# EFFECT OF PAVEMENT SURFACE PROPERTIES ON LIFE CYCLE COST ANALYSIS

BY

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THESIS

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# Abstract

Life Cycle Cost Analysis (LCCA) is one of the most well established methods used in determining the best alternative pavement project. The two main pillars of LCCA are user costs and agency costs. User costs are incurred during normal transportation operation and when there is a work zone present. Costs that occur during normal operating conditions are due to pavement surface profile, while costs that occur during work zone activities are due to agency decisions on work zone conditions. In traditional LCCA, it is assumed that work zones costs are the main part of user costs. The work zone costs include vehicle delay costs, vehicle operating costs, crash costs, and emission costs. On the other hand, costs associated with normal operating conditions, such as vehicle operating costs, are independent of project alternatives and thus they are negligible. However, recent studies have suggested that vehicle operating costs are more sensitive to roughness and texture profile than initially thought. Therefore, even slight changes in pavement surface profile may affect user costs. This study introduces a methodology that considers normal operating conditions in LCCA; including pavement surface properties. The approach is presented in a Microsoft Excel Visual Basic (VBA) tool. Finally, a case study is presented to illustrate the importance of user costs for normal operating conditions and their effect on LCCA. Analysis showed that for medium to low traffic roadways, the impact of normal operating costs is significant when compared to work zone costs. Furthermore, decreasing the number of treatment activities may increase the user costs because the pavement is less frequently improved. In addition, as would be expected, it was found that with increasing discount rates, the significance of normal operating costs further increase.

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# Chapter 1: Introduction

## 1.1 Background

It is tempting for decision makers and elected officials to make budgetary-based short-term plans. After all, there are budget and time constraints for decision making. Although short-term planning may reduce cost, it will have long-term impact. With growing demand for long lasting transportation infrastructures, long-term costs could be crucial for decision making (Stanford University, 2005).

Life Cycle Cost Analysis (LCCA) is an analysis technique used to evaluate the long-term costs of different alternatives (Walls & Smith, 1998). This is different than cost-benefit analysis (CBA), usually used by agencies. The CBA aims to quantify the benefits as well as the costs of an investment. Benefits are assumed by various alternatives when performing LCCA.

For pavement LCCA, traditionally, there are two main types of cost: Agency costs and user costs. Agency costs are the costs that are associated with materials, construction, rehabilitation and maintenance stages of a project. These costs are easy to estimate if rehabilitation strategies are known. User costs, on the other hand, are costs that are incurred by the roadway user. These costs could be due to fuel consumption, tire wear and tear, vehicle maintenance and repair, traffic delay, crash, and emission. User costs are generally difficult to estimate because of inherit uncertainty if traffic and their association with pavement condition.

The LCCA was first introduced to the US agencies by The American Association of State Highway Officials (AASHTO) “Red Book” in 1960. In 1969, available data were combined to be used in a systematic life cycle costing approach (Winfrey 1969). In 1972, LCCA was first recommended to the agencies by AASHTO as part of the1972 Pavement Design Guide. However, it was not adopted because there was no clear framework for agencies to follow. In 1984, the Federal Highway Administration (FHWA) examined 36 pavement projects built since 1960 and prepared the “FHWA Pavement Selection Based on Life Cycle Costs”. That was one of the first examples that compare various pavements over their service lives. Only agency costs, related to construction and maintenance, were considered. In 1996, revised section 303 of the National Highway System (NHS) required agencies to use LCCA for the NHS projects. Federal Highway Administration released “Life Cycle Cost Analysis in Pavement Design” in 1998, which included user costs. In 2004, FHWA released “RealCost.” An LCCA tool; and in 2011, the National Cooperative Highway Research Program developed a process for pavement selection based on LCCA, NCHRP 703.

Nowadays, there are several calculation models, used by agencies, to conduct LCCA (e.g., QUEWZ in Australia and COMPARE in Great Britain). One of the most common models used by many countries, including the US, is Highway Design and Management (HDM), which was developed by the World Bank and has several versions (Huvstig, 1998). Although the models are powerful, they have not been used to their designed extent. The HDM models were recently calibrated for their applications in the US (Zaabar and Chatti, 2012).

Currently, LCCA is used in major projects. Although it is a good tool for decision making, it requires a number of assumptions and prediction models. These assumptions include inflation rate, discount rate, traffic conditions, and performance of the roadway for the next decades. Additionally, the agency must select the costs to be included in the analysis.

## 1.2 Problem Statement and Objective

In 2014, Caltrans explored 17 agencies nationwide and reported that the range of parameters used by agencies for LCCA analysis were not consistent. Although all explored agencies supported LCCA, only 60% apply LCCA regularly. Some of the reported limitations are the difficulty of the process and the inclusion of user costs (ASCE, 2014).

Unfortunately, there is no standardized approach for calculating user costs in LCCA. Traditional LCCA only considers work zone related costs such as delay costs and idling costs. It is a common practice to assume normal vehicle operation costs are equal for various alternatives. Therefore, LCCA guidelines generally overlook normal operating costs such as fuel consumption, tire wear-tear and repair costs. However, pavement condition, especially pavement roughness. Impacts on operating costs is greater than earlier estimates (Chatti, 2012). To improve LCCA prediction capabilities, normal operating costs must be included in the analysis.

The objective of this study was to determine the impact of normal operation costs on LCCA. To achieve that this study introduced a new methodology to improve LCCA accuracy, including user costs.

# Chapter 2: Pavement LCCA Terminology

For pavement projects, there are two main pillars of incurred costs: agency costs and user costs. Agency costs are acquired by an owning agency. Agency costs include material, labor, and equipment costs related to the initial construction and maintenance of a pavement. Quantification of these costs is rather straightforward because these costs are usually well documented in unit processes or pay items. However, it is important to adjust for changing money value when analyses of agency costs are performed

User costs, on the other hand, are the costs incurred by users driving on the section that the owning agency is responsible for maintaining. These costs are the main focus for this study.

Aside from the two main pillars, discounting rate and price adjusting must be performed to adjust the spent money for the time value of money (TVM). This chapter introduces the necessary concepts and background information for pavement LCCA.

## 2.1 Time Value of Money (TVM)

Changes in the value of money over time must be accounted for by correcting for inflation and discounting rates. While both corrections are necessary for LCCA, inflation and discounting are different processes and should not be confused with each other.

Inflation captures the purchasing power of a currency over time. To capture the variation of prices or wages because of inflation, Consumer Price Index (CPI) is used to scale the value of money from one year to another. The U.S. Bureau of Labor Statistics publishes yearly CPI values for each economic sector.

Equation 2.1 is usually used to account for inflation. For example, if the price of a gallon of fuel in 2000 is \$2.00, the CPI in 2000 is 172.2, and the CPI in 2015 is 237.07, then the price of a gallon of fuel is calculated as follows: $2 * \frac{237.07}{172.2} = \$2.75 \text{ per gallon}$.

$$Dollars_{Base\ Year} = Dollars_{Data\ Year} * \frac{Price\ Index_{Base\ Year}}{Price\ Index_{Data\ Year}} \quad (2.1)$$

So, \$2.75/gal is considered the fuel price (the amount of money someone would spend at the gas pump) in 2015. This type or money is called real dollars. Real dollars define the price of an item that is adjusted with inflation to another year. On the other hand, current dollars define the price of an item in that given year. In this case, the \$2/gal price of gas in 2000 would be considered current dollars. Current dollars are useful when the price of an item is known for each year, like fuel. However, the prices of various unit items are not collected every year, and conversion to real dollars using inflation correction is necessary.

Once price is adjusted for inflation, it should be adjusted for discounting. Discounting is also referred to as adjusting for the opportunity value of time. The opportunity value of time as it applies to current versus future funds can be understood in terms of the economic return that could be earned on funds in their next best alternative use (FHWA, 2011). This is because a dollar spent in 2000 would have a different purchasing power than a dollar spent in 2015. In other words, discounting captures the present value of a stream of payments made at different times. There are different methods for calculating the present value of an investment. In this study, present worth calculation is used. Present worth of any future investment is calculated as follows:

$$Present\ Value = Future\ Value * \frac{1}{(1+discount\ value)^{number\ of\ years}} \tag{2.2}$$

Continuing with the aforementioned example, if one would like to determine the amount of money to set aside in 2000 to buy a gallon of fuel in 2015, discounting should be used. Assuming a discount rate of 3%, $2.00 * \frac{1}{(1+0.03)^{(2015-2000)}} = \$1.29/gallon$.

Note that the \$2/gal that was reported initially as the actual price of fuel in 2000 does not match the \$1.29/gal present cost. \$2/gal is the money one needs to buy a gallon of fuel in 2000. On the other hand, \$1.29 is the money one needs to save in 2000 to buy a gallon of fuel in 2015. This is why inflation and discounting are separate concerns.

In traditional pavement LCCA, adjustment for inflation is only done at the beginning of calculation and the unit prices for different items are converted to construction year dollars using discounting. Then, the real discount rate is used to adjust for discounting. This method is adopted in this study.

## 2.2 Agency Costs

Agency costs, the first pillar of pavement LCCA, defines the cost incurred by the agency responsible for a project. It consists of the initial construction, material, equipment, and labor costs as well as the operation and safety costs associated with maintenance activities.

There are terminal values associated with agency costs as well. These include salvage value, which is the net value of recycled materials after a project's lifetime, and remaining service life, which is the residual value of a project.

When agencies bid for a project, they usually use pay items in their contracts to bid prices for unit items or unit processes. This makes agency cost calculations easier because it lowers the uncertainty involved in price determination. Pay items were used in this study to quantify the agency costs. A detailed explanation of pay items is presented in Chapter 6. Agency costs have two types of costs, described as construction costs and salvage value that are related to the maintenance schedule and lifetime of the pavement

## 2.3 User Costs

This study's focus, user cost, is defined as the costs incurred by the user driving on a pavement section. User cost consists of two main parts: those due to normal operating conditions, where the cost is mainly a function of pavement condition, and those due to a maintenance activity, where there is a work zone present that restricts traffic flow.

When the term user cost is used, it usually refers to monetized user costs. There are also user costs that are difficult to monetize, such as the comfort of the user, local economic impacts of a specific project, and noise pollution. These costs are usually ignored since they are very difficult to quantify.

In Chapter 4, components of user costs along with the calculation methodologies used in this study are further discussed.

## 2.4 Analysis Period

In every LCCA, there are multiple alternatives. It would be ideal for the alternatives to have the same service life. That would make the comparison straightforward. In practice however, alternatives rarely have the same service life. Therefore, an analysis period is needed to provide a baseline. For instance, if alternatives A and B are being compared and A has a service life if 50 years while B has 45, the minimum of two, 45 in this case, would be selected as analysis period. For accurate comparison, the remaining five years of A must be accounted for. If an asset still have a useful life after the analysis period, the salvage value must be determined (Ozbay et al, 2003). One straightforward approach for determining salvage value is reducing the cost of the final maintenance activity proportionally. For instance, if the final maintenance activity for alternative A is on year 35 and it is intended to last until year 50, the cost at year 35 would be multiplied by (45-35)/(50-35) to consider the cost reduction.

## 2.5 Computational Methods

There are two main approaches for LCCA: deterministic and probabilistic. LCCA is comprised of a large number of uncertainties, and each method addresses uncertainties differently.

In deterministic analysis, every single LCCA parameter is determined. Parameters are usually based on historical data. Because of its computational simplicity, most LCCA methodologies are deterministic. However, deterministic analysis overlooks real life data uncertainty. Hence, results are usually complemented with sensitivity analysis to capture the effects of these uncertainties.

The second approach for LCCA is probabilistic analysis. In this method, selected variables have a probability distribution and may be modeled as stochastic parameters. This requires changing the stochastic parameters for each of several thousand runs of a LCCA model. This approach is also known as Monte Carlo Analysis. Since probabilistic analysis reports a distribution of values, it is more powerful at capturing uncertainty than deterministic analysis, which provides a singular sensitivity value. RealCost, a commonly used LCCA tool that has been developed by the FHWA, adopts this approach.

In this study, a deterministic approach was used because the considered analysis methods are too advanced to utilize a probabilistic approach.

# Chapter 3: Work Zone User Cost Components

User costs are comprised of work zone costs and normal operating costs. In this section, work zone related user costs are discussed. Work zone costs occur whenever there is an activity that disrupts the normal operating conditions of a road. This disruption results in delays, negative impacts on the surrounding community, and safety concerns. In this study, only delay costs, fuel costs, and crash costs due to work zones were considered.

## 3.1 Delay Cost Calculation

Delay costs are one of the major components of work zone user costs. There are many ways to compute the amount of delay. It is rather easy to compute the number of vehicles in the work zone as a function of time, since hourly annual average daily traffic (AADT) is usually known. Since the capacity of the work zone lanes is also known, the amount of cars in the work zone area for any given time can be calculated. The queue length and queue speed are important parameters to determine since they define the rate at which a queue forms, traverses, and dissipates. There are different tools for calculating delay costs. One of the most popular LCCA tools, RealCost, bases its estimations on an hourly traffic demand and capacity analysis (FHWA, 1998).

In this study, traffic delay estimates were obtained from two-phase traffic models reflecting normal and construction conditions. To develop these two-phase models, normal capacity and queue density for both normal operating and construction conditions were calculated by multiplying the number of open lanes by the per-lane capacity and per-lane queue density provided by the project conditions.

Delays occur whenever work zone conditions restrict the flow of normal operating conditions. Total delay may be calculated using Equation 3.1:

$$Total\ Delay\ (hours) = \left(\frac{VMT_{construction}}{FFS_{WZ}} + \frac{VMT_{queue}}{v_D}\right) - \frac{VMT_{construction} + VMT_{queue}}{FFS} \quad \textbf{(3.1)}$$

Where,

$VMT_{construction}$ = Vehicle miles travelled when a work zone is present without queues;

$VMT_{queue}$ = Vehicle miles travelled when a queue is present;

FFS = Free flow speed during normal operating conditions;

$FFS_{WZ}$ = Free flow speed with presence of work zone; and

$v_D$ = Speed of vehicles in queue.

Free-flow speed under normal operating conditions was estimated using the Highway Capacity Manual, HCM 2010:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\, TRD^{0.84} \tag{3.2}$$

Where,

FFS = Free-flow speed;

$f_{LW}$ = An adjustment factor for lane width;

$f_{LC}$ = An adjustment factor for lateral clearance; and

TRD = Total ramp density or number of exit ramps per mile.

The lateral clearance on highways for this study is assumed to be at least six ft on either side; therefore, $f_{LC}$ is assumed to be 0 as recommended by the Highway Capacity Manual (HCM). $f_{LW}$ factors are given below:

$f_{LW}$ = 0 if Lane width (ft) x >=12

$f_{LW}$ = 1.9 if Lane width (ft) 12 > x >=11

$f_{LW}$ = 6.6 if Lane width (ft) x <11

Work zone free-flow speeds were estimated using the model presented by Hajbabaie et. al (2015) as shown in Equation 3.3:

$$FFS_{WZ} = 9.95 + 33.49\, f_{Sr} + 0.53\, f_S - 5.60\, f_{LCSI} - 3.84\, f_{Br} - 1.71\, f_{DN} - 1.45\, f_{Nr} \tag{3.3}$$

Where,

$FFS_{WZ}$ = Free-flow speed through the work zone;

$f_{Sr}$ = Ratio of the non-work zone speed limit to the work-zone speed limit;

$f_S$ = Posted speed in the construction zone;

$f_{LCSI}$ = Lane Closure Severity Index: Inverse of the open lane ratio (total/open) multiplied by the inverse of the number of open lanes;

$f_{Br}$ = Barrier type, in which 0 is awarded for concrete barriers and 1 for cone or drums;

$f_{DN}$ = Day/night indicator, in which 0 is awarded for daytime construction and 1 for nighttime construction; and

$f_{Nr}$ = Number of ramps within three mi upstream and downstream of the work zone.

$v_D$ can be calculated by Equation 3.4:

$$v_D = \frac{q_{max,WZ}}{k_D} \tag{3.4}$$

Where,

$q_{max,WZ}$ = Capacity of the work zone;

$k_D$ = Density of traffic in the queue corresponding to $q_{max,WZ}$ as given by equation 3.5:

$$k_D = k_{jam} - \frac{q_{max,WZ}}{w_p} \tag{3.5}$$

Where,

$k_{jam}$ = Queue density of the freeway under normal operating conditions; and

$w_p$ = The speed at which the front-of-queue propagates upstream, given by equation 3.6:

$$w_p = \frac{q_{max}}{k_{jam} - \frac{q_{max}}{FFS}} \tag{3.6}$$

VMT$_{construction}$ is the number of vehicles traversing the construction area times the length of the construction. VMT$_{queue}$, however, requires the calculation of a queue length or a queue area.

$$VMT_{queue} = \mathrm{A_D} \times q_{max,WZ} \tag{3.7}$$

The area of the queue, A$_D$, is the area between the front and back of the queue over time. If the front of the queue hasn't surpassed the back of the queue, the area will be trapezoidal in shape and is given by Equation 3.8:

$$A_D^t = 1 \text{ hour} \times \left| \frac{1}{2}\left(x_{front}^{t-1} + x_{front}^{t}\right) - \frac{1}{2}\left(x_{back}^{t-1} + x_{back}^{t}\right) \right| \tag{3.8}$$

Where,

$A_D^t$ = Area in the queue between hour (t-1) and t;

$x_{front}^t$ = Location of the front of the queue at time t, which is given by Equation 3.9; and

$x_{back}^t$ = Location of the back of the queue at time t, which is given by Equation 3.10:

$$x_{front}^t = x_{front}^{t-1} + 1\ hour\ \times w_p \tag{3.9}$$

$$x_{back}^t = x_{back}^{t-1} + 1\ hour\ \times w_{Vol,D} \tag{3.10}$$

Where $w_{Vol,D}$ is the speed at which the back of the queue will propagate and is given by Equation 3.11:

$$w_{Vol,D}^t = \frac{q_{Vol}^t - q_D}{k_{Vol}^t - k_D} \tag{3.11}$$

Where $q_{Vol}^t$ is the flow associated with the volume at time t.

The area of the queue for hour in which the queue dissipates will be triangular and is given by Equation 3.12:

$$w_{Vol,D}^t = \frac{q_{Vol}^t - q_D}{k_{Vol}^t - k_D} \tag{3.12}$$

Where T is the fraction of an hour in which the queue exists, and is given by Equation 3.13:

$$T = \left((\mathrm{t} - 1) - t^{end}\right) + \left(\frac{x_{back}^{t-1} - x_{front}^{t-1} + 1\ hour \times w_{Vol,D}^{t}}{w_p}\right) \tag{3.13}$$

Once total delay is computed using Equation 1, the total delay time in hours can be converted to delay cost using driver wages for each vehicle type provided in FHWA estimates for driver wages in the RealCost Technical Document (FHWA, 1998). Calculation is given in Equation 3.14:

$$Delay\ Cost_A = Total\ Delay * Wage_A * \%_A Traffic * f_o * f_b \tag{3.14}$$

Where,

$\text{Wage}_A$ = Hourly wage of a driver in a given vehicle type. Vehicle types in this study include passenger cars, small trucks, medium trucks, and large trucks;

$\%_A$Traffic = Percentage of vehicle type A in traffic;

$f_o$ = Occupancy factor or the average number of individuals in vehicle type A; and

$f_b$ = Business travel factor. If a vehicle's travel purpose is personal and not business, passengers' hourly wages are decreased by 50% for local roads and 70% for interstates. Then, this reduction factor is multiplied by the percentage of Vehicle Type A for personal use.

## 3.2 Crash Costs

It is reported that work zones increase crash risk by approximately 60% (Ullman et al., 2008). Therefore, there is a need for a crash modification factor (CMF) for work zones when they exist. However, there are additional measures that an agency usually takes in order to prevent crashes in work zones. Unfortunately, data for these prevention measures are not widely available and are case dependent. This makes crash costs one of the most unpredictable components of user costs. However, because crash costs are not the main focus of this study, FHWA recommended values were used for crash calculations. When calculating crash cost, both CMF and the aforementioned precautions should be kept in mind. Crash cost is given in Equation 3.15:

$$Crash\ Cost_{CrashTypeX} = \mathrm{CMF} * \mathrm{PCF} * \frac{A*10^{6}}{T*L*AADT*365} * Cost_{CrashTypeX} \tag{3.15}$$

Where,

CMF = Crash modification factor;

PCF = Precaution factor;

A = Average number of crashes for the analysis period for crash type X;

T = Analysis duration in years;

L = Length of the roadway segment; and

AADT = Annual average daily traffic.

For $\text{Cost}_{\text{CrashTypeX}}$, the severity of the accident must be taken into consideration, especially the human capital costs and comprehensive costs. The KABCO injury scale is widely used for assessing the severity of crashes. In the KABCO scale, K is fatal, A is incapacitating, B is injury, C is possible injury, and O is property damage only. Once the severity of the crash is known, the cost of a crash could be determined for each scale using FHWA crash cost estimates from 2011 as given in the table below (FHWA, 2011).

TABLE 3.1 FHWA crash cost estimates. Data from 2001 (After FHWA, 2011).

| Speed Limit (mph) | Max Injury Severity in Crash | Human Capital Cost per Crash | | Comprehensive Cost per Crash | |
|---|---|---|---|---|---|
| | | Mean | Std Dev | Mean | Std Dev |
| <=45 | No Injury | $8,512 | $997 | $10,249 | $1,408 |
| <=45 | B or C | $33,369 | $4,561 | $60,333 | $9,021 |
| <=45 | A | $163,157 | $15,153 | $316,380 | $33,532 |
| <=45 | K | $975,643 | $30,468 | $3,234,016 | $114,015 |
| <=45 | Injured, Severity Unknown | $67,342 | $22,127 | $129,418 | $42,249 |
| <=45 | Unknown | $14,386 | - | $22,841 | - |
| >=50 | No Injury | $3,672 | - | $4,015 | - |
| >=50 | B or C | $54,605 | $32,590 | $101,712 | $61,756 |
| >=50 | A | $116,545 | $26,407 | $189,805 | $36,182 |
| >=50 | K | $1,022,983 | $1,695 | $3,404,944 | $2,819 |
| >=50 | Injured, Severity Unknown | $61,573 | - | $146,281 | - |
| <=50 | Unknown | N.A. | N.A. | N.A. | N.A. |

# Chapter 4: Normal Operation User Cost Components

## 4.1 Overview

In addition to work zone costs, there are costs related to normal operation affected by pavement condition. Some of these costs can be monetized as fuel consumption, tire wear and tear, and repair costs, whereas some may not be monetized, such as ride comfort and noise. Only fuel, tire wear and tear, and repair costs were considered in this study. Three types of normal operation costs may be considered: base costs, differential costs, and total costs.

Base costs are the costs associated with travel from one point to another. These costs do not affect life cycle cost analysis (LCCA) and are independent of project alternatives. Most LCCA documents are prepared by agencies and follow similar assumptions. An LCCA document prepared by Caltrans (2013) states, “Although user costs are incurred during normal operating conditions, they are not considered in LCCA because normal travel costs are not dependent on individual project alternatives.” This statement is true for base costs.

Differential costs, on the other hand, are extra costs due to pavement condition. These are extra costs incurred on the user because of agency’s decision regarding maintenance schedule and are associated with pavement condition. These costs are project alternative dependent. International Roughness Index (IRI) is one proxy for distinguishing between base costs and differential costs. It can be assumed that below a base IRI value, all incurred costs are base costs. Once the pavement condition starts to worsen and IRI increases above that selected base level, differential costs are incurred. Total costs are the sum of base costs and differential costs. Figure 4.1 illustrates this relationship.

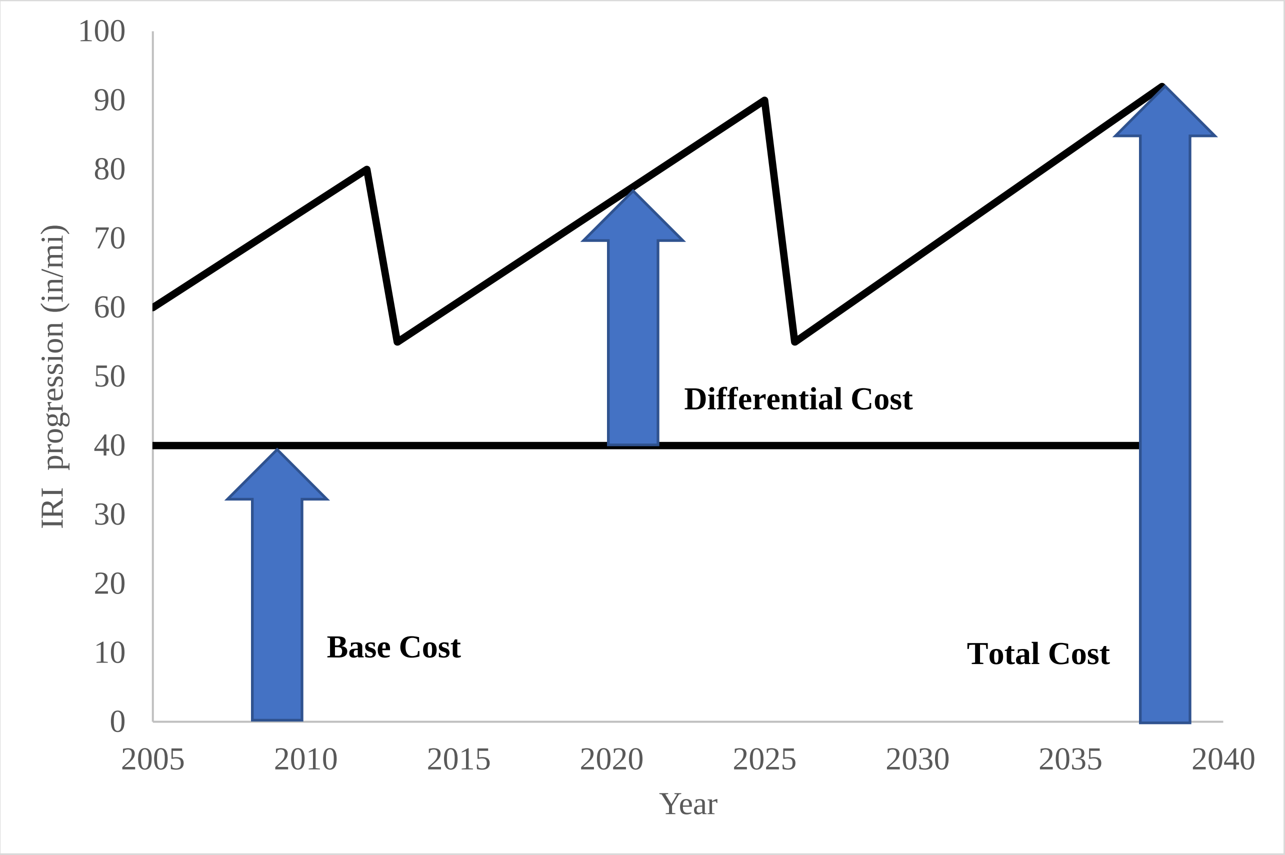


**FIGURE 4.1 Illustration of total, base, and differential costs.**

The cost difference between two project alternatives is caused by differential costs. To calculate differential costs, it is important to quantify the variation in pavement condition between project alternatives. Pavement condition difference may refer to present serviceability index (PSI), roughness, or texture. It is widely accepted that roughness is the largest contributor to rolling resistance and thus operating costs (Hammarström et al., 2012). Roughness was used in this study as the main measure of pavement condition through IRI.

Once the variation in pavement condition is quantitatively established, differential costs may be accurately computed as a function of pavement conditions. Traditional LCCA approaches assume that the differential costs are negligible between projects; based on work conducted by the World Bank in 1997. That study suggests that the operating costs are not sensitive to IRI below 150 in/mi. Because the IRI for most highways and tollways in the US below 150in/mi, it is commonly accepted that differential costs are negligible between project alternatives (World Bank, 1997).

Recent studies illustrate that the vehicle operating costs are more sensitive to IRI levels than initially thought. Figure 4.2 illustrates that vehicle operating costs start increasing at an IRI level of 60 in/mi instead of 150in/mi. As traffic increases, these additional costs might build up and start affecting LCCA results (Zaabar and Chatti, 2012).

