Evaluation of Life Cycle Impacts of Intersection Control Type Selection [Final Report]

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Abstract:

The methodology provided in this report provides guidance for NCDOT conversions of two-way stop controlled intersections to other intersection types to enhance the effective allocation of public funds. The findings of this project have been incorporated into the study's primary deliverable, the spreadsheet-based NCDOT Intersection Life Cycle Cost Comparison Tool, which combines enhanced HCM 2010 methodologies and standard cost benefit analysis methodologies to calculate the long-term net benefits of converting a two-way stop controlled intersections to three different intersection options: 1) all- way stop controlled, 2) signalized, and 3) roundabout types. This deliverable is designed for use during the planning phase of potential intersection conversion projects to help stakeholders identify the most cost-effective conversion configuration option. This report summarizes the findings of all project tasks.

Key Words **Life Cycle Cost Analysis, Benefit Cost Analysis, Intersection Conversion, Two-Way Stop**	Distribution Statement

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Executive Summary

North Carolina Department of Transportation Research Project No. 2014-11: Evaluation of Life Cycle Impacts of Intersection Control Type Selection was initiated in response to the North Carolina General Assembly's request for highway project life cycle cost analysis procedures.

Two-way stop controlled (TWSC) intersections can frequently be converted to other facility types to improve safety, operations, and other types of issues. Yet, transportation agencies across the United States, including the NCDOT, have historically lacked standardized guidance for considering the cost effectiveness of various intersection control types over the course of their life cycles. Consequently, this research effort was funded to provide guidance for NCDOT conversions of TWSC intersections to other intersection types to enhance the effective allocation of public funds. For the purpose of this study, a two-way stop controlled intersection is defined as a four-way intersection with no control mechanism for the main approach and stop signs positioned at the minor approach.

The findings of this project have been incorporated into the study's primary deliverable, a spreadsheet-based NCDOT Intersection Life Cycle Cost Comparison Tool. This user-friendly computational engine is to be used during the planning phase of potential intersection conversion projects to help stakeholders identify the most cost-effective conversion configuration option. The tool combines enhanced Highway Capacity Manual 2010 methodologies and standard cost benefit analysis methodologies to calculate the long-term net benefits of converting a TWSC intersections to three different intersection alternatives: 1) all-way stop controlled, 2) signalized, and 3) roundabout types.

The tool created through this project is the only of its kind in the nation, perhaps the world. Similar tools used by other agencies require that users derive data for variables such as delay and safety in a secondary external platform and then manually enter that data into the intersection analysis tool. Alternatively, the tool delivered with this study calculates all of the necessary LCCA variables within one computational engine, increasing efficiency and decreasing the opportunity for error, with the goal of saving the NCDOT staff time and money during the planning stages of a project. In addition, a tool user guide was created and is delivered along with this report.

Based on user inputs and standard state and national figures, site-specific construction and maintenance, user delay, and safety costs and benefits are calculated for each of the three conversion types. As part of this study, new empirically-based defaults were developed for many of the variables necessary for this process. Cost and benefit calculations for each alternative are projected into the future using a methodology that considers the changing value of money over time. The resulting dollar figures can be compared to identify the intersection type that offers the greatest return on investment to North Carolina citizens over a user-specified time period.

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1. Introduction

As areas of North Carolina continue to grow, Two-Way Stop Controlled (TWSC) intersections that were once adequate for traffic demands may experience safety and operational issues. One way to address these issues is to convert a TWSC intersection to another facility type, most commonly all-way stop controlled (AWSC), roundabout, and traffic signal types. Each of these control alternatives has advantages and disadvantages that can result in long-term benefits and costs to the state of North Carolina, however analyzing and comparing these outcomes can be a complex task, discussed further in Sections 1 and 2 of this report.

In 2013, the North Carolina House Appropriations Subcommittee on Transportation called for the NCDOT to conduct life cycle cost analyses, or long-term cost-benefit assessments, on all highway projects on a new location (North Carolina House Appropriations Subcommittee, 2013). Conducting such analyses can be challenging, as both North Carolina and the United States as a whole have historically lacked guidance regarding the long-term cost effectiveness of various intersection control types. Consequently, this research effort seeks to develop a model for evaluating the life cycle costs and benefits of intersection control alternatives to TWSC, and aims to integrate these findings into a spreadsheet-based computational tool the NCDOT can use to efficiently and uniformly analyze potential conversions over a user specified period of time.

1.1. Background

Life Cycle Cost Analyses (LCCAs) are designed to help public agencies and lawmakers choose the project option that best utilizes public funds by comparing the potential long-term costs and benefits of a project in monetary terms (Swiss, 2002). Because conducting a thorough LCCA can take significant time and resources, intersection conversion decisions in North Carolina and other states are often made using limited data and short-term cost and benefit projections. As a result, the long term costs and benefits of a conversion choice are often not the focus of the decision-making process, if they are evaluated at all (Misuraca, 2014). Instead, options with minimal up-front costs such as signal-controlled configurations have been historically selected over more initially expensive alternatives such as roundabouts (NCHRP 03-110, 2016).

It is vital, however, that transportation agencies like the NCDOT examine the long-term impact of different conversion alternatives because many of the costs and benefits associated with intersection reconfigurations may not be realized until years, sometimes decades, after an initial conversion. Consequently, in the absence of a more thorough analysis such as a LCCA, the most cost-effective alternative may not be selected and public funds may be inefficiently allocated (Litman, and Doherty, 2009).

Additionally, many transportation agencies lack guidance on LCCA models and the standardized inputs for the typed of data these models require. While the NCDOT has made efforts to develop and distribute data, such as Crash Modification Factors (CMFs), that can be used across Divisions, the Department currently lacks standards for many of the other inputs necessary for intersection conversion LCCA calculations, such as typical construction and maintenance costs.

Identifying standard analysis models and inputs could significantly limit the NCDOT's transaction costs and increase the agency's ability to uniformly compare progress in intersection conversion decision making over time (Misuraca, 2014; Litman and Doherty, 2009).

1.2. Objectives

In a time of growing demand for limited financial resources, the legislature is taking measures to ensure that the NCDOT is allocating financial resources using sound economic principles. Given the fiscal importance of estimating and comparing the long-term outcomes of intersection conversion alternatives, the primary objective of this research is to provide guidance for NCDOT conversions from a TWSC intersection to other types in order to enhance the effective allocation of public funds. As such, the deliverables of this study include:

1) a LCCA-based quantitative model that accounts for variables that impact the life cycle costs of various intersection conversions being considered;
2) standardized inputs and guidance for variables needed to analyze an intersection using this model; and
3) a spreadsheet-based computational tool that uses this model to streamline intersection conversion LCCAs for transportation planners

1.3. Scope

Due to the complexity of evaluating the life cycle costs of a conversion, this research is specifically focused on establishing sound a method for analyzing conversions from TWSC intersections with four legs to all-the-way stop controlled (AWSC), signalized, or roundabout intersection types. Consequently, neither the model nor the tool should be used to calculate conversions for other intersection types, such as three-legged intersections. Additionally, this research is not designed to determine the life cycle costs of intersection conversions at interchanges or in areas highly influenced by interchange entry and exit traffic.

The spreadsheet-based NCDOT Life Cycle Cost Analysis Tool employs site-specific user inputs as well as state and national standards to calculate the long-term costs and benefits of converting the specific intersection of interest. This computational engine is unique, because unlike other intersection analysis tools used by the Florida Department Transportation and other agencies in the country, this tool calculates variables such as delay, safety, and other long-term costs and benefits within one platform. Such in-tool calculations are designed to save the State of North Carolina valuable time and money by increasing efficiency and decreasing the risk of errors that can occur when data is transferred from other software platforms and reports.

Standard methodologies are used to calculate operational and safety data, as well as the changing value of money over time. The final outputs of the model are the total estimated long-terms costs of converting the existing TWSC intersection. The long-term benefits minus the costs of each of the three intersection conversion options are compared side-by-side to help users identify the intersection type that will provide the greatest return on investment over time. After an analysis, the computational engine can be used to print a report that clearly outlines these outcomes, including informational tables.

The site-specific construction and maintenance, user delay, and safety costs and benefits associated with each conversion type are considered in this analysis. Other factors such as environmental impacts are not considered in calculations. While the Intersection Life Cycle Cost Comparison Tool provides useful data, it is not intended to be the only information used to inform intersection decisions. Other factors that may influence intersection selection, such as stakeholder input, right-of-way availability, and funding flexibility, are not considered in the model of this tool.

2. Literature Review

This study incorporates a variety of research and data from both Life Cycle Cost Analysis and transportation literature. Additionally, the methodology developed through this study utilizes models from the Highway Capacity Manual (HCM), the Highway Safety Manual (HSM), and state specific safety models where possible. The application of these models is further explained in a later section of this report.

2.1. Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCCA), also known as benefit-cost analysis, methodology is being increasingly used by transportation agencies across the country to systematically evaluate and compare transportation projects (NCHRP Report 483, 2003).

LCCAs are used to *monetize* variables of different types so that they can be compared using a common monetary unit like the dollar (United States Office of Management and Budget, 1992). Monetizing, or applying a monetary value to non-monetary variables, such as improved roadway safety, helps planners and policymakers account for both the social and fiscal costs and benefits of a project. This is particularly useful because the projected future costs and benefits of different projects can be directly compared when these variables are converted into consistent and measurable monetary units. This helps decision-makers identify the option that provides the greatest potential benefits in the long-run (United States Office of Management and Budget, 1992; Swiss, 2002).

