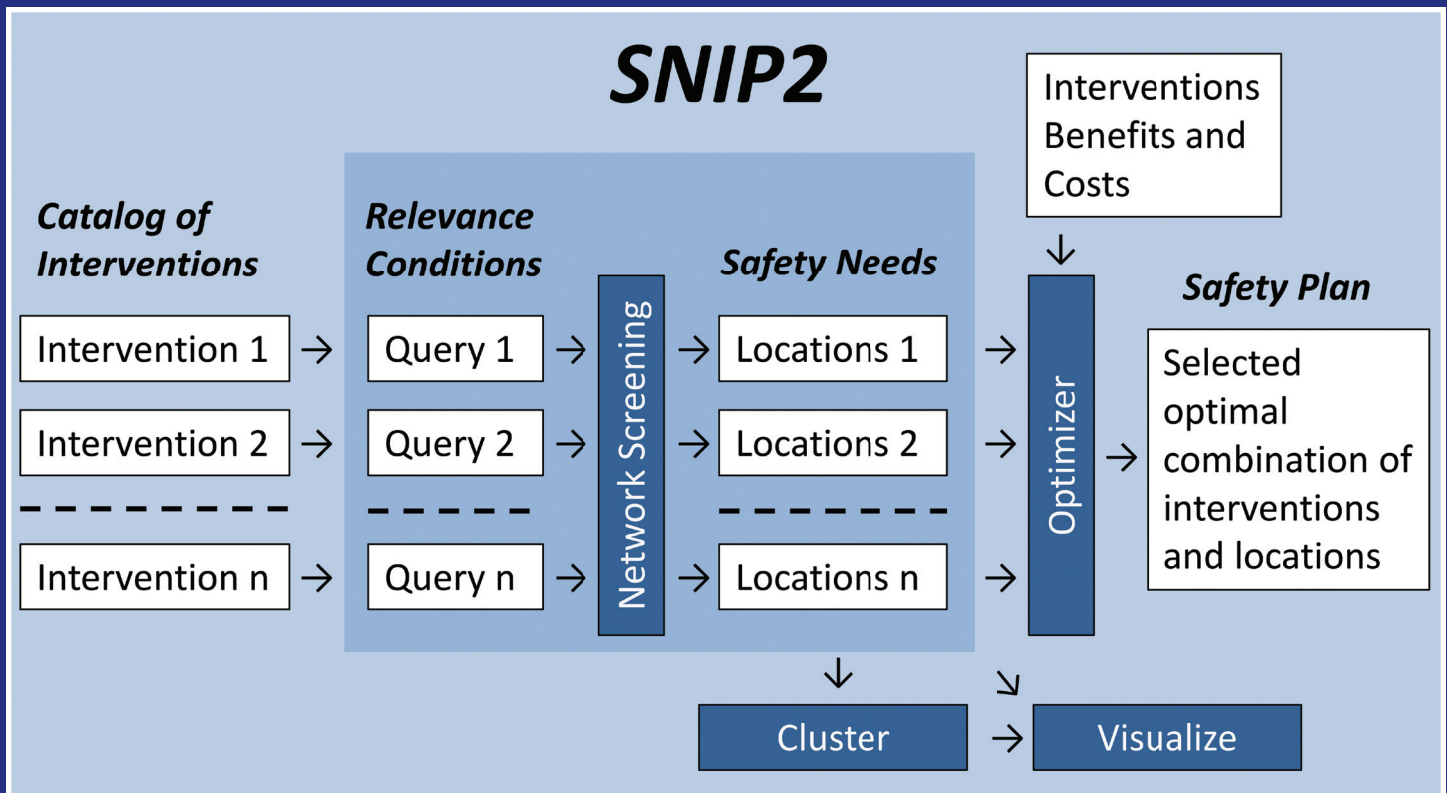


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A Systematic Approach to Identifying Traffic Safety Needs and Intervention Programs for Indiana *Volume I—Research Report*



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| 16. Abstract This report presents the results of JTRP Project “A Systematic Approach of Identifying Safety Intervention Programs for Indiana (SNIP2),” which aimed to develop SNIP2 to support identification of roads that have excessive crashes of the types defined by the user. In addition, this tool is capable of selecting the best combination of high-crash roads and relevant safety interventions that maximizes the safety benefits and keeps the total cost within the budget and other user-defined constraints. Unlike other studies considering the implementation time of safety projects, the optimization objective of SNIP2 is to identify an optimal combination of countermeasures renewable within a long time horizon. This simplification is accomplished by representing the projects through their annualized costs and benefits. It allows consideration of many projects for large road networks and it makes the SNIP2 suitable for identification of safety focus areas in strategic safety plans. The SNIP optimizer – a heuristic approximation of a large-size mixed integer knapsack problem based on a greedy search was extensively tested and evaluated. It was found producing optimal or near-optimal solutions in a sufficiently short time. Another research result is a comprehensive catalog of countermeasures for Indiana – a list of countermeasure names, road and crash conditions for the countermeasure relevance, corresponding crash modification factors, and countermeasure costs. The SNIP2 is computer software developed with close collaboration with the INDOT future users. It includes an updated crash and state road database. A user’s manual describes on the necessary details of the software and various aspects of its use. Two example studies are also included in the manual to illustrate its use and to better presents the SNIP2 features. | | | |
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EXECUTIVE SUMMARY

A SYSTEMATIC APPROACH TO IDENTIFYING TRAFFIC SAFETY NEEDS AND INTERVENTION PROGRAMS FOR INDIANA: VOLUME I—RESEARCH REPORT

Introduction

A systemic approach to identifying road locations that exhibit safety problems was provided by the Safety Needs Identification Program (SNIP) developed by the Purdue University Center for Road Safety (CRS) in 2011. That project aimed to prove the concept of a road network screening method by developing a working prototype tool. This report presents the results of a new JTRP project aimed to develop a next version—SNIP2. As does its predecessor, SNIP2 supports identification of roads that have excessive crashes of the types defined by the user. In addition, this tool is capable of selecting the best combination of high-crash roads and relevant safety interventions that maximizes the safety benefits and keeps the total cost within the budget and other user-defined constraints. SNIP2 can also estimate the cost and the safety effect of a given safety plan.

Findings

- The conceptual framework of the safety screening tool was developed in order to cope with the complexity of the data management and safety screening operations. There are two major components: (1) Data Renewal Process (DRP) and the user-end interface with a computational engine, and (2) a crash and roadway database.
- Unlike other studies considering the implementation time of safety projects, the optimization objective of SNIP2 is to identify an optimal combination of countermeasures renewable within a long time horizon. This simplification is accomplished by representing the projects through their annualized costs and benefits. It allows consideration of many projects in large road networks and it makes the SNIP2 suitable for identification of safety focus areas within a realistic strategic safety plan.

- The optimizer—a new component of SNIP2—applies a greedy search to a heuristic approximation of a large-size mixed integer knapsack problem. The algorithm was extensively tested and evaluated using randomized solutions. The developed algorithm was found producing optimal or near-optimal solutions sufficient for the considered application domain. The algorithm is sufficiently flexible to easily incorporate needed constraints. The time-efficiency meets the user's specifications.
- One of the research results is a comprehensive catalog of countermeasures for Indiana—a list of countermeasure names, road and crash conditions for the countermeasure relevance, corresponding crash modification factors, and countermeasure costs. The developed catalog can be edited and then utilized for developing an Indiana strategic safety plan and for other purposes.
- The SNIP2 runs in the MS Windows XP/Vista/7/8 environment. It requires the MS .NET Framework 4.0, MS SQL Server, and Google Earth or ArcGIS Explorer.

Implementation

The SNIP2 is computer software developed with close collaboration of INDOT future users. It includes an updated crash and state road database. A user manual describes the necessary details of the software and various aspects of its use. Two example studies are also included in the manual to illustrate its use and to better presents the SNIP2 features.

The SNIP2 is a complex tool that requires a careful implementation plan. Its implementation to INDOT's practice includes three phases:

1. Intensive SNIP2 testing by a selected small group of INDOT users (several weeks).
2. One-day workshop organized by INDOT to demonstrate the software through hands-on practice and to identify potential SNIP users.
3. Organization-wide SNIP2 implementation with continuing feedback to the Center of Road Safety.

The Center for Road Safety is involved in all three phases of the SNIP2 implementation by providing requested help, collecting the users' feedback, and implementing the recommendations.

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1. INTRODUCTION

In July 2012, Moving Ahead for Progress in the Twenty-first Century (MAP-21) authorized funding for federal-aid highway projects, highway safety programs, transit programs, and other projects. MAP-21 builds upon and updates a host of highway, transit, bicycle, and pedestrian programs and guidelines that were first established in 1991. Among its provisions, MAP-21 continues the funding of the Highway Safety Improvement Program (HSIP) and sets a streamlined agenda for the purpose of accelerating our nation's efforts in reducing highway fatalities and serious injuries on public roads. The 2010 revision of the Indiana Strategic Highway Safety Plan (SHSP) states that "...the Indiana Strategic Highway Safety Plan identifies critical highway safety problems and opportunities for saving lives, reducing suffering and economic losses resulting from traffic crashes. It also serves to coordinate the traffic safety activities of state agencies, municipal entities and private highway safety organizations." The importance of an integrated approach to traffic safety, data analyses, application of the latest research, and best practices from across the U.S. are emphasized as a means of generating a sound basis and tools for safety management decisions. The strategies in the SHSP emphasis areas were identified in the Indiana SHSP and state agencies (the Indiana Department of Transportation (INDOT), the Indiana Criminal Justice Institute, and the Indiana State Police) continue their efforts to improve road safety in Indiana.

A systemic approach to identifying road locations that exhibit safety problems consistent with the SHSP safety emphasis areas was provided by the Safety Needs Identification Program (SNIP) developed by the Purdue University Center for Road Safety (CRS) in 2011 within Joint Transportation Research Program (JTRP) Project No. SPR-3315. That project aimed to prove the concept of a road network screening method by developing a working prototype tool. This report presents the results of JTRP Project No. SPR-3616, "A Systematic Approach of Identifying Safety Intervention Programs for Indiana (SNIP2)," which aimed to develop a next version of SNIP—SNIP2—that could be fully implemented. As does its predecessor, SNIP2 supports identification of INDOT-administered roads that have excessive crashes of the types defined by the user. In addition, this tool needs to be capable of selecting the best combination of high-crash roads and relevant safety interventions that maximizes the safety benefits and keeps the total cost within the budget and other user-defined constraints. For that purpose, SNIP2 encompasses the concepts developed and tested in SNIP as well as a new module that facilitates selection of the most cost-effective combination of road locations and safety countermeasures. The Indiana local roads are not included in the current tools because data available for these roads at the system level are currently insufficient.

This report presents the SPR-3616 research effort and its outcome pertaining to the new elements of

SNIP2. More details regarding SNIP can be found in the past report on SNIP (Tarko et al., 2011). The second volume of this report, "SNIP2 User Manual," explains how to use the tool.

2. SNIP CONCEPTS

SNIP2 includes two major components:

1. The Data Renewal Process (DRP) that prepares the updated SNIP2 database (Figure 2.1).
2. The SNIP2 tool including the user's interface and the up-to-date database (Figure 2.2).

The DRP is performed on a regular basis, most typically once a year, by a dedicated team in charge of maintaining the SNIP2 in an up-to-date version.

The SNIP2 tool is a computer application that supports the following four operations (see Figure 2.2):

1. Identification of high-crash road elements (segments, intersection, and ramps) that exhibit excessive numbers or proportions of crashes of a type defined by a user,
2. Clustering the identified high-crash road elements into larger sections that exhibit similar safety needs.
3. Visualization of the individual road elements and road clusters on digital maps, and
4. Selection of the most cost-effective combination of road elements and safety countermeasures according to the user-defined budget and other constraints.

2.1 Data Renewal Process

The Data Renewal Process (DRP) includes updating the existing data by reaching to sources for new data, reformatting them to meet the standards of the CRS database (called also master database), integrating these data into tables that meet the master database specifications, and replacing the existing data. These new formatted and integrated data are then post-processed to prepare them for use by the network safety screening tool. The data maintenance is facilitated by a suite of procedures developed by the CRS or available in ArcGIS. The data updating may be performed annually or when a major change of data at any of the data sources occurs to reflect these changes to the screening process.

The DRP facilitates the updating of the GIS and non-GIS data in a convenient and short time. The data management procedures include ArcGIS geo-processing and VBA-implemented and Model Builder codes that are not packaged as a single module, but rather which are used separately as needed to maintain the flexibility of the data management process. The DRP acquires data from the sources, reformats and pre-processes it, and links it together. This procedure is presented in Tarko et al. (2011).

2.2 Road Network Screening

The Road Network Screening module facilitates screening of road elements to identify high-crash locations. A

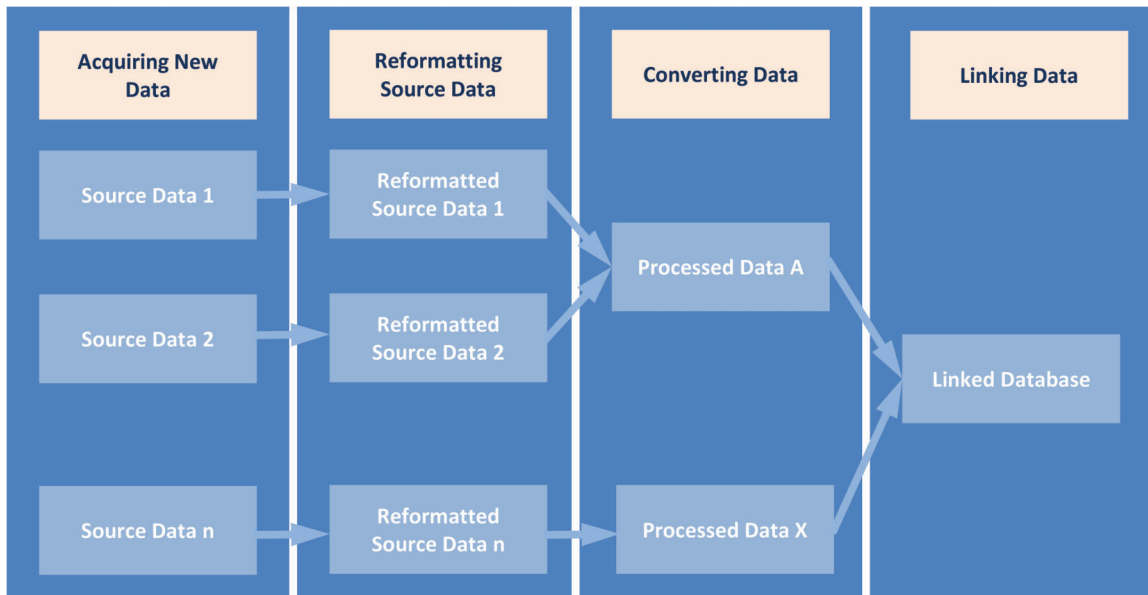


Figure 2.1 SNIP Data Renewal Process.

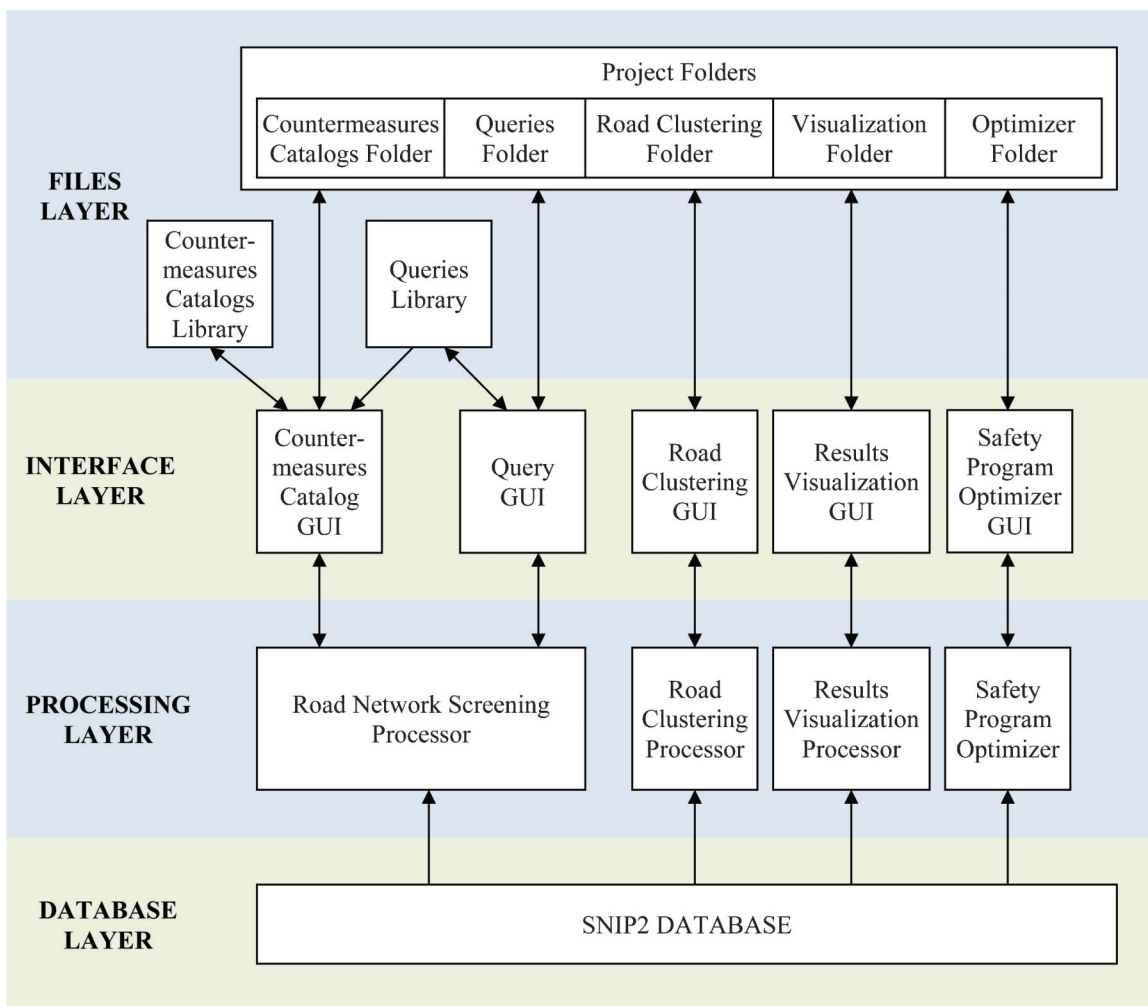


Figure 2.2 SNIP2 architecture.

road location is a road intersection, an interchange roadway segment, a road segment or a ramp. A *road intersection* is a portion of the roads within the intersection impact zone. The intersection center is defined as a point, and the 250-foot segments adjacent to the intersection point define the intersection impact zone. A *road interchange* is a portion of the roads within the interchange impact zone. The interchange impact zone consists of freeway and non-freeway segments. For freeway segments the interchange zone extends 1500 ft beyond the farthest merging or diverging point. The non-freeway segments extend 250 ft beyond the farthest merging or diverging point. A *road segment* is a road stretch between the intersection/interchange impact zones. Long road segments are divided into smaller parts to allow more specific location with safety needs (such as curves). Rural segments longer than 0.5 mile are divided into sub-segments whose lengths are as close to 0.5 mile as possible. Urban road segments longer than 0.25 mile are divided into sub-segments whose lengths are as close to 0.25 mile as possible. A *ramp* is the part of interchange that permits traffic from one highway to pass through the junction without directly crossing the other traffic stream.

The Road Network Screening module facilitates building Queries and Countermeasures Catalogs and performs screening tasks that identify crashes and road elements that meet the query criteria. For example, the user may need a list of rural road segments with narrow shoulders that are experiencing a considerable number of severe single-vehicle crashes in order to identify locations where widening shoulders might be justified. The Queries and Catalogs built by the user are saved in a Project Folder for later project continuation. The user also has an option of saving the Queries and Catalogs to Libraries to be used in other future projects. The Road Network Screening Processor executes the screening task by accessing the SNIP2 Database and searching for crashes and roads according to a query currently in use; and the results of the screening task are saved in the Project Queries Folder. These results can be then accessed by other SNIP2 processors (clustering, visualization, and optimizer). The screening method has been modified and is described in Appendix A.

2.3 Road Clustering

Road segments and intersections that exhibit an excessive number of crashes may be concentrated along longer road sections. The clustering module builds a cluster starting with the road element which has the strongest evidence of high-crash situation. The algorithm allows adding a road element if to the current cluster if: (1) the element is adjacent to the currently built cluster, (2) it has sufficiently high confidence that it experiences too many crashes. When no additional element can be added to the cluster, the clustering tool stops building the current cluster and searches for a next road element suitable to build a new cluster. The

clustering ends when no suitable road elements can be found. The user can restrict the clusters building only along the same routes to follow the common practice in scoping road studies.

Clustering road elements can reveal large scale safety issues that otherwise might be overlooked if the screening analysis is focused on individual spots. For example, clustering segments with excessive numbers of rear-end crashes may reveal a spill-over safety effect that originated at a signalized intersection with a capacity shortage or where traffic signals are poorly coordinated. Similarly, clustering smaller geographic units, such as townships, with a particular safety problem (e.g., speeding) can help identify larger areas where police enforcement or campaigning might be beneficial.

Clustering state road segments and intersections along state routes can help INDOT identify parts of corridors that require certain road improvements from a safety standpoint. These clusters might be found useful in scoping such projects. This procedure is presented in more detail in Tarko et al. (2011) and also shown in Appendix B.

2.4 Results Visualization

The road network screening module saves the results of a query in a tabular format convenient for clustering and for additional processing as needed. The final results may also be displayed on GIS maps to visualize the spatial distribution of the identified roads. Such visualization is beneficial in presenting the results to decision-makers and to identify spatial pattern not detectable otherwise. Since the identified road components are geo-coded with the respective latitude and longitude, they can be visualized with the display features offered by Google Earth and ArcGIS. This procedure is presented in more detail in Tarko et al. (2011) and also shown in Appendix C.

2.5 Safety Program Optimizer

The user has an option of developing a list of road elements and relevant safety countermeasures for these roads that maximize the safety benefit within a pre-selected budget level. The primary input to the optimization is a user-defined or selected Countermeasures Catalog. The catalog includes all the specific countermeasures to be considered. The catalog also includes for each countermeasure the following inputs: queries that yield the relevant road segments, Crash Modification Factors (CMFs) to evaluate the safety benefit of the countermeasure applied to a relevant road element, and unit costs needed to estimate the countermeasure's implementation cost. The estimated benefits and costs are annualized. The optimizer selects the pairs of countermeasures that correspond to the road elements to maximize the overall benefit within the assumed budget. The results are saved in the Optimizer Folder as a list of road elements with applied countermeasures and

corresponding economic benefits and costs together with summarized economic indicators.

The Road Network Screening, Road Clustering, and Results Visualization modules are described with more details in Tarko et al. (2011). The companion volume provided together with this report, the User Manual, describes the details of a new Graphical User Interface developed for SNIP2 which provides more convenience and flexibility in building and performing queries. The Manual also describes the Data Renewal Process.

The remainder of this report focuses on the new component of the SNIP—the Optimizer—and its needed inputs: the CMFs and the unit costs of the safety countermeasures.

3. DATA MANAGEMENT

3.1 Data Sources

The **road network** representation is a “spatial backbone” of SNIP. The data consist of polylines that represent road segments. Intersections were added through processing the initial network shape file and the associated segment data.

The **Indiana road inventory** provides geometric data, including the number and width of lanes, the type and width of shoulders, the type and width of medians, the Annual Average Daily Traffic (AADT) and other pieces of information.

Ramp data are present in the Indiana road inventory. The ramp data found in the Indiana road inventory have been used due to its better quality and particularly due to its higher level of completeness.

Bridge data are extracted from the National Bridge Inventory (NBI) online database (<http://www.fhwa.dot.gov/bridge/nbi/ascii.cfm>). This dataset is in a tabular

format and includes the coordinates for the bridge center points.

County, township, and city/town boundary shape files are available at the Indiana Map website (<http://www.indianamap.org>). The Indiana Map is a collaborative effort of the Indiana Geographic Information Office (GIO), the Indiana Geographic Information Council (IGIC), the Indiana Department of Transportation (INDOT), the Indiana Geological Survey (IGS), the University Information Technology Services (UITS) of Indiana University, and other federal, state, and local partners. However, these databases require additional information from other sources. Land-use, demographics, and employment data are integrated by spatially joining the Traffic Analysis Zone (TAZ) level information, which is available from the Modeling and Forecasting Section of INDOT, with the township and county information. This type of integration from smaller to larger aggregation levels help in the integration of the necessary exposure variables for crash screening. For example, the number of registered vehicles was an exposure condition to conduct crash rates based on safety screening. Since this information was available in the TAZ data, it was aggregated to a higher geographic unit, city, or township by spatial join. A list of all the important basic data collected for building the master record sets is shown in Table 3.1.

Crash data from Indiana State Police provides detailed crash information including locations, vehicles involved, drivers, injured people, weather and road conditions, and contributing circumstances.

All the sources with GIS coordinates should have a unique coordinate system to maintain the consistency of the spatial relations. In this case, the Universal Transverse Mercator (UTM) North American Datum (NAD) 1983 zone 16 was the coordination system for

TABLE 3.1
Data sources for safety screening tool

| Component Dataset | Contents | Source | Derivative Database |
|---|--|---|--|
| Road network | Roadway network | INDOT | Intersection points layer |
| Indiana road inventory | Geometric information such as lanes, median, shoulder; pavement data such as roughness or rutting and AADT (adjusted/total counts) | INDOT | Ramp layer |
| Traffic counts | Traffic counts (not adjusted) | MPOs or local transportation agencies (collected as part of other CRS projects) | |
| Bridge data | Bridge geometry information; condition indices; construction and maintenance data such as year of construction, maintenance date, etc. | National Bridge Inventory (NBI) online source (http://www.fhwa.dot.gov/bridge/nbi/ascii.cfm) | Bridge GIS layer |
| INDOT traffic controllers maintenance layer | Traffic controllers location and type | INDOT | n/a |
| Land-use and demographic data in traffic analysis zones (TAZ) | Employment by types, industry profile, demographic profile, and population (from 2000 census) | Modeling and Forecasting Section, INDOT | Aggregated information into city, townships, and county levels |
| County, township and city boundary layer | Name, geographic extent, and IDs | Indiana maps (http://www.indianamap.org/) | |
| Crash data (2003–2012) | Collision, unit, operator information, etc. | Indiana State Police | n/a |

the network layer and hence all other shape files. Any shape files in different coordinate systems were converted to this particular datum.

3.2 Data Preprocessing

3.2.1 Adjusting AADT

AADT values in the Indiana road inventory database are provided for the years when traffic was measured. AADT values for other years were estimated by interpolation between the AADTs for earlier and later years. If the AADT was known only for the earlier year or only for the later year, then the annual traffic growth factors recommended by INDOT were used.

Some roads had 24-hour traffic counts with the date of traffic measurement. These counts were converted to the AADT by applying proper conversion factors that accounted for weekly and monthly traffic variability on various types of roads (values recommended by INDOT).

3.2.2 Preprocessing of the Road Network Layer

As discussed earlier, the Indiana road inventory layer does not contain information about intersections so it was necessary to create intersections by processing the road network shape file and the bridge data. Also, it was important to consider generic classifications that are already utilized by INDOT.

Long road segments are divided into smaller pieces to allow more specific location of the segments with safety needs. Rural segments longer than 0.5 mile are divided into sub-segments whose lengths are as close to 0.5 mile as possible. Urban road segments longer than 0.25 mile are divided into sub-segments whose lengths are as close to 0.25 mile as possible.

Preprocessing the network involves certain operations on the shape file to make it ready for data integration. Therefore, only roads with a value of 1 on the system variable were selected, but all segments were

used to create the intersection layer. Table 3.2 shows the basic roadway segments and intersection types.

3.2.3 Creating Intersections

Since information about intersections is not available, it was necessary to create a process that identifies intersections. The steps to create the intersections layer are explained in Table 3.3. A total of 1,075 and 23,441 state-state and state-local intersections were created, respectively.

3.3 Preparing the Road Network

3.3.1 Splitting Segments

Splitting long segments into short pieces of uniform length is needed for more precise identification of locations with safety issues. Before the splitting process was performed, the network needed to be “un-split” by using the GIS geo-processing tool that avoids combining segments of different names and different types. This step ensured reasonable homogeneity of the combined segments and avoided segment identification problems. Then, the combined segments, most of which start and end at intersections, were split into shorter element segments using the rules in Figure 3.1. The *round* operation is the standard rounding rule applied to zero decimal digits after rounding.

3.3.2 Linking Geographic Areas

Each network element (segment or intersection) is linked to several types of geographic areas such as county, township, or city/town, based on its inclusion inside the geographic area. All elements were connected to a specific township or county, and only those elements within the geographic jurisdiction boundaries of a city/town were connected to the corresponding city/town.

TABLE 3.2
Basic segment and intersection types

| Segment Type | Segment Code | Intersection Type | Intersection Code |
|-------------------------------|--------------|--------------------------------|-------------------|
| Rural two-lane | 1 | Rural state intersection | 1 |
| Rural multilane | 2 | Rural state-local intersection | 2 |
| Rural interstate | 3 | Urban state intersection | 3 |
| Urban multilane | 4 | Urban state-local intersection | 4 |
| Urban two-lane | 5 | | |
| Urban freeway | 6 | | |
| Urban one-way | 7 | | |
| Rural interchange freeway | 8 | | |
| Rural interchange non-freeway | 9 | | |
| Urban interchange freeway | 10 | | |
| Urban interchange non-freeway | 11 | | |
| Ramp, loop, other | 13 | | |

TABLE 3.3
Creating intersection process

| Process | Input | Tools | Output |
|------------------------------------|---|---|--|
| Split polylines | INDOT inventory layer | Data management tools features feature to line | Road layer split at any intersecting point |
| Create end points | Road layer split at any intersecting point | Data management tools features feature vertices to points | End point layer |
| Detect duplicate segments | End point layer | Excel find all segments with the same start and end point coordinates | List of segments to be removed |
| Remove duplicated segments | Road layer split at any intersecting point list of segments to be removed | Link select | Single segment layer split at any intersecting point |
| Create possible intersection layer | End point layer | Remove duplicated points | Possible intersection layer |
| Remove bridges | Possible intersection layer bridges layer | Overlay | Possible intersection layer |
| Remove merges on freeways | Possible intersection layer INDOT inventory layer | Overlay | Intersection layer |
| Assign intersection attributes | Intersection layer INDOT inventory layer | Overlay summary statistics frequency | Intersection layer |
| Traffic control | Intersection layer INDOT traffic controllers maintenance layer | Overlay | Intersection layer |

3.3.3 Updating Intersection Layer

After integrating the network with the geographic areas, many attributes related to roadway geometry and traffic counts, such as median, shoulder, or AADT information, also were brought in as attributes of the segments. Therefore, it was necessary to update or bring new information to the intersection layer. Intersection link information was obtained by using the ArcGIS geo-processing tool “generate near table.” A very small buffer radius was used (e.g., < 1 ft) for the geo-processing tool so that only the adjoining segments were considered to form the near table. After running this operation, each intersection ID was referenced to the adjoining segment IDs. Once the near table was generated, each intersection could be associated with the adjoining segments to receive the required information. Major and minor road AADTs were determined based on averaging the link AADT values for a particular roadway. Also, information about medians, shoulders, etc. was integrated with the intersection. Finally, the signalization information was obtained from the INDOT traffic controllers maintenance layer. The following attributes were updated or added as part of this operation: link names, link IDs, major road AADT, minor road AADT, control type (signalized or not), number of legs.

3.3.4 Crash Assignment

Crashes were assigned to roads by considering the crash attributes and the proximity to particular segments and intersections. The proximity-based method included: (1) finding nearby road elements to the crash location based on the coordinates from the police report; (2) matching the characteristics between the road network and the police reports; and (3) road element selection. The crash assignment method is discussed below.

Convert crash records to a shape file. The latitude and longitude values of crash locations found in the electronic crash records were imported to ArcGIS. Using the ArcGIS geo-processing tool called “Display XY data,” all crashes having valid coordinates were displayed on an ArcGIS map. The point display file was then exported to a shape file. The new shape file was then projected against the segment and intersection shape file. After this operation, crash shape files for each year (2003 to 2012) containing the collision information were generated.

Nearby road elements. The road network GIS layers, along with all the crashes, were plotted in GIS. A proximity tool, “Near Table” in ArcGIS, is used to identify crashes that are within 250 feet of each intersection. At the most, four elements of each type were identified as potential candidate elements for each crash and moved to the matching process.