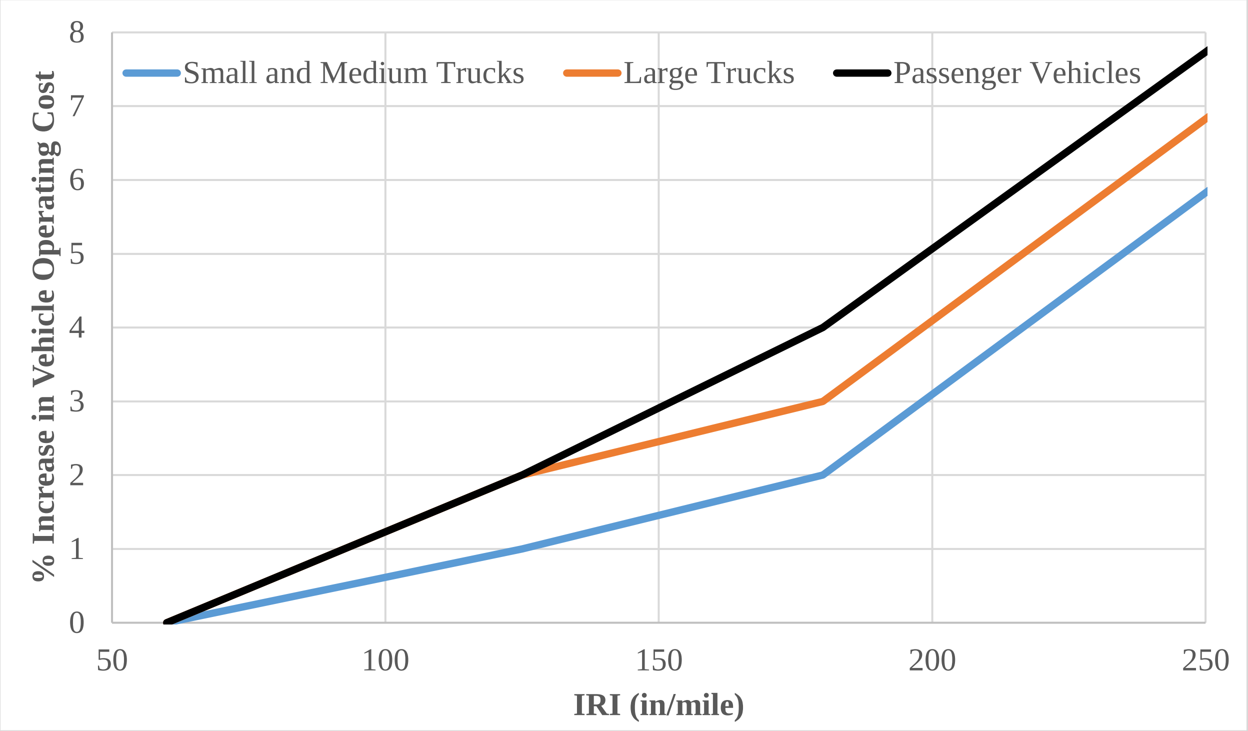


**FIGURE 4.2 Revised vehicle operating costs vs. pavement roughness (Zaabar and Chatti, 2012).**

Differential user costs during normal operation are fuel costs, tire wear and tear costs, and maintenance costs. For each cost item, unit costs are needed to connect consumption models to costs. For example, the unit price of fuel is needed to convert fuel consumption into costs, using consumption models. Similarly, for tire wear and tear, consumption models predict the number of tires worn due to pavement condition; the unit cost of a tire is needed to connect consumption to cost.

Increasing the IRI over the lifetime of the pavement would increase fuel consumption, tire wear and tear, and vehicle repair costs. Therefore, an accurate IRI progression model is also important for accurate cost estimation. The following sections discuss the consumption models for fuel, tire, and repair costs as well as unit costs for each item.

## 4.2 Unit Costs

In this study, unit costs were obtained from NCHRP 720 report and presented in Table 4.1 (Zaabar and Chatti, 2012). Fuel costs were obtained from the U.S. Energy Information Administration and scaled with consumer price index (CPI) to the construction year if data were not available. Tire cost, repair cost, and fuel cost data were obtained from 2007, 2011, and 2016, respectively.

**TABLE 4.1 Unit Costs for Vehicle Operation**

| | Unit Costs | | |
|---|---|---|---|
| | Fuel Cost ( 2016 $/gal) | Tire Cost (2007 $/tire) | Repair and Maintenance Costs (2011 $/mi) |
| Small car | $2.45 | $100 | 0.064 |
| Medium car | $2.45 | $100 | 0.064 |
| Large car | $2.45 | $100 | 0.064 |
| Van | $2.45 | $150 | 0.083 |
| Four-wheel drive | $2.45 | $150 | 0.083 |
| Light truck | $2.45 | $175 | 0.083 |
| Medium truck | $2.77 | $200 | 0.092 |
| Heavy truck | $2.77 | $250 | 0.119 |
| Articulated truck | $2.77 | $250 | 0.191 |
| Mini bus | $2.77 | $150 | 0.199 |
| Light bus | $2.77 | $175 | 0.083 |
| Medium bus | $2.77 | $200 | 0.092 |
| Heavy bus | $2.77 | $250 | 0.119 |
| Coach | $2.77 | $250 | 0.191 |

## 4.3 Fuel Consumption

The roughness energy model used in this study relies on vehicle specific power relationships (VSP) to estimate additional rolling resistance and fuel consumption caused by changes in roughness. In particular, a regression model was created using previously developed MOVES simulations correlating HDM-4 models (Ziyadi et al., 2017). This model, known as the roughness speed impact model (RSI), estimates the increase in fuel consumption per unit increase in roughness. The model is given below:

$$RSI_{t=0}^{Energy}: \hat{E}(v, IRI) = \frac{p}{v} + (ka.IRI + da) + b \times v + (kc.IRI + dc) \times v^2 \quad \textbf{(4.1)}$$

Where E is the energy consumed per VMT in MJ, v is the speed of the vehicle in mph, and model coefficients are given below.

### TABLE 4.2 Model Coefficients for Different Vehicle Types

| **Coefficients** | **Passenger Car** | **Small Truck** | **Medium Truck** | **Large Truck** |
|---|---|---|---|---|
| *ka* | 6.70E-01 | 7.68E-01 | 9.18E-01 | 1.40E+00 |
| *kc* | 2.81E-04 | 1.25E-04 | 1.33E-04 | 1.36E-04 |
| *dc* | 2.1860E-01 | 3.0769E-01 | 9.7418E-01 | 2.3900E+00 |
| *da* | 2.1757E+03 | 7.0108E+03 | 9.2993E+03 | 1.9225E+04 |
| *b* | -1.6931E+01 | -7.3026E+01 | -1.3959E+02 | -2.6432E+02 |
| *p* | 3.3753E+04 | 1.1788E+05 | 1.0938E+05 | 8.2782E+04 |

Once the energy is calculated, energy is converted to gallons of fuel using the conversion rates presented in Table 4.3.

TABLE 4.3 Conversion Rates for Different Vehicle Types

| | **Unit Process** | **Type** | **Unit** | **MJ / GAL** |
|---|---|---|---|---|
| **Passenger Vehicle** | Petrol, unleaded, at regional storage/US- US-EI U | Gasoline | MJ | 131.10 |
| **Small Truck** | Petrol, unleaded, at regional storage/US- US-EI U | Gasoline | MJ | 131.10 |
| **Medium truck** | Diesel, low-sulphur, at regional storage/US- US-EI U | Diesel | MJ | 144.85 |
| **Large Truck** | Diesel, low-sulphur, at regional storage/US- US-EI U | Diesel | MJ | 144.85 |

Texture-related fuel consumption, on the other hand, only affects heavy vehicles. Although it is relatively small when compared to consumption because of roughness, it should still be considered. The energy equation for texture depends only on vehicle speed ($v$) in mph and reported in increase in Mega Joules (MJ) per increase in mean profile depth (MPD) in inches (Zaabar and Chatti, 2012).

$$\delta Etexture\ (\%) = 0.02 - 2.5 \times 10 - 4 \times (v - 35) \qquad \textbf{(4.2)}$$

## 4.4 Tire Wear and Tear

The tire wear and tear costs are adopted from the NCHRP 720 report (Zaabar and Chatti, 2012). The HDM4 models were taken as a baseline and were calibrated with field data. It was found that on average at a base IRI level of 60 in/mi and at 0.04 in mean profile depth (MPD), percent tire wear per tire of passenger vehicles, small, medium, and large trucks are 0.0025 %/mi, 0.0046 %/mi, 0.0046 %/mi and 0.0015 %/mi respectively. 100% corresponds to total wear of a tire when a tire tread depth reaches to 0.126 inches.

As IRI levels increase, tire wear and tear costs also increase. Therefore, for each IRI level that is larger than 60 in/mi, IRI correction factors were used to correctly estimate the costs. The correction factors for 70 mph are illustrated in Figure 4.3.

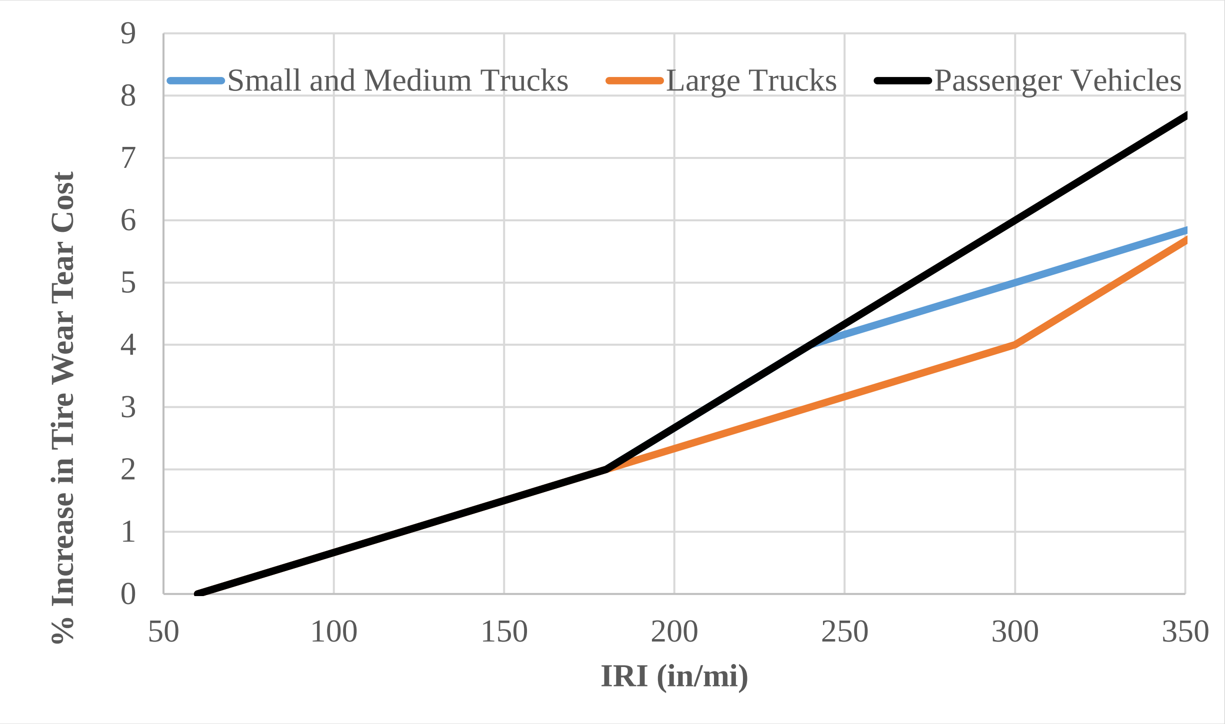


**FIGURE 4.3 Increase in tire wear and tear costs with IRI.**

## 4.5 Repair and Maintenance

It is difficult to decouple regular maintenance of vehicles from that incurred due to road-specific condition such as roughness. The NCHRP 720 report provides a simulation for road networks based on vehicle dynamics simulations. For a base IRI of 60 in/mi and 0.04 in MPD, it was found that cost of repair and maintenance per 1000 mi for passenger vehicles, small, medium, and large trucks are $64, $147, $186 and $198, respectively. Repair costs are found to be less sensitive to roughness than fuel and tire wear. Repair costs do not increase because of roughness until an IRI level of 180 in/mi, which is not reached by many highway roads that are kept in a relatively smooth condition, but might be significant for medium- and low-traffic sections. The relation of maintenance cost with IRI is given in Figure 4.4.

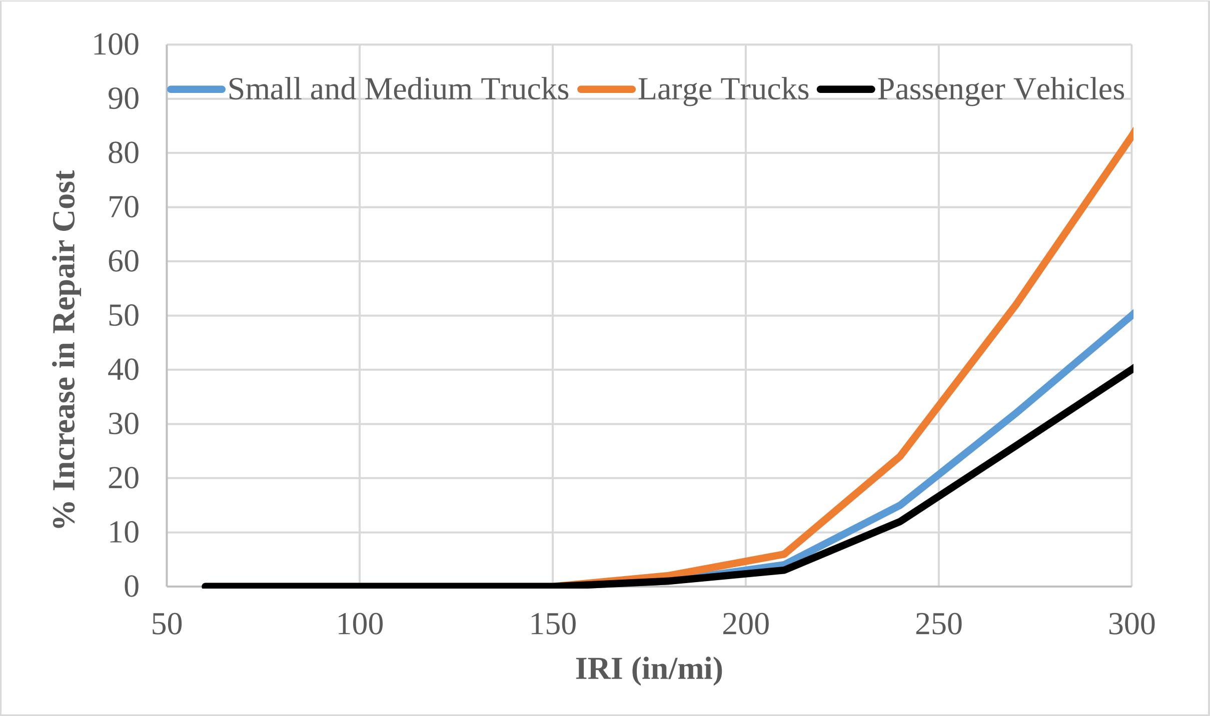


FIGURE 4.4 Increase in maintenance costs with IRI.

# Chapter 5: Tool Development

To perform a sustainability assessment of a system, both cost and environmental impacts should be considered. Life cycle assessment (LCA) is a technique used to assess environmental impacts associated with all stages of a product's life. For pavement systems, it includes “materials and construction,” “maintenance and rehabilitation,” “use,” and “end of life” stages. The LCA methodology has recently been used for pavement applications (Santos et al, 2014, Harvey et al 2013).

From an LCA standpoint, agency costs incur from the “materials and construction,” “maintenance and rehabilitation,” and “end of life” stages. User costs, on the other hand, incur during the “use” stage, when vehicles are using the infrastructure. Work zone user costs can be associated with either the “use” stage or the “maintenance and rehabilitation” stage.

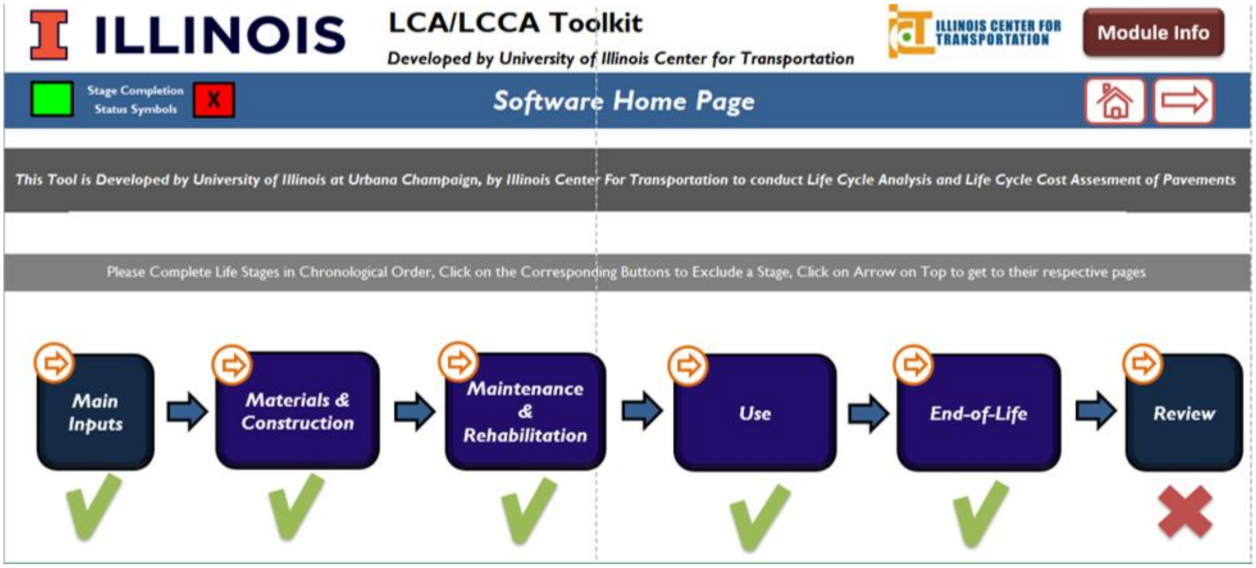
Even though LCA and LCCA are separate analyses and should not be confused, it is important for an agency to be aware of both environmental and economic impacts. In 2016, the Illinois Center for Transportation ICT developed an LCA tool to be used by the Illinois Tollway (Al-Qadi, et al., 2016). This study introduces an LCCA module built on top of the LCA tool. In this section, details of the LCCA module are discussed.

## 5.1 Overview of the Tool

Any construction project has four distinct stages: materials and construction, maintenance and rehabilitation, use, and end of life.

The materials and construction stage refers to the first major rehabilitation or reconstruction that is applied to the pavement structure. The maintenance stage includes the maintenance activities that are performed for the analysis period or design period of the structure. The use stage refers to the usage of the section by passenger vehicles or trucks. Types of vehicles considered in this tool are passenger vehicles, small trucks, medium trucks and large trucks. The use stage includes both the times at which there is no work zone and the times when there is a work zone. Finally, the end of life is the final stage of the project in which it is either terminated or recycled.

A tool has been developed to capture all these stages and their economic impacts. The overall design of this tool will not be discussed herein; it is documented somewhere else (Al-Qadi, et al., 2016).



This Tool is Developed by University of Illinois at Urbana Champaign, by Illinois Center For Transportation to conduct Life Cycle Analysis and Life Cycle Cost Assesment of Pavements

Please Complete Life Stages in Chronological Order, Click on the Corresponding Buttons to Exclude a Stage, Click on Arrow on Top to get to their respective pages

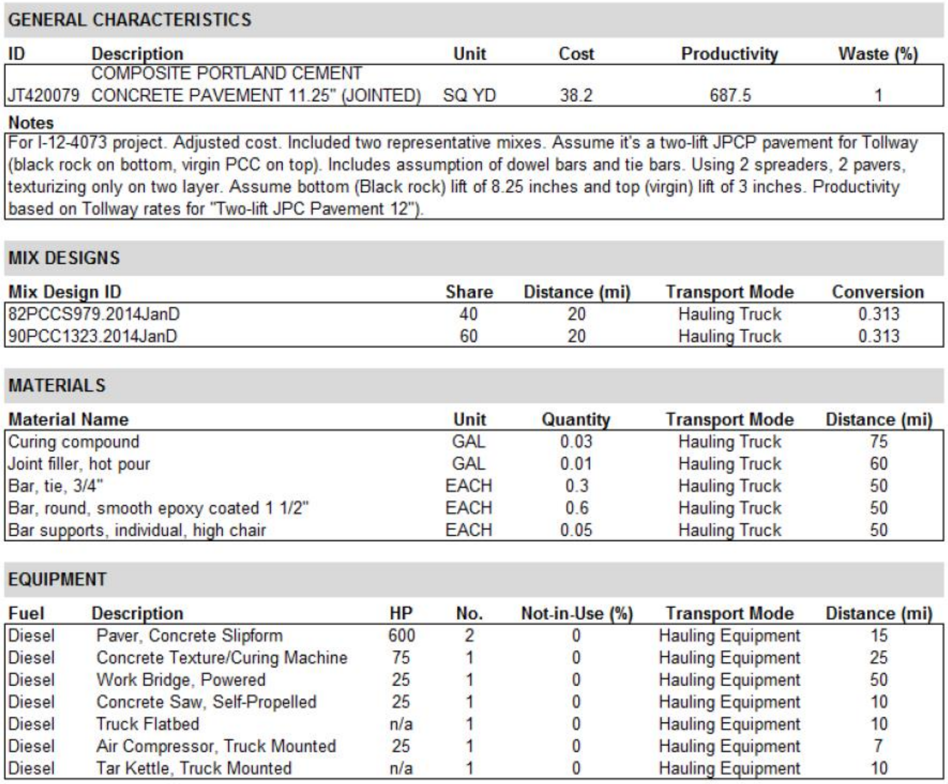
FIGURE 5.1 LCA/LCCA Tool Home Page

The tool uses pay items to make it easier for contractors to use the tool. A pay item is defined as a specific unit of work for which a price is provided and the contractor is paid while a highway is under construction.

## 5.2 Pay Item Framework

Traditional LCA and LCCA tools require users to enter the design cross-section, length, and cost manually. The main limitation of this approach is that contractors or agencies usually work with pay items when they bid for or design a project. Pay items are breakdowns of a task into their individual elements. Figure 5.2 shows an example of pay item, 11.25-in composite Portland cement concrete. To construct a square yard of this specific pay item, different materials and equipment are needed. Each type of material or equipment has different costs that contribute to the overall cost of the pay item.

Each pay item can have multiple unit processes connected to it. From an LCA standpoint, it is very important to know the environmental impacts of each unit process for the materials and equipment that construct the pay item. From an LCCA standpoint, however, only needed the cost of that pay item per unit and the year at which that cost is reported so that that item can be incorporated in the agency cost calculation.



**GENERAL CHARACTERISTICS**

| ID | Description | Unit | Cost | Productivity | Waste (%) |
|---|---|---|---|---|---|
| JT420079 | COMPOSITE PORTLAND CEMENT CONCRETE PAVEMENT 11.25" (JOINTED) | SQ YD | 38.2 | 687.5 | 1 |

**Notes**

For I-12-4073 project. Adjusted cost. Included two representative mixes. Assume it's a two-lift JPCP pavement for Tollway (black rock on bottom, virgin PCC on top). Includes assumption of dowel bars and tie bars. Using 2 spreaders, 2 pavers, texturizing only on two layer. Assume bottom (Black rock) lift of 8.25 inches and top (virgin) lift of 3 inches. Productivity based on Tollway rates for "Two-lift JPC Pavement 12").

**MIX DESIGNS**

| Mix Design ID | Share | Distance (mi) | Transport Mode | Conversion |
|---|---|---|---|---|
| 82PCCS979.2014JanD | 40 | 20 | Hauling Truck | 0.313 |
| 90PCC1323.2014JanD | 60 | 20 | Hauling Truck | 0.313 |

**MATERIALS**

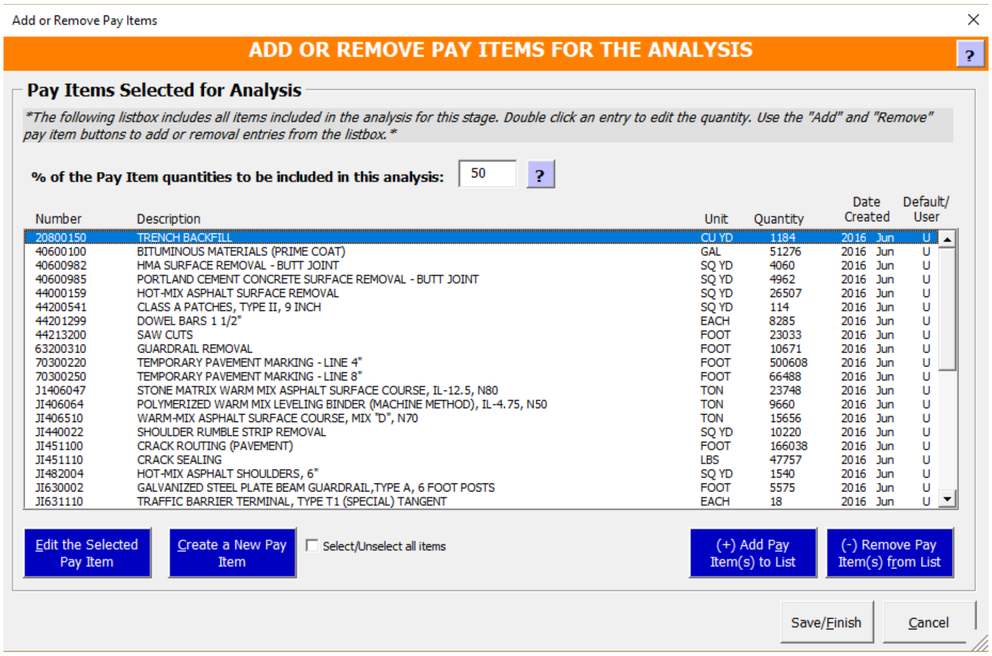
| Material Name | Unit | Quantity | Transport Mode | Distance (mi) |
|---|---|---|---|---|
| Curing compound | GAL | 0.03 | Hauling Truck | 75 |
| Joint filler, hot pour | GAL | 0.01 | Hauling Truck | 60 |
| Bar, tie, 3/4" | EACH | 0.3 | Hauling Truck | 50 |
| Bar, round, smooth epoxy coated 1 1/2" | EACH | 0.6 | Hauling Truck | 50 |
| Bar supports, individual, high chair | EACH | 0.05 | Hauling Truck | 50 |

**EQUIPMENT**

| Fuel | Description | HP | No. | Not-in-Use (%) | Transport Mode | Distance (mi) |
|---|---|---|---|---|---|---|
| Diesel | Paver, Concrete Slipform | 600 | 2 | 0 | Hauling Equipment | 15 |
| Diesel | Concrete Texture/Curing Machine | 75 | 1 | 0 | Hauling Equipment | 25 |
| Diesel | Work Bridge, Powered | 25 | 1 | 0 | Hauling Equipment | 50 |
| Diesel | Concrete Saw, Self-Propelled | 25 | 1 | 0 | Hauling Equipment | 10 |
| Diesel | Truck Flatbed | n/a | 1 | 0 | Hauling Equipment | 10 |
| Diesel | Air Compressor, Truck Mounted | 25 | 1 | 0 | Hauling Equipment | 7 |
| Diesel | Tar Kettle, Truck Mounted | n/a | 1 | 0 | Hauling Equipment | 10 |

FIGURE 5.2 Example Pay Item Breakdown

The agency cost component of the tool is constructed using the pay item framework. Any time a pay item is entered, its cost is first converted to the construction year using CPI, and then discounting is applied to find the final present worth of the cost. The LCA/LCCA tool is structured in a way that the user can add or remove each pay item and change its quantity as shown in Figure 5.3. The user also has the ability to change the unit processes, materials, and equipment related to a pay item as given in Figure 5.4.