In addition, one of the core assumptions of the LCCA method is that money today will be worth less in the future because of its investment potential (Jawad, and Ozbay, 2005). In order to account for the changing value of money and resources over time, LCCA models include a method called *discounting*. Similar to the idea of inflation, discounting adjusts monetized costs and benefits to reflect how their value will typically decline over time (Litman and Doherty, 2009). As shown the equation in Equation 1 below, each cost and benefit is multiplied by a carefully selected anticipated rate of change, which compounds annually over the period of analysis selected by the user (United States Office of Management and Budget, 2015).

Equation 1. Discounting

$$PV = \frac{AB_{y_f}}{(1+r)^{y_f - y_i}}$$

where:

PV = present value
AB (or AC) = annual benefit (or annual cost)
r = the discount rate
y_f = the final year in which the benefit or cost occurs
y_i = the initial year of analysis

Once discounted, the benefits are subtracted from costs for each option to identify its *Net Present Value (NPV)*, or total long-term benefits. The option with the highest NPV is that which would provide the greatest return on investment over time and is therefore the recommended conversion type for the site of interest (United States Office of Management and Budget, 1992).

Although a widely used method, LCCA does have some limitations. For example, LCCAs do not address equity issues, such as variances in individuals' access to a roadway or the impact of different construction periods on area businesses. Additionally, standards for the valuation of certain variables may vary by organization, state, or even user preference (Swiss, 2002).

2.2. Conversion Types

Although innovative intersection designs such as Restricted Crossing U-turns are becoming more popular in the United States, TWSC intersections are most frequently converted to roundabouts, traffic signals, and all-way stop controlled types (FHWA, 2010). When compared to TWSC types, research shows that each of these configurations can reduce collisions. However, the degree of reduction can not only depend significantly on the control type, but also on the area type (urban, suburban, or rural), and other factors.

Furthermore, each of the three intersection conversion types is associated with unique costs and benefits that can accumulate at different rates over different time periods. Conversion to an AWSC intersection can reduce collisions with only minimal construction and maintenance costs but may result in increased delay as volumes increase. Signalization can reduce delay for side street movements but may require higher construction, maintenance, and operational costs. Conversely, roundabouts often require significant initial investment due to construction costs but can dramatically increase safety and effectively reduce delay under the right conditions (Han, Li, and Urbanik, 2008; Jiang, 2012; Sides, Seals, and Walwork, 2005; FHWA, 2004b; NCHRP Report 672, 2010).

3. Methodology

This study uses a two-way stop controlled intersection as the starting point, or baseline, for comparing three different potential conversion types: all-way stop controlled, signalized, and roundabout intersections. Accordingly, the model first projects the long term outcomes, such as delay times, that would be expected at the intersection if the TWSC facility was not converted, and then subtracts these values from the projected outcomes of each alternative. Per LCCA methodology, the difference between the projected outcomes of the TWSC option and those of each alternative are then monetized.

Consequently, only the costs and benefits that are expected to result from a given conversion option will be counted monetarily in the model. For example, instead of incorporating the costs of previous accidents at a given intersection, only the benefits of the potential reduction in crashes due to a given conversion will be analyzed because the assumption is that without any conversion accident trends at the site will follow historical patterns. For the purpose of this study, a two-way stop controlled intersection is defined as a four-way intersection with no control mechanism for the main approach and stop signs positioned at the minor approach.

3.1. Variable Types and Defaults

Research on the costs and benefits of intersection conversions typically focuses on three categories of variables: 1) construction & maintenance, 2) user delay, and 3) safety (Sides, Seals, and Walwork, 2005; FHWA, 2010; Day, Hainen, and Bullock, 2013). Another factor often considered in analyses, environmental impact, is not included in this study due to time and resource limitations (FHWA, 2010). However, this research does include considerations for the amount of fuel consumed due to idling, which does have environmental ramifications.

Monetizing each of the three variable types considered in the LCCA calculations of this model involves unique inputs, standard values, and adjustments for changes in these values overtime. Standardized, or *default values* are used in calculations throughout the developed model tool in order to both limit user input time and to enhance the uniformity of the LCCA processes.

Extensive research was conducted to identify the most appropriate default values for monetizing the costs and benefits calculated by this tool, such as the average reduction in crashes expected for a specific conversion type and the average number of expected passengers per vehicle. Federal and state standards as well as state transportation data and findings from peer-reviewed research were used to inform the defaults in this tool. All of the monetary default variables used have been converted to 2015 dollars for consistency.

When available, standard values already established by reputable state and national sources were used to develop defaults for the variables in this study's analytical model. State standards were prioritized over federal ones, with the assumption that these values would more accurately reflect North Carolina data. In some cases, defaults for a particular variable include a mixture of both federal and state values. All default values and their sources are outlined in later sections of this report, as well as Appendices 1 and 2, which include the references for each default.

3.2. Construction and Maintenance

Unlike many other variables measured in LCCAs, construction and maintenance costs can be monetized more readily based on similar historic projects. Most LCCA literature refers to the period of construction as “Year 0” because additional costs and benefits do not typically begin to accumulate until a facility is completed (Swiss, 2002). Additionally, construction costs are typically considered to be a one-time expenditure that occurs only at the time period prior to project completion. Therefore, a discount rate is not applied to initial construction costs in LCCAs, and only costs and benefits that begin after Year 0 will be discounted (Minnesota Department of Transportation, 2015; Swiss, 2002). Maintenance costs, on the other hand, are typically discounted and are considered to accumulate annually (Minnesota Department of Transportation, 2015).

3.2.1. Construction Costs

Construction costs for the purposes of this study are the capital funds needed to convert an intersection from a two-way stop to another intersection type, including pre-construction (right-of-way purchases and preliminary engineering) and physical construction (utility moves/additions, infrastructure changes/additions, etc.). Defaults for the typical cost of converting a TWSC intersection to each alternative type were established by the research team because NCDOT lacked standardized values for typical facility construction costs and federal data was not appropriate for North Carolina-specific estimations.

These estimates were developed based on actual intersection conversion costs for a five-year period, which were provided by the NCDOT. These conversion projects were funded through the Spot Safety Program, for which the Department allocated funding through an internal competition based on safety need. The dataset includes more than 700 projects, a third of which were identified as conversions from TWSC to one of the three alternatives of interest. Construction data, contracts, and before and after maps were analyzed for each conversion project. In some cases, NCDOT division staff were contacted to provide clarification on site-specific construction details. The projects were then categorized based on the characteristics of the re-configurations involved in the facility conversion, such as roadway realignment, utility movement, and right-of-way purchase. This method was applied with the consideration that the up-front costs needed to convert an intersection can vary greatly due to conversion type and site-specific characteristics.

Based on these characteristics, each project was categorized into one of three tiers of construction complexity (low, average, and high) for each of the three conversion types. The average cost for conversions of each category was then calculated to develop three tiers of typical construction costs (low, average, and high) for each alternative type, as shown in Exhibit 1 below. The three tiers of construction cost were developed to provide planners the flexibility to choose the best cost estimates based on the characteristics of the site of interest. For example, a conversion at an intersection that would require a realignment may be significantly more costly than one that does not and as a result a user may chose a funding option higher than the lowest option. Model users can also opt to enter values other than the those used for the cost tiers of this methodology.

Exhibit 1. Default Construction Cost Tiers

Intersection Type	Construction Costs	Cost	Description
Roundabout	Low	$500,000	basic one-way roundabout installation with minimal right-of-way (ROW) purchase
	Medium	$750,000	significant ROW purchase OR significant utility move
	High	$1,000,000	significant ROW purchase AND one or more of these: significant utility move, realignment, raising of intersection, or other additional features costing more than $10,000
AWSC	Low	$10,000	basic installation: marking and signs
	Medium	$25,000	addition or removal of flashers
	High	$75,000	two or more of these: addition or removal of island and/or pavement, addition/removal of flasher, utility work, or other feature
Signal	Low	$60,000	standard installation with few to no additional costs, aside from pedestrian signal heads installation
	Medium	$90,000	connect to city signal system AND at least one of these: installation of pedestrian signal heads, crosswalks, utility move, lane reassignment, or other feature OR at least two of these: installation of pedestrian signal heads, crosswalks, utility move, lane reassignment, or other feature
	High	$300,000	turn lanes installed and/or realignment, likely ROW purchase OR three or more of these: installation of pedestrian signal heads, crosswalks, utility move, lane reassignment, or other feature

3.2.2. Time from Analysis to Completion

The time between the initiation of a conversion project and its opening, or *time to completion* can vary significantly between conversion options. For example, converting a TWSC intersection to a roundabout may require moving utilities while conversion to AWSC may require little more than adding additional stop signs to a location. As a result, unique periods to completion are applied for each alternative in this and other LCCA models to ensure more accurate life cycle cost comparisons for projects.

Accounting for this variance in an intersection conversion analysis is important because projected benefits and costs of an intersection do not begin to accumulate until the standard construction period has concluded, which can vary by a month to years for different alternatives. For example, if the average signalized intersection takes six months to complete, benefits and costs do not begin until the first day of the seventh month from the day of the analysis because theoretically the signalized intersection does not exist until that time.

This variance in construction timeframes is accounted for in the analytical model by utilizing standards for average time to completion periods for each alternative type. These defaults, shown in Exhibit 2 below, were developed by the NCDOT for this study based on past project data and expertise.

Exhibit 2. Defaults for Time from Analysis to Completion, in years

Intersection Type	Roundabout	AWSC	Signal
Time (years)	1.5	0.2	0.5

Costs and benefits will not be counted until after construction is completed. As seen in Exhibit 2 above, “Year 0,” or the timeframe prior to construction, may actually be a period more or less than a year for some alternative intersection types. However, the time period of analysis will be the same for all alternatives, based on the timeframe selected by the model user. For example, if the timeframe of analysis is 25 years and the model assumes a roundabout will require 1.5 years for construction, then Year 1 for the roundabout alternative will begin after 1.5 years and only 23.5 years of costs and benefits will be analyzed for the facility.