Matching score. Four types of elements are considered: road segments, intersections, interchanges, and ramps. For each element type, different verification criterion is applied to score the matching between police reports and element characteristics.

- **Ramps:** The following matches are required for verification purposes:
 - Road names using soundex1 procedure
 - Jurisdiction
- **Interchanges:** The following matches are required for verification purposes:
 - Road names using soundex1 procedure
 - Jurisdiction
 - Functional classification
- **Intersections:** The following matches are required for verification purposes:

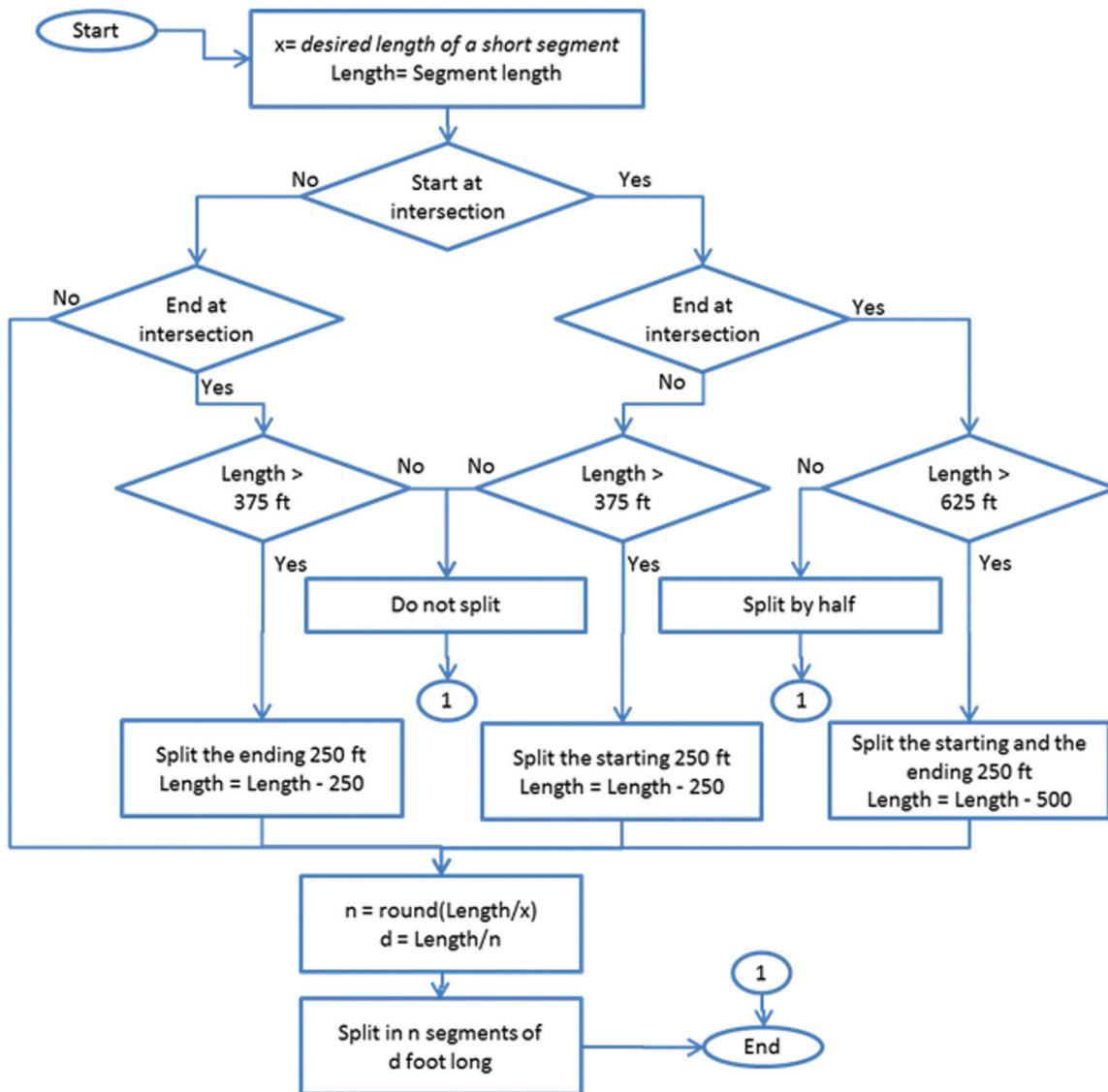


Figure 3.1 Segment splitting rules.

- Road names using soundex1 procedure for all road names
 - Jurisdiction
- *Segments*: The following matches are required for verification purposes:
 - Road names using 1-soundex procedure (1-soundex converts an alphanumeric string to a four-character code that is based on how the string sounds when spoken)
 - Jurisdiction
 - Functional classification

Road element selection. Once all potential candidates are scored, each road element type is sorted by its best score and distance. If the police report indicates a ramp, the best scored ramp is selected. If the police report indicates any type of intersection, the best scored intersection is selected. All unassigned crashes are then assigned to segments, interchanges, or ramps based on the minimum distance. All crashes assigned to an intersection leg are moved to the adjacent segment. If there is no adjacent segment, then the crash is assigned to the intersection.

Additional comments are given below to better understand the crash-road assignment method.

The most important criterion is the coordinates recorded in the crash data.

Road names are available from the crash data as well as in the GIS layers. If the road name could be matched between these two data sources, it could provide very good confidence (1,000 points). The names are matched using the *Soundex* procedure to avoid misspelling problems.

County ID and township ID are also used to verify the assignment. However, for some roads or intersections (e.g., all county line roads), they are at the border and the ID might not match. Also, for the township ID, police officers may not have a very good idea about township; thus, this variable only provides limited information (100 for county ID and 10 for township ID).

TABLE 3.4
Road classification criteria

| Road Classification in Road Network | | Road Classification in Crash Dataset | | | | |
|-------------------------------------|--------------------------|--------------------------------------|----------|------------|-------------|-----------------|
| | | Interstate | US Route | State Road | County Road | Local/City Road |
| Rural System | Interstate | 100 | 50 | | | |
| | Principal arterial | 50 | 100 | 100 | | |
| | Minor arterial | | 100 | 100 | | |
| | Major collector | | 50 | 100 | 100 | 100 |
| | Minor collector | | | 50 | 100 | 100 |
| | Local | | | | 100 | 100 |
| Urban System | Interstate | 100 | | | | |
| | Other Freeway/expressway | 100 | 50 | | | |
| | Principal arterial | | 100 | 100 | 50 | |
| | Minor arterial | | 100 | 100 | 100 | 100 |
| | Collector | | | | 100 | 100 |
| | Local | | | | 100 | 100 |

TABLE 3.5
Crash assignment summary for state road system

| Year | Segments | Intersections | Ramps | Total |
|------|----------|---------------|-------|-------|
| 2003 | 27775 | 17929 | 3617 | 49321 |
| 2004 | 27752 | 18243 | 3811 | 49806 |
| 2005 | 27278 | 16067 | 3006 | 46351 |
| 2006 | 24871 | 13816 | 2311 | 40998 |
| 2007 | 29110 | 15394 | 2172 | 46676 |
| 2008 | 32825 | 16219 | 3549 | 52593 |
| 2009 | 29309 | 14970 | 2826 | 47105 |
| 2010 | 24159 | 18926 | 2378 | 45463 |
| 2011 | 25575 | 19548 | 3683 | 48806 |
| 2012 | 24927 | 20722 | 3983 | 49632 |

Finally, the road's functional class is used for assignment. Although it is likely for police officers to mix some categories (e.g., Arterial versus Collector), the functional class could still provide very useful information; for instance, if a crash is recorded between a freeway and a parallel local street, the functional class could tell the difference even without the identification of road names. The matching criteria used are shown in Table 3.4.

The detailed descriptive statistics of crashes assigned to different roadway elements are shown in Table 3.5.

It is important to mention that local crashes are not taken into account in the above data and the corresponding percentage of assigned crashes is near 70%.

3.4 Preparing Final Dataset for Interface

In the last phase of the data preparation, a SAS script merges the crash data to their respective assignments to the different types of infrastructure elements. Further processing of the crash data expands the number of variables available for screening. Finally, the crash and element variables are renamed to conform to the screening component requirements. The resulting crash, segment, and intersection tables are then transferred to the SQL server SNIP2 database and are ready to be accessed by the SNIP2 screening component. The relational database structure of the master record datasets is shown in Figure 3.2.

Master Record Datasets Structure

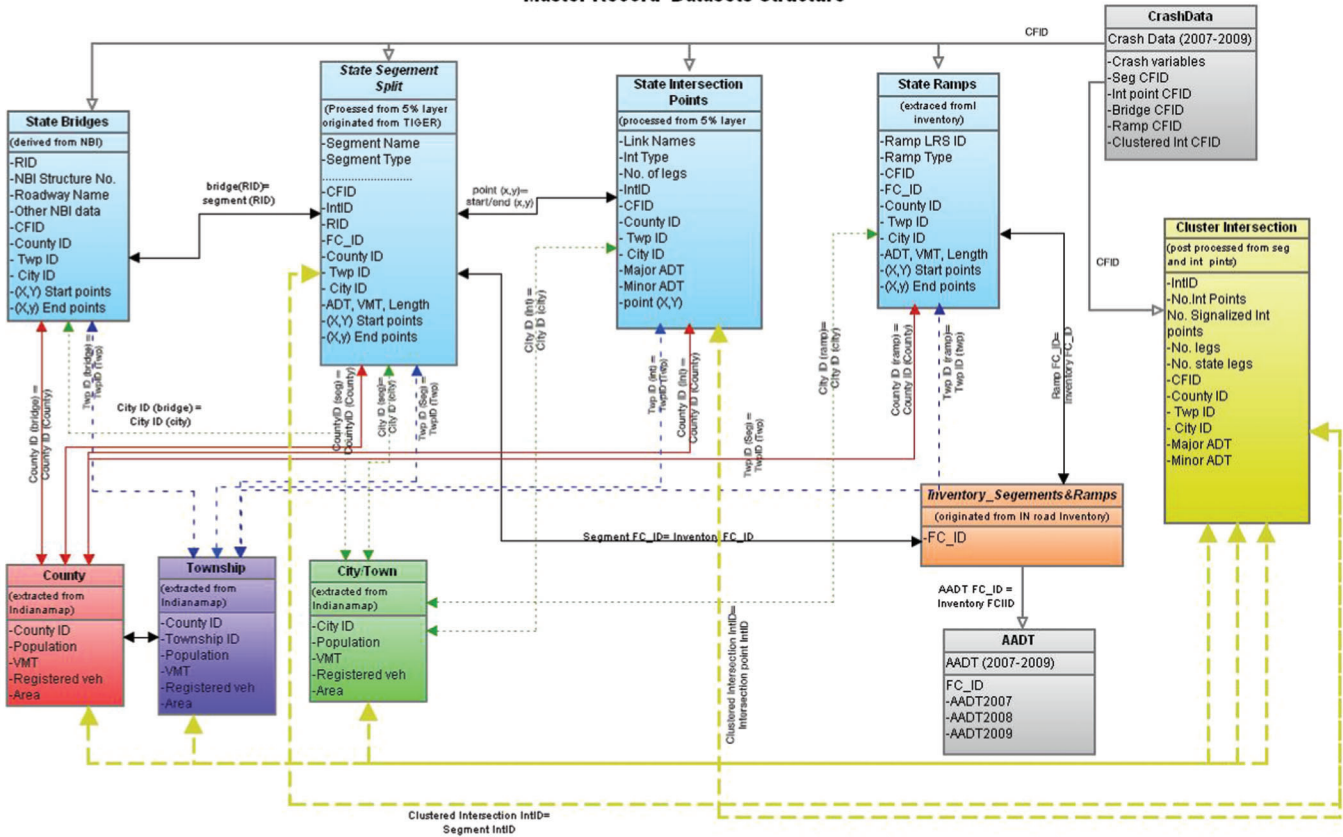


Figure 3.2 Dataset structure for the screening tool.

4. INPUTS TO THE OPTIMIZATION MODULE

4.1 Crash Modification Factors

The commonly-used and practical method of quantifying the safety benefit is the Crash Reduction Factor (CRF), which represents the expected number of crashes saved as a result of the improvement. Typically, CRFs are available for different severity levels and sometimes for certain types of crashes (target crashes). Recently, so-called Crash Modification Factors (CMF) have been introduced and they are used interchangeably with the CRFs. The relation between the two factors is: $CMF = 1 - CRF/100$ where CRF is expressed in percentages while the CMF is a proportion and it has no units. The primary source of CMFs (or CRFs) is the Crash Modification Factors Clearinghouse website supported by the Federal Highway Administration.

4.1.1 Literature Review

NCHRP 500 series reports provide guidance for the implementation of the AASHTO Strategic Highway Safety Plan. This is a series in which relevant information is assembled into single concise volumes, each pertaining to specific types of highway crashes (e.g., run-off-road) or contributing factors (e.g., aggressive driving). Other research studies are summarized below.

Mauga and Kaseko (2010) developed statistical models that related access management (AM) features

with traffic safety in midblock sections of street segments. The objective of the study was to evaluate and quantify the impact of the AM features on traffic safety in the midblock sections. A cross-sectional regression model was used to determine that segments with raised medians had lower crash rates by 23% compared to segments with Two-Way Left-Turn Lanes (TWLTLs) in urban area for all crash severities and 21%, 21%, and 33% for KA, BC, and O respectively.

Elvik and Vaa (2004) suggested installing a queue warning changeable countermeasure to reduce rear-end crashes. Meta-analysis was used in the study, and the author showed that this intervention could reduce KA and BC crashes by 21% in both urban and rural areas, but could increase O crashes by 16% for both areas. Tarko et al. (2007) proposed to reduce the degree of horizontal curvature; after performing a regression model, four different equations yielded the CRFs for KA, BC, and O for rural areas.

The addition of lighting at intersections was studied by Donnell et al. (2010), which produced a framework to estimate the safety effects of fixed lighting at a variety of intersection types and locations. A sample framework was demonstrated using Minnesota intersection data; and the results indicated a much lower overall safety benefit from lighting than the previous published studies; the CRF was approximately 8% in both urban and rural areas, which was consistent with the estimates included in the Highway Safety Manual research.

In terms of intersection geometry, Harwood et al. (2003) presented the results of research that performed a well-designed before-after evaluation of the safety effects of providing left- and right-turn lanes for at-grade intersections. The types of improvement projects evaluated included installation of added left-turn lanes, added right-turn lanes, and extension of the length of existing left- or right-turn lanes. An observational before-after evaluation of these projects was performed using several alternative evaluation approaches. The research concluded that the Empirical Bayes method provided the most accurate and reliable results and showed the CRFs for different severities in urban and rural areas.

Lu, Dissanayake, Zhou, and Yang (2001) evaluated the safety and operational impacts of two alternative left-turn treatments from driveways/side streets. The two treatments were direct left-turns and right-turns followed by U-turns. Safety analyses of the alternatives were conducted using two major approaches: traffic crash data analysis and conflict analysis. The results showed that replacing direct left-turns with indirect left-turns could decrease all crashes for KA and BC by 43%, 20% for O, and 28% for all types of crashes in urban and rural areas. Further, this replacement specifically could reduce rear-end crashes by 13% and angle crashes by 35%. Schoon et al. (1994) proposed the countermeasure of converting intersections to roundabouts. The before-and-after method was applied in the study, and they found it reduced 65% of the crashes for KA and BC in urban and rural areas and 42% of the O crashes in both areas. Monsere et al. (2006) indicated that applying CRFs for sight distance improvement reduced approximately 11% of crashes in rural areas.

Fitzpatrick and Park (2010) evaluated the safety effectiveness of the high-intensity activated crosswalk (HAWK) device; before-after evaluations compared crash predictions for the after period (which assumed the treatment had not been applied) to the observed crash frequency for the after period (with the treatment installed) using an empirical Bayes (EB) method. The results showed that there was a 29% reduction in total crashes, a 69% reduction in pedestrian crashes, and a 15% reduction in severe crashes. Gan et al. (2005) concluded that constructing pedestrian bridges or tunnels can reduce pedestrian-related crashes by 86% in urban areas; and installing sidewalk could result in a 74% reduction in pedestrian-related crashes in urban areas.

Park and Saccomanno (2005) evaluated the relationship between countermeasures and collision occurrence at railroad at-grade crossings by using a sequential analytic strategy that combined the tree-based data stratification method with the generalized linear regression technique. They concluded that there was an 87% reduction in crashes in urban and rural areas; and implementing a grade-separated crossing could avoid 100% of crashes. The Illinois Department of Transportation initiated the Highway Safety Improvement Program (HSIP) in 2006, and they found that eliminating grade railroad crossings completely eliminated crashes in both urban and rural areas.

Elvik and Vaa (2004) introduced the intervention of installing guardrails to prevent run-off road crashes. Their meta-analysis indicated a 43% reduction in KA crashes in urban and rural areas and a 17% reduction in BC crashes in both areas for all type of crashes; in terms of run-off-road crashes, KA and BC were reduced by 44% and 47%, respectively, in both urban and rural areas. According to a cable median barrier report created by the Minnesota Department of Transportation (2010), cable median barriers can reduce fatal crashes by 90 percent. Adding a flattening crest of curve, according to Hovey and Chowdhury (2005), can reduce crashes by 51% and 20% for KA and BC, respectively, in urban and rural areas.

Persaud et al. (2003) studied adding centerline rumble strips and concluded they could reduce approximately 15% and 14% of BC and all types of crashes, respectively, in rural areas. When shoulder rumble strips were added, there were 13% and 18% crash reductions related to BC and all types of crashes, respectively, in both urban and rural areas. Traffic calming and speed limit countermeasures are applicable to Indiana; and according to Elvik and Vaa (2004), Park, Park, and Lomax (2010), and Parker (1997), in urban areas, a 16% crash reduction for KA, 24% for BC, 10% for O, and 18% for all types of crashes were possible.

Widening shoulders is applicable in Indiana; and according to Tarko et al. (2007), different equations can be applied to calculate CRFs for shoulder widening. Elvik and Vaa (2004) and Montella (2009) reported that installing a combination of chevron signs, curve warning signs/advisory speed signs, and sequential flashing beacons could reduce KA, BC, and all types of crashes by 24%, 51%, and 34% respectively, in both urban and rural areas.

Retiming signal change intervals to ITE standards can be applied in Indiana; and according to Retting et al. (2002), there was a 12% crash reduction for BC and 8% for all type crashes in both urban and rural areas. However, there appeared to be an increase in rear-end crashes. Increasing the visibility of signals could also reduce crashes according to Srinivasan et al. (2008), Sayed et al. (2005), and Sayed et al. (2007), where an 8% reduction for all types of crashes in urban areas was reported and a 3% reduction in rural areas. Changing from permissive or permissive/protected to protected-only phasing could reduce all types of crashes by 1% and left-turn crashes by 99% in urban area according to Harkey et al. (2008). In NCHRP Report 500, installing new flashers could reduce all types of crashes by 30% in both urban and rural areas. The Illinois Department of Transportation, in their Safety 1-06 Highway Safety Improvement Program, reported that new signal installations could reduce all types of crashes by 30%, right-angle crashes by 67%, and rear-end crashes by 38% in both urban and rural areas. According to Tan (2010), re-striping four-lane undivided to two-lane with bicycle lanes could reduce all type of crashes by 29% in both urban and rural areas.

4.1.2 Proposed Countermeasures and Crash Modification Factors

After reviewing the past literature including NCHRP reports, JTRP reports, and the CMF clearinghouse website, a first draft catalog of safety countermeasures was completed and sent to the INDOT SAC members for review. The SAC members provided feedback by deleting some safety countermeasures which were not applicable to Indiana and adding some additional safety countermeasures which should be considered in Indiana. Also, they provided the capital cost for each safety countermeasure if implemented in Indiana. The catalog of safety countermeasures was finalized according to the comments and recommendations from SAC members, and the conditions of each safety countermeasure were defined.

The first draft of the safety countermeasures was based mainly on information from the CMF Clearinghouse website. There are many safety countermeasures listed at the CMF website and the criteria for selecting those that are appropriate for Indiana are:

1. Only those countermeasures that had a 3-star quality rating or above were selected. The star rating indicates the quality or confidence in the results of the study producing the CRF. The star rating is based on a scale (1 to 5), where 1 indicates the lowest or worst rating, and 5 indicates the highest or best rating. The CMF Clearinghouse review process rates the CMF according to five categories—study design, sample size, standard error, potential bias, and data source—and judges the CMF according to its performance in each category. It assigns a star rating based on the cumulative performance in the five categories. Only those countermeasures that were applicable in Indiana were selected. Different states have different conditions; and only the countermeasures that are applicable in Indiana were selected based on the judgment of INDOT experts.
2. The questionnaire to INDOT experts was distributed and is shown in Appendix B. This survey was the vehicle for INDOT experts to provide comments on the countermeasures list, such as deleting or adding some safety countermeasures where appropriate.
3. Based on the feedback, the final list of safety countermeasures was developed, which included 30 safety countermeasures grouped in 14 categories as shown in Table 4.1.

Once the final safety countermeasures list applicable for Indiana was developed, the CRFs for each countermeasure were calculated using the following procedure:

1. Based on the CMF Clearinghouse website, countermeasures below 3-star quality were deleted.
2. Then weighted average CRF was calculated based on its star quality.

4.2 Cost of Safety Countermeasures

Another important input to the SNIP2 Optimizer is the capital cost figures for all safety interventions, and more accurately, the unit costs per item or mile. Lamptey and Labi (2004), the Highway Economic Requirements System Technical Report (FHWA, 2000), the NCHRP Synreport 191, and Lamptey et al. (2011) provided some useful information in order to quantify the costs of safety interventions for this report; and the INDOT SAC members provided some of the missing cost information for Indiana specifically.

When searching for the unit cost of each countermeasure, there were some available resources in past resources in Indiana (Lamptey & Labi, 2004). Also, in the Indiana contracts database, the unit cost of reducing horizontal curvature is \$2,500,000/mile. In the FHWA's Highway Economic Requirements System Technical Report (FHWA, 2000), the unit cost of installing guardrail is \$225,000/mile on urban interstate and urban two-lane roads, \$185,000/mile on rural interstate, rural multi-lane, and rural two-lane. In NCHRP SynReport 191, the unit cost of adding centerline rumble strips is around \$1,500/mile in rural multi-lane and rural two-lane (Lamptey & Labi, 2004). Also, the unit cost of adding shoulder rumble strips on both sides is \$6,000/mile in rural interstate and rural multi-lane. According to Lamptey et al. (2011), the unit cost of widening a 2-ft. shoulder is \$123,000/mile. For other safety countermeasures, there was inadequate information to provide the unit costs. Therefore, a Safety Countermeasures/Programs Survey (Appendix B) was sent out to INDOT SAC members.

Taking into account that the unit cost could vary significantly by location, for each countermeasure, different cost were assigned by road element type as shown in Table 4.2. The shaded spaces indicate that the safety countermeasures are not applicable in those particular conditions; a blank space indicates that there was no available information for those costs at this time.

4.3 Conditions of Safety Countermeasures

Although there are many safety countermeasures, the countermeasure that will be applied will be determined from the types of crashes that occur at the location, and thus the conditions for each safety countermeasure needed to be defined.

Table 4.3 shows the detailed conditions of each safety countermeasure.

TABLE 4.1
Crash reduction factors for safety countermeasures

| Category | Countermeasures | Crash Type | Urban | | | | | Rural | | | | | Reference | | |
|---------------------|---|--|------------|----|-----|-----|----|-------|----|-----|---|--|-----------|-------------------------|--|
| | | | KA | BC | O | All | KA | BC | O | All | | | | | |
| Access management | Replace TWLTL with raised median | All | 21 | 21 | 33 | 23 | | | | | | | | Mauga and Kaseko (2010) | |
| | Install queue warning changeable signs | Rear end | 16 | 16 | -16 | | 16 | 16 | 16 | -16 | | | | Elvik and Vaa (2004) | |
| ITS | Alignment | Reduce horizontal curvature by X degree | | | | | | | | | | | | | |
| | | Add lighting at intersections | All | | | 8 | E | E | E | E | | | | | Tarko et al. (2007) |
| | Intersection geometry | Add left-turn lanes to major road approaches at intersections | Night-time | | | 8 | | | | | | | | | Donnell et al. (2010) |
| | | Add right-turn lanes to major road approaches at intersections | All | 37 | 37 | 45 | 58 | 58 | 58 | 58 | | | | | Harwood et al. (2003) |
| | | Replace direct left-turns with indirect left-turns | All | 9 | 9 | 16 | 9 | 9 | 9 | 16 | | | | | Harwood et al. (2003) |
| Pedestrians | Replace direct left-turns with indirect left-turns | All | 43 | 43 | 20 | 28 | 43 | 43 | 20 | 28 | | | | | Xu, L. (2001) |
| | Convert intersection to roundabout | Rear end | | | 13 | | | | | 13 | | | | | |
| | Sight distance improvements | Angle | | | 35 | | | | | 35 | | | | | |
| | Install pedestrian hybrid beacon (HAWK) at intersection | All | 65 | 65 | 42 | 29 | 65 | 65 | 42 | 11 | | | | | Schoon and Van (1994) |
| | Construct pedestrians bridge or tunnel | All | 15 | 15 | | 69 | | | | | | | | | Christopher et al. (2006) |
| | Install sidewalk | All | | | | 86 | | | | | | | | | Fitzpatrick and Park (2010) |
| | Install gates at crossings with signs | P | | | | 74 | | | | | | | | | Fitzpatrick and Park (2010) |
| | Build a grade-separated crossing | P | | | | 87 | | | | | | | | | Gan et al. (2005) |
| | Eliminate railroad crossing | All | | | | 100 | | | | | | | | | Park and Saccomanno (2005) |
| | Install guardrail | All | | | | 100 | | | | | | | | | Park and Saccomanno (2005) |
| Roadside | Install cable median barrier | All | 43 | 17 | | 43 | 17 | 17 | | | | | | | HSIP (2006) |
| | Flatten crest of curve | Run off road | 44 | 47 | | 44 | 47 | 47 | | | | | | | Elvik and Vaa (2004) |
| Roadway delineation | Add centerline rumble strips | All | 90 | | | 90 | | | | | | | | | Elvik and Vaa (2004) |
| | Add shoulder rumble strips | All | 51 | | | 20 | 51 | 51 | | | | | | | MnDOT (2010) |
| | Traffic calming and speed limits | Run off road | 13 | | | 18 | 13 | 13 | | | | | | | Hovey and Chowdhury (2005) |
| Speed management | Traffic calming and speed limits | All | 16 | 24 | 10 | 18 | 16 | 24 | 10 | 18 | 9 | | | | Persaud et al. (2003) |
| | | | | | | | | | | | | | | | Griffith (1999) |
| | | | | | | | | | | | | | | | Elvik and Vaa (2004); Park and Lomax (2010); Park (1997) |

TABLE 4.1
(Continued)

| Category | Countermeasures | Crash Type | Urban | | | | | Rural | | | | | Reference | | | |
|------------------------------|---|--------------------|-------|----|-----|-----|---|-------|----|-----|-----|----|-----------|--|--|--|
| | | | KA | BC | O | All | E | KA | BC | O | All | E | | | | |
| Shoulder treatment | Widen inside shoulder width | All | | | E | | | | | | | | | | | |
| | Widen outside shoulder width | All | | | | | | | | | | | | | | Tarko et al. (2007) |
| | Install a combination of chevron signs, curve warning signs/advisory speed signs, and sequential flashing beacons | All | 24 | 24 | 51 | 34 | E | 24 | 24 | 24 | 51 | 34 | | | | Tarko et al. (2007) |
| Signs | Install a combination of chevron signs, curve warning signs/advisory speed signs, and sequential flashing beacons | All | 24 | 24 | 51 | 34 | E | 24 | 24 | 24 | 51 | 34 | | | | Elvik and Vaa (2004); Montella (2009) |
| | Retiming signal change intervals to ITE standards | All | 12 | -8 | -12 | 8 | | 12 | -8 | -12 | 8 | | | | | Retting et al (2002) |
| | | Rear end | -8 | -6 | 37 | 39 | | -8 | -6 | 37 | 39 | | | | | |
| | | Angle | | | | 4 | | | | | 4 | | | | | |
| | | Vehicle/bicycle, p | | | | 8 | | | | | 8 | | | | | |
| Intersection traffic control | Retiming signal change intervals to ITE standards | All | | | | | | | | | | | | | | Srinivasan et al. (2008); Sayed and Pump (2005); Sayed and Pump (2007) |
| Road diet | Increase visibility of signals | All | | | | | | | | | | | | | | Harkey et al (2008) |
| | Change from permissive or permissive/protected to protected-only phasing | All | | | | | | | | | | | | | | |
| | New flasher installation | All | | | | | | | | | | | | | | NCHRP 500 |
| | New signal installation | All | | | | | | | | | | | | | | HSIP (2006) |
| | Re-stripe four-lane undivided to two-lane with bicycle lanes | All | | | | | | | | | | | | | | Tan (2010) |

E= equation; HAWK = high intensity activated crosswalk; P= pedestrians.

