LCCA-based Decision Assistance Tool for Indirect Left Turn (ILT) Intersections using Excel-driven Highway Capacity Software

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ABSTRACT
This paper explains the principles involved in the development of an MS Excel–based decision assistance tool for indirect left turn (ILT) intersections. This tool, termed Signalized Intersection Life Cycle Cost Analysis (SILCC), analyzes three types of ILT intersections: (i) MUT, (ii) CFI, and (iii) jughandles. So far, no tools have been developed that are capable of analyzing ILT intersections while incorporating cost and benefit aspects. In contrast, SILCC is designed to incorporate cost and benefit aspects in the evaluation of ILT intersections. It is interfaced with the Highway Capacity Software (HCS) and hence can perform macro-level operational analysis. It considers delay, fuel consumption, and emissions as operational performance measures. It is capable of performing life cycle cost analysis (LCCA) and providing net present value (NPV) and benefit-to-cost ratio (B/C) as surrogate measures of performance. Planners can use NPV or B/C for decision support while deciding among several alternatives for economic and efficiently operating ILT intersections. Additionally, SILCC features the flexibility to alter input values so that it can be used for multiple conditions and criteria. A case study of rural traffic volume conditions indicated that an MUT intersection had the highest NPV of benefits for both new construction and retrofits. However, because the construction cost for MUT retrofits was high for the particular condition, an MUT intersection had the highest B/C for new construction and a jughandle had the highest B/C for retrofits.

INTRODUCTION

Indirect left turn (ILT) intersections are being adopted at locations where conventional intersections fail to satisfy expected operational and safety levels. There are multiple ILT configurations that provide superior performance to conventional intersections for a range of volume configurations. The present analytical procedure for evaluating the performance of ILT intersections ignores the economic aspect. A decision based on such an analysis may lead to a cost-insensitive solution. Meanwhile, the construction of ILT intersections is associated with a relatively large investment. Therefore, it is imperative for planners to weigh the intersection designs based on the benefit of the services and the related costs throughout the service period prior to deciding on a design for implementation. In this context, this study was designed to develop a tool called Signalized Intersection Life Cycle Cost Analysis (SILCC), which can incorporate the economic aspect along with the traffic operational elements to provide decision assistance for the selection of optimal alternatives.

SILCC is capable of analyzing three types of ILT intersections: (i) median U-turn (MUT), (ii) continuous flow intersections (CFI), and (iii) jughandles. Each type is compared to a standard four-legged intersection with a protected left turn movement on both a major street and minor street. The tool provides a marginal net present value (NPV) of benefits as well as a benefit-to-cost ratio (B/C) for ILT intersections as decision support for planners during the selection of suitable alternatives.

LITERATURE REVIEW

There is a significant body of literature that reports superior performance for ILT intersections, such as MUT, CFI, and jughandles, as compared to a conventional intersection under a range of volume conditions *(1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, and 25)*. A few studies *(5, 8, 14, and 26*) have also discussed the construction costs of ILT intersections. Despite an exhaustive body of literature documenting the performance of ILT, there are no decision assistance tools to quickly compare multiple ILT intersections while considering operational benefits in terms of system-level performance and the cost associated with the construction, operation, and maintenance of such intersections throughout the life cycle period. Even in terms of operational performance, the existing tools either produce very simplistic performance measures or are very time consuming to use. This section provides a brief overview of the tools available to help planners choose an appropriate ILT for a given intersection.

Most studies use micro-simulation tools to compare the operational performance of ILT intersections *(9, 10, 12, 13, 16, 19, 25, 27, and 28)*. These studies invest significant resources into running the micro-simulation models. Some of the time consuming steps involved in performing micro-simulation runs are as follows:

i. Collecting and coding detailed data on origin and destination volumes and signal control inputs.
ii. Calibrating models to replicate the observed driver behavior.
iii. Performing multiple runs for different volume scenarios. For example, 1,920 simulation runs are needed to evaluate 24 hourly volumes over a design life of 20 years for 4 intersection types.
iv. Analyzing the results and reporting the decision choice can be time consuming.