3.2.3. Annual Maintenance Costs

Maintenance costs include annual and incremental operations and upkeep costs, such as landscaping and signal timing, as well as the cost of revising an intersection at the end of its anticipated service life. Similar to construction costs, different facility types can have significantly different maintenance costs (FHWA, 2010: NCHRP Report 672, 2010).

When calculating maintenance costs, the analytical model utilizes unique annual maintenance costs for the anticipated service life in years for each of the three intersection types. The annual maintenance costs applied for each intersection alternative are the standard defaults that the

NCDOT uses in-house for analyses. These values were established by NCDOT are based on existing national literature and local experience. As shown in Exhibit 3 below, it is projected that both roundabouts and signalized intersections will incur a maintenance cost of $2,500 annually while AWSC types will require $0 in annual upkeep.

Exhibit 3. Annual Maintenance Costs

Intersection Type	Roundabout	AWSC	Signal
Annual Maintenance Cost	$2,500	$ 0	$2,500

3.2.4. Facility Service Life

Each of the three intersection alternatives also has a unique end of service life, or life expectancy, at the end of which it is anticipated that the facility will need significant revision(s). The LCCA model of this study uses default values for the facility service life period that were developed by the NCDOT via expert panels and historical data. These values are shown in Exhibit 4 below. In the year following an intersection type's anticipated end of service life period, the tool applies the cost of the lowest construction tier for that type instead of that year's annual maintenance cost, with the assumption that facilities will need to be upgraded at that time.

Exhibit 4. Anticipated Facility Service Life and Minimum Facility Replacement Costs

Intersection Type	Roundabout	AWSC	Signal
Minimum Replacement Cost	$500,000	$10,000	$60,000
Service Life (Years)	25	6	10

In consideration of these varied service life periods and national defaults for analysis periods, the model is designed to analyze projects only between 10 and 25 years into the future. In the United States, the typical period of analysis used for transportation improvement projects is 20 years (Minnesota Department of Transportation, 2015). The 10 to 25 year range aligns with the literature and also allows time for some benefits to accumulate for each alternative in addition to allowing planners the flexibility to select a timeframe that is appropriate for the intersection of interest.

For example, users may want to select a time frame closer to 10 years in cases where decision-makers plan to use a conversion as a temporary solution due to a longer range plan for the area of interest. For cases in which the user makes input choices based on future plans or insights about an area, users can explain plans in the comment sections of the tool's printable report. This report, explained further in the *Printable Report* section below, includes details from the analysis and provides a space users can use to comment on inputs and other factors of the analysis, as they desire.

3.3. User Delay

User, or passenger, delay is an important measure for evaluating an intersection (Han, Li, and Urbanik, 2008). In alignment with findings from multiple peer-reviewed studies, the user delay analysis portion of this tool is based on the assumption that conversion from a two-way stop controlled intersection to a more complex type will decrease delay (Sides, Seals, and Walwork, 2005). The methodology used for calculating the delay times for each intersection type is explained in the *Framework* section of this study. It should be noted that delay calculations in this methodology are solely focused on vehicle demand and do not account for pedestrian or bike usage.

Congestion and related traffic delays can come at a high price for roadway users, and should therefore be considered when examining the costs of a transportation decision (Virginia Department of Transportation, 2013). Typically, these costs occur due to time lost waiting in traffic, increased vehicle wear and tear, fuel lost due to idling, and other factors. Instead of approaching user delay as a cost, the methodology of this study treats conversion-related *reductions* in delay as a benefit by subtracting delay outcomes expected with the current TWSC from that projected for an alternatives and monetizing the difference.

Monetizing user delay for a specific site and conversion type involves several different variables. This model monetizes delay using two key variables: the value of fuel consumed while idling and the value of travel time. Other potential variables impacting delay costs were not considered due to their measurement complexity and variability.

3.3.1. <u>Fuel Used While Idling</u>

User delay and idling are positively correlated in that when user delay decreases it is anticipated that idling will decrease, and vice versa (FHWA, 2005; HCM, 2010). Consequently, idling is an important variable to capture when comparing the delay-related life cycle costs and benefits of different intersection alternatives. The Argonne National Laboratory estimates that in the United States idling results in more than 6 billion gallons of wasted fuel at a cost of more than $20 billion each year (United States Department of Energy, 2013).

In addition to increased fuel costs, delay can come at a financial cost to drivers in the form of increased vehicle maintenance, decreased vehicle life span, and increased pollution (United States Department of Energy, 2013). Because changes in vehicle maintenance costs, vehicle life spans, and environmental ramifications can be challenging to accurately monetize, the model focuses on the value of fuel to monetize idling projected to occur due to various intersection conversions.

The idling cost per second used is calculated in the model by multiplying the cost of fuel per gallon of unleaded fuel for passenger vehicles and diesel fuel for heavy vehicles separately by the average number of gallons expected to be consumed per second respective to vehicle type. To increase the precision of idling cost and benefit estimations, model users are asked to input the cost per gallon of unleaded (for passenger vehicles) and diesel (for heavy vehicles) fuel on the day of analysis. The U.S. Department of Energy's standards for the average amount of fuel consumed per hour by passenger and heavy vehicles, shown below in Exhibit 5 is then applied and resulting values are divided by 3600 to identify the average amount of fuel consumed per second due to idling.

Exhibit 5. Gallons of Fuel Consumed Per Hour of Idling

Gallons of Fuel Consumed Per Hour	
Passenger Vehicle	0.39
Heavy Vehicle	0.69

Source: U.S. Department of Energy, 2014

In order to determine the total cost of delay for the specific intersection of interest, the costs of idling per second for both passenger and heavy vehicles are then multiplied separately by the control delay per second for each roadway approach. These calculations provide the unique idling cost per second per vehicle for each of the approaches specific to the intersection of interest.

3.3.2. Value of User Travel Time

A LCCA variable called *value of travel time*, is also considered in delay monetization methods. Applying a value to travel time follows the logic that the time of all roadway users has a monetary value, and as a result, increased delay results in a cost to users. For the purposes of this study, value of travel time is calculated using valuation standards released by the Texas A&M Transportation Institute, which estimates the value of an hour of time for passenger and heavy vehicles (Schrank, Eisele, Lomax, and Bak, 2015). These figures are shown in Exhibit 6 below.

Exhibit 6. Defaults for Value of User Travel Time

Value of User Travel Time Per Hour Per Person		
Passenger Vehicle	$	17.67
Heavy Vehicle	$	94.04

These values are divided by 3600 to identify the cost of delay to each passenger per second. Because it cannot be assumed that only one person is occupying each vehicle at an intersection, this cost is multiplied by the default of 1.25 persons per vehicle produced the Texas A&M Transportation Institute to develop the cost per second per vehicle (Eisele, Schrank, Lomax, and Bak, 2015).

To bring the fuel cost per vehicle and the user travel time cost together, the cost of idling per second per vehicle is then added to the cost of each second of travel time per vehicle. These figures, which are calculated separately for passenger and heavy vehicles types, provide the total cost of delay by vehicle type.

The total cost of delay for a vehicle is then multiplied by the peak volume of vehicles per hour for each individual approach to produce the total cost per vehicle. These values are next divide by a K factor and multiplied by 365 days a year to identify the total annual cost for vehicles at each approach. Finally, all of the values for all of the approaches are added to calculate the total costs for all vehicles annually at the given intersection.

3.3.3. Volume Growth Factor Per Year

For each year of analysis, this model applies an annual volume growth factor in order to adjust future projected delay times. Similar to discounting, the resulting percentage increases in traffic demand compound over time, as shown in the equation in Equation 2 below.

Equation 2. Volume Growth

$$Volume\ Growth = (T_2/T_1)^{1/(Y2-Y1)}$$

where:

T1 = traffic flow in year Y1
T2 = traffic demand in year Y2
With the annual traffic growth compounding

Source: FHWA, 2007

Defaults for volume growth factors are not included in this model, as growth factors will vary from site to site based on a variety of variables such as anticipated area population growth and business development.

3.4. Safety

Often, a key factor in the decision to convert a TWSC intersection to another type is safety. Research shows that a conversion from TWSC to all of the three types examined in this tool – AWSC, signalized and roundabouts – have been shown to reduce the number of collisions at an intersection (Sides, Seals, and Walwork, 2005; FHWA, 2004b; FHWA, 2010).

3.4.1. Crash Modification and Reduction Factors

In order to project how different intersection conversion types can reduce collisions for a particular site, this projects model utilizes Crash Reduction Factors (CRFs). CRFs express the percentage of crashes that are expected to decrease with the implementation of a given countermeasure (FHWA, 2014). CRFs are the inverse of Crash Modification Factors, also called

Accident Modification Factors, which are multiplicative factors that are used to calculate the number of crashes that are projected to occur after a specific countermeasure is implemented (FHWA, 2016).

For example, an intersection conversion that is expected to reduce crashes by 20% would have a CMF of .80. This means that if a site had 100 crashes annually prior to the conversion, it is projected that the number of crashes would be reduced to 80 each year after the conversion. Alternatively, the CRF for a conversion option expected to reduce crashes by 20% would be 20. Both CRFs and CMFs can be applied to existing crash frequency data as a ratio of change expected to occur with the installation of a countermeasure (HSM, 2010), however, this tool uses CRFs because the research team found that they are more easily understood by tool users and decision-makers.

