FAMU-FSU
College of Engineering

DECISION SUPPORT TOOL FOR IMPROVING SAFETY AT INTERSECTIONS IN FLORIDA

Image source: https://nicolettilawfirm.com/most-dangerous-intersections-throughout-hillsborough-county/

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16. Abstract			

Road crashes are one of the primary causes of deaths and severe injuries in the United States (U.S.). Intersections have been identified as the most hazardous locations on roadways. To reduce the number of accidents at intersections, Department of Transportations (DOTs) use various methods and tools such as Safety Analyst as explained in the Highway Safety Manual (HSM) and Intersection Control Evaluation (ICE) to identify the most dangerous intersections, diagnose the problem and suggest countermeasures based on economic analysis. Despite the use of these tools by various agencies, they still have limitations and are outdated as they have not accounted for the new wave of technology of connected and automated vehicles (CAVs). Hence, there is a need for an advanced decision support tool, which can account for CAVs and minimize the existing limitations.

This project aims to develop an optimization model-based standalone decision support tool, which can efficiently perform the following: (1) develop an accident prediction model for intersections in the State of Florida (using accident data) that is capable of forecasting the number of accidents at intersections; (2) identify the most dangerous intersections that require safety improvements (based on accident prediction and crash severity analysis); (3) account for specific operational constraints (such as accident history since the most recent safety improvement); (4) estimate crash reduction, considering the crash reduction factor (CRF) of all countermeasures and associated statistics; and (5) identify and recommend the most effective mitigation measures, considering the available budget constraints.

The new decision support tool is expected to not only assist Florida Department of Transportation and other relevant agencies with efficient decision making, but also reduce or even eliminate the occurrence of accidents at intersections within the State of Florida.

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List of Acronyms

AASHTO: American Association of State Highway and Transportation Officials.
AV: Autonomous Vehicles
CV: Connected Vehicles
CAP-X: Capacity Analysis at Junctions
CAV: Connected and Autonomous Vehicles
FDOT: Florida Department of Transportation
FHSMV: Florida Highway Safety and Motor Vehicles.
FHWA: Federal Highway Administration
ICE: Intersection Control Evaluation
Internet of Things (IOT)
HSM: Highway Safety Manual
OPTISA: Optimization Tool for Intersection Safety Analysis
SA: Safety Analyst
SPICE: Safety Performance for Intersection Control Evaluation
V2V: Vehicle-to-Vehicle (V2V)
V2I: Vehicle-to-Infrastructure

1. Overview

This report is aimed at proposing an Intersection Decision Support Optimization tool that will improve intersection safety and operations for all users of the roadway. This tool addresses the gaps that are in the Highway Safety manual (HSM) and other existing methods and tools for addressing intersection crash problem. It incorporates the use of new technologies, connected and automated vehicles (CAVs) as key alternatives in making informed decision to address the problem of intersection crashes. It is expected that this report will help readers and other relevant agencies with efficient decision making to improve intersection safety.

1.1 Problem Description

In the year 2015, Florida ranked as the number one state in the country with the most intersection-related traffic fatalities. Out of 2,699 fatal crashes that were recorded in Florida in 2015, 696 fatalities occurred at intersections, or approximately 26% of all traffic fatalities (FHSMV, 2016). This prompt the need to address the intersection crash problem in Florida.

In response to the Florida's intersection crash problem, Florida Department of Transportation (FDOT) created a Strategic Highway Safety Plan (SHSP) that emphasized on the intersection safety, and developed an Intersection Control Evaluation (ICE) manual to aid in addressing the problem of intersection crashes (FDOT, 2018). The ICE tool is a quantitative analysis tool that is used to evaluate several intersection control strategies based on safety, operational, environmental and benefit-cost analyses. According to the Federal Highway Administration (FHWA), several states use ICE tool in the intersection decision making process. Some of these states include Minnesota, California, Georgia, Pennsylvania and Nevada (FHWA, 2018).