Several studies have developed statistical models that predict the micro-simulation–generated performance measures using a range of volume-based input variables *(24, 29, and 30)*. These models reduce the time spent in step three listed above, but steps one and four are still time consuming. These statistical models also require re-calibration and re-evaluation prior to the evaluation of new conditions.

Another set of tools used for decision assistance includes tools based on simplistic critical lane volume analysis. Examples of such tools include (i) Intersection Design Alternative Tool (IDAT), (ii) Alternative Intersection Selection Tool (AIST), and (iii) Capacity Analysis and Planning of Junctions (CAP-X). These MS Excel–based tools compare multiple intersection types on the basis of volume-to-capacity ratios generated using critical lane volume analysis *(31, 32, 33, 34, and 35)*. The drawback for such tools is that the volume-to-capacity ratio is a relatively simplistic performance measure. The volume-to-capacity ratios are not easily understood by decision makers or the general public and hence cannot be used to effectively communicate the results. Additionally, the volume-to-capacity ratios cannot be monetized to perform a benefit-to-cost analysis for the selected ILT intersections.

The Highway Capacity Software (HCS) can also be used to compare the performance of multiple ILT intersections. The benefits of using HCS as a screening tool are as follows:

i. HCS is faster than micro-simulation in generating estimates of performance measures.
ii. HCS is based on multiple studies conducted throughout United States. HCS uses results from these studies to generate appropriate calibration factors to calibrate HCS for existing operating conditions. For example, the gap acceptance threshold for heavy vehicles can easily be selected from the appropriate table to model given field conditions. These thresholds are a result of multiple validation and calibration studies.
iii. HCS produces several important performance measures, such as delays, that can easily be understood and monetized.

The current version of HCS (6.50 at the time of this study) does not allow direct coding of ILT intersections. However, a few studies have used indirect techniques to successfully code ILTs in HCS 6.50 *(26, 36)*. There is also a plan to include the direct coding of ILT intersections in the next release of HCS. Despite of the benefits listed above, performing multiple runs of HCS can be time consuming. Additionally, there are no tools that can quickly compile and report the performance of different ILT intersections for a given intersection.

An important aspect that the current tools and past studies about ILT intersections are missing is the inclusion of cost and benefit in the evaluation. Because the implementation of ILT intersections is associated with a relatively large investment, it is imperative for planners to evaluate ILT intersections in terms of costs and benefits before reaching a decision. A few studies *(26, 37)* provide an economic analysis of ILT intersections. However, they were more focused on either specific types of ILT intersections or specific engineering projects, and a generic decision support system cannot be developed based on those findings. Against this backdrop, the incorporation of cost and benefit into the evaluation of ILT intersections for the development of a decision support system is a new concept. It should be noted that a similar tool using micro-simulation could potentially be developed but will be significantly more time consuming to use and would need external optimization routines.

DELAY ESTIMATION

Volume Input and HCS Network

SILCC provides for the input of bidirectional hourly volumes for a 24 hour period for major streets and unidirectional hourly volumes for a 24 hour period for minor streets. The bidirectional volume can be multiplied by a user's defined balance factor (BF) to compute each approach volume for a major street, which can be further divided into through and left turn volumes by multiplying by a user's defined left turning percentage (LTP). For minor streets, SILCC considers 0.5 as the BF and 5% as the LTP and performs the calculation internally. Similarly, users have the flexibility to input different truck percentages. SILCC projects the volumes throughout a life cycle period of 20 years based on the user's defined annual increment. By default, SILCC considers a 2% annual increment of traffic on major streets and a 1% annual increment of traffic on minor streets. Each of the four intersections, (i) standard signalized intersections, (ii) MUT, (iii) CFI, and (iv) jughandles, have a total of 480 volume combinations, including a 20 year projection for each hourly volume for 24 hour periods. All the intersections were coded in HCS Streets. Network coding for MUT and CFI was adopted from the method prescribed in a report published by the University of Florida *(36)*, and it was further extended for jughandles. Fully actuated signal operation was taken into account.