The CRF defaults used in this model are from sound transportation studies and are the most reliable figures identified in the FHWA's CMF Clearinghouse (http://www.cmfclearinghouse.org/). CRFs specific to North Carolina were used when appropriate studies were available. Unique CRFs are used for rural, urban, and suburban locations, shown below in Exhibit 7.

Exhibit 7. Crash Reduction Factor Defaults

Anticipated Reduction in Crashes by Type	Roundabout	AWSC	Signal
K & A Injury Crashes (Urban)	29%	71%	23%
K & A Injury Crashes (Suburban)	78%	71%	44%
K & A Injury Crashes (Rural)	71%	71%	44%
B & C Injury Crashes (Urban)	29%	71%	23%
B & C Injury Crashes (Suburban)	78%	71%	44%
B & C Injury Crashes (Rural)	71%	71%	44%
PDO Crashes (Urban)	29%	61%	44%
PDO Crashes (Suburban)	78%	61%	44%
PDO Crashes (Rural)	71%	61%	44%

Source: FHWA, 2016

3.4.2. Crash Costs

The benefits of increased safety are monetized by applying the NCDOT's annual KABCO costs, based on injury by severity. Exhibit 8 includes descriptions of KABCO severity categories and the standard costs associated with each crash category are shown in Exhibit 9.

Exhibit 8. NCDOT Crash Severity Type Categories

Crash Severity Types	
Category	**Description**
K (fatal)	Death occurred within twelve months of the crash
A (disabling)	Injuries serious enough to prevent normal activity for at least one day such as massive loss of blood, broken bones, etc.
B (evident)	Non-fatal or A injuries are evident at the scene such as bruises, swelling, limping, etc.
C (possible)	No visible injury but there are complaints of pain or momentary unconsciousness
O (property damage only)	Pain or momentary unconsciousness

Source: NCDOT, 2013

Exhibit 9. Crash Costs by Severity Type

NCDOT Safety Costs (one per crash)		
K & A Injury Types:	$	4,544,000
B & C Injury Types:	$	134,000
Property Damage Only:	$	6,700

Source: NCDOT, 2014

The proportional reduction in crashes is multiplied by the KABCO costs that would be anticipated to occur on average each year if the intersection of interest remained a TWSC type. For example, if the annual collision costs expected at a TWSC control intersection are $5 million, then a conversion with CRF of 20 would be result in a benefit of $1 million annually due to a 20% reduction in crashes. These crash costs are monetized using three different crash categories and associated tiers of costs: 1) K + A injuries, 2) B + C injuries, and 3) PDO injuries, as shown in Exhibit 9. These are the same three combined cost categories used by the NCDOT for their in-house calculations.

3.5. Discounting

Based on extensive research, this study uses a 3% discount rate. This rate is within the 3-5% standard recommended by the FHWA (FHWA, 2004a), and is also in alignment with the standards released in 2016 by the United States Office of Management and Budget (United States Office of Management and Budget, 2016).

As discussed earlier, it should be noted that not all costs and benefits begin accumulating in Year 1 of a project and are therefore discounted based on the year that they begin. For example, if a onetime cost occurs in Year 5, it will be discounted based on five years of a 3% rate compounded. For additional information, see the discounting formula (Formula 1) in Section 2.1.

4. Framework

To optimize efficiency and user-friendliness, both the methodology of this study and the accompanying tool are broken into eight steps, which are organized by input and variable type. The steps and their descriptions are as follows:

1) Global Inputs
2) Traffic Demand
3) Crash Data
4) Roundabout Configuration
5) All-Way Stop Configuration
6) Signal Configuration
7) Results
8) Printable Report

The methods and unique inputs used for each of these steps are explained in the following sections. Within the tool, dynamic graphic user interfaces are included for many steps to optimize the accuracy of inputs and user understanding. After these eight steps, the user is directed to a "Results" tab, which shows the outputs of the analysis. This tab is explained at the end of this report. Step-by step user instructions for the computational engine are available in the tool user guide.

4.1. Global Inputs

Several site-specific details are required in *Step 1: Global Inputs* of the intersection comparison framework, including:

1) ***Major and Minor Approach Name:*** Names of the intersecting roadways of interest.
2) ***County:*** Name of county where intersection is located.
3) ***Analyst Name:*** Name of the person using the tool.
4) ***Major Approach Orientation:*** Ordinal direction of the minor approach roadway, either "North-South" or "East-West."
5) ***Analysis Date:*** Analysis date in the form MM/DD/YYYY.
6) ***NCDOT Division:*** Number of the NCDOT division responsible for the location.
7) ***Does the TWSC intersection have a median with a width of 20+ feet?:***
   Select Configuration type, either "Yes" or "No," based on the configuration of the TWSC intersection.
8) ***Operation Analysis Period (Years)***: Number of years desired into the future that the tool will consider when calculating Life Cycle Costs. The methodology is designed to analyze periods of time only between 10 and 25 years. Note: The analysis period begins on the data the model is applied, the *Analysis Date*.
9) ***Volume Growth Factor Per Year (Anticipated):*** Percent of traffic volume growth that the intersection is expected to experience annually (NCDOT recommends 2-3%).
10) ***Current Percent Heavy Vehicle (%):*** Percentage of the vehicles as the intersection which are considered heavy vehicles.

11) ***Peak Hour Factor (PHF):*** Input the ratio of the total hourly traffic volume against the busiest 15-minute interval.
12) ***Area Type:*** Type of location (Rural, Urban, or Suburban) at which the intersection is located.
13) ***Current Unleaded Fuel Costs:*** Current unleaded fuel price for North Carolina, which can be obtained via the American Automobile Association's website: http://fuelgaugereport.aaa.com/states/north%20carolina/.
14) ***Current Diesel Fuel Costs:*** Current diesel fuel price for North Carolina, which can be obtained via the American Automobile Association's website: http://fuelgaugereport.aaa.com/states/north%20carolina/.

Exhibit 10 below shows what the spreadsheet tool *Global Inputs* entry table looks like.

Exhibit 10. Global Inputs Table Example

Major and Minor Approach Name:	**Road A and Road B**
County:	**Wake**
Analyst Name:	**John Doe**
Major Approach Orientation:	**East-West**
Analysis Date (MM/DD/YYYY):	**3/21/2016**
NCDOT Division:	**5**
Does the TWSC intersection have a median with a width of 20+ feet?:	**Yes**
Operation Analysis Period (Years, min=10,max=25):	**21**
Volume Growth Factor Per Year (recommended 2% to 3%):	**3.0%**
Current Percent Heavy Vehicle (%):	**2%**
Peak Hour Factor (PHF):	**0.90**
Area Type:	**Suburban**
Current Unleaded Fuel Cost ($/gal):	**$2.00**
Current Diesel Fuel Cost ($/gal):	**$2.00**

After completing the inputs, tool users can either choose to move forward with the next steps by clicking "Proceed to Step 2" or can choose to view the aforementioned default values by clicking "See Default Values," which will take them to a separate tab. To prevent inconsistencies in the use of the tool, these default values should only be adjusted by those personnel within NCDOT who will be providing default updates and who have the password needed to do so.

4.2. Traffic Demand

The next step of the analysis process is entering traffic demand data for the current TWSC intersection of interest. In this step, the user will input information about the traffic demand that is currently observed at the intersection, which will be used in the underlying methodologies to evaluate delay. The model allows the flexibility to provide one of the three following ways to characterize traffic demand: 1) Hourly Counts 2) Peak Hour Count, or 3) AADT. Each of these methods is discussed below in the following sections.

4.2.1. Hourly Counts

According to a NCDOT panel of experts, turning movement counts will likely be the predominant method that users will use to enter traffic volume data. As such, it is the first method shown in the tool. To ensure the accuracy of delay calculations, users are advised to use the *Hourly Count* method only when 13 or more hours of turning movement count data is available. This correlates with the recommended practice in the MUTCD for considering signal timing devices and is the standard that the NCDOT uses internally when conducting turning movement counts.

Within the tool, users can select the beginning and end of the time period for which turning movement count data is available. For example, a user may have a dataset of 13-hour turning movement counts starting at hour 6 and ending at hour 19, and the entry table in the tool will adjust accordingly. The user is then asked to provide a turning movement count for each of the four approaches, which will then be used to populate the daily traffic pattern. The tool will apply a value of zero for each count in each hour for which the user does not provide data. For example, if only 13 hours of turning movement counts are provided it will be assumed that all of the counts for the remaining 11 hours of the 24 hour period are zero. This is because the delay incurred outside those time periods is assumed to be minimal compared to that incurred during the count.

4.2.2. Peak Hour Count

In some cases, the user may not have sufficient turning movement count data for the peak periods of the day. Therefore, the tool provides a method for entering traffic demand during the peak hour. In this case, the *Peak Hour Count* method can be selected by the user. It is recommended that users chose this option when 12 hours or less of turning movement count data is available.