Despite its uses by various DOTs, ICE tool is mostly used for new construction or major redesign of the existing intersection and it is yet to include CAV's intersection control strategies as one of the alternatives. Moreover, HSM proposes a systematic approach for identifying and proposing countermeasures for the roadway network crashes including those occurring at intersections. This approach is applied in the Safety Analyst Analytical Tools (AASHTO, 2019). Safety Analyst implements state-of-the-art analytical procedures for use in the decision-making process to identify and manage a systemwide program of site-specific improvements to enhance highway safety by cost-effective means. Although, this tool is very robust in highway safety management process, it is not free and does not include evaluation of intersection control strategies. Hence, the need for decision support optimization tool, which can combine both tools and use of CAVs to identify most dangerous intersections, determine the appropriate countermeasures and make an informed decision on the best countermeasure or control strategy.

1.2 Stakeholders

The stakeholders for this project include FDOT who are involved in data collection and are responsible for improving intersection safety. Private sectors who can assist FDOT with the technology to implement CAVs solutions. Tool developers which include the team from the FAMU-FSU college of Engineering, FDOT IT department and Third-Party web developer who will be responsible for developing, and maintaining the tool. In order to make informed decision about a new or modified intersection, the goals and the needs of the community and all road users are to be considered. Hence, other stakeholders include the community i.e. neighboring businesses and residents and travelers.

1.3 *Organization of the Report*

The remaining part of this report proceeds as follows: (1) Section two presents the description of the proposed solution and how it could address the existing problem; (2) Section three is focused on the Concept of Operations (Con-ops) for the solution including the current situation, justification of the changes and the concept of the proposed system; (3) Section four provides the work breakdown including cost and timeline; and (4) Section 5 gives the anticipated impacts of the proposed solution.

2. Proposed Solution

To address the intersection crash problem, a decision support optimization tool for intersection safety analysis (OPTISA) is proposed. OPTISA combines the HSM safety analysis methodology and the ICE tool. It addresses the gaps in these two methods, adds the use of CAVs, develops an optimization model for decision making and it is specific to intersections only. The framework of this tool is shown below in Figure 1.

This framework is composed of the following stages;

- **Network screening** – identify and rank intersections based on crash frequencies and severity.

- **Diagnosis** – identify crash contribution factors at intersections. Haddon Matrix is used to analyze those factors. In this study, an updated Haddon Matrix is proposed to address new factors including CAV technology.

- **Minor/Major change requirements** – this stage has been added to the proposed tool in order to determine appropriate procedure to take if minor or major changes are needed at the intersection. This requirement will depend on the diagnosis results, past intersection modifications and longer-term plans for the intersection.

- **Countermeasure/Control strategy selection** – selects possible and appropriate safety countermeasures or control strategy to reduce the average crash frequency. It is based on the pre-suggested lists of countermeasures and control strategies. CV/AV strategies have been added to the list.

- **Economic appraisal/ICE (stage 2)** – evaluates the benefits and costs of the possible safety countermeasures/Conducts operational, safety, and environmental assessment of the control strategies.

- **Priority ranking/ ICE (stage 3)** – ranks intersections and proposed improvements projects/control strategies based on benefit and cost estimates determined by the economic appraisal tool. A modified optimization tool is proposed in this stage.

- **Implementation** – performs the proposed improvements on the selected intersections.

- **Post implementation evaluation** – assesses effectiveness of a safety countermeasure/control strategy in reducing crash frequency by conducting before-and-after evaluations.

