AMERICAN UNIVERSITY OF BEIRUT

A FRAMEWORK FOR PRIORITIZING ARTERIAL/FREEWAY INTERCHANGE TYPES USING MULTI-CRITERIA ANALYSIS

by
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AN ABSTRACT OF THE THESIS OF

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Major: Transportation Engineering

Title: A Framework for Prioritizing Arterial/Freeway Interchange Types using Multi-Criteria Analysis

An interchange is a road junction that typically uses grade separation to accommodate different volumes of traffic safely and efficiently through interconnecting roads. There are many types of interchanges, each of which has different characteristics and applications. Different interchange types are appropriate to use in certain contexts. Previous research related to evaluation of different interchange alternatives has focused on a limited set of criteria, mainly operational performance and safety, while few others included cost impacts.

In this thesis, a prioritization framework is proposed for selecting a suitable interchange type for grade-separated intersection configurations based on a variety of performance measures, including operational performance, socio-environment, safety, and cost. The assessment is based on a multi-criteria analysis (MCA) approach. A linear additive model is used to evaluate each scheme on a set of criteria derived from several objectives. The relative importance of the criteria is obtained using the Analytic Hierarchy Process (AHP). In making a decision, Saaty's AHP/Eigenvector method involves ranking the alternatives based on a set of criteria. The weights of these criteria are derived using multilevel hierarchic structures.

This research introduces a case study at the intersection of Sheikh Jaber road and Prince Bandar Bin Abdulaziz road in Riyadh city. Three different Arterial/Freeway interchange types are compared based on the set of performance criteria. This research helps in defining the main factors that play a significant role in determining the preferred design scheme, and the extent to which each of these factors has an effect on the overall priority of a certain interchange configuration. The results of the study showed that the Diverging Diamond Interchange (DDI) outperformed its interchange counterparts and was chosen as the most preferred interchange configuration. The Single Point Urban Interchange (SPUI) ranked second while the Tight Urban Diamond (TUDI) was least preferred. Sensitivity tests were undertaken to determine the effects of changing the scores or the weights on the overall results. These tests revealed the robustness of the model as the overall scores remained stable under different tested scenarios.

CONTENTS

5: CONCLUSIONS...174

ILLUSTRATIONS

Figure Page

TABLES

Table Page

CHAPTER 1

INTRODUCTION

1.1 Background

An interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways on different levels (American Association of State Highway and Transportation Officials, 2004). A wide variety of interchanges exist to accommodate different volumes of traffic safely and efficiently through interconnecting roads. Interchanges vary from single ramps connecting local streets to complex and comprehensive layouts involving two or more highways.

The selection of the appropriate type of interchange, along with its design, is influenced by many factors such as operational performance, socio-environmental impacts, safety, and costs. The main component of the prioritization process is to determine how well an interchange scheme meets such objectives. Given the wide range of objectives and the difficulty in assigning a monetary value to all economic and non-economic factors, it is necessary to move away from the conventional assessment approaches that consider a single criterion and use the multi-criteria analysis instead (Tsamboulas, 2007).

The multi-criteria analysis (MCA) consists of the evaluation of a number of specific criteria derived from general objectives. The main advantage of this type of analysis lies in quantifying technically the different criteria and analyzing them; thus paving the way for evaluating the impacts of all criteria (Kulkarni et al., 2004).

1.2 Research Goals and Objectives

The aim of this research is to develop a framework for prioritizing Arterial/Freeway interchange types taking into account a set of different criteria. This framework uses a linear additive multi-criteria approach where the weights of the criteria are derived using the Analytic Hierarchy Process (AHP). This method allows for assessing the impacts of criteria among a hierarchy tree by eliciting judgments in the form of paired comparison. A case study is adopted to illustrate the typical implementation of the developed framework.

1.3 Research Contributions

Most of the earlier research focused on comparing different types of interchanges based on their operational performance using microscopic simulation analysis. Some researchers included safety concerns as a part of their analysis. Fewer research attempts have been made to quantify the cost implications for implementing these interchanges, while none considered the socio-environmental impacts.

This research helps in prioritizing the Arterial/Freeway interchanges based on four main criteria group: Operational performance, Socio-Environmental Impacts, Safety, and Costs. Since these groups reflect financial and non-financial factors, it was necessary to move away from the conventional assessment approach that was used abundantly in the literature, such as cost-benefit analysis, and use instead a multi-criteria analysis approach. Hence, the use of the MCA adds to the novelty and value of this research. This research introduces and evaluates several weighting methodologies following which the most appropriate method, Saaty's AHP/Eigenvector, is chosen for being systematic, easy to implement, and transparent.

Using an online questionnaire, the judgments of several decision-maker groups including: Junior Engineers, Senior Engineers, Professors, and Stakeholders are elicited based on which the relative importance of different criteria is determined. In computing the scores of interchanges on these criteria, several scoring functions are developed. Finally, this research concludes with a case study in the city of Riyadh whereby three different Arterial/Freeway interchange types are evaluated using the proposed prioritization framework. The results of the case study are further explored based on sensitivity tests to consider the possible differences in judgment among the decision-maker groups and to build more confidence in the results through exploring the effects of changing several factors on the overall ranking.

1.4 Thesis Organization

The remainder of this thesis is divided into 4 chapters:

- **Chapter 2**: Presents a literature review of studies focusing on the different types of interchanges with emphasis on the operational performance, safety, and costs. No evaluation techniques for prioritizing the interchanges on a set of criteria were evident; a preference was made according to the performance of the alternatives based on a single criterion. In addition, this section articulates the need for Multi-Criteria Analysis (MCA) with emphasis on the Analytic Hierarchy Process (AHP).
- **Chapter 3**: Outlines the proposed evaluation framework with a definition of the different criteria. Also, this section illustrates the scoring guidelines, focuses on the weighting methodology, presents the online questionnaire, and derives the criteria weights.

- **Chapter 4**: Presents a case study in Riyadh, the capital of Kingdom Saudi Arabia (KSA), with highlights on the scoring of schemes and ranking of alternatives. In addition, this section introduces a sensitivity analysis and presents the outcome of the analyses.
- **Chapter 5**: Identifies the research contributions, presents conclusive remarks and states the major findings, and possible extensions of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

An interchange is a road junction that typically uses grade separation to accommodate different volumes of traffic safely and efficiently through interconnecting roads. There are many types of interchanges, each of which has different characteristics and applications. Different interchange types are appropriate to use in certain contexts.

Several studies have covered the topic of prioritizing different interchange alternatives to determine the preferred design. Many practitioners and academics dealt with this subject from different perspectives including the operational performance and safety, while few others considered cost impacts. Several methods have been used to determine the performance of interchanges such as microscopic simulation, analytical models, field observations, and questionnaires.

This chapter summarizes the findings of the relevant literature focusing on interchange type selection and ranking alternatives using multi-criteria analysis. The first section presents the studies that focused on comparing conventional types of diamond interchanges (TUDI) with unconventional counterparts (SPUI) and (DDI), followed by an operational comparison for the two unconventional types. The second section introduces the commonly used tools for conducting microscopic simulation and presents the adopted measures of effectiveness for analyzing and determining the preferred interchange scheme. Finally, the last section illustrates the importance of using Multi-Criteria Analysis for prioritizing different interchange types and introduces the Analytic Hierarchy Process (AHP).

2.2 Background Information

2.2.1 Interchange Types and Classifications

Due to the significant increase in traffic and congestion on urban freeways, the need has arisen for novel intersection designs to accommodate high volume traffic and relieve congestion. AASHTO (American Association of State Highway and Transportation Officials, 2004) classifies intersections into three types: at-grade intersections, highway grade separations without ramps, and interchanges. Each intersection type accommodates traffic to varying degrees of efficiency, thus being practical for certain situations. At-grade intersections are typically used at low functional road classes where traffic volumes are relatively low. On the other hand, interchanges are recognized for their ability to accommodate high volumes of traffic in a safe and efficient manner using grade separations.

As stated in the AASHTO (American Association of State Highway and Transportation Officials, 2004), interchanges are classified into two main types: System Interchanges and Service Interchanges. The first type connects freeways to other freeways, while the second connects freeways to arterials and other classification roads. In this research, we shall focus on service interchanges connecting freeways with crossing arterial roads. The conventional diamond interchange shall be compared with two other unconventional configurations of comparable sizes, namely the Single-Point Urban Interchange (SPUI) and the Diverging Diamond Interchange (DDI).

Diamond interchange, the most prevalent type of arterial interchange, typically consists of two relatively close intersections with coordinated signal controls. Two signal phases are required to allow for the through and left turning movements from the arterial to the freeway and another two phases for left turning vehicles from the off ramps into the arterial, for a total of four phases. The diamond interchanges are classified into three different types according to the distances between the two intersections (Chaudhary et al., 2000), as follows:

- **Conventional Diamond Interchange (DI)**: An interchange having a distance greater than 800 feet (240 meters) between the two intersections. It is typically located in rural areas and is controlled by stop signs.
- **Compressed Diamond Interchange (CDI)**: A diamond having a distance of 400 to 800 feet (120 to 240 m) between both intersections. The CDI is usually found in suburban areas and is typically controlled by traffic signals.
- **Tight Urban Diamond Interchange (TUDI)**: A diamond interchange having a distance less than 400 feet (120 m) between the two intersections. The TUDI is usually located in highly developed areas and is always signal controlled.

The **Single Point Urban Interchange (SPUI)** is a relatively new design offering improved road capacity, safer operations, and requiring lower road right-of-way than the conventional diamond interchange (Qureshi et al., 2004). Unlike the other conventional diamond interchanges, the SPUI merges all ramp terminals into one signalized intersection thus allowing concurrent off-ramp left-turns to proceed simultaneously. Three signal phases are required to allow for all vehicular movements from/to the crossing roads.

The **Diverging Diamond Interchange (DDI)** is a new design that was developed by Chlewicki in 2003 and implemented for the first time in the United States in 2009 to accommodate left-turn movements onto arterials while eliminating the need for left-turn phasing; hence only two phases are required. Unlike the conventional type, the DDI features a reversal of the directional traffic movements on the arterial crossing road where through and left-turn vehicles are switched to the opposite sides in between the ramp terminals (Hughes et al., 2010).

The schematic layout plans of the three different interchange configurations are shown in the below figures:

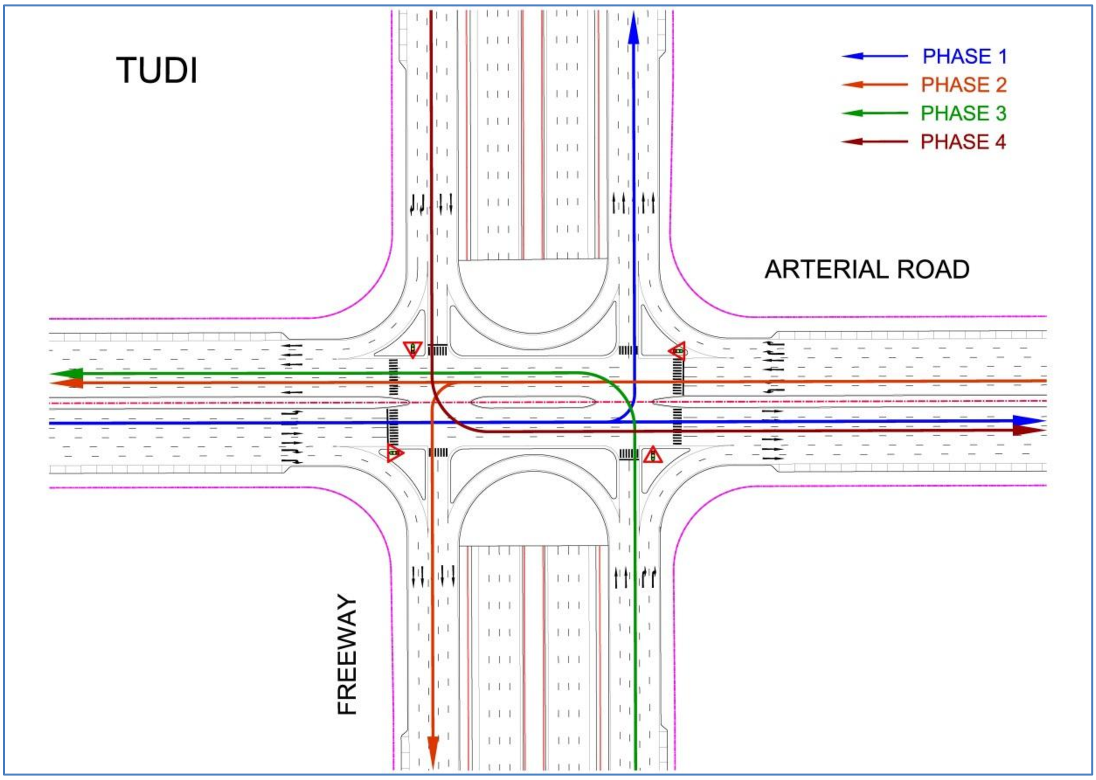

Figure 2-1: Layout Plan for a Tight Urban Diamond Interchange (TUDI)

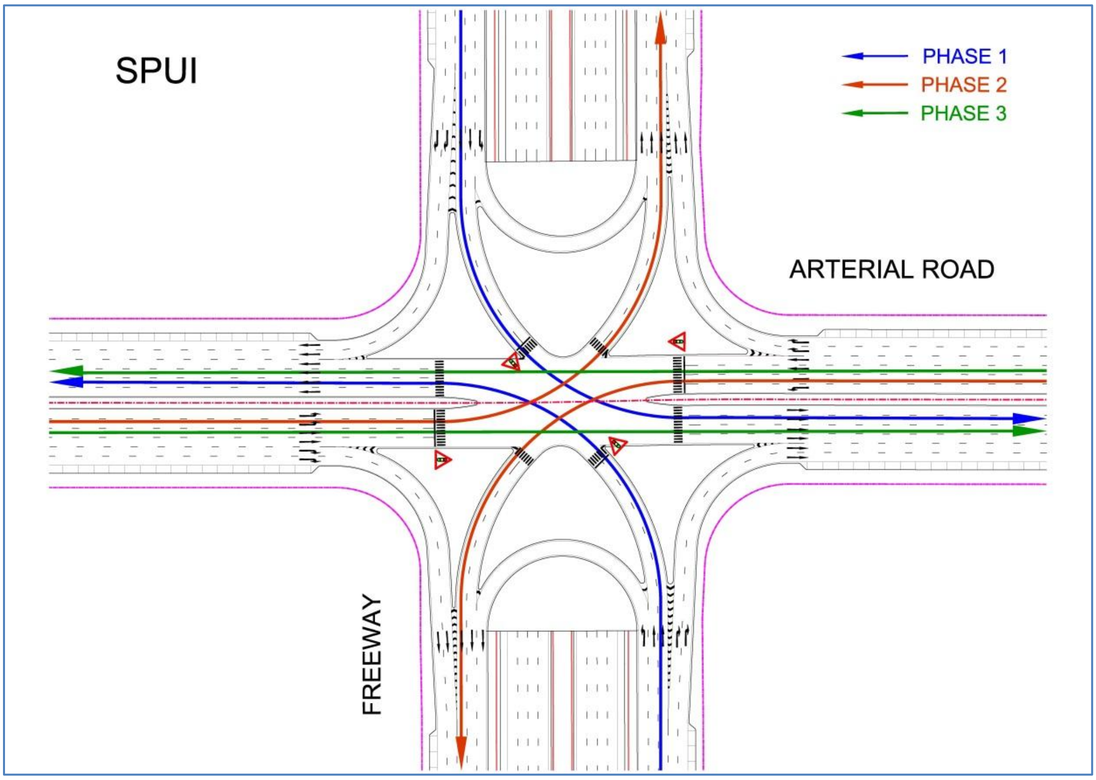

Figure 2-2: Layout Plan for a Single Point Urban Interchange (SPUI)

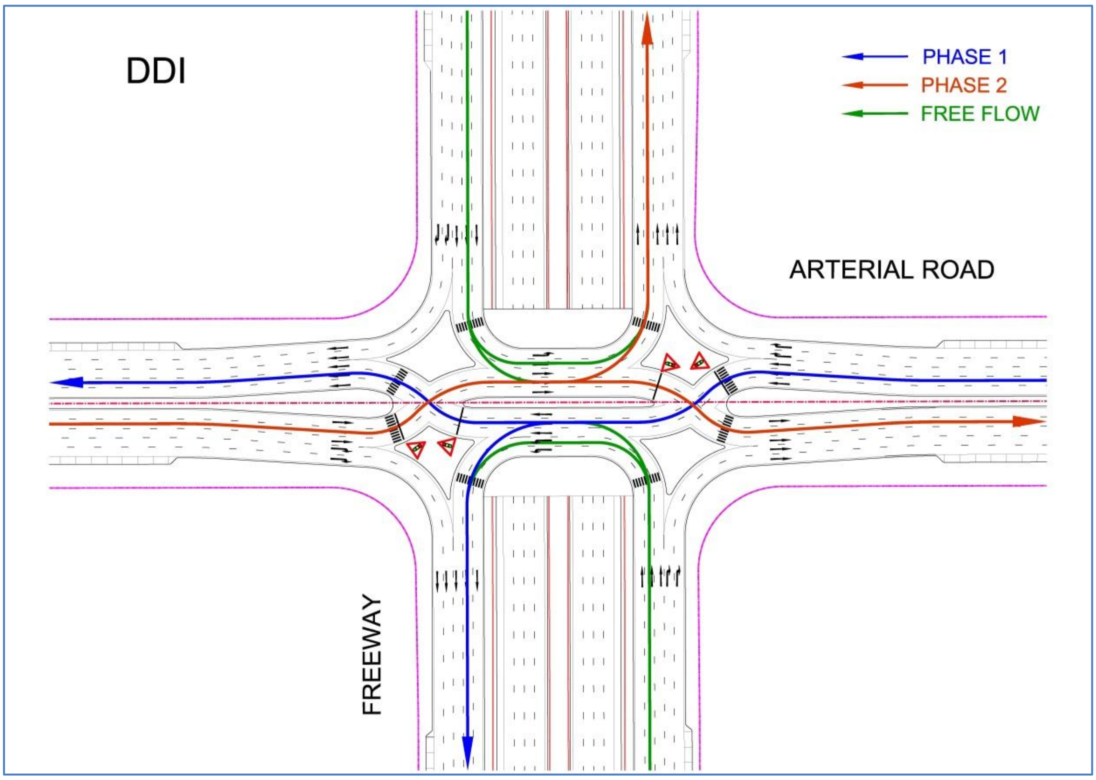

Figure 2-3: Layout Plan for a Diverging Diamond Interchange (DDI)

2.2.2 Single Point Urban Interchange (SPUI)

Due to limited state transportation budgets, inefficient designs for some existing interchanges, and limited right-of-way, several studies were initiated to propose new interchange designs that can accommodate high traffic volumes with potential cost savings.

In the early 1970s, a new interchange concept emerged to cater for the increased traffic demand levels, and provide safer operations, known as the single point urban interchange (SPUI). Since then, several studies were undertaken to determine the characteristics of this design and check its performance. In December 1996, the Federal Highway Administration (FHWA) in collaboration with Virginia Department of Transportation (VDOT) prepared a brief study evaluating the operational and safety characteristics of the SPUI and its conventional diamond counterpart. Guidelines were developed to identify the traffic and geometric conditions that favor one type over the other (Garber et al., 1996). The guidelines were developed based on the operational performance and safety while a questionnaire survey was conducted with state traffic engineers to reveal their experience with the two types of interchanges. The researchers concluded that the SPUI is a safe, efficient urban interchange design that can decrease delay and congestion, and uses less land area than other types. The proportion of accidents at the center of the intersection was found higher at conventional diamonds whereas the ramp accidents were significantly greater at SPUIs (Garber et al., 1996).

Three years later, Virginia Department of Transportation prepared a study to aid designers in the selection of the optimum interchange design. Several methods were used to develop the guidelines such as a review of the relevant literature, a nationwide survey of state engineers, and a series of CORSIM microscopic simulations. Ten interchanges were studied and the results revealed that the SPUI ranked first in requiring the least right-of-way and providing easier arterial coordination than conventional diamond interchanges; however, the construction cost was 10% to 20% higher for SPUIs (Garber et al., 1999). As for safety, the researchers found that SPUIs experienced high percentage of angle and sideswipe accidents where the predominant collision location is at cross roads unlike the diamond that faced high percentages of accidents at the center of the intersection. As for the operational performance, the conventional interchange was found to operate at an acceptable level of service at low volume levels while the SPUIs experienced lower delays at all tested scenarios. Based on these results, the guidelines for interchange type selection were prepared taking into consideration the right-of-way availability, construction cost, safety, traffic and operational performance (Garber et al., 1999).

In 1997, the Department of Transportation in Michigan (MDOT) was considering the SPUI as an alternative design for rehabilitating and upgrading many of its freeway interchanges located in urban environments. To evaluate the appropriateness of the SPUI, a preliminary review of literature and email survey with other state departments of transportation were conducted. Due to the significant inconsistent responses and lack of information, a telephone survey was used to locate the appropriate sites for field review (Dorothy et al., 1997). Site observations were made as the design and operational performance of the existing SPUIs were analyzed including geometric design, signal operation, pedestrian control, pavement marking, and landscaping. Dorothy et al. (1997) came to the conclusion that SPUI is a good and viable interchange design and should be taken into consideration in future studies.

In 2004, Missouri Department of Transportation (MoDOT) examined the state of practice for three functional SPUIs in Missouri. A comprehensive report was prepared to provide design guidelines for SPUIs and to offer a set of warrants for when to install a SPUI as compared to Diamond Interchanges (Qureshi et al., 2004). After conducting an extensive literature review, a questionnaire was developed to examine the current state of practice related to the planning, design, and construction of SPUIs. Qureshi et al. (2004) studied different key geometric and operational characteristics of the SPUI including grade separation, roadway characteristics, skew angles, turning radii, signal phasing, and traffic volume. Results showed that limited Right-of-Way and increase in capacity are the main reason for installing SPUIs. When frontage roads are needed, SPUIs are not recommended as the number of signal phases increases and consequently the delays for the overall network. In addition, SPUIs were found not to accommodate pedestrian crossings effectively and have higher construction costs than conventional Diamond Interchanges (Qureshi et al., 2004).

Other research efforts were also undertaken to examine the operational performance of the SPUI and other diamond interchanges using microscopic simulation (Jones et al., 2003; Sharp et al., 2000). CORSIM, a stochastic time-based micro simulation tool, was used for modeling and Synchro was used for optimizing the signal timing plans. Several measures of effectiveness were selected for performing the operational comparison, including the average speed, volume served, phase failures, percent stops, and delay times. For the tested volume scenarios and traffic control conditions, the researchers found that the SPUI provided better system operational performance than TUDI. The SPUI experienced lower delays, higher average travel speeds, fewer phase failures, and lower percentage of stops (Jones et al., 2003; Sharp et al., 2000).

Similarly, Bared et al. (2003) used microscopic simulation models to determine the operational performance of interchanges at various demand levels. A total of 101 traffic flow scenarios were modeled in CORSIM to determine the performance.

Statistical models based on the non-linear regression method were further developed estimating three main variables: delays, stop time, and percent stops. It was concluded that the SPUI outperformed the diamonds at high volumes especially for left-turning movements.

Two years later, Bared et al. (2005) studied the performance of the SPUI and TUDI interchange configurations from a safety perspective. A crash comparison of the two types of interchanges was conducted using data from 27 existing diamond interchanges and 13 SPUIs in the state of Washington. A negative binomial model was developed to predict total crashes, injuries, and fatalities on interchanges. Based on the safety comparison analysis, Bared et al. (2005) concluded that SPUIs were safer than TUDIs in terms of injury and fatality frequencies; however, there was no significant difference between both types regarding the total number of crashes.

Similarly, Zhou et al. (2014) analyzed the performance of the interchanges on Illinois freeway from a safety perspective. Statistical characteristics of wrong way crashes on existing diamond and single point interchanges were studied from three different aspects: crash, vehicle, and person related crashes. Zhou et al. (2014) proposed a method for predicting possible wrong-way entry points by analyzing wrong-way driver demographic information, driver physical condition, driver injury severity, vehicle characteristics, and collisions. The researchers found that a large proportion of wrong-way crashes occurred during weekends at late hours. Nearly 70% of wrong-way vehicles were passenger cars and 60% of wrong-way drivers were driving under the influence (Zhou et al., 2014).

Amer (2009) examined introducing pedestrians in the design of the signal timing and presented its effect on the performance of the SPUI and the TUDI. Based on the ADA requirements to include pedestrian mobility, microscopic simulation analysis was conducted to measure the average control delay for both types of interchanges. Two pedestrian walking speeds and three different traffic volumes were tested in CORSIM. Amer (2009) concluded that the SPUI provided significant improvement in the overall efficiency of the interchange at high traffic volumes, while both configurations performed similarly at low and medium traffic volumes. In addition, pedestrian walking speed had a minor effect on the control delay with all traffic volumes.

2.2.3 Diverging Diamond Interchange (DDI)

In 2003, Chlewicki proposed a novel interchange design known as the Diverging Diamond Interchange (DDI) to relieve congestion while accommodating different traffic patterns (Chlewicki, 2003). The aim of this interchange is to better accommodate left-turning vehicles through switching the traffic directions in between the ramp terminals and hence eliminating a phase in the signal cycle. In the DDI, the traffic on the crossing road maneuvers differently from the conventional diamond interchange, as traffic switches from one side to the opposite side in between the ramp terminals. As such, two signal lights are needed for this design, one at each crossover. Furthermore, Chlewicki (2003) analyzed the operational performance of the DDI under various demand levels and compared it to an existing traditional diamond in Baltimore County, Maryland using micro simulation software Synchro 5 and SimTraffic 5. The results showed that the diverging diamond interchange (DDI) operated much more efficiently than the traditional design whereby the total delay for the conventional diamond was about three times greater than the DDI, the stop delay was over four times as much, and the total stops were nearly double. A noticeable benefit of the DDI is the reductions in construction costs and right-of-way costs in addition to the fewer conflict points as compared to a conventional diamond interchange. Nevertheless, the most evident challenge in this design is safety, as driver confusion may arise especially for first time users. However, this confusion can be reduced with good geometric design, proper signing, and roadway markings and signals. Chlewicki (2003) further discussed the future scope of research that includes an analysis with different volume levels and turning movement ratios in addition to the proper use of speed and super-elevation rates at the crossover junctions.

Similarly, Bared et al. (2005) analyzed the DDI with four different traffic scenarios and compared it with the conventional designs. Traffic operations and pedestrian movements were simulated using VISSIM software and signal timing plans were optimized using TRANSYT-7F. The analysis was carried out by changing the number of lanes between the crossover locations. Two different DDI designs were evaluated as follows:

- A four-lane DDI in which the total number of lanes along the crossing road is four in both directions.
- A six-lane DDI in which the total number of lanes along the crossing road is six in both directions.

In summary, the major findings of this study confirmed the previous results provided by Chlewicki (2003), whereby under high traffic volumes, the DDI design outperforms the conventional counterpart (TUDI) through offering lower delays, lower stop time, fewer number of stops, and shorter queue lengths. Moreover, the capacity of all signalized movements was found to be higher for the DDI, especially for the left-turn movements, thus exclusive left turn lanes are no more necessary. In addition, the operational performance in the presence of pedestrians was tested, and a similar level of service to the conventional design was achieved (Bared et al., 2005).

Sharma et al. (2007) followed a similar methodology as Bared et al. (2005) and came out with similar conclusions. The DDI design was analyzed for unbalanced traffic volume scenarios using VISSIM software. Traffic signal timings were obtained using Synchro after optimization. The study encompassed a cost-effectiveness analysis for the DDI and the conventional interchange design. Sharma et al. (2007) found that the performance of the DDI was better than the conventional diamond configuration through offering lower delays, lower travel time, and smaller queue lengths. In addition, the DDI showed increased capacity for the critical movements, particularly the left-turns. The authors concluded that the time costs and vehicle operating costs are significantly reduced with the reduction of delays.

In 2007, the Federal Highway Administration (FHWA) in collaboration with the Missouri Department of Transportation (MoDOT) began addressing some of the safety concerns, such as human errors due to unfamiliarity, using a driving simulator to better understand the drivers’ behavior as they negotiate through the DDI (Bared et al., 2007). Different measures of effectiveness were considered to examine the safety performance, such as the wrong-way violations, navigation errors, red-light violations, and speed. Two variations of signing and pavement marking were used for the DDI creating two different alternatives along with the standard diamond alternative. 74 licensed drivers of different ages and gender were recruited for the experiment. The results of this study showed that fewer wrong-way movements, red-light violations, and navigation errors occurred within the DDI design as compared to the conventional configuration (TUDI). These fewer violations along with lower speed and lower potential number of conflict points combine to ensure that a properly designed, signed, and striped DDI will prove to be safer than a traditional diamond interchange (Bared et al., 2007).

In June 2009, after the operation of the first DDI in the United States, the Federal Highway Administration (FHWA) was interested in determining how well the interchange actually works when compared to the theoretical studies. A technical report was prepared validating the initial theoretical insights, as the DDI experienced low delays, few stops, reduced stop times, and short queue lengths on site (Bared, 2009). It was concluded that the DDI design offered benefits over the conventional interchange designs due to its efficient two-phase operation, narrower bridge structure width, lower costs, fewer conflict points, reduced vehicular delays, and reduced environmental impacts (Bared, 2009).

Because of the DDI's potential benefits and increasing popularity in the US, the FHWA opted to include this novel design in a comprehensive report entitled "Alternative Intersections/ Interchanges: Informational Report (AIIR)" that covered four intersection designs and two interchange designs offering benefits compared to the traditional designs. The report articulated the advantages and disadvantages of the DDI interchange type and provided some recommendations on signal phasing, access management for nearby properties, pedestrian and bicycle accommodation, and safety requirements (Hughes et al., 2010). The DDI was found to be beneficial in situations where high left-turning volumes are governing in addition to its effective two-phase signal rather than the conventional four phases. On the other hand, a major drawback of the DDI is driver confusion especially in between the ramp terminals; however, with proper signing and marking and effective use of glare screens these driving errors are significantly reduced (Hughes et al., 2010).

As for the signal timing plans, FHWA researchers optimized the DDI design using two-phase signals at both junctions. Compared to the conventional interchanges, the DDI permits relatively shorter cycle lengths at the signalized junctions; hence, the lost time per signal was reduced (Hughes et al., 2010). In cases where frontage road access is needed, the DDI is not preferred since an additional signal phase is needed to cater for the through movements. Furthermore, the researchers incorporated a detailed section for signing and marking schemes based on MoDOT's practice. Additional care was exerted for pedestrian movements, especially for those with visual impairments, and a list of measures to direct pedestrians through the interchange was suggested. Operationally, VISSIM was used to compare performance of the DDI to that of the conventional diamond interchange (CDI). It was found that the DDI outperformed the CDI when the on-ramp left turning volumes were high and the major road through volumes were moderately balanced. The four-lane bridge DDI processed the same volume as the six-lane bridge CDI, thus the Diverging Diamond interchanges provided tremendous cost savings by having reduced bridge structures (Hughes et al., 2010).

In May 2010, MoDOT released a report based on its knowledge and experience with building and operating the first DDI in the United States. The report entitled "Missouri's Experience with a Diverging Diamond Interchange: Lessons Learned" covered several topics related to the DDI including various design elements, construction issues, operational performance, as well as public involvement (MoDOT, 2010). The report comprised suggestions for improving road geometrics, signing, pavement marking, medians, and pedestrian access. Researchers focused on the design speed where a range between 20 and 30mph was desired to prevent any vehicular encroachment between adjacent lanes. In addition, three main elements of the crossover geometrics were discussed: the crossing angle with its impact on driver comfort, the tangent length beyond the crossover junctions, and the radii of the curves approaching and following the crossover. Lane widths and shoulders were briefly assessed and physical barriers were recommended to separate opposing directions of traffic given that enough sight distance is covered. Signals and mast arm locations were properly located to prevent any blocked view, and signal phasing plans were optimized taking into consideration pedestrian movements. Finally, MoDOT’s Engineering Policy Guide (EPG) was updated to reflect the experience gained with the Diverging Diamond Interchanges (MoDOT, 2010).

In February 2011, MoDOT in collaboration with HDR Engineering conducted an evaluation of the first Diverging Diamond in the United States. The purpose of this evaluation was to validate on previous traffic operations and to assess safety and public perceptions of the new interchange (Chilukuri et al., 2011). Using VISSIM as a micro-simulation tool, the researchers concluded that left-turn movements in a DDI experienced noticeable decrease in delays and queues unlike the through movements that experienced higher delays. Nonetheless, the overall traffic flow through the DDI was improved. As for safety, the total crashes within the first year of operation were reduced to half, the left turn type crashes were eliminated and the rear-end type crashes were slightly reduced. Finally public perception surveys were conducted with different public users to gain valuable information on the existing DDI configuration and thus enhance safety and traffic operations. It was noted that a high percentage of users expressed their satisfaction with the new design as the traffic flow had improved and the crashes were most likely to be reduced. A higher percentage of respondents expressed good understanding of how the interchange operates with the current design of islands and the proper use of signing and pavement marking (Chilukuri et al., 2011).

After the success MoDOT had with its first DDI, Illinois Department of Transportation (IDOT) was interested in exploring the option of replacing an existing diamond interchange on I-88 at Illinois Route 59, with a Diverging Diamond Interchange (Salley et al., 2012). A feasibility study was carried out to determine the optimal design solution taking into consideration the current and forecasted traffic operations in addition to the different safety requirements. Microscopic simulation was needed to model the complex interchange configurations; hence, VISSIM was used to evaluate the operational impacts, measure intersection delays, and to determine the queues within the interchange impact area. The results, similar to others, showed that the DDI design offers improvements in interchange capacity and reduces the delay and queues especially for high volume traffic. Besides, the DDI was found to offer advantages over the standard diamond by reducing the number of lanes needed at the signalized junctions, reducing the number of potential crashes as a result of the lower number of conflict points, and reducing interchange delays by using two-phase signal operations rather than the common three phases (Salley et al., 2012).