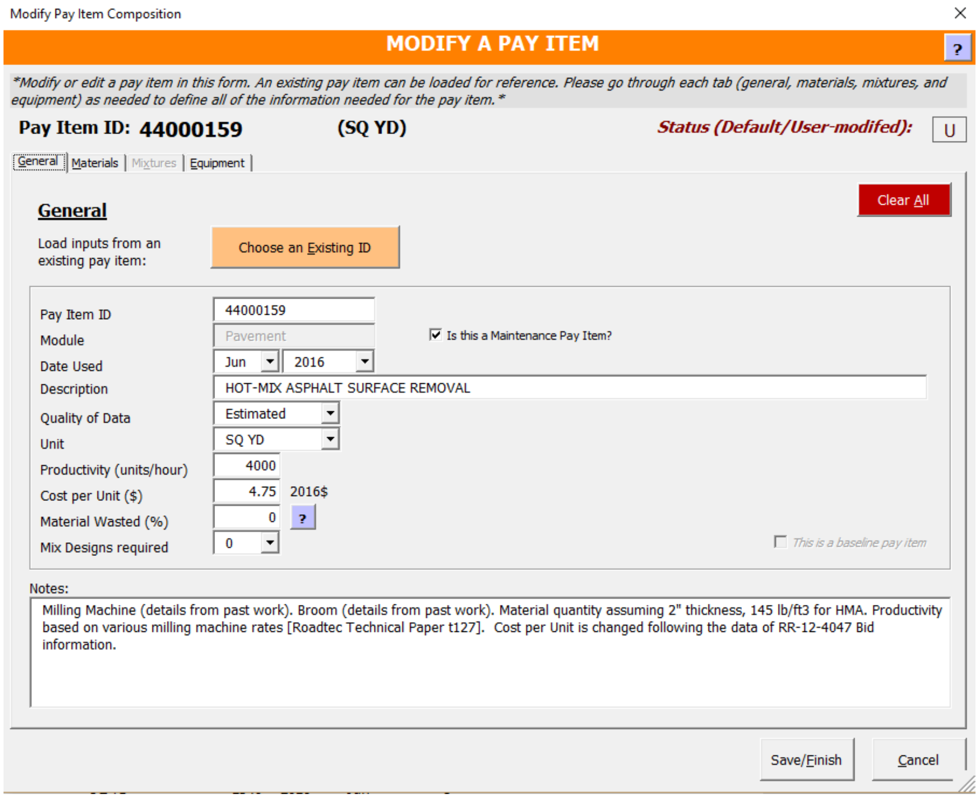
*The following listbox includes all items included in the analysis for this stage. Double click an entry to edit the quantity. Use the "Add" and "Remove" pay item buttons to add or removal entries from the listbox.*

**% of the Pay Item quantities to be included in this analysis:** 50

| Number | Description | Unit | Quantity | Date Created | Default/ User |
|---|---|---|---|---|---|
| 20800150 | TRENCH BACKFILL | CU YD | 1184 | 2016 Jun | U |
| 40600100 | BITUMINOUS MATERIALS (PRIME COAT) | GAL | 51276 | 2016 Jun | U |
| 40600982 | HMA SURFACE REMOVAL - BUTT JOINT | SQ YD | 4060 | 2016 Jun | U |
| 40600985 | PORTLAND CEMENT CONCRETE SURFACE REMOVAL - BUTT JOINT | SQ YD | 4962 | 2016 Jun | U |
| 44000159 | HOT-MIX ASPHALT SURFACE REMOVAL | SQ YD | 26507 | 2016 Jun | U |
| 44200541 | CLASS A PATCHES, TYPE II, 9 INCH | SQ YD | 114 | 2016 Jun | U |
| 44201299 | DOWEL BARS 1 1/2" | EACH | 8285 | 2016 Jun | U |
| 44213200 | SAW CUTS | FOOT | 23033 | 2016 Jun | U |
| 63200310 | GUARDRAIL REMOVAL | FOOT | 10671 | 2016 Jun | U |
| 70300220 | TEMPORARY PAVEMENT MARKING - LINE 4" | FOOT | 500608 | 2016 Jun | U |
| 70300250 | TEMPORARY PAVEMENT MARKING - LINE 8" | FOOT | 66488 | 2016 Jun | U |
| J1406047 | STONE MATRIX WARM MIX ASPHALT SURFACE COURSE, IL-12.5, N80 | TON | 23748 | 2016 Jun | U |
| JI406064 | POLYMERIZED WARM MIX LEVELING BINDER (MACHINE METHOD), IL-4.75, N50 | TON | 9660 | 2016 Jun | U |
| JI406510 | WARM-MIX ASPHALT SURFACE COURSE, MIX "D", N70 | TON | 15656 | 2016 Jun | U |
| JI440022 | SHOULDER RUMBLE STRIP REMOVAL | SQ YD | 10220 | 2016 Jun | U |
| JI451100 | CRACK ROUTING (PAVEMENT) | FOOT | 166038 | 2016 Jun | U |
| JI451110 | CRACK SEALING | LBS | 47757 | 2016 Jun | U |
| JI482004 | HOT-MIX ASPHALT SHOULDERS, 6" | SQ YD | 1540 | 2016 Jun | U |
| JI630002 | GALVANIZED STEEL PLATE BEAM GUARDRAIL,TYPE A, 6 FOOT POSTS | FOOT | 5575 | 2016 Jun | U |
| JI631110 | TRAFFIC BARRIER TERMINAL, TYPE T1 (SPECIAL) TANGENT | EACH | 18 | 2016 Jun | U |

☐ Select/Unselect all items

FIGURE 5.3 List of Pay Items for a Given Project



*Modify or edit a pay item in this form. An existing pay item can be loaded for reference. Please go through each tab (general, materials, mixtures, and equipment) as needed to define all of the information needed for the pay item.*

**Pay Item ID: 44000159** **(SQ YD)** ***Status (Default/User-modifed):*** U

Load inputs from an existing pay item:

| | |
|---|---|
| Pay Item ID | 44000159 |
| Module | Pavement |
| Date Used | Jun 2016 |
| Description | HOT-MIX ASPHALT SURFACE REMOVAL |
| Quality of Data | Estimated |
| Unit | SQ YD |
| Productivity (units/hour) | 4000 |
| Cost per Unit ($) | 4.75 2016$ |
| Material Wasted (%) | 0 |
| Mix Designs required | 0 |

☑ Is this a Maintenance Pay Item?

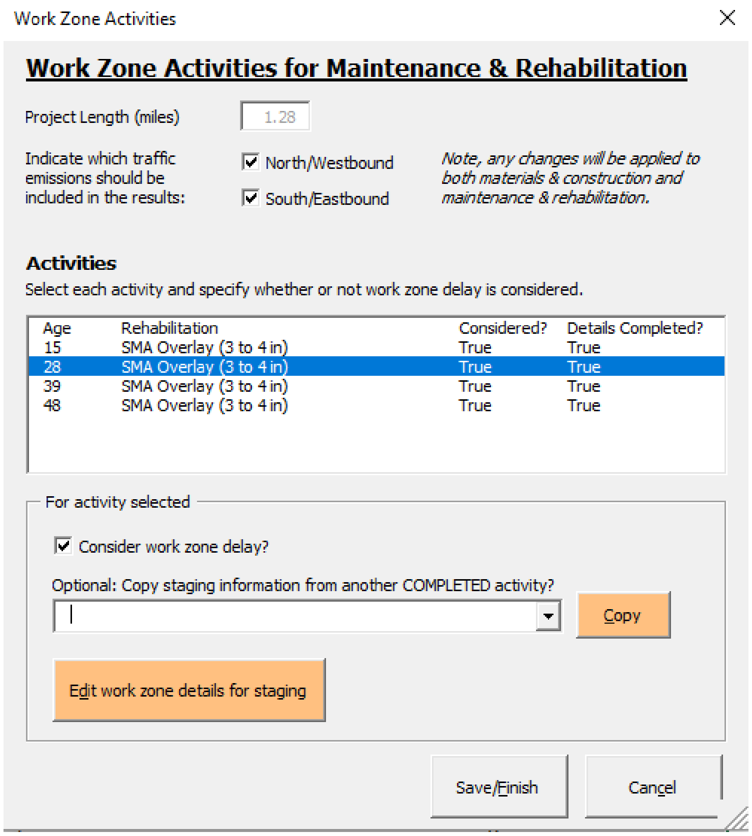
☐ *This is a baseline pay item*

Notes:
Milling Machine (details from past work). Broom (details from past work). Material quantity assuming 2" thickness, 145 lb/ft3 for HMA. Productivity based on various milling machine rates [Roadtec Technical Paper t127]. Cost per Unit is changed following the data of RR-12-4047 Bid information.

FIGURE 5.4 Pay Item Modification

## 5.3 Work Zone Configuration

The tool calculates the environmental impact and user costs caused by work zone activities. Work zones occur either during initial construction or maintenance stages. For a work zone, the user first defines the maintenance activities associated with work zones as shown on Figure 5.5. Second, for each work zone activity, the user defines the number of stages, completion rate, and the work zone geometry as shown in Figures 5.6 through 5.9. Once this information has been collected from the user, it is used to calculate the delay cost and the work zone fuel consumption.



**Work Zone Activities for Maintenance & Rehabilitation**

Project Length (miles) 1.28

Indicate which traffic emissions should be included in the results:
☑ North/Westbound
☑ South/Eastbound

*Note, any changes will be applied to both materials & construction and maintenance & rehabilitation.*

**Activities**

Select each activity and specify whether or not work zone delay is considered.

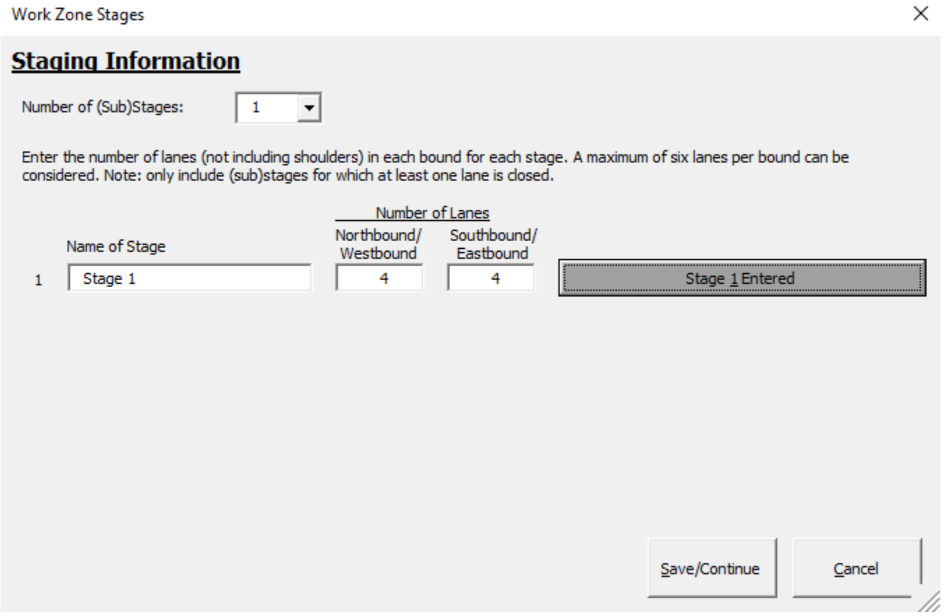
| Age | Rehabilitation | Considered? | Details Completed? |
|---|---|---|---|
| 15 | SMA Overlay (3 to 4 in) | True | True |
| 28 | SMA Overlay (3 to 4 in) | True | True |
| 39 | SMA Overlay (3 to 4 in) | True | True |
| 48 | SMA Overlay (3 to 4 in) | True | True |

For activity selected

☑ Consider work zone delay?

Optional: Copy staging information from another COMPLETED activity?

FIGURE 5.5 Maintenance Activities in Work Zone Selection User Form



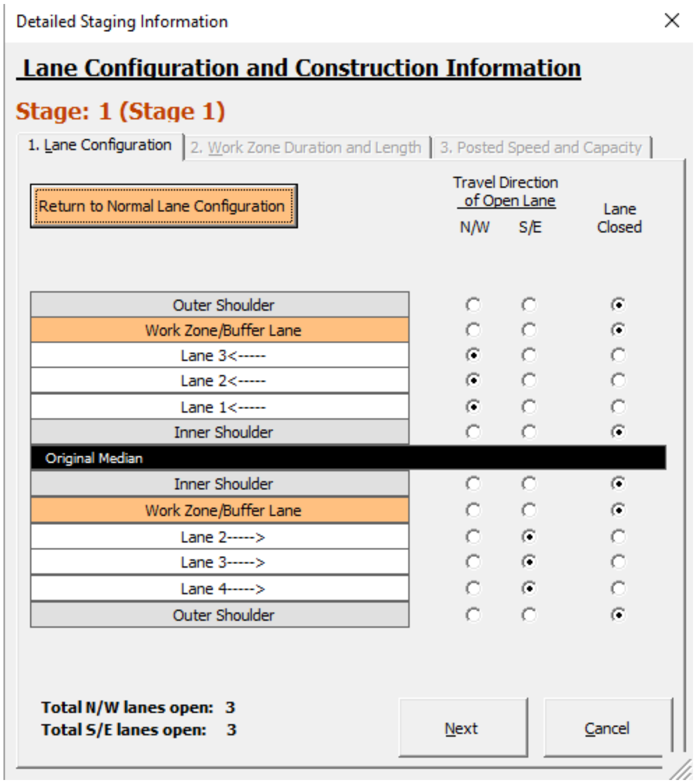
**Staging Information**

Number of (Sub)Stages: 1

Enter the number of lanes (not including shoulders) in each bound for each stage. A maximum of six lanes per bound can be considered. Note: only include (sub)stages for which at least one lane is closed.

| | | Number of Lanes | |
|---|---|---|---|
| | Name of Stage | Northbound/ Westbound | Southbound/ Eastbound |
| 1 | Stage 1 | 4 | 4 |

FIGURE 5.6 Work Zone Stages



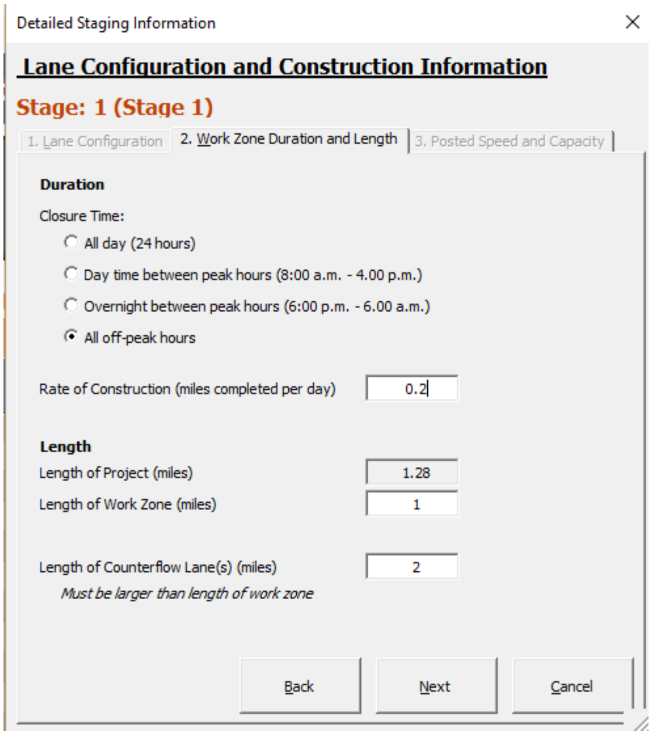
**Lane Configuration and Construction Information**

**Stage: 1 (Stage 1)**

| | Travel Direction of Open Lane | | Lane Closed |
|---|---|---|---|
| | N/W | S/E | |
| Outer Shoulder | ○ | ○ | ● |
| Work Zone/Buffer Lane | ○ | ○ | ● |
| Lane 3<----- | ● | ○ | ○ |
| Lane 2<----- | ● | ○ | ○ |
| Lane 1<----- | ● | ○ | ○ |
| Inner Shoulder | ○ | ○ | ● |
| Original Median | | | |
| Inner Shoulder | ○ | ○ | ● |
| Work Zone/Buffer Lane | ○ | ○ | ● |
| Lane 2-----> | ○ | ● | ○ |
| Lane 3-----> | ○ | ● | ○ |
| Lane 4-----> | ○ | ● | ○ |
| Outer Shoulder | ○ | ○ | ● |

**Total N/W lanes open:** 3
**Total S/E lanes open:** 3

FIGURE 5.7 Work Zone Geometry



**Lane Configuration and Construction Information**

**Stage: 1 (Stage 1)**

**Duration**

Closure Time:

○ All day (24 hours)

○ Day time between peak hours (8:00 a.m. - 4.00 p.m.)

○ Overnight between peak hours (6:00 p.m. - 6.00 a.m.)

● All off-peak hours

Rate of Construction (miles completed per day): 0.2

**Length**

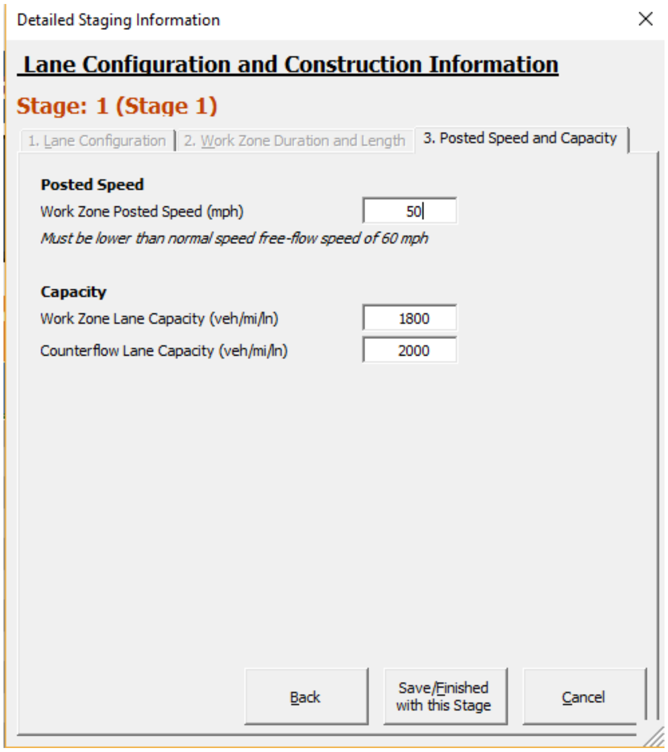
Length of Project (miles): 1.28

Length of Work Zone (miles): 1

Length of Counterflow Lane(s) (miles): 2

*Must be larger than length of work zone*

FIGURE 5.8 Work Zone Completion Rate


Detailed Staging Information

Lane Configuration and Construction Information

Stage: 1 (Stage 1)

Posted Speed

Work Zone Posted Speed (mph) 50

*Must be lower than normal speed free-flow speed of 60 mph*

Capacity

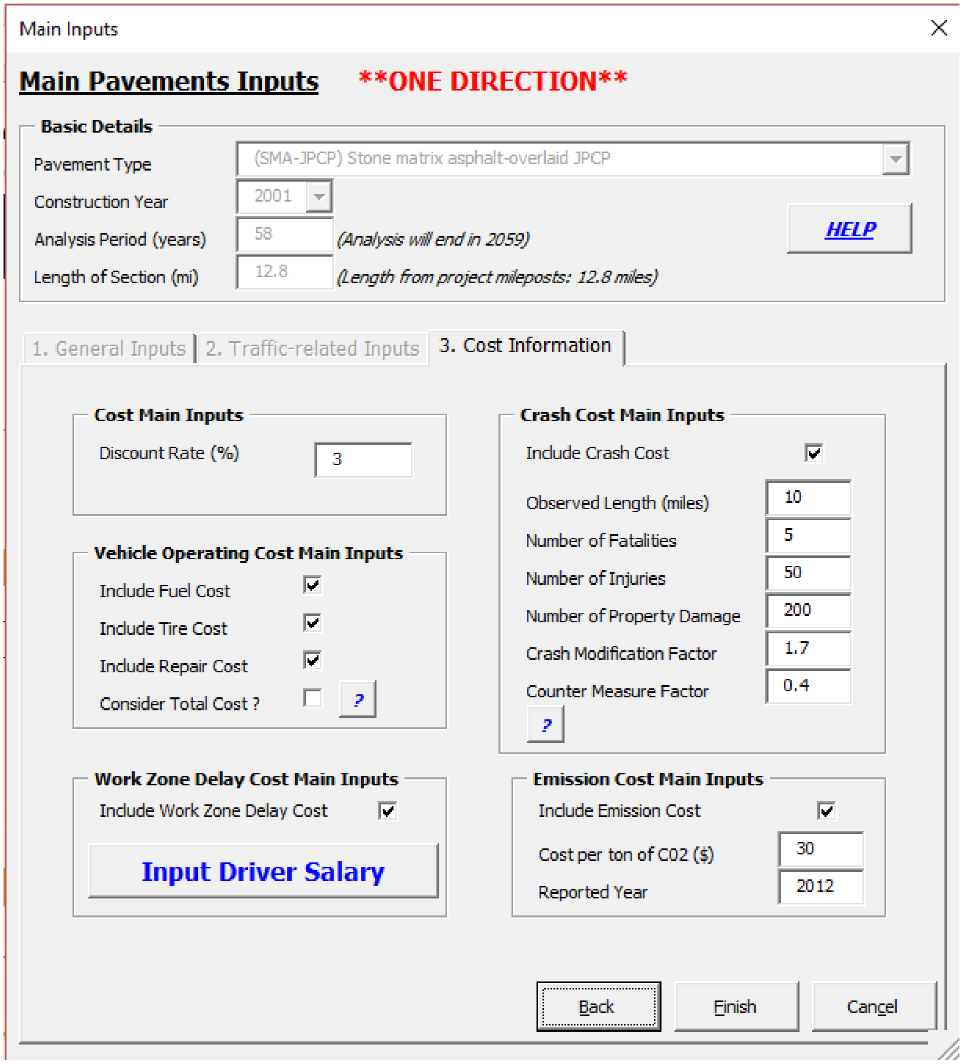
Work Zone Lane Capacity (veh/mi/ln) 1800

Counterflow Lane Capacity (veh/mi/ln) 2000

FIGURE 5.9 Work Zone Speed and Capacity

## 5.4 User Cost Inputs

The user costs considered in this study were: work zone delay costs, fuel costs, tire wear and tear costs, repair costs, crash costs, and emission costs. The user is required to input the discount rate for analysis, the cost items to be included in the analysis, crash rate information, emission cost information, and driver salaries as given in Figure 5.10.



Main Inputs

**Main Pavements Inputs** **ONE DIRECTION**

**Basic Details**

Pavement Type: (SMA-JPCP) Stone matrix asphalt-overlaid JPCP

Construction Year: 2001

Analysis Period (years): 58 *(Analysis will end in 2059)*

Length of Section (mi): 12.8 *(Length from project mileposts: 12.8 miles)*

1. General Inputs | 2. Traffic-related Inputs | 3. Cost Information

**Cost Main Inputs**

Discount Rate (%): 3

**Vehicle Operating Cost Main Inputs**

Include Fuel Cost ☑

Include Tire Cost ☑

Include Repair Cost ☑

Consider Total Cost ? ☐

**Work Zone Delay Cost Main Inputs**

Include Work Zone Delay Cost ☑

**Crash Cost Main Inputs**

Include Crash Cost ☑

Observed Length (miles): 10

Number of Fatalities: 5

Number of Injuries: 50

Number of Property Damage: 200

Crash Modification Factor: 1.7

Counter Measure Factor: 0.4

**Emission Cost Main Inputs**

Include Emission Cost ☑

Cost per ton of C02 ($): 30

Reported Year: 2012

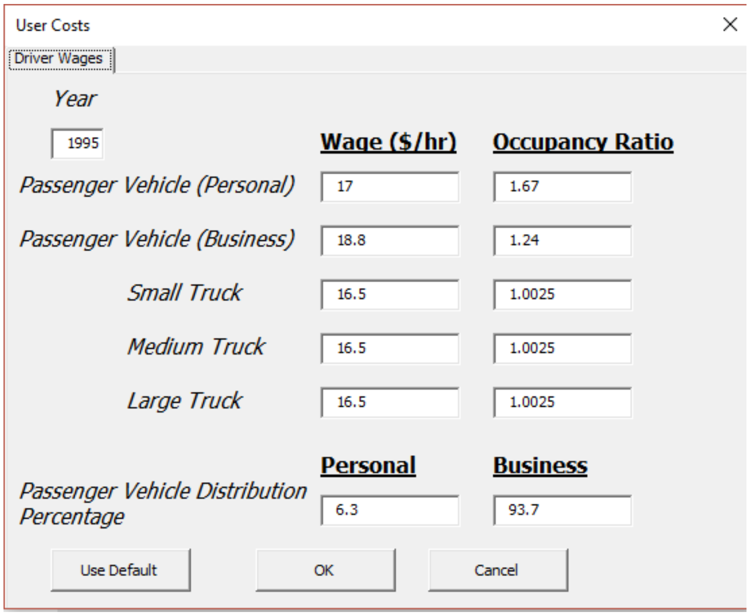
FIGURE 5.10 Cost Inputs Main User Interface

Vehicle operating costs can be included or excluded from the analysis. As a default, only differential vehicle operating costs are computed, but the user also has the option to calculate total vehicle operating costs. If this option is not selected, vehicle operating costs are calculated according to a base IRI level of 40 in/mi. Cost is calculated only if the pavement roughness is greater than 40 in/mi.

The salaries of drivers, vehicle occupancy rates, and the percentage of drivers on business trips are required to calculate work zone delay as shown in Figure 5.11. The default values are provided from the 1998 FHWA LCCA document (FHWA, 1998).

Crash cost input calculations require the user to enter the number of crashes for a given analysis period for a selected length. Using the unit costs of crashes, explained in Chapter 4, the crash rates are converted into cost.

Emission cost calculations require the user to enter a cost per ton of $CO_2$. Since the tool was initially developed as an LCA tool, emissions are already calculated and reported. By assigning a dollar value to these emissions, the user has the power to combine LCA and LCCA results in a very simplistic manner.



*Year* 1995

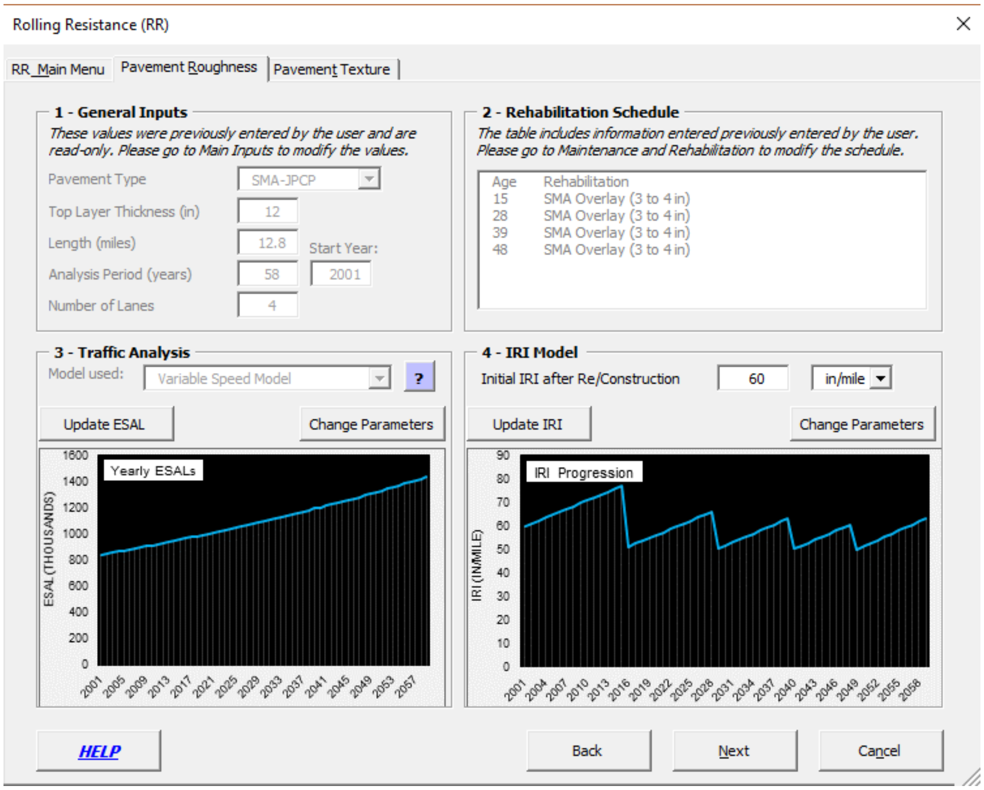
| | **Wage ($/hr)** | **Occupancy Ratio** |
|---|---|---|
| *Passenger Vehicle (Personal)* | 17 | 1.67 |
| *Passenger Vehicle (Business)* | 18.8 | 1.24 |
| *Small Truck* | 16.5 | 1.0025 |
| *Medium Truck* | 16.5 | 1.0025 |
| *Large Truck* | 16.5 | 1.0025 |

| | **Personal** | **Business** |
|---|---|---|
| *Passenger Vehicle Distribution Percentage* | 6.3 | 93.7 |

FIGURE 5.11 Driver Wages Input

## 5.5 IRI Progression Visualization

The IRI progression model described in Chapter 4 is used to construct the roughness progression as shown in Figure 5.12. The user has the flexibility to change the IRI progression model parameters as needed.