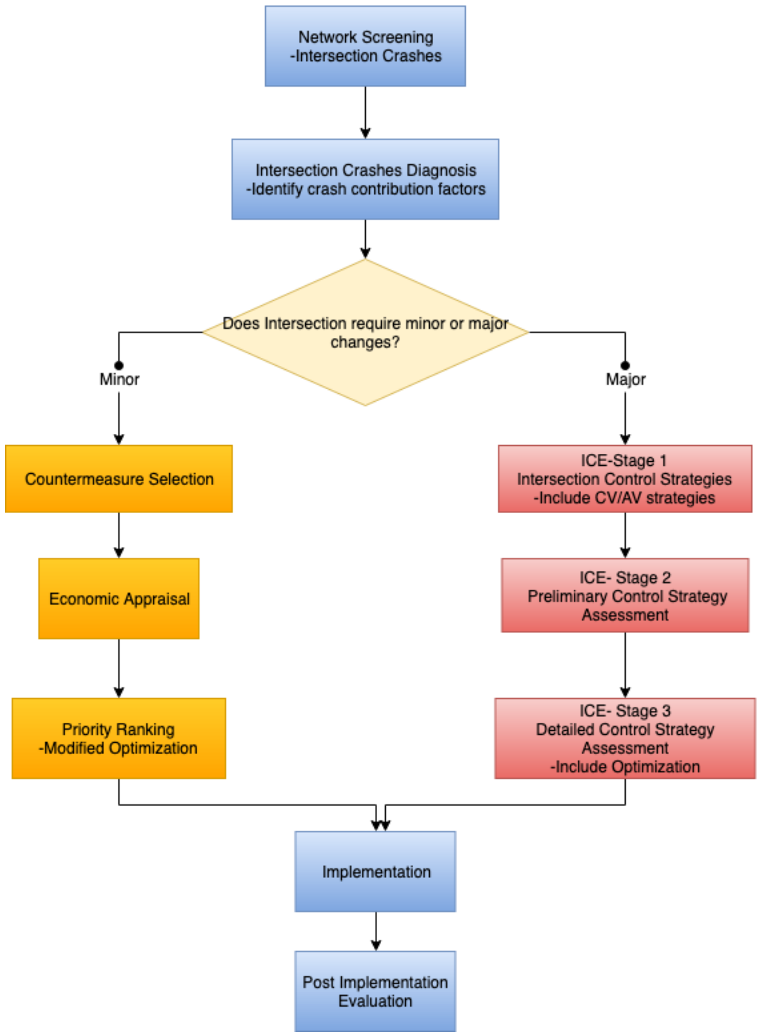

Figure 1. Framework of the Proposed Tool

2.1 Players within the Proposed Solution

The players within the proposed solution include the FHWA, State DOTs, State and local partners, and other end users (such as research institutes, institutions, traffic engineers, highway designers, planners etc.), car manufacturers.

3. Con-ops for Solution

This section describes the Con-Ops for the solution by first explaining the current system and the problem to be solved, followed by the justification of the proposed changes and then, the high-level overview of the proposed solution.

3.1 Current System Situation

Intersections are designed points of conflict in all roadway systems where all modes of traffic cross paths as they travel through or turn from one route to another. According to the National Highway Traffic Safety Administration (NHTSA) approximately 40% of all vehicle crashes in the US occur at intersections (NHTSA, 2019).

Highway safety Manual and Safety Analyst

American Association of State Highway and Transportation Officials (AASHTO) has provided a detailed methodology in the HSM and tool "Safety Analyst" which implements the HSM methodology to thoroughly conduct safety analysis and address specific safety improvements that involve physical modifications to the highway system. The Safety Analyst comprises of a set of software tools which implements state-of-the-art analytical procedures used for decision making process for site-specific improvements to enhance highway safety by employing cost-effective approach. There are six safety management tools integrated into the Safety Analyst; (i) network screening, (ii) diagnosis, (iii) countermeasure selection, (iv) economic appraisal, (v) priority ranking, and (vi) countermeasure evaluation. The Safety Analyst can either act as a complete toolbox or can be used for any of the six modules. The Safety Analyst tool is employed to determine which sites have the highest potential for safety improvement and is designed to address the limitations that are associated with the conventional (traditional) safety analysis methods.

Overview of each stage within the HSM and Safety Analyst

(1) **Network screening:** It involves a process that reviews a system of the transportation network to identify locations with higher impact potential in terms of crash frequency reduction when a countermeasure is applied. This is the first step in the highway safety management process shown in the HSM. The HSM identifies 5 major steps accompanying the network screening process: Establishing focus, Identification of network and reference population, performance measures selection, screening method selection and evaluation of results.

