Chapter 7

Evaluation of Safety Projects
7.1 INTRODUCTION

Highway safety continues to be a major issue in transportation. The past decade has seen significant improvements in highway safety. However, continuing and evolving trends in the highway environment dictate that this area of transportation should continue to be given due attention. Such trends include aging of physical infrastructure, increasing demand, scarcity of resources, changing composition of the traffic stream, and the emphasis on operational accountability of resources for highway management. As states move towards overall highway infrastructure asset management, there is increasing consideration of how road safety can be proactively incorporated in the long range transportation planning process. Prior to the Transportation Equity Act for the 21st Century (TEA-21), most state and local highway agencies focused on the development of safety improvements designed to mitigate existing safety problems that were identified from historical crash records. Such an approach rarely considered safety as part of the long range transportation planning process due to the difficulty in identifying future safety deficiencies within the network resulting from changes in the transportation system environment. With the enactment of TEA-21, state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) are required to include safety as a priority in their transportation planning programs in a more comprehensive and system-wide context. To facilitate incorporation of safety in the planning and design phases of highway development, the Federal Highway Administration (FHWA) has developed the Interactive Highway Safety Design Module (IHSDM) - a suite of software analysis tools allowing highway project designers and planners to evaluate the safety implications of alternative geometric designs on two-lane rural highways. However the integration of safety management on existing road network into the transportation planning process still remains an issue. In other words, what improvements must be done to the existing network, where and when to implement these improvements within the planning horizon?

A management approach is therefore necessary to identify those engineering elements that would best enhance highway safety within the constraints of budget and at the same time satisfy needs, preserve the physical condition of the facilities, and fulfill the national goals of energy and environment. This chapter presents various approaches for safety investment evaluation and programming at both project and network levels. Programming involves a process of selecting and scheduling safety improvement projects on the basis of relative urgency of work, and a key element of such process is matching needed projects with available funds to accomplish the highway improvement objectives within a given period [Sinha, 1981]. This includes determination of system-wide safety needs for existing road sections at the current time and also in the future. The framework also provides a mechanism for the selection of cost-effective safety improvements and develops a multi-year safety investment strategy within budgetary constraints over a planning horizon. The framework can also be used to determine the impact of various funding levels on system-wide safety.
7.1.1 Definition of a Road Crash

A road crash can be defined as a collision involving at least one moving vehicle and another vehicle or object. The term vehicles broadly refer to bicycles, ridden animals, non-motorized vehicles, and animal-drawn transport, as well as motorbikes, cars, trucks and buses [Ferguson et al., 2000]. Road crashes are usually caused by factors such as driver error, mechanical failure and poor roadway design. Patterns of highway crashes include:

- Collision on the carriageway between a vehicle and another vehicle, pedestrian, object or an animal,
- Collision off the carriageway such as vehicle collision with a tree after loss of control on the carriageway,
- Non-collision on carriageway such as loss of load or breakdown of vehicle,
- Non-collision off carriageway such as a roll-over after loss of control on the carriageway,
- Fall from a vehicle in operation on the highway.

7.1.2 Severity Types of Road Crashes

Road crashes can be broadly classified into three severity categories:

1. **Fatal Crashes** result in one or more fatalities within thirty days of occurrence,
2. **Injury crashes** result in one or more injuries that are not fatal,
3. **Property damage only crashes** result in loss of all or part of an individual’s vehicle and/or property resulting from a road crash not involving injury to a person.

Road crashes can also be weighted on an injury scale by assigning using indices to the level of severity of the road crash. The two commonly used injury scales are the Abbreviated Injury Scale (AIS) and the KABCO Injury Scale.

7.1.2.1 Abbreviated Injury Scale (AIS) for Crash Severity

The Abbreviated Injury Scale (AIS) is an anatomical scoring system was first introduced in 1969 by the Association for the Advancement of Automotive Medicine. As shown in Table 7-1, AIS ranks injuries on a scale of 0 to 6: 0 is No Injury, 5 is Critical Injury and 6 is Non-Survivable Injury (fatal). The injuries represents the 'threat to life' associated with an injury and not a measure of the severity of the injury. When multiple injuries are involved or a crash injures several people, the AIS score of the most life-threatening injury (Maximum AIS, or MAIS) is often used to summarize the type and extent of injury. The AIS is updated periodically to provide a reasonably accurate ranking of the severity of injury [Blincoe at al., 2002].
Table 7-1: Abbreviated Injury Scale (AIS) [Blincoe et al., 2002]

<table>
<thead>
<tr>
<th>Code</th>
<th>Severity</th>
<th>Injury Description</th>
<th>Cost per Injury (2000 Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIS 6</td>
<td>Fatal</td>
<td>Decapitation, torso transaction, massively crushed chest</td>
<td>$3,366,388</td>
</tr>
<tr>
<td>AIS 5</td>
<td>Critical</td>
<td>Spinal chord injury, excessive second or third degree burns, cerebral concussion (unconscious more than 24hrs)</td>
<td>$2,402,997</td>
</tr>
<tr>
<td>AIS 4</td>
<td>Severe</td>
<td>Partial spinal cord severance, spleen rupture, leg crush, chest wall perforation, cerebral concussion (unconscious less than 24 hours)</td>
<td>$731,580</td>
</tr>
<tr>
<td>AIS 3</td>
<td>Serious</td>
<td>Major nerve laceration; multiple rib fracture, abdominal organ contusion; hand, foot or arm crush/amputation</td>
<td>$314,204</td>
</tr>
<tr>
<td>AIS 2</td>
<td>Moderate</td>
<td>Major abrasion or laceration of skin, cerebral concussion finger or toe crush/amputation, close pelvic fracture</td>
<td>$157,958</td>
</tr>
<tr>
<td>AIS 1</td>
<td>Minor</td>
<td>Superficial abrasion or laceration of skin, digit sprain, first-degree burn, head trauma with headache or dizziness</td>
<td>$15,017</td>
</tr>
<tr>
<td>AIS 0</td>
<td>Uninjured</td>
<td>No injury</td>
<td>$1,962</td>
</tr>
</tbody>
</table>

7.1.2.2 KABCO Injury Scale

Instituted by the American National Standards Institute (ANSI), the KABCO injury scale is designed for police coding of crash details at a crash scene. The KABCO coding does not require medical judgment; the police officer on the crash scene assesses the injuries sustained and assigns a code depending on the level of severity as shown in Table 7-2. The KABCO coding has been criticized because it does not consistently classify injuries [Miller et al., 1991]. For example, a broken arm and a severed spinal cord are considered to be of equal severity. In order to reduce the variability in police reporting the National Highway Safety and Transportation Administration (NHSTA) uses both AIS and KABCO scales to describe the extent of a given injury.

Table 7-2: KABCO Scale for Crash Severity [NSC, 2001]

<table>
<thead>
<tr>
<th>Code</th>
<th>Severity</th>
<th>Injury Description</th>
<th>Cost per Injury (2000 Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Fatal</td>
<td>Any injury that results in death within 30 days of crash occurrence.</td>
<td>3,214,290</td>
</tr>
<tr>
<td>A</td>
<td>Incapacitating</td>
<td>Any injury other than a fatal injury, which prevents the injured person from walking, driving, or normally continuing the activities the person was capable of performing before the injury occurred. e.g., severe lacerations, broken limbs, skull etc.</td>
<td>$159,449</td>
</tr>
<tr>
<td>B</td>
<td>Injury Evident</td>
<td>Any injury, other than a fatal injury or an incapacitating injury which is evident to observers at the scene of the accident in which the injury occurred. e.g., abrasions, bruises, minor cuts etc.</td>
<td>$41,027</td>
</tr>
<tr>
<td>C</td>
<td>Injury Possible</td>
<td>Any injury reported which is not a fatal, incapacitating or non-incapacitating evident injury. e.g., pain, nausea, hysteria etc.</td>
<td>$19,528</td>
</tr>
<tr>
<td>PDO</td>
<td>Property Damage Only</td>
<td>Property damage to property that reduces the monetary value of that property.</td>
<td>$1,861</td>
</tr>
</tbody>
</table>
7.1.3 Factors Affecting Road Crashes

The frequency of road crash and level of severity is affected by various factors described below:

7.1.3.1 Roadway Characteristics

Unfavorable road geometry (e.g., width, alignment, and sight distances) and topography (e.g., steep grades and mountain passes) are associated frequent road crashes. Also, a higher number of crashes are experiences at rural road sections [BTS, 2000]. The frequency of road crashes have been found to be directly proportional to the traffic density (vehicles/lane-mile), however the severity tends to increase with vehicle speeds. The risk of fatality increases with the change of speed on impact to the fourth power [Stuster et al., 1998]. Research has also shown that crash rates are lowest on moderately congested roads (volume to capacity ratio of 0.6), and increase at lower and higher congestion levels [Zhou et al., 1997]. Consequently, the number of crashes per vehicle-mile tends to be greater in urban areas, but fatalities per vehicle-mile tend to be higher on uncongested, rural roads. Table 7-3 shows how crash and fatality rates vary by road type and area code. Crash rates are three times higher for urban driving but fatality rates are more than twice as high for rural driving.

<table>
<thead>
<tr>
<th>Functional Class</th>
<th>Rural</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>1.19</td>
<td>0.61</td>
</tr>
<tr>
<td>Other</td>
<td>2.32</td>
<td>1.10</td>
</tr>
<tr>
<td>Collector</td>
<td>2.67</td>
<td>0.73</td>
</tr>
<tr>
<td>Local</td>
<td>3.43</td>
<td>1.22</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>2.18</strong></td>
<td><strong>0.94</strong></td>
</tr>
</tbody>
</table>

Figure 7-1: Fatality Rates by Functional Class per 100 million VMT [BTS, 2001].
7.1.3.2 Driver Characteristics

Driver behavior and characteristics such as age, experience and alcohol or drug influence also contribute significantly to road crashes. Younger and older drivers tend to have relatively high crash rates per vehicle-mile. Statistics indicates that young people (who constitute 6-7% of the total population) account for approximately 14% of road fatalities. Professional drivers (truck, bus, taxi, etc.) tend to have low per-mile crash rates, but relatively high crash rates per vehicle-year because of their high annual mileage. Intoxicated drivers tend to have crash rates many times higher than sober drivers per vehicle-mile. In 2000, 31% of all traffic fatalities involved at least one intoxicated driver (blood alcohol concentration exceeding 0.10 g/dl).

7.1.3.3 Vehicle/Mode Characteristics

Vehicle design features affect crash frequency and severity. Differences in size, weight and shape of vehicles in a traffic stream can increase the likelihood of collisions. Also, occupants in the passenger cars are twice as likely to have fatalities as those in heavier vehicles. Newer vehicles tend to have design features and safety equipment that provide greater crash protection, compared to older models. Buses and other transit vehicles tend to have low crash rates per mile, and have low injury rates for occupants. Sport Utility Vehicles and large vans tend to have a high rate of roll-over crashes, while motorcycles, bicycles and pedestrians (vulnerable road users) tend to have greater injuries when involved in a crash.

7.1.4 Statistics and Trends in Road Safety

Traffic safety data collected over the past years by the Bureau of Transportation Statistics (BTS) annual report shows that the fatality rates reduced from 1.7 fatalities per 100 million vehicle-miles in 1995 to 1.5 fatalities per 100 million vehicle-miles in 2000 representing a decrease of about 12% over 5 years. [BTS, 2001] This trend can be attributed to a number of factors, notably the use of airbags, seat belt and child restraints, improved state and local educational programs on alcohol use while driving and stricter law enforcement requiring reduced tolerance for drunken driving. In 2000, an estimated 14,104 people were saved by use of restraints (seat belts, air bags and motorcycle helmets).

Statistics relating to vehicle occupancy fatalities also shows a decrease in vehicle occupancy fatalities for passenger cars but increased for trucks. For non-occupant fatalities a general decrease in over the years is observed. Also occupants of motorcycles are about 20 times more likely to be involved in fatal crashes than occupants of passenger cars. However, bus occupants are 4 times less likely to be involved in fatal crashes compared to passenger car occupants. Figures 7-2 and 7-3 illustrate such trends.
Figure 7-2: Trends in Nationwide Number of Fatalities [BTS, 2001].