Batch Processing and Estimation of Control Delay

To run all 480 combinations for each of the four intersection types, HCS was interfaced with MS Excel by developing macros to administer the batch processing of HCS files through MS Excel. The HCS output provided the control delay (seconds/vehicle) for each movement of signalized intersections and signalized crossovers.

Travel Delay and Delay at Median Openings and Crossovers for MUT and Jughandle

SILCC considers 45 mph and 35 mph to be the default speeds on major and minor streets, respectively. However, users have the flexibility to alter the speeds by adjusting all the parameters that depend on speed in the input sheet as well as in the HCS file. The travel delay for left turn movements was calculated based on speed and distance. The distances are based on the geometry of the ILT intersections, which can be altered by users. The estimation of delay at median openings and crossovers at the ramp merge points of jughandles was performed using queueing flow theory assuming Poisson distribution of arrivals and exponential distribution of service with a single server. This is also known as an M/M/1 queue. The total system delay of an M/M/1 queue is the sum of queue delay and server delay expressed by the following equation:

$$W_s = \frac{\lambda}{\mu \times (\mu - \lambda)} + \frac{1}{\mu} \quad (1)$$

where W_s is the total system delay, λ is the arrival flow rate, and μ is the departure flow rate.

The departure flow rates for the median opening and crossover are the same as for the capacity of the opening or ramp junction. The rates are based on opposing flow, critical gap, and follow-up headway, as provided by the Highway Capacity Manual 2010 (HCM 2010) *(38)* equation to compute the capacity of stop-controlled movement using a gap acceptance model. The follow-up headway and critical gap were calculated based on HCM 2010 equations 19-30 and 19-31 for the respective values for U-turn movements at MUT median openings and right turn movements at jughandle crossovers. These equations are expressed as follows:

$$C_{p,x} = \frac{V_{c.x}\, e^{-\frac{v_{c,x} t_{c,x}}{3600}}}{1 - e^{-\frac{v_{c,x} t_{f,x}}{3600}}} \quad (2)$$

$$t_{c,x} = t_{c,base} + t_{c,HV} P_{HV} \quad (3)$$

$$t_{f,x} = t_{f,base} + t_{f,HV} P_{HV} \quad (4)$$

where $C_{p,x}$ is the potential capacity of movement x (vehicles/hour), $V_{c.x}$ is the conflicting flow rate for movement x (vehicles/hour), $t_{c,x}$ is the critical headway for minor movement (s), $t_{f,x}$ is the follow-up headway for minor movement x (s), $t_{c,base}$ is the base critical headway, $t_{c,HV}$ and $t_{f,HV}$ are the adjustment factors for heavy vehicles, P_{HV} is the proportion of heavy vehicles for movement, and $t_{f,base}$ is the base follow-up headway.

The values for base critical headway and follow-up headway can be obtained from HCM 2010 Exhibit 19-10 and Exhibit 19-11, depending on the type of movement. For median openings, the corresponding values from these exhibits for a U-turn from a major street should be used. Similarly, for crossovers of jughandles, corresponding values from these exhibits for a right turn from a minor street should be used. The adjustment factors for heavy vehicles for critical headway and follow-up headway are dependent on lane configurations and are also provided by HCM 2010.