In 2012, Chlewicki prepared a study summarizing his remarks about the lessons learned from six operating DDIs in the United States and provided recommendations to further enhance the performance of future DDIs. The study was made to understand the operational effects of the different design elements in the DDI, and to prioritize the important elements by separating theory and anecdotal evidence from reality and science (Chlewicki, 2012). The study explored a wide range of design elements comprising design geometry, signal operations, and pedestrian accessibility. Some elements were discussed explicitly for their importance in reducing driver confusion while others were further elaborated to resolve any misconception in the existing literature. The author concluded that sight distance issues should receive more attention and related it with proper location of signs and signal heads. The second lesson focused on the drivers' approaches to the crossover intersections so that they may be guided with proper lanes before entering the DDI. Wrong way arrows were also found to be effective in preventing wrong way movements along with proper geometric design (Chlewicki, 2012).

Vaughan et al. (2012) prepared a study comprising initial findings of the first four installed DDIs in the United States. The study focused mostly on the operational performance of the interchanges and addressed some safety concerns. For this effort, field data were collected at all four locations and were used for calibration and validation of VISSIM micro-simulation. Field data comprised traffic volumes, peak period queues, vehicular conflicts, incidents, pedestrian and bicycle observations, and user surveys. The research team eventually provided recommendations about geometry, signal timing, safety and other operational considerations that could help practitioners in providing better designs for future DDIs. Some of the recommendations focused on signalizing right-turn movements from the off-ramps, providing the merging points as far away as possible from the crossover point, and encouraging the agencies to explore signal timing in more detail through studying the DDIs together with nearby signals as a system. Particular attention to access management near the interchange was considered as poor access and circulation may cause discontent from stakeholders. Additional remarks were made regarding the accessibility of the DDI to pedestrians with vision impairments (Vaughan et al., 2012).

Unlike the 3 DDIs that were built in France, particularly in Versailles, Perreux-aur-Marne, and Seclin, all DDIs in operation in the United States are constructed in locations without frontage road which is why most of the research focused only on the interchanges without frontage roads. However, Martinez et al. in 2012 proposed and tested a signal phase sequence that permits the implementation of DDIs at freeways with parallel frontage roads. The researchers evaluated the operational performance of DDI with frontage roads (DDI-FR) against the conventional diamond with frontage roads (CDI-FR). Synchro was used to optimize the signal timing plans and calculate intersection delays and level of service, while VISSIM was used to evaluate the total network travel time, total number of stops, and the average travel times of selected movements across the interchange. After optimizing the cycle length for both interchange types, it was found that the Diverging Diamond experienced shorter cycle durations with the same traffic demand. The DDI-FR was found to have lower average delays and better LOS than the intersections in the conventional type (Martinez & Cheu, 2012). However, and as expected, the through movements at the frontage roads experienced longer delays in the Diverging Diamond. Martinez et al. (2012) concluded that most of the measures of effectiveness (MOEs), such as intersection delays, number of stops, and total network travel time, have shown that the Diverging Diamond Interchange with frontage roads provided better operational performance than the conventional type.

With the increasing popularity of the DDI in the United States, and its success in increasing traffic throughput and reducing potential traffic collisions, additional care was needed to determine how the traffic movements should be operated. Particular attention was given to signal timing plans of which an effective design could still be further improved. In this regard, Chlewicki (2010) introduced approaches for improving the DDI operation by examining the signal progressions within and outside the interchange. The author found that several factors play a role in synchronizing the two DDI signals, such as the available space between signals, vehicle speed, cycle length, and phase distribution. Chlewicki (2010) investigated the characteristics of the time-space diagrams to maximize the progression of traffic. He further proposed several synchronization strategies based on the turning movement volumes and preferred cycle lengths. Based on the signal synchronization and the time required to get from the first signal to the second, speed was adjusted at the crossover junctions. The author concluded with proposing design guidelines for optimizing signal timing plans based on traffic synchronization (Chlewicki, 2010).

Xu et al. (2011) proposed an analytical model to calculate the control delays at DDIs; the model was integrated with a newly developed approach for control delay calculations of internal movements through accommodating possible internal queue spillback. The researchers noted that simulation models were used to analyze DDI designs by computing the control delays as a measure for determination of the level of service of intersections. However, simulation models were found to be less effective in providing generalized results. The performance of the analytical model was examined in traffic simulation and compared with the conventional delay model that is used in Chapter 16 of the Highway Capacity Manual. The results showed that the proposed method is appropriate for the advanced DDI signal since the off-ramp movements are controlled; however, the base DDI signal should be further analyzed through considering stop and yield control delay calculations (Xu et al., 2011).

As observed from the literature, many transportation engineers and researchers considered traffic simulation as a preferred tool to analyze different types of interchanges. This tool was chosen regardless of the extensive efforts, time, and skills needed. Maji et al. (2013) developed a simple and an easy to use method to determine the overall performance of an interchange. The scholars described the mathematical formulations and analysis procedures to evaluate the DDI using the critical lane volume method (CLV). The method was based on obtaining traffic volume, lane configuration, lane utilization factors, and intersection capacity. The lane configuration is evaluated based on the critical merging movements hence the critical lane volume (CLV) at each node is estimated for the different conflicting movements. Lastly, the CLV at each node is divided by the intersection capacity to obtain the v/c ratio and consequently the worst LOS among both nodes is defined as the interchange LOS. The results from the adopted method were compared with the results from traffic analysis software, such as VISSIM and Synchro; the method was found to be promising and reliable. Maji et al. (2013) concluded that the adopted method can come handy in preliminary stages before using traffic simulation software for detailed analysis.

Similarly, Anderson et al. (2012) developed a discrete event simulation model to determine the performance of the DDI. The authors examined whether a non-transportation simulation program can effectively model the DDI and simulate delays for a variety of test scenarios. It was concluded that the use of the simulation model allowed for rapid evaluation of the DDI; however, this configuration was not found to be the proper solution in all locations (Anderson et al., 2012).

In a Master's thesis in 2011, Galletebeitia compared and evaluated the operational performance of several interchanges to help decision makers in selecting and determining the optimal design at a specific location. The DDI, which has gained a lot of recognition as a viable unconventional design, was compared to the most popular interchange design in North America, the Partial Cloverleaf (ParClo). For each type of interchanges, 50 different traffic volume scenarios were tested using AIMSUN as micro-simulation software while the signal timing plans were optimized using Synchro. For the balanced traffic conditions, Galletebeitia (2011) found that both designs performed similarly at low and medium traffic volumes; however, at high traffic flows, the ParClo outperformed the DDI in terms of delays and number of stops. On the other hand, the DDI experienced lower delays and stop times for unbalanced traffic conditions at high volumes and was found more effective than the partial cloverleaf.

In 2012, Ressel further explored several aspects of the DDIs in his Master's thesis at the University of Missouri. The thesis has attempted to bring together valuable pieces of literature about DDIs while examining several additional aspects of existing interchanges including performance measures, pedestrian and bicycle accommodation, access management strategies, and business surveys. VISSIM was used to analyze the operational performance of the DDIs. The choice was made for its availability/common MoDOT practice and for its capabilities as a micro simulation tool (Ressel, 2012). The optimized signal timing plans for the existing interchanges were taken from the MoDOT. Several performance measures were used for analysis such as the number of stops, total travel time, average delay, and average speed. Ressel (2012) found that the currently used signal timing plans are successful; however, they can still be improved with simple iterative methods thus providing better level of service. In addition, business surveys surrounding the DDIs were made to gauge the stakeholders' opinions about the effect the DDI had on their business, such as the accessibility and loss of property for the new interchange. Only a small percentage of respondents perceived loss of accessibility by the DDI, whereas the majority was satisfied with the design which had a positive to neutral effect on their business. The survey also attempted to gain feedback from non-motorized users, such as cyclists and pedestrians, to determine their level of satisfaction in crossing the interchanges. Ressel (2012) studied two options for pedestrian crossings: an overpass with center protected sidewalk and an underpass with perimeter sidewalks. Nevertheless, Ressel (2012) highly recommended on focusing on the accommodation of pedestrian crossings at interchanges in future studies, especially when more pedestrians are present.

In May 2013, Hu introduced in his doctoral dissertation three new methodologies to improve traffic signal operations of the DDI. For achieving the best operational performance, operational strategies were developed and tested using real-world cases and advanced simulation techniques. Hu (2013) reviewed the existing methodologies for traffic signal timing plans of the DDIs and proposed three other traffic signal operations. The first is a three phase signal timing scheme used for controlling left-turn off-ramps by yield signs. The second controls the traffic using signal-controlled off-ramps and a signal timing scheme involving seven phases, whereas the third is based on an algorithmic methodology to optimize signal timing parameters according to existing phasing schemes (Hu, 2013). Through a case study, the second proposed signal operation was tested to check whether a singular controller for a DDI can work efficiently. Microscopic simulation analysis was conducted through VISSIM using average delays and queue lengths as measures of effectiveness. The simulation results revealed that the proposed methodology reduces the average delays at peak hours. In addition, the relationship between average delay and cycle length was thoroughly tested for different control type intersections. Hu (2013) evaluated several scenarios to test the differences of average delays for a variety of route distributions and the effect the DDI crossover spacing had on the operational performance.

2.2.4 SPUI versus DDI

In addition to the various publications comparing the conventional types of Diamond interchanges with other unconventional types, several studies focused solely on the unconventional types to address operational and safety concerns. Stanek (2007) compared three unconventional types of diamond interchanges: Diverging Diamond Interchange (DDI), Single Point Urban Interchange (SPUI), and the Roundabout Diamond Interchange and exposed the advantages and disadvantages of each based on traffic operation, traffic safety, intersection capacities, pedestrian accommodation, construction costs, and Right-of-Way costs. Through a case study, all three innovative designs were analyzed using a combination of Synchro and VISSIM traffic analysis software. Synchro was used to develop optimized signal timing plans which were refined in VISSIM traffic simulation model to include the effects of signal coordination and queues at intersections. Stanek (2007) noted that SPUIs and DDIs are both recommended whenever there are high left-turn movements at ramp terminal intersections, unlike the Roundabout Diamond that is preferred for low left-turn movements. The SPUI provided improved signal progression and enhanced the throughput for cross street traffic unlike the DDI that limited the signal coordination to one direction on the cross street. As for the pedestrian crossings, the curved on-ramp approaches at SPUIs made these movements longer and potentially less visible unlike the DDI that provided controlled pedestrian crossings. A cost comparison analysis for all diamond interchange types was also prepared. The SPUI was significantly found to have higher construction costs due to its longer bridge structure that is needed to span the wide central intersection, whereas the DDI was found to have higher right-of-way costs due to the widening needed at the ramp terminal intersections (Stanek, 2007).

Siromaskul et al. (2008) examined under multiple volume scenarios the operational performance of the SPUI, DDI, and five other common interchange types. Synchro was used as a micro simulation tool to develop the coordinated signal timing plans. These plans were transferred to VISSIM to evaluate and compare the different interchange types. Several measures of effectiveness (MOEs) were taken from VISSIM for analysis, including the weighted average delay per vehicle, average density, speed, and the volume per lane at ramp areas. The DDI and SPUI both excelled at handling turning movements. The first offered benefits in reducing the required amount of lane miles in addition to the reduction in number of signal phases and conflict. The second offered benefits when tight spacing with adjacent street interchanges exists.

In a manner similar to previous researchers, Afshar et al. (2009) used comparable methodologies to conduct traffic performance analysis for unconventional types of interchanges. The authors offered traffic comparison of SPUIs and DDIs by considering delays, number of stops, and lane volume throughput as measures of effectiveness. A wide variety of hypothetical traffic flow scenarios were tested and simulation runs were carried out using VISSIM as a microscopic simulation tool. After several simulation runs, and using the critical lane volume method, Afshar et al. (2009) found that the SPUI provided higher throughput when the traffic split was balanced. On the other hand, the DDI outperformed the SPUI at high unbalanced splits. The study was also performed at saturation flow conditions where the DDI experienced lower delays than the SPUI. However, when comparing the average number of stops, the SPUI outperformed its counterpart. The authors concluded that there is no clear dominance of one design over the other; what matters is the directional distribution of traffic to decide on the optimal alternative.

Chlewicki (2011) examined a large sample of traffic movements to compare the conventional diamond, single point, and diverging diamond interchanges. The comparison, based on the critical lane volume (CLV) method, was made to determine whether the DDI can be used as an alternative to the diamond interchanges. Throughout the analysis, the cost estimate of the three different types was taken into consideration by assuming the same number of lanes over or under the bridge structures. The results of the study showed that DDI outperformed the conventional type more than two-thirds of the time in all volume combinations. Similarly, the SPUI showed better performance when compared to the conventional type. As for the SPUI and DDI comparison, Chlewicki (2011) found that the SPUI operated better when the number of through lanes was the same. However, when costs were comparable, the DDI had better traffic operations in a vast majority of the cases.

In 2013, Guerrieri et al. prepared a brief study examining several unconventional types of interchanges including the SPUI and DDI. The researchers discussed the geometric configuration of each type and concluded with the advantages and disadvantages in terms of cost, safety, and traffic performance. The SPUI was recognized as a “free-flow” interchange and was recommended to be used whenever the traffic volume on the major road is much higher than the traffic on the minor road. Similarly, the DDI was recommended for use when high left-turn and through volumes contribute to high delays. Guerrieri et al. (2013) concluded that a cost benefit analysis is required for the proper choice of an interchange layout, since the layouts that provide higher capacities are the most expensive ones.

Table 2-1 below shows the pros and cons of the different interchange types as inferred from the literature.

Table 2-1: Pros and Cons for each interchange type

Interchange Type	Pros	Cons
TUDI	Operates at an acceptable level of service at low traffic levels.	High intersection delays.
	Low construction cost.	High percentage of stops.
	Low right-of-way cost.	Need for a four-phase signal
		High percentage of accidents at the center of the intersection.
SPUI	Caters for increased traffic demand volumes.	Not preferred when there is a need to accommodate through movements using frontage roads.
	Decreases delay and congestion.	High construction cost.
	Increases the roadway capacity.	High right-of-way cost.

Table 2-1 (Continued): Pros and Cons for each interchange type

Interchange Type	Pros	Cons
SPUI	Performs well at high traffic scenarios, especially for left-turning movements.	High ramp accidents rate.
	Provides higher throughput when traffic split is balanced.	High percentage of angle and sideswipe accidents.
	Reduces the average number of stops.	Does not accommodate pedestrian crossings effectively.
	Recommended when the traffic volume on the major road is much higher than the traffic on the minor road.	Particular attention to access management is needed near the interchange.
	Safer than TUDI in terms of injury and fatality frequencies.	
DDI	Caters for higher traffic volumes.	Not preferred when there is a need to accommodate through movements using frontage roads.
	Accommodates left-turning movements.	More delays for through movement vehicles on the crossing road.
	Performs well at unbalanced volume scenarios.	Potential driver confusion especially for first time users.
	Observes lower stop time.	Impact of the crossing angle at the junctions on the driver comfort.
	Observes lower number of stops.	Impact on driver visibility and sight distance due to the crossover movements at the junctions.
	Observes shorter queue lengths.	Need for proper signing and marking.
	Reduces the extent of lane miles.	
	Has an effective two phase signal.	
	Lower construction cost.	
	Lower right-of-way cost.	
	Lower vehicle operating costs.	
	Safer than other interchange types when it is properly striped and signed.	
	Reduces the number of conflict points	
	Reduces the total number of crashes.	
	Left turn type crashes are eliminated.	
	Rear-end type crashes are reduced.	

2.3 Microscopic Simulation Analysis

Microscopic Simulation is one of the tools used to compare the operational performance of the interchange configurations. It provides researchers and practitioners the means to study and analyze traffic operations in a simulated, controlled environment. Other tools are also being used to analyze the operational performance such as analytical models, field surveys, and questionnaires; however, the available literature ascertains that their use is limited as compared to the simulation modeling, as inferred from Table 2-2.

Table 2-2: Analysis type and used microscopic simulation tools

			Interchange Type			Type of Analysis				Microscopic Simulation Tool			
Paper No.	Date	Title	Tight Diamond (TUDI)	Diverging Diamond (DDI)	Single Point (SPUI)	Analytical	Simulation	Questionnaire	Field Survey	Synchro	Vissim	Corsim	Aimsun
1	2003	New interchange and intersection designs: the synchronized split-phasing intersection and the diverging diamond interchange	√	√			√			√			
2	2005	Design and operational performance of double crossover intersection and diverging diamond interchange	√	√			√				√		
3	2007	Performance evaluation of the diverging diamond interchange in comparison with the conventional diamond interchange	√	√			√			√	√		
4	2007	Drivers' evaluation of the diverging diamond interchange		√			√						
5	2009	Double crossover diamond interchange	√	√			√				√		
6	2010	Alternative intersections/interchanges: informational report (AIIR)	√	√			√			√	√		
7	2010	Missouri's experience with a diverging diamond interchange - lessons learned.		√					√				
8	2011	Diverging diamond interchange: performance evaluation (I-44 and Route 13)	√	√			√	√	√		√		
9	2012	Easing congestion in a new way – the first diverging diamond interchange in Chicago land.	√	√			√				√		
10	2012	Learning from six (plus) operational DDIs in the US.		√									
11	2012	Early findings on the operational impacts of double crossover diamond interchanges		√			√		√	√	√		
12	2012	Double crossover versus conventional diamond interchanges both with frontage roads	√	√			√			√	√		
13	2010	Operational effects of the diverging diamond interchange		√			√						
14	2011	Control delay calculation at diverging diamond interchanges	√	√		√	√			√			

Table 2-2 (Continued): Analysis type and used microscopic simulation tools

			Interchange Type			Type of Analysis				Microscopic Simulation Tool			
Paper No.	Date	Title	Tight Diamond (TUDI)	Diverging Diamond (DDI)	Single Point (SPUI)	Analytical	Simulation	Questionnaire	Field Survey	Synchro	Vissim	Corsim	Aimsun
15	2013	Diverging diamond interchange analysis: planning tool	√			√							
16	2012	Analyzing the diverging diamond interchange using discrete event simulation		√		√							
17	2011	Comparative analysis between the diverging diamond interchange and partial cloverleaf interchange using micro simulation modeling		√			√			√			√
18	2012	Insights into the first three diverging diamond interchanges in Missouri		√			√			√	√		
19	2013	Advanced signal control strategies and analysis methodologies for diverging diamond interchanges		√			√				√		
20	1996	Comparison of the operational and safety characteristics of the single point urban and diamond interchanges	√		√		√	√	√				
21	1999	Final report-guidelines for preliminary selection of the optimum interchange type for a specific location			√			√					
22	1997	Field analysis of operation and design of single-point urban interchanges	√		√			√	√				
23	2004	Design of single point urban interchanges			√			√					
24	2000	Comparison of SPUI & TUDI interchange alternatives with computer simulation modeling	√		√		√			√		√	
25	2003	A comparison of operations of single point and tight urban diamond interchanges	√		√		√			√		√	
26	2003	Traffic planning models for single-point and tight diamond interchanges	√		√		√					√	
27	2005	Crash comparison of single point and tight diamond interchanges	√		√				√				
28	2014	Statistical characteristics of wrong-way driving crashes on Illinois freeways	√		√								

Table 2-2 (Continued): Analysis type and used microscopic simulation tools

			Interchange Type			Type of Analysis				Microscopic Simulation Tool			
Paper No.	Date	Title	Tight Diamond (TUDI)	Diverging Diamond (DDI)	Single Point (SPUI)	Analytical	Simulation	Questionnaire	Field Survey	Synchro	Vissim	Corsim	Aimsun
29	2009	Tight diamond interchange versus single point urban interchange: pedestrians prospective	√		√		√			√		√	
30	2007	Innovative diamond interchange designs: how to increase capacity and minimize cost	√	√	√		√			√	√		
31	2008	A Comparative Analysis of Diverging Diamond Interchange Operations	√	√	√		√			√	√		
32	2009	Traffic operational comparison of single-point and diverging diamond interchanges		√	√	√	√			√	√		
33	2011	Should the diverging diamond interchange always be considered a diamond interchange form?	√	√	√	√							
34	2013	An international review on one and two level innovative unconventional intersection and interchange	√	√	√								
35	2005	Some guidelines for selecting micro simulation models for interchange traffic operational analysis	√		√		√				√	√	√
36	2000	Guidelines for timing and coordinating diamond interchanges with adjacent traffic signals	√				√			√			
37	2005	Methodology for selecting microscopic simulators: comparative evaluation of AIMSUN and VISSIM					√				√		√

Nowadays simulation is being employed more often as an effective tool for selecting and evaluating alternative designs before actual implementation. The increased use of micro simulation modeling is due to the several limitations of the methodologies suggested in the Highway Capacity Manual (Dowling et al., 2004). Besides, microscopic simulation tools offer the capability of capturing the interactive effects of different model components and allow the user to observe and evaluate the buildup, dissipation, and duration of traffic congestion (Xiao et al., 2005); however, it requires extra time for data input and calibration besides the additional care for checking data errors and the model in general.

During the past decade, several traffic simulation models were developed to assist researchers and transport planners in determining the operational performance of different interchanges schemes. In this research, three widely used traffic simulation software packages were considered to select the preferred tool for simulating arterial/freeway operations. The three models VISSIM, CORSIM, and AIMSUN provide stochastic and microscopic simulation, and are characterized as follows:

- **VISSIM**: a microscopic time step based simulation model developed by PTV AG, Germany. VISSIM provides an opportunity to evaluate complex multi-modal networks, determine operational impacts, and visually simulate the results. It employs links and connectors to form networks, rather than the typical node-link representations (Planung Transport Verkehr, 2000).
- **CORSIM**: a time based microscopic simulation model developed by the U.S. Department of Transportation and Federal Highway Administration (FHWA). CORSIM provides stochastic simulation of individual vehicles

in urban roadway systems using link-node network representations (CORSIM User's Manual, 2012).

- **AIMSUN**: a time based simulation model developed by Transportation Simulation Systems (TSS) in Spain. AIMSUN provides stochastic simulation using link-node network representation (Transportation Simulation Systems, 2002).

Several studies focused on selecting the ideal simulation tool for conducting traffic operational performance. Xiao et al. (2005) presented a systematic evaluation procedure that can be used to evaluate different simulators. Two of the best regarded and widely used simulators: AIMSUN and VISSIM were compared based on a set of qualitative and quantitative evaluation criteria. According to the individual preferences, a weighting factor was assigned for each criterion to be used in the overall selection method. Using a real life implementation of the proposed procedure, it was found that the accuracy of both simulators was similar as they were able to replicate the observed volumes and speeds up to a satisfactory level (Xiao et al., 2005). Similarly, Fang et al. (2005) proposed guidelines for selecting micro simulation models by examining their capabilities and testing algorithms for analyzing specific interchange design and control scenarios. The authors concluded by identifying several critical elements for selecting the ideal simulation software such as the capability of representing specific geometric characteristics and simulating specific signal control plans. In addition, accuracy, calibration needs, and the ability to extract specific performance measures from the simulators were used to select the preferred tool (Fang et al., 2005).

For this study, VISSIM was selected as simulation software because of its wide acceptance in transportation agencies and its capabilities in modeling at the highest level of detail and complexity. Besides, the existing literature shows that the majority of academicians and researchers used VISSIM as a preferred tool for conducting traffic operational analysis (refer to table 2-1). As for the signal timing plans, Synchro was used for its ease of application and capabilities in optimizing signal timing plans. Syhcro, a comprehensive network capacity analysis and signal timing software developed by Trafficware, uses the methodologies adopted in the Highway Capacity Manual (Hush et al., 2001).

2.4 Evaluation Metrics (Measures of Effectiveness)

Measures of effectiveness (MOEs) are the system performance statistics commonly used to determine the operational performance of interchanges. It was inferred from the literature that several MOEs were selected as performance criteria to ensure a fair comparison of interchanges. Table 2-2 shows the used evaluation metrics for each of the reviewed papers. The majority of researchers used “intersection delays” as a primary measure of effectiveness to evaluate and compare the interchange designs. A relatively large number of researchers adopted “maximum queue length” and “average number of stops” as key factors in their analysis. Others focused on Level of Service, speed, left-turn movement delays, and capacity to determine the preferred design.

Based on the criteria presented in this section, average intersection delays, average number of stops, maximum queue length, and delays for left-turning movements are selected in this research as MOEs to evaluate and compare the operational performance of each configuration. Using VISSIM as a micro simulation tool, these MOEs can be extracted and are classified as follows (Planung Transport Verkehr, 2000):

- **Average Intersection Delay (sec/veh)**: is the difference between the desired/free travel time and the actual travel time for the intersection as a whole, per vehicle on average.
- **Average Delay for All Left-Turning Movements (sec/veh)**: is the difference between the desired/free travel time and the actual travel time for the left-turning movements only, per vehicle on average.

- **Average number of Stops (veh/hr)**: is the average number of stops when a vehicle enters the queue condition during the peak hour. A stop is counted if the speed of a vehicle reaches zero while proceeding through the interchange.
- **Maximum Queue Length (m)**: Queue length is measured upstream every time step using queue detectors. From these values, the maximum is computed for all approaches during the peak hour.

Table 2-3: Applied Measures of Effectiveness

			Interchange Type			Measures of Effectiveness (MOE)						
Paper No.	Date	Title	Tight Diamond (TUDI)	Diverging Diamond (DDI)	Single Point (SPUI)	Intersection Delays	Avg. Number of Stops	Max Queue Length	LOS	Speed	Avg. Delay for Left Turn Traffic	Capacity
1	2003	New interchange and intersection designs: the synchronized split-phasing intersection and the diverging diamond interchange	√	√		√	√					
2	2005	Design and operational performance of double crossover intersection and diverging diamond interchange	√	√		√	√	√	√	√	√	√
3	2007	Performance evaluation of the diverging diamond interchange in comparison with the conventional diamond interchange	√	√		√		√			√	
4	2007	Drivers' evaluation of the diverging diamond interchange		√					√	√		√
5	2009	Double crossover diamond interchange	√	√		√	√	√			√	
6	2010	Alternative intersections/interchanges: informational report (AIIR)	√	√		√					√	√
7	2010	Missouri's experience with a diverging diamond interchange - lessons learned.		√								
8	2011	Diverging diamond interchange: performance evaluation (I-44 and Route 13)	√	√		√	√			√	√	√
9	2012	Easing congestion in a new way – the first diverging diamond interchange in Chicago land.	√	√		√		√	√	√	√	√
10	2012	Learning from six (plus) operational DDIs in the US.		√				√			√	
11	2012	Early findings on the operational impacts of double crossover diamond interchanges		√		√		√	√	√		
12	2012	Double crossover versus conventional diamond interchanges both with frontage roads	√	√		√	√		√		√	√
13	2010	Operational effects of the diverging diamond interchange		√								
14	2011	Control delay calculation at diverging diamond interchanges	√	√		√		√				√

Table 2-3 (Continued): Applied Measures of Effectiveness

			Interchange Type			Measures of Effectiveness (MOE)						
Paper No.	Date	Title	Tight Diamond (TUDI)	Diverging Diamond (DDI)	Single Point (SPUI)	Intersection Delays	Avg. Number of Stops	Max Queue Length	LOS	Speed	Avg. Delay for Left Turn Traffic	Capacity
15	2013	Diverging diamond interchange analysis: planning tool	√									
16	2012	Analyzing the diverging diamond interchange using discrete event simulation		√		√		√				
17	2011	Comparative analysis between the diverging diamond interchange and partial cloverleaf interchange using micro simulation modeling		√		√	√	√			√	√
18	2012	Insights into the first three diverging diamond interchanges in Missouri		√		√	√		√	√		
19	2013	Advanced signal control strategies and analysis methodologies for diverging diamond interchanges		√		√	√	√				√
20	1996	Comparison of the operational and safety characteristics of the single point urban and diamond interchanges	√		√	√	√					√
21	1999	Final report-guidelines for preliminary selection of the optimum interchange type for a specific location			√	√	√		√	√		√
22	1997	Field analysis of operation and design of single-point urban interchanges	√		√	√						
23	2004	Design of single point urban interchanges			√							√
24	2000	Comparison of SPUI & TUDI interchange alternatives with computer simulation modeling	√		√	√	√	√	√			
25	2003	A comparison of operations of single point and tight urban diamond interchanges	√		√	√	√			√		√
26	2003	Traffic planning models for single-point and tight diamond interchanges	√		√	√	√				√	
27	2005	Crash comparison of single point and tight diamond interchanges	√		√							
28	2014	Statistical characteristics of wrong-way driving crashes on Illinois freeways	√		√							

Table 2-3 (Continued): Applied Measures of Effectiveness

			Interchange Type			Measures of Effectiveness (MOE)						
Paper No.	Date	Title	Tight Diamond (TUDI)	Diverging Diamond (DDI)	Single Point (SPUI)	Intersection Delays	Avg. Number of Stops	Max Queue Length	LOS	Speed	Avg. Delay for Left Turn Traffic	Capacity
29	2009	Tight diamond interchange versus single point urban interchange: pedestrians prospective	√		√	√						√
30	2007	Innovative diamond interchange designs: how to increase capacity and minimize cost	√	√	√			√			√	√
31	2008	A Comparative Analysis of Diverging Diamond Interchange Operations	√	√	√	√				√		√
32	2009	Traffic operational comparison of single-point and diverging diamond interchanges		√	√	√	√					√
33	2011	Should the diverging diamond interchange always be considered a diamond interchange form?	√	√	√							√
34	2013	An international review on one and two level innovative unconventional intersection and interchange	√	√	√							
35	2005	Some guidelines for selecting micro simulation models for interchange traffic operational analysis	√		√	√	√	√		√		
36	2000	Guidelines for timing and coordinating diamond interchanges with adjacent traffic signals	√									
37	2005	Methodology for selecting microscopic simulators: comparative evaluation of AIMSUN and VISSIM										

2.5 Multi-Criteria Analysis

In practice, the most common forms of criteria analyses are the Cost-Effectiveness Analysis (CEA) and the Cost-Benefit Analysis (CBA). Both methods are analytical ways of comparing different criteria by assigning monetary values to them. The first compares the costs of alternatives that provide similar kinds of output. The second, being widely used in the transportation sector, values important non-marketed outputs in money terms, assigns a monetary value to all economic and non-economic factors, and assesses the alternatives based on their costs and benefits (Department of Communities and Local Governments, 2009). The alternatives are then evaluated using an economic index such as: Net Present Value (NPV), Benefit-Cost ratio (B/C), and the Internal Rate of Return (IRR).

Despite their wide use, both approaches are criticized for their limitations in not taking into account the interactions between different criteria. For instance, if we are to choose among different alternatives and using social and economic impacts as main criteria, we might feel much more strongly negative about an alternative that imposes both socio-economic impacts than would be estimated by adding separate valuations of the two effects. In addition, the consideration of non-monetary variables, such as noise, accidents, air pollution and so on, in the analysis has been troublesome for many applications (Department of Communities and Local Governments, 2009). On the other hand, multi-criteria decision making has appeared as an alternative to deal with these problems. It often involves the combination of some criteria which are valued in monetary terms, and others for which monetary valuations do not exist (Tudela et al., 2006).

Multi-criteria analysis (MCA) consists of the evaluation of a number of strategic criteria derived from general objectives. These criteria can either be subjectively analyzed or technically quantified. MCA can deal with the difficulties facing decision-makers (engineers, experts, and academics) in handling a large amount of complex information, including quantitative and qualitative data, in a rational and consistent way (Baltussen et al., 2006; Department of Communities and Local Governments, 2009). MCA is based on the premise that any service, in this case prioritization of interchange types, can be described by its characteristics (criteria), and the extent to which the decision-makers value the interchange types depends highly on their preferences for those criteria.

MCA models are used in various situations where different decisions are made. They can be used for identifying the single most preferred option among several alternatives; ranking and prioritizing options; identifying a number of options for a more detailed appraisal; or sorting options into acceptable and unacceptable ones (Kaysi et al., 2013). MCA brings a degree of structure, analysis and openness to different types of decisions that lie beyond the practical reach of CBA (Department of Communities and Local Governments, 2009).

Given the wide range of objectives, the diversity in criteria, and the difficulty in assigning a monetary value to all factors, the chosen approach in this research had to involve a non-monetary, multi-criteria evaluation. Several approaches are used in multi-criteria analysis such as the simple approach which consists of a direct analysis of the information such as identifying dominance between the options, the Linear Additive Model (Department of Communities and Local Governments, 2009), the Goal Achievement Matrix approach (Berechman et al., 2005; Shefer et al., 1990), the Need-Based approach (Kulkarni et al., 2004), the Multi-Attribute Utility theory (Ballestero et al., 2003), the fuzzy set theory (Avineri et a., 2000; Department of Communities and Local Governments, 2009), and others.

The different MCA approaches that do not require the conversion of factors to monetary values were compared based on precision, simplicity, transparency, and their ability to assess a large number of schemes. For the aim of this research, the prioritization of arterial/freeway interchange types, the Linear Additive approach was chosen ahead of others for its ability to give a precise score for each scheme, its simplicity and ease of use for non-experts, and its ability to deal with a large number of schemes. Models of this type have a well-established record of providing robust and effective support to decision-makers working on a range of problems and in various circumstances (Department of Communities and Local Governments, 2009). Other approaches were deemed either too simple, unable to deal with a large number of schemes or unsuitable for use by non-experts in the future.