Rolling Resistance (RR)

**1 - General Inputs**

*These values were previously entered by the user and are read-only. Please go to Main Inputs to modify the values.*

Pavement Type: SMA-JPCP
Top Layer Thickness (in): 12
Length (miles): 12.8
Analysis Period (years): 58
Start Year: 2001
Number of Lanes: 4

**2 - Rehabilitation Schedule**

*The table includes information entered previously entered by the user. Please go to Maintenance and Rehabilitation to modify the schedule.*

| Age | Rehabilitation |
|---|---|
| 15 | SMA Overlay (3 to 4 in) |
| 28 | SMA Overlay (3 to 4 in) |
| 39 | SMA Overlay (3 to 4 in) |
| 48 | SMA Overlay (3 to 4 in) |

**3 - Traffic Analysis**

Model used: Variable Speed Model

**4 - IRI Model**

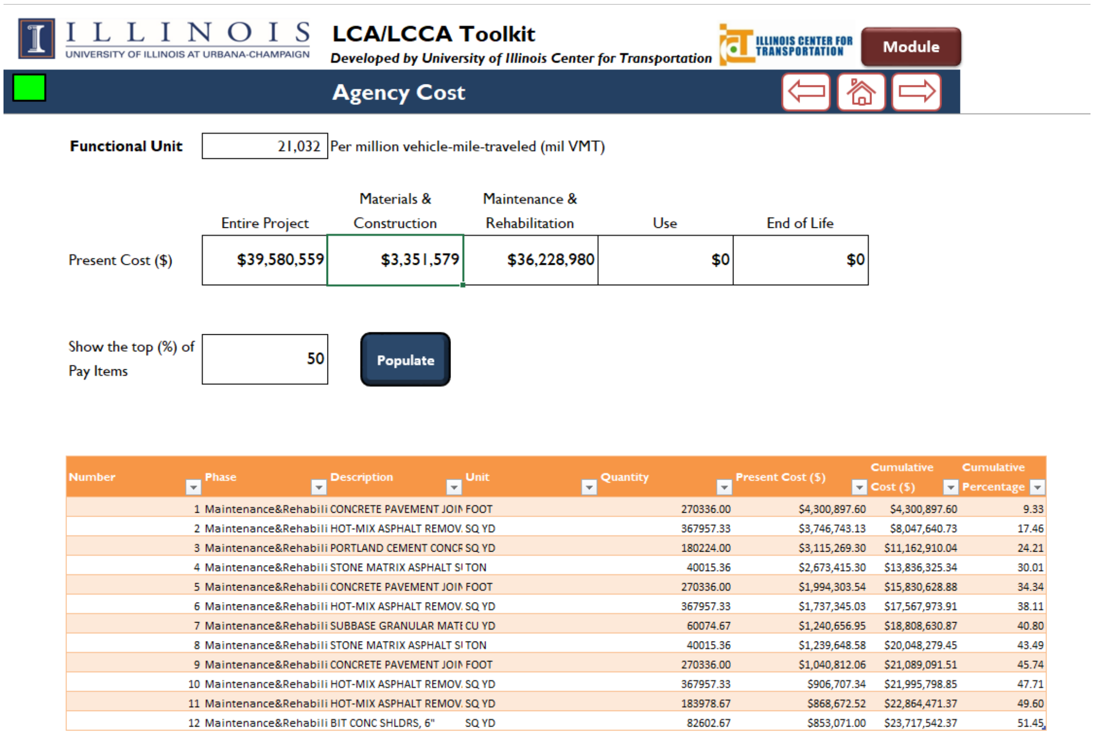
Initial IRI after Re/Construction: 60 in/mile

FIGURE 5.12 IRI Progression User Interface

## 5.6 Outputs of the tool

### 5.6.1 Agency Cost Outputs

Agency costs are computed and displayed to the user in construction year dollars as shown in Figure 5.13. Additionally, the user can see the distribution of costs between the different stages of the project and pay items as shown in Figure 5.14. The user can also plot the pay items in order of increasing cost to identify the contribution of each pay item to the total cost as shown in Figure 5.15.



**Functional Unit** 21,032 Per million vehicle-mile-traveled (mil VMT)

|  | Entire Project | Materials & Construction | Maintenance & Rehabilitation | Use | End of Life |
|---|---|---|---|---|---|
| Present Cost ($) | $39,580,559 | $3,351,579 | $36,228,980 | $0 | $0 |

Show the top (%) of Pay Items: 50

| Number | Phase | Description | Unit | Quantity | Present Cost ($) | Cumulative Cost ($) | Cumulative Percentage |
|---|---|---|---|---|---|---|---|
| 1 | Maintenance&Rehabili | CONCRETE PAVEMENT JOI | FOOT | 270336.00 | $4,300,897.60 | $4,300,897.60 | 9.33 |
| 2 | Maintenance&Rehabili | HOT-MIX ASPHALT REMOV. | SQ YD | 367957.33 | $3,746,743.13 | $8,047,640.73 | 17.46 |
| 3 | Maintenance&Rehabili | PORTLAND CEMENT CONC | SQ YD | 180224.00 | $3,115,269.30 | $11,162,910.04 | 24.21 |
| 4 | Maintenance&Rehabili | STONE MATRIX ASPHALT S | TON | 40015.36 | $2,673,415.30 | $13,836,325.34 | 30.01 |
| 5 | Maintenance&Rehabili | CONCRETE PAVEMENT JOI | FOOT | 270336.00 | $1,994,303.54 | $15,830,628.88 | 34.34 |
| 6 | Maintenance&Rehabili | HOT-MIX ASPHALT REMOV. | SQ YD | 367957.33 | $1,737,345.03 | $17,567,973.91 | 38.11 |
| 7 | Maintenance&Rehabili | SUBBASE GRANULAR MAT | CU YD | 60074.67 | $1,240,656.95 | $18,808,630.87 | 40.80 |
| 8 | Maintenance&Rehabili | STONE MATRIX ASPHALT S | TON | 40015.36 | $1,239,648.58 | $20,048,279.45 | 43.49 |
| 9 | Maintenance&Rehabili | CONCRETE PAVEMENT JOI | FOOT | 270336.00 | $1,040,812.06 | $21,089,091.51 | 45.74 |
| 10 | Maintenance&Rehabili | HOT-MIX ASPHALT REMOV. | SQ YD | 367957.33 | $906,707.34 | $21,995,798.85 | 47.71 |
| 11 | Maintenance&Rehabili | HOT-MIX ASPHALT REMOV. | SQ YD | 183978.67 | $868,672.52 | $22,864,471.37 | 49.60 |
| 12 | Maintenance&Rehabili | BIT CONC SHLDRS, 6" | SQ YD | 82602.67 | $853,071.00 | $23,717,542.37 | 51.45 |

FIGURE 5.13 Agency Cost Results

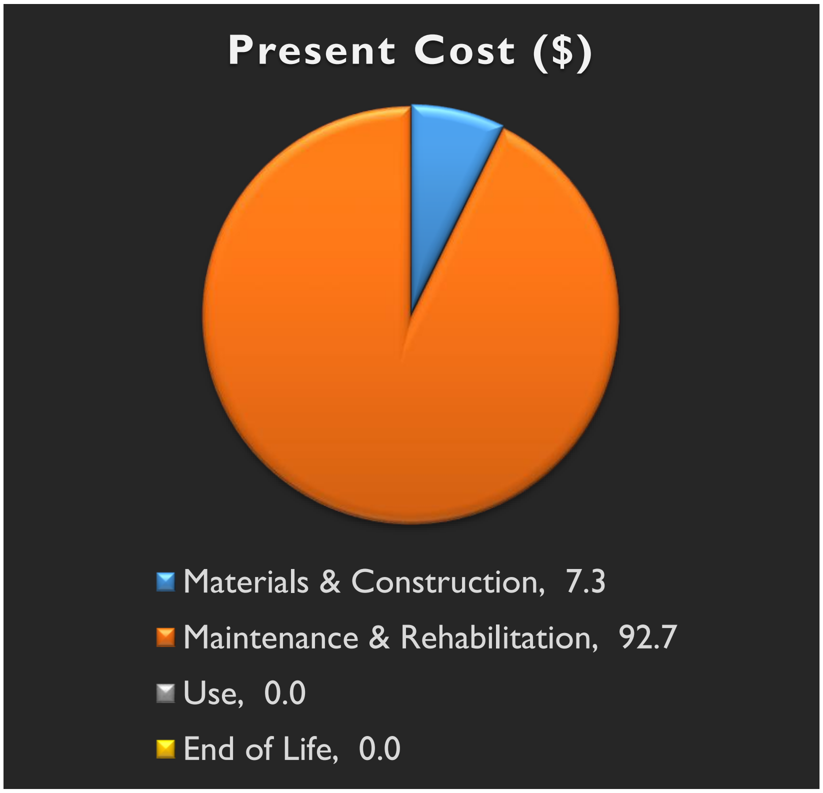


FIGURE 5.14 Example Agency Cost Distribution from the Tool

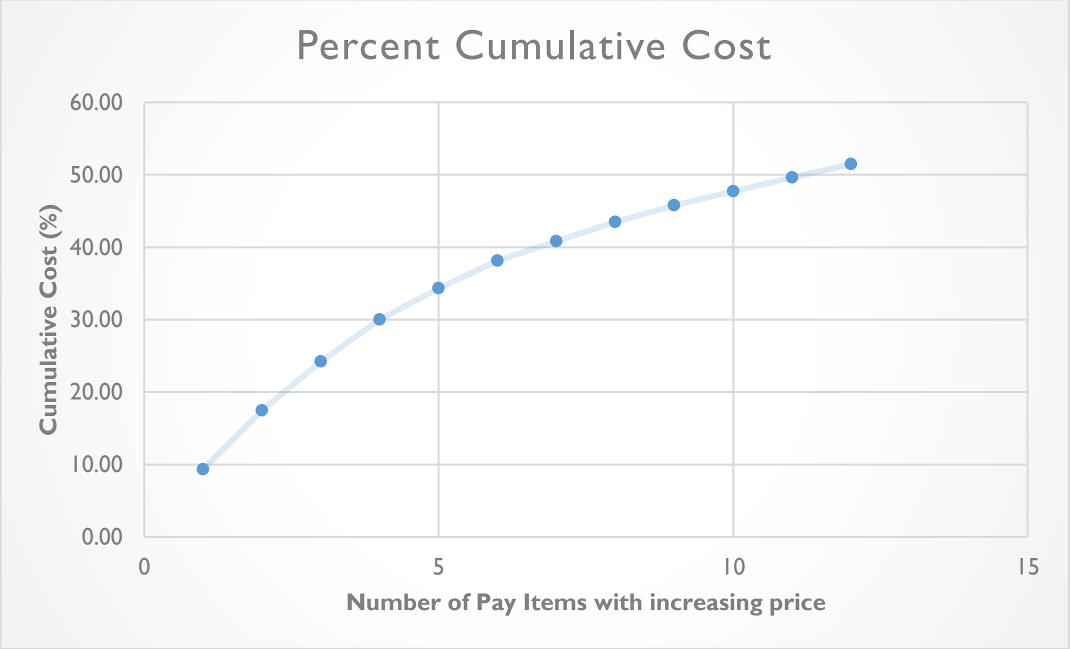
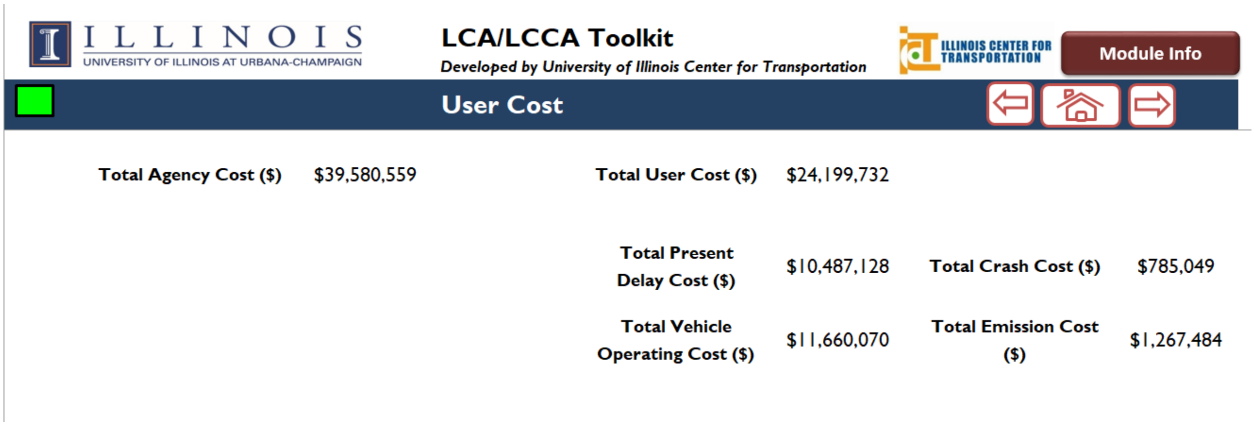


FIGURE 5.15 Example Pay Item vs. Cost Chart from the Tool

### 5.6.2 User Cost Outputs

User costs are presented to the user both numerically and graphically. The user can see the comparison of agency cost to total user cost as given in Figure 5.17, and the components of the user cost as given in Figure 5.18. For vehicle operating costs, all costs, unless otherwise stated, are the differential costs according to a base IRI of 40 in/mi.



**Total Agency Cost ($)** $39,580,559

**Total User Cost ($)** $24,199,732

**Total Present Delay Cost ($)** $10,487,128

**Total Crash Cost ($)** $785,049

**Total Vehicle Operating Cost ($)** $11,660,070

**Total Emission Cost ($)** $1,267,484

FIGURE 5.16 Example User Cost Results

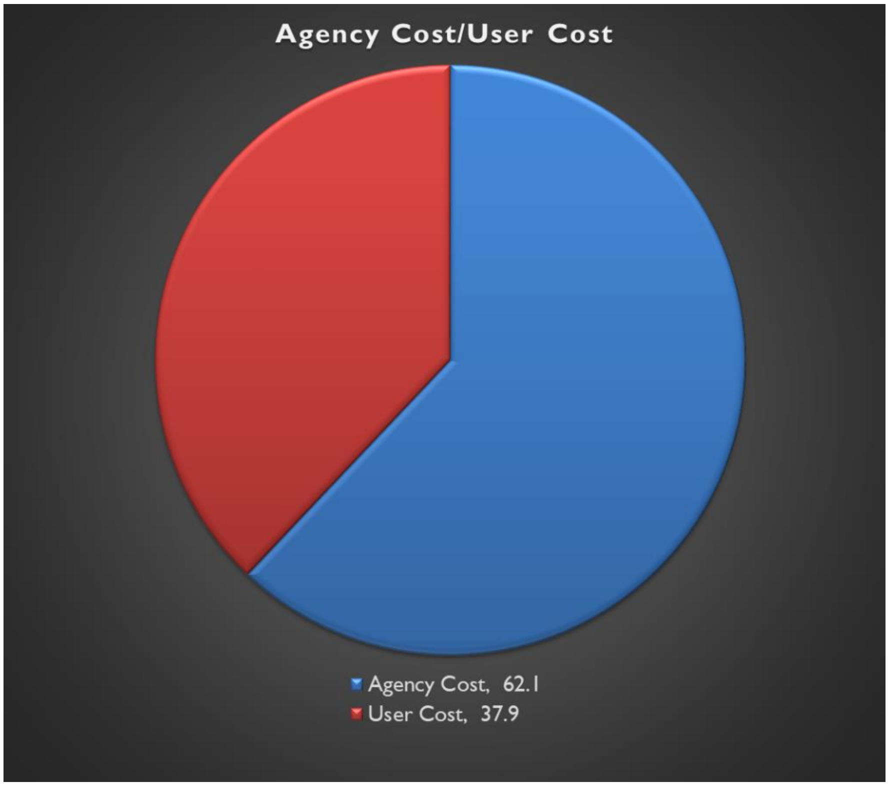


FIGURE 5.17 Example Agency, User Cost Comparison from the Tool

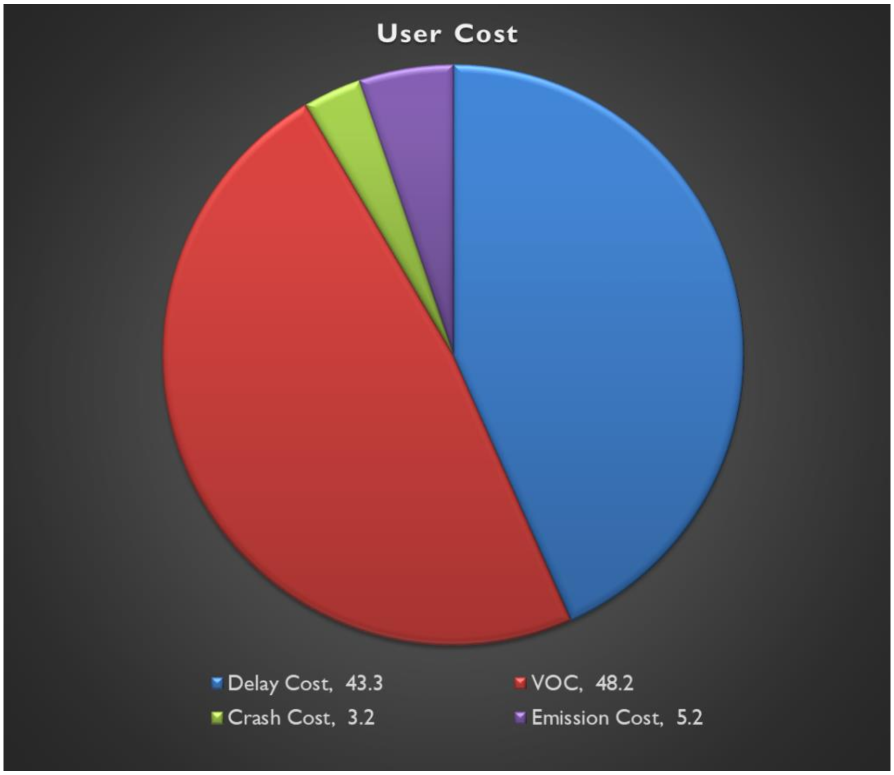


FIGURE 5.18 Example User Cost Components from the Tool

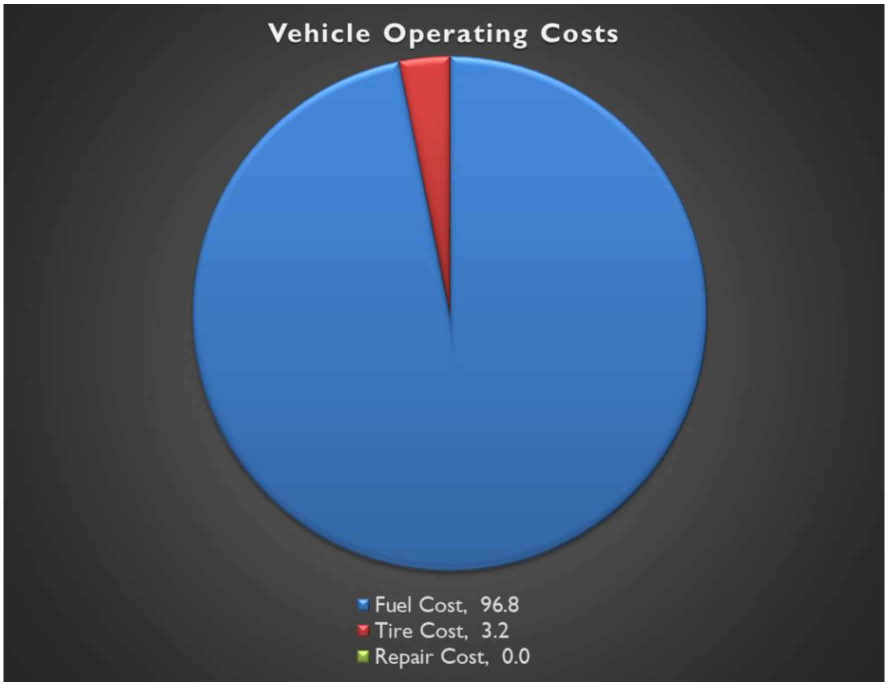


FIGURE 5.19 Example Vehicle Operating Cost Components from the Tool

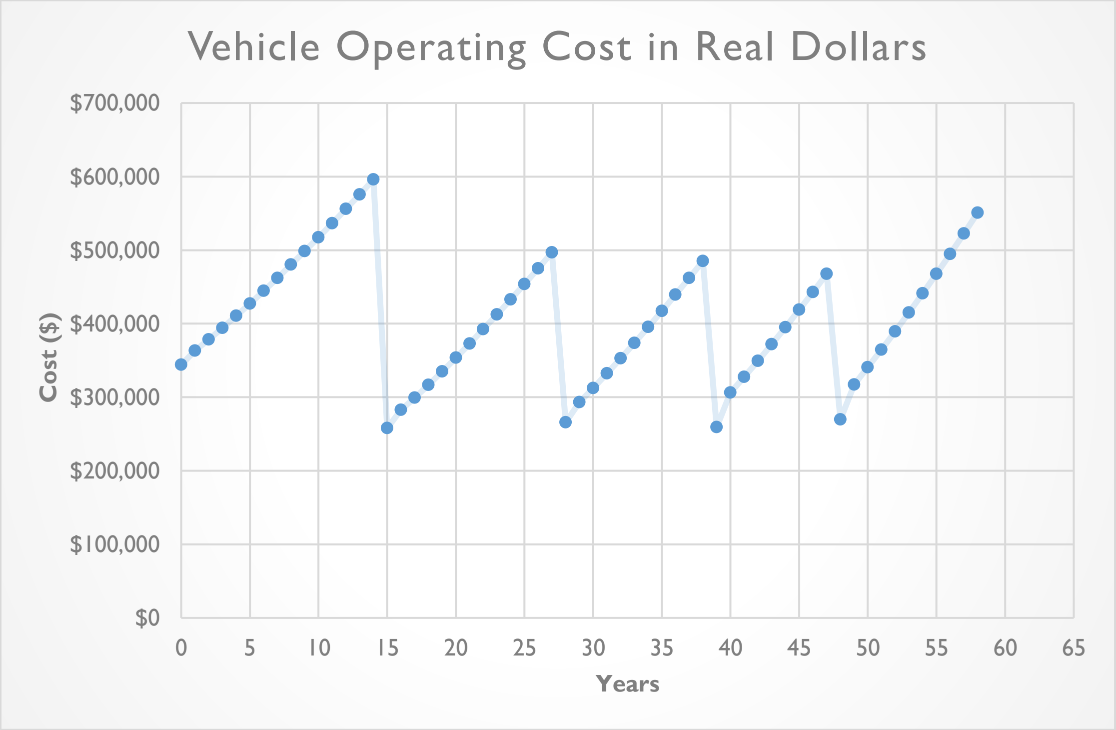
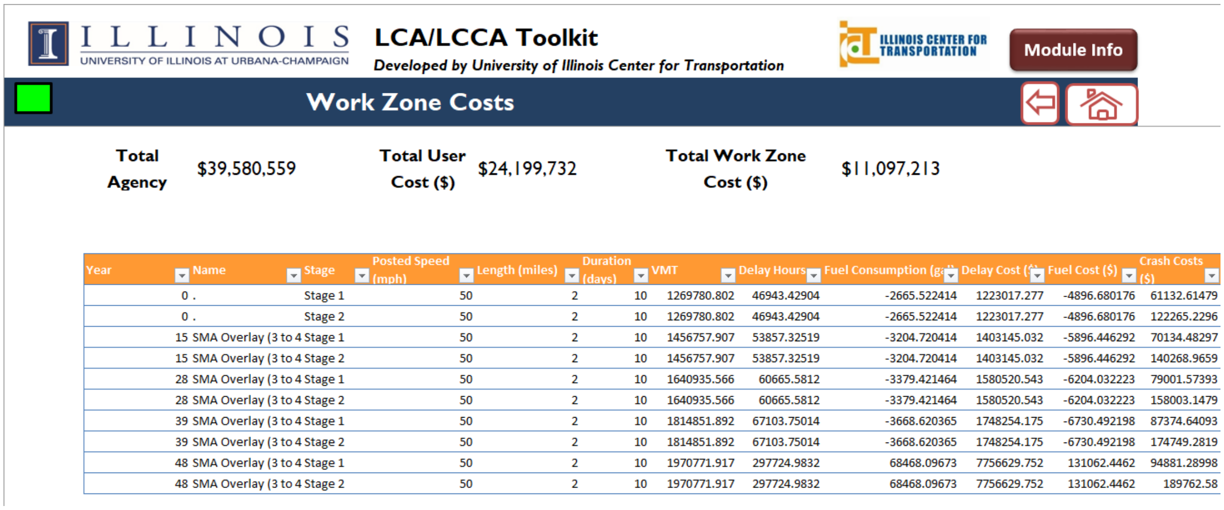


FIGURE 5.20 Example Vehicle Operating Cost over Time from the Tool

Figure 5.19 illustrates the breakdown of vehicle operating costs and FIGURE 5.20 is an example of differential vehicle operating costs for a given project. As expected, vehicle operating costs follow the IRI progression curve. They increase as the pavement deteriorates and they decrease after maintenance activity.

The user can also see the effects of the work zone on the project as shown in Figure 5.21. All work zone costs are computed as additional costs to the normal operating conditions. Therefore, if there is no queue due to work zone and only speed change delay, one would expect fuel consumption to decrease even though there is an increase in delay hours. Once a queue starts building, then fuel consumption increases due to idling.

In addition, tire wear and tear and repair costs are not reported in the work zone module of the tool. The main reason is that tire wear and tear and repair costs are already considered in normal operating conditions and the percent change of these costs because of the presence of work zones is assumed to be negligible due to the limitation of available data.



Total Agency $39,580,559

Total User Cost ($) $24,199,732

Total Work Zone Cost ($) $11,097,213

| Year | Name | Stage | Posted Speed (mph) | Length (miles) | Duration (days) | VMT | Delay Hours | Fuel Consumption (ga | Delay Cost ( | Fuel Cost ($) | Crash Costs ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | . | Stage 1 | 50 | 2 | 10 | 1269780.802 | 46943.42904 | -2665.522414 | 1223017.277 | -4896.680176 | 61132.61479 |
| 0 | . | Stage 2 | 50 | 2 | 10 | 1269780.802 | 46943.42904 | -2665.522414 | 1223017.277 | -4896.680176 | 122265.2296 |
| 15 | SMA Overlay (3 to 4 | Stage 1 | 50 | 2 | 10 | 1456757.907 | 53857.32519 | -3204.720414 | 1403145.032 | -5896.446292 | 70134.48297 |
| 15 | SMA Overlay (3 to 4 | Stage 2 | 50 | 2 | 10 | 1456757.907 | 53857.32519 | -3204.720414 | 1403145.032 | -5896.446292 | 140268.9659 |
| 28 | SMA Overlay (3 to 4 | Stage 1 | 50 | 2 | 10 | 1640935.566 | 60665.5812 | -3379.421464 | 1580520.543 | -6204.032223 | 79001.57393 |
| 28 | SMA Overlay (3 to 4 | Stage 2 | 50 | 2 | 10 | 1640935.566 | 60665.5812 | -3379.421464 | 1580520.543 | -6204.032223 | 158003.1479 |
| 39 | SMA Overlay (3 to 4 | Stage 1 | 50 | 2 | 10 | 1814851.892 | 67103.75014 | -3668.620365 | 1748254.175 | -6730.492198 | 87374.64093 |
| 39 | SMA Overlay (3 to 4 | Stage 2 | 50 | 2 | 10 | 1814851.892 | 67103.75014 | -3668.620365 | 1748254.175 | -6730.492198 | 174749.2819 |
| 48 | SMA Overlay (3 to 4 | Stage 1 | 50 | 2 | 10 | 1970771.917 | 297724.9832 | 68468.09673 | 7756629.752 | 131062.4462 | 94881.28998 |
| 48 | SMA Overlay (3 to 4 | Stage 2 | 50 | 2 | 10 | 1970771.917 | 297724.9832 | 68468.09673 | 7756629.752 | 131062.4462 | 189762.58 |

FIGURE 5.21 Example Work Zone Cost Table

# Chapter 6: Case Study

## 6.1 Base Case Inputs and Assumptions

This case study investigates the user costs of an actual resurfacing project of a southbound section of the Tri-State Tollway in Illinois. The section selected for analysis is a 12.8 mi section between mileposts 17.3 and 30.1. The project start year is 2001 and the analysis period is 58 years. The Average Daily Traffic (ADT) is 70,000 vehicles with 17.1% trucks and a total functional unit of 21,031 million vehicle-mile-travel (VMT) over the analysis period with 0.9% traffic increase each year. Posted speed is 60 mph with a capacity of 2400 vehicles per lane per hour.

There are four lanes in each direction with a width of 12 ft and there is a plan for widening one lane in each direction in year 28. There are five work zone activities, including construction and maintenance. There are four SMA overlays (3 to 4 in) activities scheduled in years 15, 28, 39 and 48. Each work zone activity has three stages. Details of the scheduling are gathered from the contractor documents and presented in the appendix.

Based on the Tollway estimates, 1 mi of construction is planned to be completed in 20 hrs of work for each stage (Ghosh et al., 2018). The Illinois Tollway does not recommend 24-hr closure for the given section. It recommends overnight closure for most cases, but allows 24-hr closures for major rehabilitation (Illinois Tollway, 2015). To provide adequate safety and shorten the work zone, it is historically acknowledged that work zones may stay in place for 24 hrs depending on the project and work type. Therefore, a 24-hr closure was assumed for these rehabilitation activities.

For each stage of the work zone, at least two lanes out of four were open. Posted work zone speed was 45 mph and the Tollway estimated work zone capacity and counter-flow lanes at 1900 vehicles/hr/lane. Queue length was capped at 5 mi.

All unit costs were estimated as explained in Chapter 5. For emission costs, cost per ton of $CO_2$ was assumed to be \$30/ton (Mallela and Sadasivam, 2011). Real discount rate was assumed to be 3%. Base IRI was assumed to be 40 in/mi and all vehicle operation costs referred to the additional (differential) costs resulting from the fact that the IRI was higher than 40 in/mi.

