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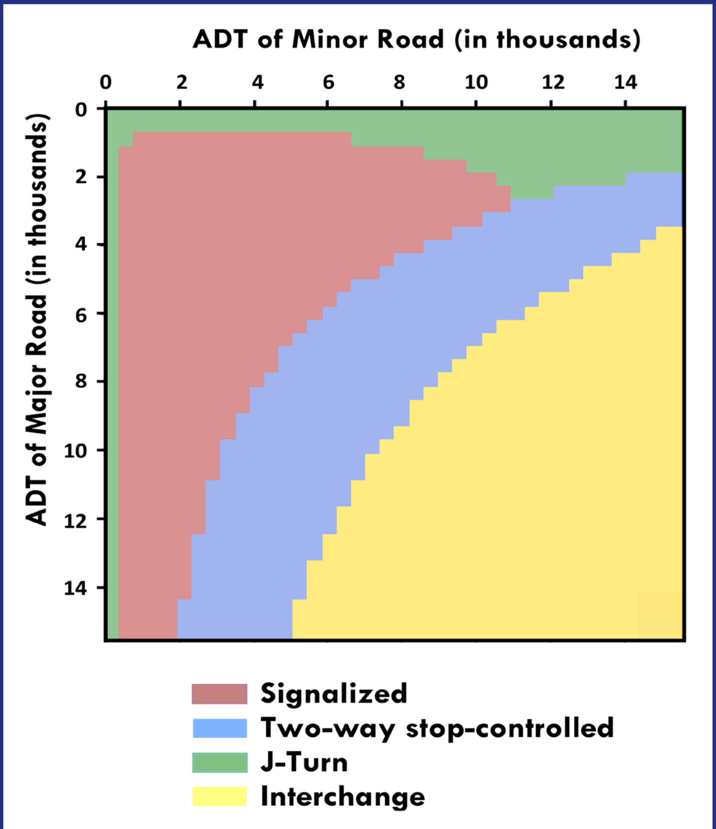
Cost-Effectiveness of Converting Signalized Arterials to Free-Flow Facilities



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16. Abstract

Traffic signals on four-lane divided signalized arterials impair mobility and exacerbate traffic congestion, driver frustration, crash risk, and overall user and community costs. This study examined the economic feasibility of converting this roadway type to free-flow corridors. A free-flowing facility does not refer to a freeway, but rather, a facility that is free of traffic control devices (such as traffic signals and stop signs) on the mainline. At the intersection level, four intersection alternatives were considered: signalized intersection (do nothing), two-way stop-controlled (TWSC) intersection, J-turn and interchange. The study developed a decision framework that evaluates the overall performance of upgrade alternatives at the intersection and corridor levels in terms of the total life-cycle agency and user cost associated with mobility and safety.

It was found that when traffic volumes are low, the TWSC intersection has superior mobility performance over J-turn and signalized intersection. Interchange and J-turn exhibited superior safety performance compared to TWSC and signalized intersections. Interchange always has the highest mobility performance particularly where the major and minor road traffic volumes are high. The study also developed nomographs to present rankings of the alternatives and established decision boundaries based on major and minor road traffic volumes. The nomographs can help INDOT identify the appropriate intersection type based mainly on the major and minor road traffic volumes.

At the corridor level, the two conversion alternatives are free-flow corridor (with a mix of TWSC, J-turn and interchanges) and freeway corridor (interchanges only). Overall, the evaluation results were found to be sensitive to traffic volumes and weight ratio of the agency cost to user cost dollar. The study also developed a spreadsheet program to facilitate implementation of the decision support framework.

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EXECUTIVE SUMMARY

Introduction

On four-lane divided signalized arterials, traffic signals pose a significant impediment to mobility. They often cause traffic congestion, driver frustration, decreased safety, and overall higher costs to highway users, the environment, and the economy through higher operating costs, emissions, and shipping delay. This research study examined the economic feasibility of converting existing signalized four-lane divided highways into free-flow corridors, where intersections with traffic signals are removed and redesigned as interchanges, J-turns, or other types of intersections. This study identified the conditions under which such conversion is cost effective and the threshold traffic volume at which converting a signalized arterial to a free-flow facility can be considered superior to doing nothing.

The developed decision framework addresses these questions by evaluating the overall performance of several corridor upgrade alternatives at two analysis levels: intersection and corridor. At the intersection level, four intersection alternatives were considered: signalized intersection (do nothing), two-way stop control (TWSC) intersection, J-turn, and interchange. The mobility and safety performance of the four alternatives were calculated, with the overall performance of an alternative measured in terms of the total life-cycle agency and user costs. This study was commissioned by the Indiana Department of Transportation to address this research need.

Findings

It was found that interchange always has the highest mobility performance. When traffic volume is very low, TWSC intersection has superior mobility performance compared to J-turn and signalized intersection. However, as traffic volume increases, delays at TWSC intersections increase significantly, while delays for the alternatives depend less on traffic volume. In terms of safety performance, interchange and J-turn are generally safer than the TWSC intersection and signalized intersections. It was found that the overall performance of TWSC intersection is the most sensitive to traffic volume.

The study also established decision boundaries based on traffic level on the major and minor roads. Nomographs were developed to present the rankings of the alternatives under given traffic volumes and the decision boundary at which the rankings of any two alternatives switch. It was found that, when the major ADT (average daily traffic) is less than 3,000 vehicles per day, the best option generally is TWSC. When the minor ADT is less than 4,000, J-turn is almost always more cost-effective than interchange, regardless of the major ADT. When the traffic volumes on major roads and minor roads are large enough, interchange is the best option. The nomographs can help the agency choose the appropriate intersection type based on the traffic volumes on both major and minor roads.

At the corridor level, the two conversion alternatives are free-flow corridor (with a mix of TWSC, J-turn, and interchanges) and freeway corridor (interchange only). Using corridor-level case studies, it was found that the freeway corridor plans are more beneficial to the users and have lower combined life-cycle equivalent uniform annual cost (EUAC) compared to the free-flow plans when agency cost and user cost are equally weighted. However, as a trade-off, the agency needs to spend much more on initial construction. Therefore, when agency cost is assigned greater weight, the freeway corridor conversion plans become very expensive and cannot compete with any other plan. The evaluation results are sensitive to traffic volume, corridor length, and the weight ratio of the agency cost to user cost dollar

Implementation

This study developed a spreadsheet program to facilitate implementation of the decision support framework. This research product is designed to facilitate implementation of the study framework and results (that is, the decision supports nomographs) to ascertain that they are appropriate and useful for the purpose for which they are intended. With the study product, INDOT is expected to be in a better position to support its decisions regarding corridor upgrades.

The intended primary user and implementor of the study is the Corridor Development Office of the Traffic Engineering Division of the Indiana Department of Transportation

In the 2019–2020 period, the research and its associated decision-making support application have been invaluable to INDOT in evaluating (quantifying), confirming, and defending both corridor-level and site- or intersection-specific traffic control strategies, the latter including proper application of non-traditional or innovative intersection forms. The most notable of those uses were two 60- and 100-mile corridors in northcentral and northern Indiana involving $100 million plus investments. For those and several others, the research findings have guided the agency's evaluation, that is, in determining the most cost-effective level of overall traffic control, be it full freeway operation, a hybrid of select interchanges and at-grade intersections, free flow operation, or more conventional designs with prevailing traffic signal control.

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1. INTRODUCTION

Highway infrastructure development is a dynamic process: highways are reconstructed, expanded, or upgraded in response to economic and societal needs. At each increment, the highway agency analyzes the existing situation based on the life-cycle costs and benefits of alternative actions, and a decision is made whether to proceed with the improvement. A specific example of this decision context is the conversion of a signalized arterial to a free-flow facility. In this specific example, the decision is made only after carefully evaluating such conversion based on its costs and benefits relative to a base case (often the do-nothing alternative). The costs and benefits can be expressed in terms of the economic (life-cycle costs) and technical (mobility enhancement) performance considerations.

In converting existing signalized four-lane divided highways to free-flow corridors, intersections with traffic signals are removed and redesigned as interchanges or J-turn intersections. The conversion still allows, at some locations, two-way stop control intersections and driveway access intersections (INDOT, 2018). A full limited-access freeway requires that all access to the facility be restricted to interchanges (no other intersection types are allowed). Minor roads and driveways must be reconstructed, and in some cases, alternate means of access must be provided using frontage roads or overpasses. The main added benefit of a freeway is the time saved due to higher permitted speeds. However, in many cases of freeway construction, the travel time savings is quite small while the cost increase is significant. It has been estimated that existing signalized four-lane divided highways can be converted to free flow corridors for 10% to 20% of the cost of a full limited access-controlled freeway facility; intersections with traffic signals can be converted to interchanges or J-turn intersections (INDOT, 2018).

1.1 Problem Statement/Motivation

The Indiana Department of Transportation (INDOT) has identified a research need to investigate and provide guidance related to the following questions: what is the benefit to cost relationship associated with the conversion of a signalized rural four-lane divided highway to free-flow facility versus full limited-access controlled freeway facilities? A tradeoff exists between the agency cost of redesign/reconstruction and the user cost of travel time) and it has been hypothesized that in certain cases, freeway conversion could represent a poor allocation of limited resources. Under which conditions is this hypothesis valid? At four-lane divided signalized arterials, traffic signals pose a significant impediment to mobility and often cause traffic congestion, driver frustration, decreased safety, and overall higher costs to highway users, the environment, and the economy through higher operating costs, emissions, and shipping delay (FHWA, 2005; Ng & Small, 2012). In such cases, there seems to exist a certain quantifiable value to mobility when traffic signals are removed from these routes: as travel time decreases and as there is increased freedom of movement on the mainline, the road users' satisfaction with the route also improves (INDOT, 2018).

In addressing these questions, an important issue is the threshold traffic volume at which converting a signalized arterial to a free-flow facility can be considered superior to doing nothing, in terms of combined economic and technical performance. This threshold may also be different for different existing local situations. To help INDOT identify the corridors on the state highway network that most warrant conversion to free-flow, it is needed to identify the appropriate benchmark traffic volumes at which it is most appropriate, from a life-cycle cost viewpoint, for upgrading.

1.2 Relevant Definitions

This research project focuses on state highway corridors in Indiana. As such, the research team has adopted the following definitions from INDOT that are used throughout the report (INDOT, 2018).

1.2.1 Intersection Definitions

Signalized intersection. An intersection where movement is controlled through the use of traffic signals. Vehicles are typically required to stop and await green signals to pass through the intersection.

Two-way stop controlled intersection. An intersection where mainline traffic is allowed to pass through the intersection without stopping, and side street traffic is required to stop and wait for a gap in traffic before passing through the intersection. On divided highways, side-street traffic may also have to wait in the median for a second gap to proceed across the second half of the intersection.

Interchange. An intersection where mainline traffic is grade-separated (either above or below) side street traffic through the use of a bridge. Mainline traffic is allowed to pass through the intersection without stopping. Access to and from the side street is provided via a system of ramps.

Median U-turn. A median U-turn (MUT) is a type of intersection where some left-turns or crossings from the mainline road or secondary crossroad are made using indirect, downstream U-turn movements. There are three subtypes of median U-turn.

Restricted crossing U-turn. A restricted crossing U-turn (RCUT) is a type of MUT where the main intersection is controlled with a signal, and the U-turns may be as well. An example of an RCUT is shown in Figure 1.1.

J-turn. A J-turn functions similarly to an RCUT, with the exception that all movements are controlled by yield or stop signs, not traffic signals. Mainline traffic is free-flowing, and side street and turning traffic must wait for a gap in mainline traffic to proceed. J-turns are the primary type of median U-turn and is a focus of this study. Figure 1.2 presents an example of a J-turn.

Boulevard left. A boulevard left is a variant of the J-turn where direct left turns from the mainline are not permitted, and vehicles are required to use the median U-turns. A signal permits side street traffic to proceed directly across the intersection. Turning traffic must wait for a gap in mainline traffic to proceed. This type of intersection may also be known as a Michigan Left. In some cases, it may also be constructed without direct crossings for side-street traffic. In this case, side street through traffic would have to make a series of turns and use the median U-turn to proceed across the mainline. An example of a boulevard left is shown in Figure 1.3.

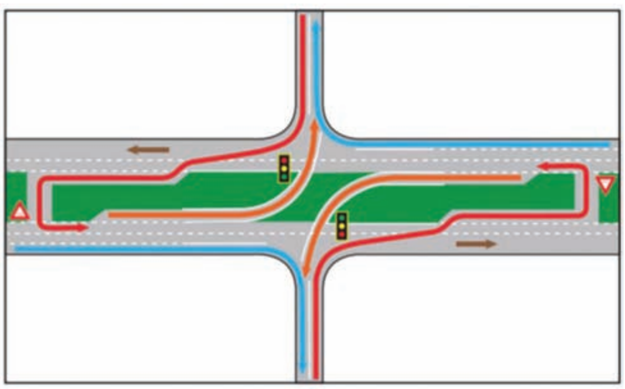


Figure 1.1 A restricted crossing U-turn (INDOT, 2018).

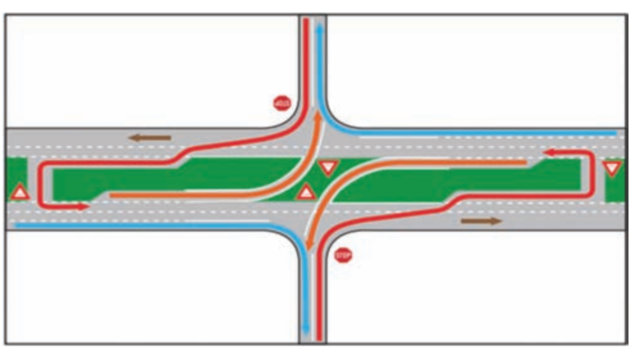


Figure 1.2 A J-turn (INDOT, 2018).

1.2.2 Roadway Classifications

Signalized arterial. A multilane, divided facility that provides access via any combination of traffic signals, two-way stop-controlled intersections, median U-turn intersections, or interchanges. Traffic on the mainline may be required to stop at red signals. Speed limits on signalized arterials tend to vary based on the intersection types, location (urban/rural), and terrain.

Free-flow arterial. A multilane, divided facility that provides access via two-way stop-controlled intersections, median U-turn intersections, or interchanges, but not signalized intersections. Traffic on the mainline is never required to stop during normal operations. The typical speed limit on Indiana free-flow arterials is 60 mph.

Freeway. A multilane, divided facility that only provides access via fully grade-separated interchanges. Traffic on the mainline is never required to stop during normal operations. The typical speed limit on Indiana freeways is 65 mph, unless the freeway is an interstate highway, in which case the typical speed limit is 70 mph.

1.3 Study Objectives

This study developed guidelines for use in determining when it is cost-effective to convert a signalized arterial to free-flow corridor or a full limited-access controlled highway in terms of both agency and user costs. The agency costs considered in this report include the construction costs and annual maintenance costs associated with each conversion alternative. The user costs consist of the travel time costs, intersection delay costs and accident costs. The analysis was carried out at two levels. At the intersection level, the economic benefits and life-cycle costs of changing a signalized intersection to free-flow facility (including two-way stop controlled (TWSC) intersection, J-turn intersection or a conventional diamond interchange) were compared. At the corridor level, the comparisons were conducted among the corridor conversion alternatives

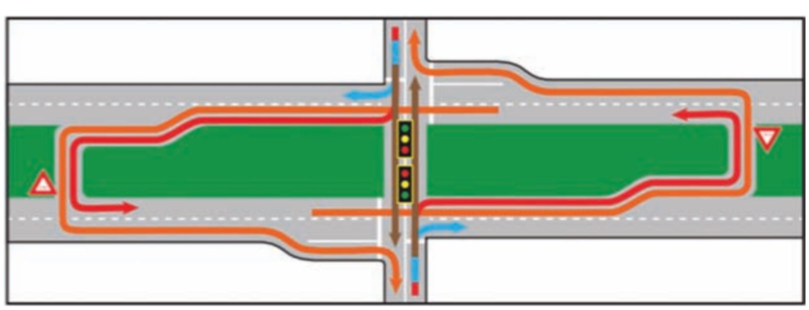


Figure 1.3 A boulevard left (INDOT, 2018).

including free-flow corridor with mix of free-flow facilities or full limited access-controlled freeway.