The MCA process followed in this thesis, involves identifying the interchange types that need to be prioritized, choosing the decision-makers who shall be involved in the MCA process, establishing the criteria by which the interchange types shall be prioritized and determining the relative importance of the criteria. The weights shall be determined based on the judgments of decision-makers. Then, the performance of each alternative on each criterion is evaluated and a score ranging from 0 to 5 is assigned. Finally, the weighted scores shall be summed across all criteria for each interchange type to obtain an overall score and consequently a rank of the alternatives is made.

2.6 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is a technique used for dealing with problems which involve the consideration of multiple criteria simultaneously. Among other multi-criteria decision making methods, AHP method is distinguished for its inherent capabilities to establish weights for a large number of different factors, of different natures, including both qualitative and quantitative data, in order to make a decision based on a formal and numerical process (Liberatore et al., 2008).

The AHP technique was developed in 1977 by Thomas Saaty who derived his theory of prioritized hierarchies. His theory consists of decomposing a complex decision making process into a hierarchical structure (Tudela et al., 2006). The hierarchy is structured from the top where objectives from a managerial stand-point are defined, to intermediate levels with criteria on which subsequent levels depend, to the lowest level that encompasses a list of alternatives (Saaty et al., 1985). The purpose of the structure is to make it possible to judge the importance of the elements in a given level with respect to some or all of the elements in the adjacent levels (Saaty et al., 2012).

AHP has been used by decision makers all over the world to model problems in diverse application areas including resource allocation, strategic planning, and public policy (Wasil et al., 2003). It is also used to rank, select, evaluate, and benchmark a wide variety of decision alternatives in transportation projects and conflict resolutions (Saaty, 1980; Saaty et al., 1989). AHP helps decision-makers in organizing their thoughts and judgments to make more effective decisions; it has been used in both academia (with more than 50 Ph.D.'s awarded in it so far) and in the top level decision making in corporations and governments (Saaty, 2006).

Scientists have used a variety of mathematical approaches to structure the problems they encounter and to perform measurement within this structure. Many have worked on measurement and on judgment solicitation (Saaty et al., 1985). In the preliminary analysis of the arterial/freeway interchange type prioritization framework, several weighting methods were considered including Saaty's AHP Method, Swing

Method, and Trade-off Method. Each method has its own distinct characteristics that make it suitable in certain situations. Below is a description of each method, highlighting the advantages of each over the others:

- **Saaty's AHP/Eigenvector Method**: is a widely accepted method which is based on the hierarchical representation of the criteria and on the comparison of these criteria in pairs ("pairwise comparison") (Hiroyuki, 2000; Kaysi et al., 2013; Saaty, 1980; Tsamboulas, 2007). It is systematic, simple to implement, and transparent. However, it may have some shortcomings, namely inconsistency and rank reversal (Kaysi et al., 2013).
- **Swing Method**: is based on two extreme hypothetical schemes; the worst "W" and the best "B" performance on all criteria (Diakoulaki et al., 2004; European Commission, 1988; Kaysi et al., 2013). This method is simple, transparent, avoids inconsistencies, and handles a large number of criteria. However, it is based on assessing the performance of all schemes on each criterion before deriving the weights, thus these weights are to be derived every time a new scheme is to be examined (Kaysi et al., 2013).
- **Trade-Off Method**: consists of pairwise comparisons of criteria. For each pair, two hypothetical schemes are considered; a scheme which performs best on one criterion but worse on the other and vice-versa for another scheme (Diakoulaki et al., 2004; Kaysi et al., 2013; Ongprasert et al., 2003). The weights are then derived based on how much the decision-makers are willing to trade off from one criterion to improve the other. Despite being sensitive to the performance range of each

criterion, this method is not transparent as it is difficult to elicit the preferences especially where there are a large number of criteria, in addition to the inconsistencies (Kaysi et al., 2013).

After examining the most widely used weighting methods, Saaty's AHP/Eigenvector method was found to be the most appropriate in the current context for the following reasons (Kaysi et al., 2013; Saaty, 2006):

1. It is simple, straightforward, and does not need advanced technical knowledge to use it;
2. It deals with the intangibles side by side with the tangibles;
3. It derives scales through reciprocal comparison rather than assigning numbers pulled directly from the mind. These weights do not have to be derived again if a new scheme is to be examined, and
4. It can process a large number of criteria by dividing the task into small sets of pairwise comparisons (PCMs).

In brief, the AHP begins with the traditional concept of ordinal ranking to stratify a hierarchy (Saaty et al., 2012). The construction of the hierarchy might require the involvement of experts, decision-makers and even possibly the general public. First, priorities are derived for the performance of the alternatives on each criterion. These priorities are derived based on pairwise assessments (Saaty et al., 2001). As noted by Salmeron et al. (2005), making pairwise comparisons is a reliable way for obtaining the actual weights as it is generally easy to evaluate relative weights for each attribute with respect to the others. These weights represent the relative importance of the criteria, sub criteria and attributes belonging to a specific nest in the hierarchy. Finally, after weighing the criteria, a linear additive process is used to obtain overall priorities for the alternatives as to how they contribute to the goal (Saaty et al., 2012).

Finally, Douligeris et al. (1992) summarized the steps needed in the AHP method into the following:

- Step 1: Set up the hierarchy;
- Step 2: Elicit judgments based on pairwise comparisons;
- Step 3: Use the Eigenvector Method to estimate the relative weights of decision elements; and,
- Step 4: Aggregate the relative weights of decision elements to arrive to a set of ratings for the decision alternatives.

CHAPTER 3

FRAMEWORK FOR EVALUATION

3.1 Introduction

In this chapter, the proposed evaluation framework for prioritizing Arterial/Freeway interchange types is introduced while establishing the goals of key players and the corresponding research objectives. These objectives are broken down into criteria which are classified within different groups and into different levels.

In addition, this chapter presents an overview of the scoring guidelines and provides the basis for scoring various criteria. This chapter identifies the adopted weighting methodology and explores the Analytic Hierarchy Method (AHP) and describes mitigation measures for the potential shortcomings of this method.

This chapter also identifies the decision-makers whose judgments are used to derive the criteria weights, and presents the online questionnaire. It further concludes with deriving the weights and emphasizes the reliability of the computed weights. Finally, these results are investigated to identify any differences in judgments between the different groups of decision-makers.

The contents of the chapter include: proposed evaluation framework, criteria groups, weighting methodology, online questionnaire, and derivation of the weights.

3.2 Proposed Evaluation Framework

The proposed framework for prioritizing Arterial/Freeway Interchange types consists of defining an exhaustive set of criteria to include possibly all factors that might affect the prioritization process of the different alternatives. These criteria are represented in hierarchical form as shown in Figure 3-1. As defined in Saaty's AHP method, functional hierarchies decompose complex criteria groups into their constituent parts according to their essential relationships. The objective of this hierarchy representation is to assess the criteria on their different levels using the pairwise comparisons (Saaty, 2006). AHP is a basic approach to decision making as it is designed to cope with both the rational and intuitive to select the best from a number of alternatives (Saaty et al., 2012).

Special attention was taken to avoid redundant criteria and to ensure that each criterion was clearly defined for further assessment. Attention was given to ensure that the criteria preference is mutually independent, that is the score of an alternative on a single criterion can be assigned without knowing the score of the same alternative on any other criterion.

The top level of the hierarchy includes the broadest criteria to be taken into consideration. The selected criteria are grouped into 4 main groups (Criteria Groups) reflecting the broad factors that have major impacts on prioritizing and ranking the alternatives, as follows: **A-Operational Performance**; **B- Socio-Environmental Impacts**; **C- Costs**; **D- Safety**.

Each main criterion is then divided into primary criteria; for instance, Operational performance is seen as a key criterion, which contains sub-criteria, such as the **Level of Service (A1)**, **Average Number of Stops (A2)**, **Maximum Queue Length (A3)**, and **Accommodation of Pedestrian Crossings (A4)**. Below this primary level are additional subdivisions that describe in more detail certain aspects of the primary level. For example, level of service can be subdivided into two more categories, such as **Intersection delays (A1-1)** and **Average delays for all left-turning movements (A1-2).**

Similarly, **Socio-Environmental Impacts (B)** is used as a criteria group and comprises **Accessibility Impact on Existing Economic Activities (B1)**, **Noise (B2)**, and **Vehicle Emissions (B3)** as primary groups.

In addition, **Costs (C)** is seen as a key criterion and includes two main sub-criteria: **Economic Costs (C1)** and **Financial Costs (C2)**. The first consists of **Total Travel Time Savings (C1-1)** and **Vehicle Operating Cost Reductions (C1-2)**. The other encompasses **Construction Costs (C2-1)** and **Right-of-Way Costs (C2-2)**.

Finally, **Safety (D)** is considered as a main criterion and includes **Crash Frequency Experience (D1)** as a primary group. Similarly, **Driver Experience (D2)** is seen as a primary group and includes two additional subdivisions: **Driver Confusion Potential (D2-1)** and **Number of Conflict Points (D2-2)**.

The suggested three-level hierarchy is shown in Figure 3-1 below.

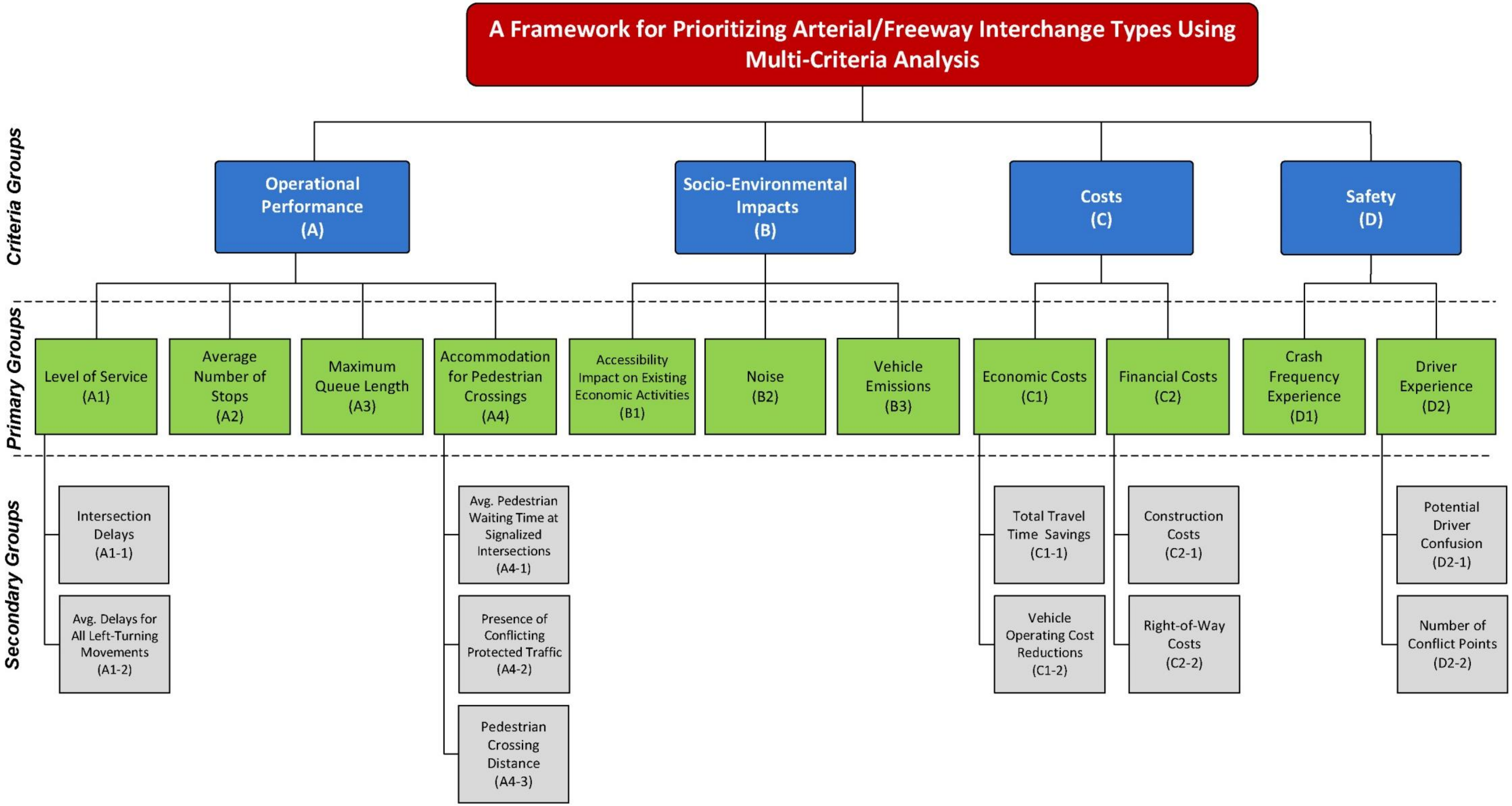

Figure 3-1: The Proposed Framework

3.3 Criteria Groups

3.3.1 Establishing Objectives

This section consists of establishing the goals and concerns of the key players and the corresponding framework objectives. It is important to identify all goals of the key players so as not to overlook any major criterion and to prevent serious conflicts at the end of the analysis. Establishing these goals provides the best means of deriving the overall objectives. This helps the prioritization framework to be as objective as possible. The overall objectives were established after a series of consultation processes with different key players, including academics, engineers and experts who are familiar with this domain (interchange types). Accordingly, the objectives were further analyzed and included the following: **Operational Performance** of the interchanges, the associated **Socio-Environmental Impacts**, **Costs**, and **Safety.**

3.3.2 Deriving Criteria

As indicated in the previous section, goals and concerns of key players help in deriving the different objectives. These objectives are broken down into criteria which reflect the concerns of the key players. As for the number of criteria to be assessed, Tsamboulas (2007) showed that the optimum number of criteria that a human mind can process without being overwhelmed is 6 to 8. On the other hand, Avineri et al. (2000) have demonstrated that the maximum number of criteria and sub-criteria for an effective evaluation should range between 8 and 15. Nonetheless, it was shown that the number of criteria in most studies ranges between 6 and 20 (UK Department of Communities and Local Government, 2009). Regardless of the number, these criteria can be grouped together to form a series of criteria and sub-criteria sets showing respectively the main objectives of this research project.

The hierarchical set of criteria should include all the important criteria needed to compare the performance of the different options. Special care was taken in the identification of the criteria so as to avoid double counting and/or overlapping. In addition, it was imperative to ensure that all criteria are mutually independent so that a preference score of an option on any criterion can be assigned without knowing what the preference scores of that option are on any other criterion. Furthermore, it was essential to ensure that each criterion is clearly defined before being assessed. As such, the below table describes in more detail the criteria used for prioritizing Arterial/Freeway interchange types.

Table 3-1: Criteria Description

Criteria Group	Primary Group	Secondary Criteria	Description
Operational Performance **(A)**	Level of Service **(A1)**	Intersection Delays **(A1-1)**	The difference between the desired/free travel time and the actual travel time for the intersection as a whole, per vehicle on average.
		Average Delays for all left-turning movements **(A1-2)**	The difference between the desired/free travel time and the actual travel time for the left-turning movements only, per vehicle on average.
	Average Number of Stops **(A2)**		A stop is counted if the speed of a vehicle reaches zero while proceeding through the interchange. The average number of stops is calculated as an average for all approaches during the peak hour.
	Maximum Queue Length **(A3)**		Queue length is considered throughout the peak hour. The maximum length is considered for all approaches.
	Accommodation of Pedestrian Crossings **(A4)**	Average Pedestrian Waiting Time at Signalized Intersections **(A4-1)**	The time needed per pedestrian on average waiting at signalized intersections to pass through the interchange. It depends on the signal timing plans and the number of signal-controlled intersections to be crossed.
		Presence of Conflicting Protected Traffic **(A4-2)**	The hourly volume of protected left-turning traffic that conflicts with the crossing pedestrians.
		Pedestrian Crossing Distance **(A4-3)**	The distance covered by pedestrians in crossing the interchange.

Table 3-1 (Continued): Criteria Description

Criteria Group	Primary Group	Secondary Criteria	Description
Socio-Environmental Impacts (B)	Accessibility Impact on Existing Economic Activities **(B1)**		The extent of constraints imposed by the interchange on the movement of traffic trying to access local activities. (e.g. continuity of through traffic along ramps)
	Noise **(B2)**		The level of noise generated by road traffic using the interchange. Noise exposure is related to vehicular speed, traffic volumes, vehicle mix, grades, and pavement characteristics.
	Vehicle Emissions **(B3)**		The extent of vehicular emissions at the interchange. It is related to the traffic volumes and a set of factors including: functional road class, vehicle speed, vehicle fleet characteristics, and ambient conditions. Main air pollutants considered are CO and HO.

Table 3-1 (Continued): Criteria Description

Criteria Group	Primary Group	Secondary Criteria	Description
Costs **(C)**	Economic Costs **(C1)**	Total Travel Time Savings **(C1-1)**	The savings in travel time costs that can potentially occur at interchanges as compared to the case of at-grade signalized intersection. These costs are calculated based on the average monetary value of time (VOT) for the peak hour.
		Vehicle Operating Cost Reductions **(C1-2)**	The reductions in vehicle operating cost incurred by all vehicles travelling through the interchange as compared to the case of at-grade signalized intersection. These reductions are computed for the peak hour only. VOC depends on vehicle usage including: fuel, tires, maintenance, repairs, and depreciation.
	Financial Costs **(C2)**	Construction Costs **(C2-1)**	The cost needed for constructing the interchange, particularly the concrete and steel structural works.
		Right-of-Way Costs **(C2-2)**	The cost needed for the Right-of-Way acquisition to properly accommodate the interchange.
Safety **(D)**	Crash Frequency Experience **(D1)**		Crash rate history/experience at similar interchanges in other locations (e.g. crashes/year). It is an indicator of safety and is used in crash data analysis.
	Driver Experience **(D2)**	Potential Driver Confusion **(D2-1)**	Potential driver confusion while traversing the interchange. It is related to the vehicle paths, intersection area, and traffic movement directions.
		Number of Conflict Points **(D2-2)**	The number of potential vehicular conflict points including crossing, merging, and diverging points.

3.3.3 Scoring Guidelines

One of the advantages of the MCA methods is that criteria can be measured either quantitatively or qualitatively. In this research, some of the criteria can be directly measured using microscopic simulation analyses with software such as VISSIM and Synchro. Measurement of other criteria can be derived through mathematical computations such as the secondary criteria under the Cost objective; others are subjectively analyzed based on expert judgments.

After measuring the performances for each scheme on each criterion, scores are assigned using a numerical scale. A score is the degree of performance of an option on a selected criterion. The numerical scales range from 0 to 5, where 0 is used to reflect the least preferred possible performance on each criterion and 5 for the most preferred possible performance. Any performance outside this range, whether below or above, would score 0 and 5, respectively.

Once the end points of the scale are determined, the intermediate scores can then be established. Different methods are used to convert the performance measure into a value score. In this research, most of the value functions used in the model have linear or inverse linear functions. In other situations, it was better to use non-linear value functions such as in the case of "Vehicle Emissions" whereas expert judgments were used to determine the scores for the cases of qualitative criteria as in the case of "Potential Driver Confusion".

3.3.4 Basis for scoring various criteria

The criteria discussed in section 3.3.2 can be categorized into three different types based on how their performance can be measured:

- ***Direct classification using available data***, such as the "Crash Frequency Experience";
- ***Direct classification using calculation of measurements***, such as "Noise" and "Vehicle Emissions" which are calculated as a function of speed and Annual Average Daily Traffic (AADT). In addition, most of the criteria under the operational performance category are computed through microscopic simulation using software like VISSIM and Synchro; and
- ***Indirect classification using professional judgment***, such as the "Potential Driver Confusion".

This section introduces in more detail the tools used for scoring the alternatives. These tools include: Micro-Simulation, Traffic Noise Model (TNM), and vehicle emission models. The use of the first, Micro-Simulation, and the related literature were presented thoroughly in section 2.3. The Traffic Noise Model and Vehicle Emissions are described below.

The **FHWA Traffic Noise Model (TNM)** was first released in March 1998 based on the culmination of six years of extensive research. The model included a new vehicle noise emissions database and state-of-the-art acoustical algorithms (Federal Highway Administration, 2014). Since then, several versions were released to provide enhancements on the acoustics and applied algorithms. In this research, *TNM version 2.5* was used for computing the noise levels and evaluating the acoustical impacts at interchanges.

TNM computes highway traffic noise at nearby receivers through combining the noise emission levels with internal speed computations to account for the full effect of roadway grades and traffic-control devices (Hankard et al., 2006; Menge et al., 1998). TNM simulates the propagation of sound energy between highway systems and nearby receivers and computes the effect of intervening ground with the theory-based acoustics that have been calibrated against field measurements. In addition, TNM computes three noise measures at user-defined receiver locations and derives correspondingly three types of contours: Sound-level Contours, Noise Reduction Contours, and Level-difference Contours between any two noise-barrier designs (Menge et al., 1998).

Several papers were published to compare different traffic noise models. Quartieri et al. (2009) found that all TNMs adopt an acoustic energy descriptor and the calculated sound levels are generally corrected by means of various parameters, such as ground absorptions, meteorological conditions, road's gradient, mean speed, and flow type (Quartieri et al., 2009). In addition, a research conducted by Colorado Department of Transportation in 2005 presented a comparison of the three most used traffic noise models: STAMINA 2.0, TNM 2.1, and TNM 2.5. The study showed that TNM 2.5 entailed the least absolute value of the error with an average error of only 0.3 dBA. In addition, the researchers found that TNM 2.5's maximum over prediction was 5.0 dBA and its maximum under prediction was only 4.4 dBA (Hankard et al., 2006).

In addition to the traffic noise, **Vehicle Emissions** pose a serious threat to air quality in heavily congested areas. According to several studies, transportation has been considered the largest single source of air pollutants in urban centers as road traffic contributes approximately to 40%, 50%, and 90% of NOx, HC, and CO emissions, respectively (Olsson, 1994; Sbayti, et al., 2002). Many models and applications have been suggested to assess the impacts of road traffic on the environment. While air quality can be assessed through field measurements, forecasting future conditions depends largely on estimating vehicle-emission factors coupled with mathematical modeling. Most of the traffic and environmental planners estimated the traffic emissions based on the average network speed along with the speed-based emission factor models (Sbayti et al., 2002). According to a study prepared by the National Cooperative Highway Research Program in 1997, determining speed profiles of the roadway networks plays an important role in estimating traffic emissions. Once speed profiles are obtained, traffic emissions can be computed on the basis of a network-wide emission factor relying on average roadway network speed, an average emission factor for every roadway functional class, or emission factors on a link-by-link basis (Chatterjee, 1997). Hence, total emissions are estimated either by multiplying the total vehicle-miles traveled (VMT) with the average emission factor or through using the link-by-link computation method.

Several papers were published to assess the impacts of vehicle emissions on the environment. Sbayti et al. (2002) investigated the effect of three levels of roadway network aggregation on emission inventories. A traffic model and an emission factor model were integrated to determine the total emissions in the future Beirut Central District. The authors concluded that choosing the appropriate approach for emissions estimation is highly dependent on the type of study required; for simple road networks, the overall-average approach is adequate (Sbayti et al., 2002). Likewise, Sadek et al. (2000) developed a decision-aid tool for multi-criteria evaluation of potential highway alignments. The analysis was made based on a wide set of criteria including pertinent geometric, environmental, and community-related parameters. Through a real case study, air quality considerations were incorporated in the environmental evaluation framework through developing models that relate emissions to vehicle speed, vehicle characteristics, traffic volumes, and other factors in conjunction with dispersion models (Sadek, et al., 1999; Sadek et al., 2000). Similarly, Zura et al. (1995) used GIS spatial analysis to locate the least-impact corridor based on a minimization of the environmental impacts.

3.3.5 Assigning Weights

Not all criteria are equally important. The relative importance of the different criteria is reflected in the framework using weights. These weights can be assigned using several approaches; the simplest way is to subjectively judge the weight of each criterion based on experience. However, in order to address the problem of subjectivity, AHP is used as it allows decision-makers to move away from the open biases towards certain criteria. The approach used in the AHP consists of pairwise comparisons of criteria whereby the weights are computed as the elements in the eigenvector associated with the maximum eigenvalue of the matrix. The advantage of this method is that it can be applied rapidly and it minimizes the subjectivity of the weight values.

3.4 Weighting Methodology

Multi-criteria analysis (MCA) is the suggested procedure to be used in the prioritization framework of the Arterial/Freeway Interchange types. A linear additive model is used in which the overall performance of an interchange type is based on the sum of its weighted performance on a set of criteria. To deal with the problem of subjectivity, the analysis was made based on the Analytic Hierarchy Process (AHP) which is the adopted weighting method in this research. The following sub-sections introduce in more detail the methodology used in the Analytic Hierarchy Process in addition to the proposed mitigations for the potential shortcomings of this method.

3.4.1 The AHP/Eigenvector Methodology

In the preliminary analysis of an appropriate prioritization framework, Saaty's AHP Method was chosen over other weighting methods because it is systematic, easy to implement, and transparent (see section 2.6). The following sub-sections illustrate the basic concepts of the AHP, including Saaty's scale, comparison matrix, the principal eigenvector, and the consistency ratio.

3.4.1.1 Saaty's Scale

Paired comparison judgments in the AHP are applied to pairs of homogeneous elements. The fundamental scale of values to represent the intensities of judgments is shown in Table 3-2. This scale has been validated for effectiveness, not only in many applications by a number of people, but also through theoretical comparison with a large number of other scales (Saaty et al., 1985; Saaty, 2006; Saaty et al., 2012).

Table 3-2: Saaty's Scale

Intensity of Importance	**Description**	**Explanation**
1	Equally important	Two activities contribute equally to the objective.
3	Moderately more important	Experience and judgment slightly favour one activity over another.
5	Strongly or essentially more important	Experience and judgment strongly favour one activity over another.
7	Very strongly more important	An activity is strongly favoured and its dominance is demonstrated in practice.
9	Extremely or overwhelmingly more important	The evidence favouring one activity over another is of the highest possible order of affirmation.

Note that 2, 4, 6, and 8 are intermediate values between two adjacent judgments. If an activity has one of the above numbers (e.g. 3) compared with a second activity, then the second activity has the reciprocal value (i.e. 1/3) when compared to the first.

3.4.1.2 Pairwise comparison matrices

The metric for consistency and the relative weights of the criteria can be derived by organizing the pairwise comparisons in the form of a matrix. For example, let us say that criterion C1 is found to be moderately more important that criterion C2, C1 strongly more important that C3 and C2 between equally important and moderately more important than C3. These pairwise comparisons are converted into numbers using Saaty's Scale (Table 3-1) and are shown in Table 3-3 below.

Table 3-3: Pairwise comparisons of Criteria C1, C2, and C3

Criterion	C1	C2	C3
C1	1	3	5
C2	1/3	1	2
C3	1/5	1/2	1

3.4.1.3 The eigenvector/ eigenvalue formulation

The next step is to calculate the maximum eigenvalue (λ_{max}) of the following preference matrix taken from Table 3-3:

$$\begin{bmatrix} 1-\lambda_{max} & 3 & 5 \\ 1/3 & 1-\lambda_{max} & 2 \\ 1/5 & 1/2 & 1-\lambda_{max} \end{bmatrix}$$

By setting the matrix determinant equal to zero, the λ_{max} is calculated to be 3.0037. Then, by replacing the derived value of λ_{max} in the above matrix, the following matrix is obtained:

$$\begin{bmatrix} -2.0037 & 3 & 5 \\ 1/3 & -2.0037 & 2 \\ 1/5 & 1/2 & -2.0037 \end{bmatrix}$$

The optimum weights are calculated by solving the following matrix equation:

$$\begin{bmatrix} -2.0037 & 3 & 5 \\ 1/3 & -2.0037 & 2 \\ 1/5 & 1/2 & -2.0037 \end{bmatrix} \begin{bmatrix} wC1 \\ wC2 \\ wC3 \end{bmatrix} =0$$

Knowing that wC1+wC2+wC3= 1, the resulting values of the weights are as follows: wC1=0.6483, wC2=0.3397, wC3=0.1220.

3.4.1.4 Consistency Ratio (the AHP metric)

The maximum eigenvalue of any pairwise comparison matrix (PCM), λ_{max}, serves as a metric for measuring consistency of criteria weights. Based on the expert knowledge and experience, Saaty et al. (1985) has suggested that 10% randomness (CR=0.10), or at most 20% is acceptable. The consistency ratio CR is calculated as follows:

$$CR = CI/RI \tag{3-1}$$

$$CI = (\lambda_{max} – n)/(n-1) \tag{3-2}$$

Where:

CR: Consistency Ratio

CI: Consistency Index

n: the matrix dimension (i.e. the number of criteria considered); and

RI: is an average random consistency index derived by Saaty from a sample of randomly generated reciprocal matrices using Saaty’s Scale. The values of RI for different n are given in Table 3-4 below.

Table 3-4: Random Consistency Index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Note that RI is equal to zero for n=1 and n=2. This is because the problem of inconsistency is absent when there are only one or two criteria being considered. In our example, CR=0.00185/0.58 = 0.00319 which is less than 0.1 hence there is no need for revision.

3.4.2 Mitigation of potential shortcomings of Saaty's AHP/Eigenvector Method

Despite being one of the most widely used weighting methods in MCA, the AHP method has attracted some concerns by decision-makers. Below is a list of these concerns along with the measures which could be used to minimize their effects on the resulting weights of the prioritization framework.

- **Inconsistency**: Usually when a decision-maker is asked to make a series of pairwise comparisons, he/she may forget prior assessments especially when the number of criteria to be assessed is greater than 4; thus inconsistency arises. However, if the decision-maker understands the system to be followed, the whole set of pairwise comparisons should stack up in a self-consistent way. Some analysts argue that pairwise comparisons could not yield true relative preferences unless they are transitive; for instance, if criterion A is scored 4 times more important than criterion B, and criterion B 3 times more important than criterion C, then A should be 3x4=12 times more important than C (Saaty, 2006). Given that Saaty's scale goes up to 9, consistency is assumed to have been achieved as long as the rank of the criteria is transitive. The consistency is checked using the consistency ratio (CR) as defined in section 3.4.1.4.

- **Expected performance**: Since the weights are derived before measuring the performance of the alternatives on each criterion, decision-makers are induced to make their own judgments about the relative importance of criteria without knowing in fact what they are comparing. This problem can be mitigated by giving the decision-makers information about the expected best and worst performance of the options on the different criteria before they make their own statements (see Questionnaire in Appendix A).
- **Rank Reversal**: In general, the ‘rank reversal’ phenomenon occurs when a new alternative/criterion is added to a decision problem, the ranking of the old alternatives change. This phenomenon is due to the change in the key players’ priorities before and after the addition or deletion is made. As inferred from the literature, this phenomenon is most likely to occur in complex hierarchy with more than 3 levels (Department of Communities and Local Governments, 2009; Saaty et al., 1985). In addition, it may occur when an irrelevant option is added or an inconsequential criterion is added. The above mitigation measures, i.e. inconsistency and expected performance, are used to minimize the occurrence of the ‘rank reversal’ phenomenon especially since the adopted framework for prioritizing arterial/freeway interchange types does not have more than 3 levels. Moreover, AHP is not used to determine the overall ranking of the options; the ranking is done using the linear additive model (as discussed in section 2.5).

3.5 Online Questionnaire

The next stage is to derive the relative weights of each criterion in each segment of the hierarchy tree. To do so, an online questionnaire was developed in which key players provided their pairwise comparisons of criteria.

3.5.1 Identifying the decision-makers

As a first step, it is imperative to identify all decision-makers. They should include all key players who may influence the decisions. In this research, as in similar transportation projects, stakeholders are considered key players whose judgments are typically used to reflect the thoughts and opinions of the government and local authorities. In addition, experts in different disciplines are encouraged to participate including junior transport engineers, senior transport engineers, and professors who are familiar with this domain.

3.5.2 Questionnaire Structure and Results

An online survey was used to elicit the judgments of each of the decision makers and determine the relative importance of criteria using pairwise comparisons. SurveyMonkey was chosen (rather than other web-tools) for its simplicity, ease of use, high satisfaction rate, cost-effective methods, and “self-serve” solutions (SurveyMonkey, 2009).

Prior to eliciting judgments and undertaking the pilot study, the survey was pre-tested on 4 respondents who provided their feedback indicating the need to simplify the use of the survey, make it easier to understand and keep it more “user-friendly”.

In this research project, emails were sent to 93 potential respondents inviting them to fill out the web-based questionnaire. Survey responses were collected from

September 14th, 2014 to October 30th, 2014. 51 out of the potential 93 respondents participated, giving a response rate of 55%. Over a period of seven weeks, 22 senior engineers participated in the survey, representing the highest percentage of participants among all decision-groups (around 43%). A relatively lower percentage of respondents were junior engineers (30%) and academic professors (20%), whereas only 4 stakeholders (7%) provided responses to the survey.

The online questionnaire was divided into several sections, including:

1. The purpose of the questionnaire explaining the objective of the research;
2. An overview of the adopted framework that was identified for prioritization;
3. A detailed description of each criterion and how interchange schemes/alternatives are expected to perform on it;
4. The steps to be taken in order to fill out the online questionnaire;
5. The preliminary ranking of the criteria to be specified by the key players which would help them keep their judgments consistent during the pairwise comparisons task; and,
6. The pairwise comparisons to be provided by the key players.

A copy of the questionnaire that was used is provided in **Appendix A**.

3.6 Derivation of the Weights

After constructing the matrices using the relative values (preferences) for the criteria, the criteria weights and consistency ratio are computed automatically by using AHP software such as *Expert Choice*. Expert Choice combines collaborative team tools and mathematical techniques to enable the decision makers to obtain the best decision in reaching a goal (Expert Choice, 2014). This software is used to structure complex frameworks, measure the importance of competing objectives and alternatives, synthesize judgments, and conduct sensitivity analyses.