(2) **Diagnosis:** This is the second step in the HSM. It diagnoses the nature of the safety problems at the specific sites and aids the users in selecting effective countermeasures to address the problems. It identifies crash patterns with crash data, historical site data, and field conditions. It uses the Haddon Matrix to identify crash contributing factors before, during, and after a crash from the perspective of human, vehicle, and roadway.

(3) **Countermeasure selection:** This is a very important step in the roadway safety management process. The overall goal is to select countermeasures that would reduce crash frequency and severity at specific sites. Basically, after the factors contributing to the observed crash patterns

are identified from the previous step, countermeasures are selected to address those factors. The crash contributing factors are divided into three different categories: (i) human, (ii) vehicle, and (iii) roadway. The Safety Analyst relies on engineering judgement to identify those factors that are expected to be the greatest contributor to each particular crash type of concern.

(4) **Economic appraisal:** The proposed OPTISA tool performs an economic appraisal of a specific countermeasures or several alternatives countermeasures for a specific site based on the steps in the Safety Analyst. The user can determine which method of economic appraisal to use to carry out the analysis. However, OPTISA has included the various cost involved in using the CAV technology. As the world move to an era where almost every system is connected to one another (e.g. internet of Things (IOT), vehicle to vehicle (V2V), vehicle to infrastructure (V2I)), the landscape for cyberattacks also increases. There has been growing concern about the vulnerability of these vehicles to, cyber-attacks and technology malfunction and vehicle malfunction. Thus, intersection safety evaluation needs to consider these costs as part of the economic appraisal when the proposed CV countermeasure strategies are selected. An effective CV countermeasure will consider the reduction in potential for cyber threats, technology malfunction on CAV. This has been incorporated into the OPTISA tool

(5) **Priority ranking**: It provides the priority ranking of the site and the proposed improvement based on the cost and benefit estimates. It considers the optimization of cost effectiveness, benefit–cost ratio, net benefits, safety benefits, construction cost, number of total crashes reduced, number of fatal- and severe-injury crashes reduced, and number of fatal- and all-injury crashes reduced with the objective of maximizing the net benefits.

(6) **Countermeasure evaluation:** Evaluates effectiveness of a safety countermeasure in reducing crash frequency or severity. It uses Empirical Bayes approach to conduct before-and-after evaluations.

HSM and Safety Analyst Limitations

HSM and Safety Analyst is widely used around the nation by various DOTs. Despite its wide applicability, there are still some limitations regarding its use and effectiveness. For instance, the Safety Analyst is not intended for direct application to non-specific highway safety improvements (e.g. vehicle design improvements, etc.). Safety Analyst is data intensive and has stringent data requirements which is a very limiting factor for site selection and prioritization methods (Alluri and Ogle 2013). Data needs to be updated into the software annually which also depends on the extent of changes to the roadway characteristics. This process can be very tedious. Safety Analyst requires a large database (i.e. memory space), and is also costly based on a survey conducted by (Alluri and Ogle 2013).

The tool may be a black box. The network screening process uses Empirical Bayesian (EB) method which is already automated in the system making it impossible for the user to understand the internal steps within the software (Alluri and Ogle 2013). In addition, the Safety Analyst automates the preparation of the collision diagrams, identification of accident types but the selection of the countermeasure is done by the user and not the software. This approach is subjective in nature (and can also be influenced by the level of experience of the responsible engineer). The engineer may argue that there already exists list of possible countermeasures that can be applied to specific contributing factors which may have been collated from series of studies, however there is need for a better and more quantitative (or systematic) approach that can be employed to select the potential countermeasures.

Other existing tools that are used for the safety analysis are ICE, FHWA Systematic Tool, and Road Safety Audits (RSA). ICE tool is used to select an intersection control strategy among various alternatives based on certain factors that will results to safety improvement. The FHWA Systematic Safety Tool prioritizes sites and select applicable countermeasures based on risk factors. The RSA involves detailed review of crash data and crash pattern by experienced professionals in order to identify the safety improvement needs. Since this report is based mainly on intersection safety the ICE tool will further be explained below.