The main results from this study include (1) comparison of the cost and effectiveness of the four intersection types (signalized, TWSC, J-turn and interchange) in terms of mobility, safety, user costs and agency costs; (2) evaluation of the overall performance of a free-flow facility compared to a full limited-access controlled freeway; (3) determination of the boundary traffic volumes on both major and minor roads that warrant the choice of either alternative; and (4) sensitivity analysis on how the boundary traffic volumes change under different agency to user cost ratio and discount rates.

The framework accommodates the practical realization that the corridor conversion decision is influenced by the specific context and location in question; therefore, the best choice as well as the benchmark traffic volume is expected to differ for different site conditions. A case study is provided to demonstrate the application of the framework to a specific road corridor. A spreadsheet program was developed in this study to give INDOT the flexibility to change any input values in the framework to reflect the local conditions at any specific location (see Appendix).

2. BACKGROUND

2.1 Summary of Past Research

Existing work in the area of freeway upgrades tends to be limited to analysis of a single type of intersection treatment studied at multiple locations to assess performance in the areas of safety, operations, delay, or cost. Limited work has been conducted at the corridor level. Bonneson, McCoy, and Eitel (1993) examined the impacts of upgrading a two-way stop-controlled intersection to either a signalized intersection or an interchange. Economic, safety, and operational costs were considered, and feasible threshold traffic levels for each treatment were suggested. The Bonneson study did not include analysis of J-turns. Reid and Hummer (2001) compared traditional (signalized) intersections with median U-turn and other unconventional intersection types, such as jug handle and bowtie intersections, and found that the unconventional intersections often exhibited superior performance compared to the conventional intersection from an operational perspective. Eyler (2005) discussed the trade-offs between signalized arterials (due to reduced capacity) and freeway conversion (cost, community impacts, and time) and discussed a possible treatment using grade separation and a connector road, similar to what has been implemented on Indiana's SR 25 corridor (included in this study). Pirdavani, Brijs, Bellemans, and Wets (2011) conducted a simulation-based operational analysis of median U-turns and found that their operational performance is generally superior to signalized intersections. However, their study criteria did not include safety effects.

Edara et al. (2013) evaluated the operational performance of J-turns in Missouri and found that they led to a reduction in total crashes and crash severity. The work also analyzed the operational performance of these intersections. However, their study adopted a wider definition of J-turn and included several different types of intersections, each with slightly different characteristics in the definition of J-turn. This made it difficult to apply this work to specific configurations of J-turn under consideration by INDOT. Bai, Ahmed, Labi, and Sinha (2017) evaluated two alternatives: widening (lane addition) and expressway upgrade treatments for a corridor-based life-cycle cost, and identified the benchmark traffic threshold for upgrading an arterial to a freeway. However, the design alternatives in their study did not include free-flow facilities.

These studies provided the groundwork for the analysis of the present study. Many focused on single intersection treatments, while others evaluated corridors albeit with limited scope (e.g., looking to only upgrade signals to interchanges). While useful, these studies did not consider all the alternatives available to INDOT, many of which are believed to provide greater benefit for a reduced cost (e.g., installing a J-turn instead of a full interchange). The present study builds upon this past work in order to complete a more comprehensive review, both at the intersection level and the corridor level.

2.2 Relative Weights of Agency Cost and User Cost

An important consideration in economic analysis of public infrastructure projects is the relative weight of the agency cost dollar and the user cost dollar (Sinha & Labi, 2007). The cost to the agency to build and operate the facility may have a higher level of importance than the cost to the users of the roadway in terms of travel time, safety, and other indirect or intangible costs. If the agency cost is assigned a weight that is much higher than that of the user cost, then the results will tend to prioritize the alternatives that have lower construction costs, even if they provide lower benefits to road users. Similarly, if the user cost is assigned a weight higher than that of the agency cost, then the results may prioritize those treatments that provide the most user benefits, even if the costs borne by the agency on construction and operations is very high. For these reasons, it is important to use in the analysis, an appropriate ratio of relative weights that does not unduly bias the results to either of these extremes.

This consideration is made complicated by the fact that agencies often do not know explicitly the appropriate ratio to assign to the weight of the agency cost dollar to the user cost dollar. To overcome this challenge, this research presents the results with a variety of agency and user cost weight ratios (1:1, 2:1, etc.), and conducts a sensitivity analysis to measure the influence of the different weight ratios on the optimal solution. Additionally, such sensitivity analysis gives the agency additional flexibility in the future in case where this ratio changes due to changing agency priorities or other factors.

2.3 Potential Study Corridors

The research team, in conjunction with the project study advisory committee (SAC) identified several corridors in Indiana for use as possible case studies. Each corridor has varying levels of traffic, different mixes of intersection types, and different mixes of urban/rural roadway. This was intentional and designed to allow the work to be flexible and easily adaptable to other corridors. Each study corridor is briefly described below. Figure 2.1 shows the location of the study corridors within Indiana.

2.3.1 SR 25 from Lafayette to Logansport

The first identified corridor is State Road 25, from Lafayette (at a roundabout with Old SR 25) to Logansport (at an interchange with US 24). This corridor was recently upgraded to a 4-lane divided arterial and passes through almost exclusively rural areas. Most intersections along the corridor are two-way stop controlled (with the exception of 2 interchanges), and several crossroads have been grade-separated through the use of bridges, connector roads, and 3-leg intersections. The corridor is approximately 34 miles long. A map of the corridor is shown in Figure 2.2.

2.3.2 US 30 from Valparaiso to Plymouth

The second corridor is US 30, from Valparaiso (at an interchange with SR 49) to Plymouth (at an interchange with US 31). This is also a 4-lane divided arterial, and is primarily rural, with the exception of short stretches at the beginning (in Valparaiso), and the end (in Plymouth). Most intersections are two-way stop controlled, with a few major intersections having been upgraded to signalized intersections, or interchanges. This corridor is approximately 39 miles long. A map of the corridor is shown in Figure 2.3.

2.3.3 US 35/SR 67 Around Muncie

The final corridor is a bypass around the city of Muncie. The southern end is signed as SR 67, which is

Figure 2.1 Location of study corridors in Indiana. (Source: Google Maps.)

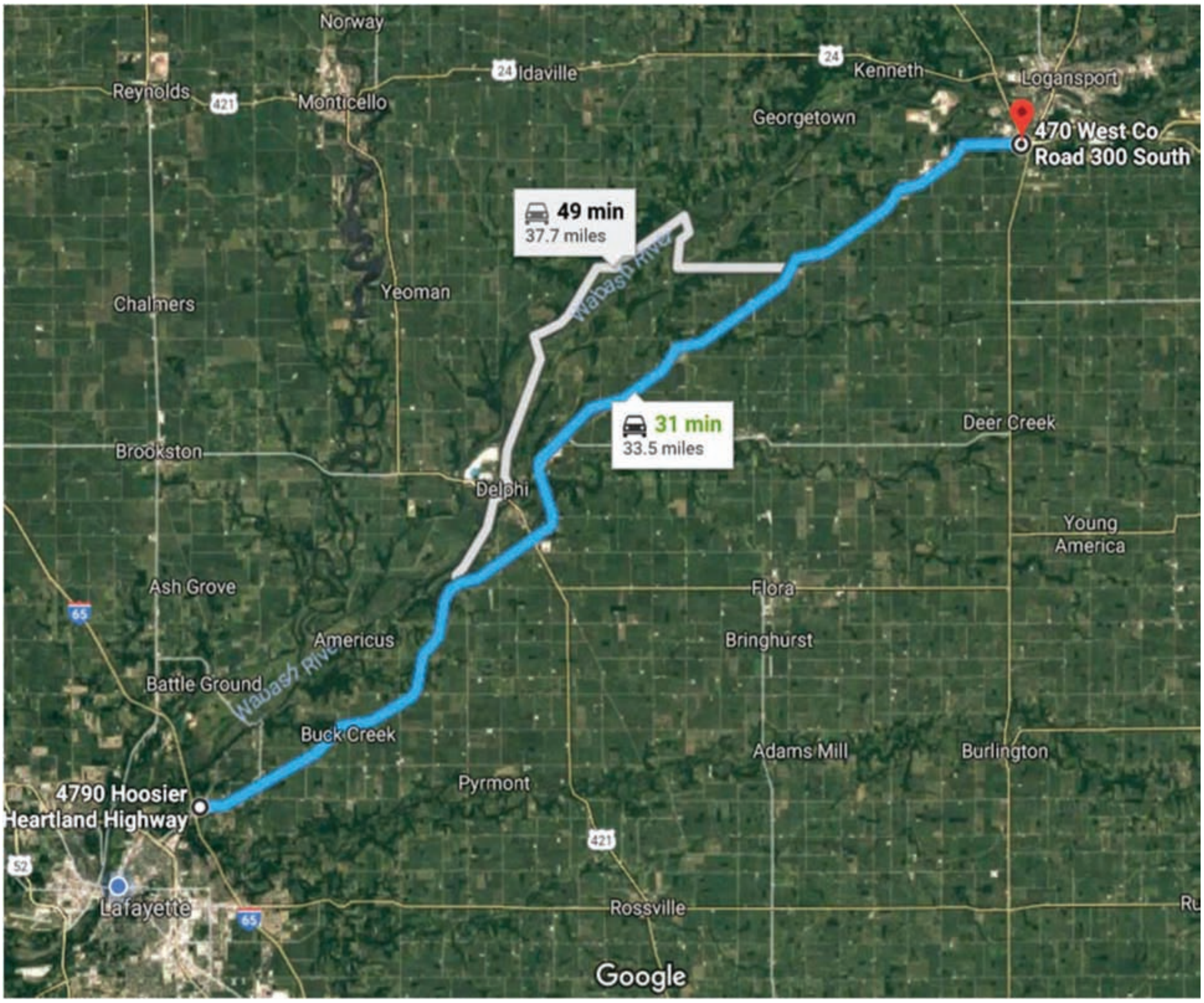


Figure 2.2 State Road 25 corridor from Lafayette to Logansport. (Source: Google Maps.)

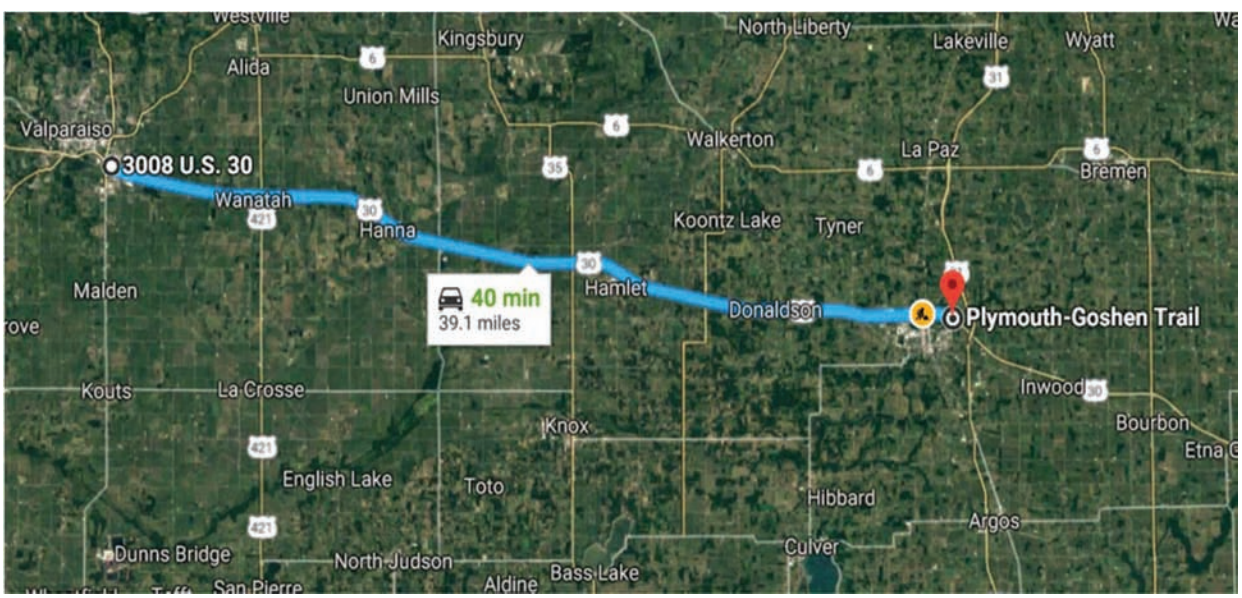


Figure 2.3 US 30 corridor from Valparaiso to Plymouth. (Source: Google Maps.)

Figure 2.4 US 35/SR 67 corridor near Muncie. (Source: Google Maps.)

joined by US 35 to run concurrently around Muncie to the north. The corridor begins as SR 67 at an interchange at Fuson Road, and continues around the south and east sides of Muncie, ending at an interchange with Old SR 3 on the north side of Muncie. The corridor is a 4-lane divided arterial and is much more urban in nature than the previous two corridors. Most intersections on the corridor are either signalized or are already upgraded to full limited-access interchanges. The corridor is approximately 10 miles long. A map of the corridor is shown in Figure 2.4.

3. FRAMEWORK AND METHODOLOGY

3.1 Framework

This study focuses on analyzing and comparing the life-cycle costs of several different intersection conversion alternatives and corridor conversion plans. A corridor plan can be considered as a sequence of intersection designs along a corridor, which may be the same or different. The general study framework is presented in Figure 3.1. The first step is to identify prospective study areas, which could be a single intersection, multiple intersections, or an entire corridor. The next step is to collect data on existing traffic, travel time, safety and environment conditions for the selected areas. This data is subsequently used as input for the analysis. Where the travel time and safety data are unavailable at the study area, the models proposed in this chapter can be used to make estimations of these data items.

An analysis of the alternatives was carried out at two levels: intersection-level and corridor-level. At the intersection-level, the conversion alternatives are: (1) signalized intersection, (2) two-way stopped controlled (TWSC) intersection, (3) J-turn intersection and (4) Interchange. At the corridor level, the alternatives considered are: (1) do nothing (existing corridor with signalized intersections), (2) free-flow corridor (corridor with a mix of TWSC intersections, J-turn or interchange), and (3) full-controlled limited-access highway or freeway (corridor with interchanges or overpass only).