ESTIMATION OF FUEL CONSUMPTION AND EMISSIONS

Estimation of Fuel Consumption

The American Association of State Highway and Transportation Officials (AASHTO) Red Book has provided a table that gives fuel consumption in gallons per minute delay ($gal_{c,min}$) by vehicle type, such as small car, big car, sport utility vehicle (SUV), two-axle single unit vehicle, three-axle single unit vehicle, and combo, according to free-flow speed *(39).* This table was utilized to compute fuel consumption at intersections and crossovers. Six vehicle categories were combined to form two categories: cars and heavy vehicles. The $gal_{c,min}$ of vehicle type car is the average of the $gal_{c,min}$ values of small cars, big cars, and SUVs. Similarly, the $gal_{c,min}$ of heavy vehicles is the average of the $gal_{c,min}$ values of two-axle single unit vehicles, three-axle single unit vehicles, and combos. Table 1 shows the $gal_{c,min}$ value of cars and heavy vehicles computed by this method. To compute fuel consumption, the delay (seconds/vehicle) for each intersection was converted to delay in vehicle minutes separately for cars and trucks. The vehicle minute delay values of cars and trucks were multiplied by the respective $gal_{c,min}$ values from Table 1 to get fuel consumption by each vehicle type. Similarly, to calculate fuel consumption from travel delay especially related to MUT and jughandles, a table was referenced in the AASHTO Red Book that provides the fuel consumption in gallons per mile for autos and trucks with respect to operating speed. The values from that table from the AASHTO Red Book are shown in Table 2.

TABLE 1 Fuel Consumption (Gallons) per Minute of Delay by Vehicle Type

Free Flow Speed (mph)	Small Car	Heavy Vehicle (Truck)
20	0.02	0.12
25	0.02	0.16
30	0.03	0.19
35	0.03	0.23
40	0.03	0.26
45	0.04	0.30
50	0.04	0.34
55	0.05	0.37
60	0.06	0.41
65	0.06	0.45
70	0.07	0.49
75	0.08	0.53

TABLE 2 Fuel Consumption Related to Operating Speed

Speed (mph)	Gallons per Mile	
	Autos	Trucks
5	0.117	0.053
10	0.075	0.316
15	0.061	0.254
20	0.054	0.222
25	0.05	0.204
30	0.047	0.191
35	0.045	0.182
40	0.044	0.176
45	0.042	0.170
50	0.041	0.166
55	0.041	0.163
60	0.040	0.160
65	0.039	0.158

Estimation of Emissions

This study estimated four major types of vehicular emissions: carbon monoxide (CO), oxides of nitrogen (NO_x), volatile oxygen compounds (VOCs), and carbon dioxide (CO_2). Cobian et al. *(40)* developed the factors to convert fuel consumption in gallons to gram unit weight of emissions like CO, NO_x, and VOCs. These factors are 69.9 grams/gallon for CO, 13.6 grams/gallon for NO_x, and 16.2 grams/gallon for VOCs. Similarly, the U.S. Department of Energy has published a document *(41)* that correlates CO_2 emissions in grams to fuel consumption for gasoline and diesel. The conversion factor for gasoline consumption to CO_2

emissions is 17.59 grams/gallon. The conversion factor for diesel consumption to CO_2 emissions is 22.37 grams/gallon.

MARGINAL USERS' AND NON-USERS' COSTS AND MONETIZATION

A user's marginal cost pertains to the difference in the cost of delay and fuel consumption when new ILT intersections are constructed instead of signalized intersections or when a standard signalized intersection is retrofitted with ILT intersections. Similarly, a non-user's cost pertains to the difference in the cost of emissions when new ILT intersections are constructed instead of signalized intersections or when a standard signalized intersection is retrofitted with ILT intersections. These costs are calculated by subtracting the amount of each item produced by a standard signalized intersection from the amount of each item produced by an ILT intersection. If the deducted value is negative, it is called a negative cost or a benefit. Unit prices of each item can be calculated either by their own rate analysis or by referencing past literature. The default unit price of time in congestion (price of delay) was considered to be $16.79/hour based on the 2012 Urban Mobility Report *(42)*. The default unit prices of fuel for diesel and gasoline were calculated by averaging the 2012 average gas prices for Nebraska provided by AAA's Fuel Gauge Report (gasoline was $3.704/gallon, diesel was $3.956/gallon) *(43)*. The default unit price of CO_2 ($0.02/kg) was taken from the 2010 Annual Supplement to the National Institute of Standards and Technology (NIST) *(44)*. The default unit price of CO ($200/ton) was taken from a technical paper by Bishop et al. *(45)*. Similarly, unit prices for NO_X ($250/ton/year) and VOCs ($180/ton/year) were taken from Muller and Mendelson *(46)* considering median damage cost. These prices are listed in Table 3. In SILCC, users are allowed to alter these prices if needed. These marginal benefits were monetized by multiplying the quantities by respective unit prices.