Intersection Control Evaluation (ICE)

ICE was developed by FHWA to objectively screen alternatives and identify an optimal geometric and control solution for an intersection (FHWA, 2019). The ICE tool is used to make informed decision, select control strategy and measure the value of the control based on selected performance measures or criteria. ICE makes use of forecasted traffic data hence; it can be categorized as a predictive tool. The framework for assessment using the ICE is divided into three-stage procedure; (i) Stage 1 - "screening" to determine the short list of all possible alternatives that merit further consideration and analysis because they meet project needs and are practical to pursue, (ii) Stage 2 - "preliminary control assessment" to determine the preferred alternative based on more detailed evaluations conducted during typical preliminary engineering activities. and (ii) Stage 3 - "detailed control assessment" to determine best alternative based on benefit and cost estimates. Each of the stage advances to the upper level stage when more than control strategy is considered viable.

ICE integrates the use of analytical tools such as Capacity Analysis for Planning of Junctions (CAP-X), Safety Performance for Intersection Control Evaluation (SPICE), SYNCHRO and ICE. The CAP-X tool is used during the screening stage, it conducts critical movement analysis (CMA) to gauge the potential performance of intersection and interchange types. CMA identifies the critical movements at an intersection and estimates whether the intersection is operating below, near, at, or over capacity. The SPICE tool is employed in both the stage 1 and stage 2; and is used for safety comparison of the intersections. The ICE is a financial analysis tool for intersection alternatives. It takes the output from the SPICE Tool to compute the benefit-cost and the net present value for the alternatives. ICE tool has been widely used by DOTs to identify alternative control strategies to improve safety and operation of intersections. Some of the limitations of the ICE tool is on the prediction of the crashes using the SPICE tool based on the HSM variables such as Crash Modification Factors (CMF) and Safety Performance Functions (SPF).

3.2 Justification of the Proposed Changes

After a careful examination of the two main existing tools for intersection safety evaluation; Safety Analyst and ICE, OPTISA was developed to combine the benefits and address the gaps that exists in both tools. Authors believe that a tool with the combination of both Safety Analyst and ICE will have a complete safety management process. As stated in the previous section Safety analyst is proprietary and needs the user to receive training to use it. It also has challenges in data input and management and it is not free. This calls for a tool that can be simply used and accommodate all steps of HSM.

The ICE tool is included in the proposed tool because the HSM/ Safety Analyst tool does not account for major changes that will involve the need for a new or modified intersection. One of the main limitations that both tools have is the lack of consideration for future technological advancement in transportation in which OPTISA will cover for that.

Connected and Automated vehicles (CAVs) were once in the realm of science fiction but now they are here and about to transform the automotive industry and the U.S. transportation system. Studies projects that CAVs will be on the road by 2030. These vehicles are expected to improve road safety and save lives. The Haddon Matrix which is used in HSM/Safety Analyst to analyze factors that contribute to crashes is not designed to address vehicles where driver has little or no control. Hence, there is a need to propose an updated Haddon Matrix which will address new factors including CAV technology. Furthermore, CV/AV control strategies capabilities need to be considered in order to identify new design and configuration that will integrate intelligent transportation solutions/ options into the intersection safety evaluation (Jing et al. 2017).

3.3 Concepts for the Proposed Tool (OPTISA)

To address the limitations in the Safety Analyst and ICE tools, this study proposes a decision support optimization tool for intersection safety analysis (OPTISA) with the modifications to the existing tools. There proposed tool comprises of eight steps; (i) network screening, (ii) diagnosis, (iii) minor/major change requirements, (iv) countermeasure/control strategy selection (v) economic appraisal, (vi) priority ranking, (vii) implementation and (viii) post implementation evaluation.

Proposed Modifications

Network Screening

In the network screening the following five steps will be considered; (1) extract intersection data to include crash data and traffic information, (2) input project information such as county, city etc. and intersection crash data in the tool, (3) input constants to be used in the intersection analysis, (4) analysis and ranking of the intersections following the methods presented in Chapter 4 of the HSM in the tool, and (5) produce reports with the crash summary.

