20,339	$115,230	$135,569	$3,512,356	0.06	267	1.183
	2008	$0	$116,247	$116,247	$3,512,356	0	267	1.175
	Total	**$2,383,331**	**$461,937**	**$2,845,268**	**$17,554,641**	**48.16**	**1335**	**-**

Table 5. Network-wide Consequences of Safety Investment Plan for $0.5 Million Budgetary Limit.

Economic Evaluation Criteria	Year	Capital Cost	Maintenance Cost	Funding Requirement	Estimated Benefits	Length of Road Improvement (miles)	Total Crashes Saved	System-Wide Crash Rate/MVMT
Benefit-Cost Ratio	2004	$0	$0	$0	$0	0	0	1.476
	2005	$110,056	$0	$110,056	$40,525	0.9	4	1.462
	2006	$40,677	$5,503	$46,180	$40,884	0.12	4	1.468
	2007	$20,339	$7,537	$27,876	$43,264	0.06	4	1.470
	2008	$266,302	$8,554	$274,856	$3,461,189	41.35	251	1.193
	Total	**$437,374**	**$21,594**	**$458,968**	**$3,585,862**	**42.43**	**263**	**-**
Cost Effectiveness	2004	$266,302	$0	$266,302	$3,019,316	41.35	218	1.220
	2005	$110,056	$10,396	$120,452	$3,059,841	0.9	222	1.212
	2006	$0	$15,899	$15,899	$3,059,841	0	222	1.224
	2007	$20,339	$15,899	$36,238	$3,062,221	0.06	222	1.232
	2008	$40,677	$16,916	$57,593	$3,062,603	0.12	222	1.223
	Total	**$437,374**	**$59,110**	**$496,484**	**$15,263,821**	**42.43**	**1106**	**-**
Net Present Value	2004	$266,302	$0	$266,302	$3,019,316	41.35	218	1.220
	2005	$110,056	$10,396	$120,452	$3,059,841	0.9	222	1.212
	2006	$0	$15,899	$15,899	$3,059,841	0	222	1.224
	2007	$0	$15,899	$15,899	$3,059,841	0	222	1.232
	2008	$20,339	$15,899	$36,238	$3,062,308	0.06	222	1.223
	Total	**$396,697**	**$58,093**	**$454,790**	**$15,261,146**	**42.31**	**1106**	**-**