TABLE 4.2
Cost of safety countermeasures

| Category | Countermeasure | Cost in \$1000s | | | | | | Unit |
|------------------------------|---|-----------------|---------------------|-------------------|-----|---------------------|-------------------|--------------|
| | | UI | Urban Multi-Lane | Urban Two-Lane | RI | Rural Multi-Lane | Rural Two-Lane | |
| Access management | Replace TWLTL with raised median | | | | | | | Mile |
| Advanced technology | Install queue warning changeable signs | 1,200 | 1,200 | | | | | System |
| Alignment | Reduce horizontal curvature | | 2,500 | 2,500 | | 2,500 | 2,500 | Mile |
| Highway lighting | Add lighting at intersection | 500 | 250 | 125 | 500 | 250 | 150 | Intersection |
| Intersection geometry | Add left-turn lanes to major road approaches at intersections | | 200 | 150 | | 200 | 150 | Intersection |
| | Add right-turn lanes to major road approaches at intersections | | 200 | 150 | | 200 | 150 | Intersection |
| | Replace direct left-turns with indirect left-turns | | 250 | | | 250 | | Intersection |
| | Convert intersection to roundabout | | 2,000 | 1,500 | | 1,500 | 1,000 | Intersection |
| | Sight distance improvements | | 2000 | | | 2000 | | Mile |
| Pedestrians | Install pedestrian hybrid beacon at intersection | | 150 | 150 | | | | Intersection |
| | Construct pedestrians bridge or tunnel | 250 | 250 | | 250 | 250 | | Structure |
| | Install sidewalk | | 120 | 120 | | 120 | 120 | Mile |
| At-grade railroad crossing | Install gates at crossings with signs | | 300 | 300 | | 300 | 300 | Crossing |
| | Build a grade-separated crossing | | 5,000 | 5,000 | | 5,000 | 5,000 | Crossing |
| | Eliminate railroad crossings | | 50 | 50 | | 50 | 50 | Crossing |
| Roadside | Install guardrail | 225 | | 225 | 185 | 185 | 185 | Mile |
| | Install cable median barrier | 100 | 100 | | 100 | 100 | | Mile |
| | Flatten crest of curve | | 1,400 | 1,400 | | 1,400 | 1,400 | Mile |
| Roadway delineation | Add centerline rumble strips | | | | | 1.5 | 1.5 | Mile |
| | Add shoulder rumble strips (cost for both sides) | | | | 6 | 6 | 3 | Mile |
| Speed management | Set and post speed limits | 1 | 1 | 0.5 | 1 | 1 | 0.5 | Mile |
| Shoulder signs | Widen shoulder | | | | | 123 | 123 | 2 ft/Mile |
| | Install chevrons, warning/ advisory signs, and/or beacons | | | | | 50 | 35 | Curve |
| Intersection traffic control | Retiming signal change intervals to ITE standards | | | | | | | Intersection |
| | Increase visibility of signals | | 10 | 10 | | 10 | 10 | Intersection |
| | Replace left-turn phase(s) with protected-only new flasher installation | | 30 | 20 | | 30 | 20 | Intersection |
| | new signal installation | | 150 | 125 | | 150 | 125 | Intersection |
| Road diet | Re-stripe four-lane undivided to two-lane with bicycle lanes | | 75 | | | 75 | | Intersection |

TABLE 4.3
Conditions of safety countermeasures

| Category | Countermeasures | Conditions |
|------------------------------|---|---|
| Access management | Replace TWLTL with raised median | Urban: TWLTL, segments, no median, four lane, sideswipe crashes, left-turn crashes |
| Advanced technology and ITS | Install queue warning changeable signs | Urban/rural: High accidents history, rear-end crashes |
| Alignment | Reduce horizontal curvature by X degree | Rural: Run off road crashes, head-on crashes; Indiana standards |
| Highway lighting | Add lighting at intersections | Urban/rural: At intersection, no lighting, night crashes |
| Intersection geometry | Add left-turn lanes to major road approaches at intersections | Urban/rural: At intersection, rear-end crashes |
| | Add right-turn lanes to major road approaches at intersections | Urban/rural: At intersection, rear-end crashes |
| | Replace direct left-turns with indirect left-turns | Urban/rural: At intersection, rear-end crashes, left-turn crashes |
| | Convert intersection to roundabout | Urban/rural: At intersection, excessive number of non-pedestrian crashes |
| | Sight distance improvements | Rural: At intersection, all crashes. |
| Pedestrians | Install pedestrian hybrid beacon at intersection | Urban: At intersection, pedestrian-related crashes |
| | Construct pedestrian bridge or tunnel | Urban: Pedestrian-related crashes |
| | Install sidewalk | Urban: Pedestrian-related crashes |
| At-grade railroad crossing | Install gates at crossings with signs | Urban/rural: Segments, rear-end crashes, train-related crashes |
| | Build a grade-separated crossing | Urban/rural: Segments, railroad |
| | Eliminate rail road crossing | Urban/rural: Segments, railroad |
| Roadside | Install guardrail | Urban/rural: Segments, have a median, head-on crashes, run-off road crashes |
| | Install cable median protection interstates | Urban/rural: Segments, head-on crashes, run-off road crashes. |
| | Flatten crest of curve | Urban/rural: Segments, head-on crashes, run-off road crashes. |
| Roadway delineation | Add centerline rumble strips | Rural: Segments, Head-on crashes (be careful with passing zones) |
| | Add shoulder rumble strips | Urban/rural: Segments, single vehicle crashes. |
| Speed management | Traffic calming and speed limits | Urban/rural: Speed-related crashes. |
| Shoulder treatment | Widen inside shoulder width | Urban/rural: Segments, run-off road crashes, head on crashes, Indiana standards |
| | Widen outside shoulder width | Rural: Segments, run-off road crashes, Indiana standards |
| Horizontal curve | Install a combination of chevron signs, curve warning signs/advisory speed signs, and sequential flashing beacons | Urban/rural: Head on crashes, run off road crashes |
| Intersection traffic control | Retiming signal change intervals to ITE standards | Urban/rural: At intersection, right-angle crashes, rear end crashes, pedestrians crashes, time intervals out of standards |
| | Increase visibility of signals | Urban/rural: At intersection, rear-end crashes |
| | Change from permissive or permissive/protected to protected-only phasing | Urban: At intersection, left-turn crashes (the result is too high, but 5 stars) |
| | New flasher installation | Urban/rural: Rear-end crashes, right angle crashes |
| | New signal installation | Urban: At intersection, unsignalized, rear-end crashes, right angle crashes |
| Road diet | Re-stripe four-lane undivided to two-lane with bicycle lanes | Urban/rural: Segments, four lanes |

5. OPTIMIZATION

The next step is optimization of the budget by applying the correct safety countermeasures to address specific safety issues. Pal and Sinha (1998) proposed an integer programming method to optimize safety improvement programs by minimizing the number of crashes while accounting for the budget constraints, the major cost components, and the effectiveness of safety interventions in addition to carrying over the unspent funds and safety impacts into future years. The Kentucky Transportation Center (2003) identified and prioritized high-crash locations in need of safety improvements and developed software to produce a generalized estimation of the benefits and costs based on CRFs and the present worth of annual benefits. The objective function in this report is non-linear and some of the constraints are still non-linear, which makes this type of programming unfeasible. Hemmecke et al. (2009) found that in the past few years, researchers from the field of integer programming had increasingly used nonlinear mixed-integer programs. Nevertheless, this is generally considered a very young field, and most of the problems and methods are not well understood or stable as in the case of linear mixed-integer programs.

In the area of heuristic methods, Hrvoje and Jadranka (2003) applied a genetic algorithm to solve a cost minimization problem and concluded that when the population is a small value (such as $n=10, 15$), the branch and bound approach is a better method to obtain the optimal solution; but if the population is much larger, the genetic algorithm is preferable.

5.1 Problem Definition

Based on the available data, which includes the road information, the crash information, and the catalog of safety countermeasures, a mixed non-linear programming was established.

The objective is to maximize the safety benefit.

$$\text{Max} \sum_{i \in \{I\}} \sum_{h \in \{H\}} \sum_{j \in \{J\}} D_{ih} CCRF_{jh} CC_h \times R_{ij} X_{ij} \quad (5.1)$$

s.t.:

Total budget constraint:

$$\sum_{i \in \{I\}} \sum_{j \in \{J\}} C_{ij} R_{ij} X_{ij} \leq TB \quad (5.2)$$

Countermeasure budget constraint:

$$\sum_{i \in \{I\}} C_{ij} R_{ij} X_{ij} \geq B_j \quad (5.3)$$

Regional budget constraint:

$$L_K \leq \sum_{i \in \{I_k\}} \sum_{j \in \{J\}} C_{ij} R_{ij} X_{ij} \leq U_K \quad (5.4)$$

Mutually exclusive constraint:

$$\sum_{j \in \{J_m\}} X_{ij} R_{ij} \leq 1 \quad (5.5)$$

Where:

D_{ih} = crash frequency at location i at level of severity h ,
 $CCRF_{jh}$ = combined crash reduction factor for countermeasure j at severity h ,

CC_h = crash cost for h severity (KA, BC, or PDO),

R_{ij} = relevant countermeasure j at location i ,

C_{ij} = cost at location i for project j ,

TB = total budget,

B_j = minimum budget for projects of type j ,

U_k = upper bound budget for regional k ,

L_k = lower bound budget for regional k ,

I_k = location I belongs to regional k ,

J_m = mutually exclusive countermeasures matrix, and

X_{ij} = binary variable.

The formulation shown in Equations 5.1 through 5.5 is consistent with mixed non-linear programming. If several countermeasures were implemented together to enhance the safety benefit at some locations, it is supposed to use combined crash reduction factors, and the equivalent is as follows (Lacy, 2001):

$$\begin{aligned} CCRF_{jh} &= 1 - [(1 - CRF_{1h}) * (1 - CRF_{2h}) \\ & * \dots * (1 - CRF_{jh})] = 1 - \prod_{j=1}^j (1 - CRF_{jh}) \end{aligned} \quad (5.6)$$

Equations 5.2 through 5.6 constitute a general formation that includes most of the practical situations but may change depending on the different circumstances at a given site.

5.2 Algorithm

The above formulations of the optimization problem were approximately solved by using the greedy heuristic search (Wilt et al., 2010).

The optimization algorithm defines the principles of the heuristic method. The first step of the algorithm is to select the hazardous crash locations and then to create a list of potential safety countermeasures. Some countermeasures can be applied together, but some of them are mutually exclusive; therefore, the list is presented in a 0-1 matrix. Next, the benefit for each countermeasure is calculated as shown in Appendix E. Then, the benefit/cost ratio is calculated for the safety countermeasures, and the highest B/C ratio is selected.

If a safety countermeasure satisfies all the constraints, then it will be implemented; however, if it violates some constraint, then it is deleted from the list. The algorithm continues running until no further countermeasures can be selected. The algorithm flowchart in Figure 5.1 shows the steps of the optimization algorithm (Romero, 2013).

Using the developed tool, the safety countermeasures for the crash location can be identified. In accordance with the assigned constraints for different conditions, the optimizer estimates the expected total cost and the total benefit and calculates the benefit/cost ratio. In

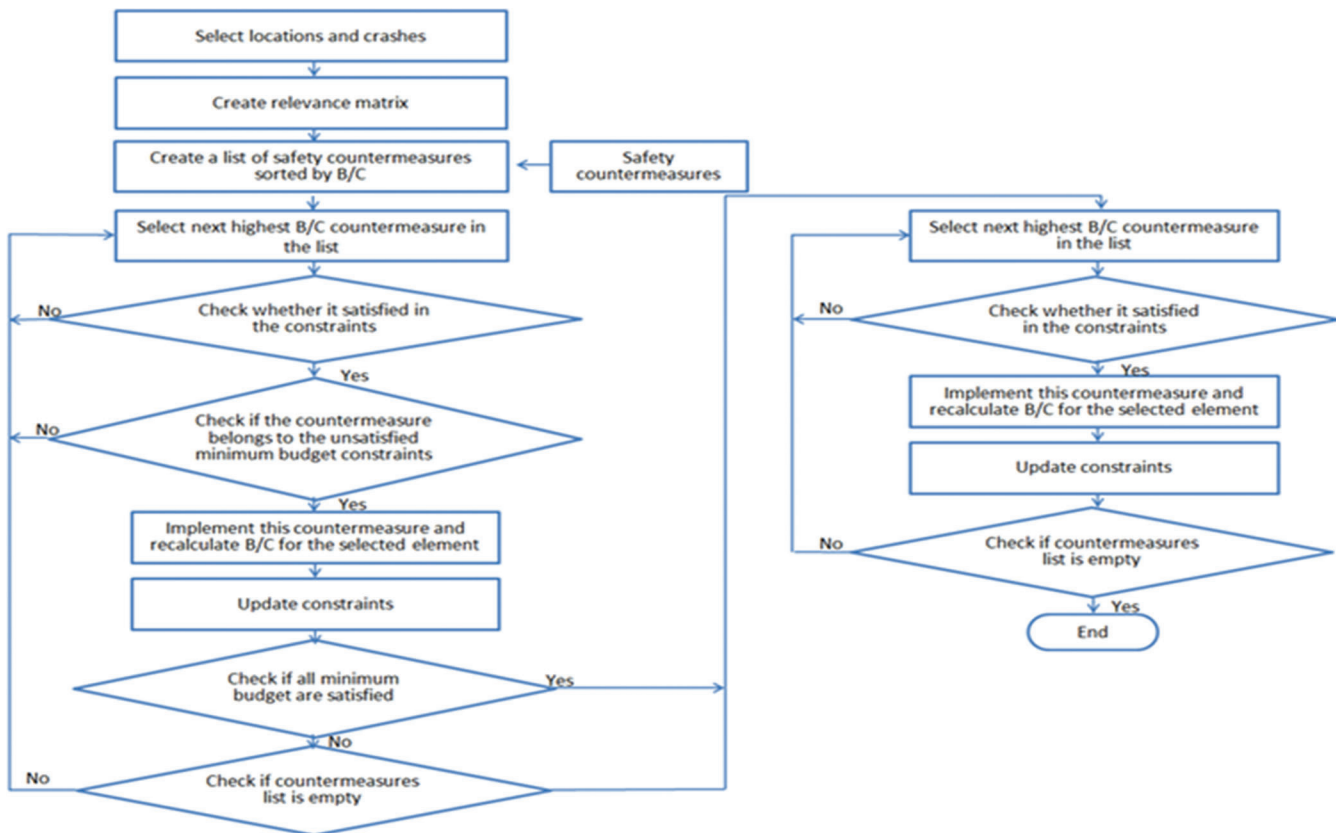


Figure 5.1 Heuristic algorithm flowchart.

order to pictorially explain the process, a figure also appears in the interface. The optimal results are saved as a.csv file.

5.3 Testing and Evaluation

The performance of the heuristic method based on a greedy search was evaluated using a subset of countermeasures and road elements.

- State-administered segments and intersections of Tippecanoe County were considered.
- Implementation of four countermeasures: install new signal; convert intersection to roundabout; widen outside shoulder width; and add shoulder rumble strips.

To test the optimization algorithm, a small sample data set was used to compare the algorithm results with an optimal solution calculated using MS Excel in order to identify the reasons for any differences in the two solutions.

The test was carried out by using different test scenarios for the sample data (e.g., dataset, constraints such as low budget, mutually exclusive countermeasures, etc.).

After all the tests were concluded, evaluation of the optimization method was performed.

- Use the Tippecanoe County dataset.
- Define several evaluation scenarios that have different budgets and constraints.

- Run the optimization algorithm to obtain the optimal solution for each evaluation scenario.
- Randomly select many different points in the feasible region and calculate the respective objective function values.
- Compare the feasible solutions to the optimal solutions.

5.3.1 Background Information

In Tippecanoe County, there are 416 intersections and 700 segments on state-administered road, all of which have an assigned unique ID in the ArcGIS maps. For each particular location, there is detailed information about the conditions at the location (e.g., whether these intersections are signalized or not, the shoulder width of the segments, etc.). Crash data for 2009 through 2011 in Tippecanoe County also were obtained from the Center for Road Safety. Each specific crash has a unique assigned ID number, and the type of crash, the weather at the time of the accident, and other conditions are available. Only state-administered roads are studied in this report.

Using the original dataset, crashes that occurred at each segment and intersection in Tippecanoe County, from 2009 through 2011, were matched. In order to decrease the crashes and enhance safety, safety countermeasures were suggested for implementation. To test the heuristic method, four countermeasures from the CRFs list were selected: (1) new traffic signal installation, (2) conversion of an intersection to a roundabout, (3) widening of the outside shoulder width, and (4)

adding shoulder rumble strips. Different safety countermeasures are appropriate for different conditions; therefore, the conditions for applicability of these four countermeasures needed to be clearly defined.

1. New signal installation:
 - State intersection
 - Unsignalized
 - Urban
 - Right-angle crashes from two different approaches and excessive crashes (five or more) in any last three years
2. Convert intersection to roundabout:
 - State intersection
 - Excessive number of non-pedestrian crashes
 - Peak hourly volume entering the intersection ≤ 1500 veh/h
$$V_{PH} = \frac{0.1 \sum_{i=1}^4 AADT_i}{2} \leq 1500 \text{ veh/h}$$
3. Add shoulder rumble strips:
 - State segments
 - Rural
 - Excessive number of single vehicle crashes
4. Widen outside shoulder width:
 - State segments
 - Rural
 - Excessive number of run-off road crashes
 - Shoulder design standards in Indiana (Indiana Design Manual, 2013) (Table 5.1 and Table 5.2)

5.3.2 Testing the Algorithm and Implementation of the Heuristic Method

In order to test the optimization algorithm, a small sample data set was selected from the dataset to form four case studies for testing various scenarios.

Case 1: Create an optimization problem with a single countermeasure. The countermeasure consisted of adding shoulder rumble strips, and 10 segments were randomly selected from the *add shoulder rumble*

strips.csv file. Five different scenarios were defined in order to test both the sequence of selection and the maximum budget constraints.

1: If the total budget is set at \$19,923, which is exactly equal to the total cost, then all the segments in Table 5.3 can be selected. The input data are presented in Figure 5.2. In the output, all the segments were selected, as shown in Table 5.4.

Self-check: The cost for all the segments in Table 5.4 is \$19,923; therefore, since the total budget was also \$19,923, all the segments could be selected. Further, the total benefit was \$58,652, and the B/C ratio was $\$58,652/\$19,923=2.944$. The results were the same as the solution that the test algorithm generated.

2: If the total budget is set at more than \$19,923, such as \$25,000, then all the segments can be selected. The resulting interface is as shown in Figure 5.3.

Self-check: The total cost, total benefit, and total B/C ratio were the same as Scenario 1 with \$19,923, \$58,652, and 2.944 respectively. The test algorithm solution was also the same.

3: If the total budget constraint is less than \$19,923, such as \$10,000, then only the segments which have relatively high B/C ratios will be selected. The resulting interface is as shown in Figure 5.4.

The output shows that six out of 10 segments were selected as shown in Table 5.5.

4: The total budget constraint is set at \$30,000, but the maximum regional budget is \$10,000 in Crawfordsville. The resulting interface is as shown in Figure 5.5.

The output shows that six out of 10 segments were selected as shown in Table 5.6.

Self-check: The selected segments were the same as Scenario 3 because all the segments were in Tippecanoe County, which is in the INDOT Crawfordsville District. Thus, under the regional budget constraint, no matter how large the total budget will be, the optimal solution is always the same.

5: If the total budget constraint is set at \$13,000, then only the segments which have relatively high B/C ratios will be selected. The resulting interface is shown in Figure 5.6.

The output shows that eight out of the 10 segments were selected as shown in Table 5.7.

TABLE 5.1
Shoulder width design standards for rural arterial

| Design Element | Rural Arterial—2 Lanes | | | Rural Arterial—4 or More Lanes |
|----------------|------------------------|---------------|----------------|--------------------------------|
| | <400 | 400≤AADT<1500 | 1500≤AADT<2000 | Not specified |
| Shoulder width | 2 ft | 4 ft | 6 ft | 10 ft |

TABLE 5.2
Shoulder width design standards for rural collector

| Design Element | Rural Collector, State Route | | | |
|----------------|------------------------------|---------------|----------------|-------|
| | <400 | 400≤AADT<1500 | 1500≤AADT<2000 | >2000 |
| Shoulder width | 2 ft | 4 ft | 6 ft | 8 ft |

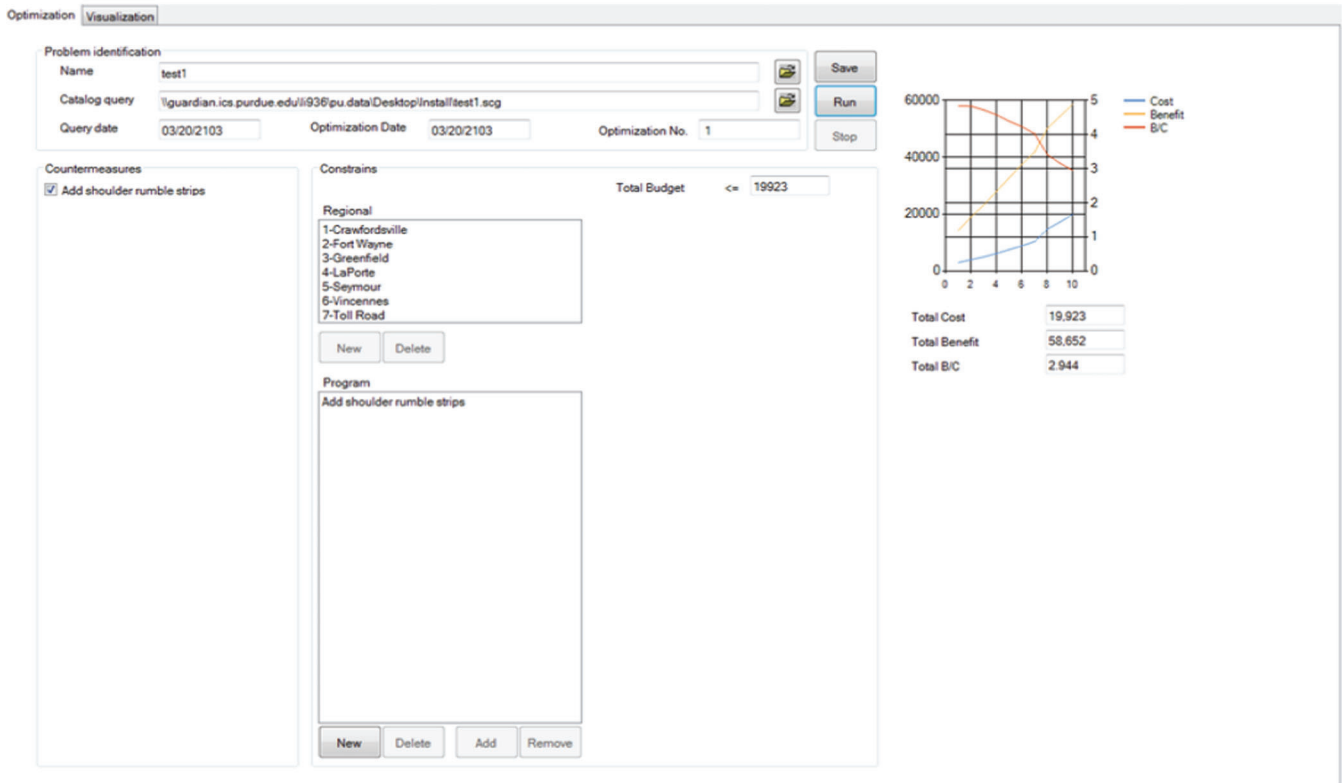


Figure 5.2 Test algorithm interface of Scenario 1 in Case 1.

TABLE 5.3
Test Case 1 sample dataset

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|------|
| 218618 | 4350 | 8463 | 1.95 |
| 225795 | 1398 | 4752 | 3.4 |
| 235280 | 987 | 4752 | 4.81 |
| 237139 | 990 | 4231 | 4.27 |
| 238149 | 2526 | 4231 | 1.68 |
| 238248 | 1512 | 4231 | 2.8 |
| 239995 | 2946 | 14257 | 4.84 |
| 247281 | 1188 | 4752 | 4 |
| 417817 | 2682 | 4231 | 1.58 |
| 420356 | 1344 | 4752 | 3.54 |

TABLE 5.4
Output of selected segments for Scenario 1 in Case 1

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|------|
| 239995 | 2946 | 14257 | 4.84 |
| 235280 | 987 | 4752 | 4.81 |
| 237139 | 990 | 4231 | 4.27 |
| 247281 | 1188 | 4752 | 4 |
| 420356 | 1344 | 4752 | 3.54 |
| 225795 | 1398 | 4752 | 3.4 |
| 238248 | 1512 | 4231 | 2.8 |
| 218618 | 4350 | 8463 | 1.95 |
| 238149 | 2526 | 4231 | 1.68 |
| 417817 | 2682 | 4231 | 1.58 |

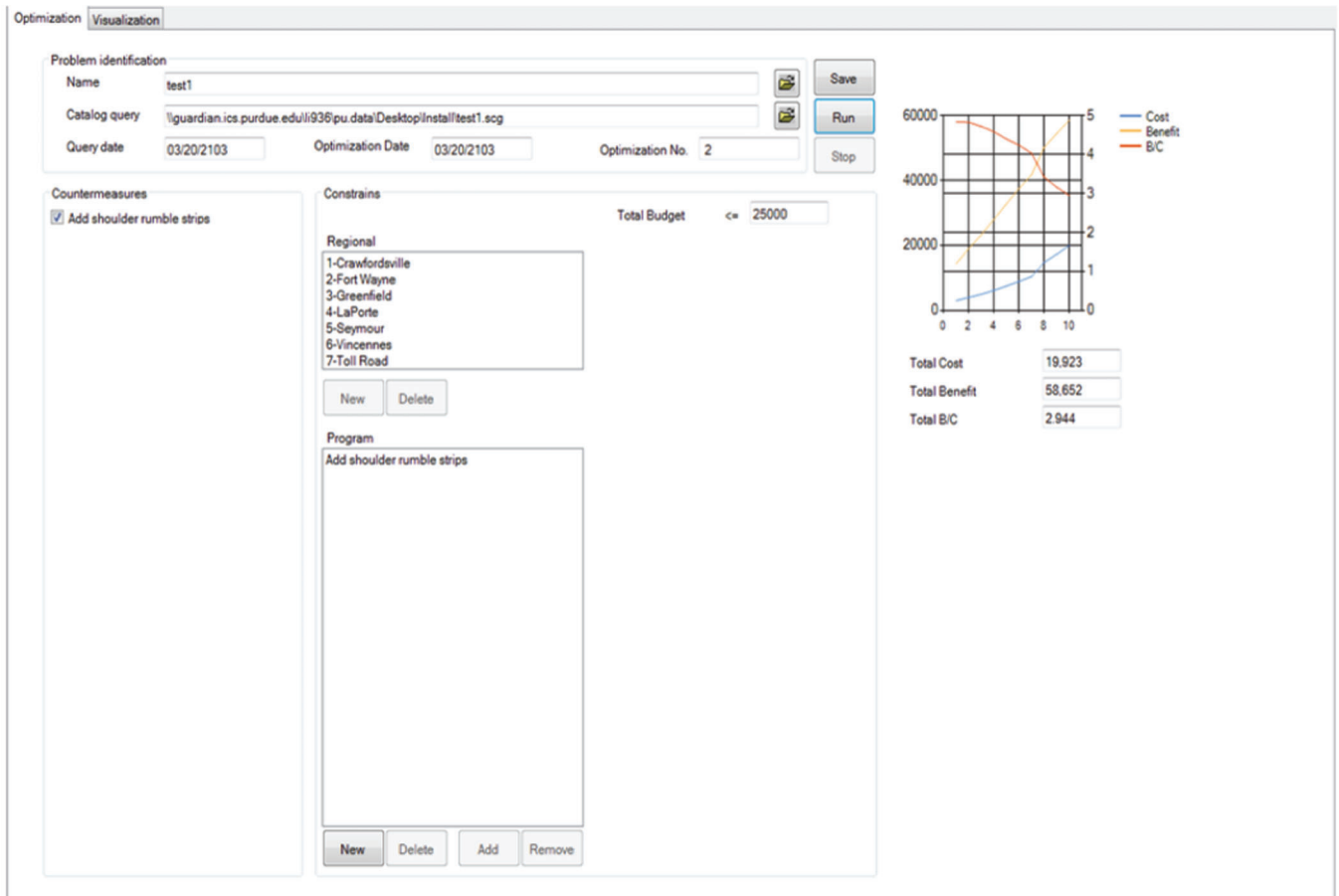


Figure 5.3 Test algorithm interface of Scenario 2 in Case 1.

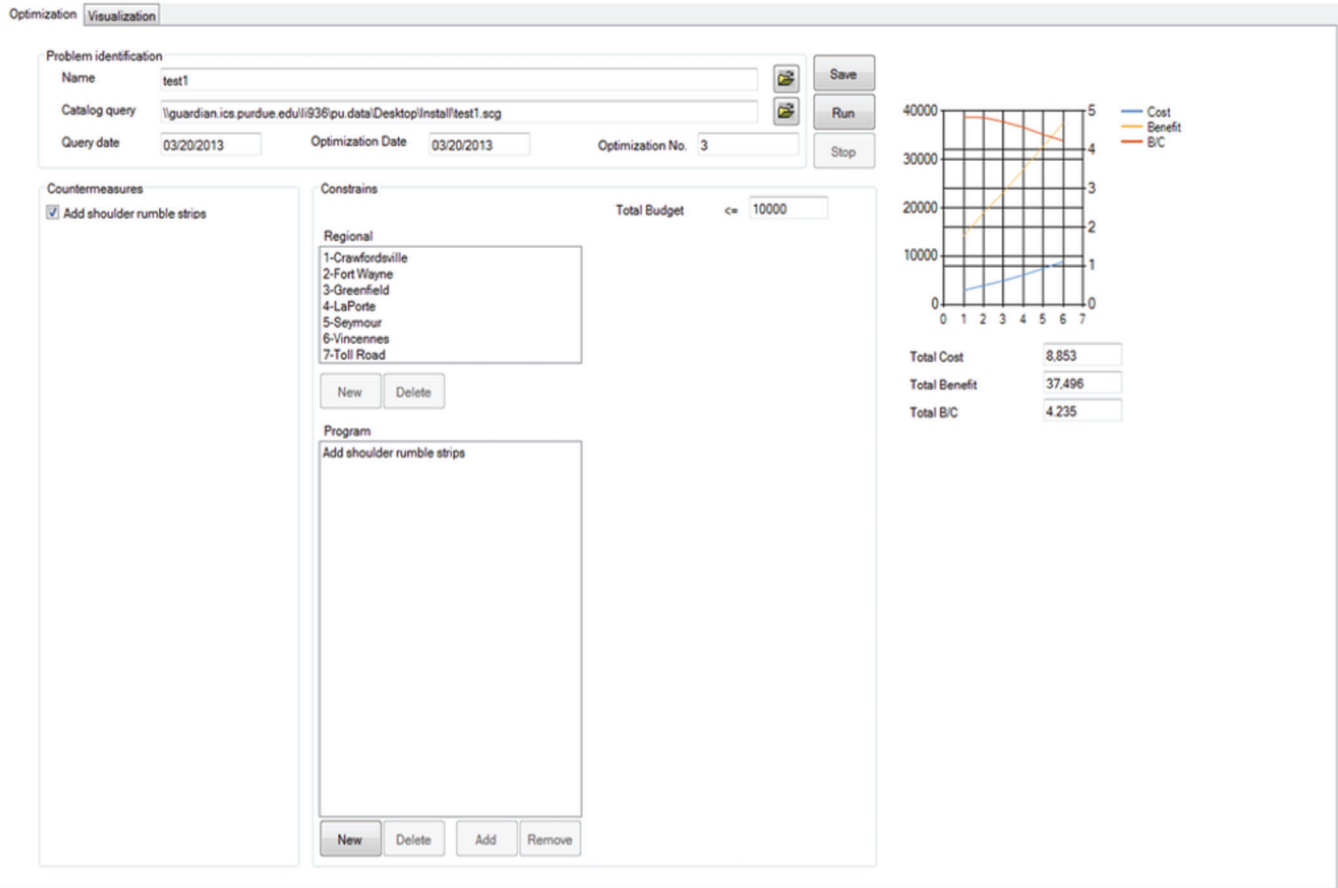


Figure 5.4 Test algorithm interface of Scenario 3 in Case 1.

TABLE 5.5
Output of selected segments for Scenario 3 in Case 1

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|------|
| 239995 | 2946 | 14257 | 4.84 |
| 235280 | 987 | 4752 | 4.81 |
| 237139 | 990 | 4231 | 4.27 |
| 247281 | 1188 | 4752 | 4 |
| 420356 | 1344 | 4752 | 3.54 |
| 225795 | 1398 | 4752 | 3.4 |

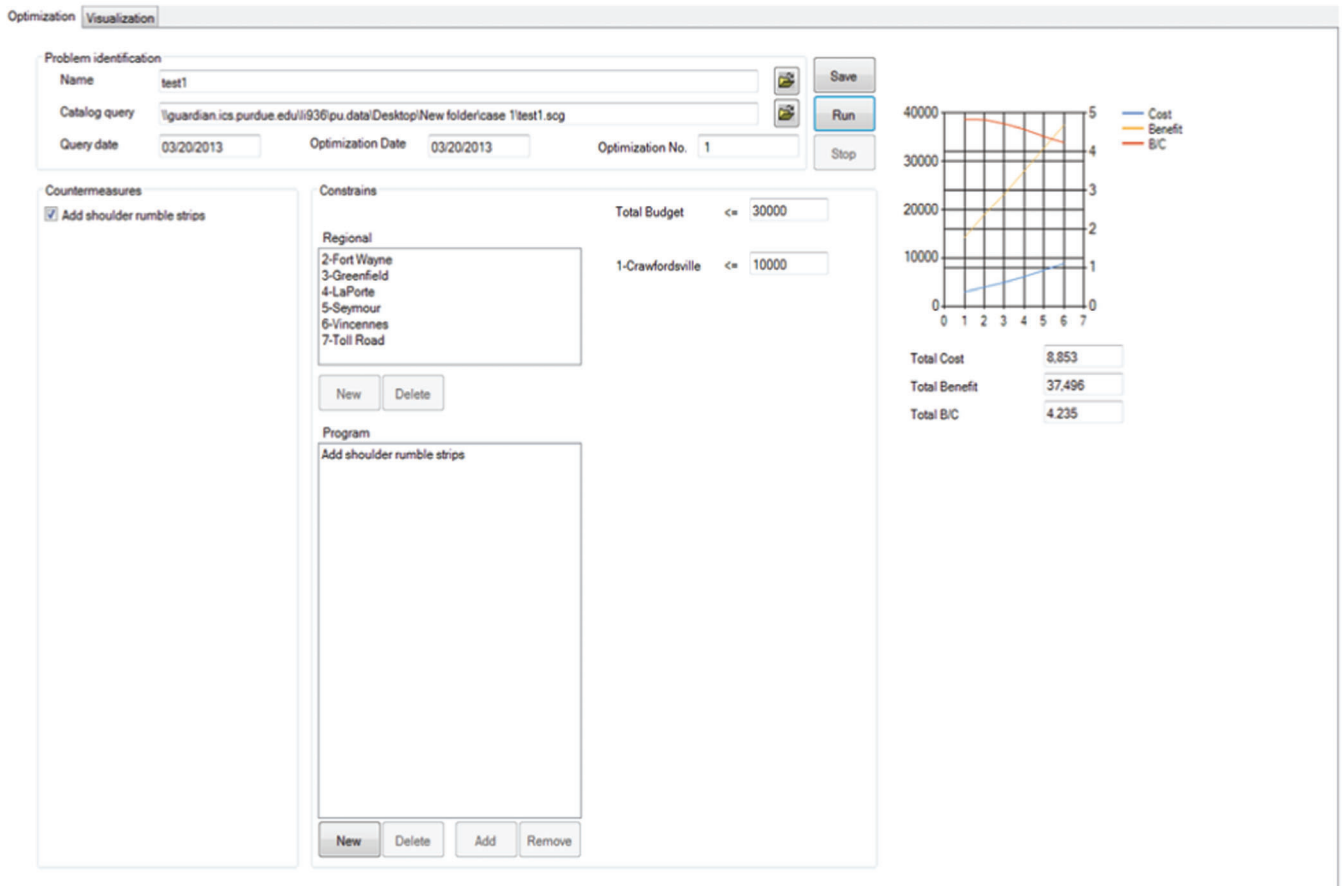


Figure 5.5 Test algorithm interface of Scenario 4 in Case 1.