Diagnosis and Countermeasure Selection

For Diagnosis an updated Haddon matrix is proposed to address the impact of the new technologies, CAVs. In selecting countermeasures, machine learning techniques or decision tree can be used to choose between viable options and unrealistic options rather than the traditionally manual procedures which are subjective. Design modifications for future roadway configurations to integrate intelligent transportation options such as CV applications and V2I applications should be considered when selecting countermeasures. To establish a CV applications as potential countermeasures, this study proposes CV strategies. These are countermeasures that may mimic, complement or extend the capabilities of the current approach or current conventional control strategies.

CV technology is an emerging technology that enables real-time traffic information and data exchange between vehicles, and between vehicles and infrastructure. Connected Vehicles (CV) and Autonomous Vehicles (AV) strategies can help to eliminate majority of the human contributing factors. In the proposed OPTISA tool CVs control strategies are considered in order to assist the analyst to identify new design and configuration that will integrate intelligent transportation solutions/options into the intersection safety evaluation (Jing et al. 2017). CVs have the potential to improve safety and mobility for the future transportation system, therefore employing strategies that would inform the deployment and application of CVs at the intersections will help to reduce crashes and improve the operational benefits of the intersections. Recently, the FHWA conducted a study to identify initiative on how infrastructure may be adjusted to accommodate CV technologies (FHWA, 2018). Florida is among the first states that have initiated testing of CVs intersection corridors. Hence, this tool will prove useful in the future. Figure 2 show the diagnosis and the countermeasure selection stages of the proposed tool.

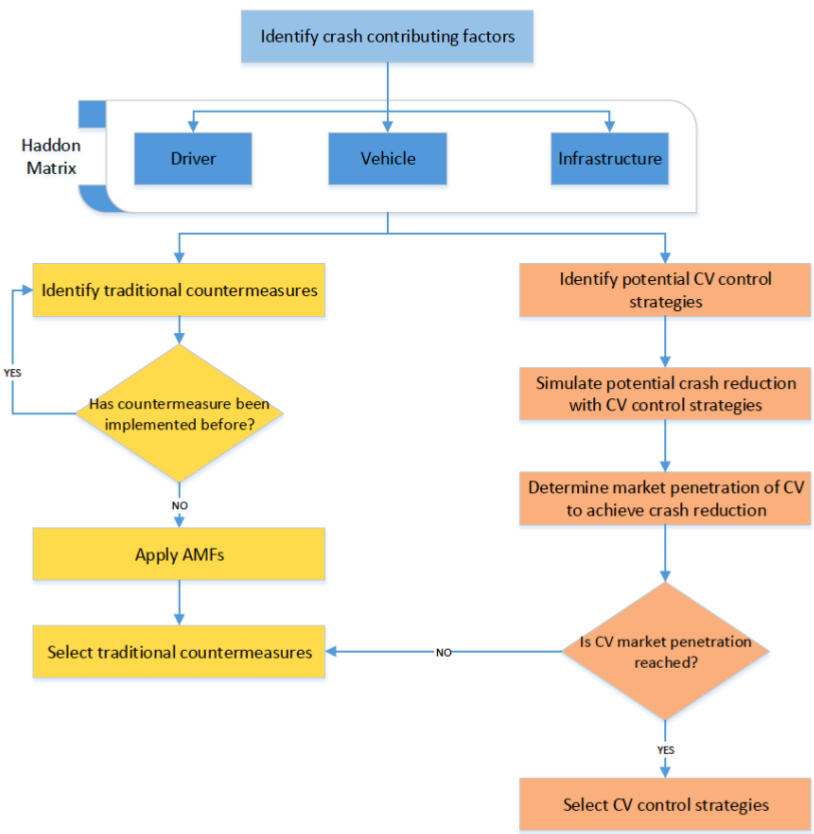

Figure 2. Diagnosis and Countermeasure Selection Stages of the Proposed Tool

Optimization Model

In the OPTISA tool a mixed integer programming model for the multi-objective resource allocation optimization problem (**MRAOP**) is proposed. The formulation of model is provided below.