At each level, the performance levels of different alternatives were compared using monetized and non-monetized measures. The monetized measures include

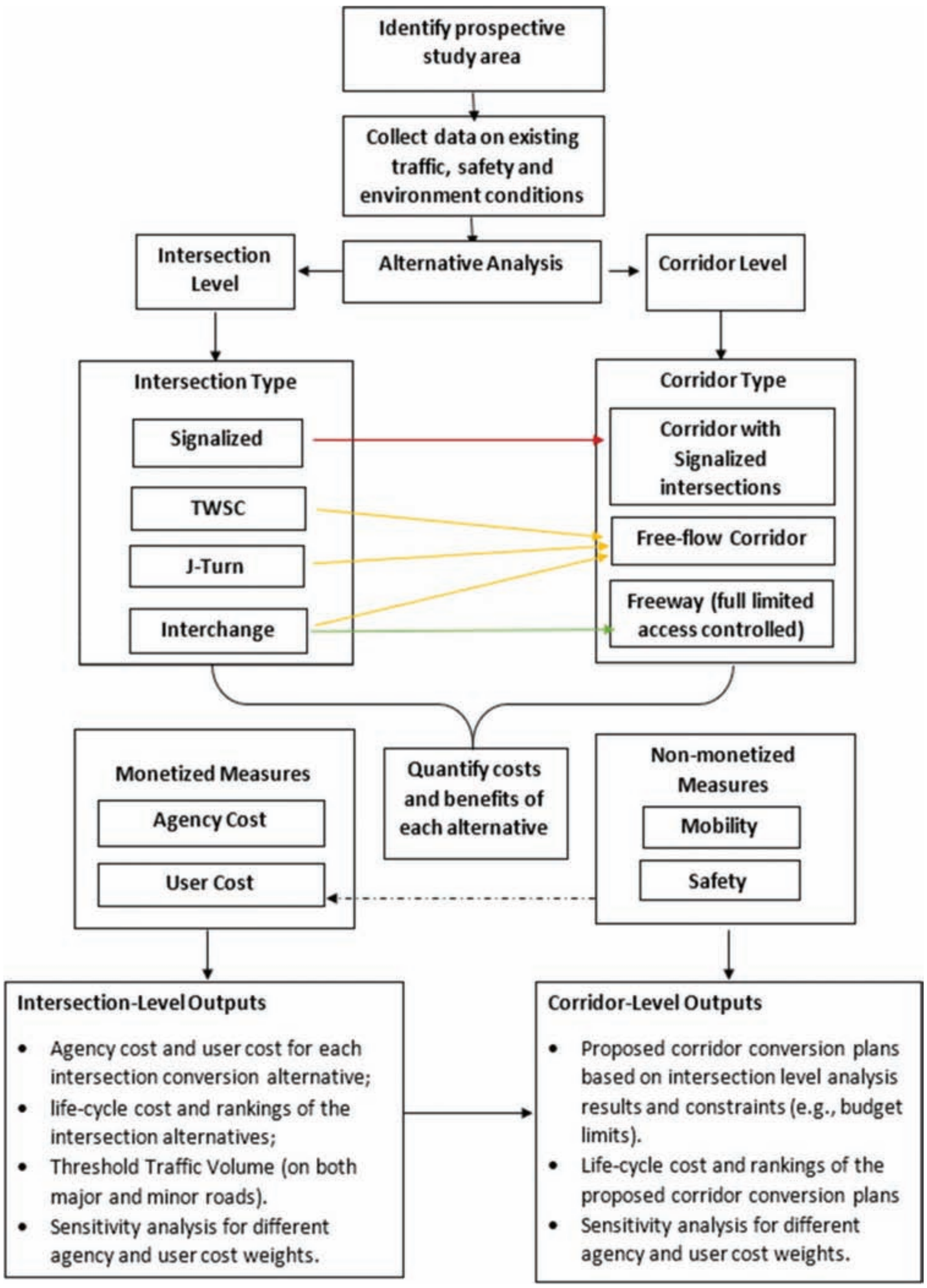


Figure 3.1 Study framework.

agency cost (construction and maintenance costs) and user cost. The non-monetized measures include mobility and safety performance, which can be converted into user cost (delay cost and crash cost). The intersection level analysis outputs include (1) estimated agency cost and user cost for each intersection alternative; (2) life-cycle cost of each alternative and the ranking of alternatives; (3) traffic volume threshold analysis results (alternative rankings under varying traffic volumes on major and minor roads). The corridor-level analysis outputs include (1) proposed corridor conversion plans based on the intersection-level analysis results and constraints (e.g., budget limit); and (2) calculated life-cycle cost for each corridor conversion plan and ranking of these plans.

3.2 Mobility and Safety Performance

Mobility and safety performance are the two major considerations for the non-monetized analysis in the current study. Mobility was measured in terms of (1) the travel time on road segment for different corridor alternatives and (2) the delay at intersections for different intersection types. The safety performance was measured in terms of the annual number of crashes at intersections. Further, it was assumed that the safety performance of the road segment is the same across different corridor alternatives due to lack of data and models. In Section 3.3, User Cost, the two user performance measures were monetized for life-cycle analysis.

3.2.1 Intersection Delay

Delay at intersections is caused mainly by vehicle deceleration/acceleration, stopping, waiting and detouring. Such delays vary significantly between different intersection types. For signalized intersections, traffic on both major road and minor road are controlled by signals and may experience delays. For TWSC, J-turn and interchanges, only traffic on the minor road and left turn/right turn traffic on the major road experience delay.

3.2.1.1 TWSC intersection delay. For the two-way stop control intersection, the drivers on the minor road experience significant delay because they have to stop before entering the intersection and wait for a sufficient gap between traffic on the major road. In this study, the average delay for minor road traffic at TWSC intersections was estimated using the model developed by Kyte et al. (1991) as shown in Equation 3.1.

$$Delay = 8 + 0.0153 * ADT_{minor}\_hourly + 0.0505 * ADT_{major}\_hourly \quad \text{(Eq. 3.1)}$$

where ADT_{minor}_hourly is the hourly traffic volume on the minor road, and ADT_{major}_hourly is the traffic volume on the major road.

Table 3.1 presents a sample calculation of the average intersection delay for the minor road users under different hourly traffic volumes. It can be seen that the delay is more sensitive to traffic volume on the major road.

3.2.1.2 J-turn intersection delay. There is rather limited information available regarding the delay experienced at J-turns. It is known that delay depends on the mainline and side-street traffic volumes, as well as the offset distance, the distance from the center of the intersection to each median U-Turn. As both traffic volume and offset distance increase, it is expected that the user delay at J-turns will also increase. However, it is difficult to find in the literature, empirical models that quantify this relationship.

In lieu of a model to predict J-turn delay, a video-based analysis was conducted. The research team was provided with approximately one hour of video footage of a recently installed J-turn at the junction of SR 114 and US 41 near Morocco, Indiana. From this footage, the delay for each vehicle was observed and recorded. This process was conducted separately for passenger vehicles and trucks, as it was expected that trucks would experience greater delay compared to passenger vehicles. To analyze the delay, the components of delay experienced by vehicles entering from the side street

TABLE 3.1
Estimated Average Delay for Traffic on Minor Road

Major Traffic (veh/hr)	Minor Traffic (veh/hr)										
	10	20	30	40	50	60	70	80	90	100	110
	Estimated Average Delay for Traffic on Minor Road (sec/veh)										
100	13.2	13.4	13.5	13.7	13.8	14.0	14.1	14.3	14.4	14.6	14.7
200	18.3	18.4	18.6	18.7	18.9	19.0	19.2	19.3	19.5	19.6	19.8
300	23.3	23.5	23.6	23.8	23.9	24.1	24.2	24.4	24.5	24.7	24.8
400	28.4	28.5	28.7	28.8	29.0	29.1	29.3	29.4	29.6	29.7	29.9
500	33.4	33.6	33.7	33.9	34.0	34.2	34.3	34.5	34.6	34.8	34.9
600	38.5	38.6	38.8	38.9	39.1	39.2	39.4	39.5	39.7	39.8	40.0
700	43.5	43.7	43.8	44.0	44.1	44.3	44.4	44.6	44.7	44.9	45.0
800	48.6	48.7	48.9	49.0	49.2	49.3	49.5	49.6	49.8	49.9	50.1
900	53.6	53.8	53.9	54.1	54.2	54.4	54.5	54.7	54.8	55.0	55.1
1,000	58.7	58.8	59.0	59.1	59.3	59.4	59.6	59.7	59.9	60.0	60.2

TABLE 3.2
J-Turn Delay Component Descriptions

Component	Description
Point 1	Stopping delay experienced on side street before entering mainline roadway
Segment 1	Travel time from stop point on side street to stop point in median U-turn
Point 2	Stopping delay experienced in median U-turn before proceeding back onto mainline roadway
Segment 2	Travel time from median stopping point either (a) back to intersection centerline for vehicles continuing on mainline or (b) to travel back to intersection and complete a right turn onto the side street for vehicles continuing on side street

TABLE 3.3
Average Passenger Vehicle and Truck Delay at J-Turns by Turning Movement

Turning Movement	Passenger Vehicles	Trucks	Average
Average Delay for Right Turn Movement (sec/veh)	3.829	9.013	5.650
Average Delay for Left Turn (via J-Turn) Movement (sec/veh)	37.063	64.499	46.376
Average Delay for Through (via J-Turn/Right) Movement (sec/veh)	40.621	67.508	48.274

were segmented as shown in Table 3.2. It was assumed that vehicles on the mainline would experience delay similar to that of a two-way stop-controlled intersection, so they were excluded from analysis. Approximately 300 vehicles per hour were observed on the major road, and approximately 80 vehicles per hour were observed on the minor road during the analysis period.

Table 3.3 provides the total delay for side street vehicles by vehicle maneuver (turn right onto mainline, turn left onto mainline (via J-turn), or proceed on side street (via J-turn). Separate values are provided for passenger vehicles and trucks.

3.2.1.3 Signalized intersection delay and interchange delay. For signalized intersections and interchanges, the delays are more independent of traffic volume and more dependent on the signal timing and detour length. At signalized intersections, traffic on both major roads and minor roads are delayed, but the lengths of delay for the minor road users are more significant. For interchanges, the delays are mostly due to the detour on the ramp for vehicles who need to enter or exit the highway. In this study, constant values (average delay per vehicle) were used to estimate the delays at signalized intersection and interchanges (as presented in Table 3.4). However, the spreadsheet program developed in this study provide the users the flexibility to change these values. Therefore, the highway agencies can use more reliable numbers for a specific intersection based on the actual signal timing or the ramp length.

3.2.1.4 Travel time on road segment. At the corridor level, the mobility performance was measured as the corridor travel time. For simplicity, an average travel time was used for each vehicle traveling on the corridor and without considering the congestion during peak hours. As shown in Equation 3.2, the corridor travel time is calculated as the corridor length divided by the speed limit for each corridor alternative.

TABLE 3.4
Average Delay per Vehicle at Signalized Intersection and at Interchange

(a) Delay at Signalized Intersection

	Delay (sec) per Vehicle
Major/Minor Road	**All Movements**
Major Road	5
Minor Road	20

(b) Delay at Interchange

	Delay (sec) per Vehicle	
Major/Minor Road	**Left Turn**	**Right Turn**
Major Road	10	3
Minor Road	15	5

$$Corridor\ Travel\ Time = \frac{Corridor\ Length}{Speed\ Limit} \quad \text{(Eq. 3.2)}$$

The speed limit and a sample calculation for a 10-mile travel time are shown in Table 3.5 for the three corridor alternatives. Speed limit information was provided by INDOT. A lower average speed limit of 45 mph was used on signalized corridors to account for the additional travel time incurred as a result of delay at signalized intersections. The data from INDOT shows that the average speeds on signalized corridors are typically lower than the posted speed limit.

3.2.2 Intersection Safety

The safety performance of intersection is quantified as the annual number of crashes at the intersection.

TABLE 3.5
Speed Limit for Three Corridor Alternatives

Corridor Alternatives	Speed Limit (mph)	Travel Time (sec) for a 10-Mile Corridor
Signalized Corridor	45	800
Free-Flow Corridor	60	600
Freeway	65	554

In this the number of crashes was estimated either using a model or based on some assumptions. For signalized intersection and TWSC intersection, the number of crashes were calculated using the models developed by Vogt (1999). For J-turn intersection, reduction factor (compared to TWSC intersection) was used based on data from the past J-turn projects in Indiana. For interchanges, a constant crash rate was adopted from Indiana Crash Facts (Indiana University Public Policy Institute, 2016).

3.2.2.1 Signalized intersection crash. In this study, crash models developed by Vogt were adopted to estimate the annual number of crashes at signalized and TWSC intersections. Vogt developed crash models for rural intersections: four-lane by two-lane stop-controlled and two-lane by two-lane signalized. The models were developed using crash and roadway data for intersections on rural roads in California and Michigan for the years 1993–1995.

The crash models for signalized intersections are presented in Equations 3.3–3.4, for the total annual number of crashes and the number of crashes involving fatality and injuries. The number of injury crashes and the number of fatal crashes were then estimated with some assumed percentages (Equations 3.5–3.6). For the analysis in this study, it was assumed 80% of the injury and fatal crashes are injury only crashes, and 20% of them involve fatalities. The number of property damage only (PDO) crashes was estimated using the total number of crashes (NRTC) minus the number of injury and fatal crashes (NRIF) (Equation 3.7).

$$NRTC = exp(-6.9536 + 0.6199 * ln(ADT_{major}) + 0.3948 * ln(AADT_{minor}) + 0.17315) \quad \text{(Eq. 3.3)}$$

$$NRIF = exp(-3.2662 + 0.2358 * ln\left(ADT_{major} * AADT_{minor}\right) + 0.1628) \quad \text{(Eq. 3.4)}$$

$$NRINJ = Percent_{Inj} * NIF \quad \text{(Eq. 3.5)}$$

$$NRFAT = Percent_{Fat} * NIF \quad \text{(Eq. 3.6)}$$

$$NRPDO = NRTC - NRIF \quad \text{(Eq. 3.7)}$$

where NRTC is the total annual number of crashes at the intersection; NRIF is the number of crashes involving injuries and fatalities at signalized intersection; NRPDO is the number of crashes involving property damage only at signalized intersection; $Percent_{Inj}$ is the percentage of crashes involving (non-fatality) injuries to the total number of injury and fatality crashes (assumed 80% in the analysis) at signalized intersections; $Percent_{Inj}$ is the percentage of crashes involving fatalities to the total number of injury and fatality crashes (assumed to be 20% in the analysis) at signalized intersection.

The main predictors used in the crash models are the AADT (average annual daily traffic) on the major road and on the minor road. Table 3.6 presents the predicted total number of crashes and the fatal and injury crashes at signalized intersections with different traffic volume. To show the impacts of traffic volume on the number of crashes, sensitivity analyses were carried out for $AADT_{major}$ and $AADT_{minor}$, respectively, as shown in Figure 3.2. There seems to be a log-linear relationship between the number of crashes and traffic volume on both major and minor roads: the number of crashes increases as the traffic volume increases but at a smaller rate.