MARGINAL AGENCY COST AND MONETIZATION

The marginal agency cost includes the marginal agency cost for both new construction of ILT intersections and retrofits of ILT intersections compared to the cost for standard signalized intersections. The marginal agency cost includes the cost of construction, preliminary engineering (PE) costs, and the additional operation and maintenance (O&M) cost. The marginal construction quantities for new construction were estimated based on the additional pavement requirement, additional signals and installations with the related accessories, and additional right of way needed for new ILT intersections compared to those values for standard signalized intersections. The construction quantities for retrofits were estimated based on the additional pavement requirement, removal of existing pavements, additional signals and installations with the related accessories, etc., needed while retrofitting standard signalized intersections with ILT intersections. The latest English average unit prices (AUP) from the Nebraska Department of Roads (NDOR) *(47)* were used as the default unit prices of items in SILCC. The default unit price of land ($4,142.5/acre) was calculated with reference to the United States Land Values 2012 Summary *(48)* by averaging the unit price of real estate land ($2,590/acre), cropland ($4,480/acre), irrigable land ($6,000/acre), and non-irrigable land ($3,500/acre). However, the users were provided flexibility to alter these rates. The PE cost involves expenses for activities from planning to final design of a project. According to Turochy et al., most state departments of transportation (DOTs) consider PE cost to be in the range of 5% to 20% of the construction cost, depending on the project size and scope *(49)*. Remaining in that range, this study considered the PE cost to be 10% of the construction cost. Contingency was assumed to be 20% of the construction cost *(26)*. These costs are listed in Table 3. The O&M unit price for CFI was estimated based on the service requirement for additional signal heads and detectors, signal retiming cost, and power supply cost. Similarly for MUT and jughandles, the unit price of O&M was fixed based on the cost for landscaping medians and the area enclosed by reverse ramps. The agency costs were monetized by multiplying the quantities of each item by respective unit prices. The computed marginal costs of all three ILT intersections having the configuration of a four-lane major street and a two-lane minor street for new construction and retrofits corresponding to the default values in SILCC are shown in Table 4.

TABLE 3 Variables and Related Information

Construction Cost Related		
Items	**Prices**	**Source of Information**
Land (Right of Way)	$4142.5/Acre	United States Land Values 2012 Summary
All other Constructed related Unit Prices	According to AUPs from NDOR	NDOR website
PE Cost	10% of construction cost	Turochy et al. (2001)
Contingency	20% of construction cost	Boddapati (2008)
Unit Prices of Operational Performance Measures		
Items	**Unit Prices**	**Source of Information**
Delay	$ 16.79/hour	2012 Urban Mobility Report
Petrol	$ 3.704/gallons	AAA's Fuel Gauge Report
Diesel	$ 3.956/gallons	
CO_2	$ 0.02/kg	U.S. Department of Energy: NIST (2010)
CO	$ 200/ton	Bishop et al. (1993)
NO_x	$ 250/ton/year	Muller and Mendelson (2009)
VOC_s	$180/ton/year	

TABLE 4 Computed Marginal Cost of ILT Intersections

Intersection Type	Construction Cost + Soft Cost Including Contingency (US $)		O&M Cost (US $)	
	New Construction	Retrofit	New Construction	Retrofit
MUT	36, 763	680, 426	2, 000	2, 000
CFI	279, 226	439, 799	24, 000	24, 000
Jughandle	64, 551	64, 635	2, 000	2, 000