The below figure shows the steps needed to choose the best alternative using Expert Choice evaluation. The process is iterative and involves combining logic and intuition with data and judgment based on knowledge and experience (Expert Choice, 2014).

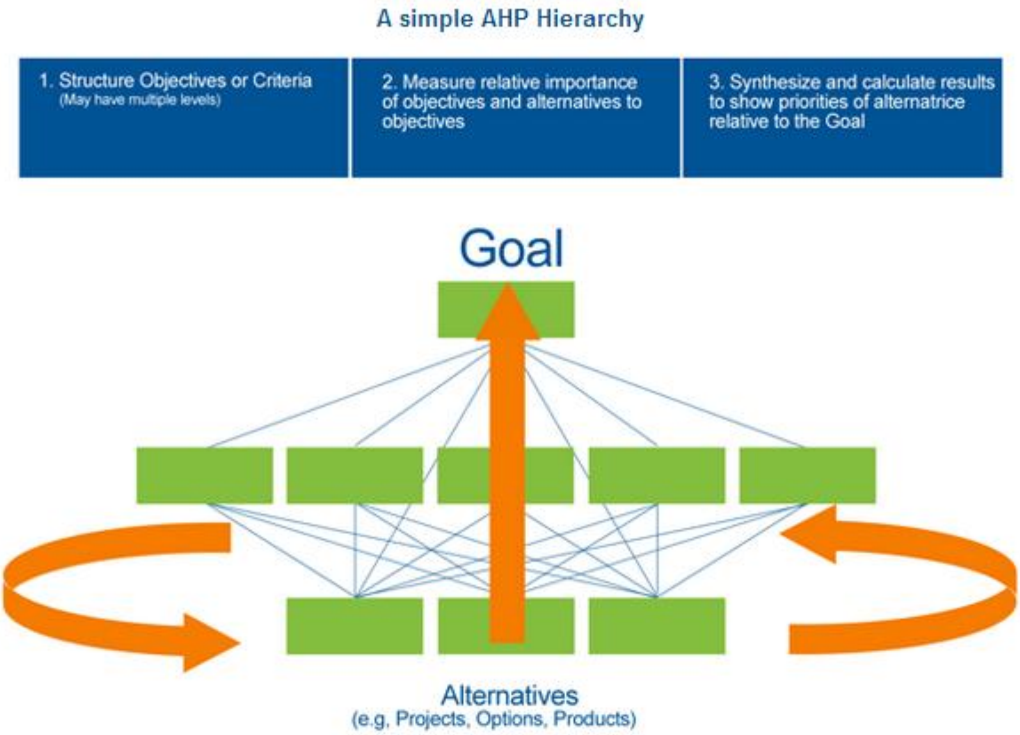

Figure 3-2: Expert Choice Evaluation Method

Structuring is the first step in making a choice of the preferred alternative. It involves identifying alternative courses of action, identifying objectives into a hierarchy, and determining which objectives each of the alternatives contributes to. Upon structuring the hierarchy of objectives and identifying the alternatives, priorities are then derived for relative importance of the objectives as well as the relative preference of the alternatives with respect to the objectives. All measures derived with *Expert Choice* possess the ratio scale level of measure; these measurements are performed using pairwise relative comparisons. Finally, synthesis of the measures according to the objectives is done using *Expert Choice*. The synthesis includes both the objective information as well as the subjectivity in the form of knowledge, experience, and judgment of the participants. Because of the structuring and measurement methods used in *Expert Choice*, the results are mathematically sound (Expert Choice, 2014).

3.6.1 Reliability of Weights Produced

The reliability of weights depends on the extent to which the pairwise judgments are consistent. The higher the consistency, the more acceptable the weight set is. On the other hand, if the judgments are less consistent, the Eigen vector reflects reality to a lesser extent, and the more the care to be taken.

3.6.1.1 Deciding on Benchmark Consistency Ratio

As discussed in section 3.4.1.4, consistency ratio (CR) is defined as the ratio of consistency index to random index. The latter is calculated for randomly generated matrices while satisfying the reciprocal property. Thus, a probabilistic interpretation would suggest that the CR is the proportion of randomness that a particular pairwise comparison matrix exhibits. In this research, three different consistency ratios were tested. The consistency ratio was computed for each respondent on each set of criteria; hence 510 different pairwise comparisons (PCM's) were analyzed in this research. The 0.1 benchmark was deemed too restrictive as it results in a high level of data loss; that is 75 out of 510 PCM's would be removed. Furthermore, setting the level at 0.15 results in significant data loss; so it was decided to use instead the 0.2 consistency ratio, an acceptable level of randomness in the judgments (Saaty et al., 1985). The 0.2 benchmark results in the removal of only 15 PCM's keeping 97.05% valid data.

3.6.1.2 Data Purging

In general, the data that is most hazardous to the integrity of the model is the data that varies from the median significantly and is inconsistent. So the data which does not fall within the consistency benchmark of 0.2 can be purged on this basis while keeping other data. This further limits the number of people contributing judgments and is reflected in the 0.2 data set.

3.6.1.3 Aggregation Method

There are two possible methods of aggregation for the AHP; aggregation of individual preferences (AIP) and aggregation of individual judgments (AIJ). Each method produces an aggregate set of weights derived from the pairwise comparisons of the decision-makers. The first, AIP method, uses the pairwise comparisons provided by all decision-makers regardless of the individual consistency ratios. The second, AIJ method, allows for the removal of inconsistent matrices before the aggregation procedure (Abbyad et al., 2011). Hence, the aggregate weight set is computed taking into account the PCMs of the decision-makers whose consistency ratios are acceptable, within the benchmark limit.

3.6.2 Results

Using the methodology presented in section 3.4.1.3 for deriving the criteria weights, and after purging the data while maintaining a benchmark of 0.2 for consistency ratio, the weights for the 17 criteria were derived for the aggregate results. The weighted average is computed for each of the 51 respondents on each set of criteria. For example, considering the main criteria weights, all 51 PCM’s were assessed based on the judgments of all respondents. 10 of these PCM’s resulted in a consistency ratio

(CR) greater than 0.2 and were thus removed from the analysis. The remaining 41 judgments were then used to determine the criteria weights, keeping around 80% of valid data.

The results showed that the *Operational Performance (A)* with a weight of 0.396 was found to be the most important criterion as perceived by the different decision-makers, *Safety (D)* ranked second in importance with a weight of 0.294, *Costs (C)* ranked third with a weight of 0.190, and *Socio-Environmental Impacts (B)* ranked fourth having a weight of 0.120.

Figure 3-3 below includes the set of weights that were obtained for the criteria to be used in the determination of the priorities of Arterial/Freeway interchange types. As shown in the figure, two weights are presented for each criterion at all levels (top, primary, and secondary). The weight on the left side represents the absolute weight within the segment to which the criterion belongs; the weights for criteria within the same segment/branch should add up to 1.000. The weight on the right side represents the weight within all sub-criteria to be scored; similarly, the weights for all sub-criteria to be scored should add up to 1.000.

Table 3-5 presents the weights of the various criteria, arranged by segments (top, primary, and secondary). The column "Overall" on the right side presents the overall weight within all sub-criteria to be scored. The rightmost side includes the overall ranking of criteria according to their relative weights. Table 3-6 sorts the criteria according to their ranking by the overall weight. This ranking indicates that the criteria with the top 5 overall weights are:

1. D1: Crash Frequency Experience (Weight = 0.207)
2. A1-1: Intersection Delays (Weight = 0.153)
3. C1-1: Total Travel Time Savings (Weight = 0.101)

4. A2: Average Number of Stops (Weight = 0.063)

5. B1: Accessibility Impact on Existing Economic Activities (Weight = 0.061)

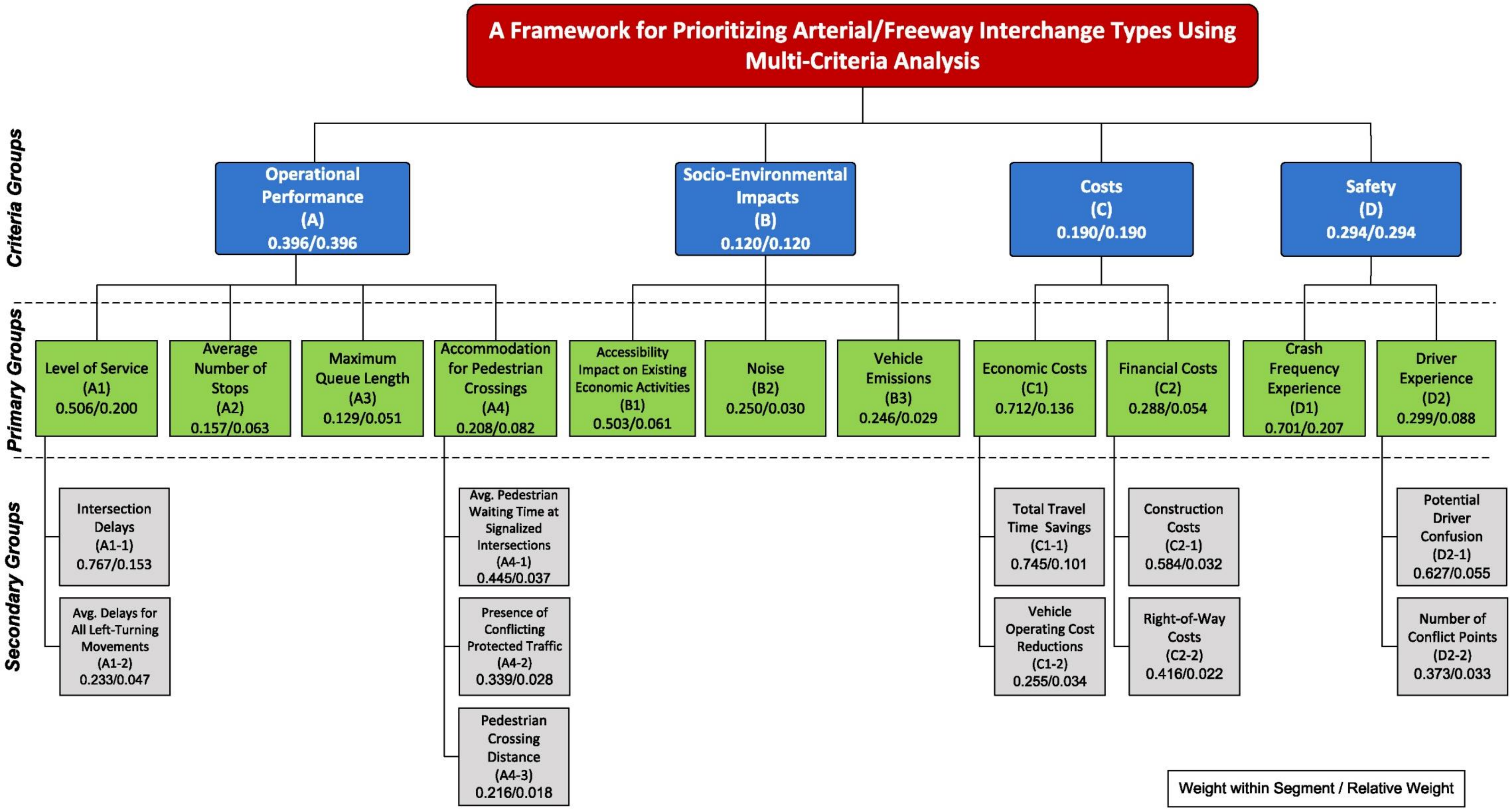

Figure 3-3: The Proposed Framework with Criteria Weights

Table 3-5: Criteria Weights by Segments

	Criterion		Weight				Rank
			Top	Primary	Secondary	Overall	
A	A1-1	Intersection Delays	0.396	0.506	0.767	0.153	2
	A1-2	Average Delays for All Left-Turning Movements	0.396	0.506	0.233	0.047	8
	A2	Average Number of Stops	0.396	0.157	1.000	0.063	4
	A3	Maximum Queue Length	0.396	0.129	1.000	0.051	7
	A4-1	Average Pedestrian Waiting Time at Signalized Intersection	0.396	0.208	0.445	0.037	9
	A4-2	Presence of Conflicting Protected Traffic	0.396	0.208	0.339	0.028	15
	A4-3	Pedestrian Crossing Distance	0.396	0.208	0.216	0.018	17
B	B1	Accessibility Impact on Existing Economic Activities	0.120	0.503	1.000	0.061	5
	B2	Noise	0.120	0.250	1.000	0.030	13
	B3	Vehicle Emissions	0.120	0.246	1.000	0.029	14
C	C1-1	Total Travel Time Savings	0.190	0.712	0.745	0.101	3
	C1-2	Vehicle Operating Cost Reductions	0.190	0.712	0.255	0.034	10
	C2-1	Construction Costs	0.190	0.288	0.584	0.032	12
	C2-2	Right-of-Way Costs	0.190	0.288	0.416	0.022	16
D	D1	Crash Frequency Experience	0.294	0.701	1.000	0.207	1
	D2-1	Potential Driver Confusion	0.294	0.299	0.627	0.055	6
	D2-2	Number of Conflict Points	0.294	0.299	0.373	0.033	11

Table 3-6: Criteria Weights by Rank (Highest to Lowest)

Criterion		Weight				Rank
		Top	Primary	Secondary	Overall	
D1	Crash Frequency Experience	0.294	0.701	1.000	0.207	1
A1-1	Intersection Delays	0.396	0.506	0.767	0.153	2
C1-1	Total Travel Time Savings	0.190	0.712	0.745	0.101	3
A2	Average Number of Stops	0.396	0.157	1.000	0.063	4
B1	Accessibility Impact on Existing Economic Activities	0.120	0.503	1.000	0.061	5
D2-1	Potential Driver Confusion	0.294	0.299	0.627	0.055	6
A3	Maximum Queue Length	0.396	0.129	1.000	0.051	7
A1-2	Average Delays for All Left-Turning Movements	0.396	0.506	0.233	0.047	8
A4-1	Average Pedestrian Waiting Time at Signalized Intersection	0.396	0.208	0.445	0.037	9
C1-2	Vehicle Operating Cost Reductions	0.190	0.712	0.255	0.034	10
D2-2	Number of Conflict Points	0.294	0.299	0.373	0.033	11
C2-1	Construction Costs	0.190	0.288	0.584	0.032	12
B2	Noise	0.120	0.250	1.000	0.030	13
B3	Vehicle Emissions	0.120	0.246	1.000	0.029	14
A4-2	Presence of Conflicting Protected Traffic	0.396	0.208	0.339	0.028	15
C2-2	Right-of-Way Costs	0.190	0.288	0.416	0.022	16
A4-3	Pedestrian Crossing Distance	0.396	0.208	0.216	0.018	17

3.6.3 Examining Results

In computing the weights, it was interesting to identify any differences in judgments between groups of decision-makers who filled out the online questionnaire and completed the pairwise comparisons. In this regard, weights resulting from the judgments were provided in four different groups: (i) Junior Engineer, (ii) Senior Engineer, (iii) Professor, and (iv) Stakeholder. Figures 3-4, 3-5, 3-6, 3-7, and 3-8 depict the obtained set of weights by the whole group (Aggregate), and by the different decision-maker groups. The figures portray the relative weights at the top, primary, and secondary levels of the hierarchy.

It can be inferred that the differences in weights seem to be rather limited at the top level of the hierarchy with the exception of Criterion A: "*Operational Performance*" and Criterion D:" *Safety*" that have a difference in the weights slightly greater than 10% especially among the Senior and Junior Engineers. As for the primary level, only two criteria display a significant difference in the weights; i.e. greater than 0.2. This high difference is shown for the *Economic Costs (C1)* and *Financial Costs (C2)* between Junior Engineers and Stakeholders whereas four other primary criteria display slight differences, as follows:

1. A4: Accommodation for Pedestrian Crossings
2. B1: Accessibility Impact on Existing Economic Activities
3. D1: Crash Frequency Experience
4. D2: Driver Experience

As for the secondary criteria, there are appreciable differences in the weights between all decision groups as follows:

i. Difference between 10% and 15%

1. A4-3: Pedestrian Crossing Distance

j. Difference between 15% and 20%

2. C1-1: Total Travel time Savings
3. C1-2: Vehicle Operating Cost Reductions
4. C2-1: Construction Costs
5. D2-1: Potential Driver Confusion

k. Difference greater than 20%

6. A4-1: Average Pedestrian Waiting time at Signalized Intersection
7. A4-2: Presence of Conflicting Protected Traffic
8. C2-2: Right-of-Way Costs
9. D2-2: number of Conflict Points

Based on the above, there is a need to analyze these differences and to validate the appropriateness of the aggregate weights.

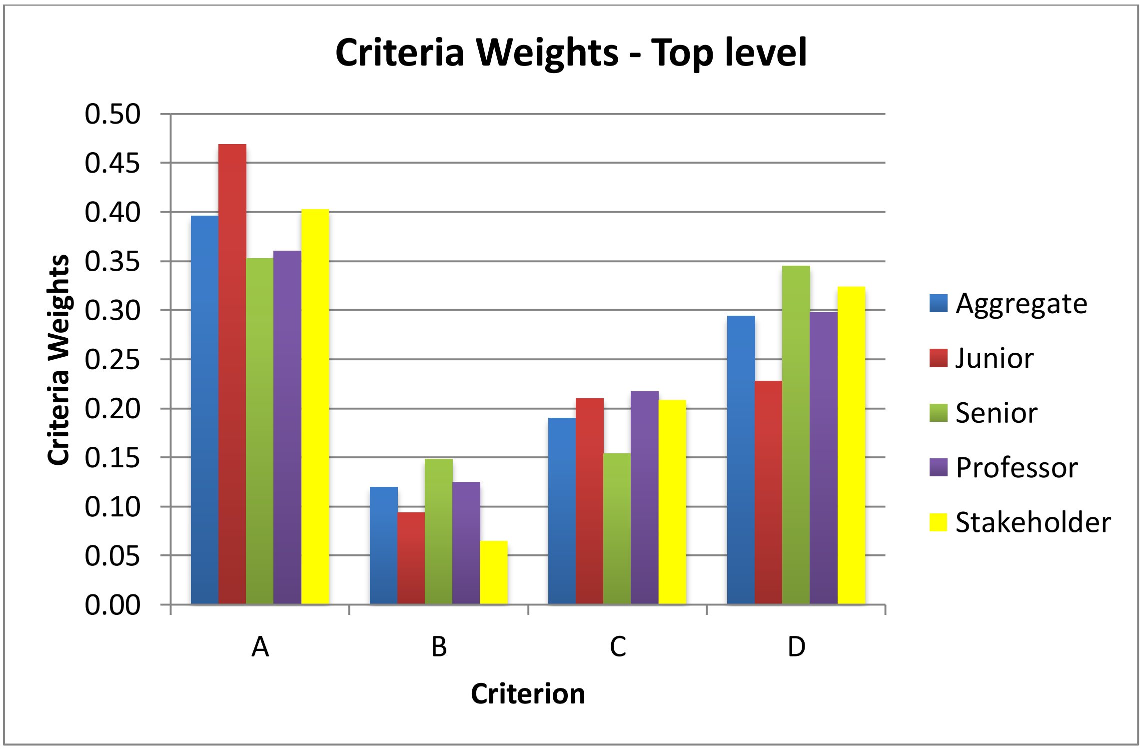

Figure 3-4: Criteria Weights (Top Level) for all group decision-makers

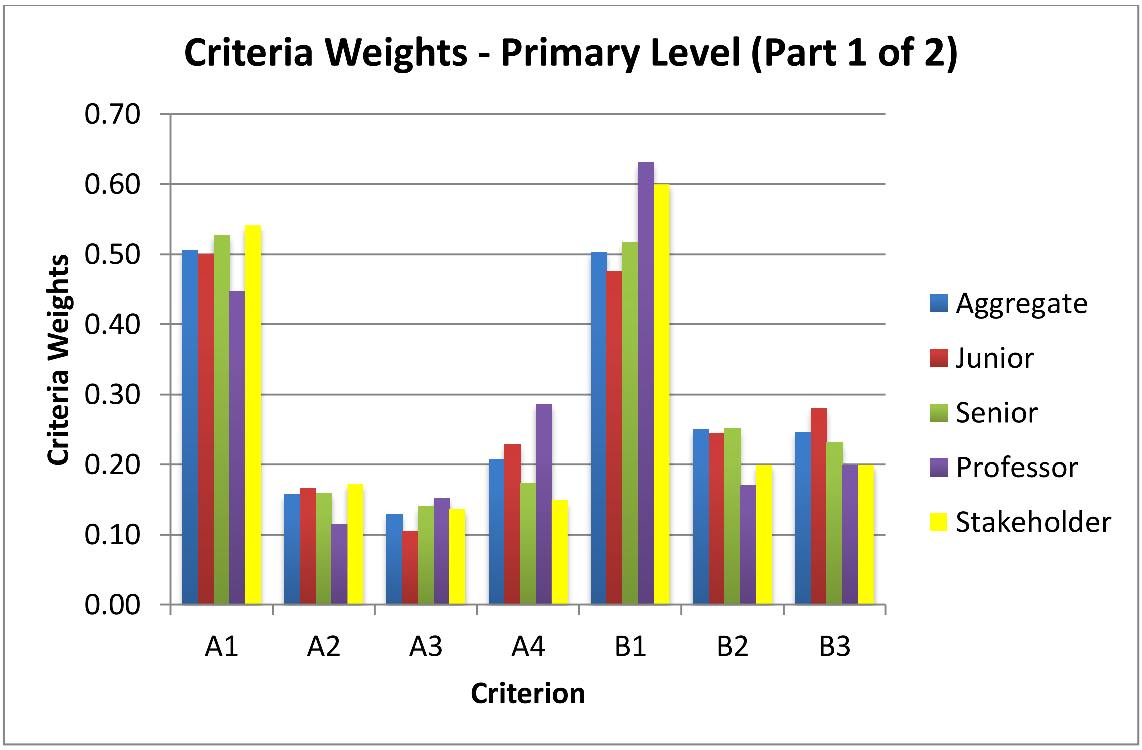

Figure 3-5: Criteria Weights (Primary Level - Part1) for all group decision-makers

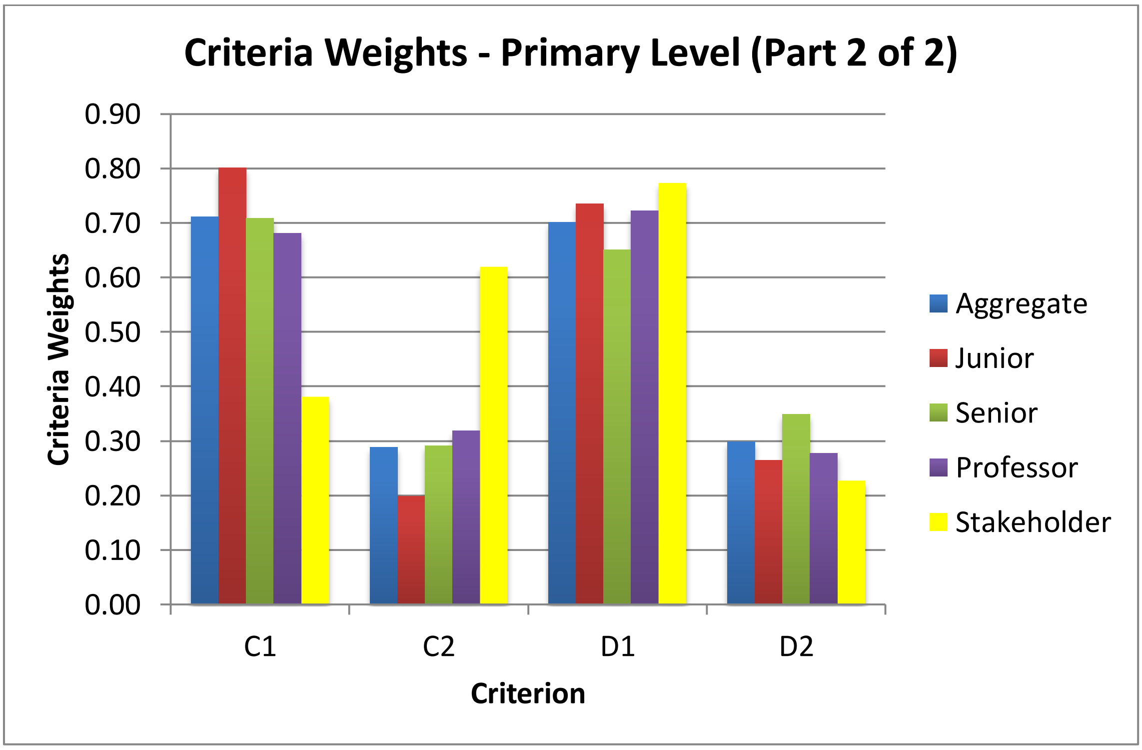

Figure 3-6: Criteria Weights (Primary Level - Part2) for all group decision-makers

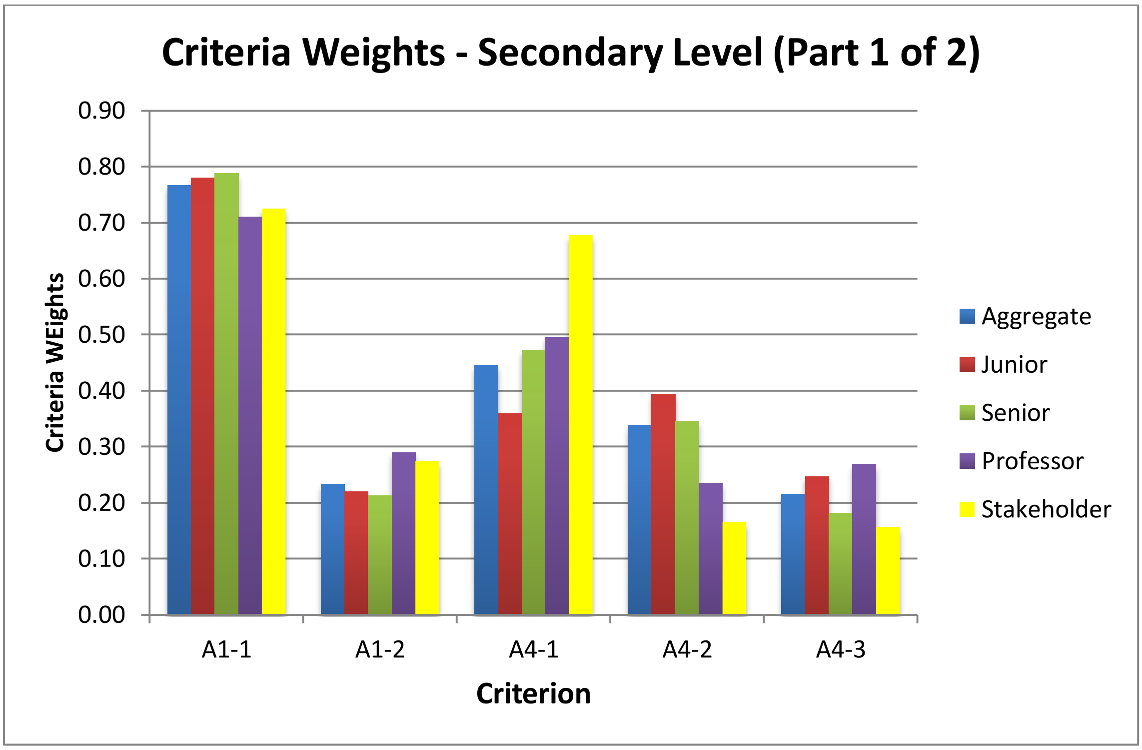

Figure 3-7: Criteria Weights (Secondary Level - Part1) for all group decision-makers

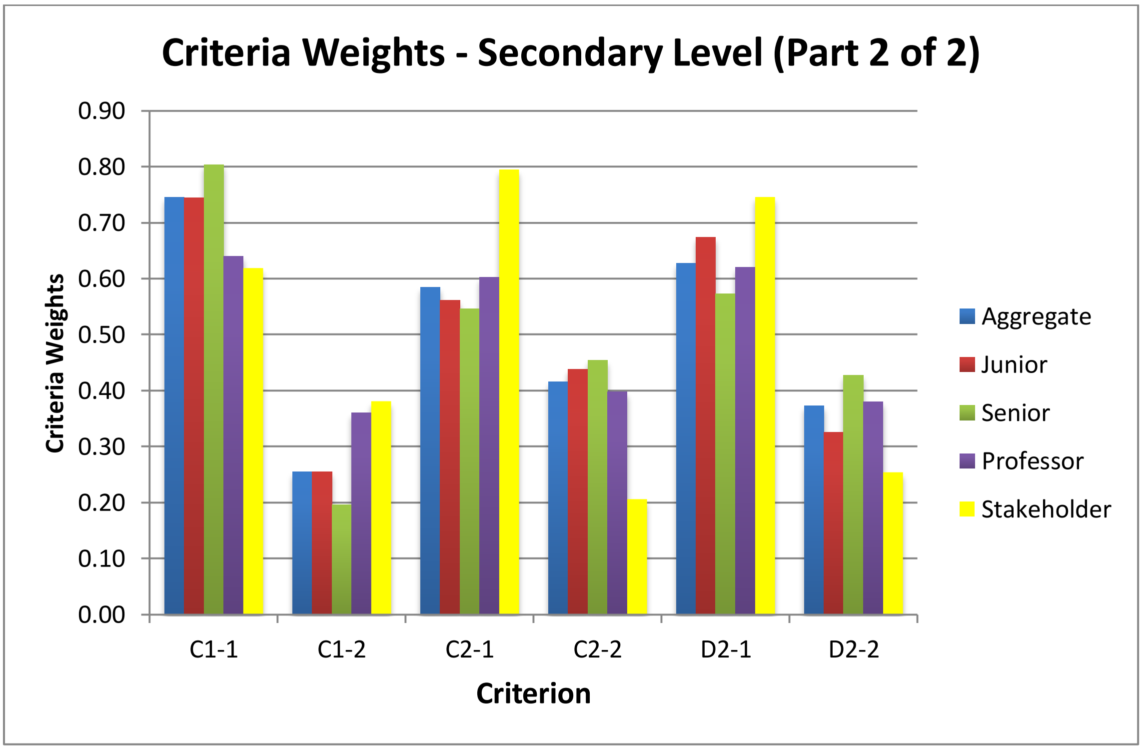

Figure 3-8: Criteria Weights (Secondary Level – Part2) for all group decision-makers

CHAPTER 4

CASE STUDY

4.1 Introduction

In this chapter, a site location for the case study is identified through which the prioritization framework is used to determine the preferred interchange configuration based on multi-criteria analysis.

Furthermore, this chapter presents the models that were used for scoring the criteria upon which an evaluation of the performance of each alternative is made. In addition, this chapter describes the scoring functions that are used to quantify the performance of the interchanges on the different criteria. Consequently, using a linear additive model, an overall ranking of the interchanges is determined and a prioritization of the arterial/freeway interchange types is achieved. Finally, sensitivity tests are explored to examine the effects of changing several factors on the overall ranking.

The contents of the chapter include: interchange site selection, data collection, scoring functions, models used in scoring, scoring the criteria, ranking the alternatives, and sensitivity analysis.

4.2 Interchange Selection

Riyadh, the capital of the Kingdom of Saudi Arabia (KSA), is one of the fastest growing cities in the Middle East. During the past couple of decades, the city of Riyadh has experienced a tremendous growth in all aspects of urban life with various economic, social and environmental impacts. The booming economy has led to significant increase in population and a concomitant rise in car ownership and overall traffic volume. Its population has risen steadily at a rate of 4.2% during the period 1990 to 2004 (Arriyadh Development Authority, 2004). According to a recent study by the ADA, the city's population is expected to increase by 40% from 5.8 million in 2012 to 8 million in addition to a 60% rise in travel demand by the year 2030 (Arab News, 2014).

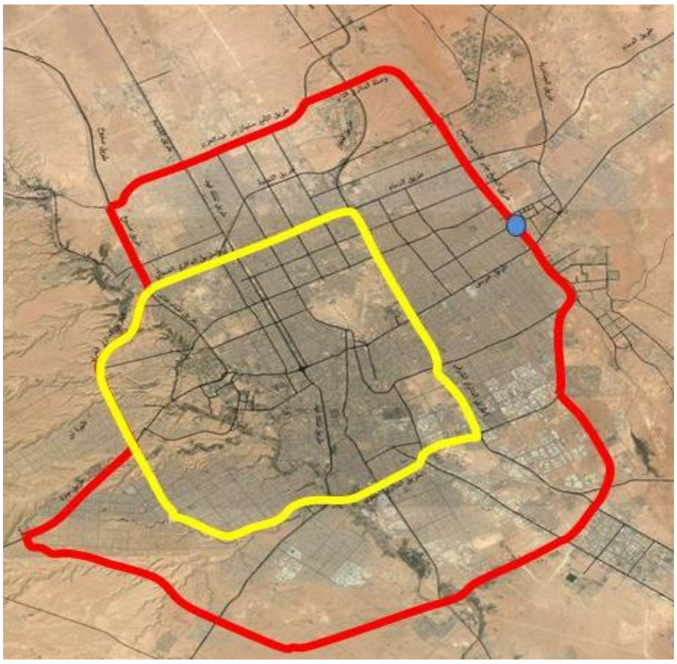

Figure 4-5: Aerial image of Riyadh City

This outburst in population is accompanied by a rapid increase in dwelling units, businesses, and most importantly road traffic which is worsened by the car culture in the city. To cater for the increasing travel demand and to provide requisite connectivity requirements for the newly developed areas in Riyadh, the city's road network is currently experiencing a vast expansion program.

One of the road corridors which will play an important role in supporting Riyadh's expansion is the "Sheikh Jaber Road" corridor. This road, being a major arterial road in Riyadh, has a significant strategic role in the city's road network, as it falls on the eastern side of the Second Ring Road as shown in Figure 4-2.