3.2.2.2 TWSC intersection crash. In this section, similar analyses were carried out for two-way stop-controlled intersections. The crash models for TWSC intersections are presented in Equations 3.8–3.9 for the total number of crashes and the number of crashes involving injuries and fatalities. Again, the number of injuries and the number of fatalities were calculated using the assumed percentages (Equations 3.10–3.11). Also, the number of PDO crashes is the difference between the total number of crashes and the number of injury and fatal crashes (Equation 3.12).

$$NRTC = exp(-6.9352 + 0.4683 * ln\left(ADT_{major\,ADT}\right) + 0.5135 * ln(AADT_{minor\_}ADT) \quad \text{(Eq. 3.8)}$$

$$NRIF = exp(-9.8454 + 0.7224 * ln(ADT_{major}) + 0.4778 * ln\ AADT_{minor}) \quad \text{(Eq. 3.9)}$$

$$NRINJ = Percent_{Inj} * NIF \quad \text{(Eq. 3.10)}$$

$$NRFAT = Percent_{Fat} * NIF \quad \text{(Eq. 3.11)}$$

$$NRPDO = NRTC - NRIF \quad \text{(Eq. 3.12)}$$

where NRTC is the total annual number of crashes at the intersection; NRIF is the number of crashes involving injuries and fatalities at TWSC intersection; NRPDO is the number of crashes involving property damage only; $Percent_{Inj}$ is the ratio of the

TABLE 3.6
Estimated Annual Number of Crashes at Signalized Intersection Under Varying Traffic Volume on Major and Minor Roads Using the Proposed Models

(a) Estimated Annual Total Number of Total Crashes (NRTC)

	$AADT_{minor}$									
	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000
$AADT_{major}$	Estimated Annual Total Number of Total Crashes (NRTC)									
2,000	1.47	1.93	2.27	2.54	2.77	2.98	3.17	3.34	3.50	3.65
4,000	2.26	2.97	3.48	3.90	4.26	4.58	4.87	5.13	5.38	5.60
6,000	2.90	3.82	4.48	5.02	5.48	5.89	6.26	6.60	6.91	7.21
8,000	3.47	4.56	5.35	6.00	6.55	7.04	7.48	7.89	8.26	8.61
10,000	3.99	5.24	6.15	6.89	7.52	8.08	8.59	9.06	9.49	9.89
12,000	4.46	5.87	6.88	7.71	8.42	9.05	9.62	10.14	10.62	11.07
14,000	4.91	6.45	7.58	8.49	9.27	9.96	10.58	11.16	11.69	12.19
1,600	5.33	7.01	8.23	9.22	10.07	10.82	11.50	12.12	12.70	13.24
18,000	5.74	7.54	8.85	9.92	10.83	11.64	12.37	13.04	13.66	14.24
20,000	6.12	8.05	9.45	10.59	11.56	12.42	13.20	13.92	14.58	15.20
22,000	6.50	8.54	10.02	11.23	12.26	13.18	14.01	14.77	15.47	16.13
24,000	6.86	9.02	10.58	11.85	12.94	13.91	14.78	15.58	16.33	17.02
26,000	7.21	9.47	11.12	12.46	13.60	14.62	15.54	16.38	17.16	17.88
28,000	7.54	9.92	11.64	13.04	14.24	15.31	16.27	17.15	17.96	18.73
30,000	7.87	10.35	12.15	13.61	14.86	15.97	16.98	17.90	18.75	19.54

(b) Estimated Annual Number of Injury and Fatal Crashes (NRIF)

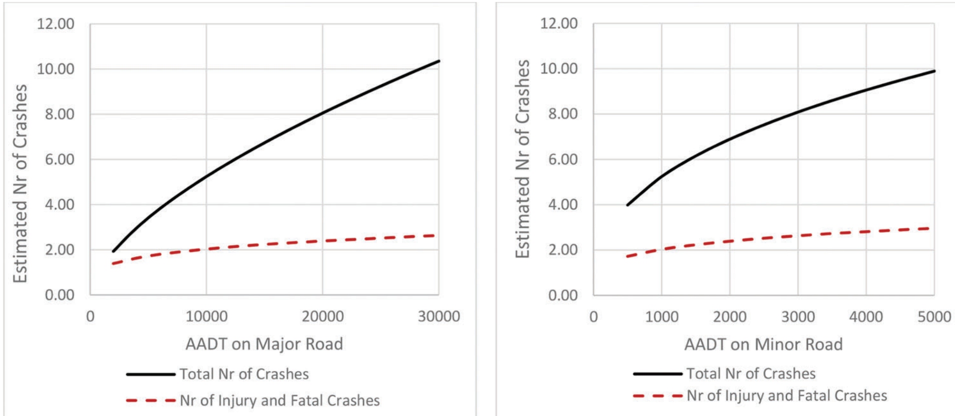
	Minor ADT									
	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000
Major ADT	Estimated Annual Number of Injury and Fatal Crashes (NRIF)									
2,000	1.18	1.39	1.53	1.63	1.72	1.8	1.86	1.92	1.98	2.03
4,000	1.39	1.63	1.8	1.92	2.03	2.12	2.2	2.27	2.33	2.39
6,000	1.53	1.8	1.98	2.12	2.23	2.33	2.42	2.49	2.56	2.63
8,000	1.63	1.92	2.12	2.27	2.39	2.49	2.59	2.67	2.74	2.81
10,000	1.72	2.03	2.23	2.39	2.52	2.63	2.73	2.81	2.89	2.96
12,000	1.8	2.12	2.33	2.49	2.63	2.74	2.85	2.94	3.02	3.09
14,000	1.86	2.2	2.42	2.59	2.73	2.85	2.95	3.04	3.13	3.21
1,600	1.92	2.27	2.49	2.67	2.81	2.94	3.04	3.14	3.23	3.31
18,000	1.98	2.33	2.56	2.74	2.89	3.02	3.13	3.23	3.32	3.41
20,000	2.03	2.39	2.63	2.81	2.96	3.09	3.21	3.31	3.41	3.49
22,000	2.07	2.44	2.69	2.88	3.03	3.17	3.28	3.39	3.48	3.57
24,000	2.12	2.49	2.74	2.94	3.09	3.23	3.35	3.46	3.55	3.64
26,000	2.16	2.54	2.8	2.99	3.15	3.29	3.41	3.52	3.62	3.71
28,000	2.2	2.59	2.85	3.04	3.21	3.35	3.47	3.59	3.69	3.78
30,000	2.23	2.63	2.89	3.09	3.26	3.41	3.53	3.64	3.75	3.84

number of crashes involving (non-fatality) injuries to the total number of injury and fatality crashes at the TWSC intersection; $Percent_{Fat}$ is the ratio of the number of crashes involving fatalities to the total number of injury and fatality crashes at the TWSC intersection.

For TWSC intersections, the determining factors of the number of crashes are the traffic volume on major and on minor roads. Again, the number of crashes was estimated under various traffic volume using the proposed models, as shown in Table 3.7.

The sensitivity analysis results are presented in Figure 3.3. The nature of the relationship between the number of crashes and the minor road traffic was found to be logarithmic. However, the relationship between the number of crashes and the traffic on major road was found to be exponential for TWSC intersections: the increasing rate increases as the traffic increases.

3.2.2.3 J-turn intersection and interchange crash. J-turns are a relatively new intersection treatment for Indiana intersections. As a result, there are very few of them that have been operational long enough to complete a fully empirical before-and-after intersection safety study. In order to estimate the safety benefits of J-turns



(a) Varying $AADT_{major}$ with fixed $AADT_{minor}$ = 1000 (b) Varying $AADT_{minor}$ with fixed $AADT_{major}$= 10,000

Figure 3.2 Sensitivity of the number of signalized intersection crashes to traffic volume on the major and minor roads.

TABLE 3.7
Estimated Annual Number of Crashes at TWSC Under Varying Traffic Volume on Major and Minor Roads Using the Proposed Models

(a) Estimated Annual Total Number of Total Crashes (NRTC)

	Minor ADT									
	500	**1,000**	**1,500**	**2,000**	**2,500**	**3,000**	**3,500**	**4,000**	**4,500**	**5,000**
Major ADT	**Estimated Annual Total Number of Total Crashes (NRTC)**									
2,000	0.83	1.19	1.46	1.69	1.9	2.09	2.26	2.42	2.57	2.71
4,000	1.15	1.64	2.02	2.34	2.63	2.89	3.12	3.35	3.56	3.75
6,000	1.39	1.99	2.45	2.83	3.18	3.49	3.78	4.05	4.3	4.54
8,000	1.59	2.27	2.8	3.24	3.64	3.99	4.32	4.63	4.92	5.19
10,000	1.77	2.52	3.11	3.6	4.04	4.43	4.8	5.14	5.46	5.76
12,000	1.92	2.75	3.38	3.92	4.4	4.83	5.23	5.6	5.95	6.28
14,000	2.07	2.95	3.64	4.21	4.73	5.19	5.62	6.02	6.39	6.75
16,000	2.2	3.14	3.87	4.49	5.03	5.53	5.98	6.41	6.8	7.18
18,000	2.33	3.32	4.09	4.74	5.32	5.84	6.32	6.77	7.19	7.59
20,000	2.44	3.49	4.3	4.98	5.59	6.13	6.64	7.11	7.55	7.97
22,000	2.56	3.65	4.49	5.21	5.84	6.41	6.94	7.44	7.9	8.34
24,000	2.66	3.8	4.68	5.43	6.08	6.68	7.23	7.74	8.23	8.68
26,000	2.76	3.95	4.86	5.63	6.32	6.94	7.51	8.04	8.54	9.02
28,000	2.86	4.08	5.03	5.83	6.54	7.18	7.77	8.32	8.84	9.33
30,000	2.96	4.22	5.2	6.02	6.75	7.42	8.03	8.6	9.13	9.64

(b) Estimated Annual Number of Injury and Fatal Crashes (NRIF)

	Minor ADT									
	500	**1,000**	**1,500**	**2,000**	**2,500**	**3,000**	**3,500**	**4,000**	**4,500**	**5,000**
Major ADT	**Estimated Annual Number of Injury and Fatal Crashes (NRIF)**									
2,000	0.25	0.35	0.42	0.49	0.54	0.59	0.63	0.68	0.72	0.75
4,000	0.41	0.58	0.7	0.8	0.89	0.97	1.05	1.12	1.18	1.24
6,000	0.55	0.77	0.94	1.07	1.19	1.3	1.4	1.49	1.58	1.66
8,000	0.68	0.95	1.15	1.32	1.47	1.6	1.73	1.84	1.95	2.05
10,000	0.8	1.11	1.35	1.55	1.73	1.88	2.03	2.16	2.29	2.41
12,000	0.91	1.27	1.54	1.77	1.97	2.15	2.31	2.47	2.61	2.74
14,000	1.02	1.42	1.73	1.98	2.2	2.4	2.59	2.76	2.92	3.07
16,000	1.12	1.57	1.9	2.18	2.43	2.65	2.85	3.04	3.21	3.38
18,000	1.22	1.7	2.07	2.37	2.64	2.88	3.1	3.31	3.5	3.68
20,000	1.32	1.84	2.23	2.56	2.85	3.11	3.35	3.57	3.77	3.97
22,000	1.41	1.97	2.39	2.74	3.05	3.33	3.59	3.82	4.04	4.25
24,000	1.51	2.1	2.55	2.92	3.25	3.55	3.82	4.07	4.3	4.53
26,000	1.6	2.22	2.7	3.1	3.44	3.76	4.05	4.31	4.56	4.8
28,000	1.68	2.35	2.85	3.27	3.63	3.96	4.27	4.55	4.81	5.06
30,000	1.77	2.47	2.99	3.43	3.82	4.17	4.49	4.78	5.06	5.32

using this limited data, the research team elected to use crash data from the longest operating J-turn in Indiana to estimate crash reductions by crash type. As this intersection (SR 114 and US 41) was previously a two-way stop-controlled intersection, crashes are represented as reductions from the two-way stop-controlled case to the J-turn case. Table 3.8(a) summarizes these crash rate reductions. These crash rates are then converted to reduction factors (compared to TWSC intersections) as shown in Table 3.8(b).

To estimate the number of crashes at interchanges, a fixed rate of 0.19 crashes per million vehicles entering the interchange was used (Indiana University Public Policy Institute, 2016). It was assumed 50% of the total crashes are PDO, 35% are non-fatal injury crashes, and 15% are fatal crashes.

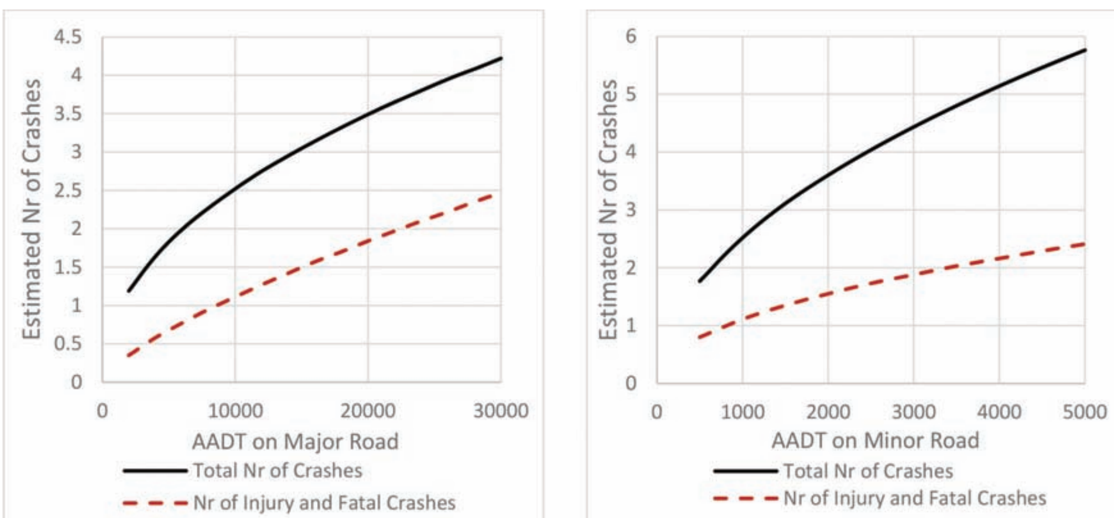
3.3 User Cost

In this section, the mobility (travel time) and safety performance (number of crashes) were monetized to yield travel time/delay cost and crash cost, which are the major components of user costs. Therefore, the travel time savings and safety savings were considered as the major user benefits.

3.3.1 Travel Time/Delay Cost

Travel time costs or delay costs are the product of time spent traveling/delaying multiplied by unit costs (e.g., cents per minute or dollars per hour), or the Value of Travel Time (VTT). In this study, the VTT values were adopted from FHWA (2005) and Bai et al. (2017), as shown in Table 3.9.

Based on the value of travel presented in Table 3.9, the corridor travel time was converted into travel time cost (TTC_{major}) for traffic on major road using Equation 3.13. The intersection delays were converted into delay costs (DC_{major} and DC_{minor}) using Equations 3.14–3.15, for traffic on major and minor roads.



(a) Varying $AADT_{major}$ with fixed $AADT_{minor} = 1000$

(b) Varying $AADT_{minor}$ with fixed $AADT_{major} = 10{,}000$

Figure 3.3 Sensitivity of number of TWSC intersection crashes to traffic volume on the major and minor roads.

TABLE 3.8
Crash Rate Reduction for J-Turn by Crash Type

(a) Crash Rate Changes Before and After J-Turn Conversion		
Crash Type	**Crash Rate Before (TWSC)**	**Crash Rate After (J-turn)**
Disabling Injury/Fatality	5.3	2.6
Minor Injury	2.3	0.3
PDO	20	11.1

(b) Reduction Factors for J-Turn Intersection Crash Estimation	
Type of Fatality	**Reduction Factor Compared to TWSC Intersections**
POD	0.45
Injury	0.62
Fatality	0.53

$$TTC_{major} = TT_{major} * AADT_{major} * (VTT_{passenger} * (1 - Percent_{minor\_truck}) + VTT_{truck} * Percent_{minor\_truck}) \quad \text{(Eq. 3.13)}$$

$$DC_{major} = Delay_{major} * AADT_{major} * (VTT_{passenger} * (1 - Percent_{minor\_truck}) + VTT_{truck} * Percent_{minor\_truck}) \quad \text{(Eq. 3.14)}$$

$$DC_{minor} = Delay_{minor} * AADT_{minor} * (VTT_{passenger} * (1 - Percent_{minor\_truck}) + VTT_{truck} * Percent_{minor\_truck}) \quad \text{(Eq. 3.15)}$$

A sample calculation of intersection delay cost was carried out for an intersection with 10,000 AADT on the major road and 1,000 AADT on the minor road. Table 3.10(a)–(b) presents the estimated total annual delay and delay cost at different intersection types. It can be seen that at this traffic volume level, the two-way stop control intersection and interchange experience less delay when compared to the J-turn and signalized intersections.

TABLE 3.9
Value of Travel Time

Type of Car	Cost per Hour per Vehicle
Passenger Car	\$18.10
Commercial Vehicle	\$34.86

Source: FHWA (2005).

3.3.2 Intersection Crash Cost

The safety performance of each conversion alternative was measured in terms of the annual number of crashes in Section 3.2.2. In this section, the safety performance was monetized to yield the crash cost (a large component of user cost) based on estimated annual number of crashes and the unit crash cost provided by National Safety Council (2015), as listed in Table 3.11, for different crash severities.