Figure 7-3: Trends in Nationwide Number of Injury Crashes [BTS, 2001].
7.2 DETERMINATION OF UNIT CRASH COSTS

Highway crash costs can be broken down into three major components: Direct and Indirect Costs, and Intangible loss. The direct and indirect costs components are referred to as the market value or economic costs, while the components of crash cost related to the valuation of lost quality of life are referred to as the non-market value crash costs.

- **Direct costs** – direct expenditure as a result of the crash such as emergency services, medical costs, insurance administration expenses, legal costs, and employer/workplace costs.
- **Indirect costs** – costs other than those directly attributable to an injury such as productivity costs in the workplace due to temporary and permanent disability and decreases in household productivity emanating from these disabilities, property damage and travel delay.
- **Intangible loss** – loss of intangible assets, such as damage to the quality of life and the pain, grief, and suffering of the victims and their relatives due to crashes.

The direct and indirect costs components are referred to as the market value or economic costs, while the components of crash cost related to the valuation of lost quality of life are referred to as the non-market value crash costs. Table 7-4 below summarizes the three major components and their elements.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Components</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Costs</td>
<td>Emergency Services</td>
<td>• Police and fire department response costs</td>
</tr>
<tr>
<td></td>
<td>Medical Costs</td>
<td>• Ambulance transport.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Emergency room and inpatient costs,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Follow-up visits, physical therapy and rehabilitation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Prescriptions, prosthetic devices</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Home modifications.</td>
</tr>
<tr>
<td></td>
<td>Insurance Administration Costs</td>
<td>• Administrative costs of insurance claims</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Defense attorney costs.</td>
</tr>
<tr>
<td></td>
<td>Legal Costs</td>
<td>• Legal fees and court costs from civil litigation</td>
</tr>
<tr>
<td></td>
<td>Workplace cost</td>
<td>• Retraining of new employees,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Overtime required to accomplish work of the injured</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Administrative costs of personnel changes.</td>
</tr>
<tr>
<td>Indirect Costs</td>
<td>Market Productivity</td>
<td>• Present discounted value of the lost wages and benefits over the victim’s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>remaining life span.</td>
</tr>
<tr>
<td></td>
<td>Household Productivity</td>
<td>• Present value of lost productive household activity.</td>
</tr>
<tr>
<td></td>
<td>Travel Delay</td>
<td>• Value of travel time delay due to resulting traffic congestion.</td>
</tr>
<tr>
<td></td>
<td>Property Damage Costs</td>
<td>• Value of vehicles, cargo, roadways and other items damaged.</td>
</tr>
<tr>
<td>Intangible Loss</td>
<td>Quality of Life and Pain and Suffering Costs</td>
<td>• Loss of expected years to live (death)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Loss of future health (non-fatal injuries)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pain, suffering grief etc.</td>
</tr>
</tbody>
</table>
Table 7-5 shows the contribution of each crash cost component to total market crash cost by level of severity for the year 2000.

Table 7-5: Summary of Nationwide Economic Crash Costs in Year 2000 (Year 2000 Constant Dollar)

<table>
<thead>
<tr>
<th></th>
<th>PDO</th>
<th>MAIS 0</th>
<th>MAIS 1</th>
<th>MAIS 2</th>
<th>MAIS 3</th>
<th>MAIS 4</th>
<th>MAIS 5</th>
<th>Fatal</th>
<th>Total</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical</td>
<td>$0</td>
<td>$3</td>
<td>$11,088</td>
<td>$6,813</td>
<td>$5,854</td>
<td>$4,794</td>
<td>$3,146</td>
<td>$924</td>
<td>$32,622</td>
<td>14.15%</td>
</tr>
<tr>
<td>Emergency Services</td>
<td>$733</td>
<td>$56</td>
<td>$452</td>
<td>$92</td>
<td>$46</td>
<td>$30</td>
<td>$8</td>
<td>$35</td>
<td>$1,453</td>
<td>0.63%</td>
</tr>
<tr>
<td>Market Productivity</td>
<td>$0</td>
<td>$0</td>
<td>$8,151</td>
<td>$10,908</td>
<td>$8,996</td>
<td>$4,151</td>
<td>$24,898</td>
<td>$60,991</td>
<td>26.45%</td>
<td></td>
</tr>
<tr>
<td>HH Productivity</td>
<td>$1,111</td>
<td>$84</td>
<td>$2,664</td>
<td>$3,193</td>
<td>$2,653</td>
<td>$1,023</td>
<td>$1,413</td>
<td>$8,010</td>
<td>$20,151</td>
<td>8.74%</td>
</tr>
<tr>
<td>Insurance Admin.</td>
<td>$2,741</td>
<td>$204</td>
<td>$3,453</td>
<td>$3,012</td>
<td>$2,379</td>
<td>$1,181</td>
<td>$645</td>
<td>$1,552</td>
<td>$15,167</td>
<td>6.58%</td>
</tr>
<tr>
<td>Workplace Cost</td>
<td>$1,208</td>
<td>$87</td>
<td>$1,175</td>
<td>$852</td>
<td>$537</td>
<td>$172</td>
<td>$78</td>
<td>$364</td>
<td>$4,472</td>
<td>1.94%</td>
</tr>
<tr>
<td>Legal Costs</td>
<td>$0</td>
<td>$0</td>
<td>$699</td>
<td>$2,172</td>
<td>$1,990</td>
<td>$1,230</td>
<td>$756</td>
<td>$4,272</td>
<td>$11,118</td>
<td>4.82%</td>
</tr>
<tr>
<td>Travel Delay</td>
<td>$18,976</td>
<td>$1,970</td>
<td>$3,620</td>
<td>$369</td>
<td>$118</td>
<td>$36</td>
<td>$87</td>
<td>$383</td>
<td>$25,560</td>
<td>11.09%</td>
</tr>
<tr>
<td>Property Damage</td>
<td>$35,069</td>
<td>$2,597</td>
<td>$17,911</td>
<td>$1,724</td>
<td>$856</td>
<td>$359</td>
<td>$89</td>
<td>$430</td>
<td>$59,036</td>
<td>25.60%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$59,838</td>
<td>$5,000</td>
<td>$49,214</td>
<td>$29,134</td>
<td>$23,430</td>
<td>$12,710</td>
<td>$10,373</td>
<td>$40,868</td>
<td>$230,568</td>
<td>100.00%</td>
</tr>
<tr>
<td><strong>Total %</strong></td>
<td>25.95%</td>
<td>2.17%</td>
<td>21.34%</td>
<td>12.64%</td>
<td>10.16%</td>
<td>5.51%</td>
<td>4.50%</td>
<td>17.72%</td>
<td>100.00%</td>
<td></td>
</tr>
</tbody>
</table>

Source: Blincoe et al., 2002.
7.2.1 Approaches for Estimating Unit Cost of Road Crashes

Various economic costing methods have been developed to assess the economic loss to society as a result of motor vehicle crashes. Available literature suggests that there is no single assessment method that is universally accepted, however the common methods used for determining the value of a fatal or a non-fatal injury are:

The Human-Capital Cost Approach
The human capital approach measures the loss to society due to a fatal crash, based on future productive potential of the victim. The approach measures only market costs (property damage, medical treatment, and lost productivity, insurance administration and legal costs, travel delay). This approach estimates the value economic value of a human life at $977,208 (in Year 2000 constant dollar), with lesser values for the various categories of injuries set by the MAIS [Blincoe et al., 2002]

The Comprehensive/Willingness to Pay Approach
This approach measures both market and non-market costs, including pain, grief, and reduced quality of life as a result of an injury. It also reflects people's willingness-to-pay for increased safety (i.e., reduced risk of crashes and reduced crash damages. Blincoe et al. [2002] estimate the value of a fatality in the range of $2-7 million, and assigns a “working value” of $3,366,388. The comprehensive willingness to pay method can be considered a more appropriate measure of the true cost of crashes to society, and could yield a value appropriate enough for use in evaluating crash prevention techniques [Forkenbrock et al., 1994]. The willingness to pay (WTP) approach has been used to develop WTP values for selected counties in Indiana [Islam, 2002].

Years Lost Plus Direct Cost Approach
This approach includes the same cost components as the Comprehensive Willingness to Pay approach. However, it replaces non-market costs with a non-monetary measure: lost years. The direct costs in this approach refer to the cost components which are assigned a monetary value. These include property damage, medical costs, emergency services, travel delay, vocational rehabilitation, workplace costs, and administrative and legal costs.

Estimation of total crash costs using the first two approaches (which are more commonly used) are described in the next section.
7.2.2 Component Items of Unit Crash Costs

This section describes the methodology for the computation of total crash costs using either the Comprehensive Approach or Human Capital Approach. Both approaches involve the estimation of the unit injury cost and the unit crash cost; however the Human Capital Approach does not in include the intangible loss component of the crash cost.

7.2.2.1 Estimation of Unit Injury Cost

The models for the estimation of the unit injury cost for each crash cost component are given below.

(a) Insurance Administration and Litigation Costs

Insurance administration costs include the administrative costs associated with processing insurance claims resulting from motor vehicle crashes and defense attorney fees. Litigation costs include the legal fees and court costs associated with civil litigation resulting from motor vehicle crashes.

(b) Legal Costs

The legal costs can be computed from the following formula [Blincoe et al., 2002]

If MAIS = 1

\[ LC = (Medical + Wage + Household) \times Pwl \times 58\% \times 29\% \times 1.492 \times 24.9\% \]

If MAIS = 2, 3, 4, 5 and \((Medical + Wage + Household) < 740,000\)

\[ LC = (Medical + Wage + Household) \times Plw \times 58\% \times 29\% \times 1.492 \times 55\% \]

If \((Medical + Wage + Household) > 740,000\) or MAIS = 6

\[ LC = 740,000 \times Plw \times 58\% \times 29\% \times 1.492 \times 55\% \]

Where

- \( LC \) = Legal costs
- \( Medical \) = Medical costs
- \( Wage \) = Lost wages
- \( Household \) = Lost household productivity
- \( Plw \) = Probability of losing work, estimated by MAIS, body part, and fracture/dislocation diagnosis from the National Automotive Sampling System (NASS) and Crashworthiness Data System (CDS) files
(c) Insurance Administration Costs

For MAIS = 1,
\[ IA = 7.46\% \times Medical + 24.9\% \times 18.3\% \times Pwl \times (Wage + Household) + 3.24\% \times Wage + 1.67\% \times (Wage + Household) + 3.61\% \times (Wage + household) + 1.76\% \times Wage + 7.85\% \times PropDamage \]

For MAIS = 2, 3, 4, 5 and (Wage + Household) \(\leq\$148,000\),
\[ IA = 7.46\% \times Medical + 55\% \times 18.3\% \times Pwl \times (Wage + Household) + 3.24\% \times Wage + 1.67\% \times (Wage + Household) + 3.61\% \times (Wage + household) + 1.76\% \times Wage + 7.85\% \times PropDamage \]

For (Wage + Household) > \$148,000,
\[ IA = 7.46\% \times Medical + 55\% \times 18.3\% \times Pwl \times (Wage + Household) + 3.24\% \times Wage + 1.67\% \times (Wage + Household) + 3.61\% \times (Wage + household) + 1.76\% \times Wage + 7.85\% \times PropDamage \]

For MAIS = 6,
\[ IA = 7.46\% \times Medical + 55\% \times 18.3\% \times (Wage + Household) + 9\% \times (Wage + Household) + 7.85\% \times PropDamage \]

Where
- \( IA \) = Insurance administrative costs
- \( Medical \) = Medical costs
- \( Wage \) = Lost wages
- \( Household \) = Lost household productivity
- \( PropDamage \) = Property damage costs
- \( Pwl \) = Probability of losing work, estimated by MAIS, body part, and fracture/dislocation diagnosis from the National Automotive Sampling System (NASS) and Crashworthiness Data System (CDS) files

(d) Medical Costs

The medical costs of an injury sustained from a crash can be obtained from the Injury Cost Model Medical Cost Equations [Miller et al., 2000] given below:

(i) Hospital Admitted Cases: The formula for computing the costs of hospital admitted crash cases is as follows:
\[ MH_i = \frac{(1 + c_i) \times (1 + a_i) \times (1 + e_i) \times H_i}{s_i} + N_i \]

and
\[ H_i = C_{f,i} + (d_i \times C_{v,i}) \]
Where

\( MH_i \) = Medical cost per diagnosis \( i \)
\( c_i \) = Health insurance claims processing cost factor
\( a_i \) = Short-term ancillary and post-discharge medical cost factor (follow-up physician visits, prescriptions, medical equipment, physical therapy, home health, etc.)
\( e_i \) = Readmission factor
\( H_i \) = Total cost of hospital visit, including professional fees
\( s_i \) = Share of medical costs incurred in short term
\( N_i \) = Nursing home cost for catastrophic injuries
\( C_{f,i} \) = Fixed cost of hospital visit (including professional fees)
\( C_{v,i} \) = Variable cost of hospital visit (including professional fees)
\( d_i \) = Length of stay in hospital (by sex and age group)

(ii) Non-Admitted Cases: The formula for computing the costs of non hospital admitted crashes is as follows:

\[
MN_{i,t} = \frac{(1 + c_i) \times (M_{i,t} + V_{i,t}) + A_{i,t}}{s_i}
\]

Where

\( MH_i \) = medical cost per diagnosis \( i \)
\( c_i \) = Health insurance claims processing cost factor
\( M_{i,t} \) = Medical payments per visit
\( V_{i,t} \) = Acute care visits per case
\( A_{i,t} \) = Other ancillary medical costs
\( S_i \) = Share of medical costs incurred in short term (used to include lifetime follow up costs)

\( t \) is an index variable equal to \( e \) if the case was treated in the emergency department (ED) or \( d \) if treated in other non admitted settings.