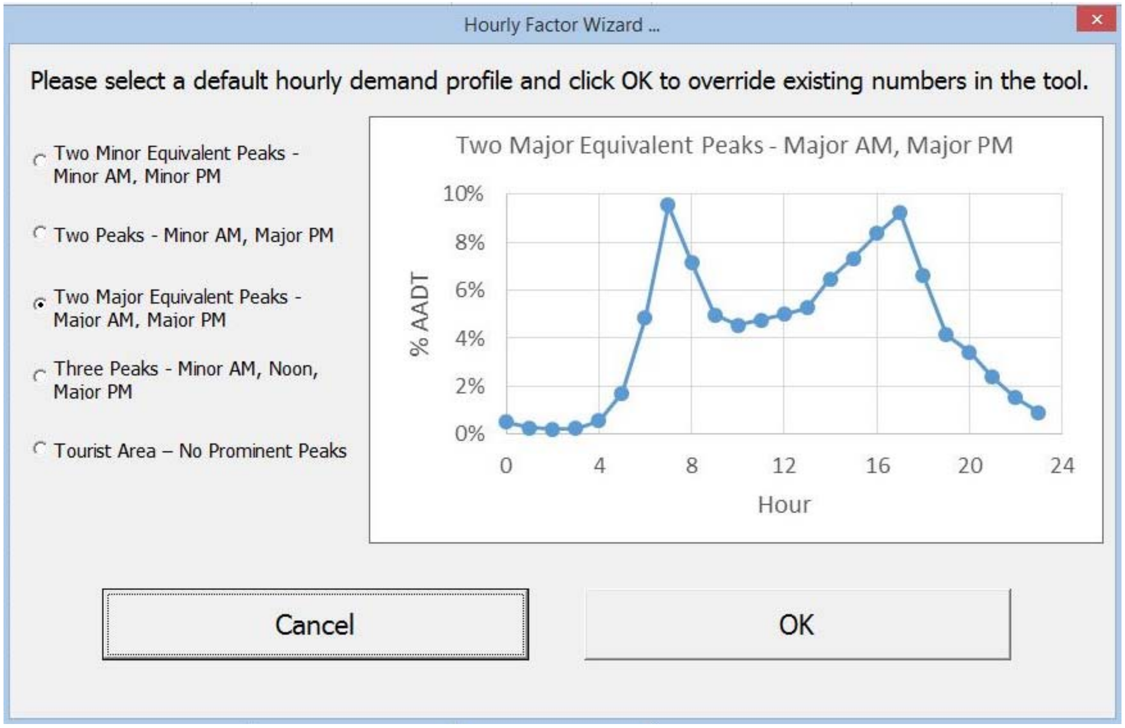
For this method, the hourly traffic flows can be entered for the four legs of the intersection for left, through, and right turns. Next, the peak hour analysis period should be entered that best represents the time period that the turning movement counts were captured. Finally, the hourly demand distribution is needed to populate demand over the entire day, which is shown in **Error! Not a valid bookmark self-reference.**.

Exhibit 11. Hourly Demand Distribution Input Table Example

Hourly Demand Default Distribution (For Default Hourly Factors Press "Insert Default Hourly Factors" button on the top left side of this spreadsheet)		
Hour		**% AADT**
From	**To**	
12 AM	1 AM	0.53%
1 AM	2 AM	0.28%
2 AM	3 AM	0.21%
3 AM	4 AM	0.26%
4 AM	5 AM	0.56%
5 AM	6 AM	1.71%
6 AM	7 AM	4.84%
7 AM	8 AM	9.55%
8 AM	9 AM	7.17%
9 AM	10 AM	4.96%
10 AM	11 AM	4.54%
11 AM	12 PM	4.76%
12 PM	1 PM	5.01%
1 PM	2 PM	5.26%
2 PM	3 PM	6.46%
3 PM	4 PM	7.33%
4 PM	5 PM	8.37%
5 PM	6 PM	9.21%
6 PM	7 PM	6.60%
7 PM	8 PM	4.14%
8 PM	9 PM	3.42%
9 PM	10 PM	2.39%
10 PM	11 PM	1.52%
11 PM	12 AM	0.92%
	sum=	**100.00%**

Although these percentages can be manually entered, the user has the option to auto-populate this table by clicking the “Insert Default Hourly Factor” button and choosing the default distribution profile which best aligns with the site of interest, as shown below in Exhibit 12. Five options for defaults are provided for the user based on NCDOT continuous count data. Similar to construction costs, typical hourly demand distributions for traffic were developed as part of this study due to a lack of North Carolina-specific defaults. Using NCDOT GIS data, five options were created based an analysis of continuous count station data for a period from 2012-13 for diverse sites at intersections across North Carolina.

Exhibit 12. Demand Distribution Profile Selection



Stations in close proximity of intersections were identified using geocoding and map inspections. Once irregular days were removed from the NCDOT dataset, a percent traffic distribution was developed for each hour on every Tuesday, Wednesday, and Thursday at each site. This method was used with the aim of capturing typical weekday distributions. Site distributions were then plotted graphically and were organized into groups with similar distributions. Outlier sites were removed from the dataset. Distributions for the sites in each category were then combined to identify an average distribution for each type, which resulted in five distinct demand distributions for areas at North Carolina intersections:

1) Two Minor Equivalent Peaks - Minor AM, Minor PM
2) Two Major Equivalent Peaks - Major AM, Major PM
3) Two Peaks - Minor AM, Major PM
4) Three Peaks - Minor AM, Noon, Major PM
5) Tourist Area - No Prominent Peaks

4.2.3. <u>AADT</u>

The final entry method for determining hourly volumes is based on planning level data using average annual daily traffic, or *AADT*. This entry method is the least accurate, but can be useful during the early planning stages of a project, especially if the user does not have access to turning movement counts. Using this method, the user is required to enter the two-directional AADT for each leg of the intersection. The input table from the tool is shown in Exhibit 13 below.

Exhibit 13. AADT Demand Flow Rate Input Table Example

Demand Flow Rate Data				
Approach	Eastbound (West Leg)	Westbound (East Leg)	Northbound (South Leg)	Southbound (North Leg)
Two-Directional AADT	4,000	4,000	9,000	8,500

A default directional distribution factor, often called the "d" factor, of 0.5 is used to provide the daily approach volume for each movement.

Next, the distribution of turning traffic for each approach is required to populate the turning movements for each approach. Exhibit 14 shows the table for entering this data. Finally, similar to the *Peak Hour Count* entry method, the hourly demand distribution is required to populate traffic demand over the entire day. The most likely entry method for this will be using one of the defaults provided in the tool by clicking the "Insert Default Hourly Factor" button.

Exhibit 14. Distribution of Turning Traffic Table Example

Current Traffic Turning Distribution				
Approach	Left Turn	Through	Right	*Sum*
EB % Movement:	10%	70%	20%	***100%***
WB % Movement:	20%	70%	10%	***100%***
NB % Movement:	25%	65%	10%	***100%***
SB % Movement:	10%	70%	20%	***100%***

4.3. Crash Data

Although brief, the next step in the model is essential for calculating the benefits of each conversion option. Users will input the total number of crashes experienced during the given timeframe, for example 5 years, at the intersection of interest, including a breakdown of 1) Fatal, 2) Type A, 3) Type B, 4) Type C, and 5) PDO collisions, as described above in *Section 3.4.2*. Note that the number input into the cells should be a whole number; however, the calculated "average number of crashes per year" values may include decimals.

The model provides the flexibility for users to enter the total number of crashes of each type that have accumulated for a period of 3 years or more, depending on what is available for the intersection of interest, as shown in Exhibit 15.

Exhibit 15. Crash Data Inputs Table Example

Number of Years Crash Data? (At Least 3 Years):	3

Crashes at Intersection					
Severity	**K**	**A**	**B**	**C**	**O**
Total Number of Crashes for All Years:	1.0	3.0	5.0	7.0	10.0
Average Number of Crashes Per Year:	0.3	1.0	1.7	2.3	3.3

4.4. Roundabout Configuration

The roundabout methodology described in chapter 21 of HCM 2010 was used to estimate the expected delay based on traffic demand data and the roundabout geometric configuration selected by the user. Exhibit 16 below shows the data users should provide in the tool for this model, including the entry lane and right turn bypass configurations for each approach. Required user inputs for the roundabout configuration are kept to a minimum to reduce the potential for error.

Exhibit 16. Roundabout Lane Configuration Data Entry Table

Roundabout Lane Configuration				
Approach	**Eastbound (West Leg)**	**Westbound (East Leg)**	**Northbound (South Leg)**	**Southbound (North Leg)**
Right-Turn bypass configuration	Add Lane	Add Lane	Yield	Yield

4.5. AWSC Configuration

This model uses the All-Way Stopped Control (AWSC) methodology described in chapter 20 of HCM 2010 to estimate the expected delay based on traffic demand data and the AWSC geometric configuration selected by the user. As seen in Exhibit 17, tool users will provide data on the number of lanes for each approach. Any entry of “No” in Lane 1 and “Yes” in Lane 2 means the approach has a shared left-through-right lane configuration. If “Yes” is also selected for Lane 1 entry then there is a left turn bay present for the left turn and the through-right are shared.

Exhibit 17. AWSC Lane Configuration Data Entry Table

AWSC Lane Configuration								
Approach	**Eastbound (West Leg)**		**Westbound (East Leg)**		**Northbound (South Leg)**		**Southbound (North Leg)**	
Lane #	**Lane #1**	**Lane #2**	**Lane #1**	**Lane #2**	**Lane #1**	**Lane #2**	**Lane #1**	**Lane #2**
Lane Exists?	Yes	Yes	Yes	Yes	Yes	No	Yes	No

4.6. Signal Configuration

The signalized intersection configuration requires some information on the range of cycle lengths and the assumed lane configuration, shown in in Exhibit 18 and Exhibit 19, respectively. Default cycle lengths designated by an NCDOT panel of experts, shown in Exhibit 18, are provided in the model and represent a reasonable minimum and maximum cycle length during all hours of operation. For instance, a much shorter cycle length is expected at an isolated intersection during off-peak time periods when traffic volumes are much lower. The maximum cycle length represents a time period sufficient for signals that may require one or more protected phases, but not necessarily a full eight-phase signal.