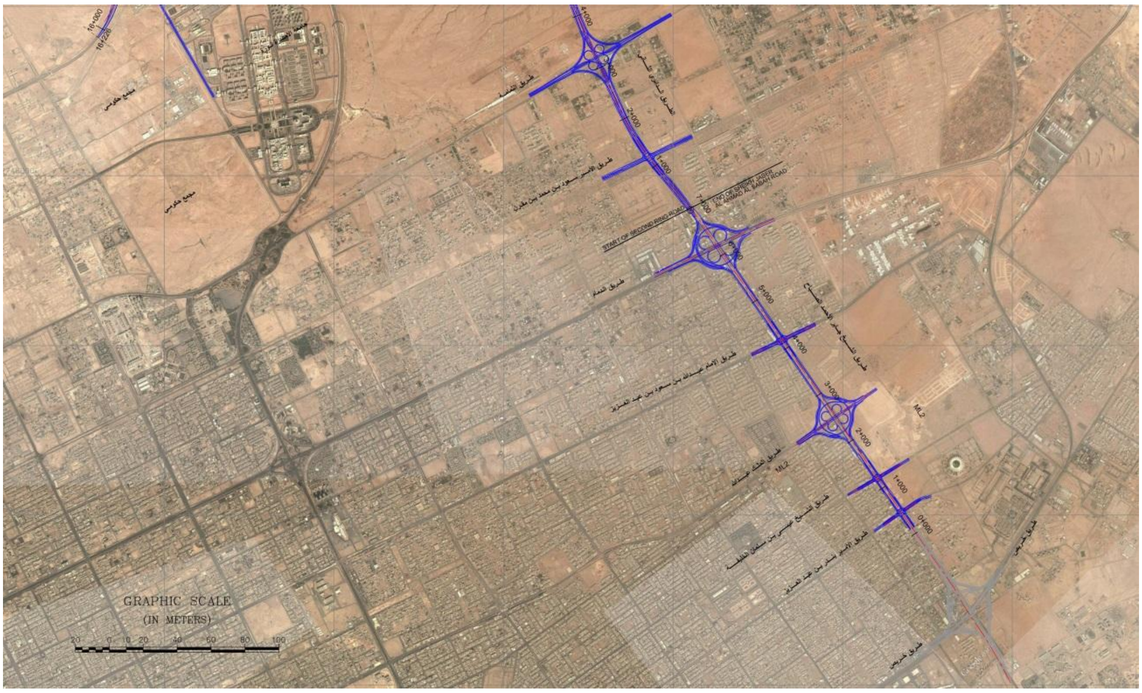

Figure 4-6: Aerial image of Sheikh Jaber Road

With the ongoing plans to upgrade this road to cater for the increased traffic demand, this road is proposed to act as a freeway to take the pressure off the congested nearby arterial roads. A case study is selected at the intersection of the **Sheikh Jaber** road (proposed freeway) with **Prince Bandar Bin Abdulaziz** road (existing arterial road) for prioritizing several interchange types using multi-criteria analysis. The selection of the case study was made due to the availability of the traffic data in Riyadh city in addition to the available geometric design plans on Sheikh Jaber road.

Figure 4-3 below shows an aerial image of the case study site location in Riyadh city.

Figure 4-7: Aerial image of the case study site location

4.3 Data Collection

In order to assess the traffic conditions along Sheikh Jaber road, it was essential to contact the engineering consulting firm which was commissioned to undertake the necessary studies and the design of the primary roads in Riyadh, KSA. To do so, we have contacted SETS, a leading regional multidisciplinary engineering and consulting firm, which offered their help in providing us with the forecasted demand volumes along Sheikh Jaber road.

(Emme/3) Traffic Model was used to assign the traffic onto the road network of Riyadh. The model, developed by Arriyadh Development Authority (ADA), was constructed for the target year 2030 covering the city of Riyadh and the road network (primary and secondary roads) within the urban areas of the city. The forecasted traffic conditions at the intersection of Sheikh Jaber road and Prince Bandar Bin Abdulaziz road were taken from the model as shown in Figure 4-4 below.

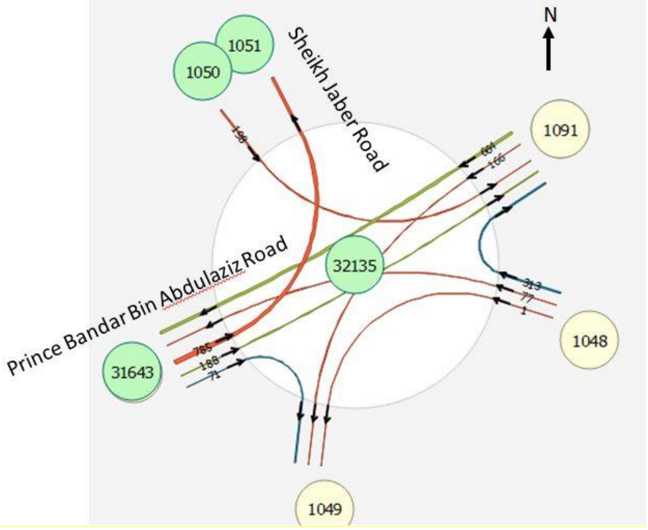

Figure 4-8: Traffic Volumes at the selected intersection

High volumes of traffic were identified for the peak hour on the crossing arterial road (Prince Bandar Bin Abdulaziz) especially for the eastbound left-turning movements from the mentioned road to the on ramps and the westbound through movements, whereas relatively low volumes of traffic were identified on the off-ramps in both directions.

4.4 Scoring Functions

The following section gives a detailed description of the scoring functions for the 17 criteria that were presented in the previous chapter (Section 3.2: Proposed Evaluation Framework) to rank and prioritize the arterial/freeway interchange types. Each interchange alternative receives a score ranging from “0” to “5” on each of those criteria. Some criteria were scored according to piecewise linear functions whereas others were scored based on discrete thresholds.

4.4.1 Intersection Delays (A1-1)

Criterion A1-1 measures the performance of the interchanges according to the projected intersection delays. The scoring functions are based on the level of service

(LOS) criteria that are provided in the Highway Capacity Manual (Exhibit 16-2) for signalized intersections (Highway Capacity Manual, 2000). Level of service (LOS) is a measure used to determine the effectiveness of intersections by analyzing traffic flows with the corresponding intersection delays. In general, the lower the intersection delays that are observed, the better the LOS an interchange achieves and consequently the higher it scores on this criterion. For example, a LOS "A" which is considered very good (low traffic density) is associated with delays ranging below 10 sec/veh and consequently scores between 4 and 5.

Table 4-1 below shows the scoring functions used for criterion A1-1. The delays shown below are computed in seconds per vehicle.

Table 4-1: A1-1 Scoring Functions

Delay Range (sec/veh)	Function used
[80 , ∞)	A1-1 Score = 0
[55 , 80)	A1-1 Score = 1 - (1/25)(Delay - 55)
[35 , 55)	A1-1 Score = 2 - (1/20)(Delay - 35)
[20 , 35)	A1-1 Score = 3 - (1/15)(Delay - 20)
[10 , 20)	A1-1 Score = 4 - (1/10)(Delay - 10)
[0 , 10)	A1-1 Score = 5 - (Delay /10)

4.4.2 Average Delay for All Left-Turning Movements (A1-2)

Criterion A1-2 measures the performance of the interchanges according to the projected average delays for all left-turning movements. Similar to the previous criterion (A1-1), the scoring functions are based on the level of service (LOS) criteria that are classified in the Highway Capacity Manual (Exhibit 16-2) for signalized intersections (Highway Capacity Manual, 2000). The classified LOS ranges from "A" to "F" relative to the delays observed per vehicle.

Table 4-2 below shows the scoring functions used for criterion A1-2. As previously noted, the lower the delays, the better the LOS that is achieved and consequently the higher the score that is assigned on this criterion. For example, an average delay of 35 sec/veh represents a LOS “D” and consequently an interchange with such delay level scores 2 out of 5 on this criterion.

Table 4-2: A1-2 Scoring Functions

Delay Range (sec/veh)	Function used
$[80 , \infty)$	A1-2 Score = 0
[55 , 80)	A1-2 Score = 1 - (1/25)(Delay - 55)
[35 , 55)	A1-2 Score = 2 - (1/20)(Delay - 35)
[20 , 35)	A1-2 Score = 3 - (1/15)(Delay - 20)
[10 , 20)	A1-2 Score = 4 - (1/10)(Delay - 10)
[0 , 10)	A1-2 Score = 5 - (Delay /10)

4.4.3 Average Number of Stops (A2)

Criterion A2 evaluates the performance of the interchanges based on the percentage of stops of all vehicles within the interchange. In scoring this criterion, a review of the percentage stops was conducted for similar types of interchanges. The results of the literature review helped in identifying the typical percentages of stops for vehicles at similar interchange types. For instance, Bared et al. (2005) found that the percentage of stops at a TUDI ranged from 80% at low traffic volume scenario reaching to 240% at extremely high volume scenarios; thus vehicles at the intersections could stop more than twice before proceeding through the interchange. Similarly, the DDI experienced 60% vehicular stops at low traffic volume scenario and increased to 140% at the higher volume scenarios.

Table 4-3 below shows the scoring functions used for criterion A2. The 0% represents an uninterrupted traffic flow and consequently a score of “5” is assigned in such cases, whereas the percentages exceeding the value "200" indicate that the vehicles stop at least twice at the signalized intersection; hence, a score of "0" is assigned.

Table 4-3: A2 Scoring Functions

% Stops Range	Function used
[200 , ∞)	A2 Score = 0
[160 , 200)	A2 Score = 1 - (1/40)(% Stops - 160)
[120 , 160)	A2 Score = 2 - (1/40)(% Stops - 120)
[80 , 120)	A2 Score = 3 - (1/40)(% Stops - 80)
[40 , 80)	A2 Score = 4 - (1/40)(% Stops - 40)
[0 , 40)	A2 Score = 5 - (% Stops /40)

4.4.4 Maximum Queue Length (A3)

Criterion A3 measures the performance of the interchanges based on the maximum queue length that is observed for all approaches at the peak hour. In scoring this criterion, it was also important to check the relevant literature regarding the queue lengths at similar interchange types. The results of the review were helpful in determining the typically observed queue lengths at interchanges with similar classifications. For instance, Bared et al. (2005) found that the maximum queue lengths at TUDI and DDI ranged from 35 meters at low traffic volumes and exceeded 300 meters at extremely high volumes.

In general, the higher the queue length, the lower the score that is assigned on this criterion. For example, an interchange with a maximum queue length of 250 meters would score "0" on this criterion whereas a score "3" is assigned for a maximum queue length of 100 meters.

Table 4-4 below shows the scoring functions used for criterion A3. The queue length used below is in meters.

Table 4-4: A3 Scoring Functions

Max Queue Length Range (meter)	Function used
[250 , ∞)	A3 Score = 0
[200 , 250)	A3 Score = 1 - (1/50)(Max Queue - 200)
[150 , 200)	A3 Score = 2 - (1/50)(Max Queue - 150)
[100 , 150)	A3 Score = 3 - (1/50)(Max Queue - 100)
[50 , 100)	A3 Score = 4 - (1/50)(Max Queue - 50)
[0 , 50)	A3 Score = 5 - (Max Queue /50)

4.4.5 Average Pedestrian Waiting Time at Signalized Intersections (A4-1)

Criterion A4-1 measures the performance of the interchanges based on the pedestrians' waiting time at signalized intersections. The scoring functions are taken from the informational guide of signalized intersections that is prepared by the Federal Highway Administration (Rodegerdts et al., 2004). These functions are based on the LOS thresholds for pedestrian crossing at signalized intersections.

Table 4-5 below shows the scoring functions used for criterion A4-1. The higher the waiting time for pedestrians to cross through the interchange, the lower the score that is assigned on this criterion. The waiting time used in the below functions is in seconds.

Table 4-5: A4-1 Scoring Functions

Waiting Time Range (sec)	Function used
[60 , ∞)	A4-1 Score = 0
[40 , 60)	A4-1 Score = 1 - (1/20)(Waiting Time - 40)
[30 , 40)	A4-1 Score = 2 - (1/10)(Waiting Time - 30)
[20 , 30)	A4-1 Score = 3 - (1/10)(Waiting Time - 20)
[10 , 20)	A4-1 Score = 4 - (1/10)(Waiting Time - 10)
[0 , 10)	A4-1 Score = 5 - (Waiting Time /10)

4.4.6 Presence of Conflicting Protected Traffic (A4-2)

Criterion A4-2 rates the performance of the interchanges based on the extent of presence of conflicting protected traffic. There are no clear guides/references that indicate the range of acceptable traffic volumes; hence the scoring functions were proposed based on professional judgment. The higher the hourly volume of protected left-turning traffic that conflicts with the crossings of pedestrians, the lower the score being assigned on this criterion.

Table 4-6 below shows the scoring functions used for criterion A4-2. For example, a score of "0" is assigned for interchanges having conflicting traffic exceeding 2000 veh/hr, "1" is assigned at 1600 veh/hr, and "5" when there is no conflicting protected traffic.

Table 4-6: A4-2 Scoring Functions

Conflicting Traffic Volume Range (veh/hr)	Function used
[2000 , ∞)	A4-2 Score = 0
[1600 , 2000)	A4-2 Score = 1 - (1/400)(Volume - 1600)
[1200 , 1600)	A4-2 Score = 2 - (1/400)(Volume - 1200)
[800 , 1200)	A4-2 Score = 3 - (1/400)(Volume - 800)
[400 , 800)	A4-2 Score = 4 - (1/400)(Volume - 400)
[0 , 400)	A4-2 Score = 5 - (Volume /400)

4.4.7 Pedestrian Crossing Distance (A4-3)

Criterion A4-3 evaluates the performance of the interchanges based on the distance covered by the pedestrians in crossing the interchange. Similar to the previous criterion (A4-2), there are no clear guides/references that indicate the acceptable ranges of pedestrian crossing distance; hence the scoring functions were proposed based on professional judgment.

Table 4-7 below shows the scoring functions used for criterion A4-3. As shown, the higher the distance that is required for pedestrians to cross through the interchange, the lower the score that is assigned for the interchange on this criterion. The crossing distance used in the below functions is in meters.

Table 4-7: A4-3 Scoring Functions

Crossing Distance Range (meter)	**Function used**
[250 , ∞)	A4-3 Score = 0
[225 , 250)	A4-3 Score = 1 - (1/25)(Distance - 225)
[200 , 225)	A4-3 Score = 2 - (1/25)(Distance - 200)
[175 , 200)	A4-3 Score = 3 - (1/25)(Distance - 175)
[150 , 175)	A4-3 Score = 4 - (1/25)(Distance - 150)
[0 , 150)	A4-3 Score = 5 - (Distance /150)

4.4.8 Accessibility Impact on Existing Economic Activities (B1)

Criterion B1 rates the performance of the interchanges based on the accessibility impacts they impose to the existing economic activities. There are no clear references/guides that can be used to determine the scoring functions of this criterion; hence professional judgment was applied.

The scoring computation for this criterion is based on the following two schemes:

- Scheme 1: If the interchange configuration imposes poor accessibility to adjacent economic activity, such as having no access for a distance of 400 or 320 meters, the interchange would receive a score of “0” and “0.6”, respectively, on this scheme. Table 4-8 below displays the scoring functions used for the first scheme of criterion B1. The distance used in the below functions is in meters.

Table 4-8: B1 Scheme 1 Scoring Functions

Dead Zone Distance Range (meter)	Function used
[400 , ∞)	B1 Sub Score = 0
[320 , 400)	B1 Sub Score = 3/5 *[1 - (1/80)(Distance - 320)]
[240 , 320)	B1 Sub Score = 3/5 *[2 - (1/80)(Distance - 240)]
[160 , 240)	B1 Sub Score = 3/5* [3 - (1/80)(Distance - 160)]
[80 , 160)	B1 Sub Score = 3/5 *[4 - (1/80)(Distance - 80)]
[0 , 80)	A4-3 Sub Score = 3/5 * [5 - (Distance /80)]

- Scheme 2: If the interchange type accommodates continuous through traffic between the ramps, it automatically receives a score of "2". Otherwise, a score of "0" is assigned. (refer to Table 4-9)

Table 4-9: B1 Scheme 2 Scoring Thresholds

Accommodation of Through Traffic	Score
No	B1 Sub Score = 0
Yes	B1 Sub Score = 2

The final score an interchange receives is calculated by adding its corresponding scores on schemes 1 and 2. The maximum score an alternative might receive is 5 ("3" from scheme 1 and "2" from scheme 2).

4.4.9 Noise (B2)

Criterion B2 evaluates the performance of the interchanges based on the level of noise generated. According to the Highway Traffic Noise Abatement Guidelines report that is developed by the FHWA, noise abatement criteria are defined for highway projects adjacent to various land use activities (Federal Highway Administration, 2010). The noise attenuation requirements under the FHWA indicate a maximum hourly sound level of 72 dBA for highway projects adjacent to developed lands and properties.

Accordingly, the scoring functions are defined in relation to the areas having sound levels exceeding the specified noise level (FHWA standards), as shown in Table 4-10 below. For example, an interchange having sound levels exceeding the FHWA standards for more than 80% of its area would score between “0” and “1” on this criterion.

Table 4-10: B2 Scoring Functions

% Area Range (Noise Level >72 dBA)	Function used
[80 , 100)	B2 Score = 1 - (1/20)(%Area - 80)
[60 , 80)	B2 Score = 2 - (1/20)(%Area - 60)
[40 , 60)	B2 Score = 3 - (1/20)(%Area - 40)
[20 , 40)	B2 Score = 4 - (1/20)(%Area - 20)
[0 , 20)	B2 Score = 5 - (%Area/20)

4.4.10 Vehicle Emissions (B3)

Criterion B3 evaluates the performance of the interchanges according to the vehicular emissions of greenhouse gases, mainly HC and CO gases that traffic going through these interchanges would result in. The scoring computation on this criterion is based on the following two schemes:

- Scheme 1: The level of HC emissions generated by the interchange. There are no clear guides/references that indicate the acceptable ranges of HC emissions; hence the scoring functions were proposed based on professional judgment. The corresponding scoring functions are shown in Table 4-11. For example, a score of “0” is assigned for interchanges having HC emissions exceeding 4000 grams per hour.
- Scheme 2: The level of CO emission generated by the interchange. Similarly, the scoring functions were proposed based on professional judgment as shown in Table 4-12. For example, interchanges having

CO emissions ranging between 8000 g/hr and 16000 g/hr would score between "1.5" and "2" on this scheme.

The final score an interchange receives is calculated by adding its corresponding scores on schemes 1 and 2.

Table 4-11: B3 Scheme 1 Scoring Functions

HC Emissions Range (g/hr)	Function used
[4000 , ∞)	B3 Sub Score = 0
[3200 , 4000)	B3 Sub Score = 2.5/5 *[1 - (1/800)(Emissions - 3200)]
[2400 , 3200)	B3 Sub Score = 2.5/5 *[2 - (1/800)(Emissions - 2400)]
[1600 , 2400)	B3 Sub Score = 2.5/5 *[3 - (1/800)(Emissions - 1600)]
[800 , 1600)	B3 Sub Score = 2.5/5 *[4 - (1/800)(Emissions - 800)]
[0 , 800)	B3 Sub Score = 2.5/5 *[5 - (Emissions /800)]

Table 4-12: B3 Scheme 2 Scoring Functions

CO Emissions Range (g/hr)	Function used
[40000 , ∞)	B3 Sub Score = 0
[32000 , 40000)	B3 Sub Score = 2.5/5 *[1 - (1/8000)(Emissions - 32000)]
[24000 , 32000)	B3 Sub Score = 2.5/5 *[2 - (1/8000)(Emissions - 24000)]
[16000 , 24000)	B3 Sub Score = 2.5/5 *[3 - (1/8000)(Emissions - 16000)]
[8000 , 16000)	B3 Sub Score = 2.5/5 *[4 - (1/8000)(Emissions - 8000)]
[0 , 8000)	B3 Sub Score = 2.5/5 *[5 - (Emissions /8000)]

4.4.11 Total Travel Time Savings (C1-1)

Criterion C1-1 measures the performance of each of the alternatives according to the savings in travel time costs that these interchanges can potentially result in. The scoring functions of criterion C1-1 are shown in Table 4-13 below. The higher the percentage of travel time savings, the higher the score the interchange alternative receives on this criterion. For example, if an interchange results in only 50% travel time savings, it would score "0" on this criterion. At 60% travel time savings, a score of "1" is assigned.

Table 4-13: C1-1 Scoring Functions

% Travel Time Savings Range	Function used
[90 ,100]	C1-1 Score = 5 - (1/10)(100 - %Savings)
[80 , 90)	C1-1 Score = 4 - (1/10)(90 - %Savings)
[70 , 80)	C1-1 Score = 3 - (1/10)(80 - %Savings)
[60 , 70)	C1-1 Score = 2 - (1/10)(70 - %Savings)
[50 , 60)	C1-1 Score = 1 - (1/10)(60 - %Savings)
[0 , 50)	C1-1 Score = 0

4.4.12 Vehicle Operating Cost Reductions (C1-2)

Criterion C1-2 ranks the performance of the interchanges according to the savings in vehicle operating costs that these interchanges can result in. Table 4-14 below shows the functions used in computing the scores for the interchange types on this criterion. The higher the reductions in VOCs, the higher the interchange scores on this criterion. For example, interchanges resulting in at least 80% VOC reductions would score between "4" and "5". At 60% VOC reductions, a score of "3" is assigned.

Table 4-14: C1-2 Scoring Functions

% VOC Reductions Range	Function used
[80 ,100]	C1-2 Score = 5 - (1/20)(100 - %Reductions)
[60 , 80)	C1-2 Score = 4 - (1/20)(80 - %Reductions)
[40 , 60)	C1-2 Score = 3 - (1/20)(60 - %Reductions)
[20 , 40)	C1-2 Score = 2 - (1/20)(40 - %Reductions)
[0 , 20)	C1-2 Score = 1 - (1/20)(20 - %Reductions)

4.4.13 Construction Costs (C2-1)

Criterion C2-1 measures the performance of the interchanges according to their construction costs. Table 4-15 below shows the functions used in computing the scores for the interchange types on this criterion. The costs shown in the below table are expressed in dollar terms. The higher the cost needed to construct the interchanges, the lower the score the interchange receives on this criterion. For example, a score of "0" is assigned for interchanges having a construction cost above $20 million. At $16 million, an interchange would score "1" on this criterion.

Table 4-15: C2-1 Scoring Functions

Cost Range ($)	**Function used**
[20,000,000 , ∞)	C2-1 Score = 0
[16,000,000 , 20,000,000)	C2-1 Score = 1 - (1/4,000,0000)(Cost - 16,000,000)
[16,000,000 , 12,000,000)	C2-1 Score = 2 - (1/4,000,0000)(Cost - 12,000,000)
[8,000,000 , 12,000,000)	C2-1 Score = 3 - (1/4,000,0000)(Cost - 8,000,000)
[4,000,000 , 8,000,000)	C2-1 Score = 4 - (1/4,000,0000)(Cost - 4,000,000)
[0 , 4,000,000)	C2-1 Score = 5 - (Cost / 4,000,000)

4.4.14 Right-of-Way Costs (C2-2)

Criterion C2-2 ranks the performance of the interchanges according to their Right-of-Way acquisition costs. Table 4-16 below shows the scoring functions that are used in computing the scores for the interchanges on this criterion. As shown below, the Right-of-Way costs are determined relative to the land area needed to properly locate the different interchange configurations. The higher the required area, the lower the score the interchange receives on this criterion. Thus, a score of "3" is assigned for interchanges having a land area of 30,000 square meter whereas as "2" is assigned for 45,000 m^2 land area.

Table 4-16: C2-2 Scoring Functions

Area Range (m^2)	**Function used**
[75,000 , ∞)	C2-2 Score = 0
[60,000 , 75,000)	C2-2 Score = 1 - (1/15,000)(Area – 60,000)
[45,000 , 60,000)	C2-2 Score = 2 - (1/15,000)(Area – 45,000)
[30,000 , 45,000)	C2-2 Score = 3 - (1/15,000)(Area – 30,000)
[15,000 , 30,000)	C2-2 Score = 4 - (1/15,000)(Area – 15,000)
[0 , 15,000)	C2-2 Score = 5 - (Area / 15,000)

4.4.15 Crash Frequency Experience (D1)

Criterion D1 measures the performance of the interchanges based on their record of crash frequencies. The scoring computation on this criterion is based on the following two schemes:

- Scheme 1: Indicates the crash frequency of interchanges per million entering vehicles. The corresponding scoring functions shown in Table 4-17 were derived based on the average crash frequencies that were observed for similar urban interchanges in Wisconsin (Knapp et al., 2005). For instance, an interchange experiencing 1 crash for every million entering vehicles (MEV) would score “1.16” on this criterion. At 1.5 crashes per MEV, a score of “0” is assigned.
- Scheme 2: Indicates the crash injuries/fatalities that are experienced at similar interchanges. The corresponding scoring functions shown in Table 4-18 are derived based on common rates observed in different American States. That is a score of “2” is assigned on this scheme for interchanges experiencing 0.06 crash injuries per million entering vehicles. Similarly, a score of “1” is assigned for 0.18 crash injuries per MEV.

The final score an interchange receives on this criterion is calculated by adding its corresponding scores on schemes 1 and 2.

Table 4-17: D1 Scheme 1 Scoring Functions

Crash Frequency Range (per MEV)	Function used
[1.5 , ∞)	D1 Sub Score = 0
[1.2 , 1.5)	D1 Sub Score = 2.5/5 *[1 - (1/0.3)(Frequency - 1.2)]
[0.9 , 1.2)	D1 Sub Score = 2.5/5 *[2 - (1/0.3)(Frequency – 0.9)]
[0.6 , 0.9)	D1 Sub Score = 2.5/5 *[3 - (1/0.3)(Frequency – 0.6)]
[0.3 , 0.6)	D1 Sub Score = 2.5/5 *[4 - (1/0.3)(Frequency – 0.3)]
[0 , 0.3)	D1 Sub Score = 2.5/5 *[5 - (Frequency / 0.3)]

Table 4-18: D1 Scheme 2 Scoring Functions

Crash Injuries/Fatalities Range (per MEV)	Function used
[0.3 , ∞)	D1 Sub Score = 0
[0.24 , 0.3)	D1 Sub Score = 2.5/5 *[1 - (1/0.06)(Frequency – 0.24)]
[0.18 , 0.24)	D1 Sub Score = 2.5/5 *[2 - (1/0.06)(Frequency – 0.18)]
[0.12 , 0.18)	D1 Sub Score = 2.5/5 *[3 - (1/0.06)(Frequency – 0.12)]
[0.06 , 0.12)	D1 Sub Score = 2.5/5 *[4 - (1/0.06)(Frequency – 0.06)]
[0 , 0.06)	D1 Sub Score = 2.5/5 *[5 - (Frequency / 0.06)]

4.4.16 Potential Driver Confusion (D2-1)

Criterion D2-1 evaluates the performance of the interchanges based on the potential driver confusion that might arise while traversing the interchanges. The scoring thresholds on this criterion are based on the following three schemes:

- Scheme 1: If the interchange has a well-defined path in between the ramp terminals, it automatically receives a score of “1.5”. Otherwise, a score of “0” is assigned. An “undefined path” is considered to be in effect when there’s a need for drivers to make more than a maneuver for a certain traffic movement. Table 4-19 shows the scoring thresholds for the first scheme on D2-1.

Table 4-19: D2-1 Scheme 1 Scoring Thresholds

Defined Path	**Score**
No	D2-1 Sub Score = 0
Yes	D2-1 Sub Score = 1.5

- Scheme 2: If the interchange has a compact intersection area, it automatically receives a score of “1.5”. Otherwise, a score of “0” is assigned for wide areas that might increase the confusion of drivers who might consequently choose unwanted paths (refer to Table 4-20).

Table 4-20: D2-1 Scheme 2 Scoring Thresholds

Intersection Area	**Score**
Wide	D2-1 Sub Score = 0
Compact	D2-1 Sub Score = 1.5

- Scheme 3: If the interchange features a reversal in traffic movements, it automatically receives a score of “0”. Otherwise, a score of “1.5” is assigned. (refer to Table 4-21)

Table 4-21: D2-1 Scheme 3 Scoring Thresholds

Traffic Movement	**Score**
Reversal	D2-1 Sub Score = 0
Direct	D2-1 Sub Score = 1.5

The final score an interchange receives is calculated by adding its corresponding scores on schemes 1, 2, and 3. A maximum score of “4.5” can be assigned for interchanges on this criterion.

4.4.17 Number of Conflict Points (D2-2)

Criterion D2-2 rates the performance of the interchanges based on the number of potential vehicular conflict points such as crossing, merging, and diverging points.

There are no clear guides/references that indicate the ranges of potential conflict points; hence the scoring functions were proposed based on professional judgment. This judgment was made upon checking the potential number of conflict points for TUDI, SPUI, and DDI configurations to include possibly all conflict point ranges for any other arterial/freeway interchange type. The higher the number of potential conflict points at an interchange, the lower the score that is assigned on this criterion. For instance, a score of "4" is assigned for 7 potential conflict points whereas a "3" is assigned for 14 potential conflict points.

Table 4-22 below shows the scoring functions used for criterion D2-2.

Table 4-22: D2-2 Scoring Functions

No. of Conflict Points Range	Function used
[35 , ∞)	D2-2 Score = 0
[28 , 35)	D2-2 Score = 1 - (1/7)(Number – 28)
[21 , 28)	D2-2 Score = 2 - (1/7)(Number – 21)
[14 , 21)	D2-2 Score = 3 - (1/7)(Number – 14)
[7 , 14)	D2-2 Score = 4 - (1/7)(Number – 7)
[0 , 7)	D2-2 Score = 5 - (Number/7)

4.5 Models used in scoring

Out of the 17 criteria that were used to rank and prioritize the arterial/freeway interchange types, three main sources of data were used for determining the scores. These sources are: (i) The VISSIM Traffic Model, (ii) The Traffic Noise Model, and (iii) The Vehicle Emissions Model. This section introduces the procedures used in these models to help in scoring the criteria.

4.5.1 VISSIM Model

VISSIM is one of the most important models used in this thesis as it was useful in determining the operational performance of interchanges, evaluating their environmental impacts, and computing their corresponding economic costs.

Thanks to the collaborative efforts of PTV Vision officials, a "*PHD and Master's Thesis License"* was provided and came in handy for simulating models for unlimited durations of time. In addition, the latest version of the software, "*PTV VISSIM 7.00",* was used for modeling the different interchange types.

The following sub-sections illustrate the six steps that were needed to develop the VISSIM-based models.

4.5.1.1 Model Components

First, a proper setup of the model components was required to define, initialize, and control the VISSIM model. These components include: Vehicle Types, Link Types, Desired Speed Decisions, Reduced Speed Areas, Conflict Areas, Stop Signs, Signal Heads, Detectors, and Queue Counters.

4.5.1.2 Geometric Configuration

- Background photo (layout Plan) was used as a source to develop the model geometrically.
- Roadways were then created using a series of links and connectors. These links/connectors were used to define the geometric elements in the model, including lane closure, grade information, and lane change formation.

4.5.1.3 Traffic Controllers

- Traffic control devices were added to model the signalized intersections. Signal Controllers were created and the optimized signal timing plans, as modeled in SYNCHRO, were entered in the “Controllers Editor” section.
- After defining the signal controller characteristics, signal heads were placed at the intersections. Each lane was then assigned with its controlling signal head. Stop signs were also placed prior to the signal heads to allow vehicles turning left or heading through to stop at the signalized intersection whereas the vehicles turning right remain in free flow movements.

4.5.1.4 Traffic Volume and Routing Decision

- After modeling the geometric configurations of the interchanges and adding the traffic control devices, traffic volumes were entered for all approaches. The hourly traffic volumes were entered for each interchange type (TUDI, SPUI, and DDI) and for the at-grade signalized intersection.
- For each link entering the intersection, routing decisions were assigned by defining the permitted movements at the intersections for approaching vehicles. Within each of the routing decisions, percentages of the traffic flow were entered to each of the three possible routes (a decision through which a driver can either continue straight, turn right or turn left).

Figures 4-5 and 4-6 depict the traffic volumes for each of the traffic movements at the arterial/freeway interchange types and the at-grade signalized intersection.