(e) Work Losses

Work loss includes the victims lost wages, household work as well as fringe benefits. It also includes lost school work, the work losses incurred by the victim’s family and friends during caring, transporting and visiting the injured, and finally the employer’s productivity losses. Work losses consist of the following four major components [Miller et al., 2000].

(i) Short-term Work Losses: These are losses experienced by injury victims as a consequence of their physical inability to work while being treated for and recovering from an injury. The lost work includes both paid employment (wage work) and household work. Short term work losses are estimated from the following equations:
VS = \[(T_h' \times w^\ast) + (T'_{h} \times w')\] (for hospital admitted victims)

VS = \[p[(T_n' \times w^\ast) + (T'_{n} \times w')\] (for non-admitted victims)

and

\[T'_h = \frac{(r \times T')}{\{(3q) + [(1 - q) p]\}}\]

\[T'_n = 3 T'_n\]

\[T'_h = 0.9 \times (365/243) \times T'_n\]

\[T'_n = 0.9 \times (365/243) \times T'_h\]

Where

- \(T'\) = Mean duration of wage work loss across all victims with wage work loss
- \(T'_{h}\) = Duration of wage work loss for hospital admitted victims
- \(T'_{n}\) = Duration of wage work loss for non-admitted victims with wage work loss
- \(T'\) = Mean duration of household work loss across all victims with wage work loss
- \(T'_{h}\) = Duration of household work loss for hospital admitted victims
- \(T'_{n}\) = Duration of household work loss for non-admitted victims with wage work loss
- \(w^\ast\) = Valuation of lost wage work
- \(w'\) = Valuation of lost household work
- \(p\) = Probability non-admitted victim will lose work
- \(q\) = Probability victim is hospital admitted
- \(r\) = Proportion of all victims with work loss = \(q + [(1 - q) \times p]\).

(ii) Long-term Work Losses: Losses experienced by Injury victims such as those associated with full or partial permanent disability following the injury recovery period. Estimates long term work losses are estimated from the following equations [Miller et al., 2000]:

\[VL = K (d_{t,h} + f \times d_{p,h})\] (for hospital-admitted victims)

\[VL = K (d_{t,n} + f \times d_{p,n})\] (for non-admitted victims)

Where

- \(K\) = Present value of lifetime work (by age group and sex)
- \(d_{t,h}\) = Probability of long-term total disability for hospital-admitted victims
- \(d_{t,n}\) = Probability of long-term total disability for non-admitted victims
- \(d_{p,h}\) = Probability of long-term partial disability for hospital-admitted victims
- \(d_{p,n}\) = Probability of long-term partial disability for non-admitted victims
- \(f\) = Percent lifetime earnings loss by victims with long-term partial disability = 0.17
(iii) Family and/or Friends Work Losses

Family and/or friends of the injury victim may incur work loss because of time spent transporting, visiting, and caring for the victim. These losses can be estimated from the following equations [Miller et al., 2000]:

\[
FF = (W \times v) + (H \times v \times B)
\]

Where

- \( W \) = Initial transportation/waiting time = 2 hours
- \( v \) = Value of time = $6 per hour
- \( H \) = Visiting time per bed day = 3 hours
- \( B \) = Number of bed days = twice the number of in-patient days (0 if non-admitted)

Therefore, \( FF = $12 + ($18 \times B) \)

(iv) Employer Related Losses

These include losses by supervisors and co-workers to modify schedules and otherwise accommodate the absence of the victim. These losses can be estimated from the following equations [Miller et al., 2000]:

\[
EM = e \left[ d_h \times C_{pd} + (1 - d_h) \times C_{td,h} \right] + (1 - e) \times C_{cg} \quad \text{(for hospital admitted victims)}
\]

\[
EM = e \left[ d_n \times C_{pd} + (p - d_n) \times C_{td,n} \right] + (1 - p) \times C_{nd} + (1 - e) \times C_{cg} \quad \text{(for non admitted victims)}
\]

Where

- \( e \) = Probability victim is (wage) employed
- \( d_h \) = Combined probability of full or partial permanent disability for hospital admitted victim
  \[= d_{h,f} + d_{h,p} \]
- \( d_n \) = Combined probability of full or partial permanent disability for non-admitted victim
  \[= d_{n,f} + d_{n,p} \]
- \( p \) = Probability of temporary work loss for non admitted victim
- \( C_{pd} \) = Cost of full and partial permanent disability = $10,856
- \( C_{td,h} \) = Cost of temporary disability = $1,308
- \( C_{td,n} \) = Cost of temporary disability = $391
- \( C_{nd} \) = Cost if no work loss = $33
- \( C_{cg} \) = Cost for caregiver work loss effect = $262

(f) Delay Costs

The delay costs is computed from the equation given in the Highway Economic Requirement system [FHWA, 2000] as
\[ \text{DELCC} = \frac{0.0886 \times \text{AADT} \times \text{CRASH}}{\text{LANES}} \]

Where
\[
\begin{align*}
\text{DELCC} &= \text{Cost of delay due to crashes (per 100 million VMT).} \\
\text{CRASH} &= \text{Crash rate on the section (per 100 million VMT).} \\
\text{LANES} &= \text{Number of lanes.}
\end{align*}
\]

(g) Intangible Losses

The quality life adjusted years (QALYs) approach used in the injury cost model can be used to estimate the intangible losses from injury crashes. QALYs is a health outcome measure that assigns a value of 1 to a year of perfect health and 0 to death. QALYs loss is determined by the duration and severity of the injury. The total QALYs lost is given by the formula [Miller et al., 2000].

\[
\text{QALY}_{\text{tot}} = \text{QALY}_{S1} + 3.762 \times \text{QALY}_{S2-5} + (PV_{\text{yrs}} - 4.762) \times \text{QALY}_{S6-99}
\]

Where
\[
\begin{align*}
\text{QALY}_{S1} &= \text{QALYs lost during the first year after injury} \\
\text{QALY}_{S2-5} &= \text{QALYs lost during years 2 – 5 after injury collectively} \\
\text{QALY}_{S6-99} &= \text{QALYs lost during years 6 until death collectively} \\
PV_{\text{yrs}} &= \text{Present value of the victims expected lifespan according to a standard life table, discounted at a 2.5% discount rate}
\end{align*}
\]

Using procedures (a) to (g) as explained above, Blincoe et al., [2002] developed the unit costs per injury for each of the crash costs components for the different severity levels of injury as shown in Table 7-6. A comparison of the market value (economic cost) and non-market value (QALYs) per injury shows that as injury severity increases, the contribution of market and non-market values (to comprehensive cost per injury) decreases and increases, respectively (Figure 7-6(a) and (b)).
Table 7-6: Unit Cost per Injury in 2000 dollars [Blincoe et al., 2002]

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>PDO</th>
<th>MAIS 0</th>
<th>MAIS 1</th>
<th>MAIS 2</th>
<th>MAIS 3</th>
<th>MAIS 4</th>
<th>MAIS 5</th>
<th>Fatal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical</td>
<td>$0</td>
<td>$1</td>
<td>$2,380</td>
<td>$15,625</td>
<td>$46,495</td>
<td>$131,306</td>
<td>$332,457</td>
<td>$22,095</td>
</tr>
<tr>
<td>Emergency services</td>
<td>$31</td>
<td>$22</td>
<td>$97</td>
<td>$212</td>
<td>$368</td>
<td>$830</td>
<td>$852</td>
<td>$833</td>
</tr>
<tr>
<td>Market Productivity</td>
<td>$0</td>
<td>$0</td>
<td>$1,749</td>
<td>$25,017</td>
<td>$71,454</td>
<td>$106,439</td>
<td>$438,705</td>
<td>$595,358</td>
</tr>
<tr>
<td>HH Productivity</td>
<td>$47</td>
<td>$33</td>
<td>$572</td>
<td>$7,322</td>
<td>$21,075</td>
<td>$28,009</td>
<td>$149,308</td>
<td>$191,541</td>
</tr>
<tr>
<td>Insurance Admin.</td>
<td>$116</td>
<td>$80</td>
<td>$741</td>
<td>$6,909</td>
<td>$18,893</td>
<td>$32,335</td>
<td>$68,197</td>
<td>$37,120</td>
</tr>
<tr>
<td>Workplace Cost</td>
<td>$51</td>
<td>$34</td>
<td>$252</td>
<td>$1,953</td>
<td>$4,266</td>
<td>$4,698</td>
<td>$8,191</td>
<td>$8,702</td>
</tr>
<tr>
<td>Legal Costs</td>
<td>$0</td>
<td>$0</td>
<td>$150</td>
<td>$4,981</td>
<td>$15,808</td>
<td>$33,685</td>
<td>$79,856</td>
<td>$102,138</td>
</tr>
<tr>
<td>Travel Delay</td>
<td>$803</td>
<td>$773</td>
<td>$777</td>
<td>$846</td>
<td>$940</td>
<td>$999</td>
<td>$9,148</td>
<td>$9,148</td>
</tr>
<tr>
<td>Property Damage</td>
<td>$1,484</td>
<td>$1,019</td>
<td>$3,844</td>
<td>$3,954</td>
<td>$6,799</td>
<td>$9,833</td>
<td>$9,446</td>
<td>$10,273</td>
</tr>
<tr>
<td>Human Capital</td>
<td>$2,532</td>
<td>$1,962</td>
<td>$10,562</td>
<td>$66,820</td>
<td>$186,097</td>
<td>$348,133</td>
<td>$1,096,16</td>
<td>$977,208</td>
</tr>
<tr>
<td>QALYs</td>
<td>$0</td>
<td>$0</td>
<td>$4,455</td>
<td>$91,137</td>
<td>$128,107</td>
<td>$383,446</td>
<td>$1,306,83</td>
<td>$2,389,179</td>
</tr>
<tr>
<td>Comprehensive</td>
<td>$2,532</td>
<td>$1,962</td>
<td>$15,017</td>
<td>$157,958</td>
<td>$314,204</td>
<td>$731,580</td>
<td>$2,402,99</td>
<td>$3,366,388</td>
</tr>
</tbody>
</table>

[Figure 7-6(b): Comprehensive Cost per Injury [Blincoe et al., 2002]]
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7.2.2.2 Estimation of Unit Cost of Crashes by Severity Category

The average cost per Fatality or Property Damage Only sustained in a road crashes can are presented in Table 7-7, while the average cost per injury is computed as the weighted average of the injury severities between MAIS 1 and MAIS 5 in Table 7-8 as follows:

Average Injury Cost per Crash Severity Type = \[ \frac{\sum N \cdot C_i}{\sum N_i} \]

Where
- \( i = 1 \) (MAIS 1) to 5 (MAIS 5)
- \( N_i = \) Number of persons involved in road crashes for MAIS \( i \)
- \( C_i = \) Cost per MAIS \( i \) injury

Table 7-7 shows the average cost per injury for the three severity categories of road crashes.