TABLE 5.6
Output of selected segments for Scenario 4 in Case 1

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|------|
| 239995 | 2946 | 14257 | 4.84 |
| 235280 | 987 | 4752 | 4.81 |
| 237139 | 990 | 4231 | 4.27 |
| 247281 | 1188 | 4752 | 4 |
| 420356 | 1344 | 4752 | 3.54 |
| 225795 | 1398 | 4752 | 3.4 |

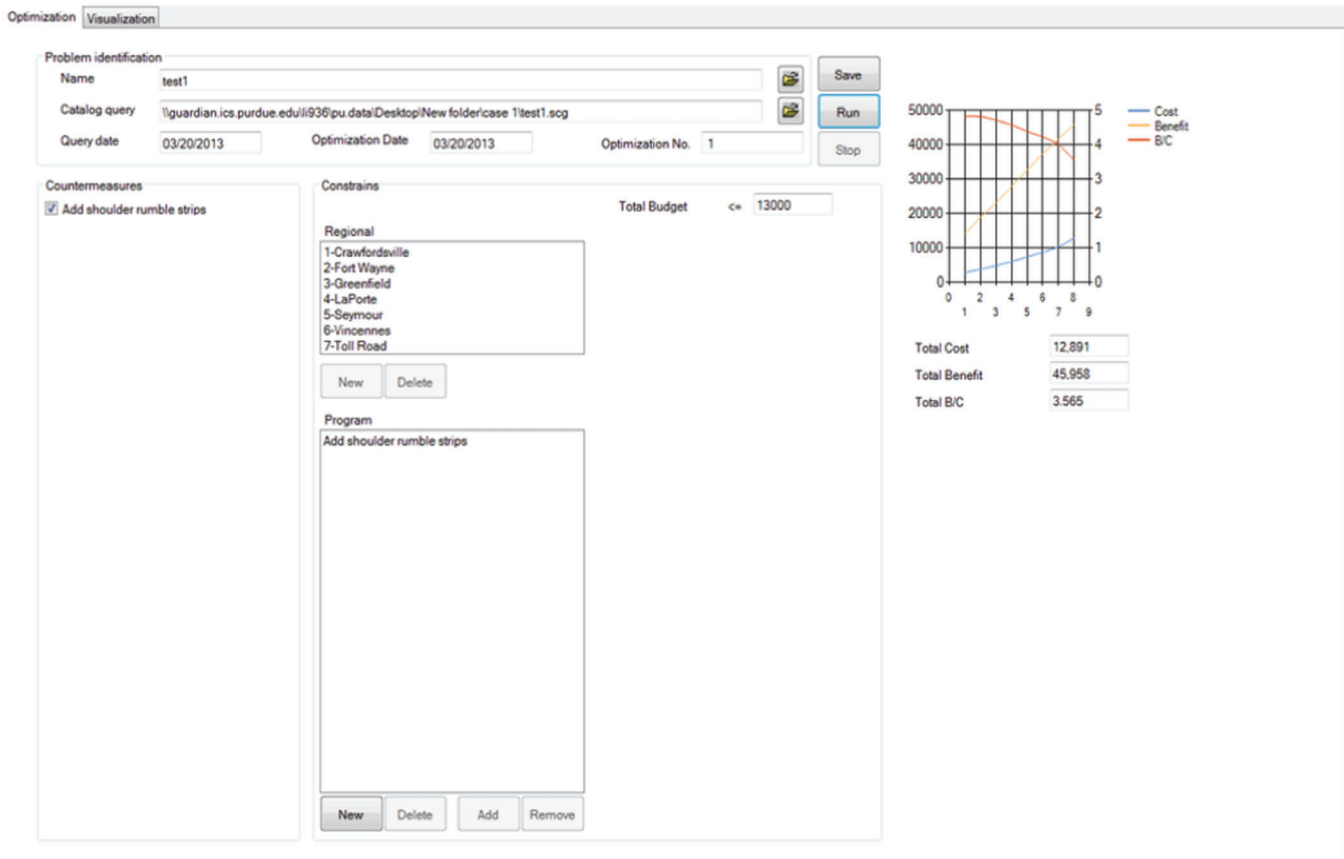


Figure 5.6 Test algorithm interface of Scenario 5 in Case 1.

Self-check: Even though CFID 218618 had a higher B/C ratio than CFID 238149, it was not selected because the total cost of the first seven higher B/C ratio segments was \$10,365 and the total budget was \$13,000. Therefore, the remaining budget was \$2,635, which was less than the CFID 218618 segment cost of \$4,350. Therefore, the next qualified candidate, CFID 238149, with a cost of \$2,526, was selected.

Case 2: Create another optimization problem with two mutually exclusive countermeasures. The safety countermeasures consisted of a new signal installation and the conversion of an intersection to a roundabout. Six intersections were randomly selected from the *new signal installation.csv* file and four intersections were

TABLE 5.7
Output of selected segment for Scenario 5 in Case 1

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|------|
| 239995 | 2946 | 14257 | 4.84 |
| 235280 | 987 | 4752 | 4.81 |
| 237139 | 990 | 4231 | 4.27 |
| 247281 | 1188 | 4752 | 4 |
| 420356 | 1344 | 4752 | 3.54 |
| 225795 | 1398 | 4752 | 3.4 |
| 238248 | 1512 | 4231 | 2.8 |
| 238149 | 2526 | 4231 | 1.68 |

selected in the *convert intersection to roundabout.csv* file as shown in Table 5.8 and Table 5.9; and two different scenarios were defined in order to test both the sequence of selection, the mutual exclusivity, and the maximum budget constraints.

I: The total budget constraint was set at \$7,000,000, which was larger than the total cost if all the intersections were selected. The resulting interface was as shown in Figure 5.7.

The output shows that nine out of the 10 intersections were selected as shown in Table 5.10.

Self-check: The total cost of implementing the safety countermeasures in all the intersections was \$6,750,000, but the optimal solution had a cost of \$5,250,000 even though the total budget constraint was larger than \$6,750,000, which was due to the fact that an intersection was selected in both datasets—CFID 6544 as shown in

TABLE 5.8
Test Case 2 subset sample dataset from *convert intersection to roundabout.csv*

| CFID Intersection | Total Cost | Total Benefit | B/C |
|-------------------|------------|---------------|------|
| 6544 | 1500000 | 256418 | 0.17 |
| 6579 | 1500000 | 284464 | 0.19 |
| 6800 | 1500000 | 216353 | 0.14 |
| 7145 | 1500000 | 284464 | 0.19 |

TABLE 5.9
Test Case 2 subset sample dataset from *new signal installation.csv*

| CFID Intersection | Total Cost | Total Benefit | B/C |
|-------------------|------------|---------------|------|
| 6303 | 125000 | 30717 | 0.25 |
| 6311 | 125000 | 19400 | 0.16 |
| 6544 | 125000 | 22633 | 0.18 |
| 6701 | 125000 | 19400 | 0.16 |
| 6727 | 125000 | 19400 | 0.16 |
| 6883 | 125000 | 29100 | 0.23 |

Table 5.8 and Table 5.9. Since the B/C ratio in the *new signal installation* table was 0.18, which was larger than the B/C ratio of 0.17 in the *convert intersection into roundabout* table, it could not be selected twice because of the mutual exclusivity constraint regardless of the size of the total budget.

2: If the total budget constraint was set at \$5,000,000, then only the intersections which have the relatively high B/C ratios will be selected. The resulting interface was as shown in Figure 5.8.

The output shows that eight out of the 10 intersections were selected as shown in Table 5.11.

Self-check: At this point, the total budget was lower than the previous Scenario 1. For the repeated CFID 6544 intersection, the B/C ratio in Table 5.9 is

higher than the value in Table 5.8. Thus, the CFID 6544 intersection in Table 5.12 was selected and the CFID 6544 intersection in Table 5.8 could not be selected because of the mutual exclusivity constraint.

Case 3: Use the same sample dataset as in Case 2, but add more minimum countermeasure constraints, such as that the cost to convert an intersection to a roundabout must be at least \$3,500,000. In this case, the interface was as shown in Figure 5.9.

The output shows that seven out of the 10 intersections were selected as shown in Table 5.12.

Self-check: Three out of the four intersections that met the minimum program constraint in the *convert intersection to roundabout* table were selected. CFID 6544 intersection in the table was selected because, after selecting two candidates in the convert intersection to roundabout table, the total cost was \$3,000,000. Since the minimum program budget was \$3,500,000, the third candidate, CFID 6544, was selected. Meanwhile, CFID intersection 6544 in the *new signal installation* table could not be selected because of the mutual exclusivity constraint. Four other intersections with relatively higher B/C ratio candidates in the *new signal installation* table were also selected in order to make use of the entire budget.

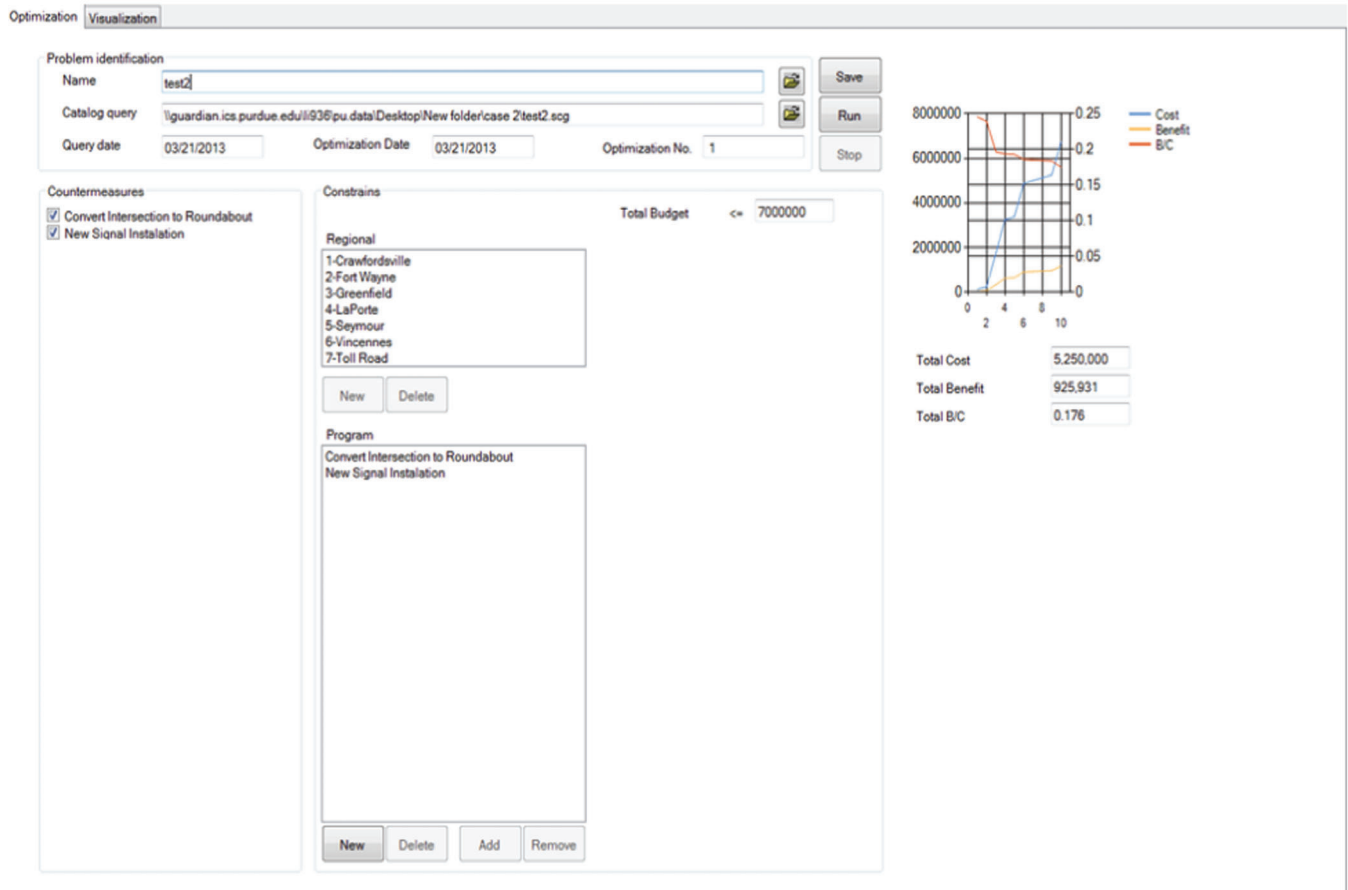


Figure 5.7 Test algorithm interface of Scenario 1 in Case 2.

TABLE 5.10
Output of selected intersections for Scenario 1 in Case 2

| CFID intersection | Applied Countermeasures | | Total Cost | Total Benefit | B/C |
|-------------------|-------------------------|---|------------|---------------|------|
| | C | D | | | |
| 6303 | 1 | 0 | 125000 | 30717 | 0.25 |
| 6883 | 1 | 0 | 125000 | 29100 | 0.23 |
| 6579 | 0 | 1 | 1500000 | 284464 | 0.19 |
| 7145 | 0 | 1 | 1500000 | 284464 | 0.19 |
| 6544 | 1 | 0 | 125000 | 22633 | 0.18 |
| 6311 | 1 | 0 | 125000 | 19400 | 0.16 |
| 6727 | 1 | 0 | 125000 | 19400 | 0.16 |
| 6701 | 1 | 0 | 125000 | 19400 | 0.16 |
| 6800 | 0 | 1 | 1500000 | 216353 | 0.14 |

C= new signal installation; D= convert intersection to roundabout; 1= applied; 0= not applied.

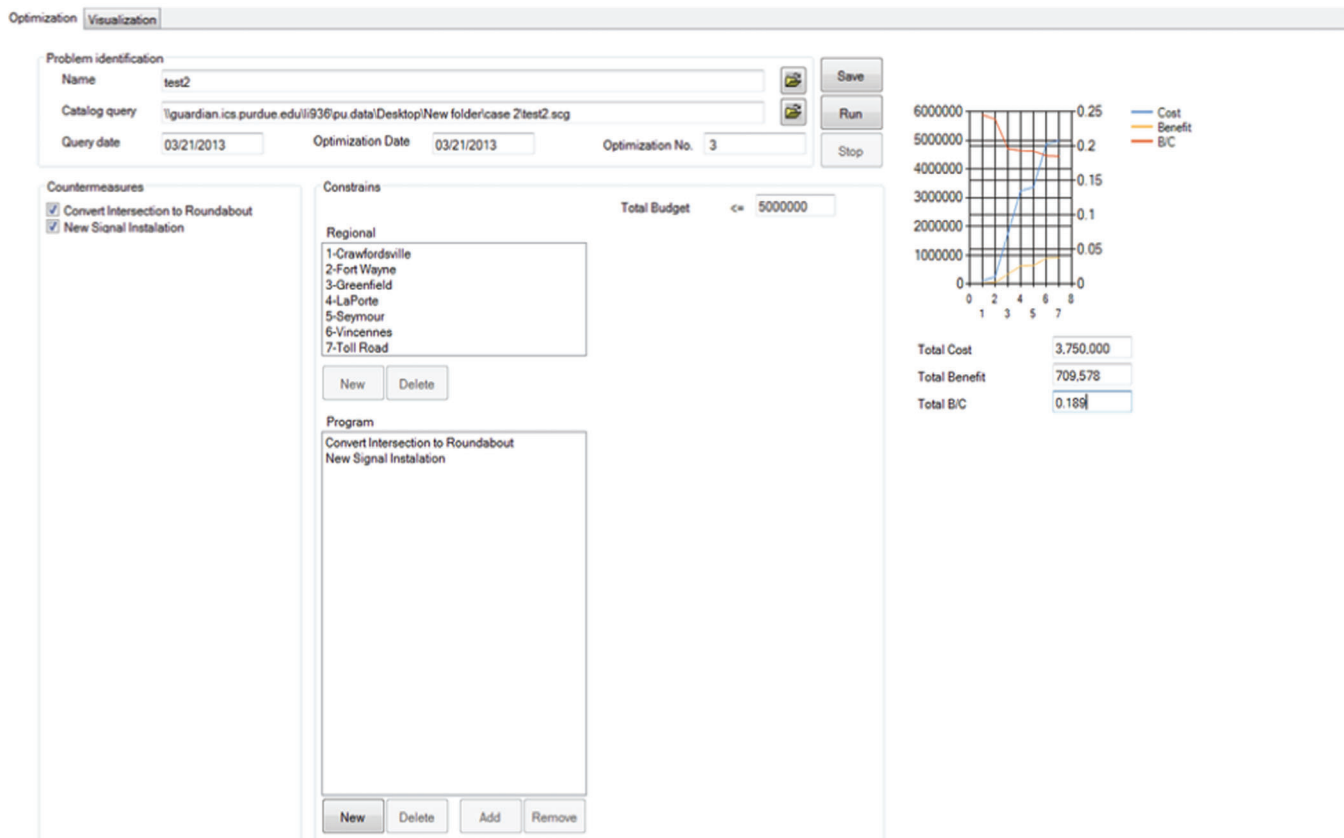


Figure 5.8 Test algorithm interface of Scenario 2 in Case 2.

TABLE 5.11
Output of selected intersections for Scenario 2 in Case 2

| CFID Intersection | Applied Countermeasures | | Total Cost | Total Benefit | B/C |
|-------------------|-------------------------|---|------------|---------------|------|
| | C | D | | | |
| 6303 | 1 | 0 | 125000 | 30717 | 0.25 |
| 6883 | 1 | 0 | 125000 | 29100 | 0.23 |
| 6579 | 0 | 1 | 1500000 | 284464 | 0.19 |
| 7145 | 0 | 1 | 1500000 | 284464 | 0.19 |
| 6544 | 1 | 0 | 125000 | 22633 | 0.18 |
| 6311 | 1 | 0 | 125000 | 19400 | 0.16 |
| 6701 | 1 | 0 | 125000 | 19400 | 0.16 |
| 6727 | 1 | 0 | 125000 | 19400 | 0.16 |

C= new signal installation; D= convert intersection to roundabout; 1= applied; 0= not applied.

TABLE 5.12
Output of selected intersections in Case 3

| CFID Intersection | Applied Countermeasures | | Total Cost | Total Benefit | B/C |
|-------------------|-------------------------|---|------------|---------------|------|
| | C | D | | | |
| 6579 | 0 | 1 | 1500000 | 284464 | 0.19 |
| 7145 | 0 | 1 | 1500000 | 284464 | 0.19 |
| 6544 | 0 | 1 | 1500000 | 256418 | 0.17 |
| 6303 | 1 | 0 | 125000 | 30717 | 0.25 |
| 6883 | 1 | 0 | 125000 | 29100 | 0.23 |
| 6311 | 1 | 0 | 125000 | 19400 | 0.16 |
| 6727 | 1 | 0 | 125000 | 19400 | 0.16 |

C= new signal installation; D= convert intersection to roundabout; 1= applied; 0= not applied.

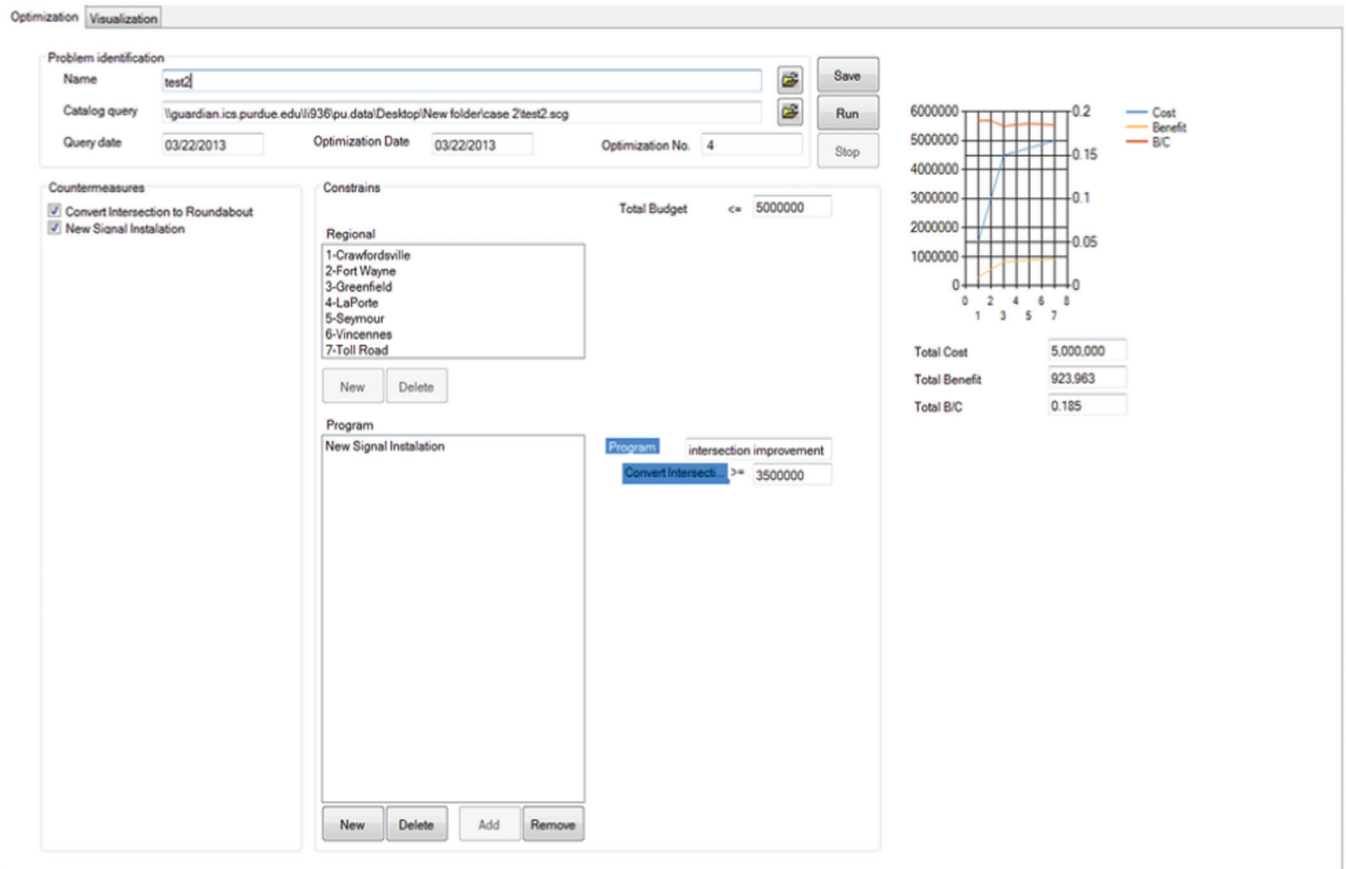


Figure 5.9 Test algorithm interface of Case 3.

TABLE 5.13

Test Case 4 subset sample dataset from *add shoulder rumble strips.csv*

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|------|
| 225795 | 1398 | 4752 | 3.4 |
| 238248 | 1512 | 4231 | 2.8 |
| 238149 | 2526 | 4231 | 1.68 |
| 218618 | 4350 | 8463 | 1.95 |
| 417817 | 2682 | 4231 | 1.58 |

Case 4: Create another optimization problem with two countermeasures. The countermeasures consisted of adding shoulder rumble strips and widening the outside shoulder width. Five segments were randomly selected in the *add shoulder rumble strips.csv* file and five segments were selected in the *widen outside shoulder width.csv* file. Since these two safety countermeasures could be carried out in the same location at the same time, they are not mutually exclusive. The sample dataset is shown in Table 5.13 and Table 5.14.

There were two identical segments named CFID-225795. When the total budget constraint was set at \$1,540,000, the interface is as shown in Figure 5.10.

In the output, all 10 segments were selected as shown in Table 5.15.

Self-check: All 10 segments, including the two identical segments, were selected because the minimum total costs of the safety countermeasures implemented in the 10 segments were \$1,539,307, which is less than the budget, and two safety countermeasures are not mutually exclusive; thus, all the segments were selected and the total benefit and total B/C ratio were \$175,195 and 0.114 respectively.

5.3.3 Evaluation of Heuristic Optimization Algorithm

The testing yielded reasonable results. Therefore, evaluation of the heuristic method was initiated. The purpose of the evaluation was to assess how closely the heuristic solution was to the optimal solution. Since the optimal solution was not known and obtaining it would be time-consuming, a random generation of feasible solutions was applied in the evaluation. A sufficient number of random solutions had to be generated to evaluate the heuristic solution. This evaluation was carried out with another computer tool that generates random solutions, checks their feasibility, calculates the objective function for feasible solutions, and computes the statistics of the solutions evaluated so far.

The number of generated feasible solutions had to be sufficiently large to claim that the results reasonably well reflected the quality of the heuristic solution. The evaluation generated positive results if the random search for a feasible solution was not better than the heuristic one, or a better solution was found in a random search that was only marginally superior to the heuristic method solution.

The specifications of the computer generating this search are as follows:

TABLE 5.14

Test Case 4 subset sample dataset from *widen outside shoulder width.csv*

| CFID Segment | Total Cost | Total Benefit | B/C |
|--------------|------------|---------------|-------|
| 244054 | 275255 | 27646 | 0.1 |
| 245175 | 341392 | 33175 | 0.097 |
| 420804 | 323045 | 33175 | 0.103 |
| 225795 | 286518 | 22117 | 0.077 |
| 247866 | 300628 | 33175 | 0.11 |

- Dell computer, Windows XP.
- Intel Core (TM) 2 Duo CPU 3.00 GHZ
- 3.25GB of RAM

Two different scenarios were defined to evaluate the heuristic algorithm. The entire original dataset is contained in Appendix C.

Scenario 1: Create an optimization problem with four countermeasures which include the following: adding shoulder rumble strips, widening the outside shoulder width, installing a new traffic signal, and converting an intersection to a roundabout. All the elements in these four files (Appendix C) were selected as the candidates. The total budget constraint is set at \$450,000 and the minimum program constraint is that the total cost of widening the outside shoulder width must be at least \$50,000. The interface is shown in Figure 5.11.

In the interface, researchers can select different countermeasures. A “√” means this countermeasure is selected and appears in the program column. There are six INDOT regions: Crawfordsville, Fort Wayne, Greenfield, LaPorte, Seymour, and Vincennes. Also, add the toll road in the region column. Researchers can select different budget constraints, regional constraints, and program constraints. The optimization column shows the current results. The horizontal axis represents the number of selected elements, the left-vertical axis represents money in dollars, and the right-vertical axis denotes the benefit/cost ratio.

After running 50 hours and 7 minutes, the results show that the random run best solution was slightly better than the heuristic method solution. The comparison information is shown in Table 5.16.

According to Table 5.16, the difference between the total safety benefit of the random and heuristic solutions is approximately 1%. The outputs of the selected elements are shown in Table 5.17.

Figure 5.12 shows that there were 28 identical location-countermeasure pairs; but there were 10 differences. One countermeasure for CFID 6303, CFID 6333, CFID 6547, CFID 6883, and CFID 7309 was in the heuristic solution, but there was no countermeasure in the random solution. One countermeasure for CFID 6800 was in the random solution, but there was no countermeasure in the heuristic solution. Two countermeasures for CFID 244054 and CFID 245175 were in the heuristic solution, while there was only one countermeasure in the random solution.

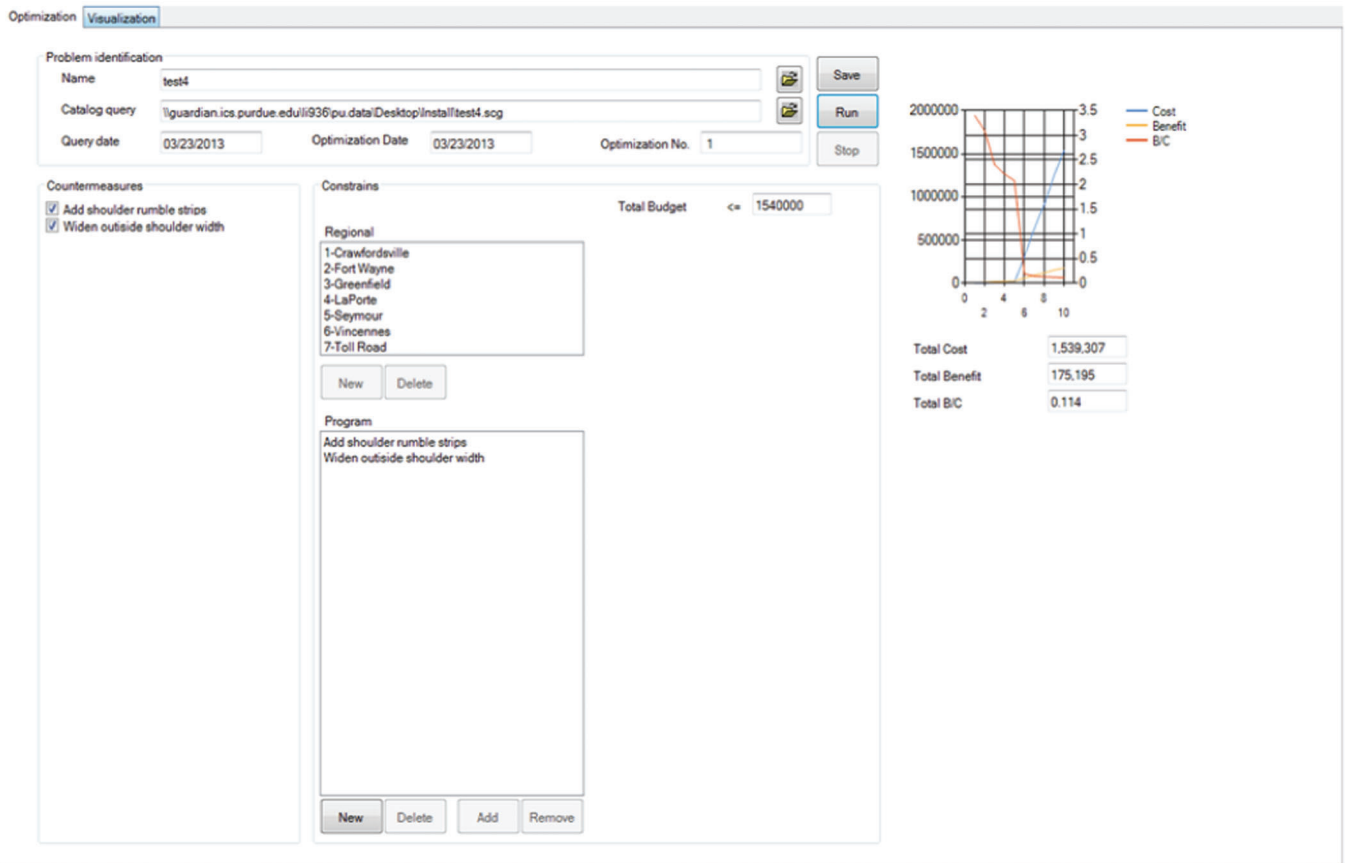


Figure 5.10 Test algorithm interface of Case 4.

TABLE 5.15
Output of selected segments in Case 4

| CFID Segment | Applied Countermeasures | | Total Cost | Total Benefit | B/C |
|--------------|-------------------------|---|------------|---------------|------|
| | A | B | | | |
| 225795 | 1 | 0 | 1398 | 4752 | 3.40 |
| 238248 | 1 | 0 | 1512 | 4231 | 2.80 |
| 218618 | 1 | 0 | 4350 | 8463 | 1.95 |
| 238149 | 1 | 0 | 2526 | 4231 | 1.68 |
| 417817 | 1 | 0 | 2682 | 4231 | 1.58 |
| 247866 | 0 | 1 | 300628 | 33175 | 0.11 |
| 420804 | 0 | 1 | 323045 | 33175 | 0.10 |
| 244054 | 0 | 1 | 275255 | 27646 | 0.10 |
| 245175 | 0 | 1 | 341392 | 33175 | 0.10 |
| 225795 | 0 | 1 | 286518 | 21121 | 0.07 |

A= add shoulder rumble strips; B= widen outside shoulder width; 1= applied; 0= not applied.