Nomenclature

Sets	
I	Set of countermeasures
J	Set of roadway intersections
Decision Variables	
$x_{ij}\ \forall i \in I, j \in J$	=1 if countermeasure *i* is implemented at intersection *j* and zero otherwise
Auxiliary Variables	
$y_{ij}\ \forall i \in I, j \in J$	=1 if countermeasure *i* can be potentially implemented at intersection *j* and zero otherwise
Parameters	
$a_j\ j \in J$	accident prediction value at roadway intersection *j*
$c_i \forall\ i \in I$	present cost of implementing countermeasure *i*
$e_i \forall\ i \in I$	effectiveness of countermeasure *i*
$FA_j\ \forall j \in J$	fatal accident prediction value at roadway intersection *j*
$IA_j\ \forall j \in J$	injury accident prediction value at roadway intersection *j*
$PD_j\ \forall j \in J$	property damage accident prediction value at roadway intersection *j*
B	budget available
w_1	cost of fatal accident
w_2	cost of injury accident
w_3	cost of property damage accident

MRAOP:

$$max \sum_{i\in I, j\in J} a_j \times e_i \times x_{i,j} \tag{1}$$

$$max \sum_{i\in I, j\in J} (w_1 \times FA_j \times e_i \times x_{i,j} + w_2 \times IA_j \times e_i \times x_{i,j} + w_3 \times PD_j \times e_i \times x_{i,j}) \tag{2}$$

Subject to:

$$\sum_{i\in I} c_i \times x_{i,j} \leq B\ \forall j \in J \tag{3}$$

$$\sum_{i\in I} x_{i,j} \leq 1\ \forall j \in J \tag{4}$$

$$x_{i,j} \leq y_{i,j}\ \forall i \in I, j \in J \tag{5}$$

In the **MRAOP** mathematical model, the objective function (1) aims to maximize the total accident reduction. The objective function (2) aims to maximize the total weighted accident reduction by severity category. Constraint set (3) ensures that the total cost of all implemented countermeasures at chosen intersection will not exceed the available budget. Constraint set (4) states that no more than one countermeasure *i* can be applied at intersection *j*. Constraint set (5) indicates that countermeasure *i* can be implemented only at potentially considered roadway intersection *j*. Auxiliary binary variable y_{ij} has been introduced to indicate if a particular countermeasure *i* can be implemented at roadway intersection *j* or not, while decision variable x_{ij} shows each intersection and suggested countermeasure, which should be applied in order to satisfy objective functions (1) and (2). The **MRAOP** mathematical model is linear and can be solved to global optimality using exact optimization algorithms (e.g. CPLEX, Frank Wolfe Algorithm, Djikstra Algorithm, etc.) within acceptable computational time for realistic size problem instances. For this study, the **MRAOP** mathematical model were coded in General Algebraic Modeling System (GAMS) and solved using CPLEX (GAMS, 2019). This exact optimization algorithm will ensure that the best possible solution is selected for all problem instances.

Mode of Operation

The proposed tool is expected to operate as an MS Excel-based spreadsheet tool that will take into account all of the proposed steps. The developed spreadsheet will have separate worksheets for each step. The tool involves use of Visual Basics (VBA) codes and functions which works when Macros enables. The user will be required to input data as directed in the tool.

4. Task and Cost Breakdown

The table below provides the breakdown of the tasks, cost, and the timeline associated with the developing the proposed tool.

Table 1. Cost and Time estimates for tasks in the Proposed Tool

Task	Cost	Time Estimate
Data collection	Personnel cost, data acquisition cost	3 months
Development of the spreadsheet tool	Personnel Cost	2 months
Testing of the tool	Distribution of the tool	2 months
Deployment	Installation, customization, etc.	3 months

5. Anticipated Impacts

The proposed tool is intended to help in the intersection safety improvements by providing an up-to-date solution to candidate sites selection for treatment. The crash reduction from the treatment of the selected sites is expected to be cost-effective. The selected control strategies are expected to bring improvement in safety, operation, mobility and environmental.

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