The total annual crash cost can be calculated using Equations 3.16–3.17 or economic cost and comprehensive cost, respectively. In the life-cycle analysis, it was found that the comprehensive crash costs are much higher compared to all the other costs (delay cost and agency cost). This causes the alternatives with higher safety performance (interchange and J-turn) to consistently be the best solution regardless of the performance of other designs. Therefore, it is recommended that the highway agencies should use the economic crash cost. The analysis results presented in the report are also based on the economic crash cost. However, in the spreadsheet program, the users are provided the flexibility to choose any one of the two cost options for the analysis.

$$Annual\ Crash\ Cost\ (Economic) = NRINJ * \$1{,}542{,}000 + NRFAT * \$45{,}800 + NRPDO * \$4{,}200 \quad \text{(Eq. 3.16)}$$

$$Annual\ Crash\ Cost\ (Comprehensive) = NRINJ * \$1{,}542{,}000 + NRFAT * \$45{,}800 + NRPDO * \$4{,}200 \quad \text{(Eq. 3.17)}$$

where *NRINJ* is the number of injury crashes, *NRFAT* is the number of fatal crashes, and *NRPDO* is the number of PDO crashes.

TABLE 3.10
Estimated Daily Intersection Delay Time and Annual Delay Cost (with 10,000 AADT on the Major Road and 1,000 AADT on the Minor Road)

(a) Estimated Daily Intersection Delay (sec)

	Major Road		Minor Road	
Intersection Type	**Passenger Car**	**Commercial Vehicle**	**Passenger Car**	**Commercial Vehicle**
Signalized	42,500	7,500	18,000	2,000
TWSC	5,525	1,500	41,571	4,619
J-Turn	5,525	1,500	29,296	5,521
Interchange	3,400	600	3,400	600

(b) Estimated Annual Delay Cost (\$)

	Major Road		Minor Road		
Intersection Type	**Passenger Car (\$)**	**Commercial Vehicle (\$)**	**Passenger Car (\$)**	**Commercial Vehicle (\$)**	**Total (\$)**
Signalized	77,993	13,764	33,033	3,670	128,460
TWSC	10,139	2,753	76,289	8,477	97,657
J-Turn	10,139	2,753	53,762	10,131	76,785
Interchange	6,239	1,101	6,239	1,101	14,681

TABLE 3.11
Unit Crash Cost

Type of Crash Severity	Average Comprehensive Cost ($/vehicle)	Average Economic Cost ($/vehicle)
Fatality	10,082,000	1,542,000
Disabling	1,103,000	90,000
Evident	304,000	26,000
Possible Injury	141,000	21,400
Injury (averaged)	516,000	45,800
PDO	4,200	4,200

Source: National Safety Council (2015).

TABLE 3.12
Estimated Annual Number of Crashes and Total Crash Cost at Intersection

(a) Estimated Annual Intersection Crashes

	Annual Total Intersection Crash				
Intersection Type	**Total Nr of Crashes**	**Injury & Fatality**	**Fatality**	**Injury**	**PDO**
Signalized	5.240	2.030	0.406	1.624	3.209
TWSC	2.522	1.115	0.223	0.892	1.407
J-Turn	1.211	0.429	0.089	0.340	0.781
Interchange	0.763	0.381	0.076	0.305	0.381

(b) Estimated Annual Intersection Crash Cost

Intersection Type	Fatality ($)	Injury ($)	PDO ($)	Total ($)
Signalized	626,184	74,395	13,478	714,057
TWSC	343,804	40,846	5,911	390,562
J-Turn	137,522	15,586	3,281	156,389
Interchange	117,631	13,975	1,602	133,209

TABLE 3.13
Construction and Maintenance Work for the Three Corridor-Level Alternatives

Corridor Conversion Plan	Construction Work	Maintenance Work
Signalized Corridor (do nothing)	None	Signalized intersection maintenance costs ($26,144 per year) Road segment maintenance costs ($1,280/mile per year)
Free-Flow Corridor	Construction of intersections: TWSC intersection ($10,000), *or* J-turn ($449,438), *or* interchange ($14,293,232)	Unsignalized intersection/interchange maintenance costs ($13,072/$65,359 per year) Road segment maintenance costs ($1,280/mile per year)
Freeway	Full controlled limited access highway ($10.1M/mile) Construction of interchange ($14,293,232) or overpass ($2.5M) Frontage roads ($4M/Mile) Right-of-way ($250,000 to $1M+)	Interchange maintenance costs ($65,359 per year) Road segment maintenance costs ($3,200/mile per year)

A sample calculation of intersection crash (economic) cost was carried out for a sample intersection with 10,000 AADT on the major road and 1,000 AADT on the minor road. Table 3.12 presents the estimated total annual number of crashes and total crash cost at different intersections for different severity types. It is noticed that the safety costs of J-turns and interchanges are much lower compared to those of the signalized and TWSC intersections.

3.4 Agency Cost

The agency costs considered in this study consist of initial construction cost and the annual maintenance costs. Table 3.13 summarizes the construction work and maintenance work needed for each of the three corridor conversion plans (do-nothing, free-flow corridor and freeway).

At the intersection level, the initial construction costs vary greatly between the three conversion alternatives.

To convert a signalized intersection to TWSC intersection, the agency costs mainly consists of the cost of signals removal and sign installations, and such costs are relatively minor compared to the other conversion alternatives. In this study, \$10,000 was assumed to be the conversion cost of a TWSC intersection. For J-turn intersection and interchange, the construction costs data were obtained from past INDOT's J-turn conversion and interchange construction projects (Table 3.14).

At the corridor-level, for free-flow corridors, the major construction costs are the cost of revising or reconstructing the intersections. For freeway corridor, the construction costs are much higher compared to a free-flow corridor because it includes not only the cost of interchange construction but also the costs of road reconstruction, addition of overpass and frontage roads, and acquisition of right-of-way. These construction cost components are shown in Table 3.14.

For the annual maintenance cost, the values estimated by previous researchers (Bonneson et al., 1993; Volovski et al., 2017) were adopted in this study. These costs were adjusted to their 2018 constant dollar values. The annual maintenance cost used in the analysis are summarized in Table 3.15.

TABLE 3.14
Construction Cost Components and Sources

Work	Cost (\$)	Source
TWSC Intersection	10,000	Assumed
J-Turn Intersection	449,438	INDOT Bidding Data
Simple Diamond Interchange:	14,293,232	INDOT Bidding Data
Overpass	2.5 M/site	INDOT
Frontage Roads	4 M/mile	INDOT
Full-Limited Access Controlled Highway	10.1 M/mile	INDOT
Right-of-Way	250,000 to 1M+	INDOT
Cul-De-Sac	50,000	INDOT

TABLE 3.15
Annual Maintenance Costs

(a) Intersections Maintenance Costs	
Type of Intersection	**Annual Maintenance Costs (\$/year)**
Un-signalized Intersection	13,072
Signalized Intersection	26,144
Diamond Interchange	65,359
(b) Road Segment Maintenance Costs	
Type of Intersection	**Annual Maintenance Costs (\$/year)**
Freeway	3,200/mile
Other Alternatives	1,280/mile

Sources: (a) converted from Bonneson et al., 1993; (b) Volovski et al. (2017).

3.5 Life-Cycle Cost Analysis

In this study, the life-cycle cost analysis was used to compare the total user and agency costs of the intersection alternatives and the corridor conversion plans, and determine the rankings of the alternatives based on the combined life-cycle cost.

3.5.1 Intersection-Level Life-Cycle Analysis

At the intersection level, the life-cycle cost analysis was carried out to compare the total combined user and agency costs of signalized intersection (do-nothing alternative), TWSC intersection, J-turn and interchange. The total annual user cost is the sum of intersection delay cost and intersection crash cost (Equation 3.18), and the life-cycle user cost is the sum of user cost at each year over the analysis period (Equation 3.19). The user benefits are defined as user cost savings compared to the do-nothing alternative and can be calculated using Equation 3.20. It can be converted into the equivalent uniform annual benefit using Equation 3.21. The total agency cost is the sum of the initial construction cost and the total maintenance cost over the analysis period (Equation 3.22). The total life-cycle cost is the combined cost of agency cost and user cost with certain weights (Equation 3.23). The total life-cycle cost can be converted into the equivalent uniform annual cost (EUAC) using Equation 3.24.

$$UC_{i,j,k} = IDC_{i,j,k} + ICC_{i,j,k} \quad \text{(Eq. 3.18)}$$

$$TUC_{i,j} = \sum_{k=1}^{AP} UC_{i,j,k} \quad \text{(Eq. 3.19)}$$

$$TUB_{i,j} = TUC_{i,j} - TUC_{Do\_Nothing,\, j} \quad \text{(Eq. 3.20)}$$

$$EUAB_{i,j} = TUB_{i,j} * \frac{DR * (1+DR)^{AP}}{(1+DR)^{AP} - 1} \quad \text{(Eq. 3.21)}$$

$$TAC_{i,j} = CC_i + \sum_{k=1}^{AP} MC_{i,j,k} \quad \text{(Eq. 3.22)}$$

$$TC_{i,j} = TAC_{i,j} + R * TUC_{i,j} \quad \text{(Eq. 3.23)}$$

$$EUAC_{i,j} = TC_{i,j} * \frac{DR * (1+DR)^{AP}}{(1+DR)^{AP} - 1} \quad \text{(Eq. 3.24)}$$

where i is the i-th intersection conversion alternative, i=0 for signalized intersection, i=1 for TWSC intersection, i=3 for J-turn and i=4 for interchange;

j is the j-th intersection along the corridor;

k is the k-th year;

AP is the length of analysis period (number of years);
DR is the discount rate;
$UC_{i,j,k}$ is the user cost for alternative i at intersection j in Year k;
$IDC_{i,j}$ is the intersection delay cost for alternative i at intersection j in Year k;
$ICC_{i,j,k}$ is the intersection crash cost for alternative i at intersection j in Year k;
$TUC_{i,j}$ is the total user cost during the analysis period;
$TUB_{i,j}$ is the total user benefits for alternative i (user cost savings compared to do nothing) at intersection j during the analysis period;
$EUAB_{i,j}$ is the equivalent uniform annual benefit for alternative i at intersection j;
CC_i is the initial construction cost for alternative i at intersection j;
$IMC_{i,j,k}$ is the intersection maintenance cost for alternative i at intersection j in year k;
$TAC_{i,j}$ is the total agency cost for alternative i at intersection j;
$TUC_{i,j}$ is the total user cost for alternative i at intersection j;
R is the ratio of user cost weight to agency cost weight;
$TC_{i,j}$ is the combined total cost for alternative i at intersection j;
$EUAC_{i,j}$ is the equivalent uniform annual cost for alternative i at intersection j.

Table 3.16 and Figure 3.4 present the sample calculations for an intersection with 10,000 AADT on the major road and 1000 AADT on the minor road and with 1:1 agency cost to user cost weight ratio. It can be seen that with these traffic conditions, the interchange has the highest user benefit, and J-turn has the lowest life-cycle cost.

3.5.2 Corridor-Level Life-Cycle Analysis

At the intersection level, the life-cycle cost analysis was carried out to compare the total combined user and agency costs of existing signalized corridor (do-nothing alternative), free-flow corridor and freeway. The corridor-level user cost is the sum of the travel time cost at all road segments along the corridor and the intersection-level user costs at all the intersection along the corridor (Equation 3.26). Similarly, the corridor-level agency cost is the sum of constructing and maintaining all the road segments and intersections along the corridor (Equation 3.30).

$$CUC_{i,k} = RTC_{i,k} + \sum_{j=1}^{N} IDC_{i,j,k} + ICC_{i,j,k} \quad \text{(Eq. 3.25)}$$

$$CTUC_i = \sum_{k=1}^{AP} CUC_{i,k} \quad \text{(Eq. 3.26)}$$

$$CTUB_i = CTUC_i - CTUC_{Do\_Nothing} \quad \text{(Eq. 3.27)}$$

$$CEUAB_i = CTUB_i * \frac{DR * (1+DR)^{AP}}{(1+DR)^{AP} - 1} \quad \text{(Eq. 3.28)}$$

$$CAC_{i,k} = CCC_{i,k} + \sum_{j=1}^{N} IMC_{i,j,k} + RMC_{i,k} \quad \text{(Eq. 3.29)}$$

$$CTAC_i = \sum_{k=1}^{AP} CAC_{i,k} \quad \text{(Eq. 3.30)}$$

$$CTC_i = CTAC_i + R * CTUC_i \quad \text{(Eq. 3.31)}$$

$$CEUAC_i = CTC_i * \frac{DR * (1+DR)^{AP}}{(1+DR)^{AP} - 1} \quad \text{(Eq. 3.32)}$$

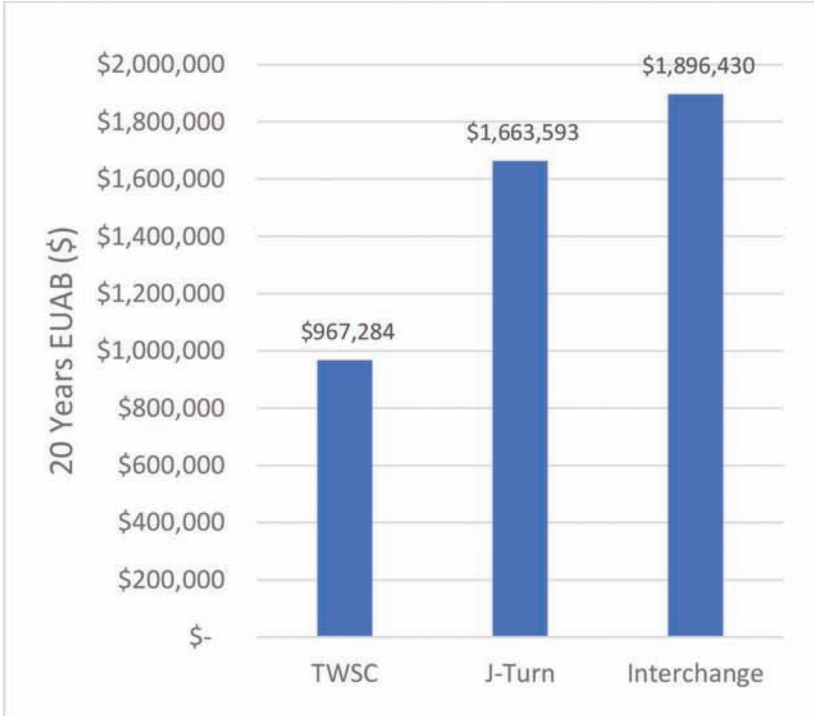
where i is the i-th proposed corridor conversion plan;
N is the total number of intersections along the corridor;
$CUC_{i,k}$ is the user cost along the entire corridor for Plan i in Year k;
$RTC_{i,k}$ is the travel time cost at all road segments along the corridor for Plan i in Year k;
$CTUC_i$ is the corridor-level total user cost for Plan i during the analysis period;
$CTUB_i$ is the corridor-level total user benefit for Plan i;
$CEUAB_i$ is the corridor-level equivalent uniform annual benefit for Plan i;
$CAC_{i,k}$ is the corridor-level total agency cost for Plan i in Year k;
$CTAC_{i,j}$ is the corridor-level total agency cost for Plan i during the analysis period;
CCC_i is the initial construction cost of the entire corridor for Plan i;

TABLE 3.16
Sample Intersection-Level Life-cycle Analysis Results (with 10,000 AADT on the Major Road and 1,000 AADT on Minor Road, and with Agency Cost: User Cost Weight = 1:1)

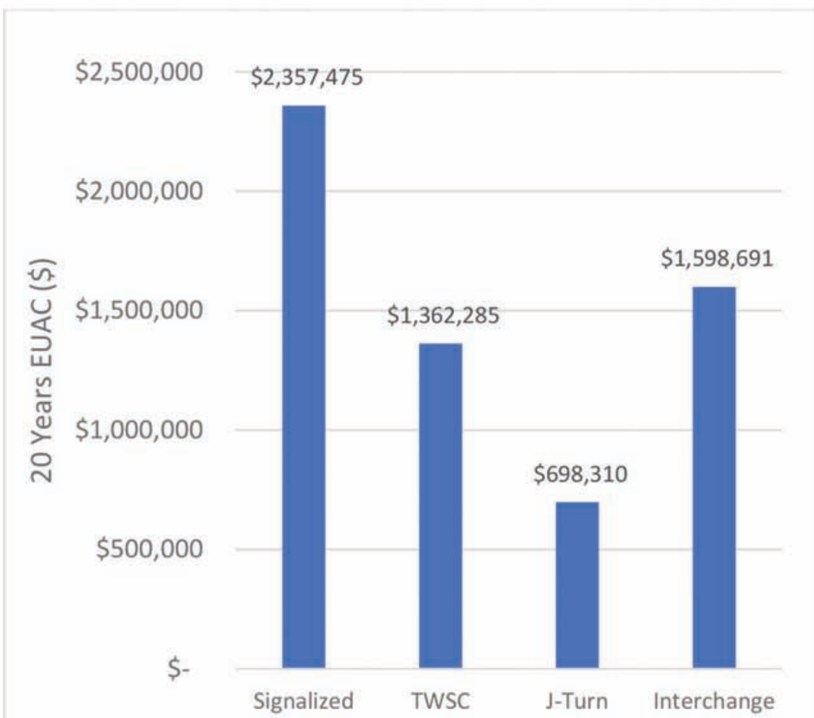
Intersection Type	Signalized ($)	TWSC ($)	J-Turn ($)	Interchange ($)
Initial Investments (CC_i)	0	10,000	449,438	14,293,232
Total Agency Cost ($TAC_{i,j}$)	778,518	399,259	838,697	16,239,497
Total User Cost ($TUC_{i,j}$)	31,260,342	18,114,633	8,651,570	5,487,238
User Benefit ($TUB_{i,j}$)	–	13,145,708	22,608,772	25,773,104
EUAB (Compared to Do Nothing)	–	967,284	1,663,593	1,896,430
Total Cost ($TC_{i,j}$)	32,038,860	18,513,892	9,490,267	21,726,735
EUAC (Combined)	2,357,475	1,362,285	698,310	1,598,691

CTC_i is the corridor-level combined total cost for Plan i during the analysis period;

$EUAC_{i,j}$ is the corridor-level equivalent uniform annual cost for Plan i at intersection j.