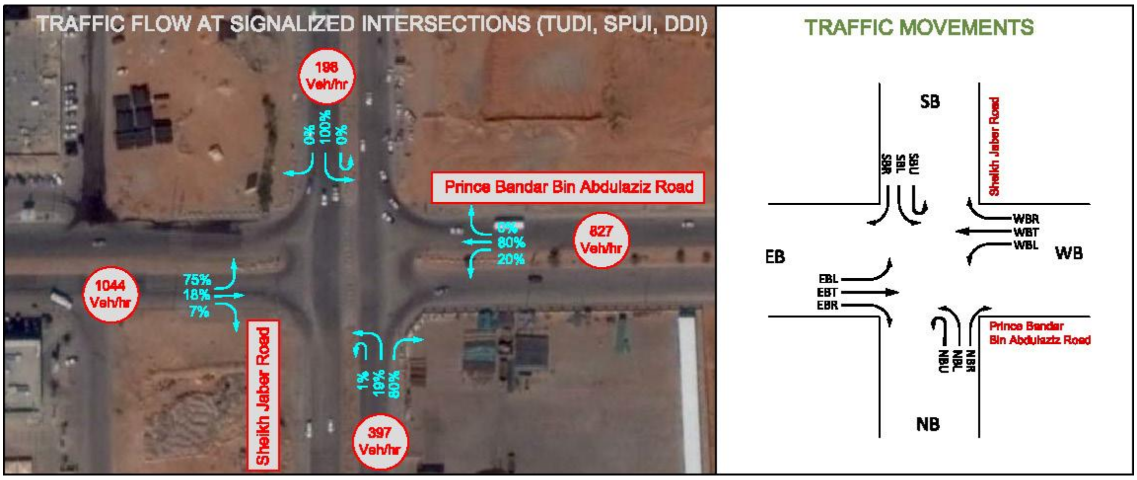

Figure 4-9: Turning movement diagram at signalized intersections (TUDI, SPUI, and DDI)

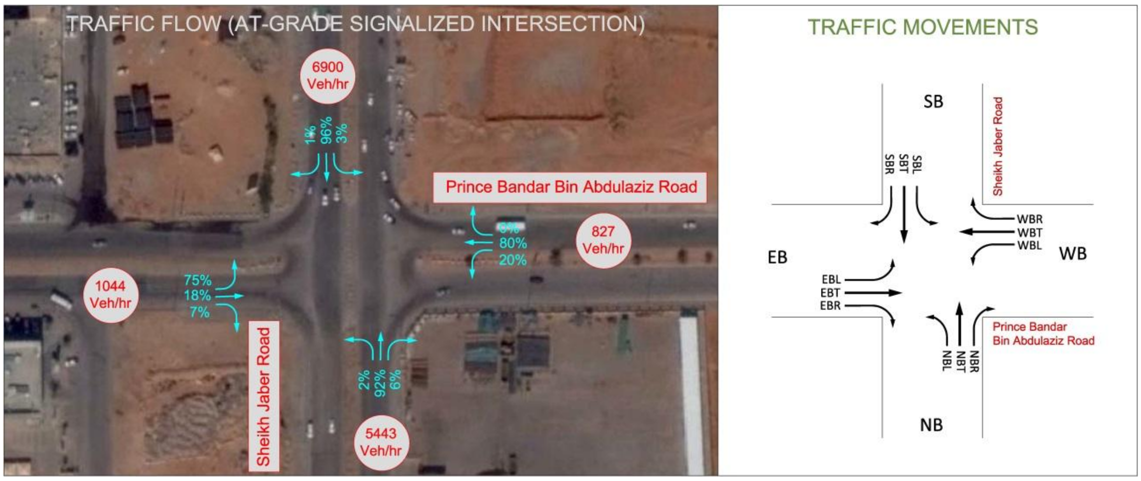

Figure 4-10: Turning movement diagram (At-grade Intersection)

4.5.1.5 Creating Output Files

- After preparing the whole network, output files were then created to provide the travel times, delay time, and queue lengths.
- Travel time sections were then defined to get either travel time or delay data. Travel time measurements were calculated from the start to the end of each defined section.

4.5.1.6 Simulation Parameters

Before running the simulation, several simulation parameters were configured, including: (i) Simulation time duration and warm-up time, (ii) number of simulations and random seed increments.

- Based on a study prepared by the Oregon Department of Transportation (2011) that aimed to provide a protocol for VISSIM simulation, the warm-up time was deemed to have been estimated once the number of vehicles present on the network ceases to increase by a minimum specified amount. In addition, if it was not feasible to extend the simulation period to uncongested time periods, the warm-up period was chosen equal to at least twice the estimated travel time at free-flow conditions to traverse the whole length of the network (Oregon Department of Transportation, 2011). As such, all simulation experiments performed in this thesis were based on simulation runs of 4500 seconds (75 minutes). A fifteen minute warm-up time was included in each run to allow traffic to stabilize before collecting data between 900 and 4500 seconds (60 minutes).
- In order to get a good impression of the possible stochastic spread of results, it was recommended to run multiple simulation runs with different random seeds. For the multiple simulation runs, a random seed increment of 5 with initial random seed of 42 was used for all tested scenarios. There are no clear guidelines that define these values. The first, random seed increment was chosen similar to other research studies (Butt, 2012). The second, initial random seed was chosen as the default value that is available in the software license. In addition, the VISSIM user manual recommends the use of 5 to 20 simulation runs depending on the type of

application (Planung Transport Verkehr (AG), 2000). For meaningful results, 10 automatic simulation runs were tested. Based on the results of multiple simulation runs, the arithmetic mean was chosen for in depth analyses.

Figures 4-7 and 4-8 below show the VISSIM-based simulation models for all interchange types (TUDI, SPUI, and DDI) in addition to the existing at-grade signalized intersection.

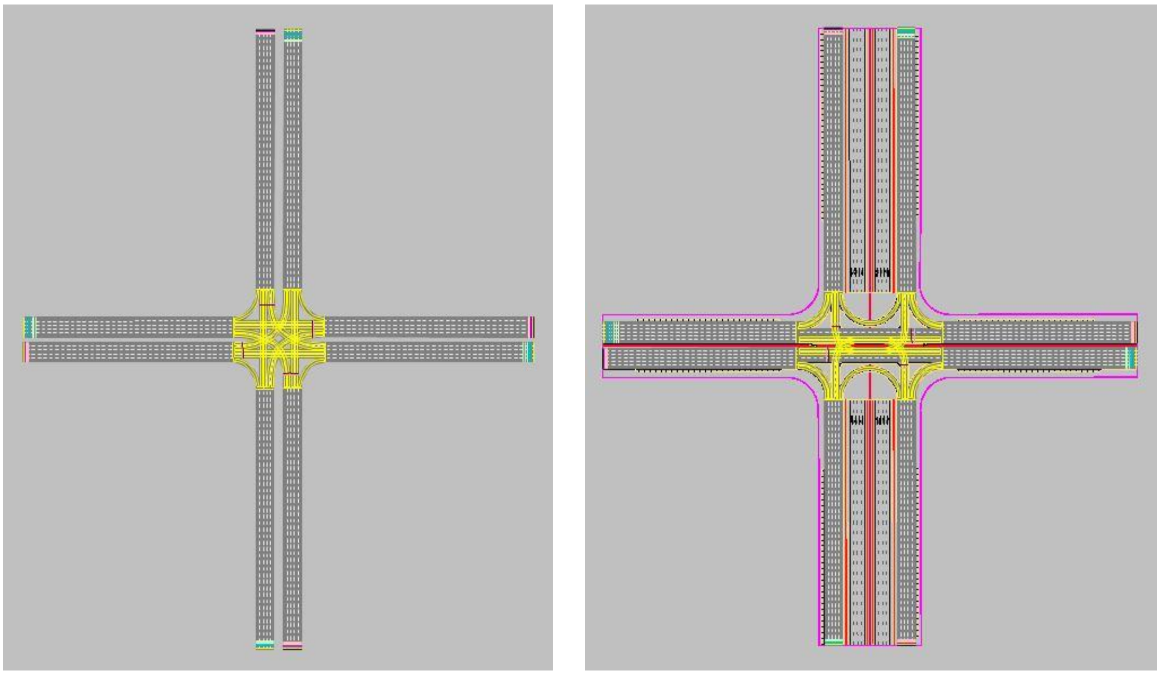

Figure 4-11: VISSIM-based traffic simulation models (at-grade intersection and TUDI)

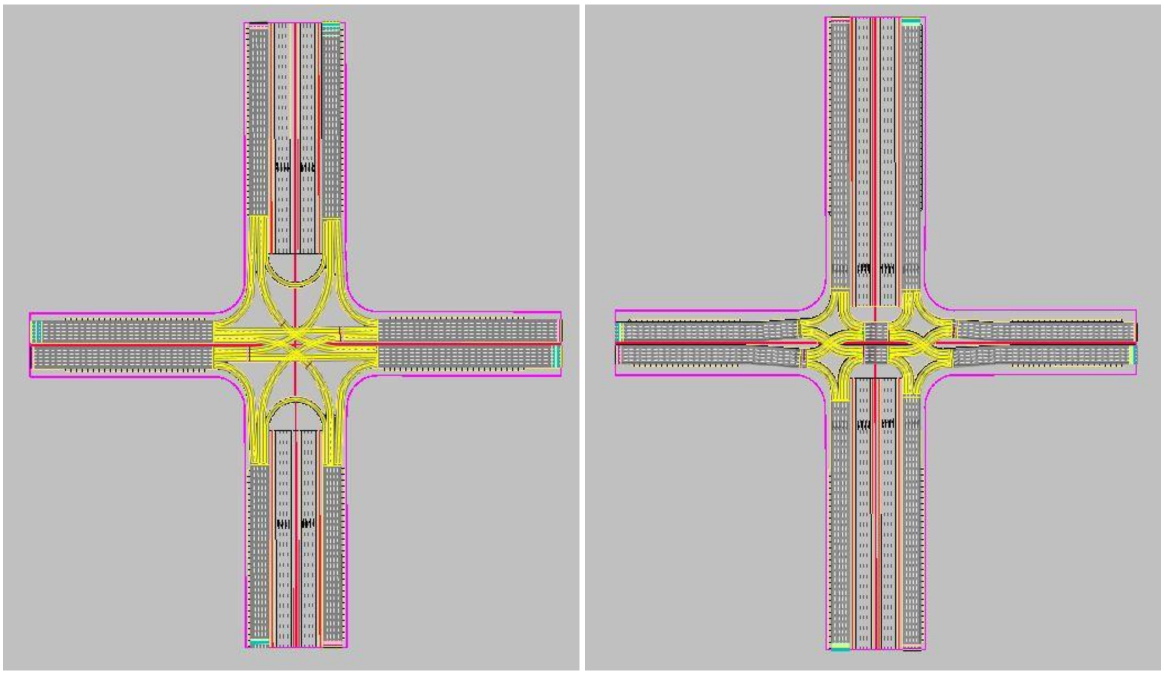

Figure 4-12: VISSIM-based traffic simulation models (SPUI and DDI)

4.5.2 Traffic Noise Model (TNM)

Noise levels were predicted for each interchange type using Traffic Noise Model TNM 2.5. This section describes the procedure used to model the interchanges and identifies the settings applied for the different TNM parameters.

To properly setup the model, the below settings were applied:

- Relative Humidity: Default value was used (50%)
- Temperature: Default value was used (20 degrees)
- Default Ground Type: Pavement
- Pavement Type: Average

To model the different interchange configurations, it was important to import the layout plans from AutoCAD to be used as a reference for digitizing the roadways accurately. Traffic volumes were then assigned on the roadway; 98% were assumed to be passenger cars and the remaining 2% were Medium Trucks. A speed of 60 kph was then assigned for all service roads and 100 kph for the freeway along Sheikh Jaber road.

After digitizing all the roadways, a number of traffic noise receivers were located along the sides of the interchanges, and barriers representing the retaining walls were included in the model. Finally, contour zones were defined and sound levels were calculated at all traffic noise receivers.

Figure 4-9 below shows a snapshot of the traffic noise models that were used.

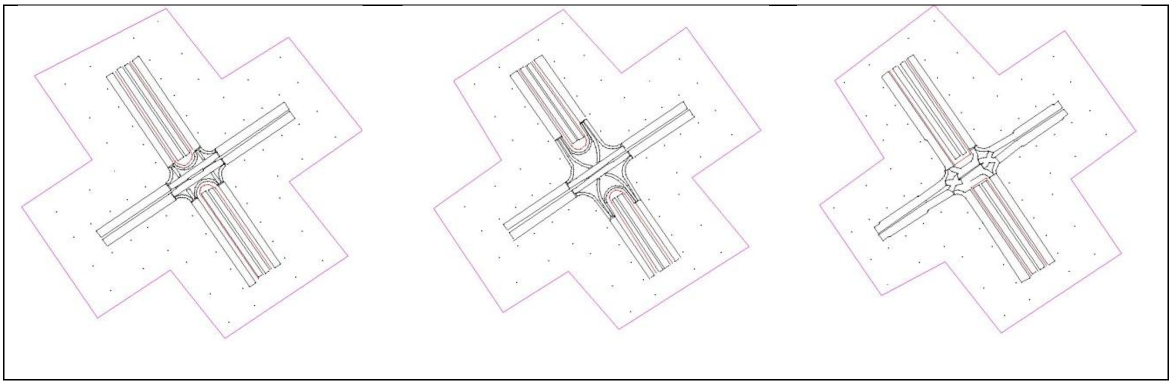

Figure 4-13: Traffic Noise Models (TUDI, SPUI, DDI)

4.5.3 *Vehicle Emissions Model*

In order to assess the impact of vehicular emissions generated at the interchanges, several studies and standards were reviewed and considered. According to the EPA standards and to previous studies (Sbayti, El-Fadel, & Kaysi, 2002), greenhouse gas emission rates were found as a function of several attributes such as vehicle speed, vehicle fleet characteristics, functional road class, type of fuel used, and weather conditions. It was decided to use the functions derived by Sbayti et. al. (2002) to estimate the emission levels on the different types of interchanges since they provide a good indicator of the effect changes in vehicle volumes and speeds have on emission rates.

Figure 4-10 shows the HC emission curves used to derive the scoring functions on criterion B3. Similarly, Figure 4-11 shows the CO emission curves to be used for scoring the criterion B3 for all interchange alternatives.

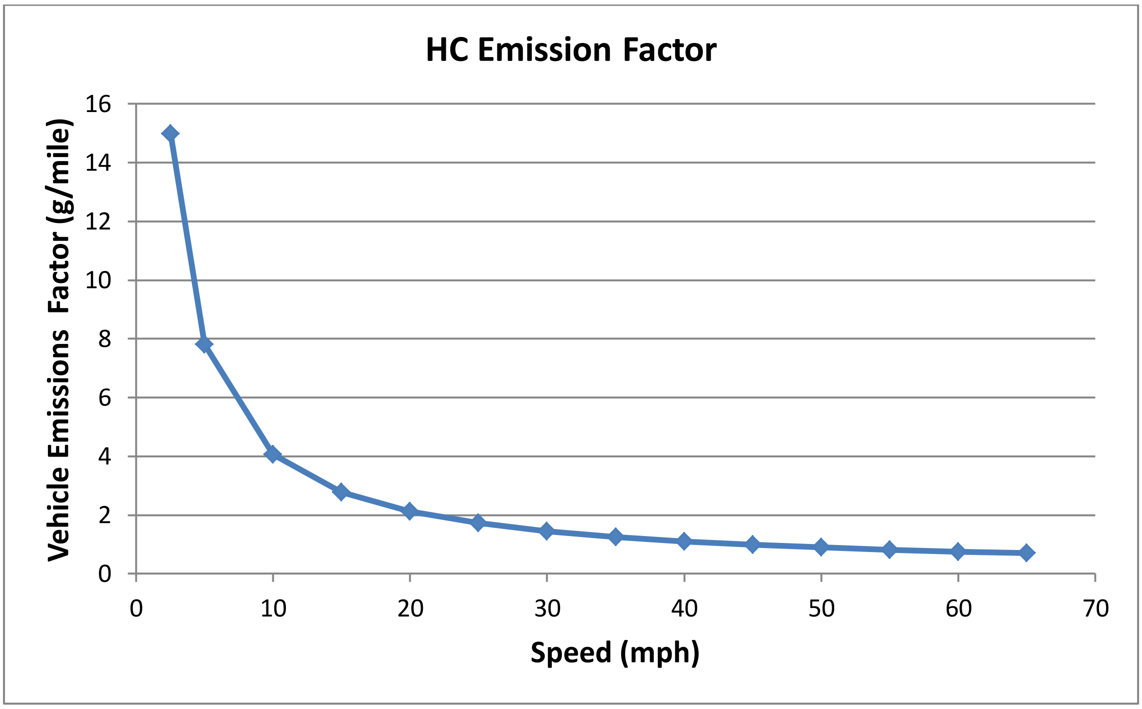

Figure 4-14: HC Emission Rate Function

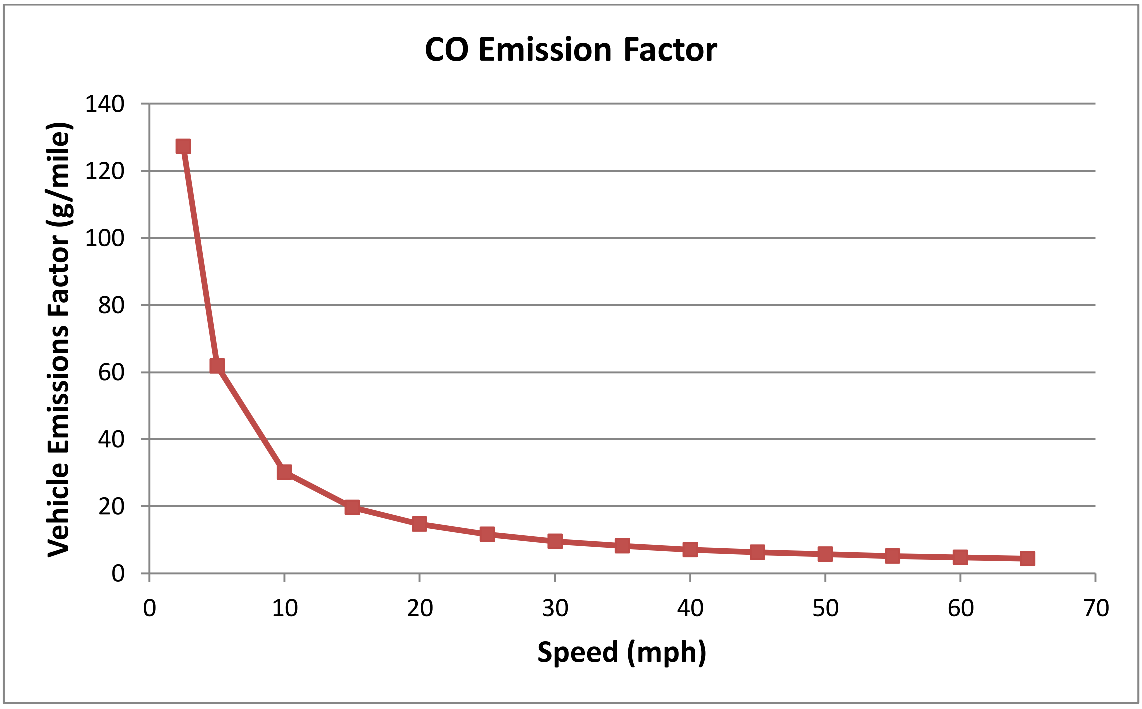

Figure 4-15: CO Emission Rate Function

4.6 Scoring the criteria

This section rates the performance of the interchange configurations based on the criteria used in the prioritization framework and scores them according to the scoring functions identified in section 4.4.

4.6.1 Intersection Delays (A1-1)

Criterion A1-1 measures the performance of the interchanges according to the projected intersection delays. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Load the VISSIM model for each of the alternatives.
2. In the "*Network Performance Measurement Results*" section, determine the delays observed at each of the interchanges.

Table 4-23 displays the intersection delay that was experienced at each of the interchanges along with the corresponding interchange scores on this criterion.

Table 4-23: Scoring A1-1

	TUDI	**SPUI**	**DDI**
Intersection Delay (sec/veh)	57.31	11.56	10.30
Score	0.91	3.84	3.97

These results are conforming to previous research whereby the DDI outperformed the other interchange types on this criterion while the TUDI performed the worst (Sharp et al., 2000; Jones et al., 2003; Afshar et al., 2009).

4.6.2 Average Delays for All Left-Turning Movements (A1-2)

Criterion A1-2 measures the performance of the interchanges according to the projected average delays for all left-turning movements. The following describes in detail the procedure followed in computing the score for this criterion.

1. Load the VISSIM model for each of the alternatives.
2. In the "*Delay Results*" section, determine the delays for the left-turning movements on all approaches.
3. Similarly, in the "*Delay Results*" section, determine the volumes of traffic for the left-turning vehicles only.

Subsequently, the average delay for all left-turning movements resulting from the implementation of any interchange type is determined.

4. The delay for the left-turning movements at each approach is then multiplied by the corresponding traffic volumes.
5. The average delays for the left turning movements are determined (weighted by volumes of left turning vehicles).

Equation 4-1 shows the formula used in computing the weighted average delay for all left-turning vehicles for each interchange type.

$$\text{Average Delay for All left-turning movements} = \frac{\sum_i (V_i \, x \, D_i)}{\sum_i (V_i)} \qquad (4\text{-}1)$$

Where V_i is the volume for the left-turning vehicles traversing the interchange from an approach i, D_i is the delay experienced for the left-turning vehicles from an approach i.

Table 4-24 shows the average delay for all left-turning movements at each of the interchanges and the corresponding scores on this criterion.

Table 4-24: Scoring A1-2

	TUDI	**SPUI**	**DDI**
Delay (sec/veh)	74.89	15.38	10.67
Score	0.20	3.46	3.93

Similar to the results of Siromaskul et al. (2008) and Guerrieri et al. (2013), the DDI and SPUI both excelled at handling left-turning movements whereas the TUDI experienced higher delays and consequently scored lower on this criterion.

4.6.3 Average Number of Stops (A2)

Criterion A2 evaluates the performance of the interchanges based on the percentage of stops of all vehicles within the network. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Load the VISSIM model for each of the alternatives.
2. In the "*Queue Results*" section, determine the number of vehicular stops for all movements on the signalized intersections.
3. In the "*Vehicle Travel Time Results*" section, determine the volume of traffic for each movement on the signalized intersections.

Subsequently, the percentage of stops is determined using the following equation.

$$\text{Percentage of stops} = \frac{\sum_i (\, S_i \text{ x } 100)}{\sum_i (V_i\,)} \qquad (4\text{-}2)$$

Where S_i is the number of vehicular stops observed at the signalized intersection for a traffic movement i, V_i is the hourly traffic volume at the signalized intersection for a traffic movement i.

Table 4-25 shows the percentage of stops for each of the interchanges and the corresponding scores on this criterion.

Table 4-25: Scoring A2

	TUDI	**SPUI**	**DDI**
% of Stops	104.06%	27.13%	35.40%
Score	2.40	4.32	4.12

When compared to previous research, these results are reasonable as the SPUI outperformed its interchange counterparts on this criterion and consequently scored higher (Sharp et al., 2000; Jones et al., 2003; Afshar et al., 2009).

4.6.4 Maximum Queue Length (A3)

Criterion A3 measures the performance of the interchanges based on the maximum queue length that is observed for all approaches at the peak hour. Below is a description of the procedure followed in computing the score for this criterion:

1. Load the VISSIM model for each of the alternatives.
2. In the "*Queue Results*" section, determine the maximum queue length that was observed on all traffic movements.

Table 4-26 shows the maximum queue length that was observed for each of the interchanges and the corresponding scores on this criterion.

Table 4-26: Scoring A3

	TUDI	**SPUI**	**DDI**
Maximum Queue Length (m)	129.10	52.03	46.82
Score	2.42	3.96	4.06

The results of this case study showed that the DDI outperformed the SPUI and TUDI and consequently scored higher on this criterion. These results are conforming to the previous research as the DDI was found to be the most preferred interchange type when considering the operational performance of each interchange (Chlewicki, 2003; Bared et al., 2005; Sharma et al., 2007; Jones et al., 2003; Afshar et al., 2009; Guerrieri et al. 2013).

4.6.5 Average Pedestrian Waiting Time at Signalized Intersections (A4-1)

Criterion A4-1 measures the performance of the interchanges based on the pedestrians’ waiting time at signalized intersections. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Load the SYNCHRO model for each of the alternatives.
2. Determine the optimized signal timing plans at each of the signalized intersections.
3. Identify the origin and destination points for the pedestrians to cross the interchanges. The considered pathway reflects the most critical crossing movement at the signalized intersection; i.e. diagonally between the opposite edges of the arterial crossing road.
4. For consistent analysis, the starting and ending points were to be taken the same for all interchange configurations, as denoted by points A and B in Figures 4-12, 4-13, and 4-14.
5. For each of the alternatives, identify the number of crossing phases and the corresponding waiting time. This results in:
    1. Four-stage crossing phase to handle the pedestrian needs at TUDI configuration. Figure 4-12 displays the locations of the signal phases as denoted by W1, W2, W3, and W4.
    2. Four-stage crossing phase to handle the pedestrian needs at SPUI configuration. Figure 4-13 displays the locations of the signal phases as denoted by W1, W2, W3, and W4.
    3. Three-stage crossing phase to handle the pedestrian needs at DDI configuration. Figure 4-14 displays the locations of the signal phases as denoted by W1, W2, and W3.

Table 4-27 shows the waiting time needed for pedestrians to cross each of the interchanges and the corresponding scores on this criterion.

Table 4-27: Scoring A4-1

	TUDI	SPUI	DDI
Waiting Time (sec)	50.00	36.50	20.00
Score	0.50	1.35	3.00

Figures 4-12 to 4-14 show the pedestrian pathways highlighted in dark blue at the different interchange types: TUDI, SPUI, and DDI.

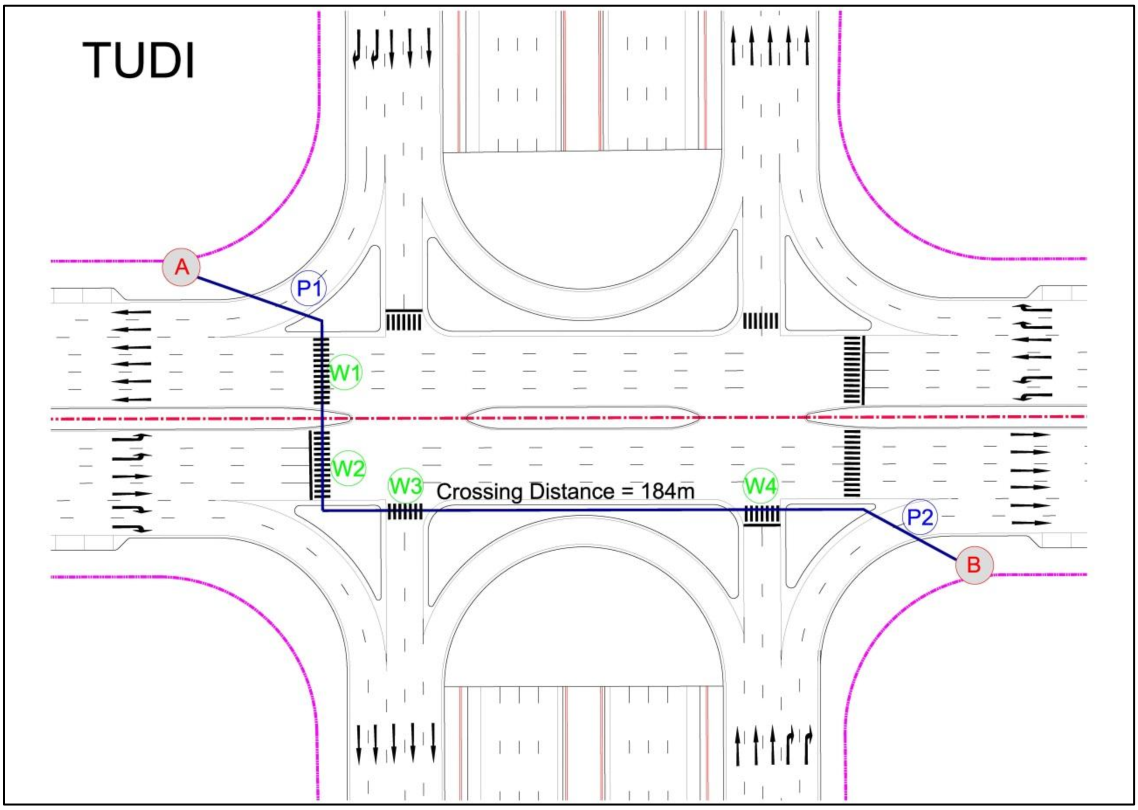

Figure 4-16: Accommodation of Pedestrian Crossings (TUDI)

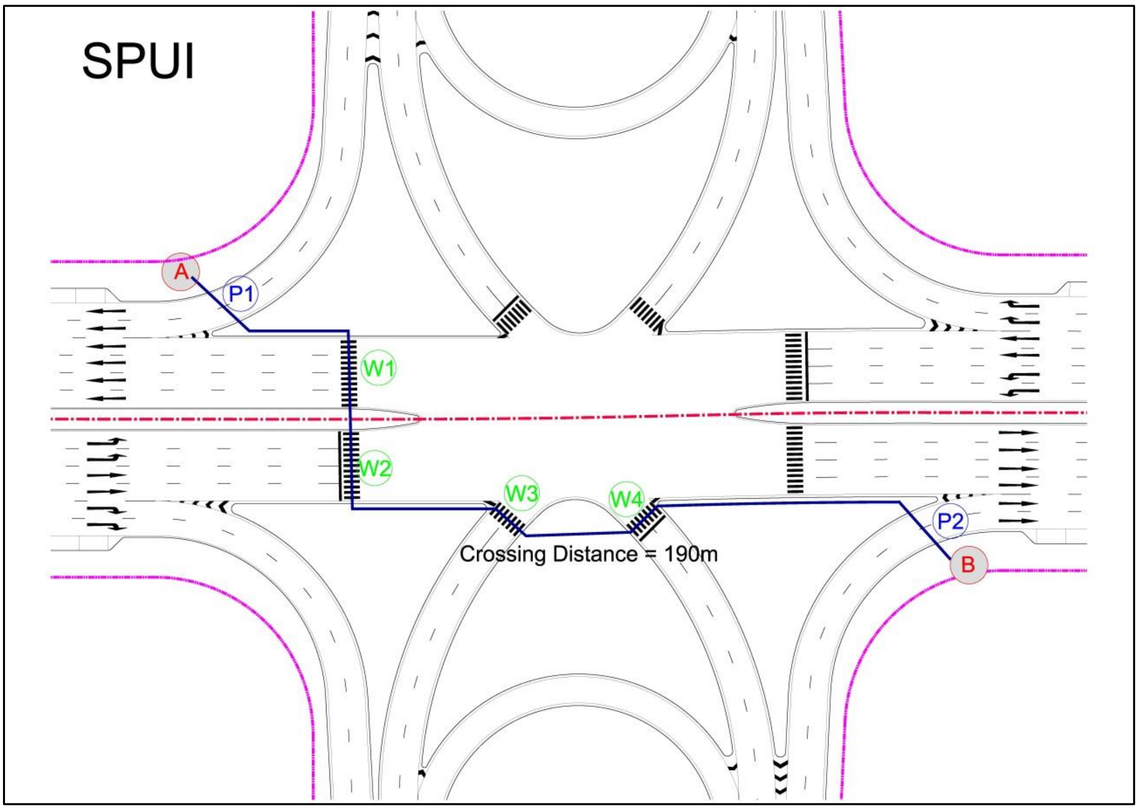

Figure 4-17: Accommodation of Pedestrian Crossings (SPUI)

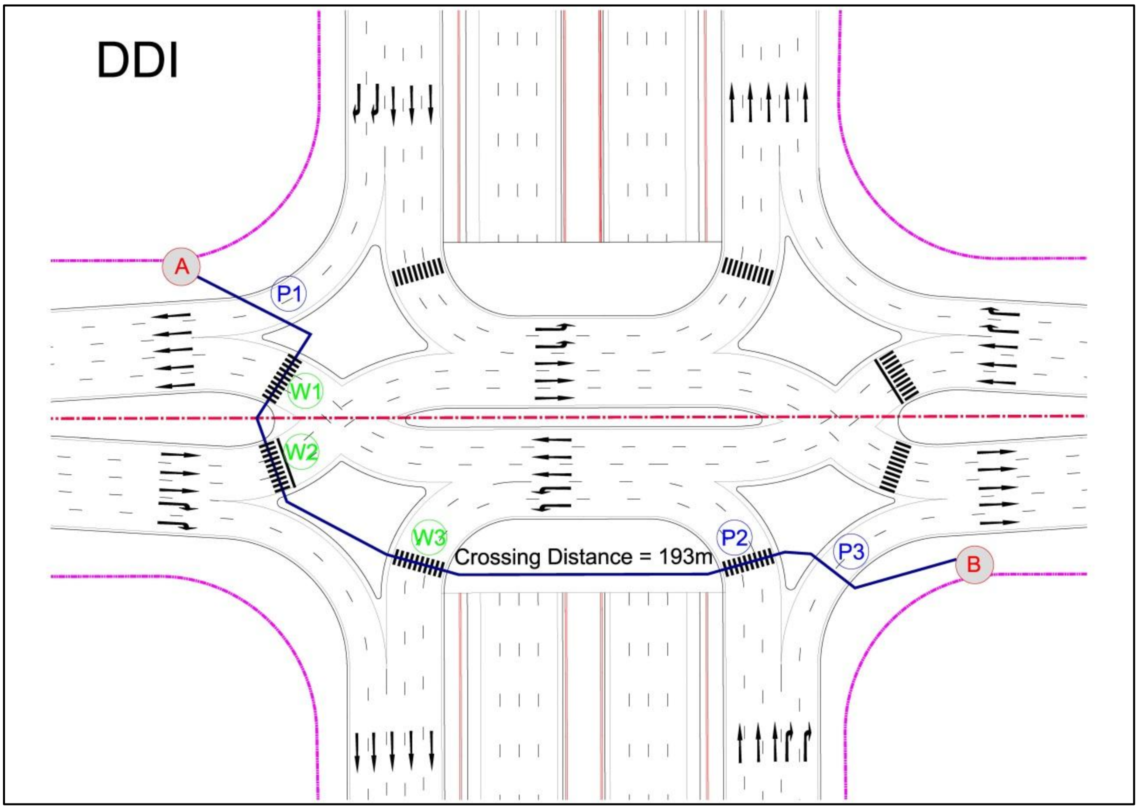

Figure 4-18: Accommodation of Pedestrian Crossings (DDI)

4.6.6 Presence of Conflicting Protected Traffic (A4-2)

Criterion A4-2 rates the performance of the interchanges to the extent of the presence of conflicting protected traffic. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Identify the origin and destination points for the pedestrians to cross the interchanges. The considered pathway reflects the most critical crossing movement at the signalized intersection; i.e. diagonally between the opposite edges of the arterial crossing road.
2. For consistent analysis, the starting and ending points to be taken the same for all interchange configurations, as denoted by points A and B in Figures 4-12, 4-13, and 4-14.
3. Load the VISSIM model for each of the alternatives.
4. In the "*Vehicle Travel Time Results*" section, determine the hourly volume of protected traffic that conflicts with the crossing of pedestrians.