LIFE CYCLE COST ANALSYIS (LCCA)

SILCC is capable of performing life cycle cost analysis (LCCA) on monetized agency, user's, and non-user's marginal costs to determine the NPV and B/C of new construction and retrofits for ILT intersections. The life cycle period of the retrofits was assumed to be 20 years. The default discount rate was kept at 3% with no inflation for each year *(26)*. However, users may alter it. The annual increase of traffic was considered to be 2% for major streets and 1% for minor streets. The delay for each of the projected volumes for a 20 year period was estimated by batch running the HCS 2010 . The respective fuel consumption and emissions and their annual costs were estimated. The operation and maintenance cost was assumed to be the same throughout the life cycle period. The NPV was estimated using the following equations:

$$NPV\ of\ Total = NPV\ of\ Benefits - NPV\ of\ O\&M\ Cost - Construction\ Cost - PE\ Cost \quad (5)$$

$$Benefit\ to\ Cost\ Ratio\ (B/C) = NPV of\ Benefits / \{NPV\ of\ O\ \&\ M\ Cost + (Construction\ Cost + PE\ Cost))\} \quad (6)$$

$$NPV\ of\ O\ \&\ M\ Cost = \left(\frac{1}{i}\right) \times \left\{1 - \frac{1}{(1+i)^N}\right\} \quad (7)$$

$$NPV\ of\ Benefits = \sum_{N=o}^{20} P_N \times \frac{1}{(1+i)^N} \quad (8)$$

where N is the life cycle period, i is the discount rate (3%), and P_N is the yearly negative or positive benefits.

If any retrofits or new ILT intersections failed due to high demand in any year throughout the life cycle period, the NPVs of those retrofits were calculated assuming a reduced life cycle period. The reduced life cycle period equals the time period up to which intersection operation is feasible. This case is applicable for MUT and jughandles because they were evaluated with

M/M/1 queues, where the server's capacity should not be exceeded by demand. This is because the queuing system works until the utilization factor (ratio of demand to service capacity) remains less than 1.

A CASE STUDY PERFORMED WITH SILCC

As a case study, a volume pattern was developed for a rural road following one of the 24 hour data patterns provided by Williams and Ardekani *(50)*. The developed pattern is shown in Figure 1. The delay, fuel consumption, and emissions were estimated for each unit of 24 hour volume data considering 10% truck and 5% left turning traffic using SILCC for the whole 20 years of the life cycle period and considering a default annual increment in traffic (2% on major streets and 1% on minor streets). A default lane configuration of a four-lane major street with a speed of 45 mph and a two-lane minor street with a speed of 35 mph was considered. The construction estimates for retrofits and new construction for ILT intersections were the same as those discussed in previous sections. Similarly, corresponding default rates of items were used as mentioned in previous sections. SILCC provided the results from the LCCA, as displayed in Table 5. The results indicate that an MUT intersection would have the highest NPV total for both retrofit and new construction. However, due to its high construction cost for retrofit, the B/C ratio of MUT is lower than that of a jughandle. MUT has the highest B/C for new construction. It should be noted that NPV is considered a more stable measure because the B/C ratio might produce different results if a cost is replaced as a negative benefit by the analyst.