Table 6. Details of the Safety Investment Plan for Each Facility in Test Network

Economic Evaluation Criteria	Year	Section ID	Length	Safety Improvement Project	Applicable Length	Capital Required	Estimated Benefit	Total Crash Reduction
Benefit-Cost Ratio	2004	79-S-025-0-01	2.4	Install paved shoulder	1.08	$207,911	$1,891,389	166
	2005	79-S-038-0-01	1.75	Widen Shoulder by 2 ft	0.9	$110,056	$162,101	16
	2006	79-U-231-0-01	7.98	Widen Shoulder by 4 ft	1.03	$251,907	$128,656	14
	2007	79-S-225-0-01	3.25	Install paved shoulder	0.06	$20,339	$4,760	0
	2008	79-S-026-0-01	7.22	Install continuous rumble strips on right shoulder	7.22	$10,469	$814,531	81
	2008	79-U-052-0-01	10.44	Install continuous rumble strips on left shoulder	10.44	$15,138	$1,021,171	84
	2008	79-S-043-0-01	6.78	Install continuous rumble strips on right shoulder	6.78	$9,831	$284,975	14
	2008	79-S-025-0-02	9.25	Install continuous rumble strips on right shoulder	9.25	$13,412	$548,531	19
	2008	79-U-231-0-02	6.58	Install continuous rumble strips on right shoulder	6.58	$9,541	$318,668	11
	2008	79-S-126-0-01	1.09	Install paved shoulder	0.12	$40,677	$383	0
Cost Effectiveness	2004	79-S-025-0-01	2.4	Install paved shoulder	1.08	$207,911	$1,891,389	166
	2004	79-S-026-0-01	7.22	Install continuous rumble strips on right shoulder	7.22	$10,469	$3,582,378	358
	2004	79-U-052-0-01	10.44	Install continuous rumble strips on left shoulder	10.44	$15,138	$4,491,197	369
	2004	79-S-043-0-01	6.78	Install continuous rumble strips on right shoulder	6.78	$9,831	$1,269,238	61
	2004	79-S-025-0-02	9.25	Install continuous rumble strips on right shoulder	9.25	$13,412	$2,443,075	84
	2004	79-U-231-0-02	6.58	Install continuous rumble strips on right shoulder	6.58	$9,541	$1,419,302	51
	2005	79-S-038-0-01	1.75	Widen Shoulder by 2 ft	0.9	$110,056	$162,101	16
	2006	79-U-231-0-01	7.98	Widen Shoulder by 4 ft	1.03	$251,907	$128,656	14
	2007	79-S-225-0-01	3.25	Install paved shoulder	0.06	$20,339	$4,760	0
	2008	79-S-126-0-01	1.09	Install paved shoulder	0.12	$40,677	$383	0
Net Present Value	2004	79-S-025-0-01	2.4	Install paved shoulder	1.08	$207,911	$1,891,389	166
	2004	79-S-026-0-01	7.22	Install continuous rumble strips on right shoulder	7.22	$10,469	$3,582,378	358
	2004	79-U-052-0-01	10.44	Install continuous rumble strips on left shoulder	10.44	$15,138	$4,491,197	369
	2004	79-S-043-0-01	6.78	Install continuous rumble strips on right shoulder	6.78	$9,831	$1,269,238	61
	2004	79-S-025-0-02	9.25	Install continuous rumble strips on right shoulder	9.25	$13,412	$2,443,075	84
	2004	79-U-231-0-02	6.58	Install continuous rumble strips on right shoulder	6.58	$9,541	$1,419,302	51
	2005	79-S-038-0-01	1.75	Install non-mountable median	1.75	$401,810	$525,326	51
	2006	79-U-231-0-01	7.98	Widen Shoulder by 2 ft	1.03	$125,953	$64,328	7
	2007	79-S-225-0-01	3.25	Install paved shoulder	0.06	$20,339	$4,760	0
	2008	79-S-126-0-01	1.09	Do Nothing	0	$0	$0	0

CONCLUSIONS

An overall transportation plan is a statement of what work is needed, when it is needed, how much it will cost, and its consequences (in terms of the operational characteristics) under a given budgetary limit. Ideally, this is the sum of plans from the constituent management systems, program areas, and special programs, for a given mode of transportation. At the current time, however, most agency transportation plans do not yet include safety and congestion management plans.

Using a case study in highway transportation, this paper shows that it is feasible to develop a framework for proactively incorporating safety in the transportation planning process. The procedure identifies potential candidate facilities in network over an analysis period; identifies facility deficiencies and dominant accident patterns, and therefore specifies appropriate safety enhancement projects. The procedure also estimates benefits and costs of these projects and determines optimal mix and timing of safety improvements at each candidate facility under given budget constraints, using integer programming. The framework also provides the current and future safety investment needs as well as a multi-year investment strategy for safety improvements for a given funding level over a specified analysis period. Also, the impact of alternative funding levels on system-wide safety can be investigated to determine the appropriate level of safety investment to meet the required safety goals established by the agency.

The paper also shows that the analysis output can be influenced by the type of economic criterion used: all else being equal, using the net present value or cost-effectiveness yielded the highest total network-wide benefits; while using benefit cost ratio yielded the least total network-wide benefits.