Table 7-7: Average Cost per Injury per Crash Severity Type

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>Human Capital Cost</th>
<th>QALY’s</th>
<th>Comprehensive Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal (MAIS 6)</td>
<td>$977,208</td>
<td>$2,389,179</td>
<td>$3,366,388</td>
</tr>
<tr>
<td>Injury (MAIS 1 – 5)</td>
<td>$82,237</td>
<td>$85,803</td>
<td>$168,041</td>
</tr>
<tr>
<td>PDO</td>
<td>$2,532</td>
<td>$0</td>
<td>$2,532</td>
</tr>
</tbody>
</table>

Table 7-8 shows the number of crashes and number of persons/vehicles involved in crashes.

Table 7-8: Number of Persons/Vehicles per Crash [Blincoe et al., 2002]

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>Number of Crashes</th>
<th>Number of persons/Vehicles involved</th>
<th>Number of Persons/Vehicles per Crash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal (MAIS 6)</td>
<td>37,409</td>
<td>41,821</td>
<td>1.12</td>
</tr>
<tr>
<td>Injury (MAIS 1 – 5)</td>
<td>2,221,773</td>
<td>4,130,430</td>
<td>1.86</td>
</tr>
<tr>
<td>PDO</td>
<td>7,013,424</td>
<td>12,288,482</td>
<td>1.75</td>
</tr>
</tbody>
</table>
The number of persons/vehicles per crash for three severity categories of road crashes is computed as follows:

\[
\text{Fatalities per fatal crash} = \frac{\text{Total Fatalities}}{\text{Total Fatal Crashes}} = \frac{41,821}{37,409} = 1.12
\]

\[
\text{Injuries per injury crash} = \frac{\text{Total Injuries}}{\text{Total Injury Crashes}} = \frac{4,130,430}{2,221,773} = 1.86
\]

\[
\text{Vehicles per PDO crash} = \frac{\text{Total Number of vehicles involved in PDO}}{\text{Total Number of PDO Crashes}} = \frac{12,288,482}{7,013,424} = 1.75
\]

Using the values obtained in Tables 7-7 and Table 7-8, the average cost per crash for each category of road crashes was obtained using either the comprehensive or human capital approach as shown in Table 7-9.

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>Number of Persons/Vehicles per Crash</th>
<th>Unit Cost per Person/Vehicle</th>
<th>Cost per Crash</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Human Capital Approach</td>
<td>Comprehensive Approach</td>
</tr>
<tr>
<td>Fatal (MAIS 6)</td>
<td>1.12</td>
<td>$977,208</td>
<td>$3,366,388</td>
</tr>
<tr>
<td>Injury (MAIS 1–5)</td>
<td>1.86</td>
<td>$82,237</td>
<td>$168,041</td>
</tr>
<tr>
<td>PDO MAIS 0</td>
<td>1.75</td>
<td>$2,532</td>
<td>$2,532</td>
</tr>
</tbody>
</table>

\[7.2.3 \text{ Estimation of Crash Frequencies (Safety Performance Functions)}\]

In the past, crash estimates were obtained either by averaging from historical accident data or using expert judgments of experienced engineers. In recent times, improvements in computational capabilities and availability of data have afforded the development crash prediction models. These models typically derived from statistical analysis are used to predict the expected number of crashes on roadways and intersections. The models are developed by obtaining a database of crash and roadway characteristics (e.g., traffic volumes, geometric design features, and traffic control features), selecting an appropriate functional form, and using regression analysis to estimate the values of the coefficients or parameters in that model.

Many crash models are typically of Poisson or generalized linear form. The number of accidents in a given space-time region can be regarded as a random variable with probabilities that are Poisson distributed. More recently, the negative binomial model (a variant of the Poisson) has been used in crash modeling. The general form of the model is given as: [Brown, 1998]
\[ A = k L Q^\alpha \exp \left( \sum \gamma_i X_i \right), \]

Where

- \( A \) = Number of crashes in a selected time period,
- \( L \) = Length of the section,
- \( Q \) = AADT of the section,
- \( X_i \) = Explanatory variable,
- \( k, \beta_i, \gamma_i \) = Constants.

Using Highway Safety and Information System (HSIS) crash and road inventory data from the states of Minnesota, Washington, Michigan and California, Vogt et al., [1998] developed the crash prediction models for two-lane rural highways and at-grade intersections for use in the crash prediction module of Interactive Highway and Safety Design Model (IHSDM). These models are described below:

(a) Roadway Segment Crash Estimation Model:

This model was developed using negative binomial regression analysis of data from 619 rural two-lane highway segments in Minnesota and 712 roadway segments in Washington. It predicts the expected number of crashes on a roadway per year based on traffic volume and geometric characteristics. The model is presented as follows [Harwood et al., 2000]:

\[
N_{hr} = \text{EXPO} \exp (0.6409 + 0.1388 \text{STATE} - 0.0846 \text{LW} - 0.0591 \text{SW} + 0.0668 \text{RHR} + 0.0084 \text{DD}) \times \sum_i (\text{WH}_i \exp (0.0450 \text{DEG}_i)) \times \sum_j (\text{WV}_j \exp (0.4652 \text{V}_j)) \times \sum_k (\text{WG}_k \exp (0.1048 \text{GR}_k))
\]

Where:

- \( N_{hr} \) = Predicted number of total accidents per year on a particular roadway segment.
- \( \text{EXPO} \) = Exposure in million vehicle-miles of travel per year = \((\text{ADT})(365)(L)(10^{-6})\).
- \( \text{ADT} \) = Average daily traffic volume (veh/day) on roadway segment.
- \( L \) = Length of roadway segment (mile).
- \( \text{STATE} \) = A parameter representing the geographical location of the segment.
- \( \text{LW} \) = Lane width (ft); average lane width if the two directions of travel differ.
- \( \text{SW} \) = Shoulder width (ft); average shoulder width if the two directions of travel differ.
- \( \text{RHR} \) = Roadside hazard rating; this measure takes integer values from 1 to 7 and represents the average level of hazard in the roadside environment along the roadway segment.
- \( \text{DD} \) = Driveway density (driveways per mile) on the roadway segment.
- \( \text{WH}_i \) = Weight factor for the \( i \)th horizontal curve in the roadway segment; the proportion of the total roadway segment length represented by the portion of the \( i \)th horizontal curve that lies within the segment. (The weights, \( \text{WH}_i \), must sum to 1.0).
DEG_i = Degree of curvature for the i\(^{th}\) horizontal curve in the roadway segment (degrees per 100 ft).

WV_j = Weight factor for the j\(^{th}\) crest vertical curve in the roadway segment; the proportion of the total roadway segment length represented by the portion of the j\(^{th}\) crest vertical curve that lies within the segment. (The weights, WV_j, must sum to 1.0).

V_j = Crest vertical curve grade rate for the j\(^{th}\) crest vertical curve within the roadway segment in percent change in grade per 31 m (100 ft) = \(|g_{j2} - g_{j1}|/l_j\).

\(g_{j1}, g_{j2}\) = Roadway grades at the beginning and end of the j\(^{th}\) vertical curve (percent);

l_j = Length of the j\(^{th}\) vertical curve (in hundreds of feet).

WG_k = Weight factor for the k\(^{th}\) straight grade segment; the proportion of the total roadway segment length represented by the portion of the k\(^{th}\) straight grade segment that lies within the segment. (The weights, WG_k, must sum to 1.0).

GR_k = Absolute value of grade for the k\(^{th}\) straight grade on the segment (percent).

(b) Intersection Crash Estimation Models

(i) Three-Leg STOP-Controlled Intersections:
This model was developed using negative binominal regression analysis with data from 382 three-leg STOP-controlled intersections in Minnesota. The data base available for model development included 5 years of accident data (1985-1989) at each intersection. The model is presented as follows [Harwood et al., 2000]:

\[N_{bi} = \exp (11.28 + 0.79\ln ADT1 + 0.49\ln ADT2 + 0.19RHRI + 0.28RT)\]

Where

\(N_{bi}\) = Predicted number of total accidents per year at the intersection.

\(ADT1\) = Average daily traffic volume (veh/day) on the major road.

\(ADT2\) = Average daily traffic volume (veh/day) on the minor road.

\(RHRI\) = Roadside hazard rating within 76 m (250 ft) of the intersection on the major road.

\(RT\) = Presence of right-turn lane on the major road (1 = right-turn lane present; 0 otherwise).

(ii) Four-Leg STOP-Controlled Intersections
This model was developed using negative binominal regression with data from 324 four-leg STOP-controlled intersections in Minnesota. The model for four-leg intersections with STOP control is presented below [Harwood et al., 2000]:

\[N_{bi} = \exp (-9.34 + 0.60\ln ADT1 + 0.61\ln ADT2 + 0.13 ND1 - 0.0054SKEW4)\]
Where
\[ N_{bi} = \text{Predicted number of total accidents per year at the intersection.} \]
\[ ND1 = \text{Number of driveways on the major-road legs within 76 m (250 ft) of the intersection} \]
\[ SKEW4 = \text{Intersection angle (degrees) expressed as one-half of the angle to the right minus one-half of the angle to the left for the angles between the major-road leg in the direction of increasing stations and the right and left legs, respectively.} \]

(iii) Four-Leg Signalized Intersections

This model was developed using negative binomial regression with data from 49 four-leg signalized intersections in California and in Michigan. The database available for model development included three years of accident data (1993-1995) at each intersection. The model predicts total intersection-related accident frequency for any four-leg signalized. The model for four-leg signalized intersections is presented below [Harwood et al., 2000]:

\[ N_{bi} = \exp (-5.46 + 0.60 \ln ADT1 + 0.20 \ln ADT2 - 0.40 PROTLT - 0.018 PCTLEFT2 + 0.11 VEICOM + 0.026 PTRUCK + 0.041 ND1) \]

Where
\[ N_{bi} = \text{Predicted number of total accidents per year at the intersection.} \]
\[ PROTLT = \text{Presence of protected left-turn signal phase on one or more major-road approaches; } = 1 \text{ if present; } = 0 \text{ if not present.} \]
\[ PCTLEFT2 = \text{Percentage of minor-road traffic that turns left at the signal during the morning and evening hours combined.} \]
\[ VEICOM = \text{Grade rate for all vertical curves (crests and sags) within 76 m (250 ft) of the intersection along the major and minor roads.} \]
\[ PTRUCK = \text{Percentage of trucks (vehicles with more than four wheels) entering the intersection for the morning and evening peak hours combined.} \]
\[ ND1 = \text{Number of driveways within 76 m (250 ft) of the intersection on the major road.} \]

Harwood et al. [2000] stated that the above models can be calibrated and adapted for use in all the states.
7.3 ESTIMATION OF TOTAL CRASH COSTS

Generally, total crash costs = unit crash costs * number of crashes. This computation is carried out for each crash severity category, and for each road section. Specifically, the procedure for estimation of the total crash costs is outlined in the following steps.

Step 1. Determine the total number of crashes occurring on all the segments and intersections using the crash prediction models described in chapter 3.

Step 2. Estimate the number of fatal, injury and property damage only crashes.

Step 3. Determine the unit crash costs by crash severity type.

Step 4. Estimate the total number of crashes as a product of the number of crashes and the unit crash cost for each crash type.

The total crash costs is computed as follows:

\[
TC = (FAT_{seg} + FAT_{int}) U_f + (INJ_{seg} + INJ_{int}) U_i + (PDO_{seg} + PDO_{int}) U_p
\]

Where

- \(TC\) = Total crash cost
- \(FAT_{seg}\) = Number of fatal crashes on road segments
- \(FAT_{int}\) = Number of fatal crashes at intersections
- \(INJ_{seg}\) = Number of injury crashes on road segments
- \(INJ_{int}\) = Number of injury crashes at intersections
- \(PDO_{seg}\) = Number of property damage only crashes on road segments
- \(PDO_{int}\) = Number of property damage only crashes at intersections
- \(U_f\) = Unit cost per fatal crash
- \(U_i\) = Unit cost per injury crash
- \(U_p\) = Unit cost per property damage only crash

Total crash costs at a present or future date is a vital input for project and network level evaluation of safety projects, as seen in subsequent sections of this chapter.
7.4 PROJECT LEVEL SAFETY EVALUATION

Project level safety evaluation involves finding the best safety treatments or combination of treatments to address an identified deficiency on a road segment or intersection. The process involves identifying all feasible alternative treatments, estimating their benefits (in terms of crash reduction), and comparing their benefits to the costs of treatment implementation and maintenance. A project may be defined as one or more treatments. In the case study presented in this chapter, each project comprises exactly one treatment.