## 6.2 IRI and Texture Progression Models

A previous study conducted for Illinois Tollway was used to generate the IRI progression (Wu, 2015). Historical IRI data was used to generate a progression and a drop model for Illinois as given in Equation 6.1:

$$\mathrm{IRI_t} = \mathrm{IRI_{t-1}} + \mathrm{a} * \mathrm{Thickness^b} * \mathrm{ESALs^c}$$

$$\mathrm{IRI\ drop} = \mathrm{m} * \mathrm{IRI_{before}} + \mathrm{n}$$

$$\mathrm{IRI_{after}} = \mathrm{IRI_{before}} - \mathrm{IRI\ drop} \tag{6.1}$$

Where,

$\mathrm{IRI_t}$ = IRI value for year t, in/mi;

$\mathrm{IRI_{t-1}}$ = IRI value for year t-1, in/mi;

Thickness = Thickness of pavement surface layer, in;

ESALs = ESALs for the design lane, million;

$\mathrm{IRI_{before}}$ = IRI value right before maintenance;

$\mathrm{IRI_{after}}$ = IRI value right after maintenance;

IRI drop = $\mathrm{IRI_{before}} - \mathrm{IRI_{after}}$;

a, b, c = Coefficients for IRI progression model; and

m, n = Coefficients for IRI drop model.

For this specific project, the coefficients were calibrated as a = 10.5592, b = -9.6806, c = 0.1318, m = 0.9340, and n = -46.211.

Texture progression for dense graded pavements is based on Lu et al., 2009 and was calibrated for Illinois as presented in equation 6.2:

$$MPD(mm) = -0.055 * \ln(age + 1) + 1.6604\ for\ Asphalt\ Surface \tag{6.2}$$

## 6.3 Traffic Modelling

A simple two-phase traffic model was used to incorporate the difference in speed during on- and off-peak hours. This data was collected from Illinois Tollway in 2013 to determine the traffic inputs during AM-peak, PM-peak, holiday, and weekend volumes. Once entered, these inputs were fed into the two-phase traffic model for calculation (Al Qadi et al., 2016).

## 6.4 Comparison Cases for Sensitivity Analysis

Using the abovementioned inputs, the user costs were calculated to set a base case. Then, sensitivity analysis was performed to quantify the significance of various factors on user costs such as traffic, activity timing, completion rate, IRI progression rate, and discount rate.

Finally, an alternative with three maintenance activities instead of four was compared to the base case. The years of maintenance activities are 17, 34, and 50. With three activities, it was assumed that the surface overlay thickness for each overlay is thicker than the case of four alternatives. But, the overall surface thickness was assumed to be the same. Since the IRI progression model does not depend on overlay surface thickness, but only on surface type, this is a good case to evaluate the effect of IRI progression on normal operating costs.

Table 6.1 summarizes the cases for the sensitivity analysis. For example, for traffic levels, the base traffic level was provided as 70,000 vehicles per day. This would refer to the case given as 100% in Table 6.1. If the base traffic level increased by 15% that would refer to the case 115% with 80,500 vehicles per day.

TABLE 6.1 Summary of Cases Considered in Sensitivity Analysis (Base Case is Bold)

| **Factors** | **Cases Compared (With respect to Base)** |
|---|---|
| Traffic Levels | 115%, **100%**, 85%, 70% |
| IRI Progression Rate | 150%, 125%, **100%**, 75%, 50% |
| Activity Timing | -2 Years, **On time**, +2 Years |
| Discount Rate | **3%**, 4%, 5% |
| Number of Activities | 3, **4** |

## 6.5 Base Case Results

The base case results are shown in Table 6.2. Agency costs constitute a significant part of the base case, at approximately 72% of total life cycle costs. Due to a 24-hr closure, there was a rather high delay cost resulting from the work zone (27% of total user costs), especially as related to the activities where the queues were formed. The queues were predicted to occur in the last three work zone activities, all extending to a length of five mi. The results also showed the significance of vehicle operation costs during normal operating conditions. The VOC was primarily governed by fuel costs, which correspond to almost 97% of total VOC as shown in Figure 6.1. Tire wear and tear costs and vehicle maintenance costs were minimal at low IRI levels, as discussed earlier.

TABLE 6.2 Overall Cost of Base Case

| Present Cost | | | | | |
|---|---|---|---|---|---|
| **Agency Cost ($)** | | **Percentage** | **User Cost ($)** | | **Percentage** |
| **Total Cost** | $ 46,101,819 | - | **Total Cost** | $17,817,598 | - |
| **Construction and Materials** | $ 3,351,579 | 7.3% | **Delay** | $4,822,952 | 27.1% |
| **Maintenance and Rehabilitation** | $ 42,750,241 | 92.7% | **Vehicle Operation** | $11,678,711 | 65.5% |
| **Use** | $ - | 0.0% | **Crash** | $52,686 | 0.3% |
| **End Of Life** | $ - | 0.0% | **Emission** | $1,263,248 | 7.1% |

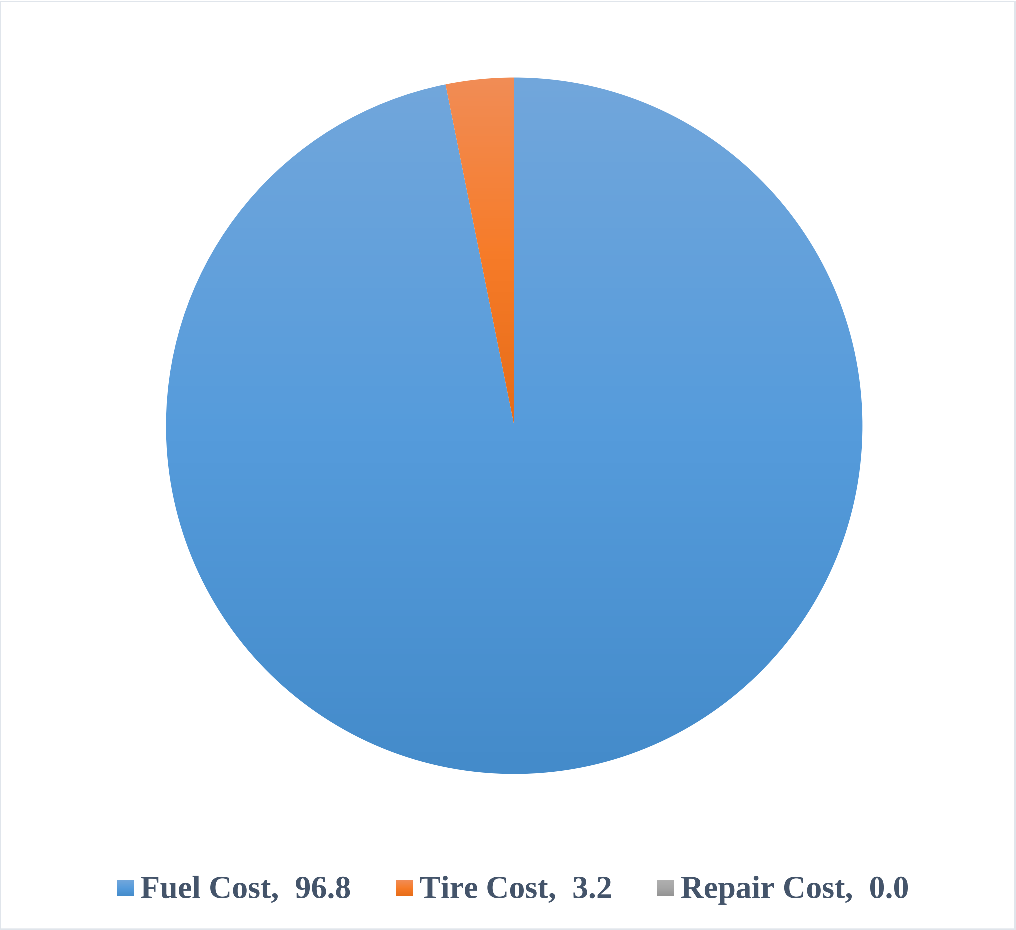


**FIGURE 6.1 Vehicle operating cost breakdown for the base case.**

Since IRI is the main component of vehicle operating costs, the IRI progression had a similar trend as the vehicle operating costs in Figure 6.2. Queue formation for years 38 and 48 during work zone activities resulted in idling, which caused additional fuel consumption. However, the fuel consumption cost due to work zone activities was only 0.5% of vehicle operating cost and was therefore considered negligible when compared with the overall differential vehicle operation costs.

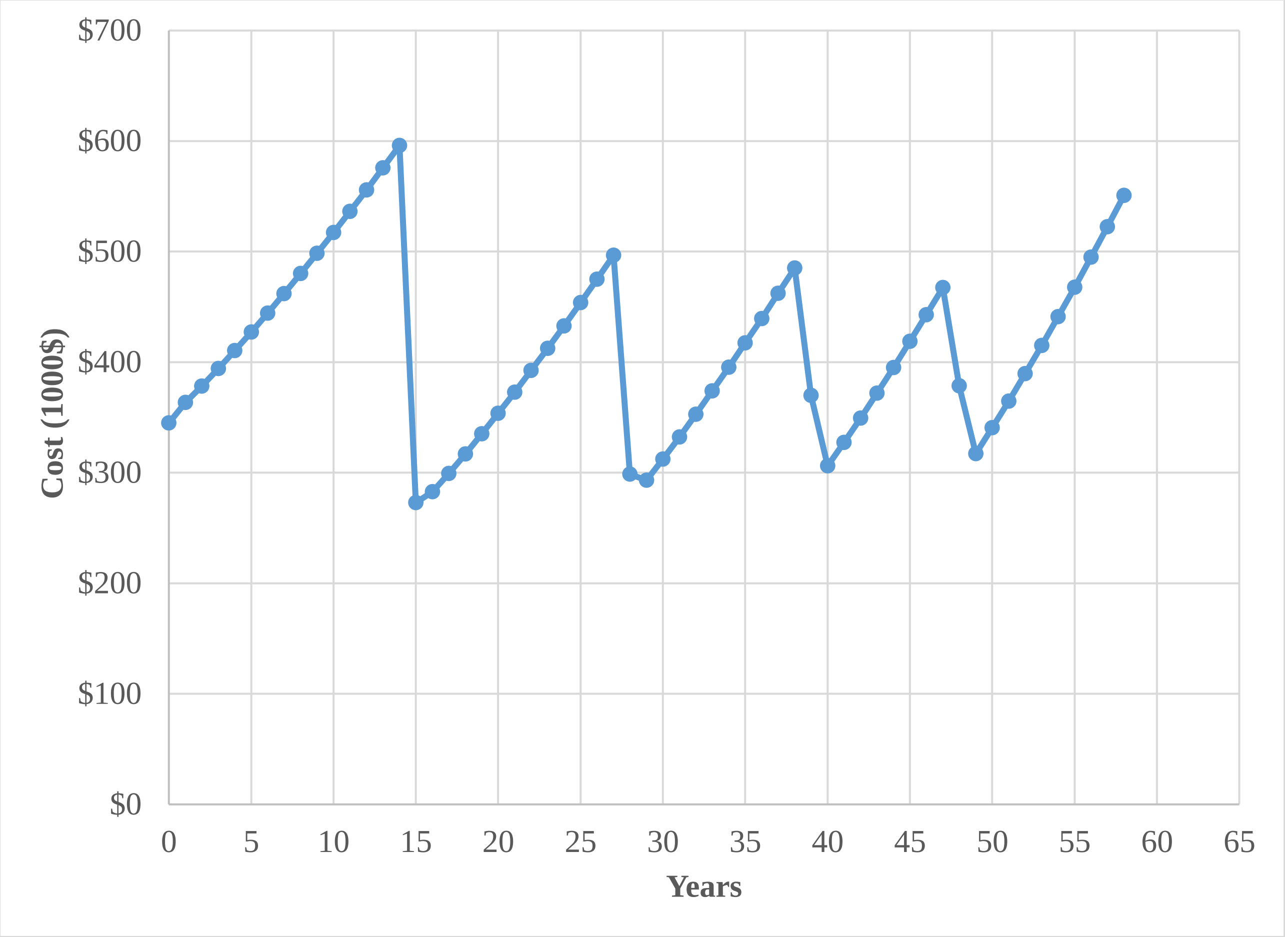


**FIGURE 6.2 Vehicle operating cost over the analysis period in real dollars.**

## 6.6 Sensitivity to Traffic

To investigate the sensitivity of delay and vehicle operating cost to daily traffic, the same analysis was performed using different average daily traffic values above or below the 70,000-vehicle base case. Sensitivity analysis with AADT and the percent of the base cost results in the following graph.

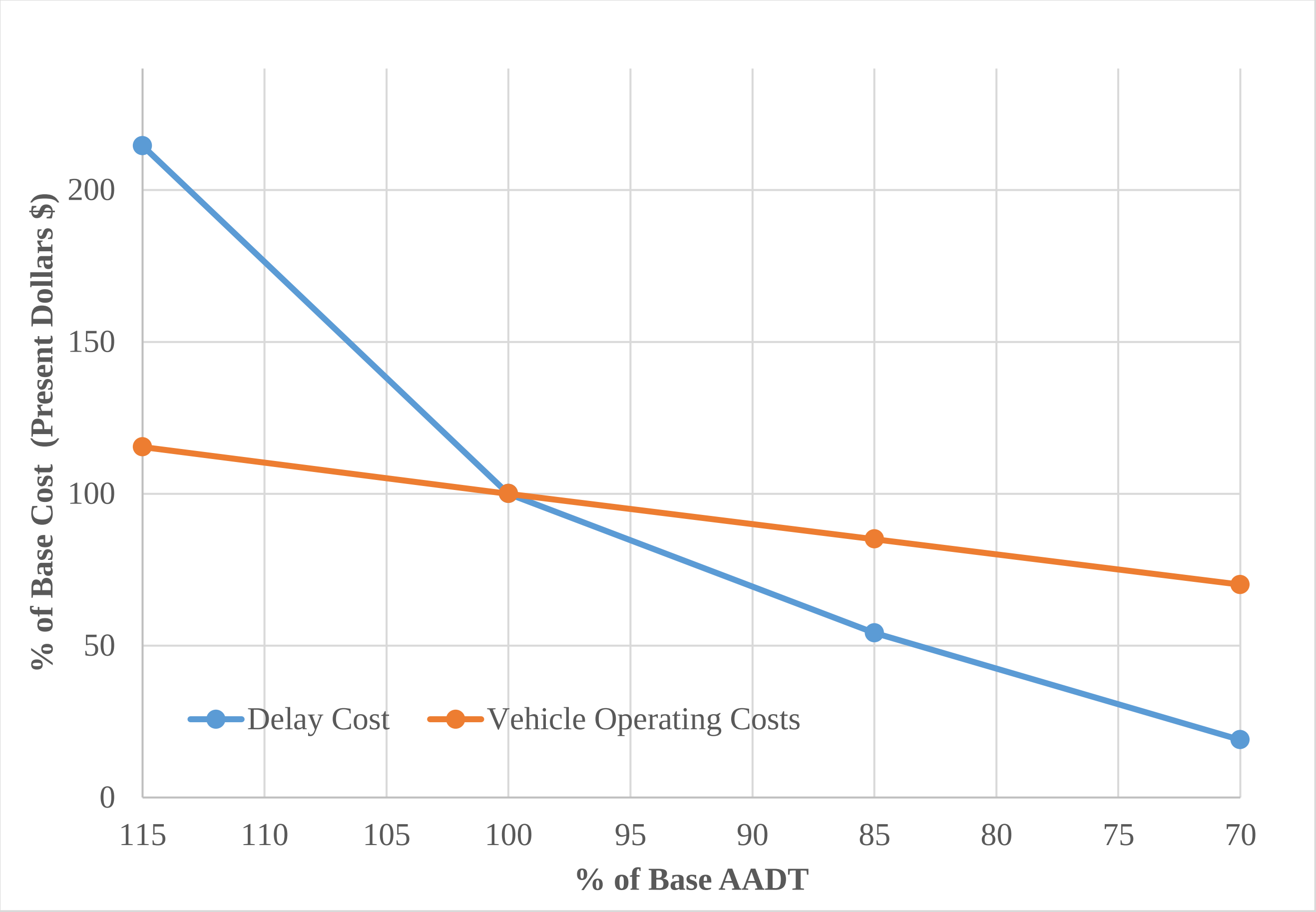


**FIGURE 6.3 Sensitivity of user costs to number of vehicles per day.**

As figure 6.3 illustrates, delay costs were very sensitive to changes in traffic. This was due to queue formation. Even though 24-hr closures are sometimes necessary for safety and quick completion of the project, they usually result in queues. Once a queue forms, the delay costs are no longer linear to the traffic level. Instead, the variation is proportional to traffic, because vehicle operation costs are directly proportional to traffic levels. This makes the vehicle operating costs even more important for low traffic sections because delay costs would be significantly less with no queue formation.

## 6.7 Sensitivity to IRI Progression Rate

The IRI progression given for this specific section assumes a fixed IRI progression rate in in/mi/year. This rate of progression greatly affects the results of LCCA. For the sensitivity analysis, the IRI progression rate was assumed to be 50%, 75%, 125% and 150% of the base case. The analysis yielded the results shown in Figure 6.4.

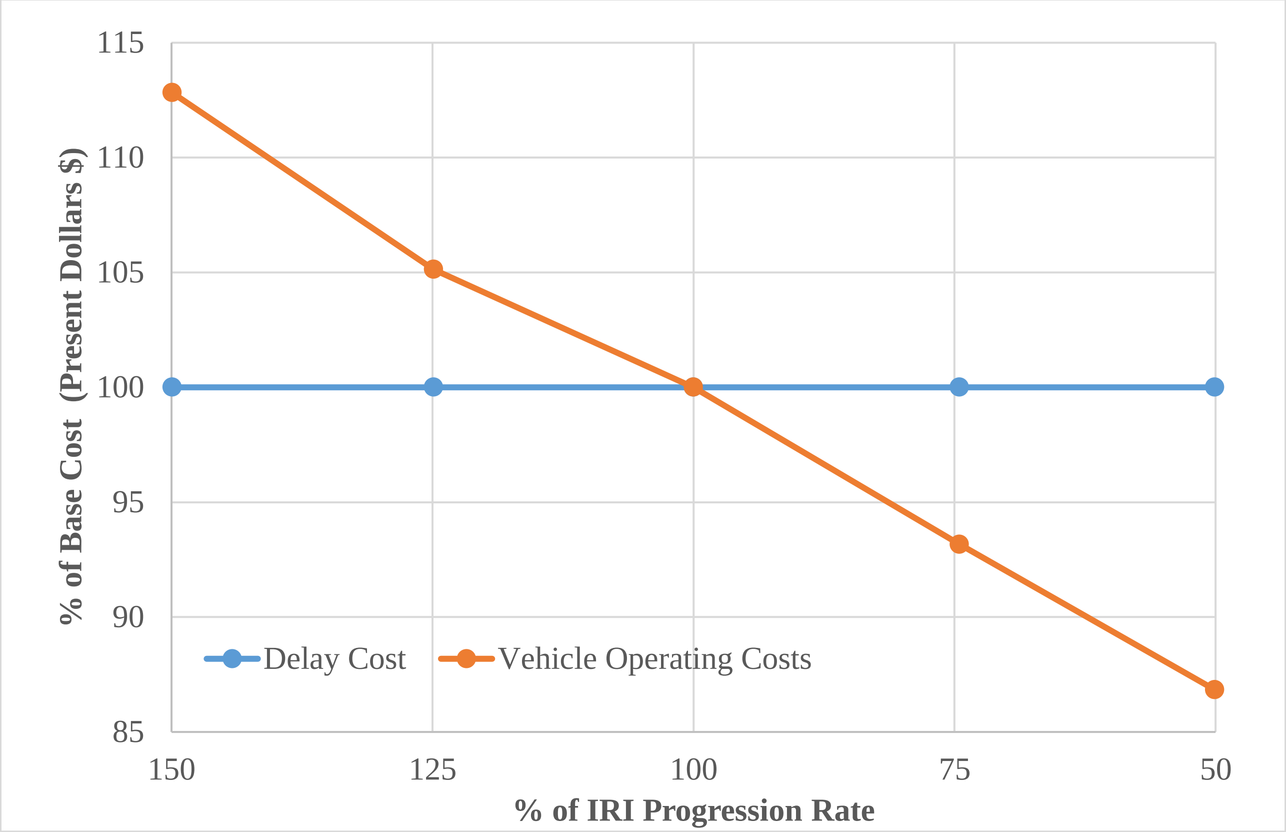


**FIGURE 6.4 Sensitivity of user costs to IRI progression rate.**

As expected, the IRI progression rate is directly proportional to vehicle operating costs since the models are also directly proportional to IRI at a given year. This figure shows the importance of having an accurate IRI progression model for accurate estimations of vehicle operating costs, whereas delay costs are not sensitive to IRI progression.

## 6.8 Sensitivity to Treatment Activity Timing

As described in the base case, the maintenance activities are scheduled at Year 15, 28, 39, and 48. However, due to budget constraints or pavement condition, those schedules may shift forward or backward. Figure 6.5 shows the effects of activity timing on user costs by shifting the activity years forward and backward by two years while keeping all other parameters constant.

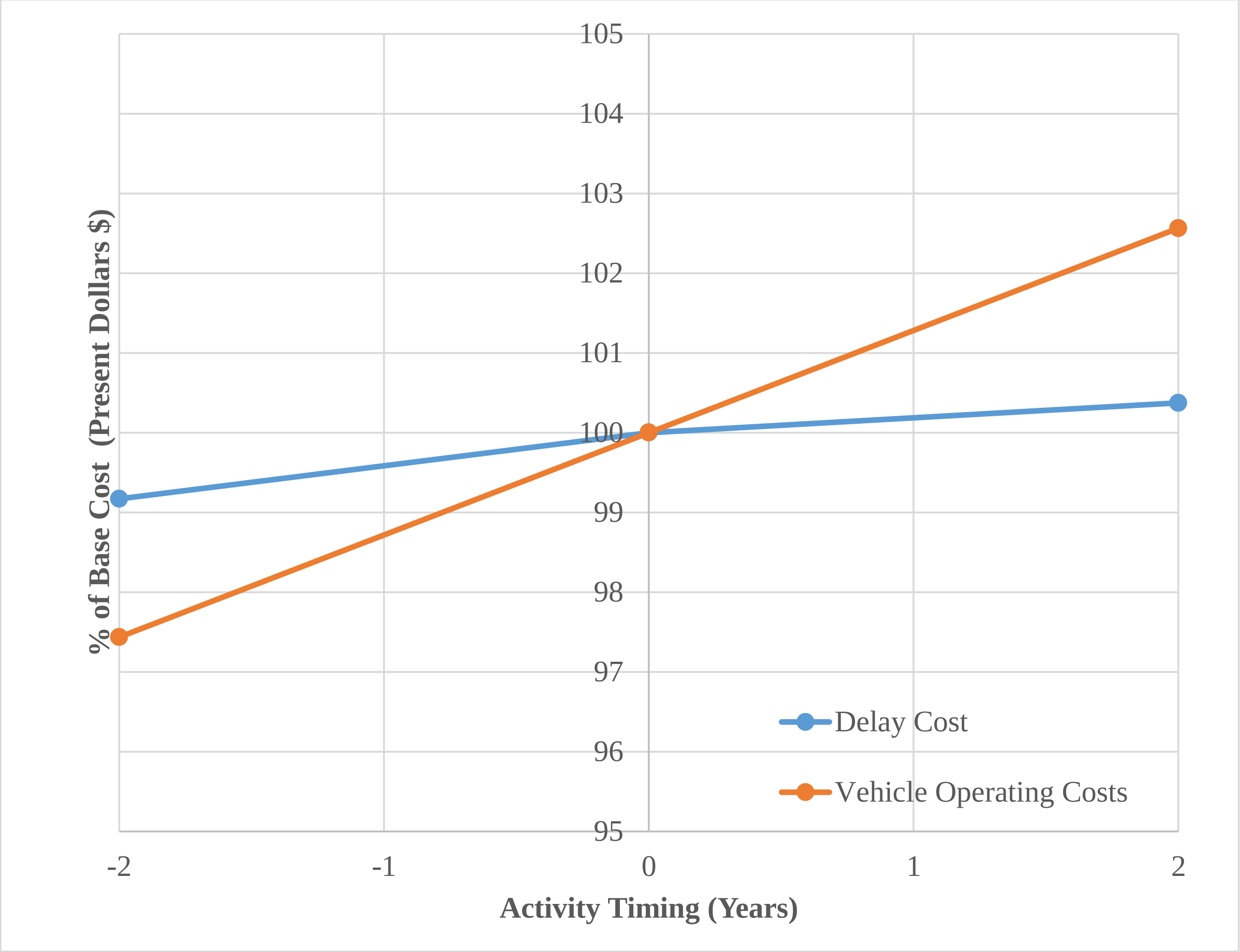


**FIGURE 6.5 Sensitivity of user costs to activity timing.**

For this example, it is clear that vehicle operating costs were sensitive to timing. From Figure 6.5, it appears that vehicle operating costs influence timing of the rehabilitation activities more than the delay cost in this project.

## 6.9 Sensitivity to Discount Rate

Especially for lengthy projects, the discount rate plays an important role when determining present cost. For the base case, the discount rate was assumed 3%. Analysis was conducted using a discount rate of 4% and 5%, as shown in Figure 6.6. In this case, delay costs were more sensitive to the discount rate because of the spread over the life of the project; vehicle operating costs were considered annual. Figure 6.6 also shows that higher discount rates affect delay costs more than vehicle operating costs.

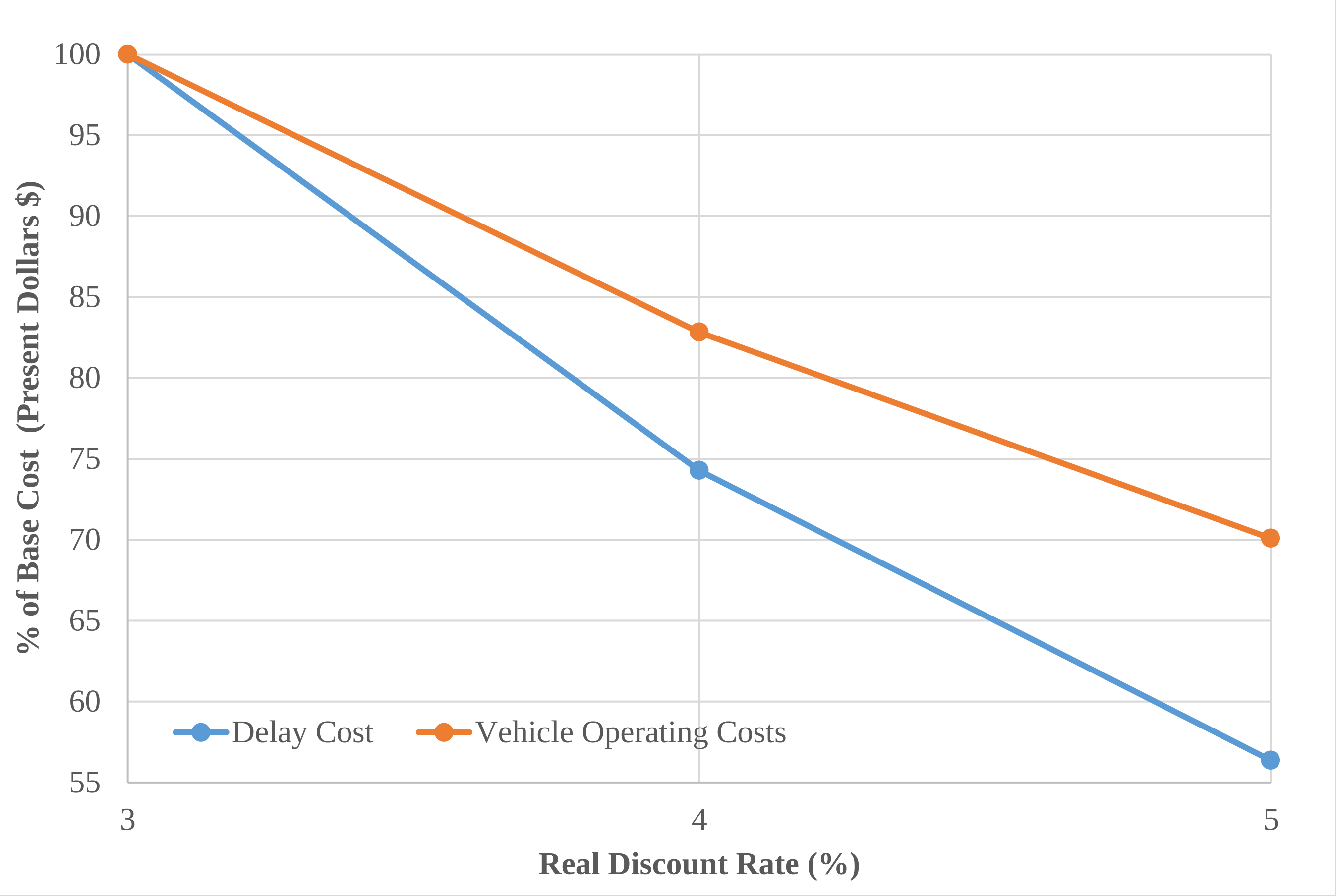


FIGURE 6.6 Sensitivity of user costs to discount rate.

## 6.10 Sensitivity to Number of Treatment Activities

For many LCCA projects, various alternatives have a different number of maintenance activities. From an agency costs and delay costs perspective, the alternative with fewer treatment activities is usually more desirable. Unfortunately, in return, vehicle operating costs might be impacted because of worse pavement conditions. In this scenario, three activities were compared to the base four treatment activities. Because the IRI progression model is assumed the same for various resurfacing thicknesses. The only difference in IRI progression results would be due to maintenance timing and numbers.