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SMS - Safety Management System Software
File Edit Reports Help
New Program
Open Program
Program Wizard
Save Changes
Run SMSS
Stop Run
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Program Settings
Analysis Results
Reports
INDOT
Historical Crash Data
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Before & After Comparison
Program Summary
Analysis Type = Road Sections
Analysis Period = 2004-2008
Road Network
Route Type = Non-Interstate Roads
Functional Class = All
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District = All
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Crash Prediction = Empirical Bayesian
Candidate Locations = Rate-Frequency Quality Control
Economic Evaluation = Net Present Value
Optimizarion = Constrained (Total Budgeting)
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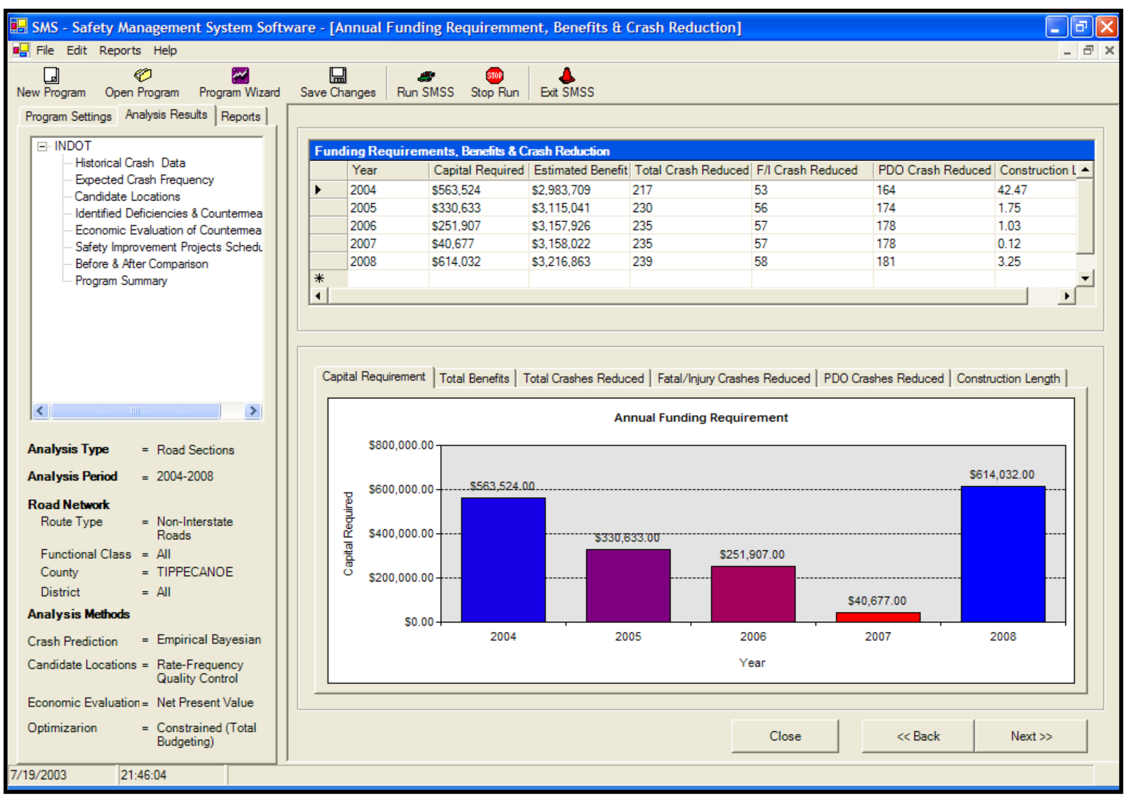
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Analysis Period = 2004-2008
Road Network
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Functional Class = All
County = TIPPECANOE
District = All
Analysis Methods
Crash Prediction = Empirical Bayesian
Candidate Locations = Rate-Frequency Quality Control
Economic Evaluation = Net Present Value
Optimizarion = Constrained (Total Budgeting)
Funding Requirements, Benefits & Crash Reduction
Year | Capital Required | Estimated Benefit | Total Crash Reduced | F/I Crash Reduced | PDO Crash Reduced | Construction L
2004 | $563,524 | $2,983,709 | 217 | 53 | 164 | 42.47
2005 | $330,633 | $3,115,041 | 230 | 56 | 174 | 1.75
2006 | $251,907 | $3,157,926 | 235 | 57 | 178 | 1.03
2007 | $40,677 | $3,158,022 | 235 | 57 | 178 | 0.12
2008 | $614,032 | $3,216,863 | 239 | 58 | 181 | 3.25
Capital Requirement
Total Benefits
Total Crashes Reduced
Fatal/Injury Crashes Reduced
PDO Crashes Reduced
Construction Length
Annual Funding Requirement
$800,000.00
$600,000.00
$400,000.00
$200,000.00
$0.00
Capital Required
$563,524.00
$330,633.00
$251,907.00
$40,677.00
$614,032.00
2004
2005
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