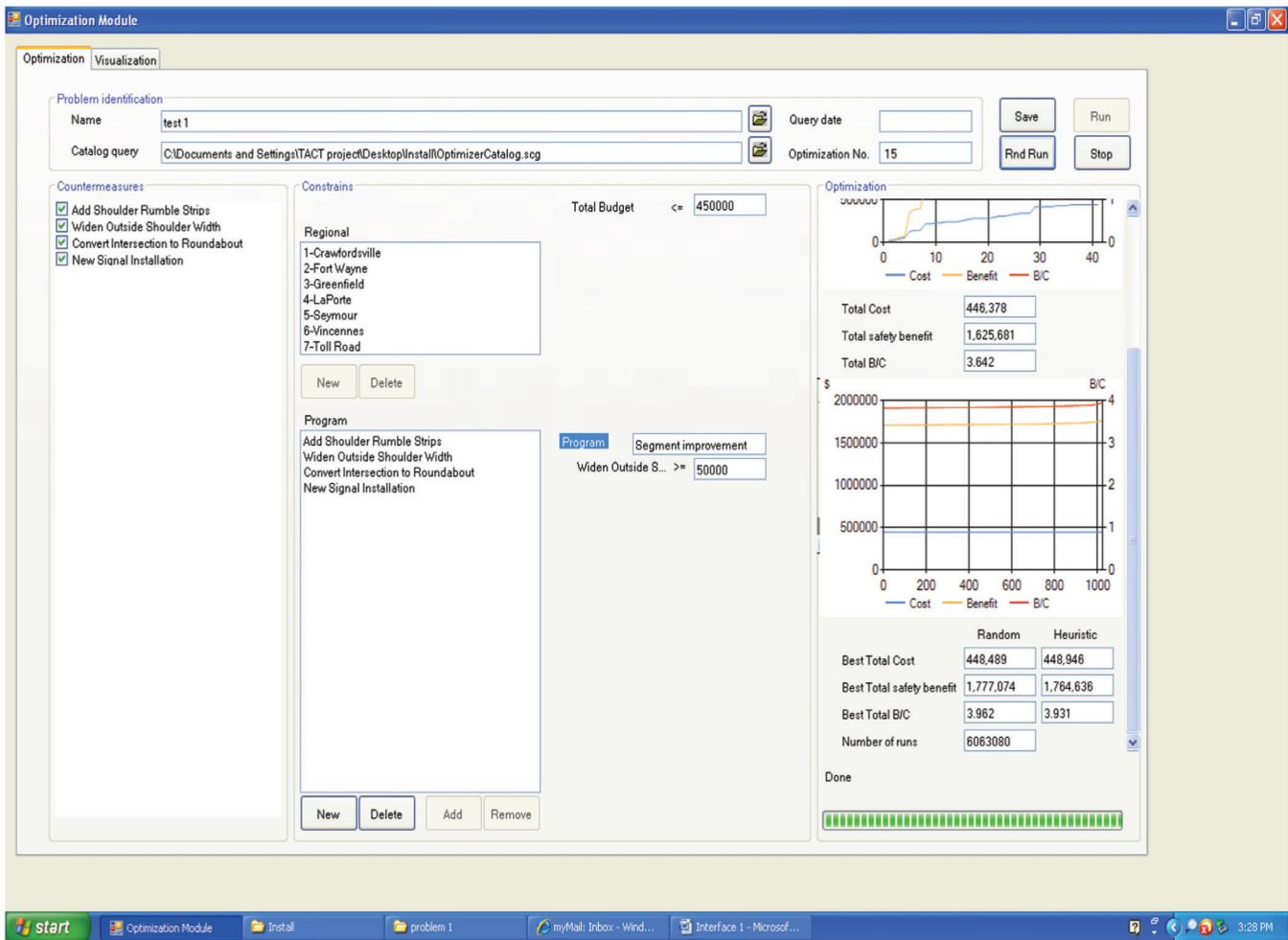


Figure 5.11 Evaluation interface of Scenario 1.

Two countermeasures for CFID 226032 and CFID 417817 were in the random solution, and only one countermeasure in the heuristic solution.

Figure 5.13 compares the safety countermeasures selected in the heuristic method solution to the random run best solution. It showed that there were 21, 5, 12, and 3 elements selected to implement add shoulder rumble strips (A), widen outside shoulder width (B), new signal installation (C), and convert intersection to roundabout (D) in the heuristic solution compared to 21, 5, 7, and 4 for the four countermeasures respectively in the random solution.

TABLE 5.16 Comparison of random and heuristic method solutions in Scenario 1

| | Heuristic | Random |
|----------------------|-----------|-----------|
| Budget spent | 448,946 | 448,489 |
| Total safety benefit | 1,764,636 | 1,777,074 |
| Total B/C | 3.931 | 3.962 |
| Number of runs | 1 | 6,063,080 |
| Execution time(s) | 0.03 | 180,420 |

The random solution was superior to the heuristic method solution because it had more safety benefits.

Scenario 2: Create another optimization problem with four countermeasures which include the following: add shoulder rumble strips, widening the outside shoulder width, installing a new traffic signal, and converting an intersection to a roundabout. All the elements in these four files are selected as the candidates. The total budget constraint is set at \$450,000, and the interface appears in Figure 5.14.

After 49 hours and 37 minutes, the results show that the heuristic method solution is slightly better than the random best solution. The comparison information is shown in Table 5.18.

According to Table 5.18, the difference in the total safety benefits between the random run best solution and the heuristic solution is approximately 1%. The outputs of selected elements are shown in Table 5.19.

Figure 5.15 shows that there were 32 identical location-countermeasure pairs. But, there were five differences. One countermeasure for CFID 6303, CFID 6333 was in the heuristic solution, but there was no countermeasure in the random solution. One counter-

TABLE 5.17
Output of selected elements in Scenario 1

| CFID Element | Heuristic Method Solution | | | | | | | | | | | | | | Current Random Run Best Solution | | | | | | | | | | | | | |
|--------------|---------------------------|---|---|---|-------------|----------------|-------|-------------|----------------|-----|--------------|-------------------------|-------|--------|----------------------------------|-------------|----------------|-----|-------------|----------------|-----|--|--|--|--|--|--|--|
| | Applied Countermeasures | | | | | | | Annual Cost | Annual Benefit | B/C | CFID Element | Applied Countermeasures | | | | | | | Annual Cost | Annual Benefit | B/C | | | | | | | |
| | A | B | C | D | Annual Cost | Annual Benefit | B/C | | | | | A | B | C | D | Annual Cost | Annual Benefit | B/C | | | | | | | | | | |
| 6275 | 0 | 0 | 1 | 0 | 12500 | 58200 | 4.66 | 6275 | 0 | 0 | 1 | 0 | 12500 | 58200 | 4.66 | | | | | | | | | | | | | |
| 6288 | 0 | 0 | 1 | 0 | 12500 | 63050 | 5.04 | 6288 | 0 | 0 | 1 | 0 | 12500 | 63050 | 5.04 | | | | | | | | | | | | | |
| 6300 | 0 | 0 | 1 | 0 | 12500 | 121250 | 9.70 | 6300 | 0 | 0 | 1 | 0 | 12500 | 121250 | 9.70 | | | | | | | | | | | | | |
| 6303 | 0 | 0 | 1 | 0 | 12500 | 30717 | 2.46 | | | | | | | | | | | | | | | | | | | | | |
| 6333 | 0 | 0 | 1 | 0 | 12500 | 37183 | 2.97 | | | | | | | | | | | | | | | | | | | | | |
| 6547 | 0 | 0 | 1 | 0 | 12500 | 30717 | 2.46 | | | | | | | | | | | | | | | | | | | | | |
| 6579 | 0 | 0 | 1 | 0 | 75000 | 284464 | 3.79 | 6579 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 | | | | | | | | | | | | | |
| 6587 | 0 | 0 | 1 | 0 | 12500 | 53350 | 4.27 | 6587 | 0 | 0 | 1 | 0 | 12500 | 53350 | 4.27 | | | | | | | | | | | | | |
| 6719 | 0 | 0 | 0 | 1 | 75000 | 256418 | 3.42 | 6719 | 0 | 0 | 0 | 1 | 75000 | 256418 | 3.42 | | | | | | | | | | | | | |
| | | | | | | | | 6800 | 0 | 0 | 0 | 1 | 75000 | 216353 | 2.88 | | | | | | | | | | | | | |
| 6883 | 0 | 0 | 1 | 0 | 12500 | 29100 | 2.33 | | | | | | | | | | | | | | | | | | | | | |
| 7069 | 0 | 0 | 1 | 0 | 12500 | 80834 | 6.47 | 7069 | 0 | 0 | 1 | 0 | 12500 | 80834 | 6.47 | | | | | | | | | | | | | |
| 7145 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 | 7145 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 | | | | | | | | | | | | | |
| 7218 | 0 | 0 | 1 | 0 | 12500 | 85684 | 6.85 | 7218 | 0 | 0 | 1 | 0 | 12500 | 85684 | 6.85 | | | | | | | | | | | | | |
| 7272 | 0 | 0 | 1 | 0 | 12500 | 54967 | 4.40 | 7272 | 0 | 0 | 1 | 0 | 12500 | 54967 | 4.40 | | | | | | | | | | | | | |
| 7309 | 0 | 0 | 1 | 0 | 12500 | 32333 | 2.59 | | | | | | | | | | | | | | | | | | | | | |
| 218618 | 1 | 0 | 0 | 0 | 621 | 8463 | 13.63 | 218618 | 1 | 0 | 0 | 0 | 621 | 8463 | 13.63 | | | | | | | | | | | | | |
| 225795 | 1 | 0 | 0 | 0 | 200 | 4752 | 23.76 | 225795 | 1 | 0 | 0 | 0 | 200 | 4752 | 23.76 | | | | | | | | | | | | | |
| 226032 | 1 | 0 | 0 | 0 | 118 | 4752 | 40.27 | 226032 | 1 | 1 | 0 | 0 | 7006 | 8469 | 1.21 | | | | | | | | | | | | | |
| 232251 | 1 | 0 | 0 | 0 | 85 | 4231 | 49.78 | 232251 | 1 | 0 | 0 | 0 | 85 | 4231 | 49.78 | | | | | | | | | | | | | |
| 234444 | 1 | 0 | 0 | 0 | 33 | 4752 | 144.0 | 234444 | 1 | 0 | 0 | 0 | 33 | 4752 | 144.0 | | | | | | | | | | | | | |
| 235280 | 1 | 0 | 0 | 0 | 141 | 4752 | 33.70 | 235280 | 1 | 0 | 0 | 0 | 141 | 4752 | 33.70 | | | | | | | | | | | | | |
| 236583 | 1 | 0 | 0 | 0 | 81 | 4231 | 52.23 | 236583 | 1 | 0 | 0 | 0 | 81 | 4231 | 52.23 | | | | | | | | | | | | | |
| 237139 | 1 | 0 | 0 | 0 | 141 | 4231 | 30.01 | 237139 | 1 | 0 | 0 | 0 | 141 | 4231 | 30.01 | | | | | | | | | | | | | |
| 238122 | 1 | 0 | 0 | 0 | 68 | 4231 | 62.22 | 238122 | 1 | 0 | 0 | 0 | 68 | 4231 | 62.22 | | | | | | | | | | | | | |
| 238149 | 1 | 0 | 0 | 0 | 361 | 4231 | 11.72 | 238149 | 1 | 0 | 0 | 0 | 361 | 4231 | 11.72 | | | | | | | | | | | | | |
| 238248 | 1 | 1 | 0 | 0 | 7956 | 12305 | 1.55 | 238248 | 1 | 1 | 0 | 0 | 7956 | 12305 | 1.55 | | | | | | | | | | | | | |
| 239231 | 1 | 0 | 0 | 0 | 159 | 4752 | 29.89 | 239231 | 1 | 0 | 0 | 0 | 159 | 4752 | 29.89 | | | | | | | | | | | | | |
| 239995 | 1 | 0 | 0 | 0 | 421 | 14257 | 33.86 | 239995 | 1 | 0 | 0 | 0 | 421 | 14257 | 33.86 | | | | | | | | | | | | | |
| 241963 | 1 | 0 | 0 | 0 | 76 | 4752 | 62.53 | 241963 | 1 | 0 | 0 | 0 | 76 | 4752 | 62.53 | | | | | | | | | | | | | |
| 244054 | 1 | 1 | 0 | 0 | 13955 | 39479 | 2.83 | 244054 | 1 | 0 | 0 | 0 | 192 | 14257 | 74.26 | | | | | | | | | | | | | |
| 245175 | 1 | 1 | 0 | 0 | 17308 | 45008 | 2.60 | 245175 | 1 | 0 | 0 | 0 | 238 | 14257 | 59.90 | | | | | | | | | | | | | |
| 245360 | 1 | 0 | 0 | 0 | 69 | 4752 | 68.87 | 245360 | 1 | 0 | 0 | 0 | 69 | 4752 | 68.87 | | | | | | | | | | | | | |
| 247281 | 1 | 0 | 0 | 0 | 170 | 4752 | 27.95 | 247281 | 1 | 0 | 0 | 0 | 170 | 4752 | 27.95 | | | | | | | | | | | | | |
| 247866 | 0 | 1 | 0 | 0 | 15031 | 33175 | 2.21 | 247866 | 0 | 1 | 0 | 0 | 15031 | 33175 | 2.21 | | | | | | | | | | | | | |
| 417817 | 1 | 0 | 0 | 0 | 383 | 4231 | 11.05 | 417817 | 1 | 1 | 0 | 0 | 11371 | 11570 | 1.02 | | | | | | | | | | | | | |
| 420356 | 1 | 0 | 0 | 0 | 192 | 4752 | 24.75 | 420356 | 1 | 0 | 0 | 0 | 192 | 4752 | 24.75 | | | | | | | | | | | | | |
| 420804 | 1 | 1 | 0 | 0 | 16377 | 41063 | 2.51 | 420804 | 1 | 1 | 0 | 0 | 16377 | 41063 | 2.51 | | | | | | | | | | | | | |

A= add shoulder rumble strips; B= widen outside shoulder width; C= new signal installation; D= convert intersection to roundabout; 1= applied countermeasures; 0= not applied countermeasures.

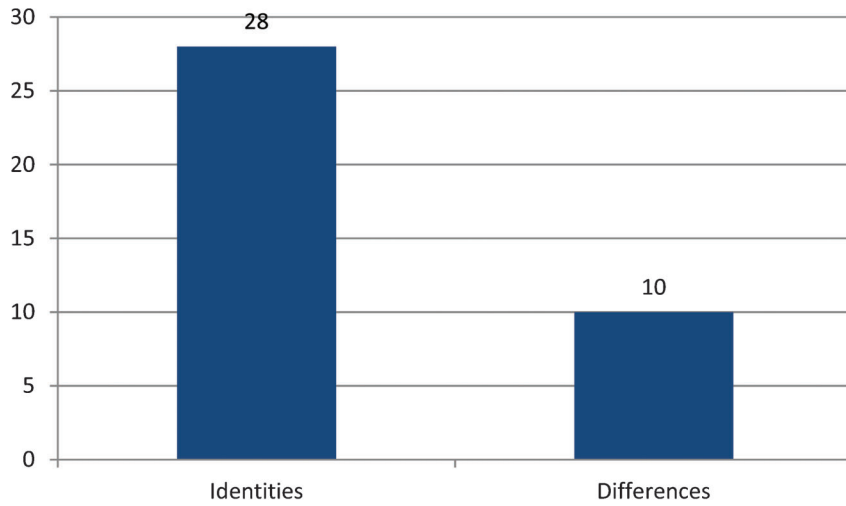


Figure 5.12 Count identities and differences elements in Scenario 1.

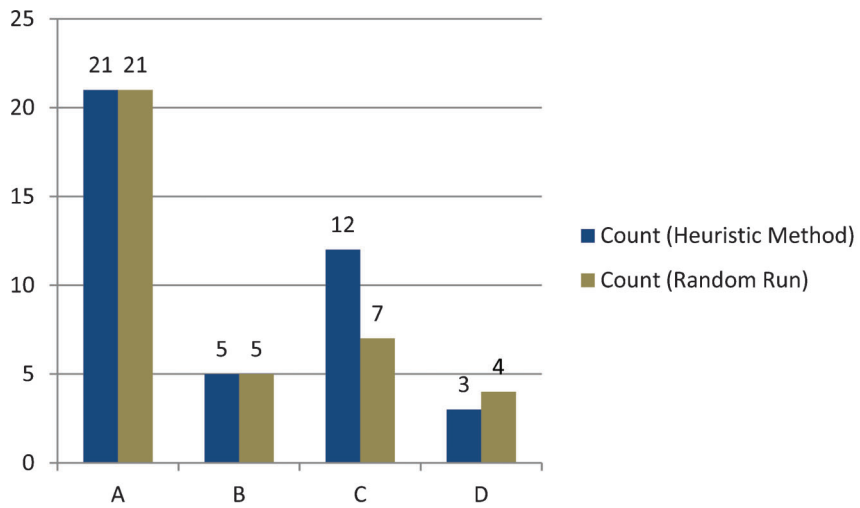


Figure 5.13 Number of selected four different safety countermeasures in Scenario 1.

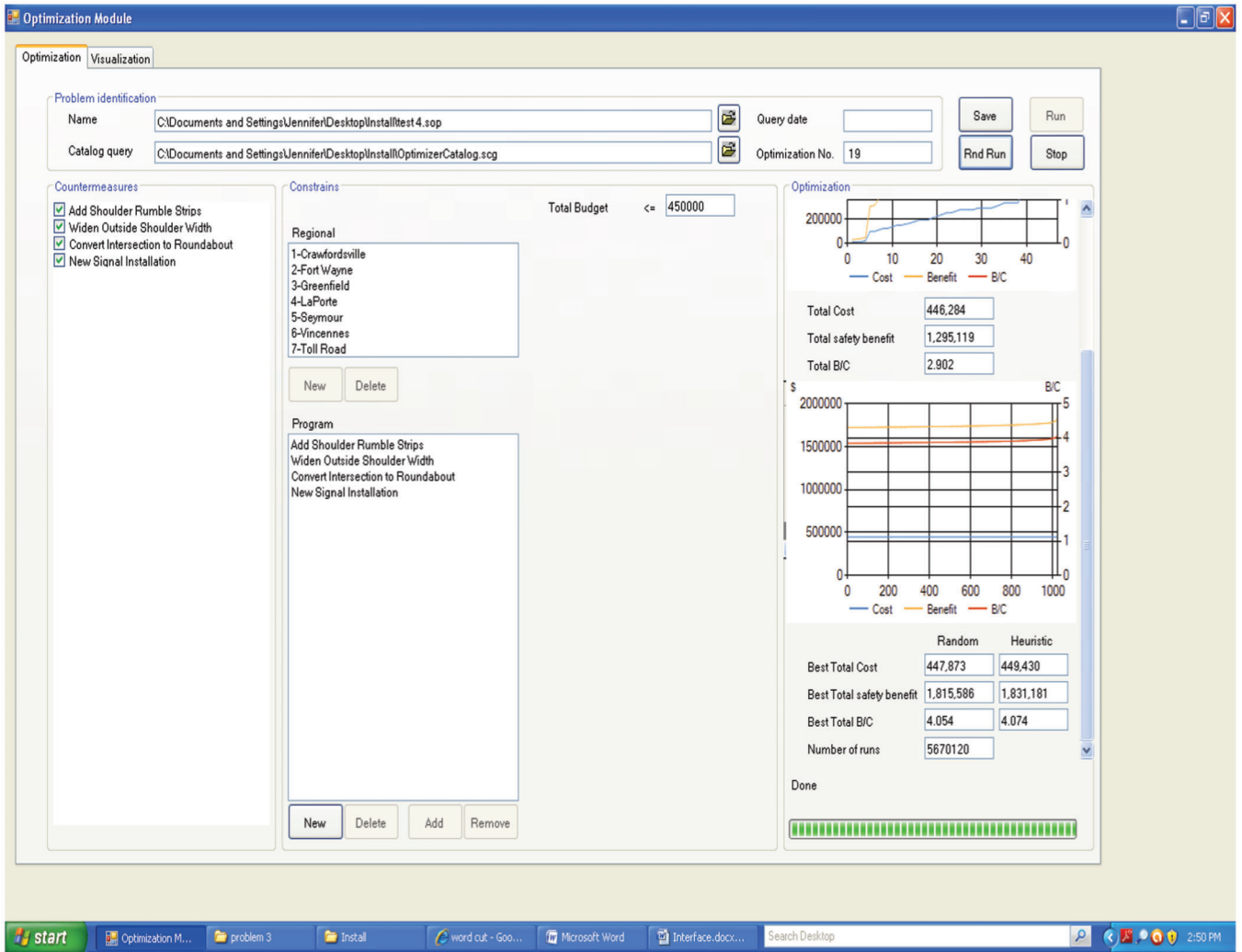


Figure 5.14 Evaluation interface of Scenario 2.

TABLE 5.18
Comparison of random and heuristic solutions in Scenario 2

| | Heuristic | Random |
|-----------------------------|-----------|-----------|
| Budget spent | 449,430 | 447,873 |
| Total safety benefit | 1,831,181 | 1,815,586 |
| Total B/C | 4.074 | 4.054 |
| Number of runs | 1 | 5,670,120 |
| Execution time(s) | 0.03 | 178,620 |

TABLE 5.19
Output of selected elements in Scenario 2

| CFID Element | Heuristic Method Solution | | | | | | | | | | Current Random Run Best Solution | | | | | | | | | | | | | | | | | |
|--------------|---------------------------|---|---|---|---|--------------|-------|----------------|-------------|---|----------------------------------|-------------------------|---|---|--------|-------|----------------|-------------|-----|---|---|---|---|---|--------|-------|--------|-------|
| | Applied Countermeasures | | | | | CFID Element | B/C | Annual Benefit | Annual Cost | D | C | Applied Countermeasures | | | | | Annual Benefit | Annual Cost | B/C | | | | | | | | | |
| | A | B | C | D | A | | | | | | | B | C | D | | | | | | | | | | | | | | |
| 6275 | 0 | 0 | 1 | 0 | 0 | 6275 | 4.66 | 58200 | 12500 | 0 | 1 | 0 | 0 | 0 | 6275 | 4.66 | 58200 | 12500 | 0 | 1 | 0 | 0 | 0 | 0 | 6275 | 4.66 | 58200 | 12500 |
| 6288 | 0 | 0 | 1 | 0 | 0 | 6288 | 5.04 | 63050 | 12500 | 0 | 1 | 0 | 0 | 0 | 6288 | 5.04 | 63050 | 12500 | 0 | 1 | 0 | 0 | 0 | 0 | 6288 | 5.04 | 63050 | 12500 |
| 6300 | 0 | 0 | 1 | 0 | 0 | 6300 | 9.70 | 121250 | 12500 | 0 | 0 | 0 | 0 | 0 | 6300 | 9.70 | 121250 | 12500 | 0 | 0 | 0 | 0 | 0 | 0 | 6300 | 9.70 | 121250 | 12500 |
| 6303 | 0 | 0 | 1 | 0 | 0 | | 2.46 | 30717 | 12500 | | | | | | | 2.46 | 30717 | | | | | | | | | | | |
| 6333 | 0 | 0 | 1 | 0 | 0 | | 2.97 | 37183 | 12500 | | | | | | | 2.97 | 37183 | | | | | | | | | | | |
| 6547 | 0 | 0 | 1 | 0 | 0 | 6547 | 2.46 | 30717 | 12500 | 0 | 1 | 0 | 0 | 0 | 6547 | 2.46 | 30717 | 12500 | 0 | 1 | 0 | 0 | 0 | 0 | 6547 | 2.46 | 30717 | 12500 |
| 6579 | 0 | 0 | 0 | 1 | 0 | 6579 | 3.79 | 284464 | 75000 | 0 | 0 | 1 | 0 | 0 | 6579 | 3.79 | 284464 | 75000 | 0 | 0 | 1 | 0 | 0 | 0 | 6579 | 3.79 | 284464 | 75000 |
| 6587 | 0 | 0 | 1 | 0 | 0 | 6587 | 4.27 | 53350 | 12500 | 0 | 0 | 1 | 0 | 0 | 6587 | 4.27 | 53350 | 12500 | 0 | 0 | 1 | 0 | 0 | 0 | 6587 | 4.27 | 53350 | 12500 |
| 6719 | 0 | 0 | 0 | 1 | 0 | 6719 | 3.42 | 256418 | 75000 | 0 | 0 | 0 | 1 | 0 | 6719 | 3.42 | 256418 | 75000 | 0 | 0 | 0 | 1 | 0 | 0 | 6719 | 3.42 | 256418 | 75000 |
| 6800 | 0 | 0 | 0 | 1 | 0 | 6800 | 2.88 | 216353 | 75000 | 0 | 0 | 0 | 1 | 0 | 6800 | 2.88 | 216353 | 75000 | 0 | 0 | 0 | 1 | 0 | 0 | 6800 | 2.88 | 216353 | 75000 |
| 7069 | 0 | 0 | 1 | 0 | 0 | 7069 | 6.47 | 80834 | 12500 | 0 | 0 | 1 | 0 | 0 | 7069 | 6.47 | 80834 | 12500 | 0 | 0 | 1 | 0 | 0 | 0 | 7069 | 6.47 | 80834 | 12500 |
| 7145 | 0 | 0 | 0 | 1 | 0 | 7145 | 3.79 | 284464 | 75000 | 0 | 0 | 0 | 1 | 0 | 7145 | 3.79 | 284464 | 75000 | 0 | 0 | 0 | 1 | 0 | 0 | 7145 | 3.79 | 284464 | 75000 |
| 7218 | 0 | 0 | 1 | 0 | 0 | 7218 | 6.85 | 85684 | 12500 | 0 | 0 | 1 | 0 | 0 | 7218 | 6.85 | 85684 | 12500 | 0 | 0 | 1 | 0 | 0 | 0 | 7218 | 6.85 | 85684 | 12500 |
| 7272 | 0 | 0 | 1 | 0 | 0 | 7272 | 4.40 | 54967 | 12500 | 0 | 0 | 1 | 0 | 0 | 7272 | 4.40 | 54967 | 12500 | 0 | 0 | 1 | 0 | 0 | 0 | 7272 | 4.40 | 54967 | 12500 |
| 7309 | 0 | 0 | 1 | 0 | 0 | 7309 | 2.59 | 32333 | 12500 | 0 | 0 | 1 | 0 | 0 | 7309 | 2.59 | 32333 | 12500 | 0 | 0 | 1 | 0 | 0 | 0 | 7309 | 2.59 | 32333 | 12500 |
| 218618 | 1 | 0 | 0 | 0 | 0 | 218618 | 13.63 | 8463 | 621 | 1 | 0 | 0 | 0 | 0 | 218618 | 13.63 | 8463 | 621 | 1 | 0 | 0 | 0 | 0 | 0 | 218618 | 13.63 | 8463 | 621 |
| 225795 | 1 | 0 | 0 | 0 | 0 | 225795 | 23.76 | 4752 | 200 | 1 | 0 | 0 | 0 | 0 | 225795 | 23.76 | 4752 | 200 | 1 | 0 | 0 | 0 | 0 | 0 | 225795 | 23.76 | 4752 | 200 |
| 226032 | 1 | 0 | 0 | 0 | 0 | 226032 | 40.27 | 4752 | 118 | 1 | 0 | 0 | 0 | 0 | 226032 | 40.27 | 4752 | 118 | 1 | 0 | 0 | 0 | 0 | 0 | 226032 | 40.27 | 4752 | 118 |
| 232251 | 1 | 0 | 0 | 0 | 0 | 232251 | 49.78 | 4231 | 85 | 1 | 0 | 0 | 0 | 0 | 232251 | 49.78 | 4231 | 85 | 1 | 0 | 0 | 0 | 0 | 0 | 232251 | 49.78 | 4231 | 85 |
| 234444 | 1 | 0 | 0 | 0 | 0 | 234444 | 144 | 4752 | 33 | 1 | 0 | 0 | 0 | 0 | 234444 | 144 | 4752 | 33 | 1 | 0 | 0 | 0 | 0 | 0 | 234444 | 144 | 4752 | 33 |
| 235280 | 1 | 0 | 0 | 0 | 0 | 235280 | 33.70 | 4752 | 141 | 1 | 0 | 0 | 0 | 0 | 235280 | 33.70 | 4752 | 141 | 1 | 0 | 0 | 0 | 0 | 0 | 235280 | 33.70 | 4752 | 141 |
| 236583 | 1 | 0 | 0 | 0 | 0 | 236583 | 52.23 | 4231 | 81 | 1 | 0 | 0 | 0 | 0 | 236583 | 52.23 | 4231 | 81 | 1 | 0 | 0 | 0 | 0 | 0 | 236583 | 52.23 | 4231 | 81 |
| 237139 | 1 | 0 | 0 | 0 | 0 | 237139 | 30.01 | 4231 | 141 | 1 | 0 | 0 | 0 | 0 | 237139 | 30.01 | 4231 | 141 | 1 | 0 | 0 | 0 | 0 | 0 | 237139 | 30.01 | 4231 | 141 |
| 238122 | 1 | 0 | 0 | 0 | 0 | 238122 | 62.22 | 4231 | 68 | 1 | 0 | 0 | 0 | 0 | 238122 | 62.22 | 4231 | 68 | 1 | 0 | 0 | 0 | 0 | 0 | 238122 | 62.22 | 4231 | 68 |
| 238149 | 1 | 0 | 0 | 0 | 0 | 238149 | 11.72 | 4231 | 361 | 1 | 0 | 0 | 0 | 0 | 238149 | 11.72 | 4231 | 361 | 1 | 0 | 0 | 0 | 0 | 0 | 238149 | 11.72 | 4231 | 361 |
| 238248 | 1 | 1 | 0 | 0 | 0 | 238248 | 1.55 | 12305 | 7956 | 1 | 1 | 0 | 0 | 0 | 238248 | 1.55 | 12305 | 7956 | 1 | 1 | 0 | 0 | 0 | 0 | 238248 | 1.55 | 12305 | 7956 |
| 239231 | 1 | 0 | 0 | 0 | 0 | 239231 | 29.89 | 4752 | 159 | 1 | 0 | 0 | 0 | 0 | 239231 | 29.89 | 4752 | 159 | 1 | 0 | 0 | 0 | 0 | 0 | 239231 | 29.89 | 4752 | 159 |
| 239995 | 1 | 0 | 0 | 0 | 0 | 239995 | 33.86 | 14257 | 421 | 1 | 0 | 0 | 0 | 0 | 239995 | 33.86 | 14257 | 421 | 1 | 0 | 0 | 0 | 0 | 0 | 239995 | 33.86 | 14257 | 421 |
| 241963 | 1 | 0 | 0 | 0 | 0 | 241963 | 62.53 | 4752 | 76 | 1 | 0 | 0 | 0 | 0 | 241963 | 62.53 | 4752 | 76 | 1 | 0 | 0 | 0 | 0 | 0 | 241963 | 62.53 | 4752 | 76 |
| 244054 | 1 | 0 | 0 | 0 | 0 | 244054 | 74.26 | 14257 | 192 | 1 | 0 | 0 | 0 | 0 | 244054 | 74.26 | 14257 | 192 | 1 | 0 | 0 | 0 | 0 | 0 | 244054 | 74.26 | 14257 | 192 |
| 245175 | 1 | 0 | 0 | 0 | 0 | 245175 | 59.90 | 14257 | 238 | 1 | 0 | 0 | 0 | 0 | 245175 | 59.90 | 14257 | 238 | 1 | 0 | 0 | 0 | 0 | 0 | 245175 | 59.90 | 14257 | 238 |
| 245360 | 1 | 0 | 0 | 0 | 0 | 245360 | 68.87 | 4752 | 69 | 1 | 0 | 0 | 0 | 0 | 245360 | 68.87 | 4752 | 69 | 1 | 0 | 0 | 0 | 0 | 0 | 245360 | 68.87 | 4752 | 69 |
| 247281 | 1 | 0 | 0 | 0 | 0 | 247281 | 27.95 | 4752 | 170 | 1 | 0 | 0 | 0 | 0 | 247281 | 27.95 | 4752 | 170 | 1 | 0 | 0 | 0 | 0 | 0 | 247281 | 27.95 | 4752 | 170 |
| 417817 | 1 | 0 | 0 | 0 | 0 | 417817 | 11.05 | 4231 | 383 | 1 | 0 | 0 | 0 | 0 | 417817 | 11.05 | 4231 | 383 | 1 | 0 | 0 | 0 | 0 | 0 | 417817 | 11.05 | 4231 | 383 |
| 420356 | 1 | 0 | 0 | 0 | 0 | 420356 | 24.75 | 4752 | 192 | 1 | 0 | 0 | 0 | 0 | 420356 | 24.75 | 4752 | 192 | 1 | 0 | 0 | 0 | 0 | 0 | 420356 | 24.75 | 4752 | 192 |
| 420804 | 1 | 0 | 0 | 0 | 0 | 420804 | 42.24 | 9504 | 225 | 1 | 0 | 0 | 0 | 0 | 420804 | 42.24 | 9504 | 225 | 1 | 0 | 0 | 0 | 0 | 0 | 420804 | 42.24 | 9504 | 225 |

A = add shoulder rumble strips; B = widen outside shoulder width; C = new signal installation; D = convert intersection to roundabout; 1 = applied countermeasures; 0 = not applied countermeasures.