Exhibit 18. Signal Min and Max Cycle Length Table Example

Signal Timing Configuration	
Minimum Cycle Length, Cmin (seconds)	45
Maximum Cycle Length, Cmax (seconds)	120

For the lane configuration options provided in Exhibit 19, users enter the lane configuration as it appears at the stop bar. For example, an entry of 0-1-0 for left-through-right would mean the approach has a shared left-through-right lane. An entry of 1-1-1 would mean the approach has a through lane with left and right turn lanes (or turn pockets). Volumes per movement and lost time per phase are calculated internally in the model.

Exhibit 19. Signal Lane Configuration Table Example

Signal Lane Configuration and Demand Flow Rate Data												
Approach	**East Bound**			**West Bound**			**North Bound**			**South Bound**		
Movement	**Left**	**Through**	**Right**	**Left**	**Through**	**Right**	**Left**	**Through**	**Right**	**Left**	**Through**	**Right**
Number of Lanes	1	2	0	1	2	0	1	1	0	1	1	0

The delay for signalized intersections is not provided as an input, but is instead estimated using a method that follows the cycle length and delay assumptions of the HCM 2010 equation in chapter 31, Section 5: Quick Estimation Method. This equation is enhanced with the additional assumptions that the intersection is isolated and running under a pre-timed operation. To account for actuation in the tool, the cycle length is updated hourly based on traffic volumes during that hour, allowing delay to be minimized similar to that of an actuated intersection.

Using the HCM recommendations, the calculated approach delay is the average delay per vehicle when the signal is operating under the pre-timed control plan. However, most isolated intersections in North Carolina are running under in *fully actuated* mode. Therefore, the calculated delay may not always reflect real world outcomes. To address this issue, 100 simulation runs were conducted in Synchro 7 to develop a fitted curve that depicts the delay difference between pre-timed and fully actuated control. The four exhibits below show the delay results and curves for converting to pre-timed to actuated control. The equations shown in each figure are used to convert to actuated control delay in the user-based tool.

Exhibit 20 and Exhibit 21 show the average approach delay for pre-timed and actuated control (y-axis) under varying volume combinations (x-axis) for both minor and major approaches.

Exhibit 20. Pre-Timed vs. Fully Actuated Control Delay for Minor Approach

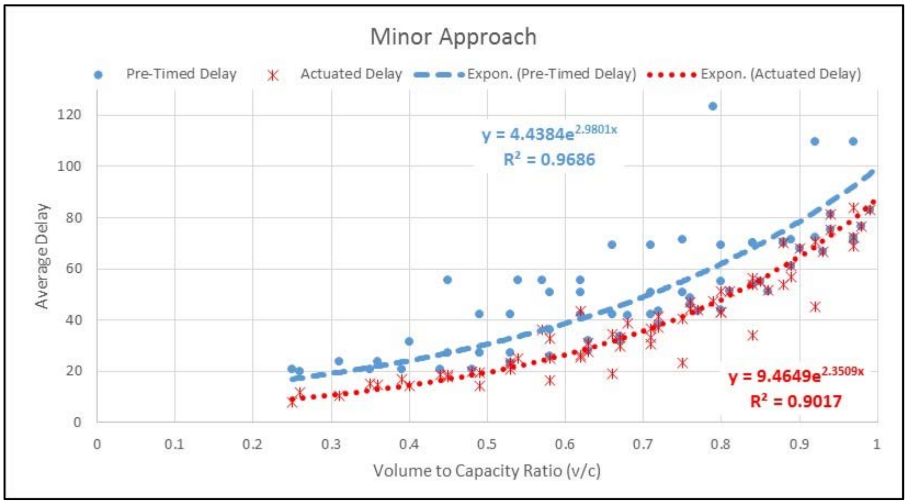


Exhibit 21. Pre-Timed vs. Fully Actuated Control Delay for Major Approach

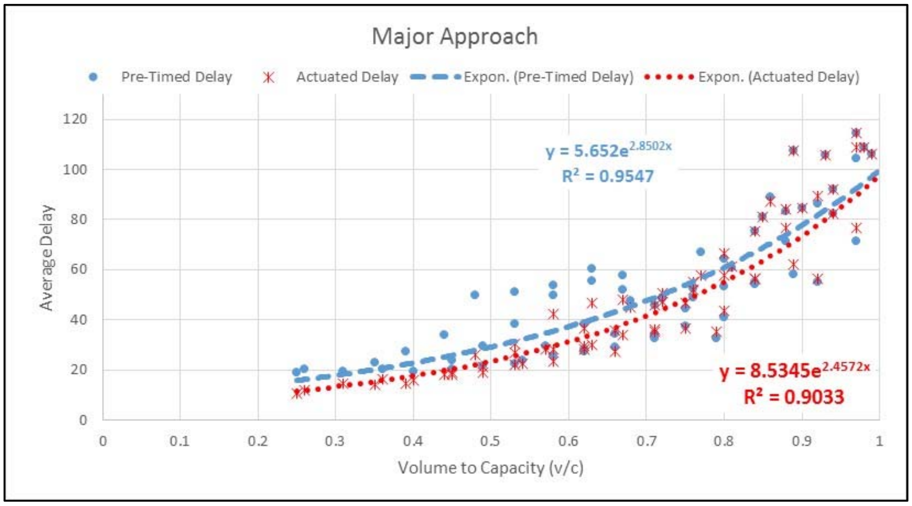


Exhibit 20 shows a clear improvement in volume-to-capacity under a fully actuated mode for the minor approach, with less improvement on the major approach, as shown in Exhibit 21. This appropriately represents the expected improvement in operations for the minor and major approaches.

Exhibit 22 and Exhibit 23 present the difference in delay for a pre-timed controlled scenario compared to fully actuated control as a percentage (y-axis) under varying volume combinations (x-axis). This percentage is used to convert the pre-timed delay values calculated using HCM procedures to provide more realistic fully actuated delay values.

The adjustment equation used in the tool's methodology is applied to convert pre-timed control delay to actuated control delay. However, the research team uses a minimum and maximum boundary of delay to ensure more accurate calculations. For example, if pre-timed delay is less than 8 seconds (the minimum assumed to start up lost time between phases), then the adjustment equation is not applied. In addition, when an intersection's volume-to-capacity ratio is greater than or equal to 1, the data is not adjusted for actuated delay conditions but the delays for a pre-timed control scenario are utilized.

Exhibit 22. Change in Delay: Pre-Timed to Fully Actuated Control for Minor Approach

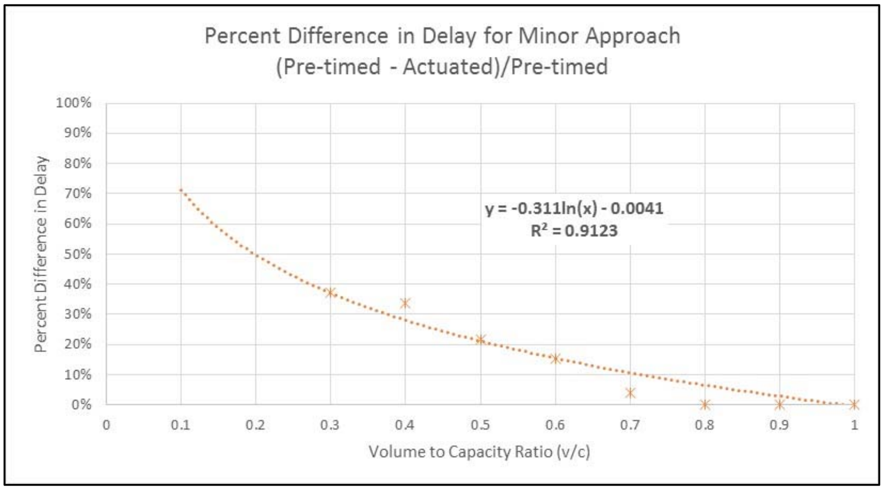
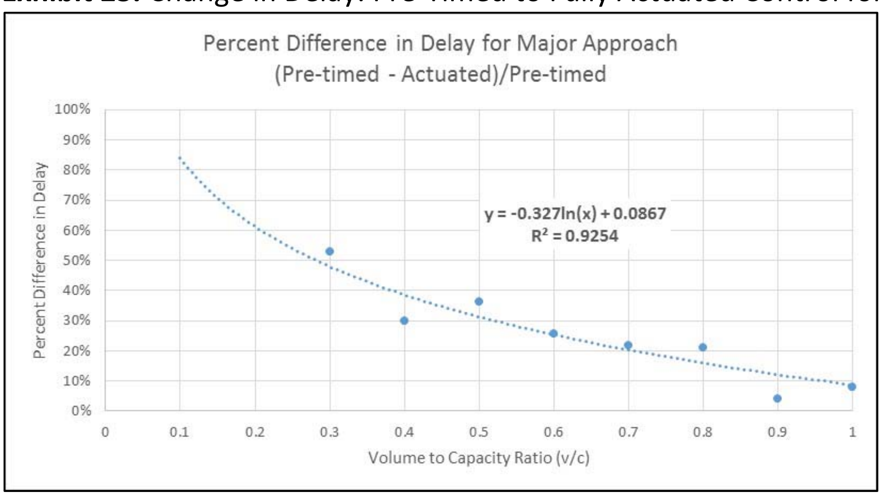


Exhibit 23. Change in Delay: Pre-Timed to Fully Actuated Control for Major Approach



Once the signal configuration is finalized, the user will run the analysis to calculate the costs and benefits of each alternative. In the tool, the "Run Analysis" button is under the signal configuration tab. The model is designed to identify if a Level of Service of F (LOS F) is reached for each of the alternatives. After running the analysis, the user will be alerted if an LOS F is projected to occur at some point during the timeframe of analysis via a pop-up message. If an LOS F is projected to occur, the user can return to the previous steps make adjustments to the period of analysis, geometric configuration(s), or other inputs to address the LOS F, if appropriate. For some intersections, high levels of demand my lead to an LOS F regardless of the geometric configurations of facilities. In such cases, users can use the comment sections of the tool's printable report to explain related recommendations.