Figures 4-12 to 4-14 display the traffic flow that may conflict the pedestrian crossings. The locations of the traffic flow are denoted by P1, P2, and P3.

Table 4-28 shows the conflicting protected traffic volumes at each of the interchanges and the corresponding scores on this criterion.

Table 4-28: Scoring A4-2

	TUDI	**SPUI**	**DDI**
Conflicting Protected Traffic (veh/hr)	477.00	473.00	546.00
Score	3.81	3.82	3.46

4.6.7 Pedestrian Crossing Distance (A4-3)

Criterion A4-3 evaluates the performance of the interchanges based on the distance covered by the pedestrians in crossing the interchange. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Identify the origin and destination points for the pedestrians to cross the interchanges. The considered pathway reflects the most critical crossing movement at the signalized intersection; i.e. diagonally between the opposite edges of the arterial crossing road.
2. For consistent analysis, the starting and ending points to be taken the same for all interchange configurations, as denoted by points A and B in Figures 4-12, 4-13, and 4-14.
3. Measure the distance needed by the pedestrians to cross the interchange from origin point A to destination point B.

Table 4-29 shows the crossing distance needed by the pedestrians to cross each of the interchanges and the corresponding scores on this criterion.

Table 4-29: Scoring A4-3

	TUDI	**SPUI**	**DDI**
Crossing Distance (m)	184	190	193
Score	2.64	2.40	2.28

Similar to other previous research, the SPUI was found not to accommodate the pedestrian crossings effectively as the crossing distance and average pedestrian waiting time were not found to be the best among all interchanges (Quereshi et al., 2004). The TUDI was found to be the most preferred based on the crossing distance criterion; the DDI outperformed the other interchange types on the pedestrian waiting time, and all interchange types experienced relatively the same conflicting protected traffic.

4.6.8 Accessibility Impact on Existing Economic Activities (B1)

Criterion B1 rates the performance of the interchanges based on the accessibility impacts they impose on the existing economic activities. Below is a description of the procedure followed in computing the score for this criterion:

1. Determine if the interchange accommodates a continuity of through traffic along the ramps. As such, the TUDI configuration receives a score of "2" on scheme 1 whereas the remaining configurations receive a score of "0).
2. For each of the alternatives, determine the dead zones imposed by the interchange configuration that may impact the accessibility to existing economic activities.
3. Measure the length of the dead zones at all four edges of the intersections.
4. Accumulate the measured distances on all edges for each interchange.

Table 4-30 shows the measured distances at the dead zones for each of the alternatives and indicates whether the interchange accommodates through traffic or not. The table includes as well the interchange scores on this criterion. The TUDI outperformed the other interchanges while the DDI ranked second on this criterion.

Table 4-30: Scoring B1

	TUDI	**SPUI**	**DDI**
Accommodation of through traffic	Yes	No	No
Dead Zone Distance	101.12	371.00	98.72
Score	4.24	0.22	2.26

Figures 4-15 to 4-17 display the dead zones (highlighted in yellow) at the different interchange configurations.

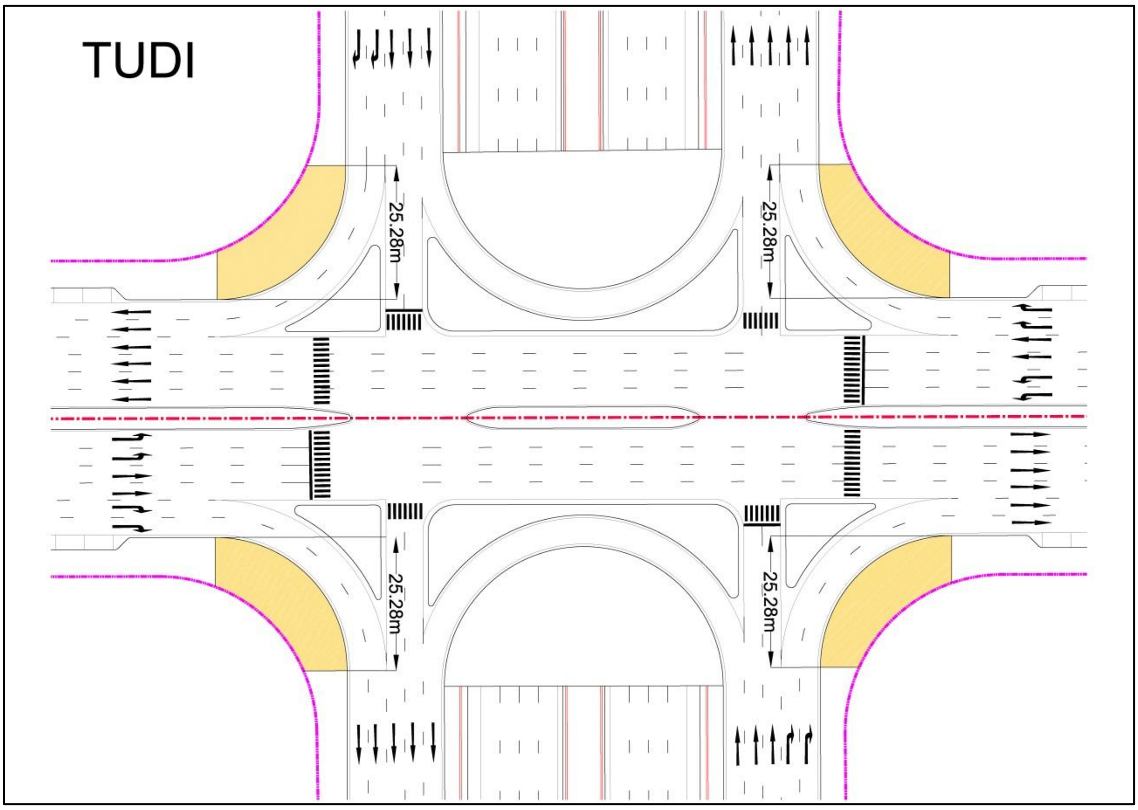

Figure 4-19: Accessibility Impacts (TUDI)

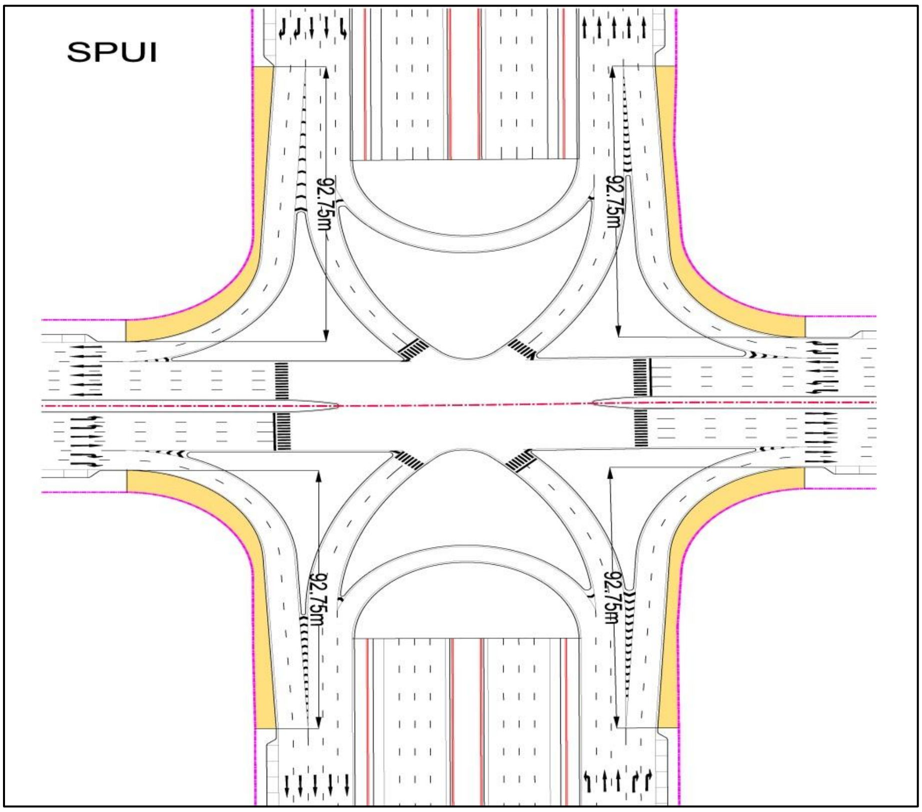

Figure 4-20: Accessibility Impacts (SPUI)

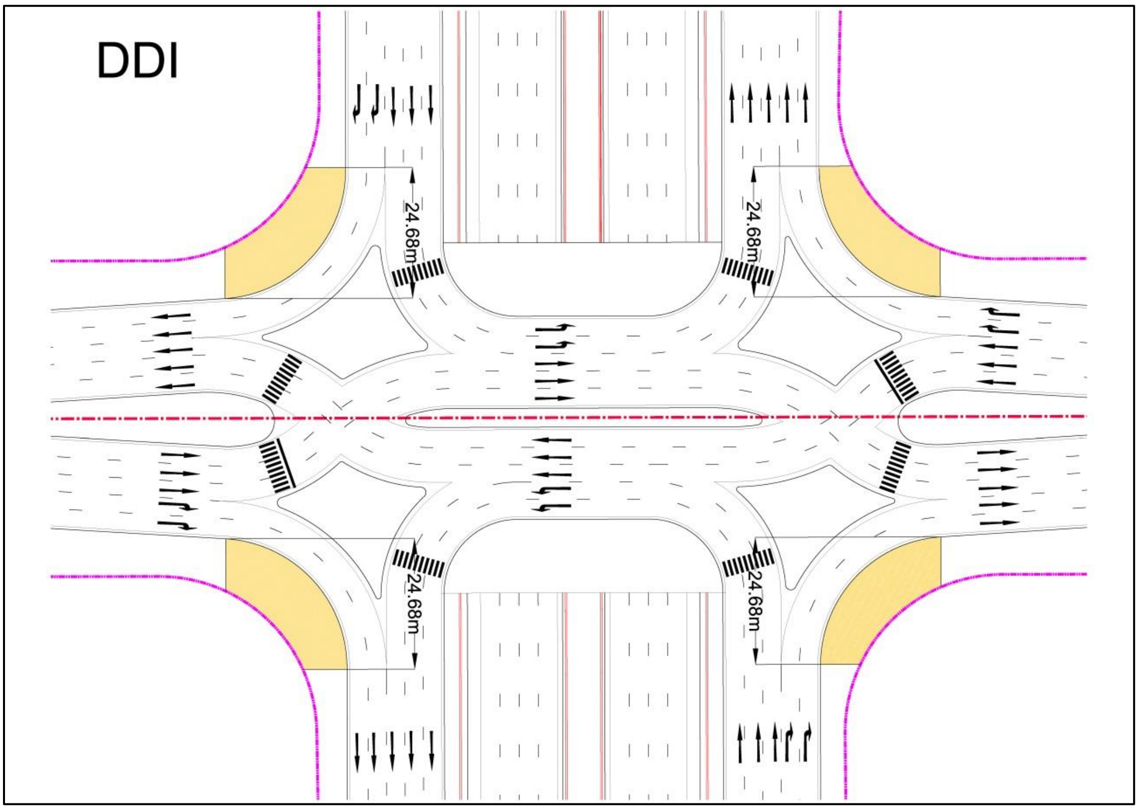

Figure 4-21: Accessibility Impacts (DDI)

4.6.9 Noise (B2)

Criterion B2 evaluates the performance of the interchanges based on the generated noise levels. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Load the Traffic Noise Model for each of the alternatives.
2. Determine the sound levels generated by the interchanges and create the related sound contours. (Refer to Figures 4-18, 4-20, and 4-22)
3. Identify the zone for which the generated sound levels are to be checked with the Noise Abatement Criteria. This zone should include at least one set of building plots and shall extend till the ramps merge with the highway.

4. As such, a 50 meter offset distance is needed from the road edge to include at least a building plot/parcel.
5. Similarly, a 250 meter distance is needed between the ramp terminals at the signalized intersections and the gore areas on the main highway. This is due to the grade separated intersection whereby a distance of 250 meters is needed to maintain the same grade levels between the ramps and the main highway; thus the on-ramps are depressed or elevated to merge with the highway. Similarly, the off-ramps can diverge from the highway and get elevated or depressed to reach the intersection level.
6. On the crossing road, a 250 meter buffer zone is created to conduct a similar analysis.
7. Using the generated sound contours and the defined interest zone, identify the areas having sound levels exceeding the criteria requirements (sound level greater than 72 dBA).

Subsequently, the percentage of area having noise levels greater than 72 dBA is determined using the following equation.

$$\text{Percentage of Area} = \frac{\sum_i (\,AN_i \text{ x } 100)}{\sum_i (AT_i\,)} \tag{4-3}$$

Where AN_i is the area within the defined zone having noise levels exceeding the noise abatement requirements computed at each side of the interchange and AT_i is the total area of the defined zone computed at each side of the interchange.

Figures 4-18, 4-20, and 4-22 illustrate the generated sound levels at the interchanges.

Figures 4-19, 4-21, and 4-23 display the areas within the defined zone that have sound levels greater than the requirements specified by the FHWA.

Table 4-31 shows the percentage of the areas having sound levels exceeding the noise abatement criteria requirements. The table includes as well the interchange scores on this criterion. The TUDI ranked first on this criterion as the percentage of area with noise levels exceeding the requirements was found to be the least. SPUI ranked second followed by the DDI.

Table 4-31: Scoring B2

	TUDI	**SPUI**	**DDI**
% Area (Noise Level > 72 dBA)	31%	48%	50%
Score	3.47	2.60	2.49

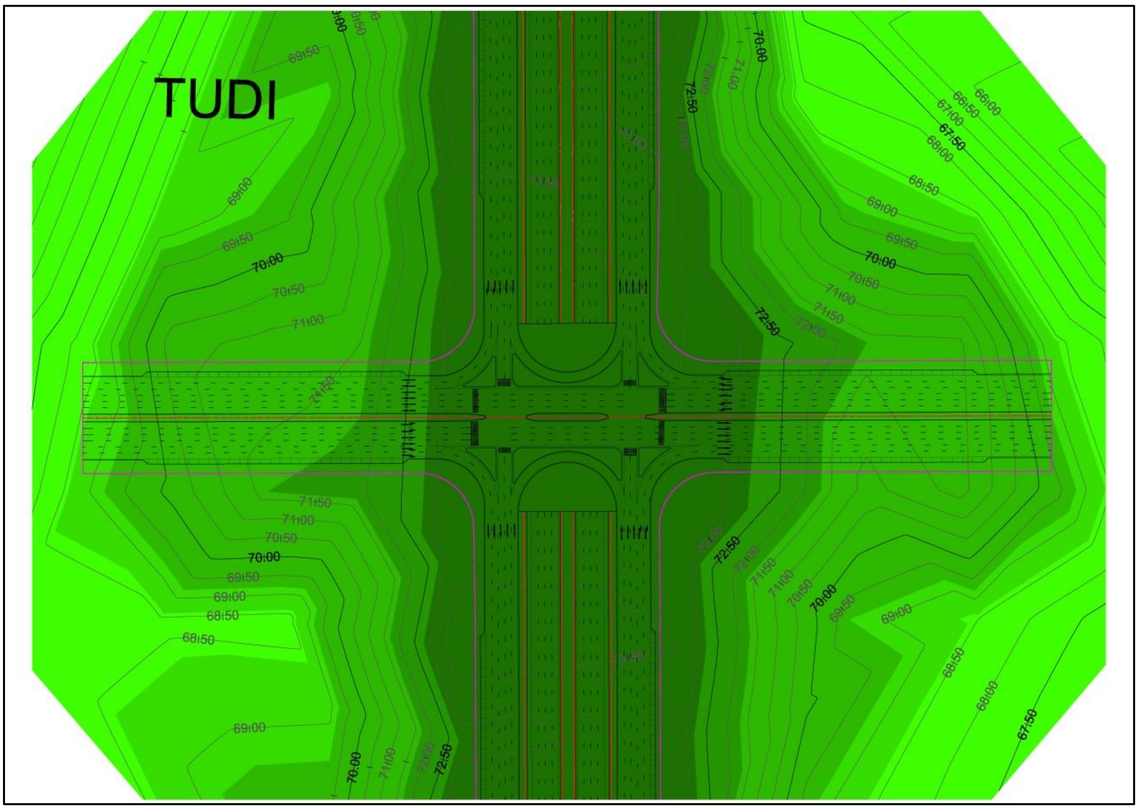

Figure 4-22: Sound Level Contours (TUDI)

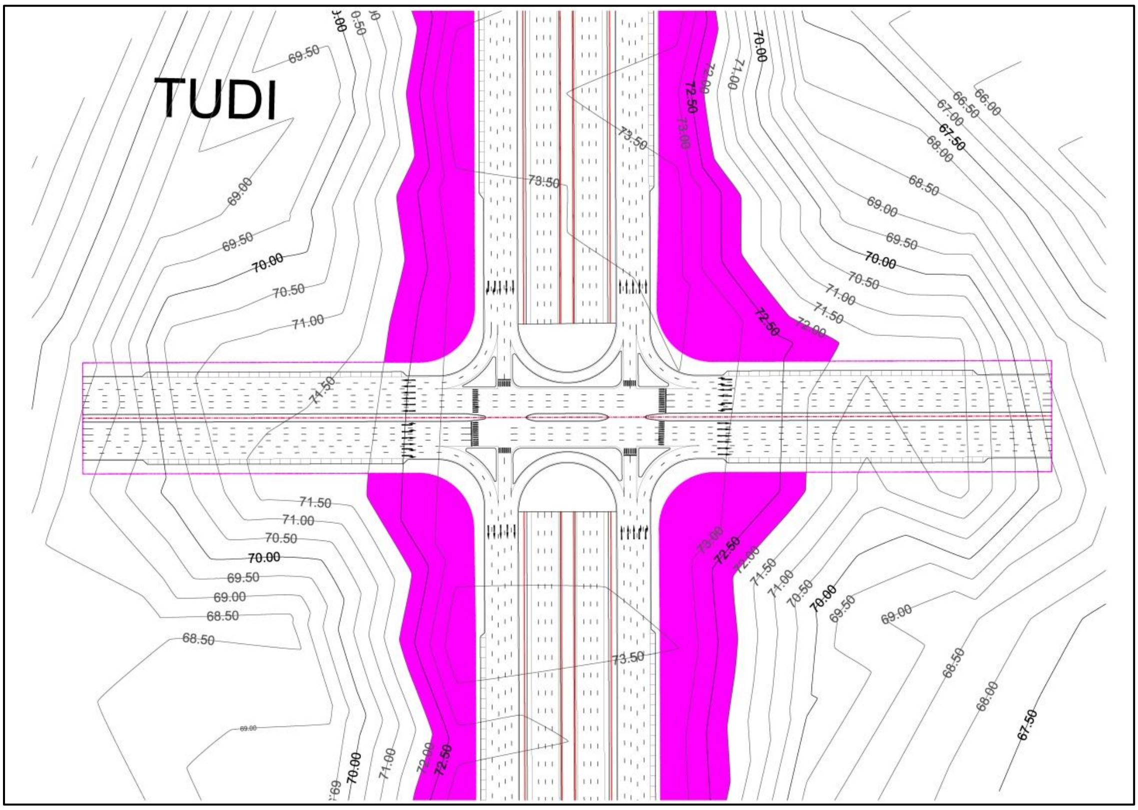

Figure 4-23: Sound levels higher than the requirements (TUDI)

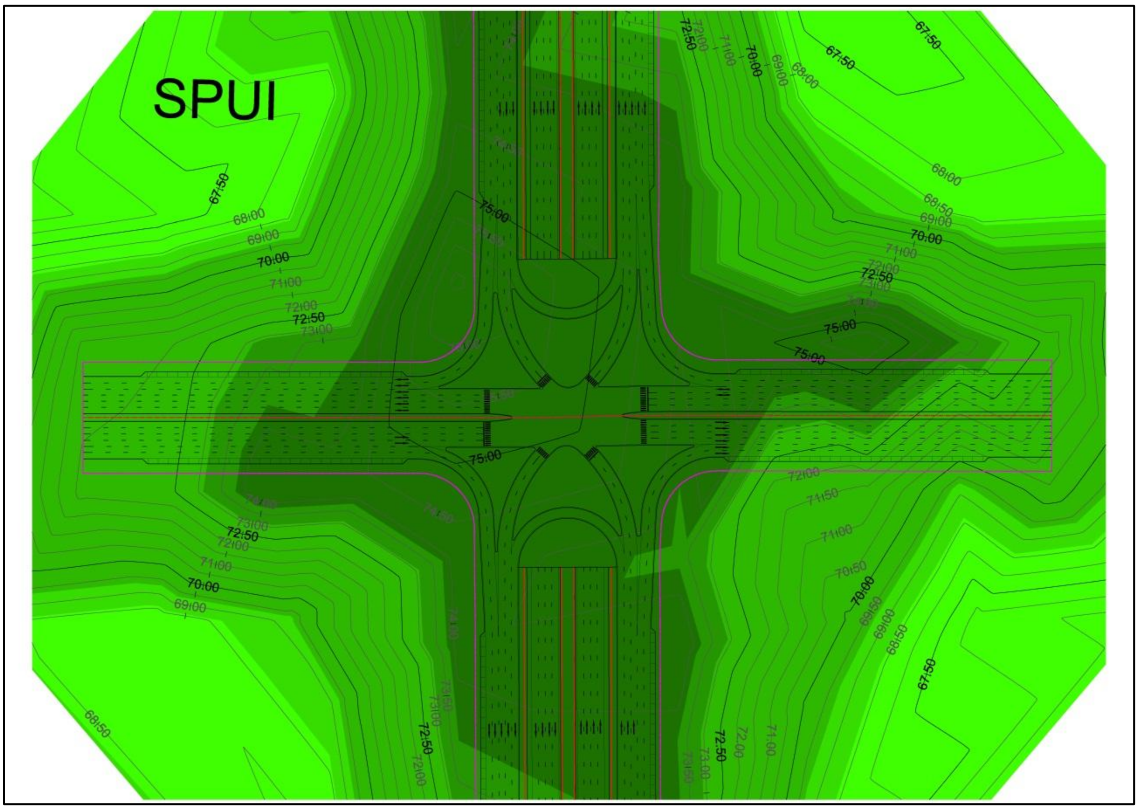

Figure 4-24: Sound Level Contours (SPUI)

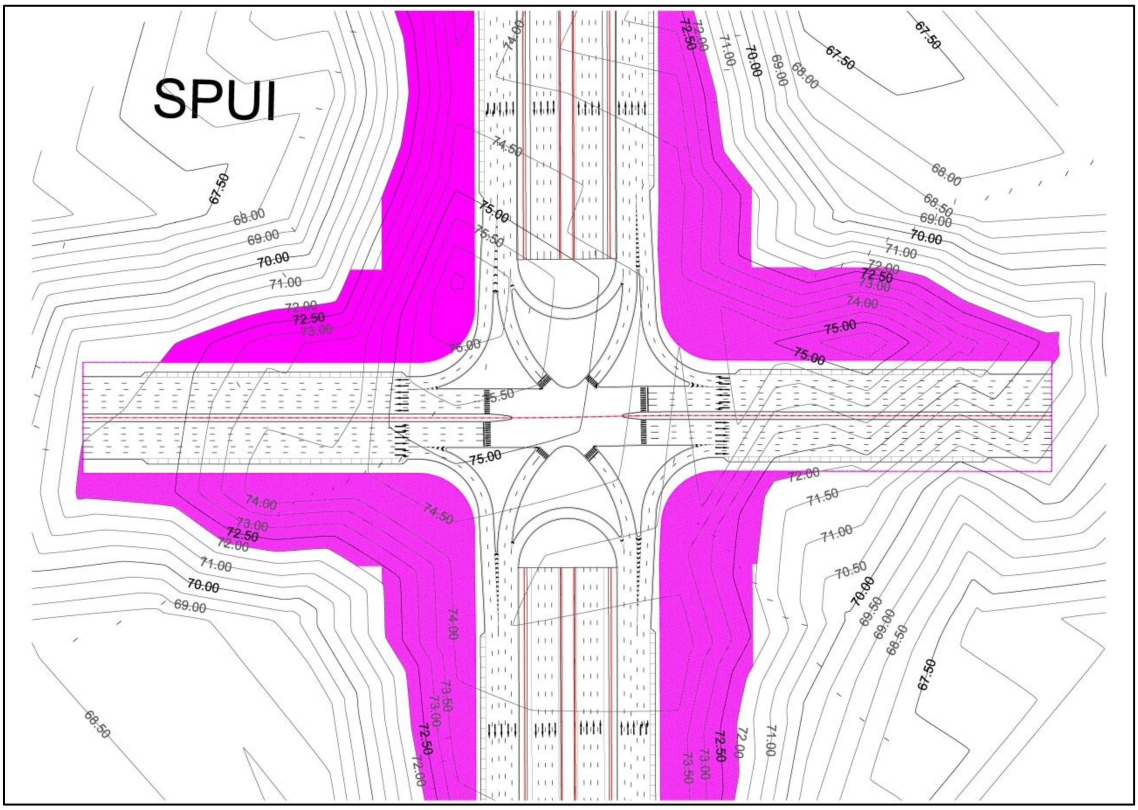

Figure 4-25: Sound levels higher than the requirements (SPUI)

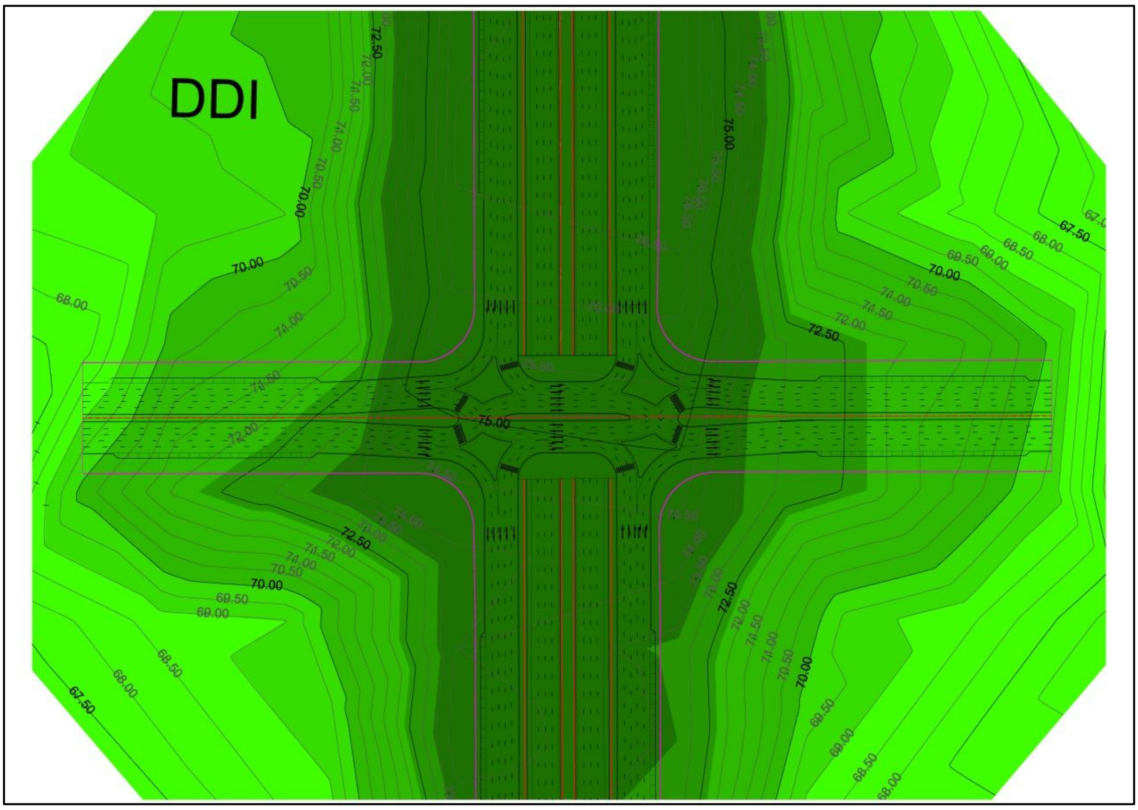

Figure 4-26: Sound Level Contours (DDI)

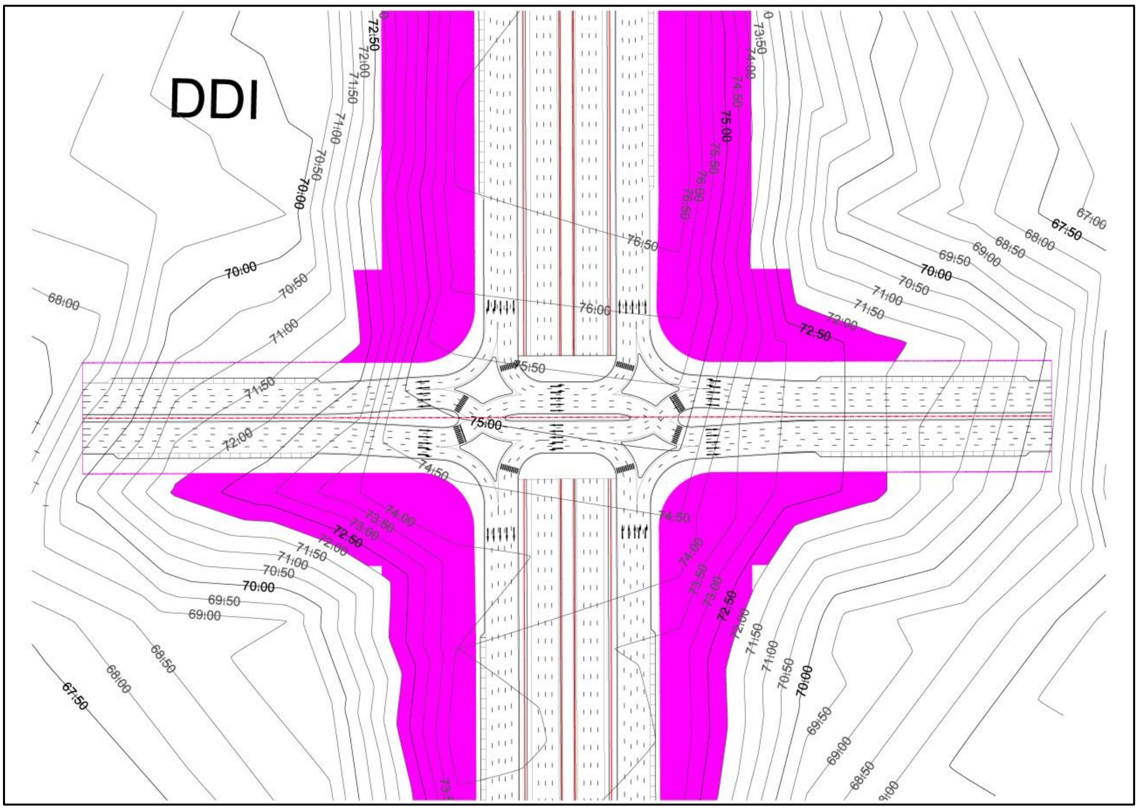

Figure 4-27: Sound levels higher than the requirements (DDI)

4.6.10 Vehicle Emissions (B3)

Criterion B3 evaluates the performance of the interchanges according to the vehicular emissions of greenhouse gases, mainly HC and CO gases. Below is a description of the procedure followed in computing the score for this criterion:

1. Load the VISSIM model for each of the alternatives.
2. In the "*Link Segment Results*" section, export the instantaneous speed, and traffic volumes for all links having segment lengths of 10 meters. The exported data shall include the simulation results for every 30 seconds.
3. Determine the vehicle-miles traveled by multiplying the length of the segments by the demand volumes present at related links.
4. For each of the greenhouse gases, determine the emission factors using the curve functions shown in Figure 4-10 (HC Emissions) and Figure 4-11 (CO Emissions).
5. Determine the HC and CO gas emissions using the following equation:

$$E_T = \sum_i (EF_i \text{ x } VMT_i) \qquad (4\text{-}4)$$

Where E_T is the total emissions (grams), EFi is the emission factor (g/vehicle-mile) computed for each segment, VMTi is the vehicle-miles traveled at each link for the peak hour.

Table 4-32 shows the greenhouse gas emissions (HC and CO gases) generated at each interchange. The table includes as well the interchange scores on this criterion. As shown below, both DDI and SPUI performed well on this criterion whereas the SPUI generated more emissions and consequently scored lower.

Table 4-32: Scoring B3

	TUDI	SPUI	DDI
HC Emissions (g/hr)	1,888.71	1,303.52	1,299.00
CO Emissions (g/hr)	14,346.72	8,461.26	8,355.90
Score	2.92	3.66	3.67

4.6.11 Total Travel Time Savings (C1-1)

Criterion C1-1 measures the performance of each of the alternatives according to the savings in travel time costs that these interchanges can potentially result in. The following gives a step by step description of the procedure followed in scoring this criterion:

1. Load the VISSIM model for each of the interchange alternatives and the at-grade intersection.
2. In the "Network Performance Measurement *Results*" section, determine the total travel time incurred by all vehicles travelling through the interchanges.
3. The reductions in travel times resulting from the implementation of any of the interchanges is determined using the following equation:

$$\text{Percentage of Travel Time Savings} = \frac{(TT_{at-grade} - TT_i)\ x\ 100}{TT_{at-grade}} \tag{4-5}$$

Where $TT_{\text{at-grade}}$ is the total travel time incurred by the vehicles on the at-grade signalized intersection, and TT_i is the total travel time incurred by the vehicles at an interchange i.