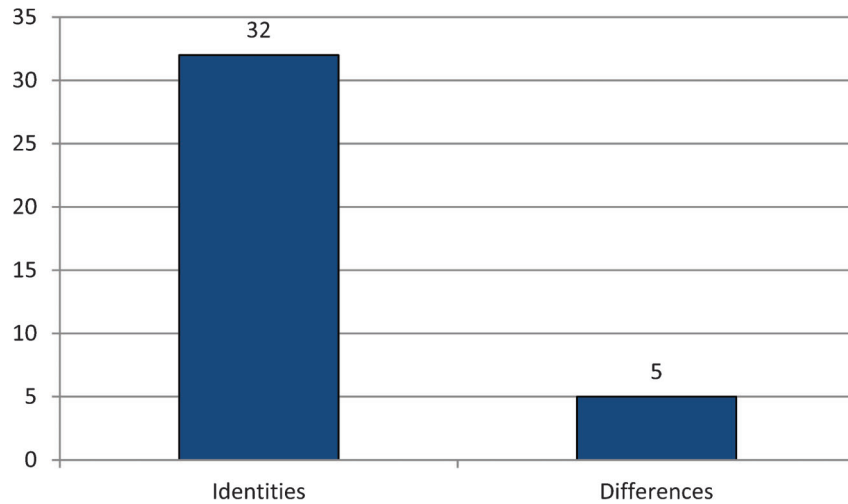


Figure 5.15 Count identities and differences elements in Scenario 2.

measure for CFID 247866 was in the random solution, but there was no countermeasure in the heuristic solution. Two countermeasures for CFID 238248 were in heuristic solution, only single countermeasure in random solution. Two countermeasures for CFID 420804 were in random solution, only single countermeasure in heuristic solution.

Figure 5.16 compares how many safety countermeasures were selected in the heuristic method solution with the random best solution. It shows that there were 21, 1, 11, and 4 elements selected to implement add shoulder rumble strips (A), widen outside shoulder width (B), new signal installation (C) and convert intersection to roundabout (D) in the heuristic solution while there were 21, 2, 9, and 4 for the four countermeasures respectively in the random solution.

In Scenario 2, currently, the heuristic method solution is better than the random solution, which means it generated positive results and more time would be needed to obtain a better random solution

than the heuristic method solution under these constraints.

Scenario 3: Create another optimization problem with four countermeasures that include the following: adding shoulder rumble strips, widening the outside shoulder width, installing a new traffic signal, and converting an intersection to a roundabout. All the elements in these four files are selected as the candidates. If the total budget constraint is set at \$500,000, the minimum program constraint is that the total cost of converting an intersection to a roundabout must be at least \$150,000. The interface is shown in Figure 5.17.

After 92 hours and 7 minutes, the results show that the random best solution is slightly better than the heuristic method solution. The comparison information is shown in Table 5.20.

According to Table 5.20, the difference between the total safety benefits of the random best solution and the

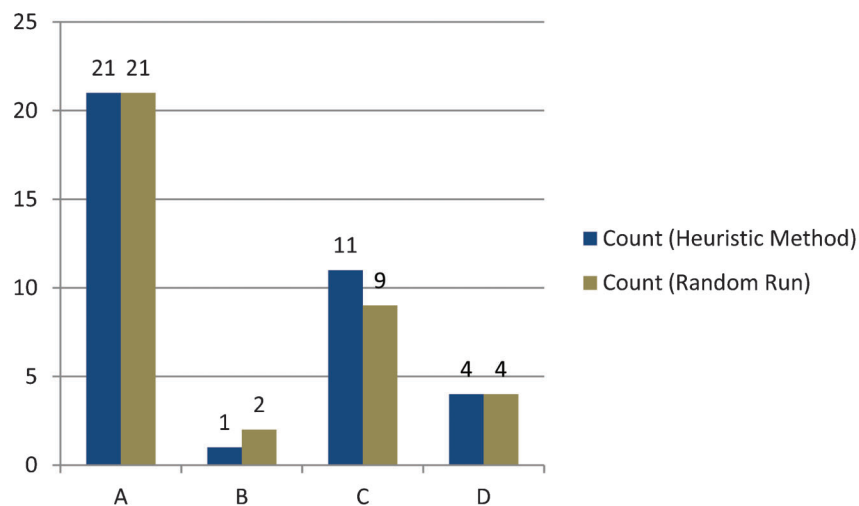


Figure 5.16 Number of selected four different safety countermeasures in Scenario 2.

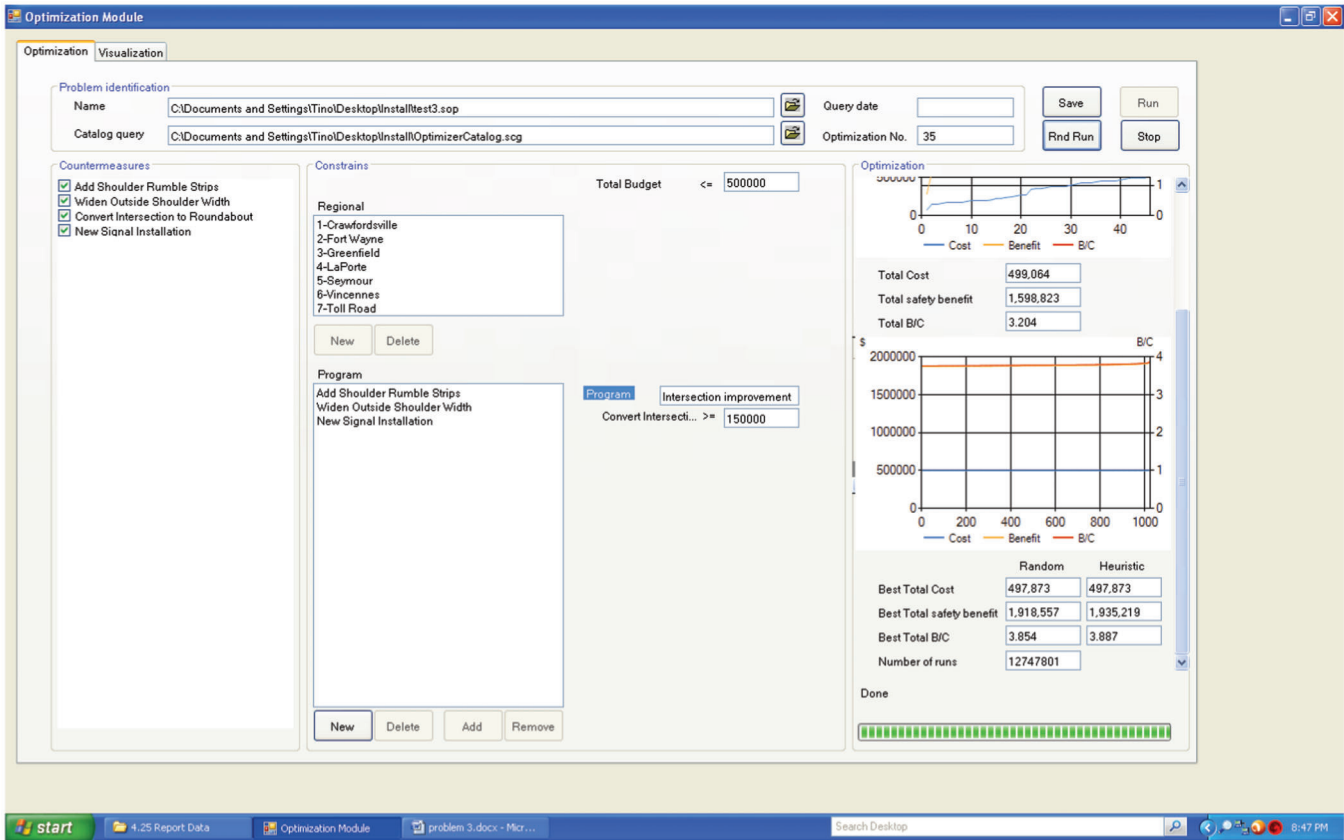


Figure 5.17 Evaluation interface of Scenario 3.

heuristic solution is approximately 1%. The outputs of selected elements are shown in Table 5.21.

Figure 5.18 shows that there were 35 identical location-countermeasure pairs. But, there were four differences. One countermeasure for CFID 6303, CFID 6883 was in the heuristic solution, and there was no countermeasure in the random solution. One countermeasure for CFID 6701 and CFID 6727 was in the random solution, and there was no countermeasure in the heuristic solution.

Figure 5.19 shows how many safety countermeasures were selected in the heuristic method solution compared to the random best solution. It shows that there were 22, 1, 13, and 4 elements selected to implement add shoulder rumble strips (A), widen outside shoulder width (B), new signal installation (C) and convert intersection to roundabout (D) in both solutions.

TABLE 5.20 Comparison of random and heuristic solutions in Scenario 3

| | Heuristic | Random |
|----------------------|-----------|------------|
| Budget spent | 497,873 | 497,873 |
| Total safety benefit | 1,935,219 | 1,918,557 |
| Total B/C | 3.887 | 3.854 |
| Number of runs | 1 | 12,747,801 |
| Execution time(s) | 0.03 | 331,620 |

The random solution was superior to the heuristic method solution because the random solution had more safety benefits.

Scenario 4: Create another optimization problem with four countermeasures which include the following: adding shoulder rumble strips, widening the outside shoulder width, installing a new traffic signal, and converting an intersection to a roundabout. All the elements in these four files are selected as the candidates. If the total budget constraint is set at \$400,000, the minimum program constraint is that the total cost of widening outside shoulder must be at least \$45,000. The interface is shown in Figure 5.20.

After 25 hours and 16 minutes, the results show that the random best solution is slightly better than the heuristic method solution. The comparison information is shown in Table 5.22.

According to Table 5.22, the difference between the total safety benefits of the random best solution and the heuristic solution is approximately 1%. The outputs of selected elements are shown in Table 5.23.

Figure 5.21 shows that there were 33 identical location-countermeasure pairs, but there were two differences. One countermeasure for CFID 247866 was in the heuristic solution, and there was no countermeasure in the random solution. One countermeasure for CFID 6547 was in the random solution,

TABLE 5.21
Output of selected elements in Scenario 3

| CFID Element | Heuristic Method Solution | | | | | | | | | | Current Random Run Best Solution | | | | | | | | | | | |
|--------------|---------------------------|---|---|---|---|--------------|-------------------------|-------|--------|---|----------------------------------|-------------|----------------|-----|-------------------------|--------|-------|--|--|-------------|----------------|-----|
| | Applied Countermeasures | | | | | CFID Element | Applied Countermeasures | | | | | Annual Cost | Annual Benefit | B/C | Applied Countermeasures | | | | | Annual Cost | Annual Benefit | B/C |
| | A | B | C | D | A | | B | C | D | A | B | | | | C | D | | | | | | |
| 6275 | 0 | 0 | 0 | 1 | 0 | 12500 | 58200 | 4.66 | 6275 | 0 | 0 | 0 | 1 | 0 | 12500 | 58200 | 4.66 | | | | | |
| 6288 | 0 | 0 | 0 | 1 | 0 | 12500 | 63050 | 5.04 | 6288 | 0 | 0 | 0 | 1 | 0 | 12500 | 63050 | 5.04 | | | | | |
| 6300 | 0 | 0 | 0 | 1 | 0 | 12500 | 121250 | 9.70 | 6300 | 0 | 0 | 0 | 1 | 0 | 12500 | 121250 | 9.70 | | | | | |
| 6303 | 0 | 0 | 0 | 1 | 0 | 12500 | 30717 | 2.46 | | | | | | | | | | | | | | |
| 6333 | 0 | 0 | 0 | 1 | 0 | 12500 | 37183 | 2.97 | 6333 | 0 | 0 | 0 | 1 | 0 | 12500 | 37183 | 2.97 | | | | | |
| 6544 | 0 | 0 | 0 | 1 | 0 | 12500 | 22633 | 1.81 | 6544 | 0 | 0 | 0 | 1 | 0 | 12500 | 22633 | 1.81 | | | | | |
| 6547 | 0 | 0 | 0 | 1 | 0 | 12500 | 30717 | 2.46 | 6547 | 0 | 0 | 0 | 1 | 0 | 12500 | 30717 | 2.46 | | | | | |
| 6579 | 0 | 0 | 0 | 1 | 0 | 75000 | 284464 | 3.79 | 6579 | 0 | 0 | 0 | 1 | 0 | 75000 | 284464 | 3.79 | | | | | |
| 6587 | 0 | 0 | 0 | 1 | 0 | 12500 | 53350 | 4.27 | 6587 | 0 | 0 | 0 | 1 | 0 | 12500 | 53350 | 4.27 | | | | | |
| | | | | | | | | | 6701 | 0 | 0 | 0 | 1 | 0 | 12500 | 19400 | 1.55 | | | | | |
| 6719 | 0 | 0 | 0 | 1 | 0 | 75000 | 256418 | 3.42 | 6719 | 0 | 0 | 0 | 1 | 0 | 75000 | 256418 | 3.42 | | | | | |
| | | | | | | | | | 6727 | 0 | 0 | 0 | 1 | 0 | 12500 | 19400 | 1.55 | | | | | |
| 6800 | 0 | 0 | 0 | 1 | 0 | 75000 | 216353 | 2.88 | 6800 | 0 | 0 | 0 | 1 | 0 | 75000 | 216353 | 2.88 | | | | | |
| 6883 | 0 | 0 | 0 | 1 | 0 | 12500 | 29100 | 2.33 | | | | | | | | | | | | | | |
| 7069 | 0 | 0 | 0 | 1 | 0 | 12500 | 80834 | 6.47 | 7069 | 0 | 0 | 0 | 1 | 0 | 12500 | 80834 | 6.47 | | | | | |
| 7145 | 0 | 0 | 0 | 1 | 0 | 75000 | 284464 | 3.79 | 7145 | 0 | 0 | 0 | 1 | 0 | 75000 | 284464 | 3.79 | | | | | |
| 7218 | 0 | 0 | 0 | 1 | 0 | 12500 | 85684 | 6.85 | 7218 | 0 | 0 | 0 | 1 | 0 | 12500 | 85684 | 6.85 | | | | | |
| 7272 | 0 | 0 | 0 | 1 | 0 | 12500 | 54967 | 4.40 | 7272 | 0 | 0 | 0 | 1 | 0 | 12500 | 54967 | 4.40 | | | | | |
| 7309 | 0 | 0 | 0 | 1 | 0 | 12500 | 32333 | 2.59 | 7309 | 0 | 0 | 0 | 1 | 0 | 12500 | 32333 | 2.59 | | | | | |
| 218618 | 1 | 0 | 0 | 0 | 0 | 621 | 8463 | 13.63 | 218618 | 1 | 0 | 0 | 0 | 0 | 621 | 8463 | 13.63 | | | | | |
| 225795 | 1 | 0 | 0 | 0 | 0 | 200 | 4752 | 23.76 | 225795 | 1 | 0 | 0 | 0 | 0 | 200 | 4752 | 23.76 | | | | | |
| 226032 | 1 | 0 | 0 | 0 | 0 | 118 | 4752 | 40.27 | 226032 | 1 | 0 | 0 | 0 | 0 | 118 | 4752 | 40.27 | | | | | |
| 232251 | 1 | 0 | 0 | 0 | 0 | 85 | 4231 | 49.78 | 232251 | 1 | 0 | 0 | 0 | 0 | 85 | 4231 | 49.78 | | | | | |
| 234444 | 1 | 0 | 0 | 0 | 0 | 33 | 4752 | 144.0 | 234444 | 1 | 0 | 0 | 0 | 0 | 33 | 4752 | 144.0 | | | | | |
| 235280 | 1 | 0 | 0 | 0 | 0 | 141 | 4752 | 33.70 | 235280 | 1 | 0 | 0 | 0 | 0 | 141 | 4752 | 33.70 | | | | | |
| 236583 | 1 | 0 | 0 | 0 | 0 | 81 | 4231 | 52.23 | 236583 | 1 | 0 | 0 | 0 | 0 | 81 | 4231 | 52.23 | | | | | |
| 237139 | 1 | 0 | 0 | 0 | 0 | 141 | 4231 | 30.01 | 237139 | 1 | 0 | 0 | 0 | 0 | 141 | 4231 | 30.01 | | | | | |
| 238122 | 1 | 0 | 0 | 0 | 0 | 68 | 4231 | 62.22 | 238122 | 1 | 0 | 0 | 0 | 0 | 68 | 4231 | 62.22 | | | | | |
| 238149 | 1 | 0 | 0 | 0 | 0 | 361 | 4231 | 11.72 | 238149 | 1 | 0 | 0 | 0 | 0 | 361 | 4231 | 11.72 | | | | | |
| 238248 | 1 | 0 | 0 | 0 | 0 | 216 | 4231 | 19.59 | 238248 | 1 | 0 | 0 | 0 | 0 | 216 | 4231 | 19.59 | | | | | |
| 239231 | 1 | 0 | 0 | 0 | 0 | 159 | 4752 | 29.89 | 239231 | 1 | 0 | 0 | 0 | 0 | 159 | 4752 | 29.89 | | | | | |
| 239995 | 1 | 0 | 0 | 0 | 0 | 421 | 14257 | 33.86 | 239995 | 1 | 0 | 0 | 0 | 0 | 421 | 14257 | 33.86 | | | | | |
| 241963 | 1 | 0 | 0 | 0 | 0 | 76 | 4752 | 62.53 | 241963 | 1 | 0 | 0 | 0 | 0 | 76 | 4752 | 62.53 | | | | | |
| 244054 | 1 | 0 | 0 | 0 | 0 | 192 | 14257 | 74.26 | 244054 | 1 | 0 | 0 | 0 | 0 | 192 | 14257 | 74.26 | | | | | |
| 245175 | 1 | 0 | 0 | 0 | 0 | 238 | 14257 | 59.90 | 245175 | 1 | 0 | 0 | 0 | 0 | 238 | 14257 | 59.90 | | | | | |
| 245360 | 1 | 0 | 0 | 0 | 0 | 69 | 4752 | 68.87 | 245360 | 1 | 0 | 0 | 0 | 0 | 69 | 4752 | 68.87 | | | | | |
| 247281 | 1 | 0 | 0 | 0 | 0 | 170 | 4752 | 27.95 | 247281 | 1 | 0 | 0 | 0 | 0 | 170 | 4752 | 27.95 | | | | | |
| 247866 | 1 | 0 | 0 | 0 | 0 | 15031 | 33175 | 2.21 | 247866 | 1 | 0 | 0 | 0 | 0 | 15031 | 33175 | 2.21 | | | | | |
| 417817 | 1 | 0 | 0 | 0 | 0 | 383 | 4231 | 11.05 | 417817 | 1 | 0 | 0 | 0 | 0 | 383 | 4231 | 11.05 | | | | | |
| 420356 | 1 | 0 | 0 | 0 | 0 | 192 | 4752 | 24.75 | 420356 | 1 | 0 | 0 | 0 | 0 | 192 | 4752 | 24.75 | | | | | |
| 420804 | 1 | 1 | 0 | 0 | 0 | 16377 | 36708 | 2.24 | 420804 | 1 | 1 | 0 | 0 | 0 | 16377 | 36708 | 2.24 | | | | | |

A= add shoulder rumble strips; B= widen outside shoulder width; C= new signal installation; D= convert intersection to roundabout; 1= applied countermeasures; 0= not applied countermeasures.

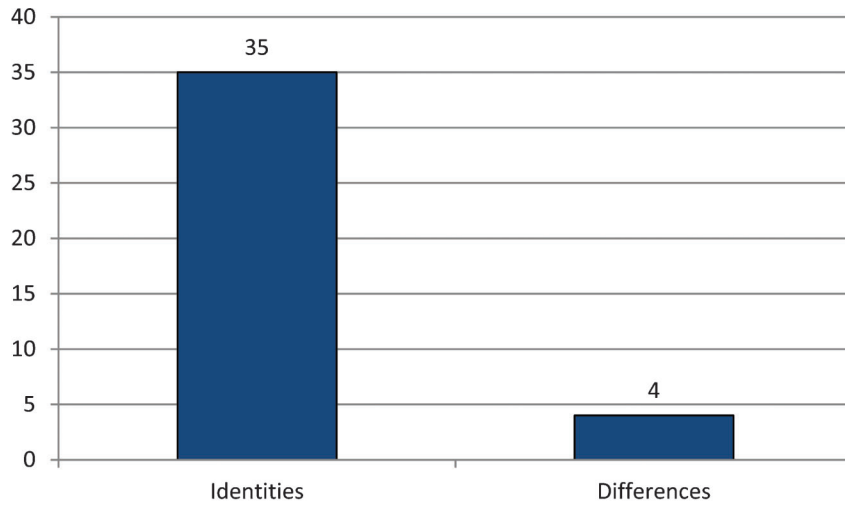


Figure 5.18 Count identities and differences elements in Scenario 3.

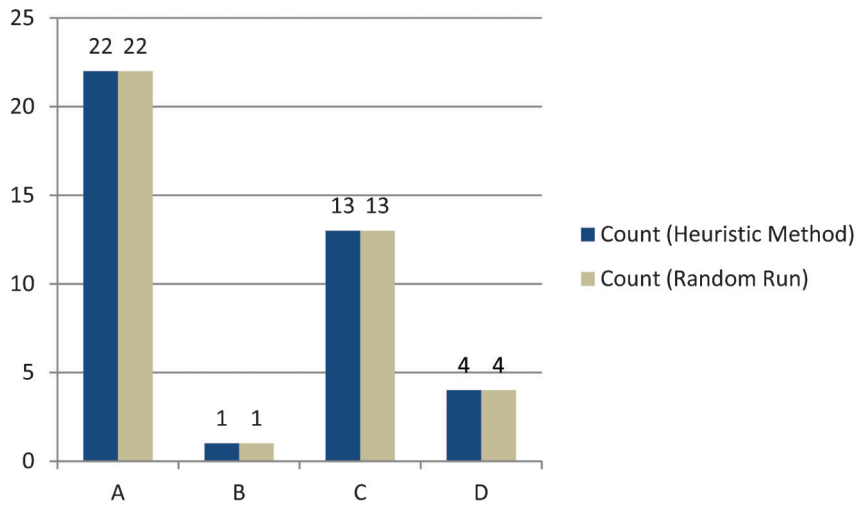


Figure 5.19 Number of selected four different safety countermeasures in Scenario 3.

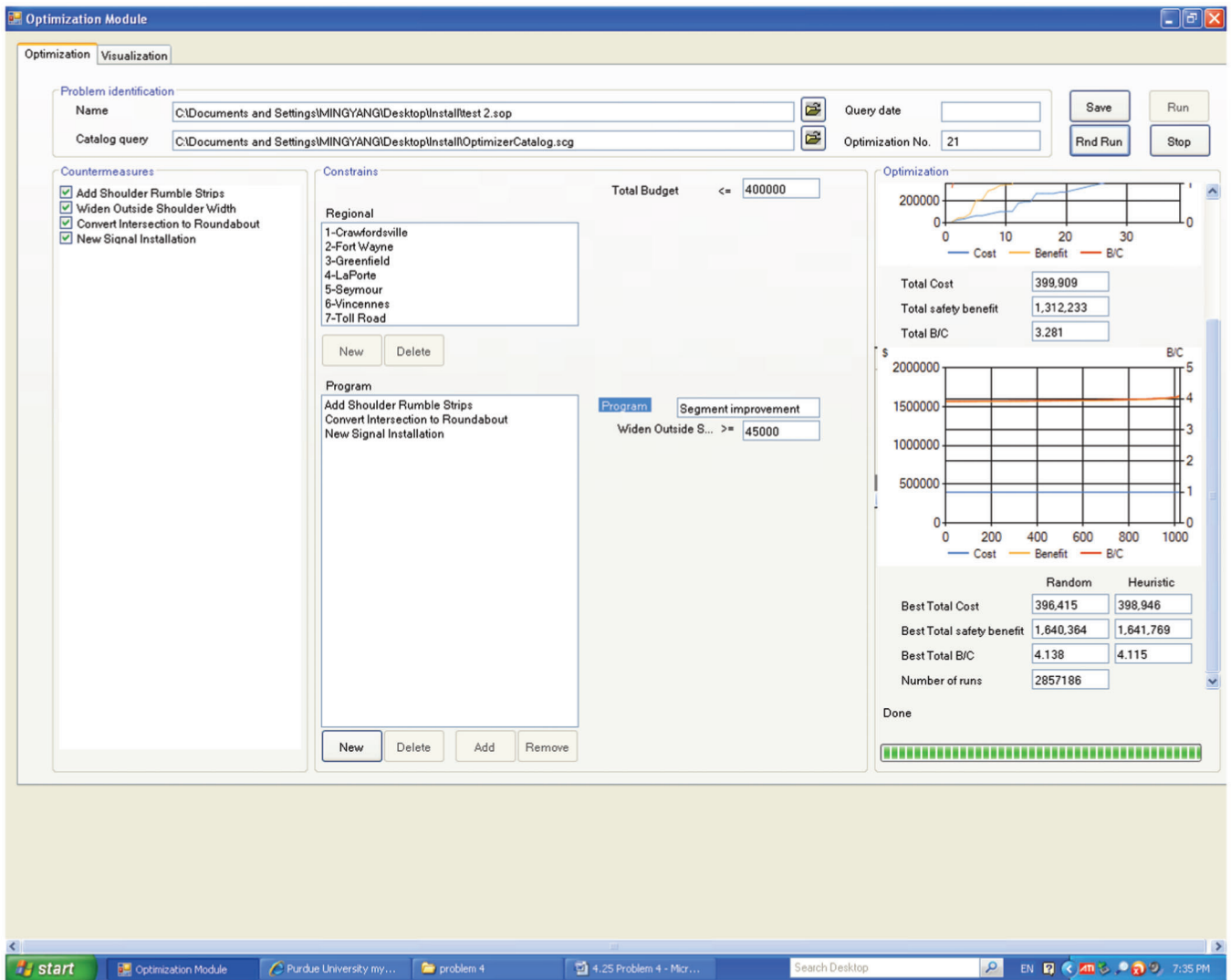


Figure 5.20 Evaluation interface of Scenario 4.

TABLE 5.22
Comparison of random and heuristic solutions in Scenario 3

| | Heuristic | Random |
|----------------------|-----------|-----------|
| Budget spent | 398,946 | 396,415 |
| Total safety benefit | 1,641,769 | 1,640,364 |
| Total B/C | 4.115 | 4.138 |
| Number of runs | 1 | 2,857,186 |
| Execution time(s) | 0.03 | 96,960 |

TABLE 5.23
Output of selected elements in Scenario 4

| CFID Element | Heuristic Method Solution | | | | | | Current Random Run Best Solution | | | | | | | | |
|--------------|---------------------------|---|---|--------------|-------------------------|--------|----------------------------------|--------------|-------------------------|---|---|---|-------|--------|-------|
| | Applied Countermeasures | | | CFID Element | Applied Countermeasures | | | CFID Element | Applied Countermeasures | | | | | | |
| | A | B | C | | D | A | B | | C | D | A | B | C | D | |
| 6275 | 0 | 0 | 1 | 0 | 12500 | 58200 | 4.66 | 6275 | 0 | 0 | 1 | 0 | 12500 | 58200 | 4.66 |
| 6288 | 0 | 0 | 1 | 0 | 12500 | 63050 | 5.04 | 6288 | 0 | 0 | 1 | 0 | 12500 | 63050 | 5.04 |
| 6300 | 0 | 0 | 1 | 0 | 12500 | 121250 | 9.70 | 6300 | 0 | 0 | 1 | 0 | 12500 | 121250 | 9.70 |
| 6333 | 0 | 0 | 1 | 0 | 12500 | 37183 | 2.97 | 6333 | 0 | 0 | 1 | 0 | 12500 | 37183 | 2.97 |
| 6579 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 | 6579 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 |
| 6587 | 0 | 0 | 1 | 0 | 12500 | 53350 | 4.27 | 6587 | 0 | 0 | 1 | 0 | 12500 | 53350 | 4.27 |
| 6719 | 0 | 0 | 0 | 1 | 75000 | 256418 | 3.42 | 6719 | 0 | 0 | 0 | 1 | 75000 | 256418 | 3.42 |
| 7069 | 0 | 0 | 1 | 0 | 12500 | 80834 | 6.47 | 7069 | 0 | 0 | 1 | 0 | 12500 | 80834 | 6.47 |
| 7145 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 | 7145 | 0 | 0 | 0 | 1 | 75000 | 284464 | 3.79 |
| 7218 | 0 | 0 | 1 | 0 | 12500 | 85684 | 6.85 | 7218 | 0 | 0 | 1 | 0 | 12500 | 85684 | 6.85 |
| 7272 | 0 | 0 | 1 | 0 | 12500 | 54967 | 4.40 | 7272 | 0 | 0 | 1 | 0 | 12500 | 54967 | 4.40 |
| 218618 | 1 | 0 | 0 | 0 | 621 | 8463 | 13.63 | 218618 | 1 | 0 | 0 | 0 | 621 | 8463 | 13.63 |
| 225795 | 1 | 0 | 0 | 0 | 200 | 4752 | 23.76 | 225795 | 1 | 0 | 0 | 0 | 200 | 4752 | 23.76 |
| 226032 | 1 | 0 | 0 | 0 | 118 | 4752 | 40.27 | 226032 | 1 | 0 | 0 | 0 | 118 | 4752 | 40.27 |
| 232251 | 1 | 0 | 0 | 0 | 85 | 4231 | 49.78 | 232251 | 1 | 0 | 0 | 0 | 85 | 4231 | 49.78 |
| 234444 | 1 | 0 | 0 | 0 | 33 | 4752 | 144.0 | 234444 | 1 | 0 | 0 | 0 | 33 | 4752 | 144.0 |
| 235280 | 1 | 0 | 0 | 0 | 141 | 4752 | 33.70 | 235280 | 1 | 0 | 0 | 0 | 141 | 4752 | 33.70 |
| 236583 | 1 | 0 | 0 | 0 | 81 | 4231 | 52.23 | 236583 | 1 | 0 | 0 | 0 | 81 | 4231 | 52.23 |
| 237139 | 1 | 0 | 0 | 0 | 141 | 4231 | 30.01 | 237139 | 1 | 0 | 0 | 0 | 141 | 4231 | 30.01 |
| 238122 | 1 | 0 | 0 | 0 | 68 | 4231 | 62.22 | 238122 | 1 | 0 | 0 | 0 | 68 | 4231 | 62.22 |
| 238149 | 1 | 0 | 0 | 0 | 361 | 4231 | 11.72 | 238149 | 1 | 0 | 0 | 0 | 361 | 4231 | 11.72 |
| 238248 | 1 | 1 | 0 | 0 | 7956 | 12305 | 1.55 | 238248 | 1 | 1 | 0 | 0 | 7956 | 12305 | 1.55 |
| 239231 | 1 | 0 | 0 | 0 | 159 | 4752 | 29.89 | 239231 | 1 | 0 | 0 | 0 | 159 | 4752 | 29.89 |
| 239995 | 1 | 0 | 0 | 0 | 421 | 14257 | 33.86 | 239995 | 1 | 0 | 0 | 0 | 421 | 14257 | 33.86 |
| 241963 | 1 | 0 | 0 | 0 | 76 | 4752 | 62.53 | 241963 | 1 | 0 | 0 | 0 | 76 | 4752 | 62.53 |
| 244054 | 1 | 1 | 0 | 0 | 13955 | 39479 | 2.83 | 244054 | 1 | 1 | 0 | 0 | 13955 | 39479 | 2.83 |
| 245175 | 1 | 1 | 0 | 0 | 17308 | 45008 | 2.60 | 245175 | 1 | 1 | 0 | 0 | 17308 | 45008 | 2.60 |
| 245360 | 1 | 0 | 0 | 0 | 69 | 4752 | 68.87 | 245360 | 1 | 0 | 0 | 0 | 69 | 4752 | 68.87 |
| 247281 | 1 | 0 | 0 | 0 | 170 | 4752 | 27.95 | 247281 | 1 | 0 | 0 | 0 | 170 | 4752 | 27.95 |
| 247866 | 0 | 1 | 0 | 0 | 15031 | 33175 | 2.21 | 247866 | 0 | 1 | 0 | 0 | 15031 | 33175 | 2.21 |
| 417817 | 1 | 0 | 0 | 0 | 383 | 4231 | 11.05 | 417817 | 1 | 0 | 0 | 0 | 383 | 4231 | 11.05 |
| 420356 | 1 | 0 | 0 | 0 | 192 | 4752 | 24.75 | 420356 | 1 | 0 | 0 | 0 | 192 | 4752 | 24.75 |
| 420804 | 1 | 1 | 0 | 0 | 16377 | 41063 | 2.51 | 420804 | 1 | 1 | 0 | 0 | 16377 | 41063 | 2.51 |

A = add shoulder rumble strips; B = widen outside shoulder width; C = new signal installation; D = convert intersection to roundabout; 1 = applied countermeasures; 0 = not applied countermeasures.