(a) Calculated EUAB

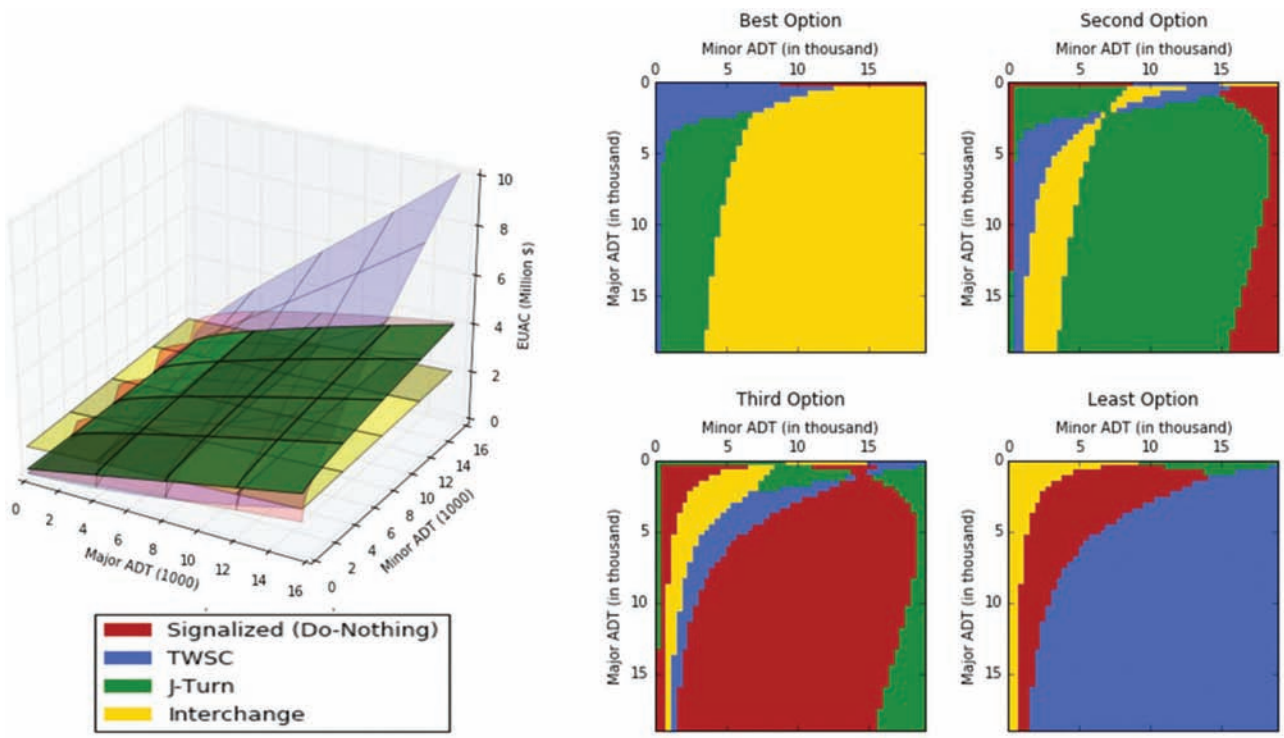


(b) Calculated combined EUAC

Figure 3.4 Sample life-cycle analysis results (user benefits and combined cost).

3.6 Traffic Threshold Analysis (Intersection Level)

The traffic volumes on the major road and minor road are two important factors that influence the



(a) EUAC of the intersection alternatives (b) Decision boundary (traffic threshold)

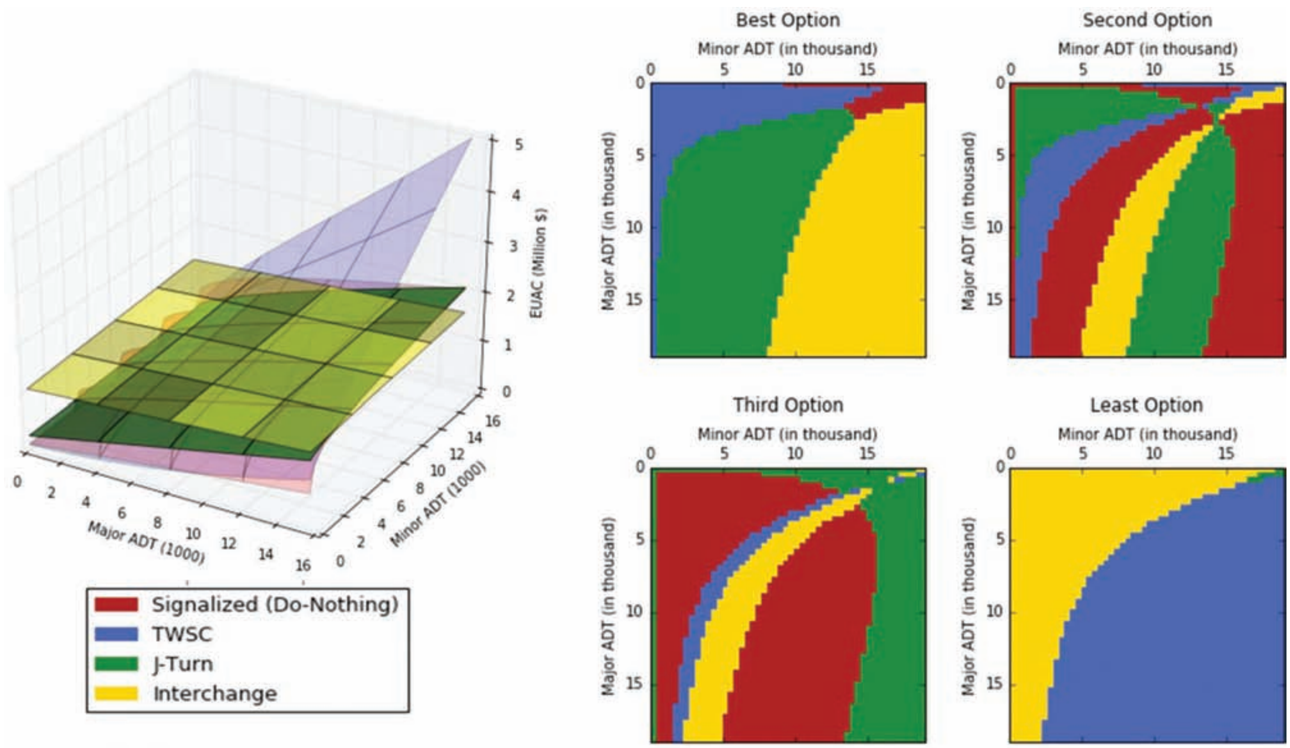
Figure 3.5 Traffic volume threshold analysis results (ACW:UCW = 1:1).

intersection conversion decisions. This is because the user costs (a large percent of the total cost) is determined largely by the number of road users. In this section, the life-cycle analysis was carried out at the intersection level, to compare the combined EUAC of the intersection alternatives (signalized, TWSC, J-turn and interchange) under different traffic volumes and with different agency cost weight to user cost weight ratios. The analysis results in this section determines the traffic volume at which an intersection conversion alternative becomes superior to the others, and therefore provide a decision boundary at which the best alternative switches (see Figure 3.5(b), "Best Option"). In addition, the decision boundary of the second best, third best and the least favorable options were also provided in the output figures. This is useful because the agencies might want to choose other options when the best option is not practically feasible due to some constraints (such as budget limit).

The traffic threshold analysis was carried out for traffic volume on major road (Major ADT) ranging from 0 to 18,000 and for traffic volume on minor road (Minor ADT) ranging from 0 to 18,000, for four different agency-user cost weight ratios (1:1, 2:1, 3:1, and 5:1). However, in reality, it is very unlikely that the minor road traffic will exceed that of the major road. Therefore, the main decision area is within the bottom triangle (in Figure 3.5(b), all options) where Major ADT exceeds the Minor ADT.

In Figure 3.5, the agency cost and user cost are weighted equally (1:1). Figure 3.5(a) presents the 20 years combined EUAC (agency cost + user cost) of the four intersection conversion alternatives in a 3-D space, where x-axis is the Major ADT, y-axis is the Minor ADT and the z-axis is the EUAC. In the 3-D space, each alternative is represented by a plane (signalized: red plane, TWSC: blue plane, J-turn: green plane, interchange: yellow plane). Figure 3.5(b) presents the decision area at a 2-D space where a certain alternative is the best option (with lowest EUAC), second option, third option or the least favorable option (with highest EUAC). For example, when Major Traffic is 10,000 and Minor Traffic is 1000, the best option is J-turn (green), the second-best option is TWSC (blue), the third-best is interchange (yellow) and the least favorable option is the signalized intersection (red). The line where two planes intersect with each other in the 3-D space in Figure 3.5(a) is the decision boundary at which the rankings of two alternatives switches in the 2-D space in Figure 3.5(b). For example, part of the line at which J-turn intersects with interchange in the 3-D space is the decision boundary in the 2-D plot at which the best option switches between J-turn and interchange.

It can be found in Figure 3.5(a) that the EUAC of TWSC intersection is the option that is most sensitive to the increase of traffic volume. This is because both intersection delay and number of crashes at TWSC intersections were estimated using models in which the



(a) EUAC of the intersection alternatives (b) Decision boundary (traffic threshold)

Figure 3.6 Traffic volume threshold analysis results (ACW:UCW = 2:1).

Major ADT and Minor ADT are the predictors. Therefore, when traffic becomes large, the TWSC becomes much more expensive compared to all other options. The EUAC of interchange is the least sensitive to the increase of traffic volume; this is because the agency cost of interchange constitutes a large percentage of the total cost. In addition, in this analysis, the agency cost is assumed to be a fixed cost, and therefore does not depend on the traffic volume.

Figure 3.5(b) presents the decision area where a certain alternative is the best option ("best area"), second option, third option, or least option. It was noticed that when the Major ADT is less than 3,000, the best option is mostly likely to be TWSC. This is because when the traffic volume in the major road is very small, traffic on the minor roads do not have to spend a long time waiting in the TWSC intersection. However, at the J-turn intersection, the minor road users always need to take a detour in order to go through the intersection or turn left and merge into the major road, and the major road users who need to turn left also take the detour. At interchanges, the left-turning traffic on both minor road and major road are delayed by traveling on the ramp. Therefore, when the traffic volume on the major road is small, the TWSC intersection has lower delay cost compared to the other alternatives. When the minor ADT is less than 4,000, J-turn is generally more cost-effective compared to the interchange, regardless of the ADT level of the major road. This is because most delay that occurs in the J-turn intersection are the detour delay encountered by the minor road users. When the traffic volumes on major road and minor road are both large, the interchange is the best option.

Figure 3.6–Figure 3.8 present the traffic threshold analysis results under different weight ratios of the agency cost and user cost. As the agency cost is assigned relatively higher weight, the decision boundaries change significantly: the area of interchange as the "best option" decreases progressively from the largest area to zero, and the area where TWSC and signalized intersection are optimal continuously increases. Also, the area where J-turn is optimal initially increases and then decreases.

The results in this section provide insight on how the rankings of the alternatives change under different traffic volumes on both the major and minor roads, and with different weight ratios of agency cost to user cost. The decision boundary plots can help highway agencies to choose appropriate intersection types based on the traffic volumes. However, when analyzing a specific intersection, it is recommended that the agency uses the spreadsheet program developed in this report. This program permits quick and interactive analysis of the sensitivity of the optimal solution to the traffic volumes and other input parameters.

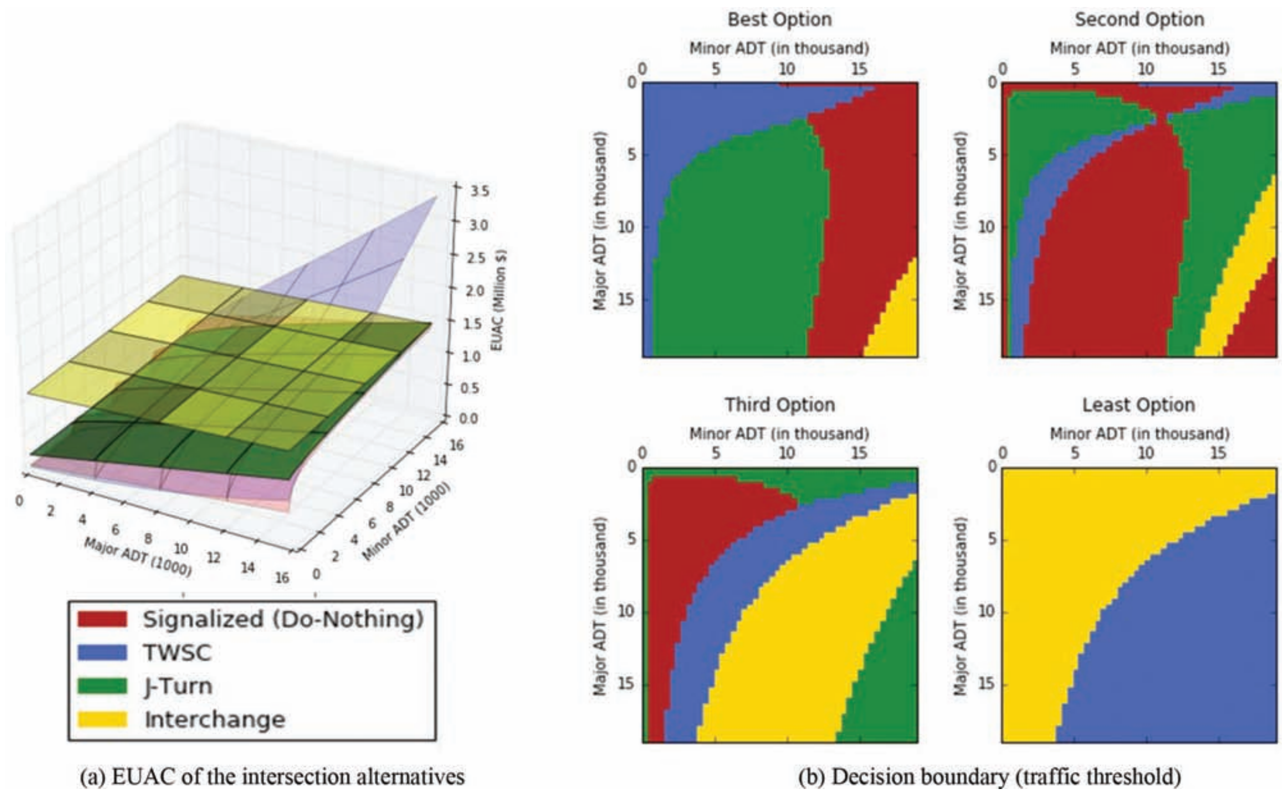


Figure 3.7 Traffic volume threshold analysis results (ACW:UCW = 3:1).