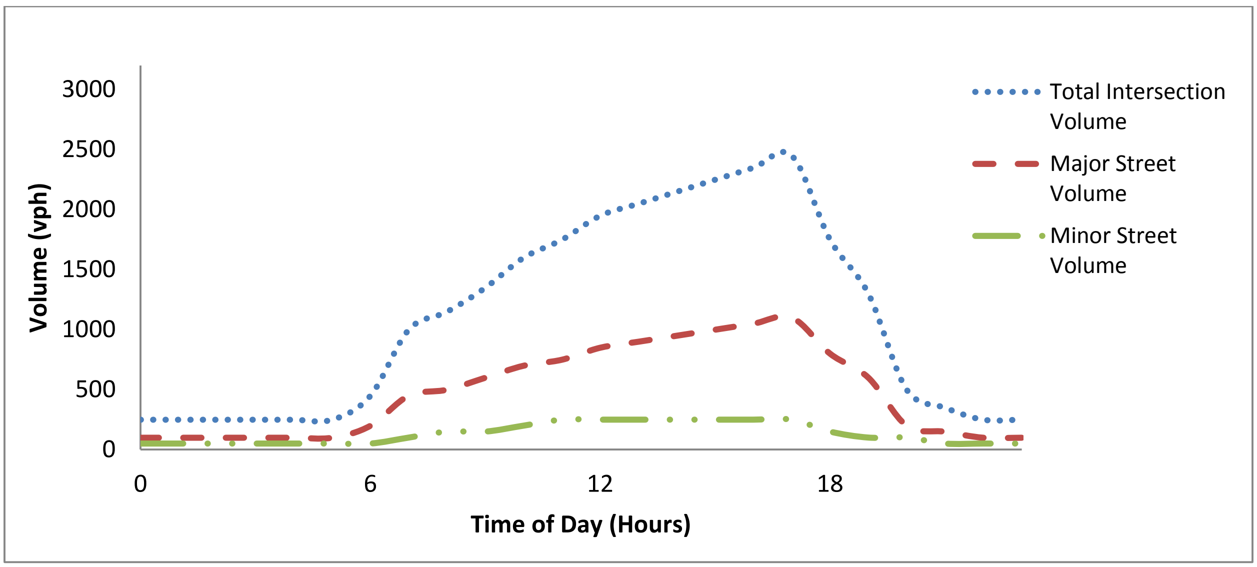

FIGURE 1 Volume pattern for a rural road

TABLE 5 LCCA Results for Case Study

Cases	LCCA Outcomes	MUT	CFI	Jughandle
New Construction	Marginal Construction + Marginal Soft Cost (US $)	36, 763	279, 226	64, 551
	NPV of Marginal O&M Cost (US $)	29, 755	357, 059	29, 755
	NPV of Marginal Operational Benefit (US $)	4, 398, 266	949, 519	2, 349, 585
	NPV Total (US $)	4, 331, 748	313, 233	2, 255, 279
	B/C	66.12	1.49	24.91
Retrofits	Marginal Construction + Marginal Soft Cost (US $)	680, 426	439, 799	64, 635
	NPV of Marginal O&M Cost (US $)	29, 755	357, 059	29, 755
	NPV of Marginal Operational Benefit (US $)	4, 398, 266	949, 519	2, 349,585
	NPV Total (US $)	3, 688, 084	152, 660	2, 255, 195
	B/C	6.19	1.19	24.89

CONCLUSION

Realizing the need to incorporate cost and benefit aspects in the decision making process, the tool developed from this study took into account the costs and benefits related to ILT treatments of standard signalized intersections, whether with new construction or with a retrofit. This is the first time that the economic aspect has been incorporated into a decision assistance tool for ILT intersections. Additionally, the tool utilizes a macroscopic-level analysis of the operation of intersections using HCS software, which provides widely acceptable estimations of performance measures. The tool also considers fuel consumption and emissions in operational analysis as well as in economic analysis. The tool was developed by keeping it as simple as possible and providing flexibility for users to alter the input to fit with the required local conditions. Overall, the developed tool can perform as a very good decision assistance tool for planners when making crucial decisions about suitable ILT treatments. Finally, a study is recommended to incorporate safety aspects and the impact of multimodal users into updates for the tool. Because past studies have noted that ILTs are relatively safe compared to conventional intersections, one can expect a safety component to increase the benefits. Similarly, a future study can further evaluate the potential impact of each cost variable in the LCCA results.

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