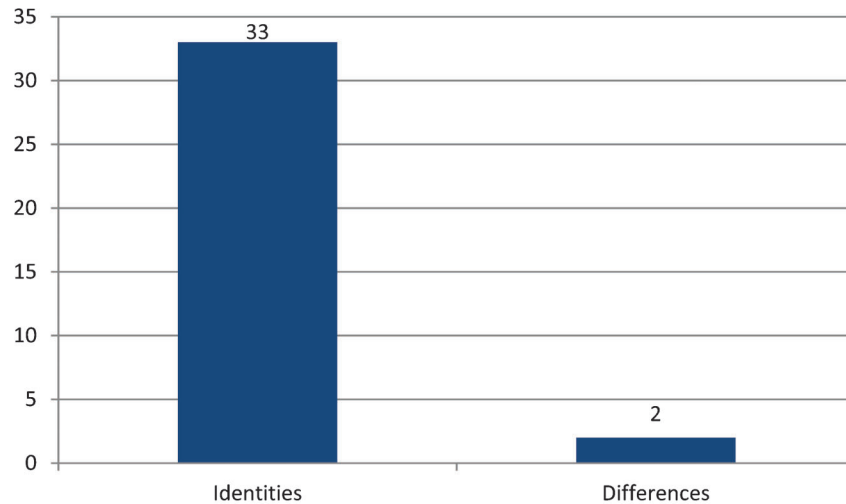


Figure 5.21 Count identities and differences elements in Scenario 4.

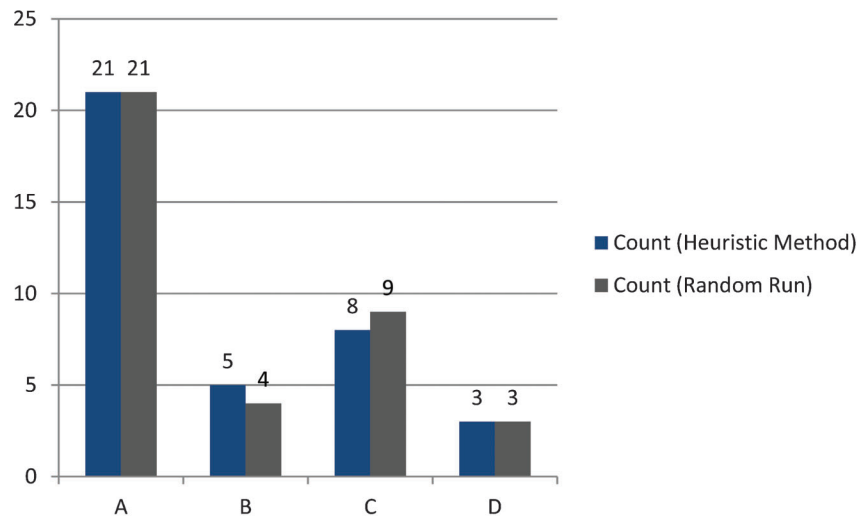


Figure 5.22 Number of selected four different safety countermeasures in Scenario 4.

and there was no countermeasure in the heuristic solution.

Figure 5.21 shows how many safety countermeasures were selected in the heuristic method solution compared to the random best solution. It shows that there were 21, 5, 8, and 3 elements selected to implement add shoulder rumble strips (A), widen outside shoulder width (B), new signal installation (C) and convert intersection to roundabout (D) in the heuristic solution compared to 21, 4, 9, and 3 for the four countermeasures respectively in the random solution.

In Scenario 4, currently, the heuristic method solution is better than the random solution, which means it generated positive results and more time would be needed to obtain a better random solution than for the heuristic method solution under these constraints.

6. SUMMARY

The conceptual framework of the safety screening tool was developed in order to cope with the

complexity of the data management and safety screening operations.

As a part of SPR 3315, the safety screening tool was developed to facilitate the overall screening for the state road elements using user-defined crash selection criteria. The user needs to specify the scope, element, and selection criteria for a particular screening. Apart from the crash selection criteria, the network selection criteria can facilitate screening for roadway deficiencies.

The draft user interface is being delivered to INDOT as part of this report. A workshop for training INDOT personnel will be arranged in the near future in order to get INDOT's feedback.

This report provides a relatively complete list of the safety countermeasures currently applicable and suitable in Indiana, which can serve as useful resources when engineers are implementing safety countermeasures to reduce the number of crashes and the severity of crash injuries in Indiana. In addition, crash reduction factors (CRFs) are proposed for each safety countermeasure; and these proposed values can be useful for the process

of safety benefit prediction. Also, the unit costs and conditions for the safety countermeasures are explained, which will provide engineers with a good approach to calculating the total costs of safety countermeasures and where to implement the possible improvements.

Testing the proposed algorithm and evaluating the heuristic method demonstrated that the heuristic method developed by Dr. Tarko and Dr. Romero is a sufficient and quick approach to obtain a good solution. The main contribution of this report is to test and evaluate the performance of the heuristic method. This heuristic method applies quite well when the total budget is large, therefore, future work can continue to develop this heuristic method to make it also work quite well when the total budget is not very large.

The presented SNIP2 relies on the quality and completeness of the input data. The limited availability of roadway data and the lack of roadside data jeopardize the effectiveness of roadway safety management. A combined use of available road inventory data, digital imagery, and high-resolution maps may provide a long sought data useful for road management. A project is needed to study the INDOT-administered roads. The developed method could be then adapted to local roads where the need for data is particularly acute.

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APPENDIX A. SCREENING CONCEPTS

IDENTIFICATION METHOD

The safety identification method includes components designed to fulfill the agency's need to systematically investigate a particular problem. The following items are the core components necessary for a successful identification method:

1. Scope, elements, and selection criteria
2. Safety performance measures
3. Exposures measures
4. Statistical evaluation measures

Scope, Elements, and Selection Criteria

Scope

Scope or domain is the geographic unit in which the user is willing to conduct the screening. In the safety screening tool, three scopes have been defined: state, county, and city/town. The scope can be limited to a particular county/township or multiple counties/townships, but should always be greater than the elements in geographic extent.

Element

Element is the smallest unit of aggregation level that a user wishes to investigate. Elements can be the facility type (e.g., segments, intersection points, intersection, ramps, or bridges) or can be a smaller geographic unit within the scope. Therefore, the scope or domain is the group of elements an agency wishes to investigate.

Selection Criteria

After defining the scopes and elements, it is important to define the selection criteria. The selection criteria basically facilitate obtaining a subset of the elements within the scope. Within the conceptual framework of safety screening, which was discussed in Chapter 2, the "Screen Rule Editor" is used to define the selection criteria, which can be of two types:

1. Crash selection criteria
2. Element selection criteria

Crash Selection Criteria

Crash selection criteria are considered in order to investigate a specific type of crash. For example, an agency might be interested in only fatal or incapacitating injury types of crashes or only nighttime crashes. An example might be obtaining only alcohol-related crash locations for targeted enforcement purposes. The crash selection criteria are mainly dependent on the crash variables and their availability.

Element Selection Criteria

Element selection criteria also have a very specific purpose. Since the Indiana road inventory is embedded in the master record sets, a user might be interested in the crash propensity for a specific design condition (e.g., a particular roadway with a specific median type/width). Combining the crash and element selection criteria can serve as a great tool for choosing candidates for a specific program. Figure A.1 shows the interaction among the scope, element, and selection criteria in the overall safety screening process.

Interrelationship of Scope, Element & Selection Criteria in Safety Screening

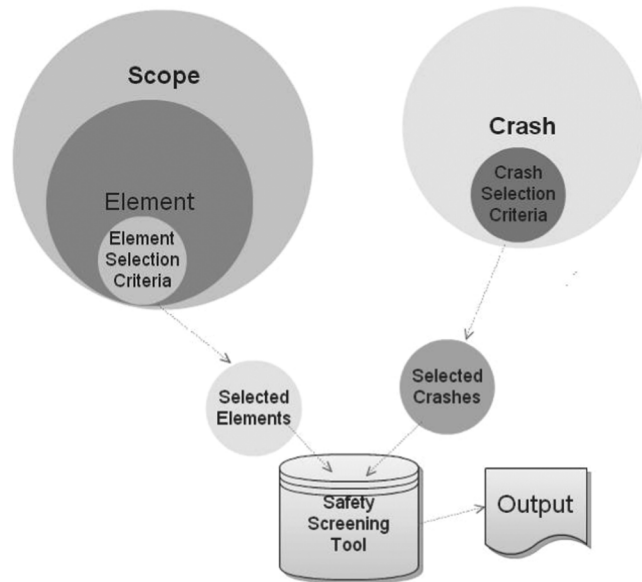


Figure A.1 Scope, element, and selection criteria for safety screening.

Safety Performance Measures

After a user defines the scope, element, and selection criteria, it is important to define the unit of identification. The identification unit is analogous to the *measures of safety* which can have three basic types:

- *Crash frequency*: Crash frequency is the crash counts of all crashes or a specific subset of crashes as determined by the user.
- *Crash cost*: Crash cost applies to all crashes or a specific subset of crashes as determined by the user.
- *Crash rate*: Crash frequency/exposure. Exposure can vary based on the type of elements selected.
- *Proportions of crash*: The proportion is the ratio of two different crash counts with the criteria, which is as follows: denominator of crash counts \geq numerator of crash counts; for example, the proportion of rear-end crashes to the total number of crashes.

Exposure Measures

Exposures are used to estimate crash rates as the ratio of the crash count and a specific measure of exposure reflecting the analyzed period. They can be AADT, VMT, or road length, depending on the element under investigation (see Table A.1).

TABLE A.1
Exposure measures for different road elements

| Element of Investigation | Exposure |
|--------------------------|---|
| County | Population, VMT, registered vehicle, area |
| City | Population, VMT, registered vehicle, area |
| Township | Population, VMT, registered vehicle, area |
| State Segment | Link volume (ADT, VMT), length |
| State-State Intersection | Total approach volume (ADT, VMT) |
| State-Local Intersection | State (major) road volume |
| Ramp | Link volume (ADT, VMT), length |
| Bridge | Link volume (ADT, VMT), length |

STATISTICAL EVALUATION

Notation

Basic variables:

c = number of studied crashes during the analysis period

w = cost of crashes on road element during the analysis period

m = estimate of the expected crashes or cost during the analysis period and for the exposure,

v = variance of the m estimate

Variables needed to calculate w, m, and v:

e = exposure on road element (AADT, length L, VMT during the analysis period)

r = number of reference crashes on road element during the analysis period

u = unit crash cost

N = number of road elements in the group of roads

S = total number of studied crashes in the group of roads during the analysis period

R = total number of reference crashes in the group of roads during the analysis period

E = total exposure in the group of roads during the analysis period

W = total cost of crashes in the group of roads during the analysis period

sub k = indicates severity level k

Two distributions are used to evaluate the statistical significance of the safety problem: Gamma distribution and Negative Binomial Distribution. Gamma distribution has parameters α and β , such that mean is $\alpha\beta$, and variance is $\alpha\beta^2$ and density:

$f(\lambda) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \lambda^{\alpha-1} \exp(-\lambda/\beta)$. The Negative Binomial distribution can be viewed as a mixture of Poisson distributions with the Poisson parameter λ distributed according to the Gamma. The parameters of Negative Binomial the distributions are inherited from the Gamma. The mean is $\alpha\beta$, and the variance is $(\alpha\beta + \alpha\beta^2)$, and density: $P(c) = \frac{\Gamma(\alpha+c)}{\Gamma(\alpha)c!} \left(\frac{\beta}{1+\beta}\right)^c \left(\frac{1}{1+\beta}\right)^\alpha$. The MS Excel parameterization of the Gamma distribution is as introduced above while the Negative Binomial distribution uses parameters: $r = \alpha + 1$ and $p = 1/(1+\beta)$.

Concepts

Let c be the recorded number of crashes of a certain type used to evaluate a road element's safety during the analysis period. An agency wants to know if this number of crashes indicates that there is a safety problem on the considered road element. The safety problem is confirmed if the number of crashes c is significantly higher than the number expected for the exposure e on the considered road element.

There are a number of exposure measures including the traffic volume entering an intersection or the vehicle-miles travelled along a road segment. The number of crashes m expected for the exposure is the product of the average crash rate S/E in the considered group of roads and the exposure e on the studied road element.

The segment length can be used if the traffic volume is missing. This option is reserved for local roads that typically do not have traffic volumes measured. The number of crashes m expected for the exposure is the product of the average crash density in the group of roads and the length of the studied road element.

Checking if the considered crashes constitute too large of a proportion of a wider category of crashes (reference crashes) is another important safety test. For example, all intersection crashes may serve as reference crashes for a proportion of right-angle crashes. The number of crashes m expected in this case is the product of the reference proportion S/R (average proportion of intersection crashes that are right-angle crashes in the group of considered intersections) and the reference crashes r at the studied intersection.

Use of Exposure E (Volume, VMT, L)

The first step is to estimate the crash rate S/E in the considered group of roads, where S is the total number of considered crashes in the group of roads and E is the total exposure in that group. The expected number of crashes m on the considered road element is the product of the exposure e on this road element and the crash rate S/E in the road group: $m = e \cdot S/E$. The variance of this estimate is caused by the varying number of S crashes scaled with e/E. The estimate m is distributed according to the Gamma distribution $G(\alpha=S, \beta=e/E)$ with the variance $v = \alpha\beta^2 = S(e/E)^2$.

The test if the actual number of crashes c is larger than the number m expected for the exposure e is done through checking if the crash count c is sufficiently far into the right tail of the distribution of crash counts around the uncertain Gamma-distributed mean m. This test calls for using the Gamma-mixture of Poisson distributions thus for using the Negative Binomial distribution $NB(\alpha=S, \beta=e/E)$. The crash count c indicates that the current safety on the road element is worse than expected for the exposure if the cumulative distribution NB at c takes high value (for example, higher than 0.95). This value is called **confidence F**—the probabilistic measure which varies between 0 and 1.

Using the Excel notation, the calculation of confidence F is:

$F = \sum_{x=0..c} \text{NegBinom.Dist}(x, r=\alpha+1, 1/(1+\beta)) = \text{Beta.Dist}(1/(1+\beta), r=\alpha+1, c+1, 1)$,

or more specifically: $F = \text{Beta.Dist}(1/(1+e/E), S+1, c+1, 1) =$

Another method of statistical significance is the **index I**—the quality control measure that tells the difference between the estimated safety and the target safety (expected for the exposure) measured with the standard deviation of the difference estimate. A high value of index I, for example, higher than 2, indicates a safety problem.

$$I = \frac{c - m}{\sqrt{v}}$$

The value I may be questionable and inconsistent with the significance F if the underlying distribution is strongly skewed to the right (Gamma and Negative Binomial distributions tend to be skewed if the expected value is close to zero). It may lead to an I-based ranking that is inconsistent with the F-based ranking. Since agencies may prefer using index I, an equivalent I_e value is proposed that is determined based on the calculated F value. It uses an "equivalent" normal distribution which preserves the original m, c, and F values. The equivalent parameter σ_e needs to be calculated. Given that the standardized cumulative normal distribution can be closely and conveniently approximated with the logistic function:

$$\Phi(c) \cong 1 - \frac{1}{1 + \exp\left(1.7 \cdot \frac{c - m}{\sigma}\right)}$$

the equivalent σ_e that provides the same F value as the Gamma distribution is:

TABLE A.2
Levels of statistical evidence

| Statistical Evidence of Safety Problem | Confidence F | Index I_e |
|--|--------------|-------------|
| None or very weak | <0.80 | <0.8 |
| Weak | 0.80–0.90 | 0.8–1.3 |
| Considerable | 0.90–0.95 | 1.3–1.7 |
| Strong | 0.95–0.99 | 1.7–2.7 |
| Very strong | >0.99 | >2.7 |

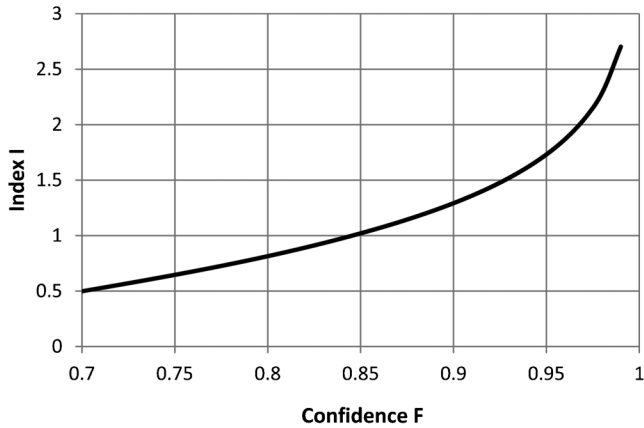


Figure A.2 Relationship between the index of Frequency I and the significance of Level F.

$$F \cong 1 - \frac{1}{1 + \exp\left(1.7 \cdot \frac{c-m}{\sigma_e}\right)}$$

or:

$$\sigma_e = \frac{1.7(c-m)}{\ln\left(\frac{F}{1-F}\right)}$$

The equivalent I_e value can be calculated as follows:

$$I_e = \frac{s-m}{\sigma_e} = \frac{\ln(F) - \ln(1-F)}{1.7}$$

To control the overflow error, small values of F and 1-F should not be used. Instead, an assumed small negative value of $\ln(F)$ and $\ln(1-F)$, for example -99, should be used. Since the equation for I_e is an approximation (although a close one), I_e should be set at a value 0 of $s=m$ to avoid an obviously counterintuitive result.

The relationship between the index I and the significance F is shown in Figure A.2 and summarized in Table A.2. It can be concluded that an I_e lower than 1.25 indicates no or weak statistical evidence of a safety problem ($F < 0.90$), and an I_e between 1.3 and 1.7 indicates considerable evidence (F between 0.90 and 0.95), and an I_e between 1.7 and 2.7 indicates strong evidence (F between 0.95 and 0.99), and an I_e larger than 2.7 indicates very strong evidence.

Proportion of Crashes

The reference proportion is the estimated proportion of studied crashes S in the reference crashes R in the group of roads: S/R.

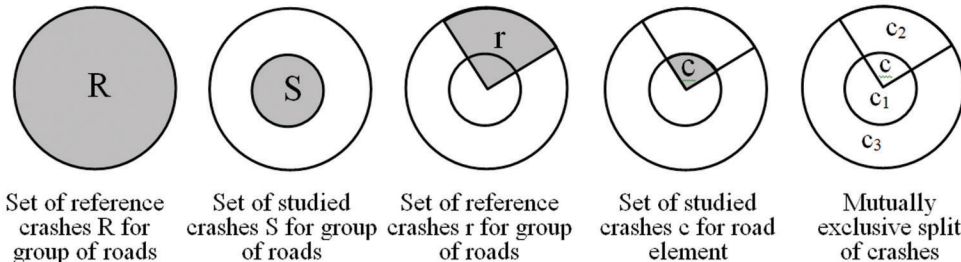


Figure A.3 Dependence between crash counts.

The expected number of crashes at a single road element which corresponds to the reference proportion is calculated as: $m=r \cdot S/R$, where r is the number of reference crashes on the road element and S/R is the proportion of studied crashes in the reference crashes in the group of roads (reference proportion). The variance of the estimate m is caused by variability of all the component crash counts: r, S, and R. These counts are not independent from each other as explained in Figure A.3. To estimate the variance of the m estimate, the crashes in the group of considered roads have been divided into four counts: c, c1, c2, c3, and c4 in a way that these counts vary independently and can be used to calculate the counts r, S, and R: $R=c+c1+c2+c3$, $S=c+c1$, and $r=c+c2$. The derivation of the variance of estimate m; $v = (2crSR+r^2SR+rs^2R-3r^2S^2)/R^3$ is described below.

The variance of $m=rs/d$ is calculated as the variance of $m=(c+c1)(c+c2)/(c+c1+c2+c3)$ with four independent sources of Poisson variance: c, c1, c2, and c3. The variance has been derived from the following equation:

$$\text{var } m(c,c_1,c_2,c_3) = \left(\frac{\partial m}{\partial c}\right)^2 \cdot c + \dots + \left(\frac{\partial m}{\partial c_3}\right)^2 \cdot c_3.$$

The validity of the derived variance and of the assumption of Gamma distribution applied to this criterion has been evaluated using simulation of 10,000 values of the m estimates for two distinct sets of values of c, r, s, and d. The simulated distribution of the m estimates and corresponding Gamma distributions with the parameters calculated in steps 2, 3, and 4 are shown in Figure A.4 (for $(c=10, s=210, r=210, d=510, m=45.3, v=18.1)$) and Figure A.5 for $(c=1, s=6, r=3, d=18, m=0.44, v=1.0)$. The simulation-based evaluation confirms the validity of the method for estimating right-hand distribution tails of m estimates.

Estimation of the significance F is made using equation:

$$F = \text{Beta.Dist}(1/(1+\beta), \alpha+1, c, 1),$$

where $\alpha=m^2/v$ and $\beta=v/m$, thus

$$F = \text{Beta.Dist}(1/(1+v/m), m^2/v+1, c, 1).$$

The Index I_e is calculated as

$$I_e = \frac{\ln(F) - \ln(1-F)}{1.7}$$

Cost Criterion

Traffic volume, AADT, and segment length are useful in calculating the expected cost of crashes on the studied road element. The expected cost of crashes can be obtained by multiplying the crash cost rate per unit exposure averaged for the studied road network with the exposure values for the studied road element.

The expected cost of crashes on a road segment or at an intersection exceeds the expected cost under the given exposure. An estimate of the expected number of crashes at severity level k is distributed according to Gamma with parameters $\alpha=c_k$ and $\beta=1$. Thus, the mean value is $m_k=c_k$ and the variance is $v_k=c_k$. The scaling property of the Gamma distribution allows assuming that the cost of all crashes of severity k at the location is also distributed

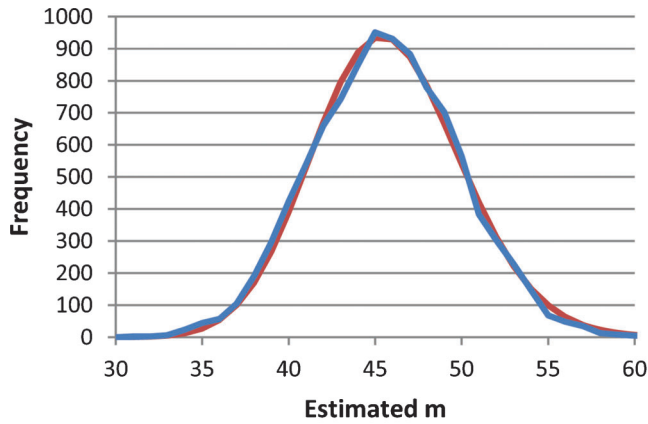


Figure A.4 Case 1: simulated (blue) versus calculated (red) distributions of m estimates.

as Gamma with parameters: $\alpha=c_k$, $\beta=u_k$. The corresponding mean $m_k=c_k u_k$, and variance $v_k=c_k u_k^2$. Thus, the cost of all crashes on the road is:

$$w = \sum_k c_k u_k$$

and the close approximation of the variance of cost estimate (confirmed with Monte Carlo experiments) is:

$$v_1 = \sum_k c_k u_k^2$$

If the cost of crashes on the road expected for the exposure can be calculated as: $m=e \cdot W/E$, where e is the exposure on the considered road element, W is the total cost of crashes in the group of roads, and E is the total exposure in the group of roads.

The estimate m has variance $v_2 = \sum_j \frac{v_{wj}}{E^2}$ which is the total cost variance and E is the total exposure in the road group. The

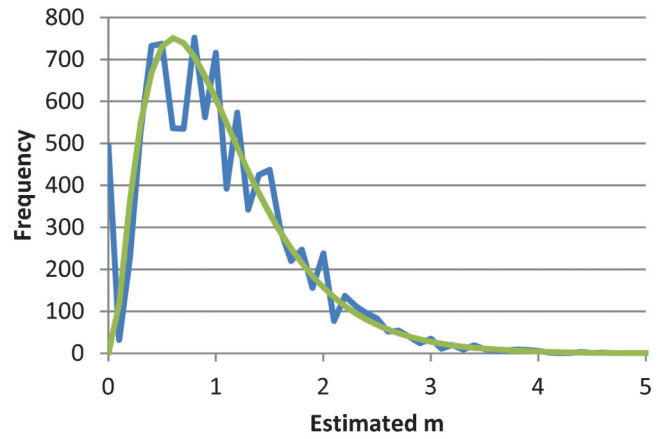


Figure A.5 Case 2: simulated (blue) versus calculated (green) distributions of m estimates.

variance of the difference between the w and m estimates is approximated with the sum of the two component variances v_1 and v_2 . The test is this time based on the Gamma distribution:

$$F = 1 - \text{Gamma.Dist}(W, \alpha = \frac{m^2}{v_1 + v_2}, \beta = \frac{v_1 + v_2}{m}, 1)$$

and index I_e is calculated as before:

$$I_e = \frac{\ln(F) - \ln(1-F)}{1.7}$$

Computations

See Table A.3, "Calculating F and I for the three screening criteria and two versions of SPF."

TABLE A.3
Calculating F and I for the three screening criteria and two versions of SPF

| Screening Criterion | Crashes/Cost on Road | | Variance v | Significance F | Index I | Index I _A |
|---------------------------------|----------------------|--------------------|---|---|---------------------|--|
| | Element | Element m | | | | |
| Crash Frequency: simplified SFP | c | m = e(S/E) | $v_1 = c$ $v_2 = S(e/E)^2$ $v = v_1 + v_2$ | $F_{CF} = \text{Beta.Dist}(1/(1+v_2/m), m^2/v_2, c+1, 1)$ | $I = (c-m)/v^{1/2}$ | $I_{AF} = (\ln(F_{CF}) - \ln(1 - F_{CF}))/1.7$ |
| Crash Frequency: full SFP | c | m = SPF(e) | $v_2 = d^2 \cdot m$ | $F_{CF} = \text{Beta.Dist}(1/(1+v_2/m), m^2/v_2, c+1, 1)$ | $I = (c-m)/v^{1/2}$ | $I_{AF} = (\ln(F_{CF}) - \ln(1 - F_{CF}))/1.7$ |
| Crash Proportion | c | m = r(S/R) | $v_1 = c$ $v_2 = (2crSR + r^2SR + S^2R - 3r^2S^2)/R^3$ $v = v_1 + v_2$ | $F_{CP} = \text{Beta.Dist}(1/(1+v_2/m), m^2/v_2, c+1, 1)$ | $I = (c-m)/v^{1/2}$ | $I_{AP} = (\ln(F_{CP}) - \ln(1 - F_{CP}))/1.7$ |
| Crash Cost: simplified SPF | w = $\sum c_k u_k$ | m = e(W/E) | $v_1 = \sum_k c_k u_k^2$ $v_2 = \sum_k d_k m_k^2 u_k^2$ $v = v_1 + v_2$ | $F_{CC} = \text{Gamma.Dist}(w, m^2/v, v/m, 1)$ | $I = (w-m)/v^{1/2}$ | $I_{AC} = (\ln(F_{CC}) - \ln(1 - F_{CC}))/1.7$ |
| Crash Cost: full SPF | w = $\sum c_k u_k$ | m = $\sum m_k u_k$ | $v_1 = \sum_k c_k u_k^2$ $v_2 = \sum_k d_k m_k^2 u_k^2$ $v = v_1 + v_2$ | $F_{CC} = \text{Gamma.Dist}(w, m^2/v, v/m, 1)$ | $I = (w-m)/v^{1/2}$ | $I_{AC} = (\ln(F_{CC}) - \ln(1 - F_{CC}))/1.7$ |

Notations in alphabetic order: c = number of crashes on road element, c_k = number of studied crashes of severity k on road element j, d = over-dispersion parameter of SPF, e = exposure on road element (AADT, length L, VMT), E = total exposure in the group of roads, m = estimate of the crashes or cost expected for the exposure, r = number of reference crashes on road element during, R = total number of reference crashes in the group of roads, S = total number of studied crashes in the group of roads, SPF(e) = estimated expected crash count on a segment for the exposure e, u_k = unit cost of crash of k severity, w = cost of crashes on road element, W = total cost of crashes in the group of roads, and v = variance of the m estimate.

APPENDIX B. ROAD CLUSTERING

The screening tool identifies which road elements experience an excessive number of crashes. Clustering these elements into longer road sections may reveal useful spatial regularities that may be useful to INDOT engineers in scoping corridor improvement projects and other safety-oriented programs.

It is important to note that elements with safety needs should be clustered based on the safety performance measures in order to obtain relevant road clusters from the safety management point of view. The following text describes the statistical basis of clustering and the clustering method itself.

STATISTICAL BASIS

There are three basic safety measures that can be used to identify road elements with excessive numbers of certain categories of crashes: crash frequency, crash rate, and crash proportion. Crashes are subject to a strong random fluctuation over time and two safety performance indices, Confidence F and Index I, are proposed to estimate the level of statistical confidence indicated in the detected excessive number of crashes as a systematic issue rather than the effect of random fluctuation.

Significance F is the probability of a safety level equal to or better than the one observed during the period of analysis if the expected safety level in the long run is average for the type of location and under the given exposure. The higher the significance of F is, the stronger the evidence is that the location experiences a real safety problem. The values of $F=0.90$ and higher are typically used.

Index I is the difference between the safety observed during the period of analysis and the safety expected given the location type and exposure divided by the standard deviation of the difference estimate. It is a simplified measure of Significance F. Values of $I=1.5$ and higher provide sufficient evidence that the location experiences a real safety problem.

Significance F is calculated as $\text{BetaDist}(1/(1+am), 1/a, c)$, while Index I is calculated as: $(c-m)/(c+am^2)^{1/2}$, where: a is the over-dispersion parameter, m is the average crash count in a long run, and c is the actual crash count in the period of analysis. Equations for calculating the values of m and a for different safety measures are shown in Table A.3.

CLUSTERING METHOD

One of the important operations of clustering road elements is evaluation of the safety level in the current clusters to ensure that the obtained clusters experience excessive numbers of crashes. A practical method of updating safety evaluations in clusters is aggregation of the safety measures of the individual network elements included in the cluster. The exact method based on Significance F is statistically and computationally troublesome because summing two Gamma variables does not yield a Gamma variable, and the convenient equivalency between Negative Binomial and Beta distribution cannot be used. Therefore, Index I, which is easy to update for clusters, is calculated instead. The following equation is used to calculate Index I for clusters of multiple road elements:

$$I = \frac{\sum_i (c - m)_i}{\sqrt{\sum_i (c + am^2)_i}}$$

where values of $(c - m)_i$ and $(c + am^2)_i$ are known for any road element i . The clustering algorithm is shown in Figure B.1. It is important to note that the clustering process is controlled by two user-selected threshold values: I_1 and I_2 . The recommended ranges are: (1.25–2) for I_1 and (0–1.25) for I_2 with the recommendation that $I_1 > I_2$. The user can restrict the clusters' building only along the same routes to follow the common practice in scoping road projects. Other restrictions may be added to the algorithm as needed. A list of clusters and their elements is obtained based on the screening results, the network topology, and the parameters set by the user.