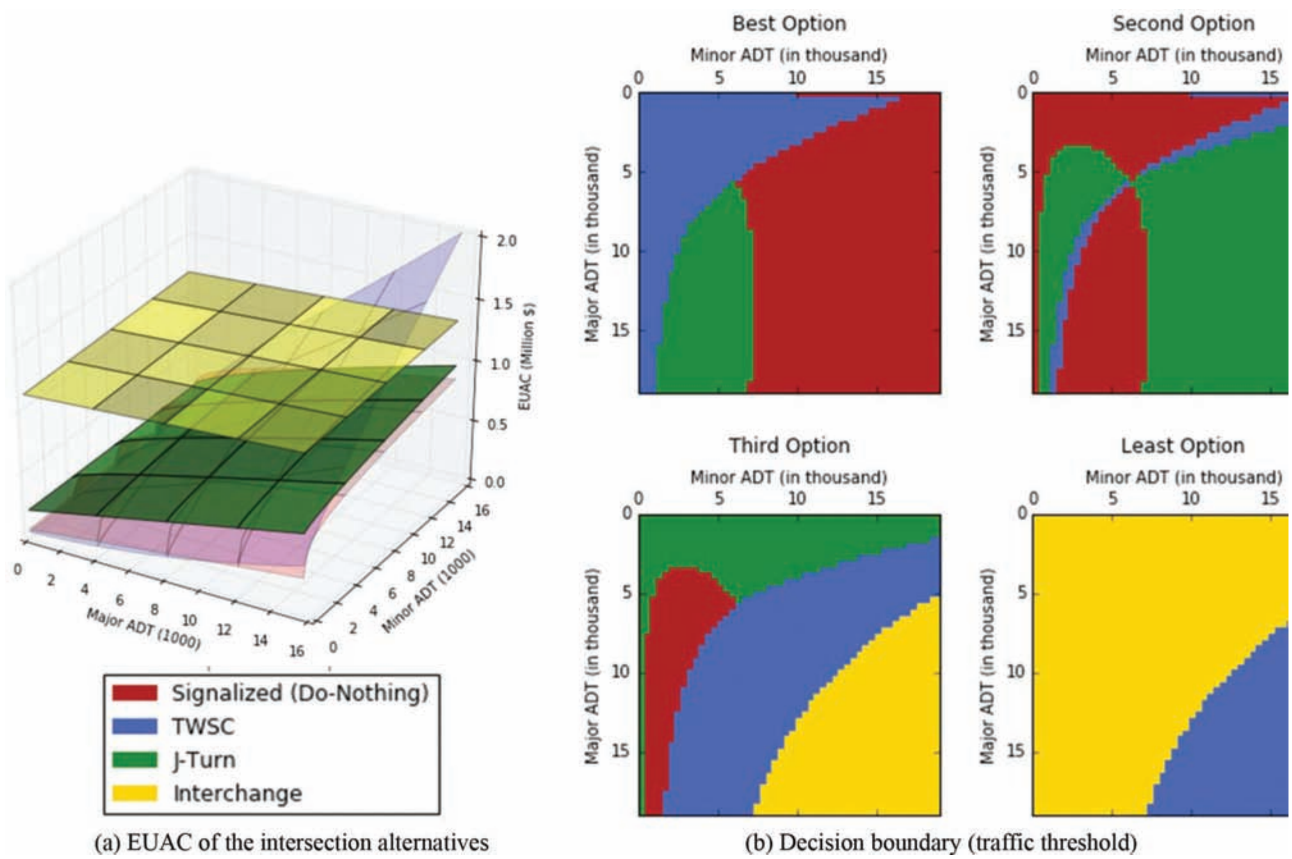


Figure 3.8 Traffic volume threshold analysis results (ACW:UCW = 5:1).

4. CASE STUDY: US 30 CORRIDOR

4.1 Corridor Overview and Traffic Data

Section 2.3 presented three potential study corridors that were suggested by the study advisory committee. In order for a complete analysis to be conducted, extensive traffic data was needed for the corridor. This data includes mainline traffic counts for each road segment, as well as traffic counts for each minor road that intersects the mainline. Most of the mainline traffic data were available from INDOT's traffic count database, although many of the rural segments did not have traffic data available. However, the largest challenge was obtaining traffic data for side roads, because most of the side roads are not under INDOT's jurisdiction. Some of this information was available through INDOT, and additional information was available from some local agencies (counties and regional planning organizations), but a large number of the side roads did not have reliable traffic count information. This situation impaired the corridor analysis, as many of the intersection treatments depend heavily on minor road traffic volumes.

The available traffic data was inadequate; therefore, a meaningful analysis of the SR 25 corridor from Lafayette to Logansport could not be performed. Although the SR 67/US 35 corridor around Muncie did have a complete set of traffic data for mainline and side roads, it was decided that, since this corridor already contained a high proportion of interchanges and grade separated intersections, it would not be a good candidate corridor for the study. The remaining study section is the US 30 corridor from Valparaiso to Plymouth, which is also the longest of the candidate corridors.

The US 30 corridor also had large sections for which traffic data were unavailable. However, there was a segment of approximately 10 miles on the Plymouth end of the corridor that did have complete traffic data available, and has fewer existing interchanges compared to the Muncie corridor. For these reasons, this segment of the US 30 corridor was chosen as the case study. Table 4.1 provides traffic, intersection, and other data with regard to the corridor.

4.2 Intersection-Level Analysis Results

A life-cycle cost analysis was carried out at the intersection level to determine the ranking of the proposed intersection conversion alternatives at each intersection along the corridor. Table 4.2(a)–(d) presents the annual intersection delay cost, intersection crash cost, combined EUAC over a 20-year analysis period (with 1:1 agency cost to user cost weight) and the ranking of intersection alternatives. According to the intersection-level results, the J-turn is the best alternative for most intersections along the corridor. However, when the traffic on the minor road is very large, interchange becomes the best option, and J-turn and TWSC become less favorable compared to signalized intersection due to the higher delay costs for minor road users.

4.3 Corridor-Level Results

In this section, various corridor plans are considered. Life-cycle analyses were carried out at the corridor level to compare the benefits and costs associated with each corridor conversion plan.

4.3.1 Corridor Conversion Plans

Table 4.3 presents 15 different corridor plans. Plan 0 is the do-nothing alternative, that is, to keep all the intersections as they exist currently. Plans 1 to 10 are free-flow conversion plans: converting the existing corridor to a free-flow corridor with a mix of TWSC intersections, J-turn intersections and interchanges. Plans 11 to 14 are freeway conversion plans: converting the existing corridor to a fully-controlled limited-access highway with a mix of interchanges and overpasses. For the freeway plans, it is not always practical to have an interchange at every intersection, therefore overpasses are used between two interchanges. For the overpasses, it is assumed that the intersection crash frequency is zero, and the delay cost is the additional travel time for drivers who need to detour to enter or exit the freeway. The detour time can be estimated by measuring the travel time from an overpass to the nearest interchange.

TABLE 4.1.
Existing Intersection Type and Traffic Information

Major Road	Minor Road	Control Type	Length (miles)	Major ADT	Major Truck (%)	Minor ADT	Minor Truck (%)
US 30	Lincoln Hwy	1WSC	1	19,900	33	120	7
	Union Rd	2WSC	1.1	19,900	33	783	7
	Tulip Rd	2WSC	0.7	16,777	33	783	7
	Rose Rd	2WSC	1.5	16,777	33	783	7
	Redwood Rd	2WSC	0.7	16,780	35	783	7
	Queen Rd	Signal	0.5	16,783	36	1,425	9
	Pioneer Dr	Signal	1.5	17,541	32	4,694	26
	N Oak Dr	Signal	1	15,685	37	11,140	6
	N Michigan St	Diamond Interchange	0.9	18,715	37	12,557	9
	Plymouth Goshen Trail	2WSC	1	16,614	39	1,884	4

TABLE 4.2
Intersection-Level Analysis Results

(a) Annual Intersection Delay Cost

	Intersection Type			
Intersection	**Signal ($)**	**TWSC ($)**	**J-Turn ($)**	**Interchange ($)**
Lincoln Hwy	359,636	136,369	184,065	1,694
Union Rd	406,434	447,000	266,944	11,054
Tulip Rd	351,324	380,956	240,412	11,054
Rose Rd	351,324	380,956	240,412	11,054
Redwood Rd	351,377	381,019	243,861	11,054
Queen Rd	403,647	654,936	332,822	20,467
Pioneer Dr	746,714	2,500,802	952,012	77,207
N Oak Dr	1,053,834	4,968,437	1,504,922	155,891
N Michigan St	1,237,762	6,716,910	1,797,746	180,353
Plymouth Goshen Trail	415,045	805,653	373,007	25,903

(b) Annual Intersection Crash Cost

	Intersection Type			
Intersection	**Signal ($)**	**TWSC ($)**	**J-Turn ($)**	**Interchange ($)**
Lincoln Hwy	679,062	469,917	234,959	437,874
Union Rd	1,071,168	1,152,897	576,449	452,375
Tulip Rd	1,025,506	1,020,040	510,020	384,069
Rose Rd	1,025,506	1,020,040	510,020	384,069
Redwood Rd	1,025,553	1,020,171	510,086	384,135
Queen Rd	1,186,904	1,358,870	679,435	398,242
Pioneer Dr	1,608,090	2,481,301	1,240,651	486,309
N Oak Dr	1,932,676	3,463,584	1,731,792	586,701
N Michigan St	2,085,947	4,162,849	2,081,425	683,976
Plymouth Goshen Trail	1,267,459	1,541,914	770,957	404,585

(c) EUAC (1:1 Agency Cost to User Cost Weight)

	Intersection Type			
Intersection	**Signal ($)**	**TWSC ($)**	**J-Turn ($)**	**Interchange ($)**
Lincoln Hwy	1,370,381	692,491	682,120	1,667,214
Union Rd	1,947,487	1,747,124	1,160,725	1,695,194
Tulip Rd	1,822,437	1,534,597	1,055,448	1,615,095
Rose Rd	1,822,437	1,534,597	1,055,448	1,615,095
Redwood Rd	1,822,561	1,534,804	1,059,565	1,615,172
Queen Rd	2,098,507	2,171,325	1,353,054	1,642,753
Pioneer Dr	3,060,054	5,163,042	2,706,047	1,812,562
N Oak Dr	3,850,993	8,575,799	3,903,158	2,022,556
N Michigan St	4,268,711	10,988,683	4,636,985	2,165,311
Plymouth Goshen Trail	2,218,990	2,516,925	1,502,414	1,656,566

(d) Alternative Rankings (1:1 Agency Cost to User Cost Weight)

	Alternative Ranking			
Intersection	**Best**	**Second**	**Third**	**Fourth**
Lincoln Hwy	J-Turn	TWSC	Signal	Interchange
Union Rd	J-Turn	Interchange	TWSC	Signal
Tulip Rd	J-Turn	TWSC	Interchange	Signal
Rose Rd	J-Turn	TWSC	Interchange	Signal
Redwood Rd	J-Turn	TWSC	Interchange	Signal
Queen Rd	J-Turn	Interchange	Signal	TWSC
Pioneer Dr	Interchange	J-Turn	Signal	TWSC
N Oak Dr	Interchange	Signal	J-Turn	TWSC
N Michigan St	Interchange	Signal	J-Turn	TWSC
Plymouth Goshen Trail	J-Turn	Interchange	Signal	TWSC

TABLE 4.3
Potential Corridor Conversion Plans

	Do Nothing	Free-Flow Conversion Plans (mix of TWSC and J-turn)					
Intersections	**Plan 0**	**Plan 1**	**Plan 2**	**Plan 3**	**Plan 4**	**Plan 5**	**Plan 6**
Lincoln Hwy	1WSC	1WSC	1WSC	TWSC	J-Turn	J-Turn	J-Turn
Union Rd	TWSC	TWSC	TWSC	J-Turn	J-Turn	J-Turn	J-Turn
Tulip Rd	TWSC	TWSC	TWSC	TWSC	TWSC	TWSC	J-Turn
Rose Rd	TWSC	TWSC	TWSC	TWSC	TWSC	J-Turn	J-Turn
Redwood Rd	TWSC	TWSC	TWSC	TWSC	TWSC	TWSC	J-Turn
Queen Rd	Signal	TWSC	TWSC	TWSC	TWSC	J-Turn	J-Turn
Pioneer Dr	Signal	TWSC	J-Turn	J-Turn	J-Turn	J-Turn	J-Turn
N Oak Dr	Signal	J-Turn	J-Turn	J-Turn	J-Turn	J-Turn	J-Turn
N Michigan	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange
Plymouth	TWSC	TWSC	TWSC	TWSC	J-Turn	J-Turn	J-Turn

	Free-Flow Conversion Plans (mix of TWSC, J-turn and interchange)				Freeway Conversion Plans (mix of interchange and overpass)			
Intersections	**Plan 7**	**Plan 8**	**Plan 9**	**Plan 10**	**Plan 11**	**Plan 12**	**Plan 13**	**Plan 14**
Lincoln Hwy	J-Turn	J-Turn	J-Turn	J-Turn	Overpass	Overpass	Overpass	Interchange
Union Rd	J-Turn	Interchange	J-Turn	Interchange	Overpass	Interchange	Interchange	Overpass
Tulip Rd	TWSC	J-Turn	J-Turn	J-Turn	Overpass	Overpass	Overpass	Interchange
Rose Rd	J-Turn	J-Turn	J-Turn	J-Turn	Overpass	Overpass	Interchange	Overpass
Redwood Rd	TWSC	TWSC	J-Turn	J-Turn	Overpass	Overpass	Overpass	Interchange
Queen Rd	J-Turn	J-Turn	J-Turn	J-Turn	Overpass	Overpass	Overpass	Overpass
Pioneer Dr	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange
N Oak Dr	J-Turn	J-Turn	J-Turn	J-Turn	Overpass	Overpass	Overpass	Overpass
N Michigan	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange	Interchange
Plymouth	J-Turn	J-Turn	J-Turn	J-Turn	Overpass	Overpass	Overpass	Overpass