In the base case, the scheduled maintenance activities were scheduled in Years 15, 28, 39, and 48. The scheduled treatment activity was SMA overlay (3 to 4 in). For the case of three maintenance activities, the assumed years were 17, 34, and 50 and the scheduled treatment activity was SMA overlay (3 to 4 in). Because the overlay thickness does not affect IRI progression, if same number of lifts, the work zone schedule and conditions were assumed to be the same. The only difference between the alternatives was the number of maintenance activities and their timing. The LCCA results are given in Table 6.3.

TABLE 6.3 Present Cost of Three Activities

| Present Cost of Three Treatments Activities | | | | | |
|---|---|---|---|---|---|
| **Agency Cost ($)** | | **Percentage** | **User Cost ($)** | | **Percentage** |
| **Total Cost** | $ 40,348,152 | - | **Total Cost** | $18,119,007 | - |
| **Construction and Materials** | $ 3,351,579 | 8.3% | **Delay** | $4,055,374 | 22.4% |
| **Maintenance and Rehabilitation** | $ 36,996,573 | 91.7% | **Vehicle Operation** | $12,659,337 | 69.9% |
| **Use** | $ - | 0.0% | **Crash** | $40,707 | 0.2% |
| **End Of Life** | $ - | 0.0% | **Emission** | $1,363,590 | 7.5% |

The overall cost of three activities was lower than four activities. Most LCCA approaches suggest user costs are lower because of less disturbance to traffic. This is true only when vehicle operation costs are not considered. As this case illustrates, even though three activities resulted in a 16% decrease in delay costs, the vehicle operation costs increased by 8%. It resulted in almost the same user cost between the two alternatives. A breakdown of user costs at each traffic level is provided in Figure 6.7.

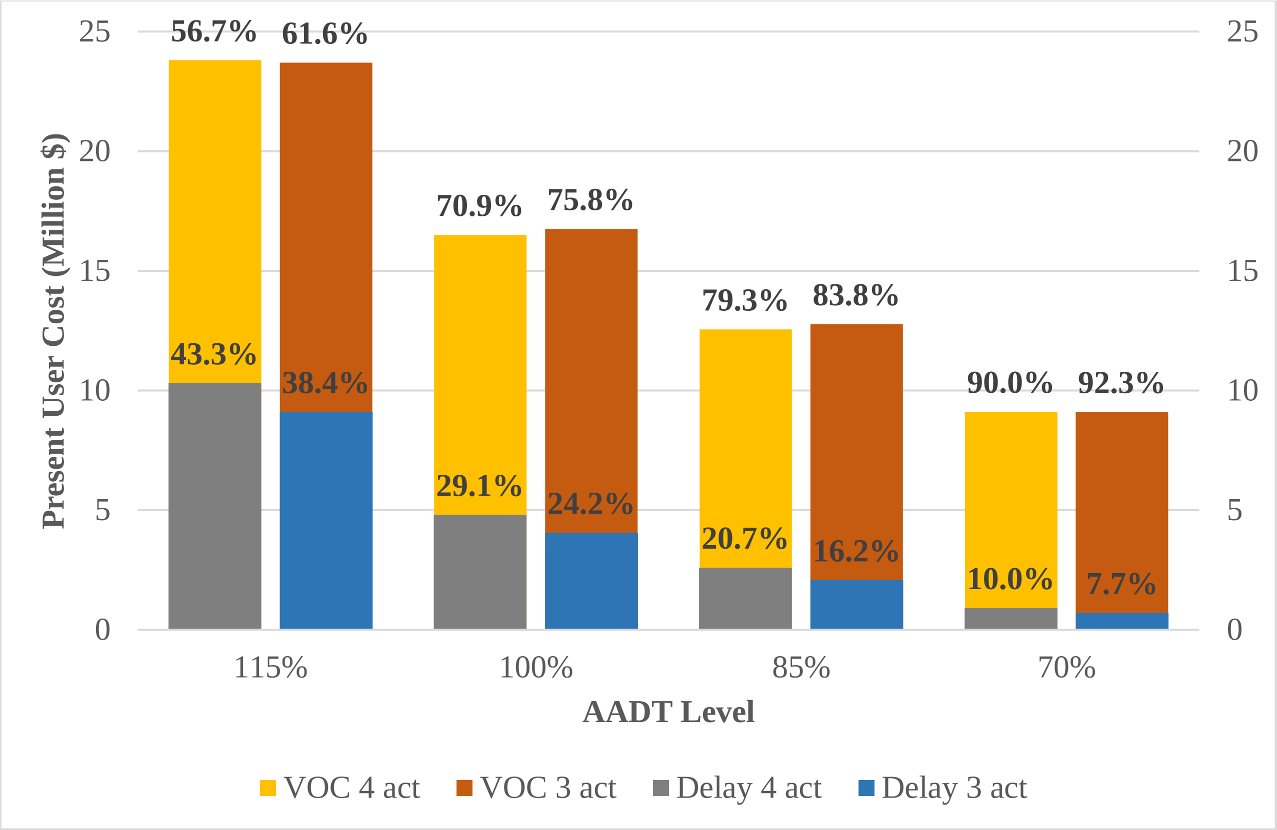


FIGURE 6.7 Sensitivity of Different Alternatives to Traffic Level

For three and four treatment activities, the delay costs were more sensitive to the traffic level than vehicle operating costs. Delay costs were reduced with decreasing traffic as would be expected. Because of the change in IRI progression, user costs remained unchanged or increased slightly; the importance of vehicle operating costs increased with decreasing traffic.

Finally, similar to the base case, a sensitivity analysis was conducted that varied the IRI progression rate for the alternative with three treatment activities. The results are presented in Figure 6.8.

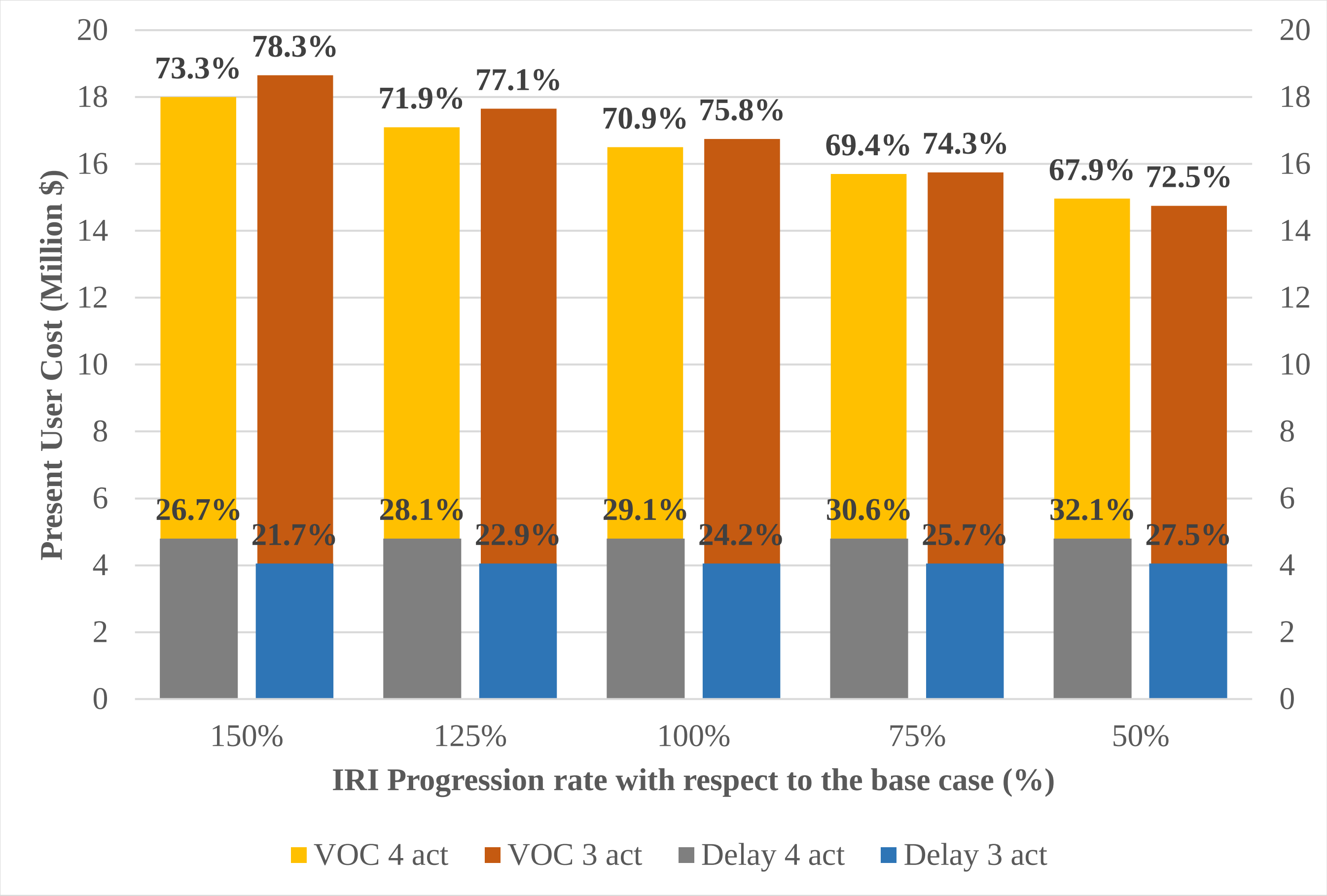


**FIGURE 6.8 Sensitivity of different alternatives to IRI progression rate.**

With rapid IRI progression, the importance of vehicle operation costs was even more prominent with a fewer number of alternatives. With three treatment activities and rapid IRI progression, it is even possible to see an increase in user costs. Also, the relative importance of vehicle operating costs, regardless of the number of treatment alternatives, increased with rapid progression as would be expected.

# Chapter 7: Summary, Conclusions, and Recommendations

This thesis focuses on the calculation of user costs in LCCA. During traditional pavement LCCA, it is a common practice to focus on work zone costs when comparing various cases while neglecting normal operating costs. For complete and more accurate life cycle cost calculations, costs associated with normal operating conditions of pavement should be included. Pavement surface conditions represented by IRI and texture can be used to calculate additional fuel costs in addition to the traditionally user vehicle operating costs, such as vehicle repair and tire wear and tear costs. A methodology for a complete user cost calculation is presented and a tool was developed to apply the methodology in real applications. A resurfacing Illinois Tollway project was used as a case study to illustrate the effects of vehicle operating costs.

The study suggests that vehicle operating costs, which require the use of a reliable IRI progression model, are important and should be included in LCCA; however, it should be included as a change between treatment alternatives rather than absolute values. With high traffic volumes, as soon as a queue starts forming in a work zone, delay costs are usually more prominent and are the deciding factor between treatment alternatives. However, for lower traffic volumes or in cases where queues are not forming, vehicle operating costs might be the deciding factor between treatment alternatives. Normal operating cost difference between treatment alternatives may be as significant as the delay costs.

Based on this study, the following conclusions are drawn:

1. A tool that conducts both LCA and LCCA was developed, including the effects of user costs under normal operation conditions.
2. Reducing number of treatment activities might increase user costs depending on traffic level.
3. When IRI progression rate increases, the significance of normal operation user costs will increase. The IRI progression rate is linearly related to fuel consumption.
4. Delay costs are more sensitive to discount rate than vehicle operating costs. This means that with increasing discount rates, the importance of vehicle operating costs will further increase.

Future work on LCCA should focus on incorporating probabilistic parameters. While deterministic analysis is fairly accurate, probabilistic analysis accounts for the variation usually presented in a separate sensitivity analysis. Once the probabilistic analysis is incorporated, the next step would be to develop a decision-making method to determine the optimum construction schedule based on LCCA. In addition, current normal operating costs are dependent on current vehicle technology. With new technologies, the emissions of vehicles may change drastically. Since fuel cost is the major cost component in normal operating costs, the sensitivity of vehicle efficiency should be investigated; including the use of electrical vehicle. Finally, connected and autonomous vehicle will change the current delay and emission calculation models since these vehicles will not behave as described in current traffic models. Therefore, the effect of autonomous and connected vehicle penetration in the networks need to be quantified.

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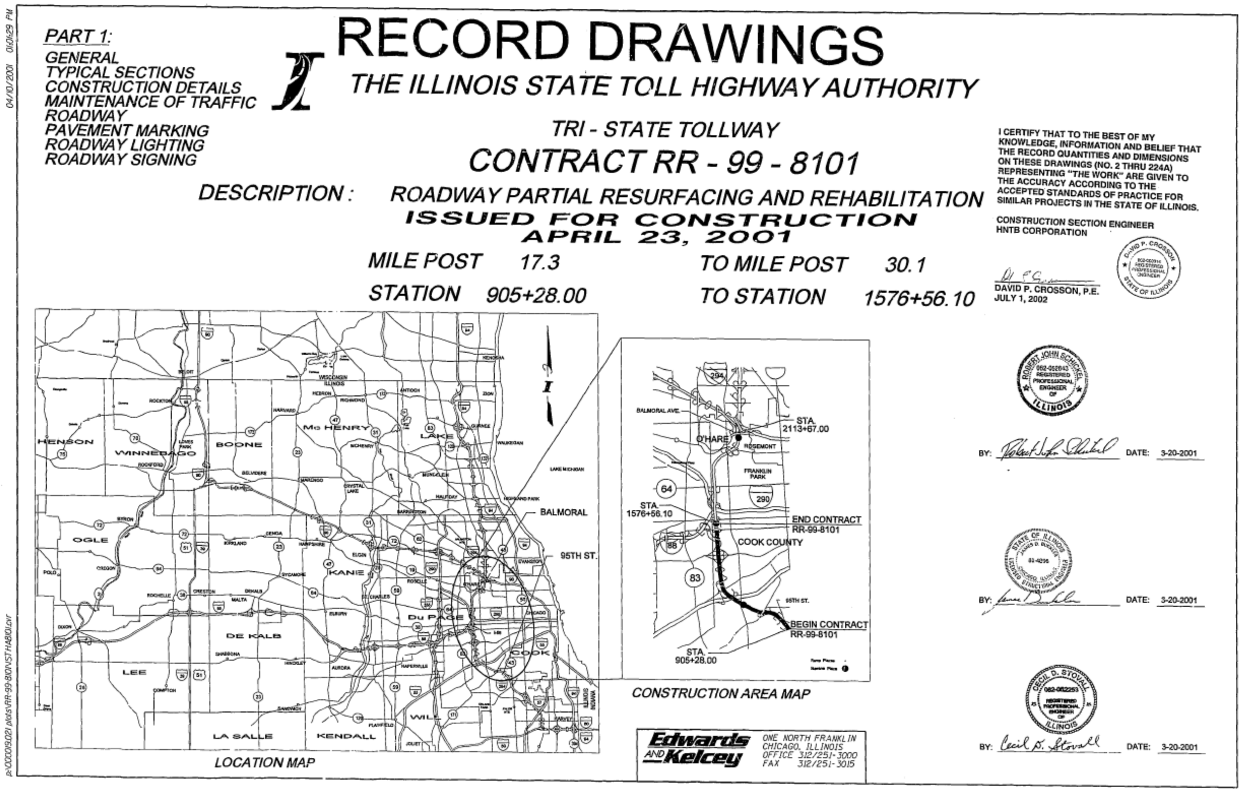
# Appendix A: Contract Documents



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PART 1:
GENERAL
TYPICAL SECTIONS
CONSTRUCTION DETAILS
MAINTENANCE OF TRAFFIC
ROADWAY
PAVEMENT MARKING
ROADWAY LIGHTING
ROADWAY SIGNING

RECORD DRAWINGS
THE ILLINOIS STATE TOLL HIGHWAY AUTHORITY
TRI - STATE TOLLWAY
CONTRACT RR - 99 - 8101

DESCRIPTION : ROADWAY PARTIAL RESURFACING AND REHABILITATION
ISSUED FOR CONSTRUCTION
APRIL 23, 2001

MILE POST 17.3 TO MILE POST 30.1
STATION 905+28.00 TO STATION 1576+56.10

I CERTIFY THAT TO THE BEST OF MY KNOWLEDGE, INFORMATION AND BELIEF THAT THE RECORD QUANTITIES AND DIMENSIONS ON THESE DRAWINGS (NO. 2 THRU 224A) REPRESENTING "THE WORK" ARE GIVEN TO THE ACCURACY ACCORDING TO THE ACCEPTED STANDARDS OF PRACTICE FOR SIMILAR PROJECTS IN THE STATE OF ILLINOIS.

CONSTRUCTION SECTION ENGINEER
HNTB CORPORATION

DAVID P. CROSSON, P.E.
JULY 1, 2002

DAVID P. CROSSON

ROBERT JOHN SCHICKEL
062-052643

BY: Robert John Schickel DATE: 3-20-2001

JAMES D. BUCKLER
81-4296

BY: DATE: 3-20-2001

CECIL D. STOVALL
062-052253

BY: Cecil D. Stovall DATE: 3-20-2001

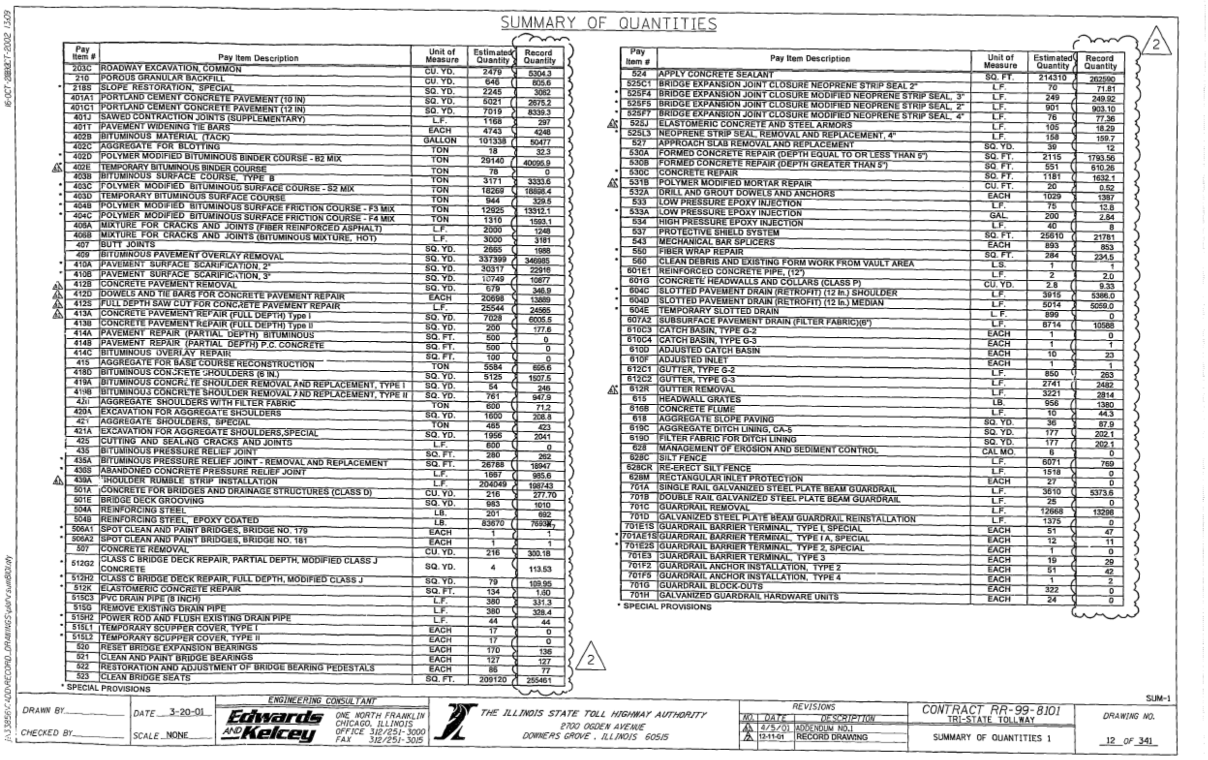
LOCATION MAP

CONSTRUCTION AREA MAP

Edwards and Kelcey
ONE NORTH FRANKLIN
CHICAGO, ILLINOIS
OFFICE 312/251-3000
FAX 312/251-3015

p:\000009\021 plots\RR-99-8101\CONSTHAB\01.dgn

FIGURE A.1 Contract Map



SUMMARY OF QUANTITIES

|  | Pay Item # | Pay Item Description | Unit of Measure | Estimated Quantity | Record Quantity |
|---|---|---|---|---|---|
|  | 203C | ROADWAY EXCAVATION, COMMON | CU. YD. | 2479 | 5304.3 |
|  | 210 | POROUS GRANULAR BACKFILL | CU. YD. | 646 | 805.6 |
| * | 218S | SLOPE RESTORATION, SPECIAL | SQ. YD. | 2245 | 3082 |
|  | 401A1 | PORTLAND CEMENT CONCRETE PAVEMENT (10 IN) | SQ. YD. | 5021 | 2675.2 |
|  | 401C1 | PORTLAND CEMENT CONCRETE PAVEMENT (12 IN) | SQ. YD. | 7019 | 8339.3 |
|  | 401J | SAWED CONTRACTION JOINTS (SUPPLEMENTARY) | L.F. | 1168 | 297 |
|  | 401T | PAVEMENT WIDENING TIE BARS | EACH | 4743 | 4248 |
|  | 402B | BITUMINOUS MATERIAL (TACK) | GALLON | 101338 | 50477 |
|  | 402C | AGGREGATE FOR BLOTTING | TON | 18 | 32.3 |
| * | 402D | POLYMER MODIFIED BITUMINOUS BINDER COURSE - B2 MIX | TON | 29140 | 40095.9 |
| △* | 402E | TEMPORARY BITUMINOUS BINDER COURSE | TON | 78 | 0 |
|  | 403B | BITUMINOUS SURFACE COURSE, TYPE B | TON | 3171 | 3333.6 |
| * | 403C | POLYMER MODIFIED BITUMINOUS SURFACE COURSE - S2 MIX | TON | 18269 | 18898.4 |
| * | 403D | TEMPORARY BITUMINOUS SURFACE COURSE | TON | 944 | 329.5 |
| * | 404B | POLYMER MODIFIED BITUMINOUS SURFACE FRICTION COURSE - F3 MIX | TON | 12925 | 13312.1 |
| * | 404C | POLYMER MODIFIED BITUMINOUS SURFACE FRICTION COURSE - F4 MIX | TON | 1310 | 1593.1 |
|  | 406A | MIXTURE FOR CRACKS AND JOINTS (FIBER REINFORCED ASPHALT) | L.F. | 2000 | 1248 |
|  | 406B | MIXTURE FOR CRACKS AND JOINTS (BITUMINOUS MIXTURE, HOT) | L.F. | 3000 | 3181 |
|  | 407 | BUTT JOINTS | SQ. YD. | 2665 | 1988 |
|  | 409 | BITUMINOUS PAVEMENT OVERLAY REMOVAL | SQ. YD. | 337399 | 346985 |
| * | 410A | PAVEMENT SURFACE SCARIFICATION, 2" | SQ. YD. | 30317 | 22916 |
| * | 410B | PAVEMENT SURFACE SCARIFICATION, 3" | SQ. YD. | 10749 | 10877 |
| △ | 412B | CONCRETE PAVEMENT REMOVAL | SQ. YD. | 679 | 346.9 |
| △ | 412D | DOWELS AND TIE BARS FOR CONCRETE PAVEMENT REPAIR | EACH | 20698 | 13889 |
| △ | 412S | FULL DEPTH SAW CUT FOR CONCRETE PAVEMENT REPAIR | L.F. | 25544 | 24565 |
| △ | 413A | CONCRETE PAVEMENT REPAIR (FULL DEPTH) Type I | SQ. YD. | 7028 | 6005.5 |
|  | 413B | CONCRETE PAVEMENT REPAIR (FULL DEPTH) Type II | SQ. YD. | 200 | 177.6 |
|  | 414A | PAVEMENT REPAIR (PARTIAL DEPTH) BITUMINOUS | SQ. FT. | 500 | 0 |
|  | 414B | PAVEMENT REPAIR (PARTIAL DEPTH) P.C. CONCRETE | SQ. FT. | 500 | 0 |
|  | 414C | BITUMINOUS OVERLAY REPAIR | SQ. FT. | 100 | 0 |
|  | 415 | AGGREGATE FOR BASE COURSE RECONSTRUCTION | TON | 5584 | 695.6 |
|  | 418D | BITUMINOUS CONCRETE SHOULDERS (6 IN.) | SQ. YD. | 5125 | 1507.5 |
|  | 419A | BITUMINOUS CONCRETE SHOULDER REMOVAL AND REPLACEMENT, TYPE I | SQ. YD. | 54 | 246 |
|  | 419B | BITUMINOUS CONCRETE SHOULDER REMOVAL AND REPLACEMENT, TYPE II | SQ. YD. | 761 | 947.9 |
|  | 420 | AGGREGATE SHOULDERS WITH FILTER FABRIC | TON | 600 | 71.2 |
|  | 420A | EXCAVATION FOR AGGREGATE SHOULDERS | SQ. YD. | 1600 | 208.8 |
|  | 421 | AGGREGATE SHOULDERS, SPECIAL | TON | 465 | 423 |
|  | 421A | EXCAVATION FOR AGGREGATE SHOULDERS,SPECIAL | SQ. YD. | 1956 | 2041 |
|  | 425 | CUTTING AND SEALING CRACKS AND JOINTS | L.F. | 600 | 0 |
|  | 435 | BITUMINOUS PRESSURE RELIEF JOINT | SQ. FT. | 280 | 262 |
| * | 435A | BITUMINOUS PRESSURE RELIEF JOINT - REMOVAL AND REPLACEMENT | SQ. FT. | 26788 | 18947 |
| * | 436S | ABANDONED CONCRETE PRESSURE RELIEF JOINT | L.F. | 1667 | 985.6 |
| △ | 439A | SHOULDER RUMBLE STRIP INSTALLATION | L.F. | 204049 | 198743 |
|  | 501A | CONCRETE FOR BRIDGES AND DRAINAGE STRUCTURES (CLASS D) | CU. YD. | 216 | 277.70 |
|  | 501E | BRIDGE DECK GROOVING | SQ. YD. | 983 | 1010 |
|  | 504A | REINFORCING STEEL | LB. | 201 | 692 |
|  | 504B | REINFORCING STEEL, EPOXY COATED | LB. | 83670 | 7693[illegible] |
| * | 506A1 | SPOT CLEAN AND PAINT BRIDGES, BRIDGE NO. 179 | EACH | 1 | 1 |
| * | 506A2 | SPOT CLEAN AND PAINT BRIDGES, BRIDGE NO. 181 | EACH | 1 | 1 |
|  | 507 | CONCRETE REMOVAL | CU. YD. | 216 | 300.18 |
| * | 512G2 | CLASS C BRIDGE DECK REPAIR, PARTIAL DEPTH, MODIFIED CLASS J CONCRETE | SQ. YD. | 4 | 113.53 |
| * | 512H2 | CLASS C BRIDGE DECK REPAIR, FULL DEPTH, MODIFIED CLASS J | SQ. YD. | 79 | 109.95 |
| * | 512K | ELASTOMERIC CONCRETE REPAIR | SQ. FT. | 134 | 1.60 |
|  | 515C3 | PVC DRAIN PIPE (8 INCH) | L.F. | 380 | 331.3 |
|  | 515G | REMOVE EXISTING DRAIN PIPE | L.F. | 380 | 328.4 |
| * | 515H2 | POWER ROD AND FLUSH EXISTING DRAIN PIPE | L.F. | 44 | 44 |
| * | 515L1 | TEMPORARY SCUPPER COVER, TYPE I | EACH | 17 | 0 |
| * | 515L2 | TEMPORARY SCUPPER COVER, TYPE II | EACH | 17 | 0 |
|  | 520 | RESET BRIDGE EXPANSION BEARINGS | EACH | 170 | 136 |
|  | 521 | CLEAN AND PAINT BRIDGE BEARINGS | EACH | 127 | 127 |
|  | 522 | RESTORATION AND ADJUSTMENT OF BRIDGE BEARING PEDESTALS | EACH | 86 | 77 |
|  | 523 | CLEAN BRIDGE SEATS | SQ. FT. | 209120 | 255461 |