7.4.1 Methodology
The evaluation procedure follows the framework shown in Figure 7-7 below.

Figure 7-7: Framework for Safety Project Evaluation.
7.4.2 Case Study

This section demonstrates the methodology for the evaluation of safety improvement projects using the unit crash cost rates presented in the previous section. Data from State Road 25, a two-lane Rural Minor Arterial road section in Tippecanoe County, is used. This was done to determine the effect of shoulder widening and grade improvement on crash costs and hence select the best alternative. A traffic growth rate of 1.9% was assumed for the segment. Where information was not available, hypothetical values were used. Table 7-10 shows the characteristics of the exiting and improved road conditions. The duration for construction of each safety treatment alternative was taken as one year.

Table 7-10: Attributes of Project Alternatives

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>Do Nothing</th>
<th>Shoulder Widening (SW)</th>
<th>Grade Improvement (GI)</th>
<th>Combined (SW + GI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic volume ($ADT$)</td>
<td>7,304 vpd</td>
<td>7,304 vpd</td>
<td>7,304 vpd</td>
<td>7,304 vpd</td>
</tr>
<tr>
<td>Length of segment ($L$)</td>
<td>3.04 miles</td>
<td>3.04 miles</td>
<td>3.04 miles</td>
<td>3.04 miles</td>
</tr>
<tr>
<td>Lane width ($LW$)</td>
<td>12 ft</td>
<td>12 ft</td>
<td>12 ft</td>
<td>12 ft</td>
</tr>
<tr>
<td>Shoulder width ($SW$)</td>
<td>3 ft</td>
<td>3 ft</td>
<td>3 ft</td>
<td>3 ft</td>
</tr>
<tr>
<td>Roadside hazard rating ($RHR$)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Driveway density ($DD$)</td>
<td>3 driveways/mile</td>
<td>3 driveways/mile</td>
<td>3 driveways/mile</td>
<td>3 driveways/mile</td>
</tr>
<tr>
<td>Horizontal curvature ($DEGi$)</td>
<td>$30^\circ$</td>
<td>$30^\circ$</td>
<td>$30^\circ$</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>Vertical curve grade rate ($V_j$)</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Grade for straight segment ($GR_k$)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cost of Improvement ($$/km$)</td>
<td>0</td>
<td>$150,000$</td>
<td>$600,000$</td>
<td>$800,000$</td>
</tr>
<tr>
<td>Maintenance cost ($$/km$)</td>
<td>$25,000$</td>
<td>$25,000$</td>
<td>$25,000$</td>
<td>$25,000$</td>
</tr>
<tr>
<td>Analysis Period</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
</tr>
<tr>
<td>Discount rate</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Salvage Value</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

7.4.2.1 Estimation of the Number of Crashes

(a) For All Crash Severity Types Combined

The following crash prediction model was used to predict the expected number of crashes on the road segment for each alternative, including the “do nothing” alternative.

$$N_{br} = ADT \times L \times 365 \times 10^{-6} \times \exp \left(0.8665 - 0.0846LW - 0.00591SW + 0.045 \times DEGi + 0.4652V_j + 0.1048GR_k \right)$$

Where the symbols have their usual meaning.
Substituting into the above equation gives the annual expected number of crashes for each alternative. For example for the existing condition the expected number of crashes can be obtained as follows:

\[
N_{fr} = 7032 \times 3.04 \times 365 \times 10^{-6} \times \exp \left( 0.8665 - 0.0846 \times 12 - 0.0591 \times 3 + 0.045 \times 30 + 0.4652 \times 4 + 0.1048 \times 3 \right) \\
= 172 \text{ crashes}
\]

Table 7-11 shows the expected total number of crashes before and after each improvement.

<table>
<thead>
<tr>
<th></th>
<th>Do Nothing</th>
<th>Shoulder Widening (SW)</th>
<th>Grade Improvement (GI)</th>
<th>Combined (SW + GI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Crashes</td>
<td>172</td>
<td>159</td>
<td>71</td>
<td>63</td>
</tr>
</tbody>
</table>

(b) Estimation of Number of Crashes for each Crash Severity Type

Table 7-12 shows the breakdown of crashes by type and the estimated crash reductions for each alternative.

<table>
<thead>
<tr>
<th></th>
<th>Alternatives</th>
<th>Fatal</th>
<th>Injury</th>
<th>PDO</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Crashes</td>
<td>Do Nothing</td>
<td>1</td>
<td>41</td>
<td>130</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>Shoulder Widening (SW)</td>
<td>1</td>
<td>38</td>
<td>120</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>Grade Improvement (GI)</td>
<td>0</td>
<td>17</td>
<td>53</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>Combined (SW + GI)</td>
<td>0</td>
<td>15</td>
<td>47</td>
<td>63</td>
</tr>
<tr>
<td>Crash Reduction</td>
<td>Do Nothing</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Shoulder Widening (SW)</td>
<td>0</td>
<td>3</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Grade Improvement (GI)</td>
<td>1</td>
<td>24</td>
<td>77</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>Combined (SW + GI)</td>
<td>1</td>
<td>26</td>
<td>83</td>
<td>109</td>
</tr>
</tbody>
</table>

The values were obtained using a ratio of the number of crashes that occurred for each crash type to the total number of crashes for the year 2000 obtained from Table 7-8. For example, for the existing conditions the number of estimated crashes by severity category, is computed as follows

\[
\text{Fatal Crashes} = \frac{37,409}{9,272,607} \times 172 = 1 \\
\text{Injury Crashes} = \frac{2,221,773}{9,272,607} \times 172 = 41 \\
\text{PDO Crashes} = \frac{7,013,424}{9,272,607} \times 172 = 130
\]
7.4.2.2 Estimation of Total Crash Costs

Table 7-13 shows the crash costs associated with the number of crashes for each alternative.

### Table 7-13: Crash Costs by Type and Project Alternative

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>Nr. of Crashes</th>
<th>Cost Per Crash</th>
<th></th>
<th>Crash Cost</th>
<th></th>
<th>Total Crash Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Comprehensive</td>
<td>Human Capital</td>
<td>Comprehensive</td>
<td>Human Capital</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Existing Conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatal</td>
<td>1</td>
<td>$3,763,418</td>
<td>$1,092,459</td>
<td>$1,092,459</td>
<td>$3,763,418</td>
<td>$17,154,947</td>
<td>$7,937,383</td>
</tr>
<tr>
<td>Injury</td>
<td>41</td>
<td>$312,556</td>
<td>$152,884</td>
<td>$6,268,244</td>
<td>$12,814,796</td>
<td>$10,584,040</td>
<td></td>
</tr>
<tr>
<td>PDO</td>
<td>130</td>
<td>$4,436</td>
<td>$4,436</td>
<td>$576,680</td>
<td>$576,733</td>
<td>$17,154,947</td>
<td>$7,937,383</td>
</tr>
<tr>
<td><strong>Shoulder Widening</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatal</td>
<td>1</td>
<td>$3,763,418</td>
<td>$1,092,459</td>
<td>$1,092,459</td>
<td>$3,763,418</td>
<td>$16,172,915</td>
<td>$7,434,371</td>
</tr>
<tr>
<td>Injury</td>
<td>38</td>
<td>$312,556</td>
<td>$152,884</td>
<td>$5,809,592</td>
<td>$11,877,128</td>
<td>$11,526,546</td>
<td></td>
</tr>
<tr>
<td>PDO</td>
<td>120</td>
<td>$4,436</td>
<td>$4,436</td>
<td>$532,320</td>
<td>$532,369</td>
<td>$16,172,915</td>
<td>$7,434,371</td>
</tr>
<tr>
<td><strong>Grade Improvement</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatal</td>
<td>0</td>
<td>$3,763,418</td>
<td>$1,092,459</td>
<td>$0</td>
<td>$0.00</td>
<td>$5,548,581</td>
<td>$2,834,136</td>
</tr>
<tr>
<td>Injury</td>
<td>17</td>
<td>$312,556</td>
<td>$152,884</td>
<td>$2,599,028</td>
<td>$5,313,452</td>
<td>$5,548,581</td>
<td></td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatal</td>
<td>0</td>
<td>$3,763,418</td>
<td>$1,092,459</td>
<td>$0</td>
<td>$0.00</td>
<td>$5,548,581</td>
<td>$2,501,752</td>
</tr>
<tr>
<td>Injury</td>
<td>15</td>
<td>$312,556</td>
<td>$152,884</td>
<td>$2,293,260</td>
<td>$4,688,340</td>
<td>$5,548,581</td>
<td></td>
</tr>
<tr>
<td>PDO</td>
<td>47</td>
<td>$4,436</td>
<td>$4,436</td>
<td>$208,492</td>
<td>$208,511</td>
<td>$5,548,581</td>
<td>$2,501,752</td>
</tr>
</tbody>
</table>

7.4.2.3 Estimation of Benefits from Safety Improvement

Table 7-14 shows the benefits associated with the implementation of each alternative. The benefits are computed as the difference between total crash costs for the existing condition (Before Improvement) and after implementation of each alternative.

### Table 7-14: Annual Monetary Benefits from Project Alternatives

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Comprehensive Approach</th>
<th></th>
<th>Human Capital Approach</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Improvement</td>
<td>After Improvement</td>
<td>Benefits</td>
<td>Before Improvement</td>
</tr>
<tr>
<td>Shoulder widening</td>
<td>$17,154,947</td>
<td>$16,172,915</td>
<td>$982,032</td>
<td>$7,937,383</td>
</tr>
<tr>
<td>Grade Improvement</td>
<td>$17,154,947</td>
<td>$5,548,581</td>
<td>$11,606,365</td>
<td>$7,937,383</td>
</tr>
<tr>
<td>Combined</td>
<td>$17,154,947</td>
<td>$5,548,581</td>
<td>$12,258,096</td>
<td>$7,937,383</td>
</tr>
</tbody>
</table>
7.4.2.4 Economic Evaluation

The economic indicators used in the economic evaluation of the project alternatives are the Incremental Equivalent Uniform Annual Return (EUAR\textsubscript{inc}) and the Incremental Benefits Cost Ratio (B/C\textsubscript{inc}). Table 7-15 shows the cost streams associated with each alternative including the existing conditions.

Table 7-15: Summary of Key Variables of Cost Stream

<table>
<thead>
<tr>
<th></th>
<th>Do Nothing</th>
<th>Shoulder Widening (SW)</th>
<th>Grade Improvement (GI)</th>
<th>Combined (SW + GI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation Cost (P) per km</td>
<td>0</td>
<td>$150,000</td>
<td>$600,000</td>
<td>$800,000</td>
</tr>
<tr>
<td>Annual Maintenance Cost (M) per km</td>
<td>$25,000</td>
<td>$25,000</td>
<td>$25,000</td>
<td>$25,000</td>
</tr>
<tr>
<td>Analysis Period (Y)</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
</tr>
<tr>
<td>Discount rate</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

The computation of these economic indicators requires the determination of the Equivalent Uniform Annual Costs (EUAC) and the Equivalent Uniform Annual Benefits (EUAB) associated with each project alternative including the existing conditions.