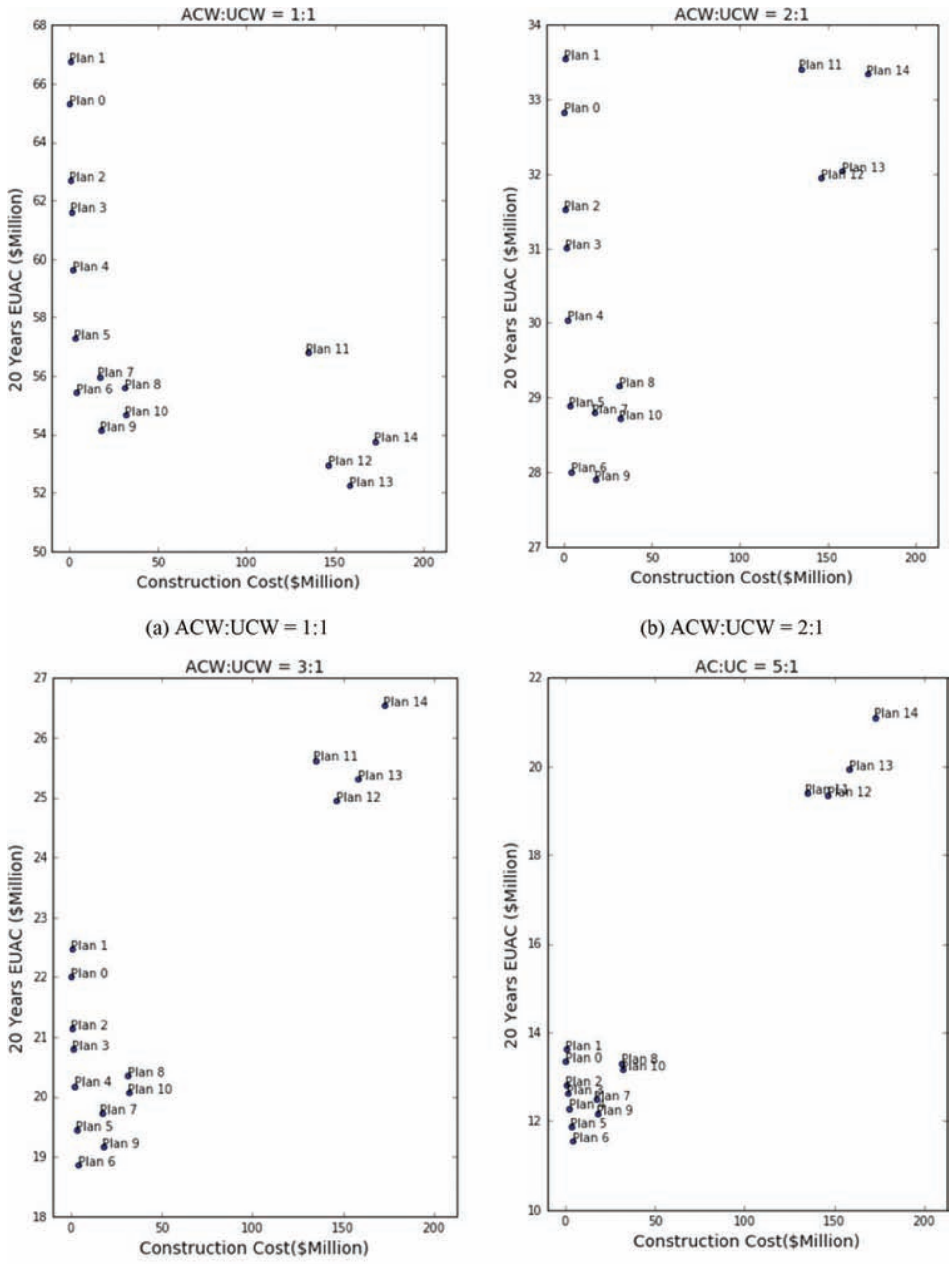
TABLE 4.4
20-Year Life-Cycle Analysis Results

			20 Years EUAC ($)			
			Agency Cost Weight: User Cost Weight			
Corridor Conversion Plan		**Construction Cost ($)**	**1:1**	**2:1**	**3:1**	**5:1**
Existing	Plan 0	0	65,324,413	32,835,046	22,005,257	13,341,426
Free-Flow Corridor	Plan 1	449,438	66,772,401	33,546,720	22,471,493	13,611,311
	Plan 2	898,876	62,700,434	31,527,272	21,136,217	12,823,374
	Plan 3	1,348,314	61,620,207	31,003,693	20,798,189	12,633,785
	Plan 4	2,247,190	59,639,502	30,046,411	20,182,048	12,290,557
	Plan 5	3,146,066	57,274,336	28,896,898	19,437,753	11,870,436
	Plan 6	4,044,942	55,430,578	28,008,090	18,867,261	11,554,597
	Plan 7	16,989,860	55,972,424	28,793,741	19,734,181	12,486,532
	Plan 8	31,283,092	55,584,531	29,164,129	20,357,329	13,311,888
	Plan 9	17,888,736	54,128,667	27,904,933	19,163,689	12,170,693
	Plan 10	31,732,530	54,665,098	28,720,948	20,072,898	13,154,458
Freeway	Plan 11	134,783,232	56,793,314	33,417,235	25,625,209	19,391,588
	Plan 12	146,576,464	52,951,410	31,949,404	24,948,735	19,348,200
	Plan 13	158,369,696	52,247,293	32,050,466	25,318,190	19,932,369
	Plan 14	172,662,928	53,756,029	33,349,932	26,547,899	21,106,273

4.3.2 Life-Cycle Analysis Results

Life-cycle analysis was carried out for each of the 15 proposed corridor plans. In addition to the intersection-level costs (crash cost, delay cost and intersection construction costs), the corridor-level analysis includes the costs incurred along the road segments (travel time cost, road segment maintenance costs and construction costs). Table 4.4 presents the corridor-level life-cycle analysis results for each corridor plan under four different weight ratios of agency cost to user cost.

Figure 4.1(a) presents the relationship between the 20-year combined life-cycle cost (EUAC) and the initial agency investments (construction cost). It was noticed



(a) ACW:UCW = 1:1

(b) ACW:UCW = 2:1

(c) ACW:UCW = 3:1

(d) ACW:UCW = 5:1

Figure 4.1 20-year EUAC ($ millions) vs. initial agency investments ($ millions) with varying ACW:UCW ratios.

that, when agency cost and user cost are equally weighted, freeway conversion Plans 12 to 14 have lower EUAC compared to the free-flow conversion plans. However, the initial investment needed for the freeway conversion plans far exceeds the costs needed for a free-flow conversion plan. Therefore, when considering the most cost-effective use of public funds, the free-flow conversion plans are superior options, despite their higher EUAC values. Among the free-flow plans, Plan 9 (add one interchange and convert all other signalized or TWSC intersections to J-turns) is the best one, followed by Plans 10 and 8. Plan 1 (converting the three signalized intersections into one J-turn and two TWSC intersections) has higher EUAC than Plan 0, which means such conversion is not economically justified.

Figure 4.1(b)–(c) present the same analysis for other agency cost weight and user cost weight. As the agency cost is assigned higher weight, the results change significantly. The freeway conversion plans become too expensive and cannot compete with any other plan. Also, of the free-flow conversion plans, the best plan changes from Plan 9 to Plan 6.

Figure 4.2 presents the relationship between the user benefits (EUAB, user cost savings compared to Plan 0)

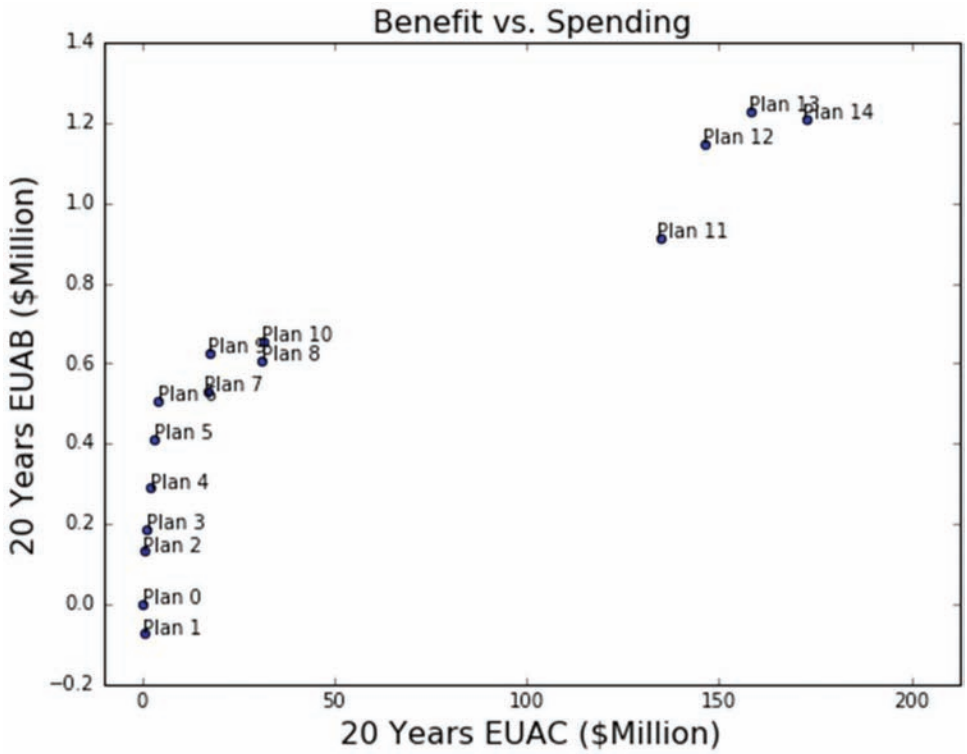


Figure 4.2 EUAB (user benefits) vs. EUAC (agency cost), 20 years, $ millions.

and the agency investments (EUAC, total construction and maintenance costs). Both the EUAC and EUAB of the freeway conversion plans are much higher than that of the free-flow options. The benefits increase rapidly as the agency cost increases at the beginning, but then increases more slowly as the agency cost becomes very high.

4.4 Conclusions

In this chapter, the framework and models introduced in Chapter 3 were applied to a case study of a 10-mile corridor along US 30 in Indiana. This corridor was chosen because (1) it has a mix of signalized and stop-controlled intersections, and (2) traffic volume data are available for most intersections. The analysis was carried out at two levels: (1) at the intersection-level, the life-cycle costs and rankings of the four intersection alternatives were calculated at each intersection; (2) at the corridor-level, 15 potential corridor conversion plans were proposed, and the corridor-level life-cycle costs were calculated for each conversion plan.

The intersection-level analysis results suggest that the J-turn is the best option at most intersections. This is because most intersections at the studied corridor have moderate traffic volumes on both major and minor roads, which justifies the costs of building a J-turn but does not justify the cost of building an interchange. Interchange is the best alternative at the three intersections where traffic volumes on both minor roads and major roads are relatively large. (One of the intersections is already an interchange.) Of the three intersections, two (N Oak Dr, N Michigan St) have very high traffic volumes on the minor roads. As a result, both J-turn and TWSC intersections have higher total delay costs compared to a signalized intersection.

The corridor-level analysis results suggest that the freeway corridor plans are more beneficial to the users and have a lower combined life-cycle EUAC than free-flow plans when agency cost and user cost are equally weighted. However, as a trade-off, the agency needs to spend relatively much more on the initial construction. Therefore, when the agency costs are given higher importance, the freeway corridor plans become very expensive and cannot compete with any other plan. With different traffic volumes and different corridor lengths, the results can be significantly different.

5. SUMMARY

This study developed a decision framework that could help address the following questions:

1. What is the overall performance of a free-flow corridor with compared to a full limited access-controlled freeway?
2. What is the best conversion alternative at an intersection?
3. What is the threshold traffic volume at which each alternative is considered superior to another?
4. What is the role of the relative weights of agency cost and user cost in corridor upgrading decision making?

The proposed decision framework addresses these questions by evaluating the overall performance of several corridor upgrade alternatives at two levels (intersection-level and corridor-level). At the intersection level, four intersection alternatives were considered: signalized intersection (do nothing), TWSC intersection, J-turn and interchange. The mobility performance and safety performance of the four alternatives were measured using models, based on a number of assumptions. This is done using both monetized and non-monetized measures. Non-monetized performance refers to safety and mobility. After monetization of the user costs, these performance considerations can be included in an economic analysis. The monetized measure refers to the weighted sum of agency costs and user costs.

5.1 Findings

It was found that the *interchange* option always has the highest mobility performance. When traffic volume is very low, the *TWSC intersection* option has superior mobility performance compared to *J-turn* and *signalized intersection* options. However, as traffic volume increases, delay at the *TWSC intersection* option increases significantly, while the delays for other alternatives are less dependent on traffic volumes. In terms of safety performance, the *interchange* and *J-turn* options are in general safer compared to the *TWSC intersection* and *signalized intersection* options. Mobility and safety performance were monetized to represent user costs and included in the economic analysis. The agency cost considered in this study includes initial construction cost and annual maintenance costs. The agency cost of converting an intersection to an interchange is much higher than those of the other alternatives. The overall performance of an alternative is measured in terms of the total life-cycle cost of both agency cost and user cost. It was found that the overall performance of the *TWSC intersection* option is most sensitive to the increase in traffic volume. This is because both intersection delay and number of crashes at a TWSC intersection were estimated by models in which the Major ADT and Minor ADT are the predictors. The overall performance of the *interchange* option is the least sensitive to the increase in traffic volume. This is because the agency cost of the *interchange* option constitutes a large percentage of the total cost. In the analysis, the agency cost is a fixed cost that does not depend on the traffic volume.

One of the most important results of this study is the establishment of the decision boundaries based on traffic level on the major and minor roads. Multiple plots were to show (1) the rankings of the intersection alternatives under given traffic volumes, and (2) the decision boundary at which the rankings of two alternatives switches. It was found that, when the major ADT is less than 3,000, the best option is mostly likely *TWSC*. When the minor ADT is less than 4,000, *J-turn* is almost always more cost-effective than *interchange*, regardless of the major ADT. When the traffic volumes on major road and minor road are both large, *interchange* is the best option. The decision boundaries were also developed for different weights of agency and user cost. It was found that, as the agency cost is increased, the decision boundaries change significantly, and the area where the *interchange* is the "best option" decreases from the largest area to zero. The areas where *TWSC* and *signalized intersection* are optimal increases continuously. Further, the area where *J-turn* is the "best option" increases initially and then decreases. The decision boundary plots can help highway agencies choose the appropriate intersection type based on the traffic volumes on both major and minor roads.

At the corridor level, the two conversion alternatives are free-flow corridor (with a mix of TWSC, J-turn, and interchanges) and freeway corridor (interchange only). To illustrate the corridor-level analysis procedure, a case study on a 10-mile section of US 30 in Indiana was carried out in Chapter 4. Fifteen different corridor conversion plans (10 free-flow plans, 4 freeway plans, and one do-nothing alternative) were proposed. Life-cycle costs were estimated and compared. The analysis results suggest that the freeway corridor plans are more beneficial to the users and have lower combined life-cycle EUAC compared to the free-flow plans when agency cost and user cost are equally weighted. However, as a trade-off, the agency needs to spend much more on initial construction. Therefore, when agency cost is assigned greater weight, the freeway corridor conversion plans become very expensive and cannot compete with any other plan. With different traffic volumes, different lengths in other corridors, and different weight ratios, the results can be significantly different.

A spreadsheet program was developed in this study to give users the flexibility to change any input values and to obtain the life-cycle cost analysis results for each intersection alternative. The spreadsheet can be also used to analyze life-cycle cost for an entire corridor by repeating the analysis for each intersection along the corridor.

5.2 Limitations and Future Work

While this study is more comprehensive than some previous studies in the domain, it does have a few limitations. First, it is limited by the availability of data. Due to the limitations of traffic data, the case study focused on only one corridor. In addition, limited information regarding the safety and operational performance of J-turns means that their impacts may not be adequately addressed in the study, which may affect the efficacy of the study recommendations.

In order to address these limitations, future work is suggested. Additional data collection on the corridors of interest (particularly traffic volume data) would allow for a more complete set of recommendations to be made for the whole corridor, not just the sections of the corridor for which traffic data are available.

Additionally, a separate and more complete study focusing on the operational performance of J-turns (using the definitions adopted for this work) would allow for more reliable approximations of their impacts on intersection delay and capacity. Additional work should also be undertaken to better understand the safety impacts of J-turns in Indiana, where they represent a new intersection design type.

Undertaking such future work will provide a better foundation for making decisions among alternative intersection treatments, including non-traditional designs such as J-turns. It is also anticipated that the framework developed in this study can be applied to other corridors or replicated in other states to conduct similar analyses.

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APPENDIX: INTERSECTION ANALYSIS PROGRAM

This Excel spreadsheet is available for download at https://doi.org/10.5703/1288284317079.

About the Joint Transportation Research Program (JTRP)

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

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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

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