* SPECIAL PROVISIONS

|  | Pay Item # | Pay Item Description | Unit of Measure | Estimated Quantity | Record Quantity |
|---|---|---|---|---|---|
|  | 524 | APPLY CONCRETE SEALANT | SQ. FT. | 214310 | 262590 |
|  | 525C1 | BRIDGE EXPANSION JOINT CLOSURE NEOPRENE STRIP SEAL 2" | L.F. | 70 | 71.81 |
| * | 525F4 | BRIDGE EXPANSION JOINT CLOSURE MODIFIED NEOPRENE STRIP SEAL, 3" | L.F. | 249 | 249.92 |
| * | 525F5 | BRIDGE EXPANSION JOINT CLOSURE MODIFIED NEOPRENE STRIP SEAL, 2" | L.F. | 901 | 903.10 |
| * | 525F7 | BRIDGE EXPANSION JOINT CLOSURE MODIFIED NEOPRENE STRIP SEAL, 4" | L.F. | 76 | 77.36 |
| △* | 525J | ELASTOMERIC CONCRETE AND STEEL ARMORS | L.F. | 105 | 18.29 |
| * | 525L3 | NEOPRENE STRIP SEAL, REMOVAL AND REPLACEMENT, 4" | L.F. | 158 | 159.7 |
|  | 527 | APPROACH SLAB REMOVAL AND REPLACEMENT | SQ. YD. | 39 | 12 |
|  | 530A | FORMED CONCRETE REPAIR (DEPTH EQUAL TO OR LESS THAN 5") | SQ. FT. | 2115 | 1793.56 |
|  | 530B | FORMED CONCRETE REPAIR (DEPTH GREATER THAN 5") | SQ. FT. | 551 | 610.26 |
| * | 530C | CONCRETE REPAIR | SQ. FT. | 1181 | 1632.1 |
| △* | 531B | POLYMER MODIFIED MORTAR REPAIR | CU. FT. | 20 | 0.52 |
|  | 532A | DRILL AND GROUT DOWELS AND ANCHORS | EACH | 1029 | 1387 |
|  | 533 | LOW PRESSURE EPOXY INJECTION | L.F. | 75 | 13.8 |
| * | 533A | LOW PRESSURE EPOXY INJECTION | GAL. | 200 | 2.84 |
|  | 534 | HIGH PRESSURE EPOXY INJECTION | L.F. | 40 | 8 |
|  | 537 | PROTECTIVE SHIELD SYSTEM | SQ. FT. | 25610 | 21781 |
|  | 543 | MECHANICAL BAR SPLICERS | EACH | 893 | 853 |
| * | 550 | FIBER WRAP REPAIR | SQ. FT. | 284 | 234.5 |
| * | 560 | CLEAN DEBRIS AND EXISTING FORM WORK FROM VAULT AREA | L.S. | 1 | 1 |
|  | 601E1 | REINFORCED CONCRETE PIPE, (12") | L.F. | 2 | 2.0 |
|  | 601G | CONCRETE HEADWALLS AND COLLARS (CLASS P) | CU. YD. | 2.8 | 9.33 |
| * | 604C | SLOTTED PAVEMENT DRAIN (RETROFIT) (12 In.) SHOULDER | L.F. | 3915 | 5386.0 |
| * | 604D | SLOTTED PAVEMENT DRAIN (RETROFIT) (12 In.) MEDIAN | L.F. | 5014 | 5059.0 |
| * | 604E | TEMPORARY SLOTTED DRAIN | L. F. | 899 | 0 |
|  | 607A2 | SUBSURFACE PAVEMENT DRAIN (FILTER FABRIC)(6") | L.F. | 8714 | 10588 |
|  | 610C3 | CATCH BASIN, TYPE G-2 | EACH | 1 | 0 |
|  | 610C4 | CATCH BASIN, TYPE G-3 | EACH | 1 | 1 |
|  | 610D | ADJUSTED CATCH BASIN | EACH | 10 | 23 |
|  | 610F | ADJUSTED INLET | EACH | 1 | 1 |
|  | 612C1 | GUTTER, TYPE G-2 | L.F. | 850 | 263 |
|  | 612C2 | GUTTER, TYPE G-3 | L.F. | 2741 | 2482 |
| △* | 612R | GUTTER REMOVAL | L.F. | 3221 | 2814 |
|  | 615 | HEADWALL GRATES | LB. | 956 | 1380 |
|  | 616B | CONCRETE FLUME | L.F. | 10 | 44.3 |
|  | 618 | AGGREGATE SLOPE PAVING | SQ. YD. | 36 | 87.9 |
|  | 619C | AGGREGATE DITCH LINING, CA-5 | SQ. YD. | 177 | 202.1 |
|  | 619D | FILTER FABRIC FOR DITCH LINING | SQ. YD. | 177 | 202.1 |
|  | 628 | MANAGEMENT OF EROSION AND SEDIMENT CONTROL | CAL MO. | 6 | 0 |
|  | 628C | SILT FENCE | L.F. | 6071 | 769 |
|  | 628CR | RE-ERECT SILT FENCE | L.F. | 1518 | 0 |
|  | 628M | RECTANGULAR INLET PROTECTION | EACH | 27 | 0 |
|  | 701A | SINGLE RAIL GALVANIZED STEEL PLATE BEAM GUARDRAIL | L.F. | 3610 | 5373.6 |
|  | 701B | DOUBLE RAIL GALVANIZED STEEL PLATE BEAM GUARDRAIL | L.F. | 25 | 0 |
|  | 701C | GUARDRAIL REMOVAL | L.F. | 12668 | 13298 |
|  | 701D | GALVANIZED STEEL PLATE BEAM GUARDRAIL REINSTALLATION | L.F. | 1375 | 0 |
|  | 701E1S | GUARDRAIL BARRIER TERMINAL, TYPE I, SPECIAL | EACH | 51 | 47 |
| * | 701AE1S | GUARDRAIL BARRIER TERMINAL, TYPE I A, SPECIAL | EACH | 12 | 11 |
| * | 701E2S | GUARDRAIL BARRIER TERMINAL, TYPE 2, SPECIAL | EACH | 1 | 0 |
|  | 701E3 | GUARDRAIL BARRIER TERMINAL, TYPE 3 | EACH | 19 | 29 |
|  | 701F2 | GUARDRAIL ANCHOR INSTALLATION, TYPE 2 | EACH | 51 | 42 |
|  | 701F5 | GUARDRAIL ANCHOR INSTALLATION, TYPE 4 | EACH | 1 | 2 |
|  | 701G | GUARDRAIL BLOCK-OUTS | EACH | 322 | 0 |
|  | 701H | GALVANIZED GUARDRAIL HARDWARE UNITS | EACH | 24 | 0 |

* SPECIAL PROVISIONS

SUM-1

DRAWN BY______ DATE 3-20-01

CHECKED BY______ SCALE NONE

ENGINEERING CONSULTANT

Edwards AND Kelcey

ONE NORTH FRANKLIN
CHICAGO, ILLINOIS
OFFICE 312/251-3000
FAX 312/251-3015

THE ILLINOIS STATE TOLL HIGHWAY AUTHORITY
2700 OGDEN AVENUE
DOWNERS GROVE, ILLINOIS 60515

REVISIONS

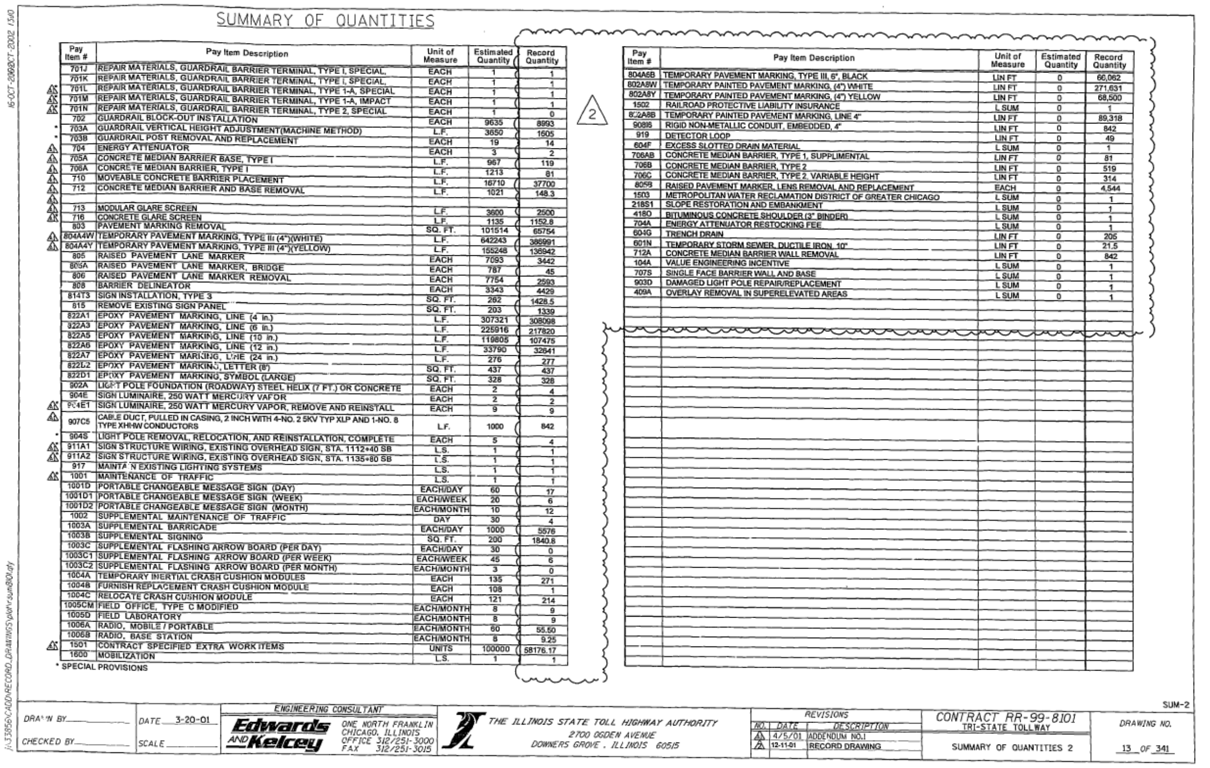
| NO. | DATE | DESCRIPTION |
|---|---|---|
| △1 | 4/5/01 | ADDENDUM NO.1 |
| △2 | 12-11-01 | RECORD DRAWING |

CONTRACT RR-99-8101
TRI-STATE TOLLWAY

SUMMARY OF QUANTITIES 1

DRAWING NO. 12 OF 341

FIGURE A.2 Pay Items for Project Part 1



SUMMARY OF QUANTITIES

|  | Pay Item # | Pay Item Description | Unit of Measure | Estimated Quantity | Record Quantity |
|---|---|---|---|---|---|
|  | 701J | REPAIR MATERIALS, GUARDRAIL BARRIER TERMINAL, TYPE I, SPECIAL, | EACH | 1 | 1 |
|  | 701K | REPAIR MATERIALS, GUARDRAIL BARRIER TERMINAL, TYPE I, SPECIAL, | EACH | 1 | 1 |
|  | 701L | REPAIR MATERIALS, GUARDRAIL BARRIER TERMINAL, TYPE 1-A, SPECIAL | EACH | 1 | 1 |
|  | 701M | REPAIR MATERIALS, GUARDRAIL BARRIER TERMINAL, TYPE 1-A, IMPACT | EACH | 1 | 1 |
|  | 701N | REPAIR MATERIALS, GUARDRAIL BARRIER TERMINAL, TYPE 2, SPECIAL | EACH | 1 | 0 |
|  | 702 | GUARDRAIL BLOCK-OUT INSTALLATION | EACH | 9635 | 8993 |
| • | 703A | GUARDRAIL VERTICAL HEIGHT ADJUSTMENT(MACHINE METHOD) | L.F. | 3650 | 1605 |
| • | 703B | GUARDRAIL POST REMOVAL AND REPLACEMENT | EACH | 19 | 14 |
|  | 704 | ENERGY ATTENUATOR | EACH | 3 | 2 |
|  | 705A | CONCRETE MEDIAN BARRIER BASE, TYPE I | L.F. | 967 | 119 |
|  | 706A | CONCRETE MEDIAN BARRIER, TYPE I | L.F. | 1213 | 81 |
|  | 710 | MOVEABLE CONCRETE BARRIER PLACEMENT | L.F. | 16710 | 37700 |
|  | 712 | CONCRETE MEDIAN BARRIER AND BASE REMOVAL | L.F. | 1021 | 148.3 |
|  |  |  |  |  |  |
|  | 713 | MODULAR GLARE SCREEN | L.F. | 3600 | 2500 |
|  | 716 | CONCRETE GLARE SCREEN | L.F. | 1135 | 1152.8 |
|  | 803 | PAVEMENT MARKING REMOVAL | SQ. FT. | 101514 | 65754 |
|  | 804A4W | TEMPORARY PAVEMENT MARKING, TYPE III (4")(WHITE) | L.F. | 642243 | 386991 |
|  | 804A4Y | TEMPORARY PAVEMENT MARKING, TYPE III (4")(YELLOW) | L.F. | 155248 | 136942 |
|  | 805 | RAISED PAVEMENT LANE MARKER | EACH | 7093 | 3442 |
|  | 805A | RAISED PAVEMENT LANE MARKER, BRIDGE | EACH | 787 | 45 |
|  | 806 | RAISED PAVEMENT LANE MARKER REMOVAL | EACH | 7754 | 2593 |
|  | 808 | BARRIER DELINEATOR | EACH | 3343 | 4429 |
|  | 814T3 | SIGN INSTALLATION, TYPE 3 | SQ. FT. | 262 | 1428.5 |
|  | 815 | REMOVE EXISTING SIGN PANEL | SQ. FT. | 203 | 1339 |
|  | 822A1 | EPOXY PAVEMENT MARKING, LINE (4 in.) | L.F. | 307321 | 308098 |
|  | 822A3 | EPOXY PAVEMENT MARKING, LINE (6 in.) | L.F. | 225916 | 217820 |
|  | 822A5 | EPOXY PAVEMENT MARKING, LINE (10 in.) | L.F. | 119805 | 107475 |
|  | 822A6 | EPOXY PAVEMENT MARKING, LINE (12 in.) | L.F. | 33790 | 32641 |
|  | 822A7 | EPOXY PAVEMENT MARKING, LINE (24 in.) | L.F. | 276 | 277 |
|  | 822L2 | EPOXY PAVEMENT MARKING, LETTER (8') | SQ. FT. | 437 | 437 |
|  | 822D1 | EPOXY PAVEMENT MARKING, SYMBOL (LARGE) | SQ. FT. | 328 | 328 |
|  | 902A | LIGHT POLE FOUNDATION (ROADWAY) STEEL HELIX (7 FT.) OR CONCRETE | EACH | 2 | 4 |
|  | 904E | SIGN LUMINAIRE, 250 WATT MERCURY VAPOR | EACH | 2 | 2 |
|  | 904E1 | SIGN LUMINAIRE, 250 WATT MERCURY VAPOR, REMOVE AND REINSTALL | EACH | 9 | 9 |
|  | 907C5 | CABLE DUCT, PULLED IN CASING, 2 INCH WITH 4-NO. 2 5KV TYP XLP AND 1-NO. 8 TYPE XHHW CONDUCTORS | L.F. | 1000 | 842 |
| • | 904S | LIGHT POLE REMOVAL, RELOCATION, AND REINSTALLATION, COMPLETE | EACH | 5 | 4 |
|  | 911A1 | SIGN STRUCTURE WIRING, EXISTING OVERHEAD SIGN, STA. 1112+40 SB | L.S. | 1 | 1 |
|  | 911A2 | SIGN STRUCTURE WIRING, EXISTING OVERHEAD SIGN, STA. 1135+80 SB | L.S. | 1 | 1 |
|  | 917 | MAINTAIN EXISTING LIGHTING SYSTEMS | L.S. | 1 | 1 |
|  | 1001 | MAINTENANCE OF TRAFFIC | L.S. | 1 | 1 |
|  | 1001D | PORTABLE CHANGEABLE MESSAGE SIGN (DAY) | EACH/DAY | 60 | 17 |
|  | 1001D1 | PORTABLE CHANGEABLE MESSAGE SIGN (WEEK) | EACH/WEEK | 20 | 6 |
|  | 1001D2 | PORTABLE CHANGEABLE MESSAGE SIGN (MONTH) | EACH/MONTH | 10 | 12 |
|  | 1002 | SUPPLEMENTAL MAINTENANCE OF TRAFFIC | DAY | 30 | 4 |
|  | 1003A | SUPPLEMENTAL BARRICADE | EACH/DAY | 1000 | 5576 |
|  | 1003B | SUPPLEMENTAL SIGNING | SQ. FT. | 200 | 1840.8 |
|  | 1003C | SUPPLEMENTAL FLASHING ARROW BOARD (PER DAY) | EACH/DAY | 30 | 0 |
|  | 1003C1 | SUPPLEMENTAL FLASHING ARROW BOARD (PER WEEK) | EACH/WEEK | 45 | 6 |
|  | 1003C2 | SUPPLEMENTAL FLASHING ARROW BOARD (PER MONTH) | EACH/MONTH | 3 | 0 |
|  | 1004A | TEMPORARY INERTIAL CRASH CUSHION MODULES | EACH | 135 | 271 |
|  | 1004B | FURNISH REPLACEMENT CRASH CUSHION MODULE | EACH | 108 | 1 |
|  | 1004C | RELOCATE CRASH CUSHION MODULE | EACH | 121 | 214 |
|  | 1005CM | FIELD OFFICE, TYPE C MODIFIED | EACH/MONTH | 8 | 9 |
|  | 1005D | FIELD LABORATORY | EACH/MONTH | 8 | 9 |
|  | 1006A | RADIO, MOBILE / PORTABLE | EACH/MONTH | 60 | 55.50 |
|  | 1006B | RADIO, BASE STATION | EACH/MONTH | 8 | 9.25 |
|  | 1501 | CONTRACT SPECIFIED EXTRA WORK ITEMS | UNITS | 100000 | 58176.17 |
|  | 1600 | MOBILIZATION | L.S. | 1 | 1 |

* SPECIAL PROVISIONS

| Pay Item # | Pay Item Description | Unit of Measure | Estimated Quantity | Record Quantity |
|---|---|---|---|---|
| 804A6B | TEMPORARY PAVEMENT MARKING, TYPE III, 6", BLACK | LIN FT | 0 | 66,062 |
| 802A8W | TEMPORARY PAINTED PAVEMENT MARKING, (4") WHITE | LIN FT | 0 | 271,631 |
| 802A8Y | TEMPORARY PAINTED PAVEMENT MARKING, (4") YELLOW | LIN FT | 0 | 68,500 |
| 1502 | RAILROAD PROTECTIVE LIABILITY INSURANCE | L SUM | 0 | 1 |
| 802A8B | TEMPORARY PAINTED PAVEMENT MARKING, LINE 4" | LIN FT | 0 | 89,318 |
| 908I6 | RIGID NON-METALLIC CONDUIT, EMBEDDED, 4" | LIN FT | 0 | 842 |
| 919 | DETECTOR LOOP | LIN FT | 0 | 49 |
| 604F | EXCESS SLOTTED DRAIN MATERIAL | L SUM | 0 | 1 |
| 706AB | CONCRETE MEDIAN BARRIER, TYPE 1, SUPPLIMENTAL | LIN FT | 0 | 81 |
| 706B | CONCRETE MEDIAN BARRIER, TYPE 2 | LIN FT | 0 | 519 |
| 706C | CONCRETE MEDIAN BARRIER, TYPE 2, VARIABLE HEIGHT | LIN FT | 0 | 314 |
| 805B | RAISED PAVEMENT MARKER, LENS REMOVAL AND REPLACEMENT | EACH | 0 | 4,544 |
| 1503 | METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO | L SUM | 0 | 1 |
| 218S1 | SLOPE RESTORATION AND EMBANKMENT | L SUM | 0 | 1 |
| 418O | BITUMINOUS CONCRETE SHOULDER (3" BINDER) | L SUM | 0 | 1 |
| 704A | ENERGY ATTENUATOR RESTOCKING FEE | L SUM | 0 | 1 |
| 604G | TRENCH DRAIN | LIN FT | 0 | 205 |
| 601N | TEMPORARY STORM SEWER, DUCTILE IRON, 10" | LIN FT | 0 | 21.5 |
| 712A | CONCRETE MEDIAN BARRIER WALL REMOVAL | LIN FT | 0 | 842 |
| 104A | VALUE ENGINEERING INCENTIVE | L SUM | 0 | 1 |
| 707S | SINGLE FACE BARRIER WALL AND BASE | L SUM | 0 | 1 |
| 903D | DAMAGED LIGHT POLE REPAIR/REPLACEMENT | L SUM | 0 | 1 |
| 409A | OVERLAY REMOVAL IN SUPERELEVATED AREAS | L SUM | 0 | 1 |

SUM-2

DRAWN BY

CHECKED BY

DATE 3-20-01

SCALE

ENGINEERING CONSULTANT

Edwards AND Kelcey

ONE NORTH FRANKLIN
CHICAGO, ILLINOIS
OFFICE 312/251-3000
FAX 312/251-3015

THE ILLINOIS STATE TOLL HIGHWAY AUTHORITY
2700 OGDEN AVENUE
DOWNERS GROVE, ILLINOIS 60515

REVISIONS

| NO. | DATE | DESCRIPTION |
|---|---|---|
| 1 | 4/5/01 | ADDENDUM NO.1 |
| 2 | 12-11-01 | RECORD DRAWING |

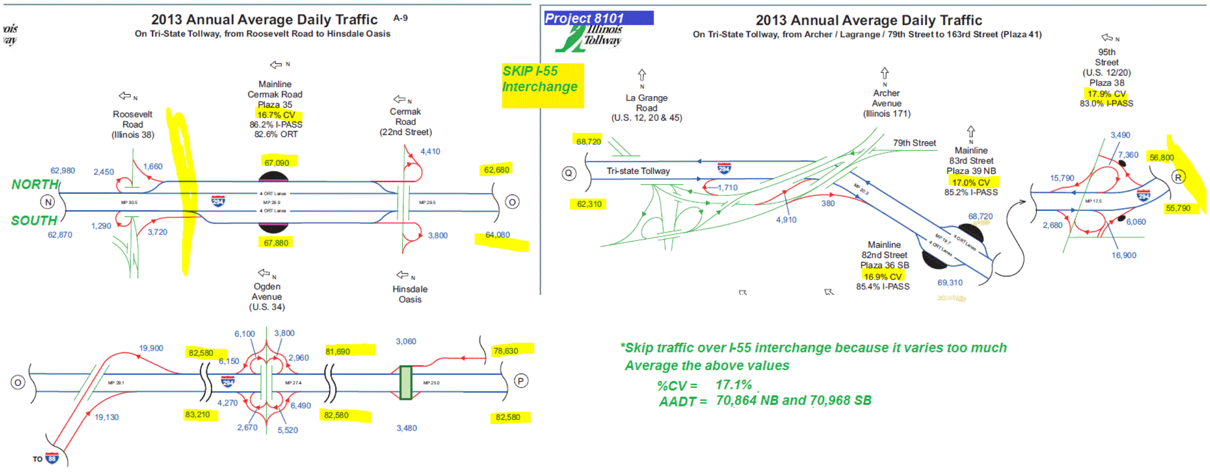
CONTRACT RR-99-8101
TRI-STATE TOLLWAY

SUMMARY OF QUANTITIES 2

DRAWING NO.

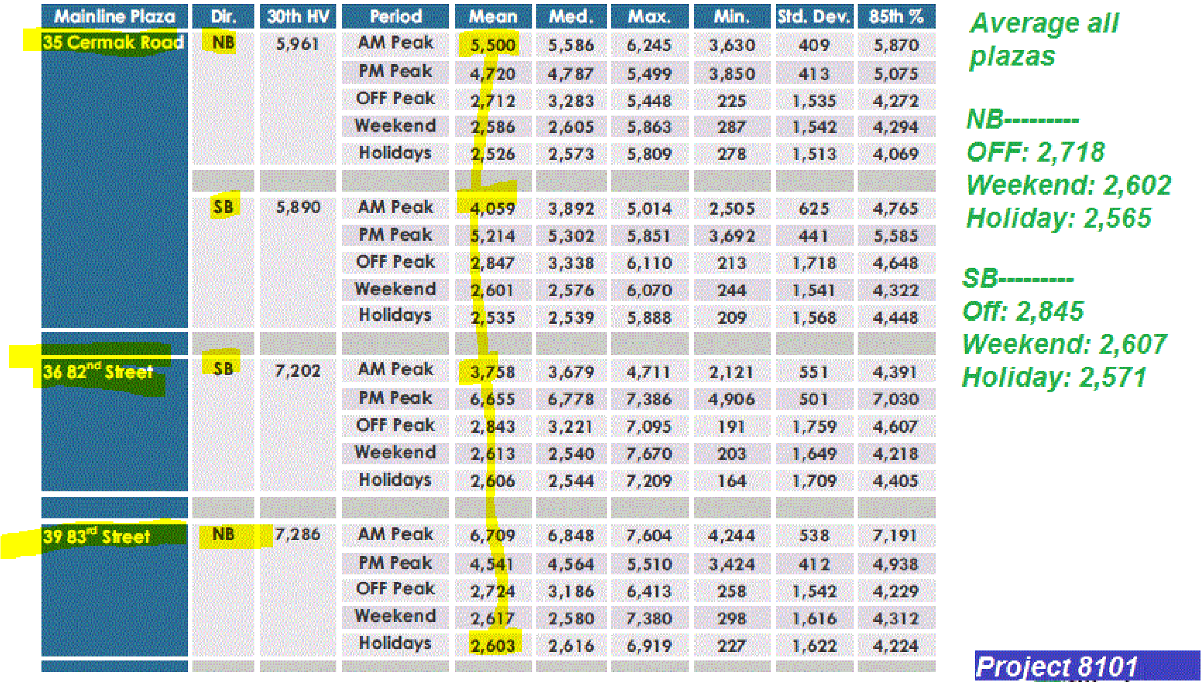
13 OF 341

FIGURE A.3 Pay Items for Project Part 2



*Skip traffic over I-55 interchange because it varies too much
Average the above values
%CV = 17.1%
AADT = 70,864 NB and 70,968 SB

FIGURE A.4 Traffic Information



| Mainline Plaza | Dir. | 30th HV | Period | Mean | Med. | Max. | Min. | Std. Dev. | 85th % |
|---|---|---|---|---|---|---|---|---|---|
| 35 Cermak Road | NB | 5,961 | AM Peak | 5,500 | 5,586 | 6,245 | 3,630 | 409 | 5,870 |
| | | | PM Peak | 4,720 | 4,787 | 5,499 | 3,850 | 413 | 5,075 |
| | | | OFF Peak | 2,712 | 3,283 | 5,448 | 225 | 1,535 | 4,272 |
| | | | Weekend | 2,586 | 2,605 | 5,863 | 287 | 1,542 | 4,294 |
| | | | Holidays | 2,526 | 2,573 | 5,809 | 278 | 1,513 | 4,069 |
| | SB | 5,890 | AM Peak | 4,059 | 3,892 | 5,014 | 2,505 | 625 | 4,765 |
| | | | PM Peak | 5,214 | 5,302 | 5,851 | 3,692 | 441 | 5,585 |
| | | | OFF Peak | 2,847 | 3,338 | 6,110 | 213 | 1,718 | 4,648 |
| | | | Weekend | 2,601 | 2,576 | 6,070 | 244 | 1,541 | 4,322 |
| | | | Holidays | 2,535 | 2,539 | 5,888 | 209 | 1,568 | 4,448 |
| 36 82nd Street | SB | 7,202 | AM Peak | 3,758 | 3,679 | 4,711 | 2,121 | 551 | 4,391 |
| | | | PM Peak | 6,655 | 6,778 | 7,386 | 4,906 | 501 | 7,030 |
| | | | OFF Peak | 2,843 | 3,221 | 7,095 | 191 | 1,759 | 4,607 |
| | | | Weekend | 2,613 | 2,540 | 7,670 | 203 | 1,649 | 4,218 |
| | | | Holidays | 2,606 | 2,544 | 7,209 | 164 | 1,709 | 4,405 |
| 39 83rd Street | NB | 7,286 | AM Peak | 6,709 | 6,848 | 7,604 | 4,244 | 538 | 7,191 |
| | | | PM Peak | 4,541 | 4,564 | 5,510 | 3,424 | 412 | 4,938 |
| | | | OFF Peak | 2,724 | 3,186 | 6,413 | 258 | 1,542 | 4,229 |
| | | | Weekend | 2,617 | 2,580 | 7,380 | 298 | 1,616 | 4,312 |
| | | | Holidays | 2,603 | 2,616 | 6,919 | 227 | 1,622 | 4,224 |