The Equivalent Uniform Annual Costs (EUAC\textsubscript{i}) for each project alternative is computed as follows:

\[
EUAC_i = (P \times L \times CRF_{(n, r\%)} + (M \times L)
\]

Where
- \(P\) = Implementation Cost
- \(CRF_{(n, r\%)}\) = Capital Recovery Factor
- \(M\) = Annual Maintenance Costs
- \(L\) = Length of Road Segment
- \(n\) = Project life span
- \(r\) = Discount rate

The Equivalent Uniform Annual Benefits (EUAB\textsubscript{i}) is the annual monetary benefit from each project alternative computed as follows

\[
EUAB_i = \sum_{k=1}^{n} S_i \times (1 + g)^{k-1} \times SPPWF_{(k, r\%)} \times CRF_{(n, r\%)}
\]

Where
- \(S_i\) = First year monetary Benefits for project alternative \(i\)
- \(SPPWF\) = single payment present worth factor
\( n \) = Project life span  
\( r \) = Discount rate  
\( g \) = Traffic growth rate 

The Equivalent Uniform Annual Return (\( EUAR_i \)) for each project alternative is computed as follows:

\[
EUAR_i = EUAB_i - EUAC_i
\]

And the Incremental Equivalent Uniform Annual Return (\( EUAR_{inc} \)) for each project alternative is computed as follows

\[
EUAR_{inc(i)} = EUAR_i - EUAR_{existing}
\]

Where 
\( EUAR_{inc(i)} \) = Incremental Equivalent Uniform Annual Return of alternative \( i \)  
\( EUAR_i \) = Equivalent Uniform Annual Return of alternative \( i \)  
\( EUAR_{existing} \) = Equivalent Uniform Annual Return of the Existing Condition

The Benefit Cost Ratio (\( B/C_i \)) for each project alternative is computed as follows:

\[
B/C_i = \frac{EUAB_i}{EUAC_i}
\]

And the Incremental Benefit Cost Ratio for each project alternative is computed as follows:

\[
B/C_{inc(i)} = B/C_i - B/C_{existing}
\]

Where 
\( B/C_{inc(i)} \) = Incremental Benefit Cost Ratio of alternative \( i \)  
\( B/C_i \) = Benefit Cost Ratio of alternative \( i \)  
\( B/C_{existing} \) = Benefit Cost Ratio of the Existing Condition

A sample calculation using the Shoulder widening alternative and the Comprehensive Approach is given as follows:

Equivalent Uniform Annual Cost (\( EUAC \))

\[
= 150,000 \times 3.04 \times \frac{0.05(1 + 0.05)^{10}}{(1 + 0.05)^{10} - 1} + 25,000 \times 3.04 \\
= $135,054
\]
Equivalent Uniform Annual Benefits (EUAB) = \[ \sum_{k=1}^{10} \frac{982,032 \times (1 + 0.019)^{k-1}}{(1 + 0.05)^k} \times \frac{0.05(1 + 0.05)^{10}}{(1 + 0.05)^{10} - 1} \] = $1,082,518

Equivalent Uniform Annual Return (EUAR) = $1,082,518 - $135,054 = $947,464

Incremental Equivalent Uniform Annual Return (EUAR_{inc}) = $947,464 - (- $76,000) = $1,023,464

The value of -$76,000 represents the Equivalent Uniform Annual Return for the existing conditions.

Benefit cost ratio (B/C) = \[ \frac{1,082,518}{135,054} = 8.02 \]

Incremental Benefit cost ratio (B/C_{inc}) = 8.02 - 0 = 8.02

Table 7-16 and Table 7-17 show the results of the economic analysis for all the alternatives considered.

### Table 7-16: Results of Economic Analysis Using Comprehensive Approach

<table>
<thead>
<tr>
<th></th>
<th>EUAC</th>
<th>EUAB</th>
<th>EUAR</th>
<th>B/C</th>
<th>EUAR_{inc}</th>
<th>B/C_{inc}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Conditions</td>
<td>$76,000</td>
<td>0</td>
<td>- $76,000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Shoulder Widening</td>
<td>$135,054</td>
<td>$1,082,518</td>
<td>$947,464</td>
<td>8.02</td>
<td>$1,023,464</td>
<td>8.02</td>
</tr>
<tr>
<td>Grade Improvement</td>
<td>$351,585</td>
<td>$12,793,988</td>
<td>$12,442,403</td>
<td>36.39</td>
<td>$12,518,403</td>
<td>36.39</td>
</tr>
<tr>
<td>Combined</td>
<td>$390,955</td>
<td>$13,512,406</td>
<td>$13,121,451</td>
<td>34.56</td>
<td>$13,197,451</td>
<td>$34.56</td>
</tr>
</tbody>
</table>

### Table 7-17: Results of Economic Analysis Using Human Capital Approach

<table>
<thead>
<tr>
<th></th>
<th>EUAC</th>
<th>EUAB</th>
<th>EUAR</th>
<th>B/C</th>
<th>EUAR_{inc}</th>
<th>B/C_{inc}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Conditions</td>
<td>$76,000</td>
<td>0</td>
<td>- $76,000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Shoulder Widening</td>
<td>$135,054</td>
<td>$554,483</td>
<td>$419,429</td>
<td>4.11</td>
<td>$495,429</td>
<td>4.11</td>
</tr>
<tr>
<td>Grade Improvement</td>
<td>$351,585</td>
<td>$5,625,437</td>
<td>$5,273,852</td>
<td>16.00</td>
<td>$5,349,852</td>
<td>16.00</td>
</tr>
<tr>
<td>Combined</td>
<td>$390,955</td>
<td>$5,991,832</td>
<td>$5,600,877</td>
<td>15.33</td>
<td>$5,676,877</td>
<td>15.33</td>
</tr>
</tbody>
</table>
7.4.3 Discussion and Conclusions

This section summarizes the methodology for project level safety evaluation using economic analysis. Total crash costs were estimated using both Comprehensive Approach and Human Capital approaches, and unit crash costs were developed for each of three different road crash severity types (fatal, injury and property damage only). The method was applied to a 3.04 mile segment of a two lane Rural Minor Arterial Road (State Road 25) in Tippecanoe County to determine the effect of shoulder widening and grade improvement on crash costs using hypothetical values. The results obtained indicate that the all the safety improvement projects considered will result in substantial benefits in terms of crash reductions and cost. The results indicated that grade improvement was a better alternative than shoulder widening since it had a higher equivalent uniform annual benefit and benefit cost ratio than shoulder widening, and was also associated with greater crash reductions. A combination of the two alternatives did not result in any significant change in either the annual returns or crash reductions from that of the grade improvement alternative. Also the incremental benefit cost ratio of the combined alternatives was less than that of the grade improvement. The grade improvement is therefore the best alternative for crash reduction. Using the comprehensive approach, the unit costs of fatal and injury crashes were found to be about 240% and 100% higher, respectively than those obtained using the human capital approach.

The above demonstration also shows that the results for all alternative safety projects were consistent regardless of approach used (Comprehensive and Human Capital Approaches). However the annual returns of the safety investment using the Comprehensive Approach was about twice that obtained using the Human Capital Approach, for all the project alternatives considered. This suggests that using the Comprehensive Approach for safety project evaluation is likely to indicate significantly higher viability of such projects.

7.5 NETWORK LEVEL SAFETY EVALUATION

This section presents similar methods that may be used for network level safety evaluation: The Indiana Safety Management System method, and the Safety Index method.

7.5.1 The Indiana Safety Management System Method

Figure 7-8 represents the analytical framework of Indiana’s safety management system for short or long range planning and implementation of safety projects in the state. The framework consists of six analytical procedures that are listed below and subsequently described in detail:

1. Definition of analysis period and network selection,
2. Estimation of expected crash frequency over analysis period,
3. Selection of candidate locations over analysis period,
4. Identification of alternative safety improvement projects,
5. Computation cost and benefits of safety improvement projects,
Figure 7-8: Framework for Safety Project Evaluation.

**Step 1 - Definition of Analysis Period and Network Selection**

The analysis could be either for a long range planning horizon (typically a 20-year period) or a short-range (typically a 3 to 5-year period). Network selection involves the definition of a subset of road sections of interest from the entire state road network by attribute such as route type, functional class, county, district or combinations of these attributes.

**Step 2 - Estimation of Expected Crash Frequency**

Similar to project level evaluation, 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 and intersections. 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.
Hauer et al. [2002]. 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 Abbes et al. [1981].

For the present study, the crash prediction procedure for the analytical framework is based on the EB method outlined by Hauer et al. [2002]. 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. In a subsequent demonstration of this methodology, this section develops separate safety performance models for fatal/injury and property damage only, using negative binomial analysis of 1997-2000 Indiana data. The model functional forms are shown in Table 7-18. With such models and data, the EB estimate of the expected safety performance of a location was computed as follows:

\[
\begin{align*}
\epsilon_i &= \omega_i a_i + (1 - \omega_i)x_i \quad - \quad (1) \\
\omega_i &= \frac{1}{1 + \frac{a_i}{\alpha \cdot L_i}} \quad - \quad (2)
\end{align*}
\]

Where

- \( \epsilon_i \) = EB estimate of crash frequency
- \( \omega_i \) = Weight factor
- \( a_i \) = Expected annual crash frequency on road section \( i \) from safety performance function.
- \( \alpha \) = 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.
Table 7-18: Safety Performance Functions for Crash Prediction

<table>
<thead>
<tr>
<th>Location</th>
<th>Safety Performance Functions</th>
<th>Overdispersion factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural two-lane segment</td>
<td>( a_{IF} = 0.208 \times L \times Q^{0.204} )</td>
<td>0.420</td>
</tr>
<tr>
<td></td>
<td>( a_{PD} = 0.712 \times L \times Q^{0.592} )</td>
<td>0.430</td>
</tr>
<tr>
<td></td>
<td>( a_t = 0.922 \times L \times Q^{0.596} )</td>
<td>0.427</td>
</tr>
<tr>
<td>Rural multi-lane segment</td>
<td>( a_{IF} = 0.107 \times L \times Q^{0.814} )</td>
<td>0.451</td>
</tr>
<tr>
<td></td>
<td>( a_{PD} = 0.634 \times L \times Q^{1.615} )</td>
<td>0.484</td>
</tr>
<tr>
<td></td>
<td>( a_t = 0.737 \times L \times Q^{0.624} )</td>
<td>0.473</td>
</tr>
<tr>
<td>Urban two-lane segment</td>
<td>( a_{IF} = 0.105 \times L \times Q^{0.080} )</td>
<td>1.253</td>
</tr>
<tr>
<td></td>
<td>( a_{PD} = 0.603 \times L \times Q^{0.996} )</td>
<td>1.349</td>
</tr>
<tr>
<td></td>
<td>( a_t = 0.733 \times L \times Q^{0.917} )</td>
<td>1.459</td>
</tr>
<tr>
<td>Urban multi-lane segment</td>
<td>( a_{IF} = 0.674 \times L \times Q^{1.415} )</td>
<td>1.588</td>
</tr>
<tr>
<td></td>
<td>( a_{PD} = 2.028 \times L \times Q^{0.590} )</td>
<td>1.946</td>
</tr>
<tr>
<td></td>
<td>( a_t = 2.641 \times L \times Q^{1.415} )</td>
<td>2.095</td>
</tr>
</tbody>
</table>

Where

- \( a_{IF} \) = 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

**Step 3 - Selection of Candidate Locations**

For safety investment, it is sought to select road sections that genuinely require some safety attention now or in the future while maximizing costs for the selected network over the analysis period. McGuigan [1981] introduced the concept of potential accident reduction as a method of identifying candidate locations, and stated that this value (the difference between observed crash count and expected crash frequency) represents the size of potential annual accident reduction for a given location. Also, Persaud [1999] used a similar method but replaced the observed crash counts with the EB estimate. Critics of the McGuigan and Persaud approaches contested their assumption that the expected crash frequency represents the level from which accidents can be reduced. Arguing that a location is considered hazardous if the probability that the expected crash rate at the location is greater than a specified critical value, Higle and Witkowski [1998] suggested using an EB estimate of crash rate for selecting candidate locations. Hauer [1992] also applied the EB method to identify candidate locations using expected crash frequencies rather than expected crash rates for identifying hazardous locations, with the contention that a location may be considered hazardous if there is a high probability that the expected crash frequency exceeds a predefined critical crash frequency.

Obviously, the selection of candidate (hazardous) locations strives to combines the best of these two methods that are based on the expected crash frequency and expected crash rate. For instance, the use of the expected crash frequency method results in the selection of locations with the highest potential benefit while the
expected crash rate method minimizes the bias of selecting locations with high traffic volume but relatively low crash rate. The method used in the Indiana SMS may therefore be considered satisfactory from both system and user perspectives. A section is selected as a candidate location for safety improvement if both expected crash frequency and crash rate obtained from the EB estimate exceed their respective critical values as shown:

\[
F_{c(it)} = D_a \cdot L_i + k \cdot (D_a \cdot L_i)^{1/2}
\]

\[
R_{c(it)} = R_a + k \cdot \left( \frac{R_a}{VMT_{it}} \right)^{1/2}
\]

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 Traveled (VMT) for road section \( i \) in year \( t \)
- \( k \) = A constant representing the statistical significance of the estimate.

These critical values may be replaced by any safety goals established by a DOT of MPO. The candidate locations are ranked based on the sum of the ratio of expected and critical crash frequencies and the ratio of the expected and critical crash rates.