4.7. Results

Once the previous six steps have been completed, user inputs are used to monetize the costs and benefits of each intersection option. The tab for the *Results* step provides the analysis findings. The first table in the sheet for this step provides a break down of the data for the first full year of each facility alternative after construction compared to projections for the same year of the current TWSC intersection, as shown
Exhibit 24.

Snapshot of Intersection Options in *1st Year of Analysis**				
Benefit/Cost	**TWSC**	**Roundabout**	**AWSC**	**Signal**
% Reduction in Fatal & Type A Crashes:	0%	78%	71%	44%
% Reduction in B & C Crashes:	0%	78%	71%	44%
% Reduction in PDO Crashes:	0%	78%	61%	44%
Annual Number of Fatal & A Injury Crashes:	2.0	0.4	0.6	1.1
Annual Number of B & C Injury Crashes:	7.0	0.4	0.6	1.1
Annual Number of PDO Crashes:	19.2	4.2	7.5	10.8
Annual Crash Cost:	$9,951,500	$2,189,300	$2,898,600	$5,572,900
Daily User Delay (hours per day):	25	18	35	26
Annual User Delay Cost:	$214,700	$158,000	$303,100	$231,700
Annual User Fuel Cost:	$7,100	$5,200	$10,000	$7,600
Construction Cost:	$0	$750,000	$25,000	$90,000
Annual Maintenance Cost:	$0	$2,500	$0	$2,500

Snapshot of Intersection Options in *1st Year of Analysis**				
Benefit/Cost	**TWSC**	**Roundabout**	**AWSC**	**Signal**
% Reduction in Fatal & Type A Crashes:	0%	78%	71%	44%
% Reduction in B & C Crashes:	0%	78%	71%	44%
% Reduction in PDO Crashes:	0%	78%	61%	44%
Annual Number of Fatal & A Injury Crashes:	2.0	0.4	0.6	1.1

Annual Number of B & C Injury Crashes:	7.0	0.4	0.6	1.1
Annual Number of PDO Crashes:	19.2	4.2	7.5	10.8
Annual Crash Cost:	$9,951,500	$2,189,300	$2,898,600	$5,572,900
Daily User Delay (hours per day):	25	18	35	26
Annual User Delay Cost:	$214,700	$158,000	$303,100	$231,700
Annual User Fuel Cost:	$7,100	$5,200	$10,000	$7,600
Construction Cost:	$0	$750,000	$25,000	$90,000
Annual Maintenance Cost:	$0	$2,500	$0	$2,500

Exhibit 24. Snapshot of Intersection Options in First Year Example

The monetized values are not discounted. This table provides a succinct snapshot of how applying a given alternative may change outcomes at the existing intersection. However, the data in this table is not the final outputs of the analysis and should not be used to compare the long-term costs of alternatives. These outputs are presented in a following table labeled the “Long-Term Difference between TWSC and Conversion Alternatives,” shown in

Exhibit 25.

Exhibit 25. Difference Between TWSC and Alternatives Example

Long-Term Difference **between TWSC and Conversion Alternatives****			
Benefits/Costs Relative to TWSC	**Roundabout**	**AWSC**	**Signal**
Crash Reduction Benefit:	$108,433,000	$107,335,000	$65,355,000
User Delay Decrease Benefit:	$792,000	($1,345,000)	($254,000)
User Fuel Cost Savings:	$27,000	($44,000)	($7,000)
Conversion Construction Cost:	$750,000	$25,000	$90,000
Regular Maintenance Cost:	$35,000	$0	$37,000
Service Life Replacement Cost:	$0	$21,000	$44,000
Total Long-Term Benefits (Net Present Value):***	***$108,467,000***	***$105,900,000***	***$64,923,000***

As shown in

Exhibit 25, this table breaks down the long-term, discounted costs and benefits of each alternative based on variable type, and most importantly, provides the ultimate deliverable of the analysis: the Net Present Values (NPV) for each option. In Life Cycle Cost Analysis methodology, the NPV of an alternative is present value (PV) of the total long-term benefits minus the PV of the total long-term costs, NPV = Σ PV (Benefits) - Σ PV (Costs), described further in Equation 3 below.

Equation 3. Net Present Value

$$\text{NPV} = \sum_{t=0}^{n} \frac{(\text{Benefits} - \text{Costs})_t}{(1+r)^t}$$

where:

NPV = net present value

t = year

r = the discount rate

n = analysis period (in years

Tool users and decision-makers should pay special attention to the Total Long-Term Benefits (Net Present Value) row of the outputs table because it outlines the total benefits minus the costs expected for each alternative over the course of the analysis period. These outputs are the NPVs of each option, which are the values that should be compared in order to identify the best intersection option based on the time frame identified by the user. The NPVs represent the benefits that the State of North Carolina can expect to gain from an intersection option. Therefore, the intersection type with the highest NPV is considered the best option because it will provide the greatest value in the long run.

It should be noted that for some conversions, user delay and the costs associated with the conversion may actually increase due to a projected level of service failure or other factors. This can vary on a case-by-case basis. In cases where user delay is increased due to a conversion, the "benefit" of decreased delay will be a negative value, which is indicted red text encased by parentheses. These values will in turn be treated as costs instead of benefits. As such, these costs will be subtracted from the value of total net benefits as opposed to being added to it.

4.8. Printable Report

Once the final outputs have been calculated in the *Results* sheet, users can proceed with editing and printing the tool's report on the analysis via the *Printable Report* tab. This report is automatically populated with the tool's data and generated from a stylized template designed to share with decision-makers. As referenced previously, tool users have the opportunity to add context the report by typing in their own explanatory notes before printing. An example of a completed report produced by the tool is in Appendix 3.

5. Sensitivity Analysis

As part of a life cycle cost analysis, it is common to perform *sensitivity analyses*, or checks on the degree to which outcomes may change due to changes in variables (Swiss, 2012). Conducting a sensitivity analysis involves applying extreme values on the high and low end to determine if a model's methodological assumptions and variable choices are sound.

5.1. Safety vs. Delay

While sensitivity analyses were rigorously conducted on a variety of variables in this study, particular attention was paid to the relationship between safety and delay. These two variable categories consistently dominated the outcomes of analysis tests on the model. For example, tests showed that high volume inputs typically result in high delay costs due to excessive facility congestion and high crash frequency typically result in significant safety benefits, and vice versa. As a result, in some cases the Net Present Values could be in the billions.

In spite of the strength of these two types of variables, the research team decided not to apply factors in the model to adjust outcomes for several reasons. First, the methodologies of other intersection analysis tools and studies around the country do not include adjustment factors. Second, the study's model incorporates sound data and models from reputable sources such as the NCDOT and HCM 2010 and applying adjustment factors would alter the value and models, potentially reducing the accuracy of analysis findings. Third, the NCDOT currently monetizes safety outcomes for internal analysis using the same methodology as this tool. Fourth, it would be time consuming to develop adjustment factors that are appropriated for the diverse intersections that may be analyzed using the methodology of this study.

5.2. Importance of Inputs

Model outcomes can also be heavily influenced by user inputs. For example, over the course of 25 years a volume growth factor of 2% could result in vastly different delay times than one of 6%. Consequently, it is vital that users use and carefully consider all available data for an intersection when selecting inputs, as they will significantly impact the tool's final outputs. For this reason, the key inputs applied by the user are included in the tool's printable report.

Model users are advised collect the data needed for each input prior to beginning the analysis process to reduce potential errors and delays in processing time. If an error is made within the tool, the user can click "Clear User Inputs" in the *Global Inputs* sheet and start over at any point in the process.

6. Conclusions and Recommendations

This research developed a methodology for quantifying the life cycle costs of converting a two-way stop controlled intersection to three alternative facilities: 1) all- way stop controlled, 2) signalized, and 3) roundabout types. This North Carolina-specific methodology was integrated into a spreadsheet-based software tool, the NCDOT Life Cycle Cost Analysis Tool, which the NCDOT can use in-house during the planning phase of intersection projects. Additionally, this tool is designed to generate reports that can be shared with all stakeholders involved in intersection conversion decision-making processes.

In alignment with transportation and Life Cycle Cost Analysis literature, the methodology of this study focused on monetizing three categories of variables: 1) Construction & Maintenance, 2) User Delay, and 3) Safety. The final product of the model's analysis, the Net Present Value for each alternative, can be easily compared by decision-makers to identify the facility that will provide the greatest return on investment for the State of North Carolina.

Compared to other similar tools in the United States, this computational engine is unique because it requires the user to input a minimum amount data. For example, interim values such as expected delays are not required because these are calculated as part of the tool's model. Such in-tool calculations can reduce time to analysis and increase efficiency, as well as help reduce bias and user error. In addition to developing a tool that streamlined intersection related computations, the research team identified the variables needed for intersection LCCAs and established variable default values that the NCDOT can use into the future.

6.1. Recommendations

Currently, the NCDOT lacks state-specific data for some variables essential to analyzing the life cycle costs of intersection alternatives. Accordingly, the research team recommends that further studies should be conducted in order to identify data with will improve the accuracy of model outcomes. Although significant efforts were made to select, and in some cases establish, North Carolina-specific data, additional data is still needed for variables such as the value of travel time and CRFs for some conversion types. It would also be beneficial for the NCDOT to develop ranges for inputs including PHF and PHV to aid model users. Generating these defaults and ranges could improve the reliability of estimations not only for this model, but for other LCCA studies conducted by the state.