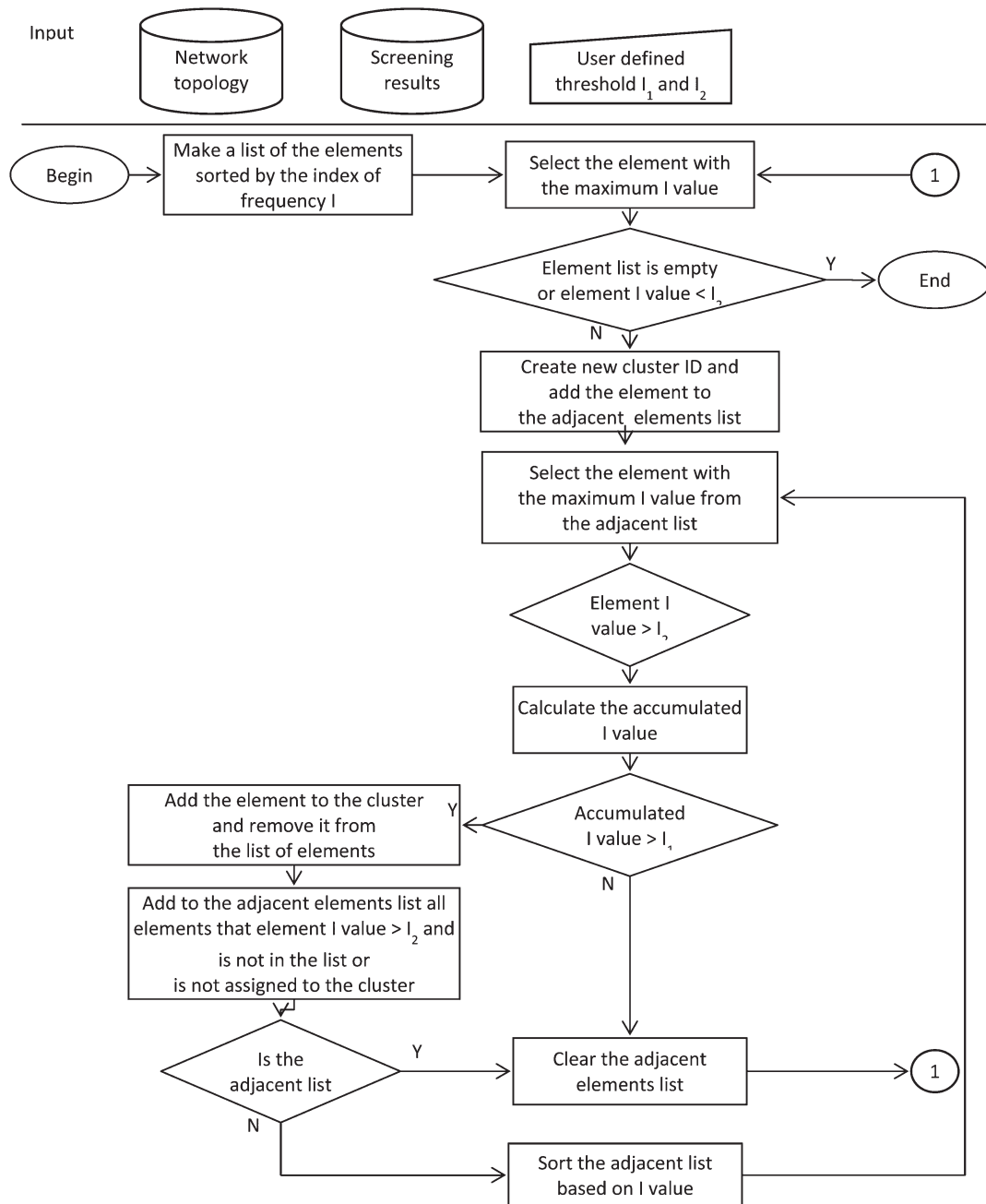


Figure B.1 Clustering algorithm flowchart.

APPENDIX C. RESULTS PRESENTATION

Result presentation is the final step of the screening process. In this phase, the user can visualize the results obtained in the standard screening or clusters/special studies. ArcGIS provides many visualization tools that can accomplish this job. Among the various features available in ArcGIS, the following three visualization tools are widely used:

- Symbology
- Labels
- Selection by attribute

Symbology refers to visualization of a feature (i.e., a single element), categories of elements, quantities, etc., by colors or symbols. Symbology has a special procedure for preparing

charts like bar charts or pie charts to be shown as part of the individual element. Figure C.1 shows a sample Symbology selection window.

Labels are useful in displaying a name or a value of a particular attribute on a map; for example, individual roads on a map can be labeled with their names to enhance visualization or to help identify a specific feature on the map. Figure C.2 shows a network layer with and without labels.

Selection by attribute can highlight particular elements of interest on a map. For example, intersections having more than 10 crashes per year can be easily selected and marked. Figure C.3 shows an example of visualization made by “select by attribute tool” in which the highlighted local roads were found to have signalization. The user can easily scan through the map once the features are selected. Details about the results display and visualization are discussed in the User Manual.

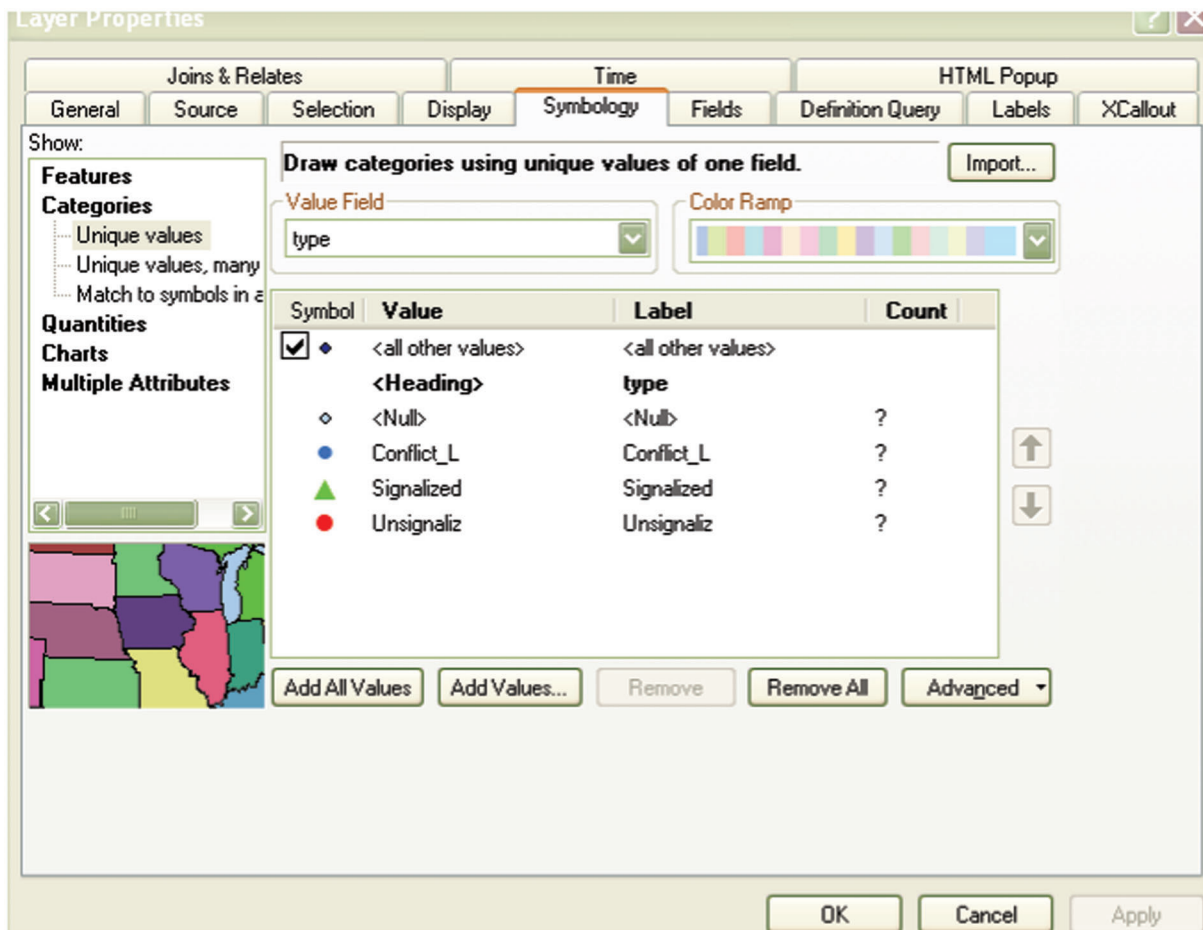


Figure C.1 Window in ArcGIS.



Figure C.2 Labeling feature (left: no labeling; right: labeling).

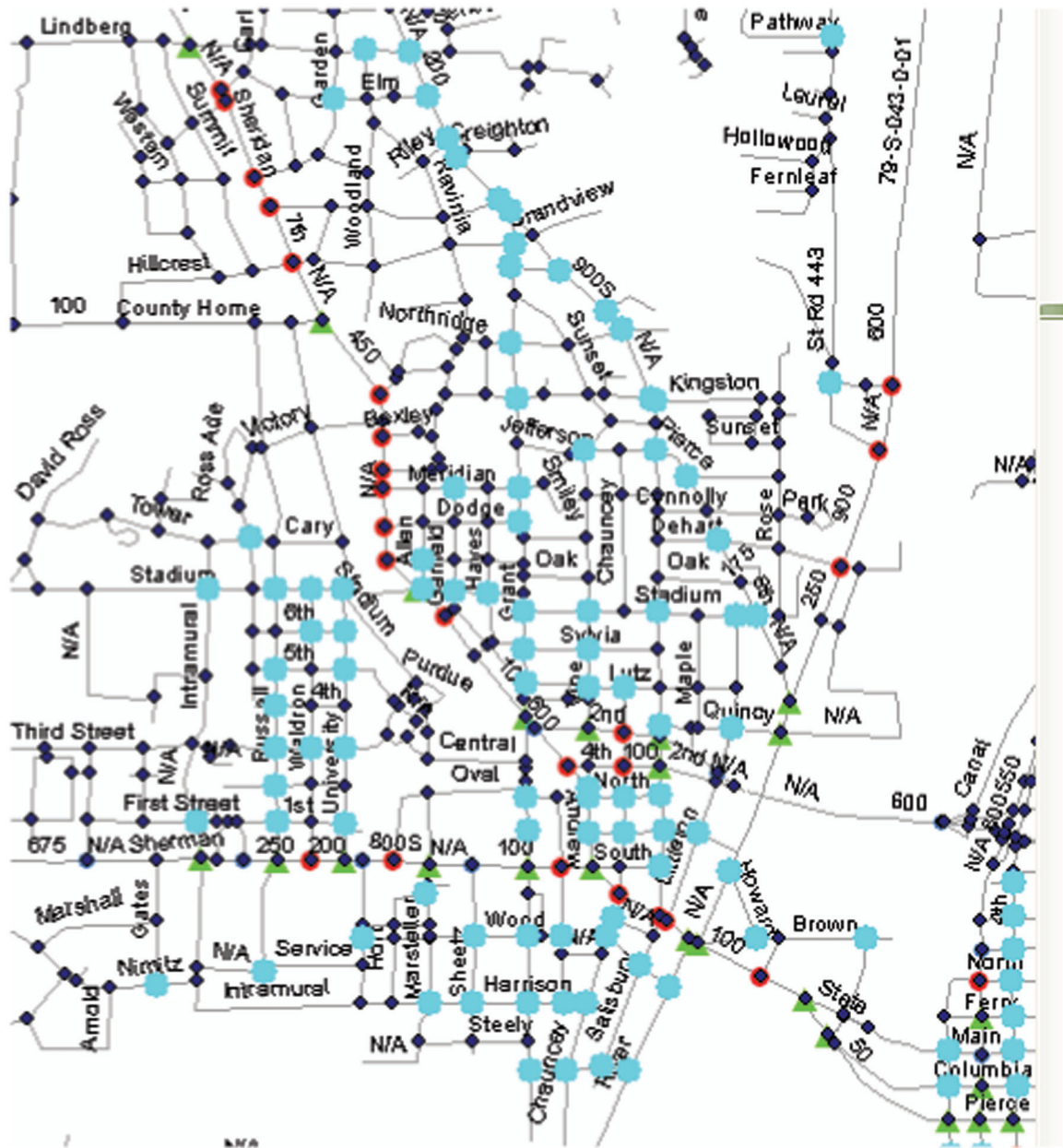


Figure C.3 Selection by attribute.

APPENDIX D. SURVEY FOR INDOT

This appendix presents the questionnaire (Figure D.1) distributed among the SAC members and other INDOT participants to collect information about the typically used countermeasures and corresponding assessed unit costs. The results of this survey are presented in Chapter 4: Inputs to the Optimization Module.

The table below presents example safety countermeasures/programs. Please mark in provided “Use in Indiana” fields those countermeasures that are already used on the INDOT-administered roads (Yes), should be considered for Indiana (Shld), or are not needed for Indiana (No). Add the unit costs of the improvements. Make a guess even if you do not have any specific numbers in mind right away. If any of the provided amounts seem incorrect, write your amounts above them.

Safety countermeasures/programs survey for INDOT

| Category | Countermeasure | Use in Indiana | | | Cost in \$1000s | | | | | | Unit | |
|------------------------------|--|----------------|------|----|-----------------|-------|-------|----|-------|-------|------|--------|
| | | Yes | Shld | No | UI | UML | UTL | RI | RML | RTL | | |
| Access management | Install a median | | | | | 230 | | | | 189 | | mi |
| | Eliminate/close driveways | | | | | | | | | | | drvwy |
| | Replace TWLTL with raised median | | | | | | | | | | | mi |
| Advanced technology | Install queue warning changeable signs | | | | | | | | | | | system |
| | Implement automated red light running enforcement | | | | | | | | | | | intrsc |
| Alignment | Reduce horizontal curvature | | | | | 2,500 | 2,500 | | 2,500 | 2,500 | | curve |
| Highway lighting | Add lighting at intersections | | | | | | | | | | | intrsc |
| Intersection geometry | Add left-turn lanes to major road approaches at intersections | | | | | | | | | | | intrsc |
| | Add right-turn lanes to major road approaches at intersections | | | | | | | | | | | intrsc |
| | Replace direct left-turns with indirect left-turns | | | | | | | | | | | intrsc |
| | Convert intersection to roundabout | | | | | | | | | | | intrsc |
| On-street parking | Prohibit on-street parking | | | | | | | | | | | mi |
| Pedestrians | Install pedestrian hybrid beacon at intersection | | | | | | | | | | | intrsc |
| | Install raised pedestrian crosswalks | | | | | | | | | | | crswlk |
| | Construct pedestrians bridge or tunnel | | | | | | | | | | | strctr |
| | Install sidewalk | | | | | | | | | | | mi |
| At-grade railroad crossing | Upgrade signs to flashing lights | | | | | | | | | | | crssng |
| | Install gates at crossings with signs | | | | | | | | | | | crssng |
| | Build a grade-separated crossing | | | | | | | | | | | crssng |
| Roadside | Install guardrail | | | | | 225 | 225 | | | 185 | 185 | mi |
| | Remove or relocate fixed objects outside of clear zone | | | | | | | | | | | object |
| Roadway delineation | Add centerline rumble strips | | | | | | | | | 1.5 | | mi |
| | Add shoulder rumble strips | | | | | | | 6 | 6 | | | mi |
| Speed management | Set and post speed limits | | | | | | | | | | | mi |
| Shoulder | Widen shoulder width | | | | | | | | | 123 | 123 | mi |
| Horizontal curve | Install chevrons, warning/advisory signs, and/or beacons | | | | | | | | | | | curve |
| Intersection traffic control | Retiming signal change intervals to ITE standards | | | | | | | | | | | intrsc |
| | Increase visibility of signals | | | | | | | | | | | intrsc |
| | Replace left-turn phase(s) with protected-only | | | | | | | | | | | intrsc |

*TWLTL-two-way left-turn lane, UI-urban interstate, UML-urban multilane, UTL-urban two-lane, RI-rural interstate, RML-rural multilane, RTL-rural two-lane, mi-mile, drvwy-driveway, system-system, intrsc-intersection, crswlk-crosswalk, strctr-structure, crssng-crossing, object-object.

Figure D.1 Safety countermeasures/programs survey for INDOT.

Please identify countermeasures and programs that are used in Indiana or should be considered for Indiana that are not included in the previous table. Use the table provided below. Add the unit costs of the improvements. Make a guess even if you do not have any specific numbers in mind right away.

Additional information survey

| Category | Countermeasure | Use in Indiana | | Cost in \$1000s | | | | | | Unit |
|----------|----------------|----------------|--------|-----------------|-----|-----|----|-----|-----|------|
| | | Yes | Should | UI | UML | UTL | RI | RML | RTL | |
| | | | | | | | | | | |
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Write additional comments:

Figure D.1 Continued.

APPENDIX E. ECONOMIC CALCULATIONS IN SNIP2

Step 1. The required input: safety countermeasures; number of PD, NI, and IF crashes during the period with crash data; average AADT in the period with crash data; unit capital costs in Y2 year dollars; service life of the countermeasures; interest rate; inflation rate; and unit costs of PD, NI, and IF crashes in Y1 year dollars. The traffic is assumed fixed over years (zero growth rate).

Step 2. Determine the crash reduction factors (*CRF*). In the case of multiple improvements, the *CRF*s for the individual improvement are combined into one value:

$$CRF = 100 \cdot \left(1 - \Pi_n \left(1 - \frac{CRF_n}{100} \right) \right),$$

where:

CRF = total percent crash reduction factor for multiple improvements,

CRF_n = crash reduction factor for the *n*th improvement.

Step 3. Calculate the expected the over-dispersion parameter *D*.

$$M = \frac{\sum_j A_j}{N}, \quad V = \frac{\sum_j (A_j - M)^2}{N-1}, \quad R = \frac{\sum_j A_j}{Y \sum_j E_j}, \quad m_j = RY \cdot E_j, \quad V_p = \frac{\sum_j (A_j - m_j)^2}{N-1},$$

$$D = \frac{V_p - M}{M^2} \text{ if } D < 0 \text{ then assume } D = 0,$$

where:

M = average annual frequency of crashes in the group of roads,

A_j = number of PD, NI, or IF crashes on road *j* during period with crash data,

N = number of roads in the group of roads,

V = variance of crashes in the group of roads,

R = average crash rate in the group of roads,

E_j = exposure (average daily VMT, AADT, length *L*) that represents exposure on road *j*,

m_j = expected number of PD, NI, IF crashes on road *j*,

V_p = average squared residual (*A_j* - *m_j*) where *m_j* = *R* · *Y* · *E_j*, and

D = over-dispersion parameter.

Step 4. Estimate the crash frequency in the period with crash data. The reported crashes and the expected crashes for the

exposure are combined.

$$a = R \cdot E$$

$$\text{If } D=0 \text{ then } \hat{a} = a, \text{ otherwise } \hat{a} = \left(\frac{1}{D} + A \right) / \left(\frac{1}{D \cdot a} + Y \right),$$

where:

â = best estimate of the PD, NI, or FI frequency (crashes/year),

a = PD, NI, or FI frequency (crashes/year) expected at location,

E = exposure measure,

D = over-dispersion parameter,

A = number of PD, NI, or FI crashes during the period with crash data (crashes in *Y* years), and

Y = (*LY* - *FY* + 1) number of years in the period with crash data (*FY* and *LY* are the first and last years of the period with crash data).

Step 5. Estimate the annual safety benefit, which is the product of the annual frequency *a* of PD, NI, or IF crashes, the *CRF*, and the crash cost adjusted for inflation.

$$B = a \cdot \frac{CRF}{100} \cdot C_1 \cdot \left(1 + \frac{F}{100} \right)^{PY - Y1},$$

where:

B = annual crash benefit for reducing crashes PD, NI, or FI,

a = PD, NI, IF crash frequency,

CRF = percent crash reduction factor of *k* severity,

C₁ = average cost of PD, NI, or IF crash in year *Y1*,

F = inflation rate, assumed to be 2% unless otherwise specified,

and

PY = present year.

Step 6. Calculate the present worth of the total agency costs, which is the accumulated capital costs of all the improvements. The changes in the maintenance costs and the salvage values are neglected.

$$C = \frac{1}{100} \cdot \left(1 + \frac{F}{100} \right)^{PY - Y2} \cdot \sum_i \left(C_{2i} \cdot \frac{(1 + I/100)^{SL_i - 1}}{(1 + I/100)^{SL_i} - 1} \right),$$

where:

C = annualized countermeasure cost,

C_{2i} = the capital cost of the *i*th improvement in year *Y2*,

I = interest rate, assume 4% unless specified otherwise, and

SL_i = service life of the *i*th improvement.

APPENDIX F. INPUT TO THE EVALUATION OF THE OPTIMIZATION METHOD

TABLE F.1
Complete dataset of *add shoulder rumble strip.csv*

| CFID Segment | Start_X | Start_Y | End_X | End_Y | CO | D | U | Mile | AADT | LSW | Total Number of Crashes | L/N | Average Number of Crashes per Year | Cost | Life Span | Annual Cost | Benefit | B/C |
|--------------|----------|----------|----------|----------|----|---|---|-------|-------|-----|-------------------------|-----|------------------------------------|------|-----------|-------------|---------|-------|
| 244054 | -86.7895 | 40.50548 | -86.7866 | 40.51146 | 79 | 1 | 0 | 0.448 | 12035 | 2 | 9 | 2 | 3 | 1344 | 7 | 192 | 14257 | 74.26 |
| 245175 | -86.7681 | 40.52096 | -86.7594 | 40.52554 | 79 | 1 | 0 | 0.555 | 12035 | 2 | 7 | 2 | 3 | 1665 | 7 | 238 | 14257 | 59.94 |
| 234444 | -86.9187 | 40.43873 | -86.9173 | 40.43884 | 79 | 1 | 2 | 0.077 | 13340 | 0 | 1 | 2 | 1 | 231 | 7 | 33 | 4752 | 144 |
| 420804 | -86.7385 | 40.53344 | -86.7304 | 40.53793 | 79 | 1 | 0 | 0.525 | 9440 | 2 | 6 | 2 | 2 | 1575 | 7 | 225 | 9504 | 42.24 |
| 420356 | -86.7955 | 40.5009 | -86.7895 | 40.50548 | 79 | 1 | 0 | 0.448 | 12035 | 2 | 4 | 2 | 1 | 1344 | 7 | 192 | 4752 | 24.75 |
| 226032 | -86.7044 | 40.3576 | -86.6996 | 40.35596 | 79 | 1 | 0 | 0.276 | 5629 | 3 | 2 | 2 | 1 | 828 | 7 | 118 | 4752 | 40.17 |
| 239995 | -86.8866 | 40.46856 | -86.881 | 40.48209 | 79 | 1 | 2 | 0.982 | 7601 | 3 | 7 | 2 | 3 | 2946 | 7 | 421 | 14257 | 33.88 |
| 225795 | -87.0424 | 40.34909 | -87.0372 | 40.35437 | 79 | 1 | 0 | 0.466 | 7822 | 3 | 3 | 2 | 1 | 1398 | 7 | 200 | 4752 | 23.79 |
| 245360 | -86.7568 | 40.52659 | -86.7541 | 40.52767 | 79 | 1 | 0 | 0.16 | 9440 | 2 | 1 | 2 | 1 | 480 | 7 | 69 | 4752 | 69.3 |
| 235280 | -87.0056 | 40.44587 | -86.9993 | 40.44589 | 79 | 1 | 0 | 0.329 | 2507 | 2 | 1 | 2 | 1 | 987 | 7 | 141 | 4752 | 33.7 |
| 241963 | -86.8134 | 40.49234 | -86.8104 | 40.49362 | 79 | 1 | 0 | 0.178 | 12035 | 2 | 1 | 2 | 1 | 534 | 7 | 76 | 4752 | 62.29 |
| 239231 | -86.8356 | 40.4708 | -86.834 | 40.47585 | 79 | 1 | 2 | 0.371 | 14115 | 2 | 2 | 2 | 1 | 1113 | 7 | 159 | 4752 | 29.89 |
| 247281 | -86.7131 | 40.54798 | -86.7067 | 40.55109 | 79 | 1 | 0 | 0.396 | 9440 | 2 | 2 | 2 | 1 | 1188 | 7 | 170 | 4752 | 28 |
| 232251 | -86.9104 | 40.42403 | -86.9122 | 40.42409 | 79 | 1 | 2 | 0.099 | 20995 | 0 | 1 | 3 | 1 | 594 | 7 | 85 | 4231 | 49.86 |
| 238122 | -86.9751 | 40.4674 | -86.9736 | 40.46739 | 79 | 1 | 2 | 0.079 | 13381 | 0 | 1 | 5 | 1 | 474 | 7 | 68 | 4231 | 62.48 |
| 238248 | -86.9993 | 40.46829 | -86.9946 | 40.46777 | 79 | 1 | 0 | 0.252 | 8888 | 2 | 3 | 5 | 1 | 1512 | 7 | 216 | 4231 | 19.59 |
| 236583 | -86.9296 | 40.4549 | -86.9281 | 40.45405 | 79 | 1 | 2 | 0.095 | 20146 | 3 | 1 | 5 | 1 | 570 | 7 | 81 | 4231 | 51.96 |
| 238149 | -86.9472 | 40.46747 | -86.9394 | 40.46674 | 79 | 1 | 2 | 0.421 | 30210 | 3 | 3 | 5 | 1 | 2526 | 7 | 361 | 4231 | 11.72 |
| 218618 | -86.7191 | 40.27014 | -86.7102 | 40.26217 | 79 | 1 | 0 | 0.725 | 6616 | 3 | 5 | 5 | 2 | 4350 | 7 | 621 | 8463 | 13.62 |
| 417817 | -86.7832 | 40.33072 | -86.7777 | 40.32578 | 79 | 1 | 0 | 0.447 | 8278 | 2 | 3 | 5 | 1 | 2682 | 7 | 383 | 4231 | 11.04 |
| 237139 | -86.933 | 40.45995 | -86.9314 | 40.45787 | 79 | 1 | 2 | 0.165 | 30210 | 3 | 1 | 5 | 1 | 990 | 7 | 141 | 4231 | 29.92 |

CO= county; D= district; U= urban; L/N= lane.

TABLE F.2
Complete dataset of *widen outside shoulder width.csv*

| CFID Segment | Start_X | Start_Y | End_X | End_Y | CO | D | U | Mile | AADT | LSW | Total Number of Crashes | | LifeSpan | Annual Cost | Benefit | B/C |
|-----------------|----------|----------|----------|----------|----|---|---|------|-------|-----|-------------------------------|---|----------|-------------|---------|------|
| | | | | | | | | | | | LN | Average Number of Crashes per Year | | | | |
| 244054 | -86.7895 | 40.50548 | -86.7866 | 40.51146 | 79 | 1 | 0 | 0.45 | 12035 | 2 | 14 | 2 | 20 | 275255 | 27646 | 2.01 |
| 245175 | -86.7681 | 40.52096 | -86.7594 | 40.52554 | 79 | 1 | 0 | 0.56 | 12035 | 2 | 18 | 2 | 20 | 341392 | 33175 | 1.94 |
| 238248 | -86.9993 | 40.46829 | -86.9946 | 40.46777 | 79 | 1 | 0 | 0.25 | 8888 | 2 | 4 | 5 | 20 | 154790 | 9846 | 1.27 |
| 420804 | -86.7385 | 40.53344 | -86.7304 | 40.53793 | 79 | 1 | 0 | 0.53 | 9440 | 2 | 16 | 2 | 20 | 323045 | 33175 | 2.05 |
| 420356 | -86.7955 | 40.5009 | -86.7895 | 40.50548 | 79 | 1 | 0 | 0.45 | 12035 | 2 | 5 | 2 | 20 | 275255 | 11058 | 0.8 |
| 226032 | -86.7044 | 40.3576 | -86.6996 | 40.35596 | 79 | 1 | 0 | 0.28 | 5629 | 3 | 2 | 2 | 20 | 137760 | 4525 | 0.66 |
| 218618 | -86.7191 | 40.27014 | -86.7102 | 40.26217 | 79 | 1 | 0 | 0.72 | 6616 | 3 | 12 | 5 | 20 | 356602 | 16115 | 0.9 |
| 417817 | -86.7832 | 40.33072 | -86.7777 | 40.32578 | 79 | 1 | 0 | 0.45 | 8278 | 2 | 4 | 5 | 20 | 219756 | 8058 | 0.73 |
| 225795 | -87.0424 | 40.34909 | -87.0372 | 40.35437 | 79 | 1 | 0 | 0.47 | 7822 | 3 | 10 | 2 | 20 | 286518 | 22117 | 1.54 |
| 247281 | -86.7131 | 40.54798 | -86.7067 | 40.55109 | 79 | 1 | 0 | 0.4 | 9440 | 2 | 6 | 2 | 20 | 243815 | 22190 | 0.91 |
| 245746 | -86.7493 | 40.52904 | -86.7385 | 40.53344 | 79 | 1 | 0 | 0.65 | 9440 | 2 | 12 | 2 | 20 | 399750 | 19987 | 1.11 |
| 247866 | -86.8693 | 40.54754 | -86.8694 | 40.55462 | 79 | 1 | 0 | 0.49 | 10214 | 4 | 16 | 2 | 20 | 300628 | 15031 | 2.21 |
| 416796 | -86.828 | 40.25861 | -86.8186 | 40.25853 | 79 | 1 | 0 | 0.5 | 1668 | 3 | 2 | 2 | 20 | 184500 | 3472 | 0.38 |
| 244054 | -86.7895 | 40.50548 | -86.7866 | 40.51146 | 79 | 1 | 0 | 0.45 | 12035 | 2 | 14 | 2 | 20 | 275255 | 27646 | 2.01 |

CO= county; D= district; U= urban; LN= lane.

TABLE F.3
Complete dataset of new signal installation.csv

| CFID | Intersection | X_COORD | Y_COORD | County | CITY | Total Number of Crashes | Average Number of Crashes per Year | Cost | Life Span | Annual Cost | Benefit | B/C |
|------|--------------|----------|----------|--------|------|-------------------------|------------------------------------|--------|-----------|-------------|---------|------|
| 6275 | | -86.9104 | 40.42796 | 157 | 771 | 36 | 12 | 125000 | 10 | 12500 | 58200 | 4.66 |
| 6288 | | -86.9092 | 40.42399 | 157 | 771 | 39 | 13 | 125000 | 10 | 12500 | 63050 | 5.04 |
| 6300 | | -86.908 | 40.42399 | 157 | 771 | 75 | 25 | 125000 | 10 | 12500 | 121250 | 9.7 |
| 6303 | | -86.9077 | 40.38944 | 157 | 807 | 19 | 6 | 125000 | 10 | 12500 | 30717 | 2.46 |
| 6311 | | -86.9069 | 40.42667 | 157 | 771 | 12 | 4 | 125000 | 10 | 12500 | 19400 | 1.55 |
| 6333 | | -86.9056 | 40.42736 | 157 | 771 | 23 | 8 | 125000 | 10 | 12500 | 37183 | 2.97 |
| 6544 | | -86.8943 | 40.42183 | 157 | 807 | 14 | 5 | 125000 | 10 | 12500 | 22633 | 1.81 |
| 6547 | | -86.8943 | 40.42001 | 157 | 807 | 19 | 6 | 125000 | 10 | 12500 | 30717 | 2.46 |
| 6587 | | -86.893 | 40.40994 | 157 | 807 | 33 | 11 | 125000 | 10 | 12500 | 53350 | 4.27 |
| 6701 | | -86.8886 | 40.41733 | 157 | 807 | 12 | 4 | 125000 | 10 | 12500 | 19400 | 1.55 |
| 6727 | | -86.8858 | 40.41734 | 157 | 807 | 12 | 4 | 125000 | 10 | 12500 | 19400 | 1.55 |
| 6883 | | -86.871 | 40.39546 | 157 | 807 | 18 | 6 | 125000 | 10 | 12500 | 29100 | 2.33 |
| 7069 | | -86.8575 | 40.39552 | 157 | 807 | 50 | 17 | 125000 | 10 | 12500 | 80834 | 6.47 |
| 7218 | | -86.8291 | 40.41765 | 157 | 807 | 53 | 18 | 125000 | 10 | 12500 | 85684 | 6.85 |
| 7272 | | -86.8166 | 40.41747 | 157 | 807 | 34 | 11 | 125000 | 10 | 12500 | 54967 | 4.4 |
| 7309 | | -86.8118 | 40.41753 | 157 | 807 | 20 | 7 | 125000 | 10 | 12500 | 32333 | 2.59 |

TABLE F.4
Complete dataset of convert intersection to roundabout.csv

| CFID | Intersection | X_COORD | Y_COORD | County | CITY | Total Number of Crashes | Average Number of Crashes per Year | Cost | Life Span | Annual Cost | Benefit | B/C |
|------|--------------|----------|----------|--------|------|-------------------------|------------------------------------|---------|-----------|-------------|---------|------|
| 6579 | | -86.893 | 40.41733 | 157 | 807 | 71 | 24 | 1500000 | 20 | 75000 | 284464 | 3.79 |
| 6719 | | -86.8867 | 40.41735 | 157 | 807 | 64 | 21 | 1500000 | 20 | 75000 | 256418 | 3.42 |
| 6800 | | -86.8772 | 40.41733 | 157 | 807 | 54 | 18 | 1500000 | 20 | 75000 | 216353 | 2.88 |
| 7145 | | -86.8437 | 40.38271 | 157 | 807 | 71 | 24 | 1500000 | 20 | 75000 | 284464 | 3.79 |

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: <http://docs.lib.purdue.edu/jtrp>

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