**Step 4 - Identification of Safety Improvement Projects**

The next step in the analytical framework is to define the set of alternative safety improvements projects to be considered for each candidate location. These improvements vary from site to site and are based on the identification of contributing factors that may be eliminated or changed so that their associated crashes will be reduced or eliminated. Safety improvements programs can be categorized into three main groups based on the contributing factors namely vehicle, driver, and road environment. In the present chapter, the framework focuses only on the road environment factors. For each candidate location, the factors considered in selecting an appropriate safety project are discussed below.

**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 [2000].
Expected Predominant Crash Pattern:

The 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 the expected frequency of the particular crash pattern at a given location significantly exceeds the critical crash frequency for that particular crash pattern. 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:

\[ P_{c(ij)} = P_{aj} + \sigma_j \quad - \quad (5) \]

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
- \( \sigma_j \) = Standard deviation for 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. It is not expected that the default set of alternative safety improvement projects for each roadway deficiency and predominant crash pattern shown in Table 7-19 will always include the entire range of feasible safety improvement projects at a given site because not all information on site conditions may be available.
Table 7-19: Default Safety Improvement Projects

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

**Step 5 - Computation of Cost and Benefits**

This procedure involves the determination of all costs and benefits associated with each alternative safety improvement project over the analysis period. The “critical year” for a given location represents the year when the location becomes hazardous. Alternative safety improvement projects for a given location may be implemented in any year within the analysis period provided that the intended implementation year is at or exceeds the critical year for that location.

**Estimation of Project Costs:**

The cost of each safety improvement project is estimated from default unit construction cost, maintenance cost and salvage cost values which were obtained from Indiana DOT. 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 equivalent uniform annual cost (EUAC) of the project when it is implemented in year \( t \) of the analysis period is estimated as follows:
EUAC\(_{ijt}\) = \[C_{ijt} \cdot \left(\frac{1}{(1 + r)^t}\right) + M_{ijt} \cdot \left(\frac{(1 + r)^{p-t} - 1}{r(1 + r)^p}\right) - S_{ijt} \cdot \left(\frac{1}{(1 + r)^t}\right)\] \times \left(\frac{r(1 + r)^p}{(1 + r)^p - 1}\right) \quad - (6)

Where
EUAC\(_{ijt}\) = Present worth of costs for safety improvement project \(j\) at location \(i\) at analysis year \(t\)
\(C_{ijt}\) = Initial construction cost for safety improvement project \(j\) at location \(i\) at analysis year \(t\)
\(M_{ijt}\) = Annual maintenance cost for safety improvement project \(j\) at location \(i\) at analysis year \(t\)
\(S_{ijt}\) = Salvage value for safety improvement project \(j\) at location \(i\) at analysis year \(t\)
\(r\) = Minimum attractive rate of return
\(n\) = Life span of the safety improvement project \(j\)
\(t\) = Analysis year = 0, 1, 2…..\(p\)
\(p\) = Analysis period in years

Estimation of project benefits:
The benefits associated with each safety improvement project depend on the expected crash reduction. The accident modification factors (AMF’s) or crash reduction factors (CRF’s) used in the present chapter were obtained from a variety of sources such as the Indiana Design Manual (10), Tarko et al., (11), Harwood et al., (12) and Harwood (13). The benefits can be computed either in non monetary terms as the total crash reduction or as equivalent uniform annual worth of benefits from the crashes reduced over the analysis period from the year of implementation of the project as follows:

\[CR_{ijt} = \sum_{s=1}^{2} N_{sit} \cdot AMF_{sij} \quad - (7)\]

\[PWB_{ijt} = \left[\sum_{t}^{p} \sum_{s=1}^{2} \left(\frac{N_{sit} \cdot AMF_{sij} \cdot CC_{sit}}{(1 + r)^t}\right)\right] \times \left(\frac{r(1 + r)^p}{(1 + r)^p - 1}\right) \quad - (8)\]

Where
\(CR_{ijt}\) = Total Crash reduction for safety improvement project \(j\) at location \(i\) at analysis year \(t\)
\(EUAB_{ijt}\) = Present worth of benefits for safety improvement project \(j\) at location \(i\) at analysis year \(t\)
\(N_{sit}\) = Expected crash frequency of severity \(s\) for location \(i\) at analysis year \(t\)
\(AMF_{sij}\) = Crash reduction factor for severity \(s\) associated with safety improvement project \(j\) at location \(i\)
\(CC_{sit}\) = Crash cost for severity \(s\) at location \(i\) in analysis year \(t\)
\(s\) = Crash severity (1 = Fatal/Injury crash, 2 = PDO crash)
\(r\) = Minimum attractive rate of return
\[ n = \text{Service life of the safety improvement project } j \]
\[ t = \text{Analysis year } = 0, 1, 2....p \]
\[ p = \text{Analysis period in years} \]

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 (7) and (8). The current framework does not include secondary benefits from these safety improvements.

**Step 6 - Optimization of investment options**

Highway agencies typically have budgetary limits for safety improvement projects. There is therefore the need to establish the most suitable safety improvement project and optimal time for implementation at each candidate location within the available budget over the analysis period. Kaji and Sinha [1980] developed a resource allocation methodology for highway safety improvements in Indiana by maximizing cost effectiveness using integer programming. Harwood et al. [2003] reviewed various methods of resource allocation such as incremental benefit cost ratio, integer programming and dynamic programming and concluded that when formulated properly, these methods produce similar results. Also integer programming is more efficient than dynamic programming and also simpler than incremental benefit cost ratio.

Indiana’s SMS uses an integer programming model, a technique known for several merits and wide availability of software tools for programming. In network level safety optimization, the objective is to maximize the total economic value for all the safety improvement projects selected. The economic value \( E_{ijt} \) of a safety improvement project \( j \) at location \( i \) at analysis year \( t \) is evaluated using any one of the following alternative economic evaluation criteria:

\[
\text{Cost effectiveness} = \frac{CR_{ijt} \cdot 1,000,000}{EUAC_{ijt} \times p} \quad - \quad (9)
\]
\[
\text{Net present value} = EUAB_{ijt} - EUAC_{ijt} \quad - \quad (10)
\]
\[
\text{Benefit cost ratio} = \frac{EUAB_{ijt}}{EUAC_{ijt}} \quad - \quad (11)
\]

The choice of economic evaluation criterion is left to the analyst.

The optimization procedure considers the following alternative scenarios:

1. Unconstrained Funding Optimization
2. Total Budgeting Optimization
3. Multi-year Budgeting with carry over of unspent budget
1. 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 in a given year. The funding needs can be determined using the following integer programming equation.

Maximize \[ \sum_{i}^{h} \sum_{j}^{m} \sum_{t}^{p} (x_{ijt}E_{ijt}) \] - (12)

Subject to \[ \sum_{j=1}^{m} \sum_{t=1}^{p} x_{ijt} = 1 \text{ for all } i \] - (13)

\[ x_{ijt} = 0 \text{ if } t \neq y_i \] - (14)

and \[ x_{ijt} = 0,1 \] - (15)

Where

\[ h = \text{Number of candidate locations within selected network} \]
\[ m = \text{Number of alternative safety improvement projects for location } i \]
\[ p = \text{Number of years in analysis period} \]
\[ t = \text{Analysis year } = 1, 2, ..., p \]
\[ y_i = \text{Year when location } i \text{ becomes hazardous (critical year)} \]
\[ E_{ijt} = \text{Economic value of safety improvement project } j \text{ at location } i \text{ for analysis year } t \]
\[ x_{ijt} = \begin{cases} 
1 & \text{if safety improvement project } j \text{ is implemented at location } i \text{ for analysis year } t \\
0 & \text{otherwise}
\end{cases} \]

Equation (12) seeks to maximize the total economic value of the selected safety improvement projects. The economic value \( E_{ijt} \) for each alternative safety improvement project at each candidate location is determined from Equation (9), (10) or (11). The constraints on the optimal solution are represented by the equalities and inequalities presented in Equations (13) - (15).

2. 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 funding allocation may be obtained by solving the following integer programming equation:

Maximize \[ \sum_{i}^{h} \sum_{j}^{m} \sum_{t}^{p} (x_{ijt}E_{ijt}) \] - (16)

Subject to \[ \sum_{j=1}^{m} \sum_{i=1}^{h} \sum_{t=1}^{p} (x_{ijt}C_{ijt} + (p-t)x_{ijt}M_{ijt}) \leq B \] - (17)
\[ \sum_{j=1}^{m} \sum_{r=1}^{p} x_{ijr} = 1 \text{ for all } i \]  \hspace{1cm} (18)

\[ \sum_{i=1}^{h} \sum_{j=1}^{m} x_{ijt} \geq 1 \text{ for all } t \]  \hspace{1cm} (19)

\[ x_{ijt} = 0 \text{ if } t < y_i \]  \hspace{1cm} (20)

and \[ x_{ijt} = 0,1 \]  \hspace{1cm} (21)

Where

\( M_{ijt} = \) Annual maintenance cost of safety improvement project \( j \) at location \( i \) for analysis year \( t \)

\( C_{ijt} = \) Initial capital cost of safety improvement project \( j \) at location \( i \) for analysis year \( t \)

\( B = \) Total Budget for analysis period.

Other symbols have their usual meaning.

Equation (16) represents the objective function of the integer program, and is similar to Equation (12). The constraints on the optimal solution are represented by Equations (17) through (21). Equation (17) constrains the total expenditure (initial capital and annual maintenance cost) by the budgetary ceiling over the analysis period. Equation (18) requires that only one safety improvement project (including do-nothing project) should be selected for each candidate location while Equation (19) requires that at least one safety improvement project should be implemented in each year of the analysis period.

3. 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

\[ \sum_{j=1}^{h} \sum_{i=1}^{m} \sum_{r=1}^{p} x_{ijr} E_{ijr} \]  \hspace{1cm} (22)

Subject to

\[ \sum_{i=1}^{h} \sum_{j=1}^{m} \sum_{k=1}^{t} (x_{ijk} C_{ijk}) + \sum_{k=1}^{t-1} ((t-k) x_{ijk} M_{ijk}) \leq \sum_{k=1}^{t} B_k \text{ for all } t \]  \hspace{1cm} (23)

\[ \sum_{j=1}^{m} \sum_{r=1}^{p} x_{ijr} = 1 \text{ for all } i \]  \hspace{1cm} (24)

\[ \sum_{i=1}^{h} \sum_{j=1}^{m} x_{ijt} \geq 1 \text{ for all } t \]  \hspace{1cm} (25)

\[ x_{ijt} = 0 \text{ if } t < y_i \]  \hspace{1cm} (26)

and \[ x_{ijt} = 0,1 \]  \hspace{1cm} (27)
Where the symbols have their usual meanings

Equation (22) is the objective function of this integer program model while the constraints are represented by Equations (23) through (27). Equation (23) constrains the annual expenditure (initial capital and annual maintenance cost) to the annual budget limit plus any excess funds carried over from the previous year. The remaining constraints are similar to those shown in Equations (17) – (21).

For any of the above integer programs, the optimal solution is the set of safety improvement projects and their respective locations and implementation years that provides the maximum economic value subject to the given constraints. The implementation schedule for the safety improvement projects is then prioritized based on the implementation year and the critical value obtained from the procedure where candidate locations were selected. For example, if two safety improvement projects are to be implemented in the same year then the one with the higher critical value is given a higher rank.

7.5.2 Software Package for Indiana Safety Management System (SAFE-MASS)

A safety management system (SMS) software package (with a user interface shown as Figure 7-9) was developed to implement the framework described in the preceding section. The software also addresses other SMS functions such as monitoring historical highway crash trends. This software was developed as a stand-alone program using Microsoft Visual Basic.Net platform. The software uses the OptiMax 2000® component library from Maximal software for the optimization routines which allows Mathematical Programming Language (MPL) models to be seamlessly and directly integrated into object-oriented programming languages such as Visual Basic.

The software was developed using a database of the entire state highway network in Indiana with their corresponding geometric and crash characteristics from 1997 to 2000. The user can select any subset of the state highway network for analysis. Also, additional highway sections can be added to the database. Each of the six procedures described in the framework constitute a module in the software and are executed in that order. The results from any module are used as the input for the subsequent module. However each module can be executed independently from each other. The software also includes defaults 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. All default values can be updated by the user.

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. The software also generates various reports and graphs of the data input and analysis output.
7.5.2.1 Case Study for Network Level Safety Planning using SAFE-MASS

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 using a hypothetical budget ceiling.