6.2. Data Updates

The majority of the variables used to monetize costs and benefits in the methodology for this study are updated annually by their sources because they are sensitive to changes in human behavior and/or the economy. Accordingly, many of the variables used in this model will need to be updated annually in order to ensure that the results are as accurate as possible.

Updates to defaults for some variables, such as relevant Crash Reduction Factors, may be released more frequently without a clear schedule. The NCDOT currently maintains a spreadsheet of in-house standards that includes many of these types of variables and plans to release updated versions of this document internally each year. It is suggested that the tool be updated with each new release. The full list of variables that will need to be updated annually based on new data are in Appendix 1, along with their sources. The variables which should be updated as needed, based on the availability of new crash reduction factors and changes to NCDOT estimates, are in Appendix 2.

It is also recommended that the NCDOT update default values in the tool on a scheduled date in February of each year. This month is recommended because most federal and state agencies release their annual standards for in either December or January. It is suggested that the tool be renamed with a new date and redistributed across all NCDOT divisions when any significant changes are applied. Additionally, the model may need to be revised in the future to incorporate significant changes in HCM or other methodologies. In such a case, time may need to be dedicated to updating the tool and the release of a new version may be warranted.

7. Future Research

The development of this methodology provides many opportunities for future research. The model and defaults established as part of this research could be applied to future LCCAs for other types of projects in the state. In addition, the methodology and the tool framework could be expanded to analyze other intersection types or could be adapted to analyze other types of construction projects.

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Appendix 1
Defaults To Be Updated Annually

Type	Details	Default Value	Source
Crash Costs	K & A Injury Types	$4,544,000	NCDOT annual crash cost estimates (2013)
	B & C Injury Types	$134,000	
	Property Damage Only	$6,700	
Value of User Travel Time	Per Passenger Vehicle (per hour)	$17.67	TTI Annual Urban Mobility Report (Schrank, Eisele, Lomax, and Bak. 2015. 2015 Urban Mobility Report. Appendix A Methodology for the 2015 Urban Mobility Scorecard. College Station, TX: Texas A&M Transportation Institute.)
	Per Heavy Vehicle (per hour)	$94.04	
Number of Riders Per Vehicle	Passenger Vehicle	1.25	TTI Annual Urban Mobility Report (Schrank, Eisele, Lomax, and Bak. 2015. 2015 Urban Mobility Report. Appendix A Methodology for the 2015 Urban Mobility Scorecard. College Station, TX: Texas A&M Transportation Institute.)
	Heavy Vehicle	1.25	
Fuel Burnt Per Hour of Idling	Passenger Vehicle (gallons)	0.39	U.S. Department of Energy (2014)
	Heavy Vehicle (gallons)	0.69	

Appendix 2

Defaults To Be Updated Incrementally As Needed

Type	Details	Default Value			Source
		Roundabout	AWSC	Signal	
Construction Cost	Low	\$500,000	\$10,000	\$60,000	NCDOT Spot Safety Program data (2008-13)
	Medium	\$750,000	\$25,000	\$90,000	
	High	\$1,000,000	\$75,000	\$300,000	
Incremental Costs	Minimum Facility Replacement	\$500,000	\$10,000	\$60,000	
	Annual Maintenance	\$2,500	\$0	\$2,500	NCDOT Project Development Crash Reduction Information (April 2015)
Time	Analysis to Facility Opening (years)	1.5	0.2	0.5	NCDOT expert panel (2015)
	Service Life (years)	25	6	10	NCDOT Project Development Crash Reduction Information (April 2015)
Crash Reduction Factors	K & A Injury Crashes (Urban)	29%	71%	23%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; Mcgee et al., 2003
	K & A Injury Crashes (Suburban)	78%	71%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
	K & A Injury Crashes (Rural)	71%	71%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
	B & C Injury Crashes (Urban)	29%	71%	23%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; Mcgee et al., 2003
	B & C Injury Crashes (Suburban)	78%	71%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
	B & C Injury Crashes (Rural)	71%	71%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
	PDO Crashes (Urban)	29%	61%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
	PDO Crashes (Suburban)	78%	61%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
	PDO Crashes (Rural)	71%	61%	44%	NCHRP Report 572, 2007; Simpson and Hummer, 2010; NCHRP Report 617, 2008
Signal Timing Configuration	Minimum Cycle Length, Cmin (secs)	45			NCDOT expert panel (2015)
	Maximum Cycle Length, Cmax (secs)	120			

Appendix 3

Example of Printable Report

NCDOT Intersection Life Cycle Cost Analysis (LCCA) of Road A and Road B

Date of Analysis:	3/21/2016	**DOT Division:**	1
Analyst Name:	John Doe	**County of Intersection:**	Wake
Period of Time Analyzed (years) :	21	**Annual Volume Growth:**	3%
Area Type:	Suburban	**Peak Hour Factor**:	0.90

Configuration Proposed by Analyst:

Configuration Proposed by Tool: Roundabout

Analyst Comments:

Level of Service F Reached for Proposed Configuration(s)? No

Details:

Analyst Comments:

NCDOT Defaults Changed?

Details:

Analyst Comments:

ITRE This analysis was conducted using Version 1.0 of the NCDOT Intersection Life Cycle Cost Analysis Tool.

Current Two-Way Stop Controlled Intersection Details

Crash Data for 5 Years

Number of Crashes by Severity	K	A	B	C	O
Average Number of Crashes Per Year:	0.40	1.60	2.40	4.60	19.20

Injury Types:
K (fatal): Death occurred within twelve months of the crash
A (disabling): Injuries serious enough to prevent normal activity for at least 1 day (massive loss of blood, broken bones, etc.)
B (evident): Non-fatal or A injuries are evident at the scene such as bruises, swelling, limping, etc.
C (possible): No visible injury but there are complaints of pain or momentary unconsciousness
O (property damage only): No physical injury

User Demand

Approach (Leg of Intersection)	Eastbound (West Leg)	Westbound (East Leg)	Northbound (South Leg)	Southbound (North Leg)
Peak Period Demand Flow Rate (vph):	382	358	191	167

Long Term Costs and Benefits of Each Alternative

The below tables outline the anticipated long-term costs and benefits of each intersection type being considered for this location, compared to the current two-way stop controlled intersection. Note that these values have been adjusted for the changing value of money over time at a standard rate of 3% per year, similar to inflation.

Period of Analysis

The Life Cycle Cost Analysis for this site calculated costs and benefits 21 years into the future, with no benefits incurred until the year construction is anticipated to be completed for each alternative.

Benefits Minus Costs Relative to TWSC

This table summarizes the final outputs of the Life Cycle Cost Analysis and should be used when comparing the long-term return on investment of each alternative. The alternative considered the most cost-effective option is the one with the greatest long-term benefits, or highest Net Present Value.

	Roundabout	All Way Stop Controlled	Signal
Total Long-Term Benefits (Net Present Value):	*$108,467,000*	*$105,900,000*	*$64,923,000*

Assumed Costs Relative to Two-Way Stopped Control

This table shows only the anticipated long-term costs of each alternative.

	Roundabout	All Way Stop Controlled	Signal
Conversion Construction Cost:	$750,000	$25,000	$90,000
Regular Maintenance Cost:	$35,000	$0	$37,000
Service Life Replacement Cost:	$0	$21,000	$44,000
Total Long-Term Costs:	$785,000	$46,000	$171,000

Assumed Benefits Relative to Two-Way Stopped Control

This table shows only the anticipated long-term benefits of each alternative. Note that occasionally an alternative is projected to not perform as well as the two-way stop controlled intersection. In this case, the assumed benefit will instead be a cost, and will be subtracted from the benefits total instead of added, indicated by () around the given dollar amount.

	Roundabout	All Way Stop Controlled	Signal
Crash Reduction Benefit:	$108,433,000	$107,335,000	$65,355,000
User Delay Decrease Benefit:	$792,000	($1,345,000)	($254,000)
User Fuel Cost Savings:	$27,000	($44,000)	($7,000)
Total Long-Term Benefits:	$109,252,000	$105,946,000	$65,094,000

- Crash reduction estimates based on national and state research.
- Projected number of crashes based on current crash statistics for the intersection adjusted by the expected percent reduction.
- Annual crash costs are based on NCDOT's annual standardized crash cost report multiplied by the anticipated number of crashes.

alternative will look like into the future. Note that this table is for reference only. It is not the final output of the Intersection Life Cycle Cost Analysis Tool and should not be used to compare the long-term costs of TWSC vs. conversion alternatives.

Benefit/Cost	Two-Way Stop Controlled	Roundabout	All Way Stop Controlled	Signal
% Reduction in Fatal & Type A Crashes:	0%	78%	71%	44%
% Reduction in B & C Crashes:	0%	78%	71%	44%
% Reduction in PDO Crashes:	0%	78%	61%	44%
Annual Number of Fatal & A Injury Crashes:	2.0	0.4	0.6	1.1
Annual Number of B & C Injury Crashes:	7.0	0.4	0.6	1.1
Annual Number of PDO Crashes:	19.2	4.2	7.5	10.8
Annual Crash Cost***:	$9,951,500	$2,189,300	$2,898,600	$5,572,900
Daily User Delay (hours per day):	25	18	35	26
Annual User Delay Cost:	$214,700	$158,000	$303,100	$231,700
Annual User Fuel Cost:	$7,100	$5,200	$10,000	$7,600
Construction Cost:	$0	$750,000	$25,000	$90,000
Annual Maintenance Cost:	$0	$2,500	$0	$2,500

* Crash reduction estimates based on national and state research.

** Projected number of crashes based on current crash statistics for the intersection adjusted by the expected percent reduction.

*** Annual crash costs are based on NCDOT's annual standardized crash cost report multiplied by the anticipated number of crashes.