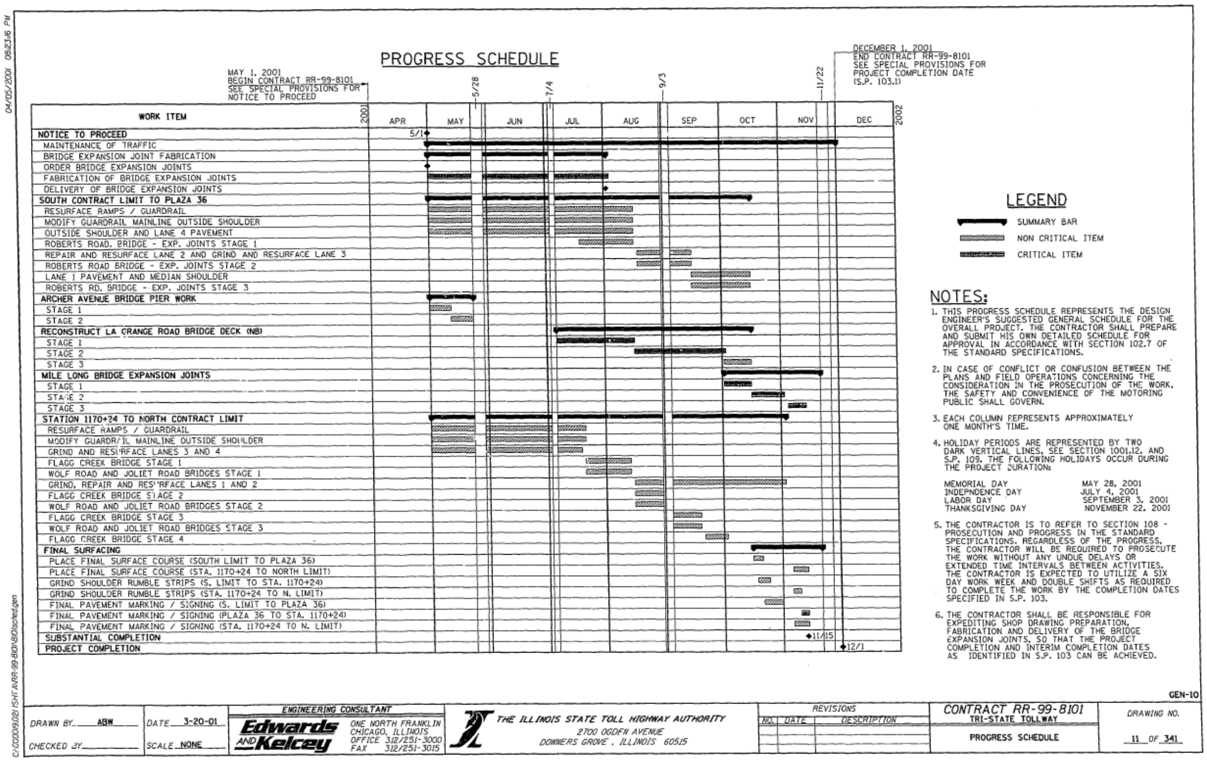
*Average all plazas*

*NB---------*
*OFF: 2,718*
*Weekend: 2,602*
*Holiday: 2,565*

*SB---------*
*Off: 2,845*
*Weekend: 2,607*
*Holiday: 2,571*

*Project 8101*

FIGURE A.5 Traffic Distribution



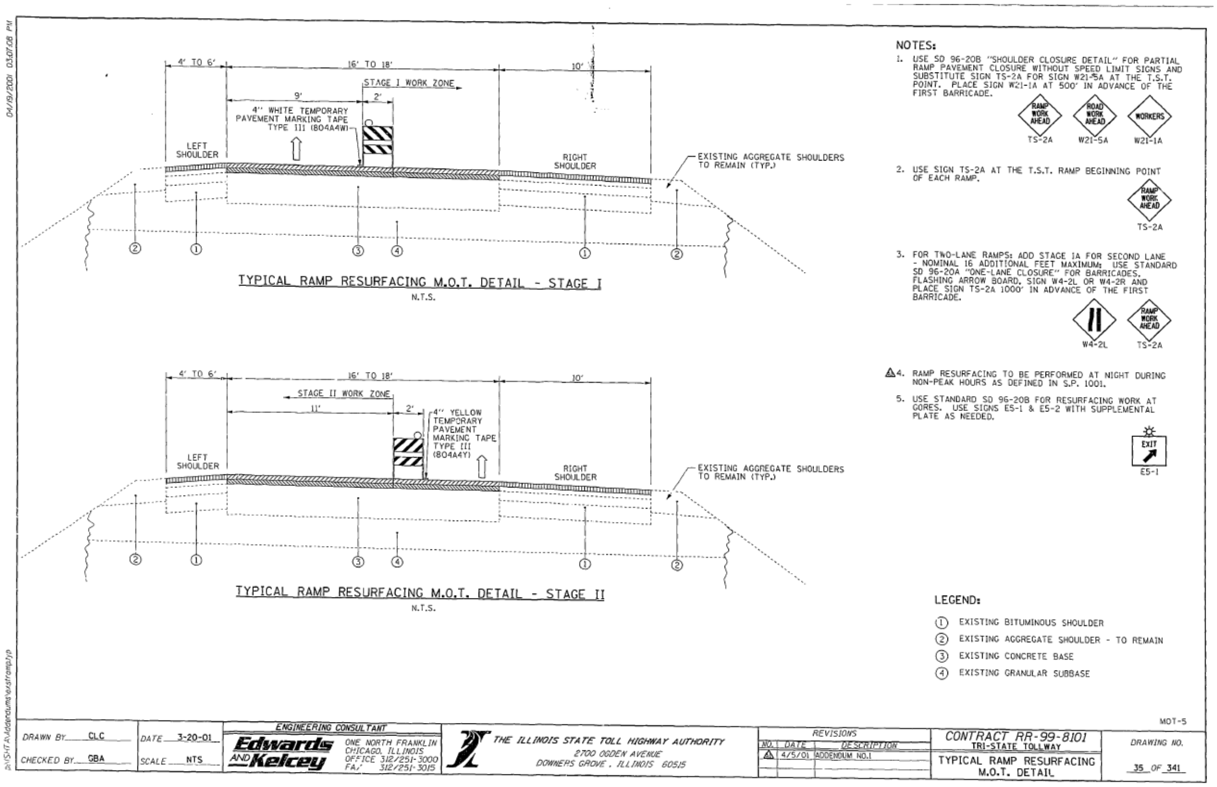
NOTES:

1. THIS PROGRESS SCHEDULE REPRESENTS THE DESIGN ENGINEER'S SUGGESTED GENERAL SCHEDULE FOR THE OVERALL PROJECT. THE CONTRACTOR SHALL PREPARE AND SUBMIT HIS OWN DETAILED SCHEDULE FOR APPROVAL IN ACCORDANCE WITH SECTION 102.7 OF THE STANDARD SPECIFICATIONS.
2. IN CASE OF CONFLICT OR CONFUSION BETWEEN THE PLANS AND FIELD OPERATIONS CONCERNING THE CONSIDERATION IN THE PROSECUTION OF THE WORK, THE SAFETY AND CONVENIENCE OF THE MOTORING PUBLIC SHALL GOVERN.
3. EACH COLUMN REPRESENTS APPROXIMATELY ONE MONTH'S TIME.
4. HOLIDAY PERIODS ARE REPRESENTED BY TWO DARK VERTICAL LINES, SEE SECTION 1001.12. AND S.P. 109. THE FOLLOWING HOLIDAYS OCCUR DURING THE PROJECT DURATION:

| | |
|---|---|
| MEMORIAL DAY | MAY 28, 2001 |
| INDEPNDENCE DAY | JULY 4, 2001 |
| LABOR DAY | SEPTEMBER 3, 2001 |
| THANKSGIVING DAY | NOVEMBER 22, 2001 |

5. THE CONTRACTOR IS TO REFER TO SECTION 108 - PROSECUTION AND PROGRESS IN THE STANDARD SPECIFICATIONS. REGARDLESS OF THE PROGRESS, THE CONTRACTOR WILL BE REQUIRED TO PROSECUTE THE WORK WITHOUT ANY UNDUE DELAYS OR EXTENDED TIME INTERVALS BETWEEN ACTIVITIES. THE CONTRACTOR IS EXPECTED TO UTILIZE A SIX DAY WORK WEEK AND DOUBLE SHIFTS AS REQUIRED TO COMPLETE THE WORK BY THE COMPLETION DATES SPECIFIED IN S.P. 103.
6. THE CONTRACTOR SHALL BE RESPONSIBLE FOR EXPEDITING SHOP DRAWING PREPARATION, FABRICATION AND DELIVERY OF THE BRIDGE EXPANSION JOINTS, SO THAT THE PROJECT COMPLETION AND INTERIM COMPLETION DATES AS IDENTIFIED IN S.P. 103 CAN BE ACHIEVED.

FIGURE A.6 Schedule for Initial Construction



NOTES:

1. USE SD 96-20B "SHOULDER CLOSURE DETAIL" FOR PARTIAL RAMP PAVEMENT CLOSURE WITHOUT SPEED LIMIT SIGNS AND SUBSTITUTE SIGN TS-2A FOR SIGN W21-5A AT THE T.S.T. POINT. PLACE SIGN W21-1A AT 500' IN ADVANCE OF THE FIRST BARRICADE.
2. USE SIGN TS-2A AT THE T.S.T. RAMP BEGINNING POINT OF EACH RAMP.
3. FOR TWO-LANE RAMPS: ADD STAGE 1A FOR SECOND LANE - NOMINAL 16 ADDITIONAL FEET MAXIMUM: USE STANDARD SD 96-20A "ONE-LANE CLOSURE" FOR BARRICADES, FLASHING ARROW BOARD, SIGN W4-2L OR W4-2R AND PLACE SIGN TS-2A 1000' IN ADVANCE OF THE FIRST BARRICADE.
4. RAMP RESURFACING TO BE PERFORMED AT NIGHT DURING NON-PEAK HOURS AS DEFINED IN S.P. 1001.
5. USE STANDARD SD 96-20B FOR RESURFACING WORK AT GORES. USE SIGNS E5-1 & E5-2 WITH SUPPLEMENTAL PLATE AS NEEDED.

FIGURE A.7 Scheduling Part 1

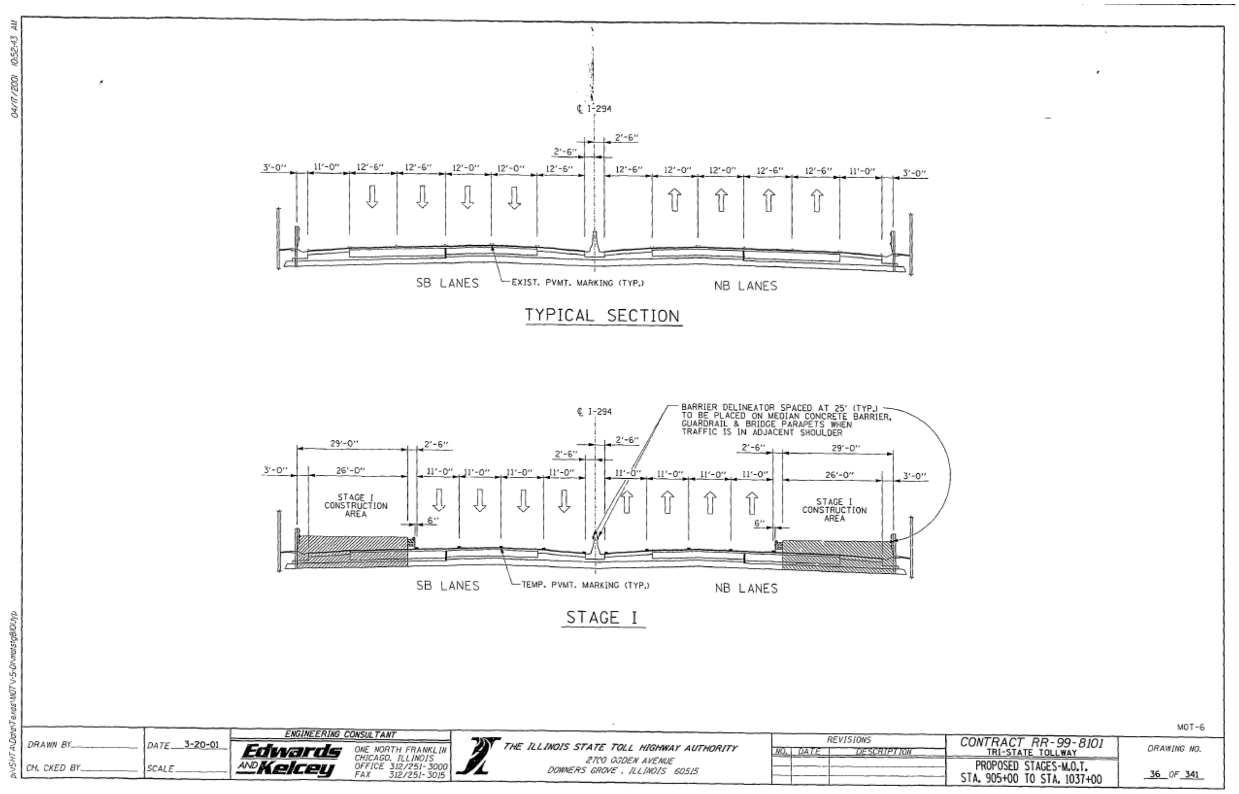


FIGURE A.8 Scheduling Part 2

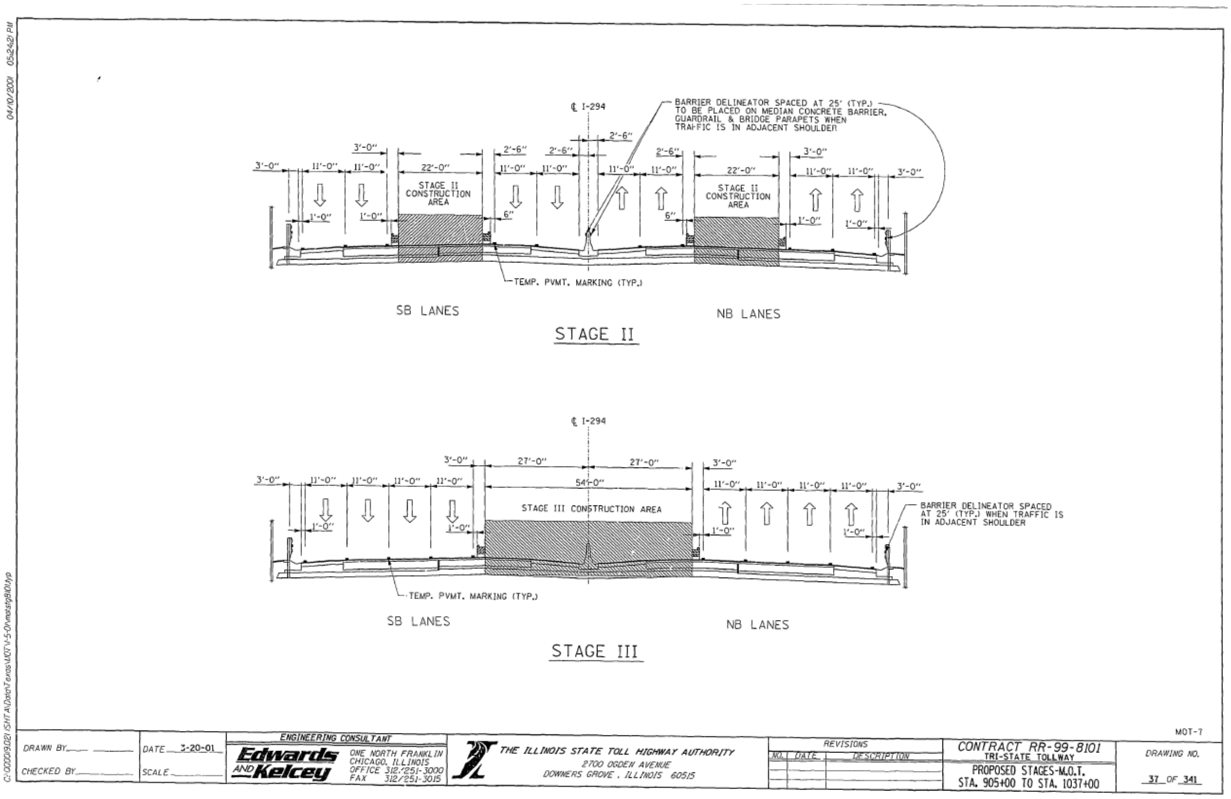


FIGURE A.9 Scheduling Part 3

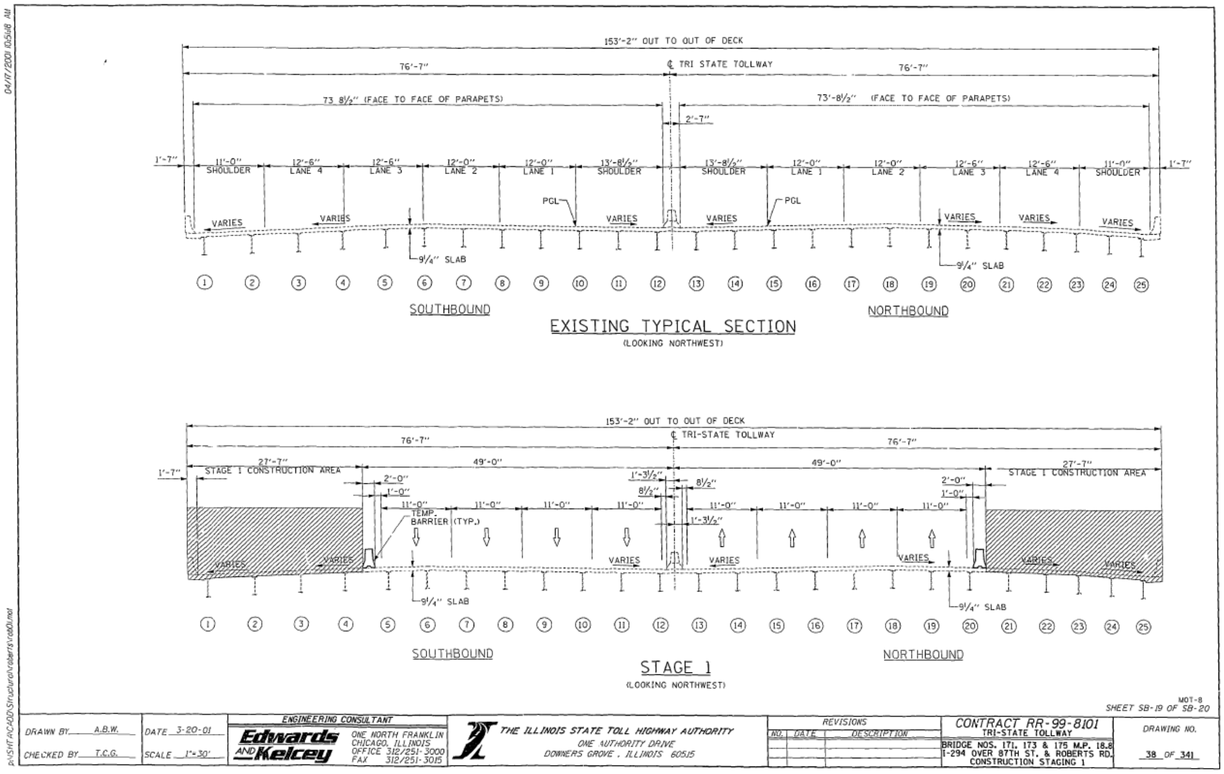


FIGURE A.10 Scheduling Part 4

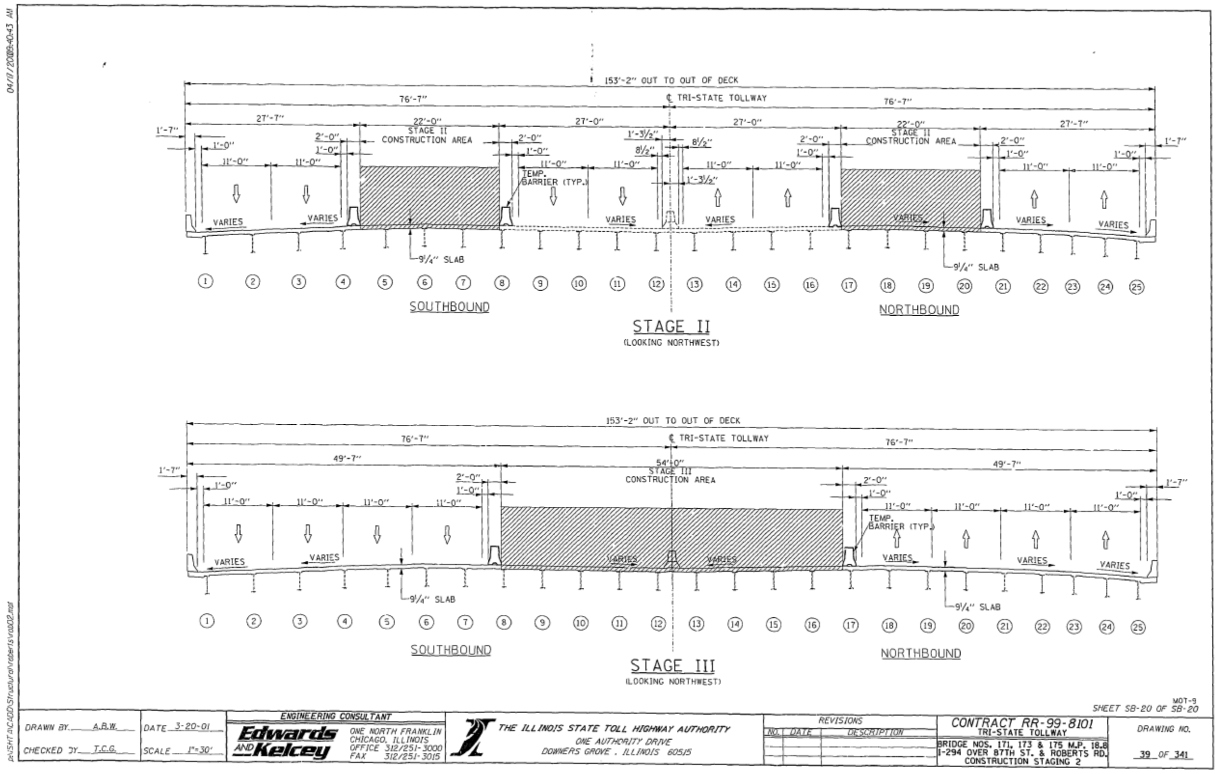
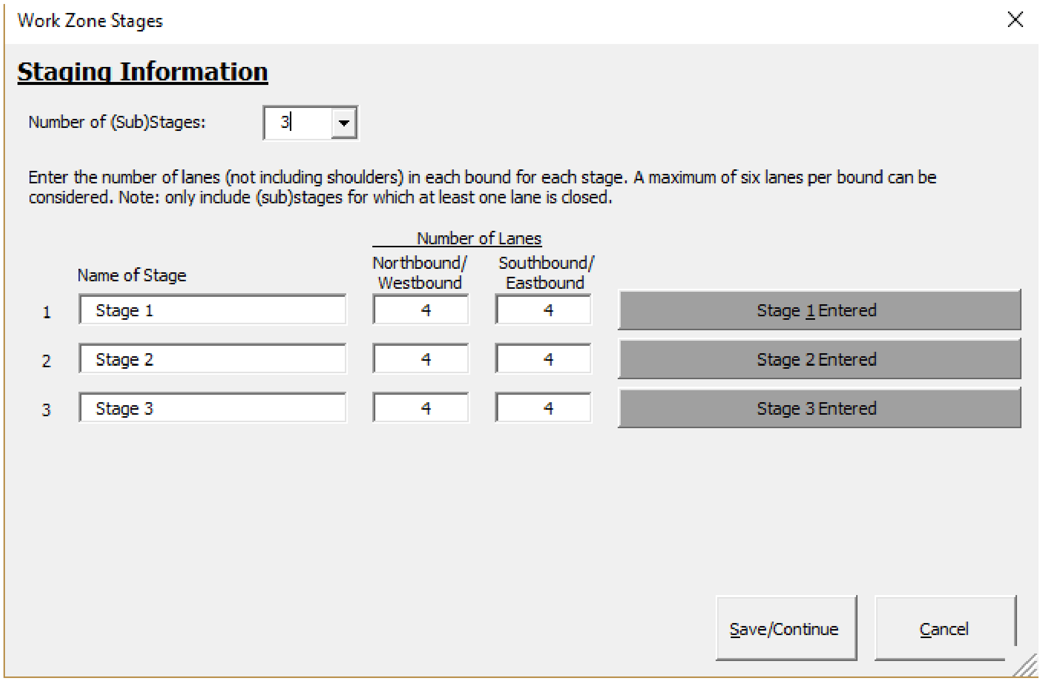


FIGURE A.11 Scheduling Part 5

# Appendix B: Work Zone Inputs



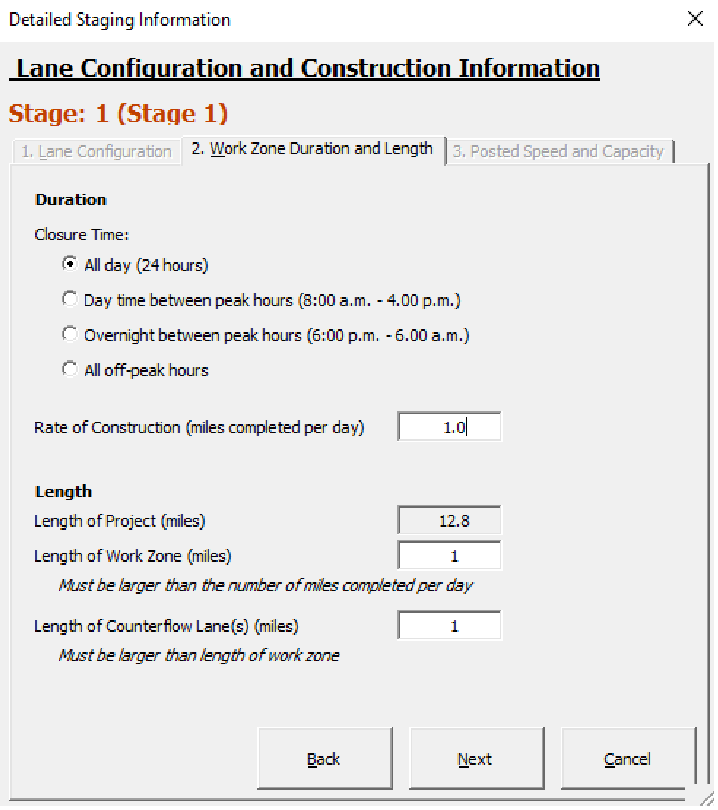
**Staging Information**

Number of (Sub)Stages: 3

Enter the number of lanes (not including shoulders) in each bound for each stage. A maximum of six lanes per bound can be considered. Note: only include (sub)stages for which at least one lane is closed.

| | Name of Stage | Number of Lanes | |
|---|---|---|---|
| | | Northbound/ Westbound | Southbound/ Eastbound |
| 1 | Stage 1 | 4 | 4 |
| 2 | Stage 2 | 4 | 4 |
| 3 | Stage 3 | 4 | 4 |

FIGURE B.1 Sub Stage Information



**Lane Configuration and Construction Information**

**Stage: 1 (Stage 1)**

**Duration**

Closure Time:

- ● All day (24 hours)
- ○ Day time between peak hours (8:00 a.m. - 4.00 p.m.)
- ○ Overnight between peak hours (6:00 p.m. - 6.00 a.m.)
- ○ All off-peak hours

Rate of Construction (miles completed per day): 1.0

**Length**

Length of Project (miles): 12.8

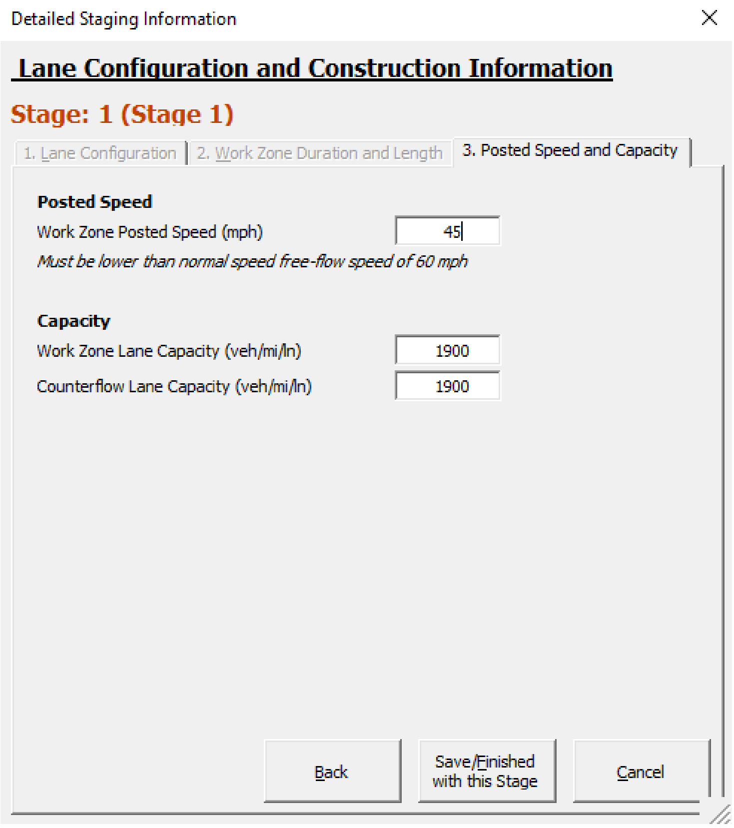
Length of Work Zone (miles): 1

*Must be larger than the number of miles completed per day*

Length of Counterflow Lane(s) (miles): 1

*Must be larger than length of work zone*

FIGURE B.2 Base Completion Rate


Detailed Staging Information

**Lane Configuration and Construction Information**

**Stage: 1 (Stage 1)**

**Posted Speed**

Work Zone Posted Speed (mph): 45

*Must be lower than normal speed free-flow speed of 60 mph*

**Capacity**

Work Zone Lane Capacity (veh/mi/ln): 1900

Counterflow Lane Capacity (veh/mi/ln): 1900

FIGURE B.3 Work Zone Capacity