(a) Description of Data and Analysis

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.

Ten roadway sections were identified from Step 3 of the framework as candidate locations deserving some safety attention during the analysis period. Eight locations were identified in the first year (2004) and one location each in 2006 and 2007. Table 7-20 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 done for the unconstrained funding and total budgeting scenarios using three different economic evaluation criteria. A lower funding level was applied to the total budgeting constrained optimization scenario to determine the impact on system-wide safety.

Table 7-20: Characteristics of Candidate Locations

<table>
<thead>
<tr>
<th>Section ID</th>
<th>Functional Class</th>
<th>Nr. of Lanes</th>
<th>Average AADT</th>
<th>Average Crash Rate</th>
<th>Avg. Crash Frequency</th>
<th>Critical Value</th>
<th>Critical Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>79-S-025-0-01</td>
<td>UOPA</td>
<td>4</td>
<td>2.4</td>
<td>19458</td>
<td>6.78</td>
<td>48.13</td>
<td>8.789</td>
</tr>
<tr>
<td>79-S-026-0-01</td>
<td>UOPA</td>
<td>2</td>
<td>7.22</td>
<td>28362</td>
<td>4.13</td>
<td>42.73</td>
<td>7.532</td>
</tr>
<tr>
<td>79-S-038-0-01</td>
<td>UOPA</td>
<td>2</td>
<td>1.75</td>
<td>23286</td>
<td>3.7</td>
<td>31.43</td>
<td>5.352</td>
</tr>
<tr>
<td>79-U-052-0-01</td>
<td>UOPA</td>
<td>4</td>
<td>10.44</td>
<td>27924</td>
<td>2.86</td>
<td>29.17</td>
<td>5.238</td>
</tr>
<tr>
<td>79-S-043-0-01</td>
<td>ROPA</td>
<td>2</td>
<td>6.78</td>
<td>6187</td>
<td>3.76</td>
<td>8.48</td>
<td>4.729</td>
</tr>
<tr>
<td>79-S-025-0-02</td>
<td>ROPA</td>
<td>2</td>
<td>9.25</td>
<td>9425</td>
<td>2.28</td>
<td>7.84</td>
<td>3.848</td>
</tr>
<tr>
<td>79-U-231-0-01</td>
<td>UOPA</td>
<td>2</td>
<td>7.98</td>
<td>14741</td>
<td>2.53</td>
<td>13.6</td>
<td>2.968</td>
</tr>
<tr>
<td>79-S-126-0-01</td>
<td>UCOLL</td>
<td>2</td>
<td>1.09</td>
<td>3610</td>
<td>0.7</td>
<td>0.92</td>
<td>2.471</td>
</tr>
</tbody>
</table>
Figure 7-9: Indiana Safety Management System (SAFE-MASS) User Interface
(b) Discussion of Analysis Results

Scenario 1 - Unconstrained Funding Optimization (Needs Assessment):

The unconstrained funding optimization scenario was used to determine the current and future funding needs and the optimum mix and timing of safety improvements projects. The results are summarized as Table 7-21. The funding requirement in each year includes both construction and the maintenance costs of that year’s safety improvement projects. The results indicate a total funding need of $2,539,911 for safety improvements during the analysis period when BCR or CE evaluation criteria is used and $2,845,268 when NPV is used. The results also show the current and future funding needs for each year of the analysis period with the greater part of the needs being required in the first year. As observed, no capital investment is required for the analysis years 2005 and 2008 due to the fact that no candidate locations were identified during these years however maintenance needs for previously installed safety improvement projects still exists.

Table 7-21: Current and Future Safety Funding Needs for Tippecanoe County - Scenario 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Capital Cost</th>
<th>Maintenance Cost</th>
<th>Funding Requirement</th>
<th>Estimated Benefit</th>
<th>Lgth of Rd. Improvement</th>
<th>Total Crashes</th>
<th>System-wide Crash Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>$2,071,238</td>
<td>$0</td>
<td>$2,071,238</td>
<td>$3,422,033</td>
<td>47.25</td>
<td>258</td>
<td>1.173</td>
</tr>
<tr>
<td>2005</td>
<td>$0</td>
<td>$100,643</td>
<td>$100,643</td>
<td>$3,422,033</td>
<td>0</td>
<td>258</td>
<td>1.171</td>
</tr>
<tr>
<td>2006</td>
<td>$40,677</td>
<td>$100,643</td>
<td>$141,320</td>
<td>$3,422,392</td>
<td>0.12</td>
<td>258</td>
<td>1.184</td>
</tr>
<tr>
<td>2007</td>
<td>$20,339</td>
<td>$102,677</td>
<td>$123,016</td>
<td>$3,424,772</td>
<td>0.06</td>
<td>258</td>
<td>1.193</td>
</tr>
<tr>
<td>2008</td>
<td>$0</td>
<td>$103,694</td>
<td>$103,694</td>
<td>$3,424,772</td>
<td>0</td>
<td>258</td>
<td>1.185</td>
</tr>
<tr>
<td>Total</td>
<td>$2,132,254</td>
<td>$407,657</td>
<td>$2,539,911</td>
<td>$17,116,003</td>
<td>47.43</td>
<td>1290</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Capital Cost</th>
<th>Maintenance Cost</th>
<th>Funding Requirement</th>
<th>Estimated Benefit</th>
<th>Lgth of Rd. Improvement</th>
<th>Total Crashes</th>
<th>System-wide Crash Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>$2,362,992</td>
<td>$0</td>
<td>$2,362,992</td>
<td>$3,509,976</td>
<td>48.1</td>
<td>267</td>
<td>1.163</td>
</tr>
<tr>
<td>2005</td>
<td>$0</td>
<td>$115,230</td>
<td>$115,230</td>
<td>$3,509,976</td>
<td>0</td>
<td>267</td>
<td>1.161</td>
</tr>
<tr>
<td>2006</td>
<td>$0</td>
<td>$115,230</td>
<td>$115,230</td>
<td>$3,509,976</td>
<td>0</td>
<td>267</td>
<td>1.174</td>
</tr>
<tr>
<td>2007</td>
<td>$20,339</td>
<td>$115,230</td>
<td>$135,569</td>
<td>$3,512,356</td>
<td>0.06</td>
<td>267</td>
<td>1.183</td>
</tr>
<tr>
<td>2008</td>
<td>$0</td>
<td>$116,247</td>
<td>$116,247</td>
<td>$3,512,356</td>
<td>0</td>
<td>267</td>
<td>1.175</td>
</tr>
<tr>
<td>Total</td>
<td>$2,383,331</td>
<td>$461,937</td>
<td>$2,845,268</td>
<td>$17,554,641</td>
<td>48.16</td>
<td>1335</td>
<td>-</td>
</tr>
</tbody>
</table>

Scenario 2 – Total Budgeting Constrained Optimization (Funding Level = $500,000):

A hypothetical but realistic budget constraint of $500,000 was used for the total budgeting constrained optimization scenario. In using this budgetary constraint, the optimization procedure is forced to select improvements with lower costs and benefits or defer the implementation of some safety projects in order to satisfy the budgetary constraint. Table 7-22 shows the results of this optimization scenario. 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.
Table 7-22: Multi-Year Safety Investment Strategy for Tippecanoe County (Budget = $500,000) - Scenario 2

<table>
<thead>
<tr>
<th>Econ. Evaluation Criterion</th>
<th>Year</th>
<th>Capital Cost</th>
<th>Maintenance Cost</th>
<th>Funding Requirement</th>
<th>Estimated Benefit Improvement</th>
<th>Total Crashes Saved</th>
<th>Crash Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2004</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>0</td>
<td>1.476</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>$110,056</td>
<td>$0</td>
<td>$110,056</td>
<td>$40,525</td>
<td>0</td>
<td>1.462</td>
</tr>
<tr>
<td>Benefit Cost Ratio</td>
<td>2006</td>
<td>$40,677</td>
<td>$5,503</td>
<td>$46,180</td>
<td>$40,884</td>
<td>0.12</td>
<td>1.468</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>$20,339</td>
<td>$7,537</td>
<td>$27,876</td>
<td>$43,264</td>
<td>0.06</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>$266,302</td>
<td>$8,554</td>
<td>$274,856</td>
<td>$3,461,189</td>
<td>41.35</td>
<td>251</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$437,374</td>
<td>$21,594</td>
<td>$458,968</td>
<td>$3,585,862</td>
<td>42.43</td>
<td>263</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>$266,302</td>
<td>$0</td>
<td>$266,302</td>
<td>$3,019,316</td>
<td>43.55</td>
<td>218</td>
</tr>
<tr>
<td>Cost Effectiveness (crashes per $)</td>
<td>2005</td>
<td>$110,056</td>
<td>$10,396</td>
<td>$120,452</td>
<td>$3,059,841</td>
<td>0.9</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>$0</td>
<td>$15,899</td>
<td>$15,899</td>
<td>$3,059,841</td>
<td>0</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>$20,339</td>
<td>$15,899</td>
<td>$36,238</td>
<td>$3,062,221</td>
<td>0.6</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>$40,677</td>
<td>$16,916</td>
<td>$57,593</td>
<td>$3,062,603</td>
<td>0.12</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$437,374</td>
<td>$59,110</td>
<td>$496,484</td>
<td>$15,263,821</td>
<td>42.43</td>
<td>1106</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>2004</td>
<td>$266,302</td>
<td>$0</td>
<td>$266,302</td>
<td>$3,019,316</td>
<td>43.55</td>
<td>218</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>$110,056</td>
<td>$10,396</td>
<td>$120,452</td>
<td>$3,059,841</td>
<td>0.9</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>$0</td>
<td>$15,899</td>
<td>$15,899</td>
<td>$3,059,841</td>
<td>0</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>$20,339</td>
<td>$15,899</td>
<td>$36,238</td>
<td>$3,062,221</td>
<td>0.6</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>$40,677</td>
<td>$16,916</td>
<td>$57,593</td>
<td>$3,062,603</td>
<td>0.12</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$396,697</td>
<td>$58,093</td>
<td>$454,790</td>
<td>$15,261,146</td>
<td>42.31</td>
<td>1106</td>
</tr>
</tbody>
</table>

From the results, a total expenditure of $458,968, $496,484 or $454,790 is required for safety improvements during the analysis period when BCR, CE or NPV is used respectively as the economic evaluation criteria. These funding requirements represent a decrease of 82%, 80% and 84% respectively from that of the needs assessments. As expected the total benefit from this scenario also decreased by 79%, 11% and 13% respectively from that of the previous scenario due to the budgetary constraint. The sharp decrease in benefits when the benefit cost ratio is used compared to the other evaluation criteria can be attributed to deferment of safety improvements in the initial years of the analysis period.

The impact of a lower funding level on annual crash rates can also be obtained by comparison of the analysis results from the two scenarios. This can be used as a guide to determine the optimum funding level that suits an agency’s long term safety goals.
Table 7-23: Optimal Set and Timing of Safety Improvement Projects for Tippecanoe County

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

The framework described in this chapter shows how safety can be proactively incorporated in the short and long range transportation planning programs for state departments of transportation (DOT’s) and metropolitan planning organizations (MPO’s). The procedure identifies 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. It also
estimates benefits and costs of these alternatives and selects an optimal mix and timing of safety improvements for implementation at each candidate location for a given budget constraint 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 DOT or MPO.

7.6 EVALUATION OF OTHER SAFETY PROJECTS

As discussed in the introductory section of this chapter, there are several dimensions in addressing the road safety problem. The approaches for evaluating the impacts of safety investments, as discussed in this chapter, deal primarily and directly with road environment crash factors. The methods may be applicable to the evaluation of enforcement investments or regulatory initiatives such as increased patrols, changed speed limits, stricter DUI laws, etc. However, project specific or systemwide impact evaluation of other safety investments and initiatives such as vehicle related policies (seat belts, air bags, etc.) and operator related policies (age restrictions, etc.) may be carried out using a different approach.
REFERENCES


Brown, H. (1998), Modeling Delay and Safety on Arterial Streets to Evaluate Access Control Alternatives, M.S. Thesis Purdue University, West Lafayette IN.


Forkenbrock, D.J., Foster, N.S.J., Pogue T.F., (1994), Safety and Highway Investments, University of Iowa, Public Policy Center, Midwest Transportation Center, Iowa City, IA.