Table 4-33 shows the percentage of travel time savings for each interchange. The table includes as well the interchange scores on this criterion. Both DDI and SPUI resulted in high travel time savings whereas the TUDI had lower savings and thus it was assigned a lower score.

Table 4-33: Scoring C1-1

	TUDI	**SPUI**	**DDI**
% Travel Time Savings	66.18%	74.01%	74.16%
Score	1.62	2.40	2.42

4.6.12 Vehicle Operating Cost Reductions (C1-2)

Criterion C1-2 ranks the performance of the interchanges according to the savings in vehicle operating costs that these interchanges can result in. Below is a description of the procedure followed in computing the score for this criterion:

1. Load the VISSIM model for each of the alternatives.
2. In the "*Link Segment Results*" section, export the instantaneous speed, and traffic volumes for all links having segment lengths of 10 meters. The exported data shall include the simulation results for an interval of 30 seconds.
3. Assuming a traffic composition of 2% for Medium Trucks and 98% for passenger cars, determine the traffic volumes at each segment link.
4. At signalized intersections, the vehicle operating costs are primarily dependent on the speed of vehicles; accordingly, the VOCs are derived and are used similar to the Beirut peripherique feasibility study as shown in equation (4-6). This equation does not reflect the absolute values of vehicle operating costs but is rather meant to reflect the relative changes in VOCs with respect to the changes in speed and transport modes.

$$\text{Vehicle Operating Costs} = C_1 + [\, C_2 \; x \exp \; (-C_3 \; x \; V_i)] \qquad (4\text{-}6)$$

Where the vehicle operating costs are calculated in dollars per thousand kilometers, V_i is the average speed of vehicles (kph) at a link segment i, and the remaining coefficients represent parameters specific to the vehicle types, as follows:

a. C1 = 120.662 for passenger cars; C1 = 457.152 for Medium Trucks.

b. C2 = 284.828 for passenger cars; C2 = 959.999 for Medium Trucks.

c. C3 = 0.083 for passenger cars; C3 = 0.095 for Medium Trucks.

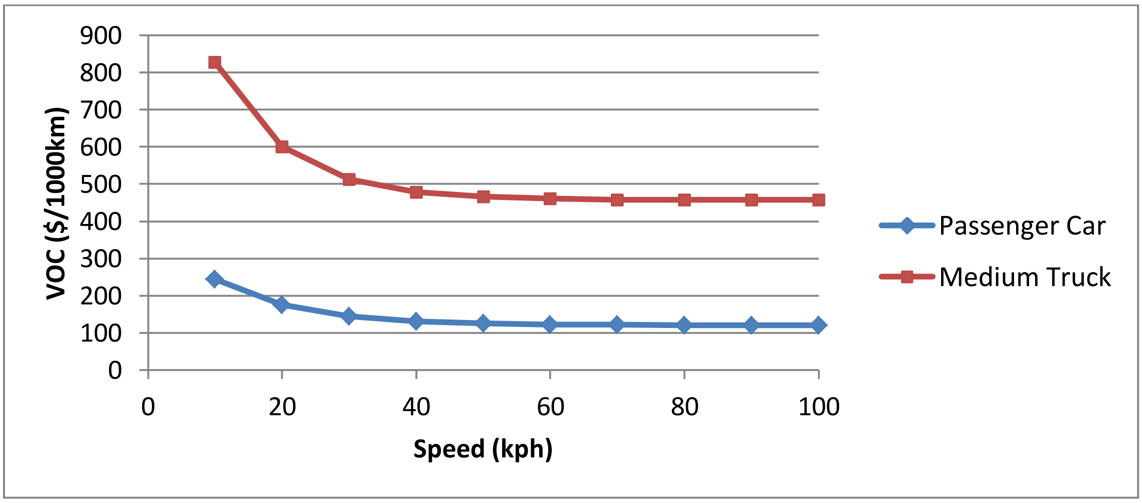

Figure 4-28: Vehicle Operating Costs for Passenger Car and Medium Truck

Using equation (4-6), the above figure displays for each transport mode the changes of vehicle operating costs with respect to speed. It can be inferred that the vehicle operating costs are much higher for medium trucks than they are for passenger cars. It is also interesting to note that each of the modes results in an approximately similar VOC for speeds greater than 40 kph. Below this speed, the VOCs increase at a higher pace to reach beyond $800 per 1000 km for medium trucks and more than $200 per 1000 km for passenger cars at very low speeds.

5. The reductions in vehicle operating costs resulting from the implementation of the interchange is determined using the following equation:

$$\text{Percentage of VOC Reductions} = \frac{(VOC_{at-grade} - VOC_i)\ x\ 100}{VOC_{at-grade}} \qquad (4\text{-}7)$$

Where $VOC_{at\text{-}grade}$ is the vehicle operating costs incurred by the vehicles on the at-grade signalized intersection, and VOC_i is the vehicle operating cost incurred by the vehicles at a link segment i.

Table 4-34 shows the percentage of VOC reductions at each interchange. The table includes as well the interchange scores on this criterion. Almost all interchanges resulted in similar VOC reductions and thus they were assigned similar scores.

Table 4-34: Scoring C1-2

	TUDI	**SPUI**	**DDI**
% VOC Reductions	54.54%	55.47%	52.05%
Score	2.73	2.77	2.60

4.6.13 Construction Costs (C2-1)

Criterion C2-1 measures the performance of the interchanges according to their construction costs. According to a study prepared by SETS to undertake the design of primary roads in Riyadh, KSA, it was found that the concrete and steel structural works contributed to the highest cost percentage among the different construction works, such as: earthwork, bituminous construction, incidental construction, roadway lighting, and traffic control devices. This high percentage, which exceeded 60%, is primarily due to the high cost of bridge structure that is needed to span the central intersection.

Due to the high cost percentage and the role of the bridge structures in determining the construction costs as the cost of other components were found to be relatively similar for all three interchange types, it was decided to compare the cost of constructing the interchanges based on the bridge structures only. To compute the bridge structure costs, the following is applied:

1. Determine the area of the bridge structure that is needed to span the central intersection. Figures 4-25 to 4-27 display the dimensions of the bridge structures at each of the interchanges.
2. Accordingly, the construction costs of the bridge structure is computed using the following equation:

$$\text{Construction Costs} = Bridge\ Area_i\ x\ 2133 \qquad (4\text{-}8)$$

Where the construction cost is in dollars, Bridge Area$_i$ is measured in m^2 for each interchange and 2133 represents the unit cost in dollars per square meter of bridge area; this is equivalent to 8,000 Saudi Riyals, which is a common cost for bridge structures used in the Gulf and Kingdom of Saudi Arabia in particular.

Table 4-35 shows the estimated construction cost (Bridge structure) required for each interchange configuration and the corresponding scores on this criterion. The DDI resulted in the lowest construction costs unlike the SPUI that scored the least due to its wide central intersection and large bridge structure. These results are conforming to previous studies that have considered the SPUI as the most expensive interchange type (Chlewicki, 2003).

Table 4-35: Scoring C2-1

	TUDI	**SPUI**	**DDI**
Cost ($)	10,240,917.33	16,788,181.33	6,706,112.00
Score	2.44	0.80	3.32

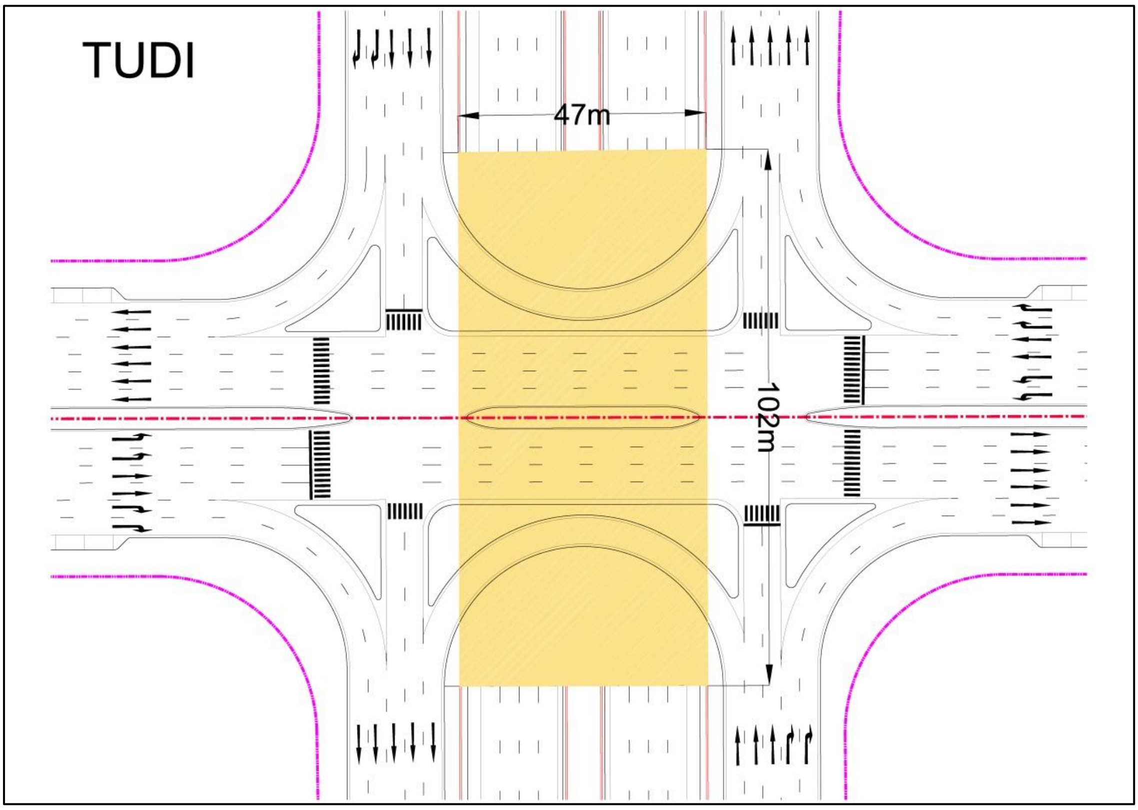

Figure 4-29: Bridge Structure (TUDI)

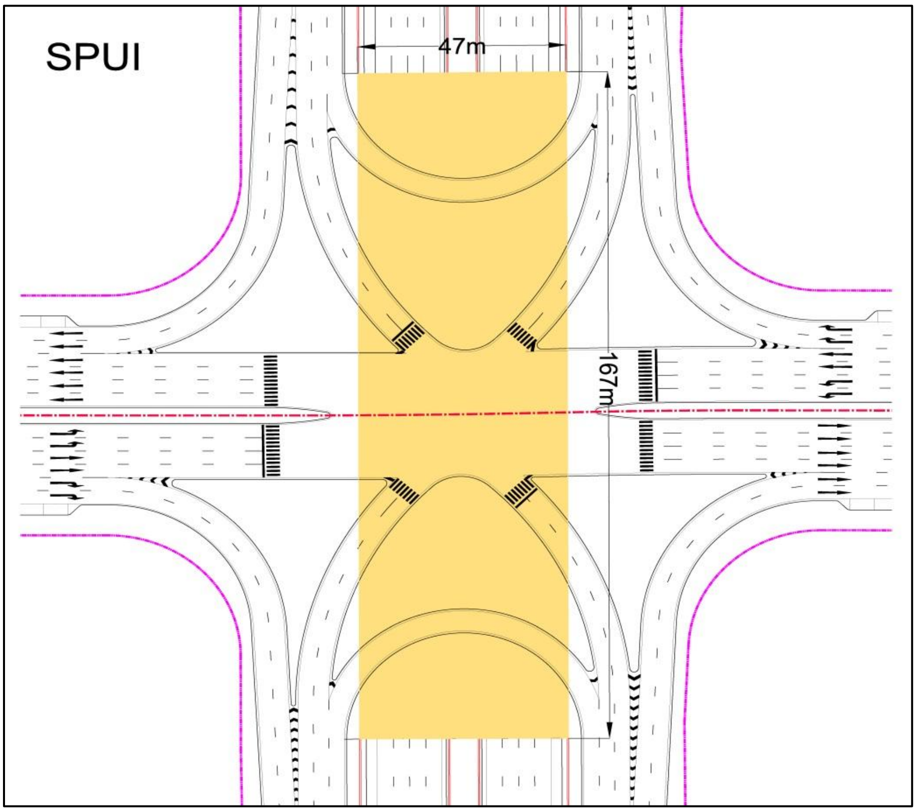

Figure 4-30: Bridge Structure (SPUI)

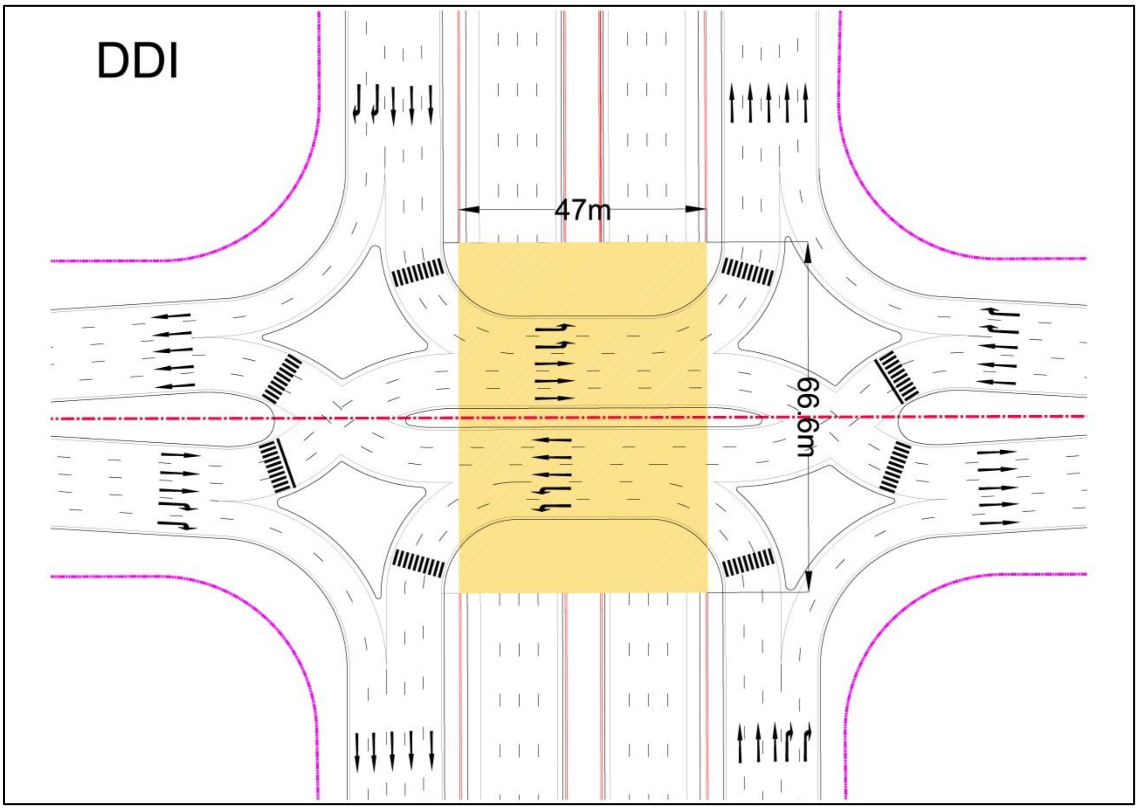

Figure 4-31: Bridge Structure (DDI)

4.6.14 *Right-of-Way Costs (C2-2)*

Criterion C2-2 ranks the performance of the interchanges according to their Right-of-Way acquisition costs. These costs are estimated by multiplying the area needed to accommodate the interchange properly by a unit price. In order to compare the right-of-way costs of the different interchange configurations, the area of each should be computed after defining the extent of its limits.

This limit is bounded 250 meters downstream the ramp terminals; hence it extends to reach the gore areas adjacent to the main highway. Similarly, on the crossing arterial road, a 250 meter buffer distance is needed to tie in with the natural ground level.

Table 4-36 shows the area needed to properly accommodate the different interchange configurations and their corresponding scores on this criterion. All three interchanges were found to have similar right-of-way; thus, all were assigned similar scores.

Table 4-36: Scoring C2-2

	TUDI	**SPUI**	**DDI**
Area (m2)	63,469	66,980	61,837
Score	0.77	0.53	0.88

4.6.15 Crash Frequency Experience (D1)

Criterion D1 measures the performance of the interchanges based on their record of crash frequencies. In order to populate this criterion for the three interchanges, crash statistical data is needed to analyze the crash frequency/rate at the considered interchanges. To do so, a number of academics and individuals at FHWA and at State Departments of Transportation (such as USDOT, MoDOT, VDOT, IDOT, MDOT, UDOT, and others) were contacted to collect statistical data such as: (i) Total Crashes, (ii) Number of Injuries/ Fatal Crashes (iii) Average Annual Daily Traffic on cross streets and ramps, and (iv) years of statistical data. Despite the numerous people contacted, no relevant data was available due to the following:

- At the time of writing, no statistical data was available for the DDI due to its recent introduction and its first implementation (June 2009) in the United States.
- For the other interchange configurations, the U.S. law requires the state agencies to make public records (including statistical crash data) available to American citizens only.
- The requested information was considered to be intensive as it involves a great deal of time for the different DOT's staff to complete. For instance,

the MoDOT opted not to assist with this research as it is currently beyond its interest.

- The only type of information that can be made available is on fatal crashes as it comes from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS). However, the level of refinement within the FARS database is limited to identifying the location of the crash within the interchange and does not include information regarding the configuration or characteristics of the interchange.

Due to the unavailability of sufficient data, all interchange types were given a default score of "1" on this criterion.

4.6.16 Potential Driver Confusion (D2-1)

Criterion D2-1 evaluates the performance of the interchanges based on the potential driver confusion that might arise while traversing the interchanges. Three different schemes were used to evaluate the driver confusion. Only the DDI was found to have an undefined path in between the ramp terminals and thus it receives a score of "0" on the first schemes while the other two types score "1.5". As for the intersection area, the SPUI has been found to have a wide central intersection; thus, the possibility of drivers to get confused along their way is high; hence it automatically receives a score of "0" unlike the other interchange types. Finally, due to the reversal in traffic movement that is only featured in the DDI, a score of "0" has been assigned.

Table 4-37 summarizes the performance of the three interchange configurations based on the potential driver confusion that may arise and indicates the corresponding scores on this criterion.

Table 4-37: Scoring D2-1

	TUDI	**SPUI**	**DDI**
Defined Path	Yes	Yes	No
Intersection Area	Compact	Wide	Compact
Traffic Movement	Direct	Direct	Reversal
Score	5.00	3.50	2.00

The TUDI outperformed the other interchanges on this criterion. This is due to its defined path, compact intersection area, and the direct traffic movements. The DDI ranked the lowest due to its reversal in traffic movements and its undefined path.

4.6.17 Number of Conflict Points (D2-2)

Criterion D2-2 rates the performance of the interchanges based on the number of potential vehicular conflict points. Figures 4-28, 4-29, and 4-30 illustrate the locations of the merging, diverging, and crossing conflict points that can potentially be experienced on the TUDI, SPUI, and DDI configurations, respectively.

Table 4-38 indicates the potential number of conflict points at each of the interchange configurations and the corresponding scores on this criterion. The DDI was found to have only 14 possible conflict points and consequently scored high unlike the TUDI that had 26 conflict points and thus ranked the lowest.

Table 4-38: Scoring D2-2

	TUDI	**SPUI**	**DDI**
Potential Number of Conflict Points	26	22	14
Score	1.29	1.86	3.00

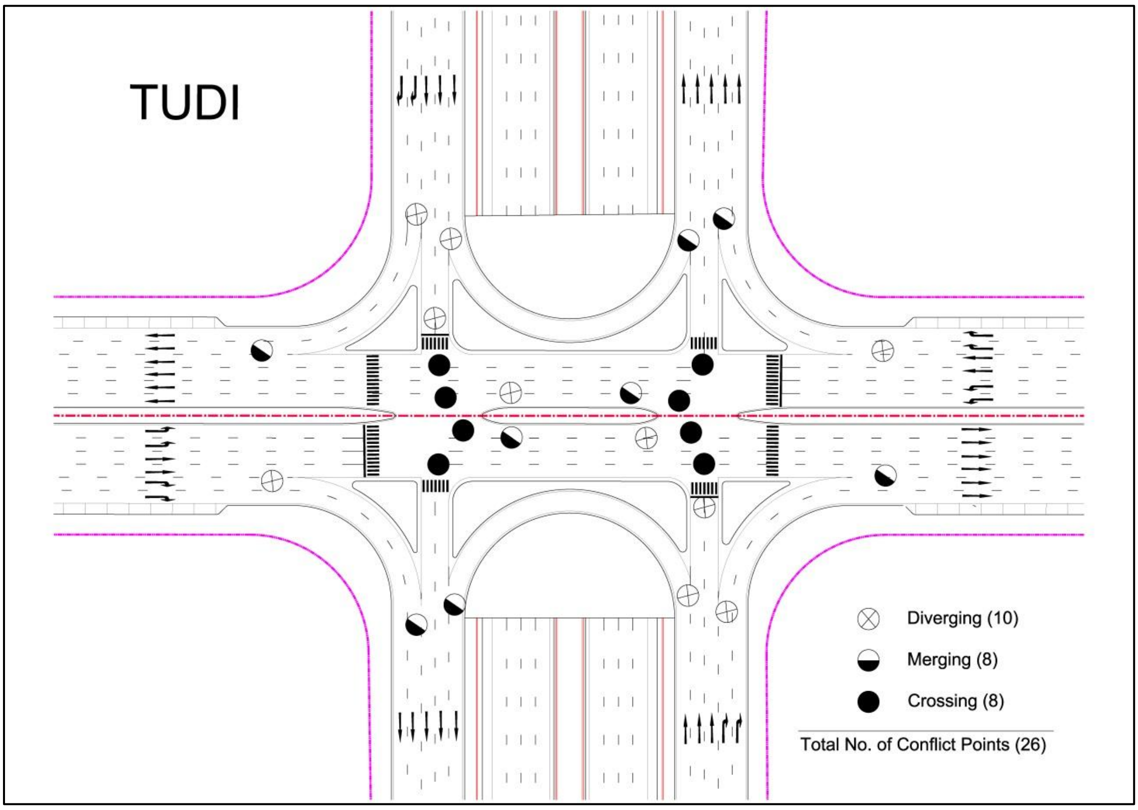

Figure 4-32: Conflict Points (TUDI)

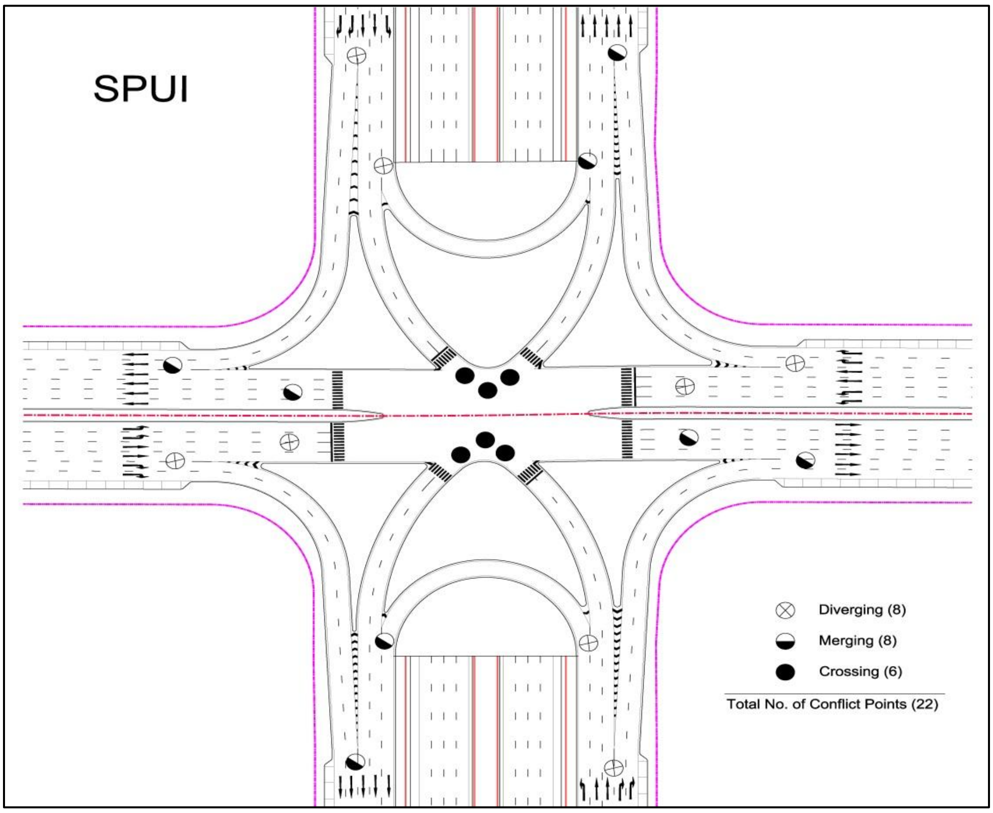

Figure 4-33: Conflict Points (SPUI)

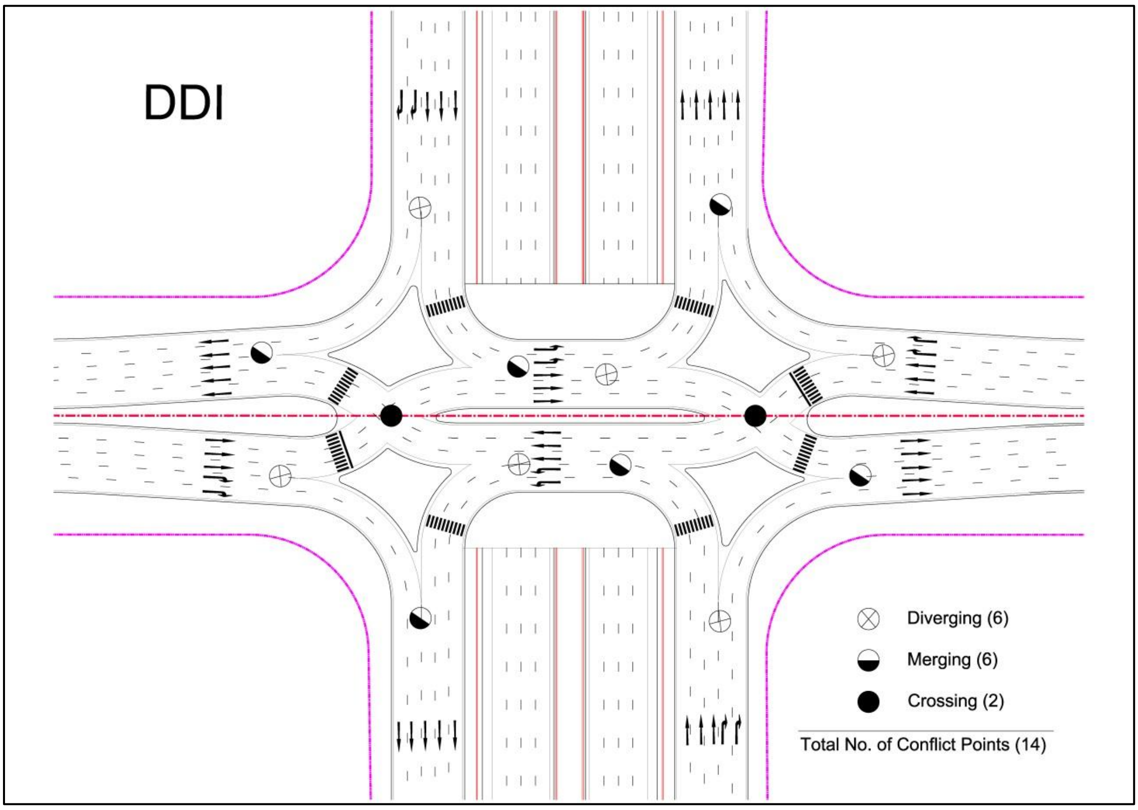

Figure 4-34: Conflict Points (DDI)

4.7 Ranking the alternatives

Given that a main advantage of the MCA method is that it does not require the conversion of all factors to monetary values, a linear additive approach is adopted as a main tool for the assessment and prioritization of the different interchange schemes. The linear additive model consists of calculating the overall value score of a proposed interchange type by adding its weighted score on a set of criteria:

$$S_i = \sum_{j=1}^{n} W_j S_{ij} = W_1 S_{i1} + W_2 S_{i2} + \cdots + W_n S_{in} \qquad (4\text{-}9)$$

Where S_i is the total value score of scheme i; W_j is the relative weight of criterion j; S_{ij} is the value score of scheme i on criterion j; and n is the total number of criteria. It should be noted that the relative weights of the criteria should add up to unity:

$$\sum_{j=1}^{n} W_j = 1 \tag{4-10}$$

According to the adopted methodology, Table 4-39 below displays the computed weights and introduces the scores of each interchange alternative for each of 17 the criteria. Using the linear additive model, the weighted scores are then derived as shown in the far right side of Table 4-39 and a rank is then determined for each alternative. It was found that the DDI ranked first and was chosen as the most preferred interchange configuration for the case study. The SPUI ranked second while the TUDI was the least preferred.

Table 4-39: Weighted Score Table

	Weight				Rank	Score			Weighted Score		
Criterion	Top	Primary	Secondary	Overall		TUDI	SPUI	DDI	TUDI	SPUI	DDI
A2	0.396	0.157	1.000	0.063	4	2.40	4.32	4.12	0.149	0.269	0.256
A3	0.396	0.129	1.000	0.051	7	2.42	3.96	4.06	0.123	0.202	0.207
B1	0.120	0.503	1.000	0.061	5	4.24	0.22	2.26	0.255	0.013	0.136
B2	0.120	0.250	1.000	0.030	13	3.47	2.60	2.49	0.104	0.078	0.075
B3	0.120	0.246	1.000	0.029	14	2.92	3.66	3.67	0.086	0.108	0.108
D1	0.294	0.701	1.000	0.207	1	1.00	1.00	1.00	0.207	0.207	0.207
A1-1	0.396	0.506	0.767	0.153	2	0.91	3.84	3.97	0.139	0.590	0.609
A1-2	0.396	0.506	0.233	0.047	8	0.20	3.46	3.93	0.010	0.161	0.183
A4-1	0.396	0.208	0.445	0.037	9	0.50	1.35	3.00	0.018	0.049	0.110
A4-2	0.396	0.208	0.339	0.028	15	3.81	3.82	3.64	0.106	0.107	0.101
A4-3	0.396	0.208	0.216	0.018	17	2.64	2.40	2.28	0.047	0.043	0.041
C1-1	0.190	0.712	0.745	0.101	3	1.62	2.40	2.42	0.163	0.242	0.244
C1-2	0.190	0.712	0.255	0.034	10	2.73	2.77	2.60	0.094	0.095	0.090
C2-1	0.190	0.288	0.584	0.032	12	2.44	0.80	3.32	0.078	0.026	0.106
C2-2	0.190	0.288	0.416	0.022	16	0.77	0.53	0.88	0.018	0.012	0.020
D2-1	0.294	0.299	0.627	0.055	6	5.00	3.50	2.00	0.276	0.193	0.111
D2-2	0.294	0.299	0.373	0.033	11	1.29	1.86	3.00	0.042	0.061	0.099
								Weighted score	1.916	2.456	2.702
								Rank	3	2	1

4.8 Sensitivity Analysis

Uncertainty stems from the imprecision of the model inputs or the disagreement between the different decision-makers. It can exist in three areas of the model namely in the measurements of the performance of the options on each criterion, in the form of the scoring function, and in the weights.

Sensitivity tests explore the effects of changing the scores or the weights on the overall results. If the results are relatively stable in the face of these tests, then the model is considered to be robust. In other words, if the differences between the overall scores of the alternatives under different sets of weights are small, then the initial results are deemed reliable. Sensitivity analysis does not resolve the problem of uncertainty, but it builds more confidence in the results. Sensitivity tests are also helpful in resolving conflicts between key players/decision-maker groups.

4.8.1 Sensitivity with respect to changing volumes

In addition to using the forecasted traffic volumes throughout a case study, it is important to study the sensitivity with respect to traffic volumes on a more continuous scale in order to determine the robustness of the model. Accordingly, the sensitivity is tested by varying forecasted traffic volumes for the year 2030.

4.8.1.1 Impact of increasing traffic volumes

In this sensitivity analysis, four different traffic scenarios were tested. The impact of increasing the traffic volumes by an additional 25%, 50%, 75%, and 100% on the performance of alternatives and the corresponding scores on the related criteria was analyzed thoroughly. The following subsections describe the impacts of increasing the traffic volumes on the affected criteria.

4.8.1.1.1 Impact on Intersection Delays (A1-1)

This section describes the impacts of increasing the traffic volumes on the intersection delays. The below figures display the delays experienced by the three interchanges and the at-grade signalized intersection. In general, and as expected, the at-grade intersection witnessed high delays (above 300 sec/veh) on all tested scenarios. Furthermore, the TUDI was found more sensitive to changing volumes whereby the delays increased steeply from 57 sec/veh at actual case study volumes to nearly 250 sec/veh at the 100% increase in volumes; consequently, it scored “0” after just 25% increase. On the other hand, lower sensitivity was witnessed for SPUI and DDI as the increase of traffic volumes did not have the same level of impacts on the intersection delays. Noticeably, the DDI experienced the lowest delays and consequently ranked first on this criterion. The SPUI experienced quite similar delays.

Figure 4-31 illustrates the intersection delays at all tested scenarios. Figure 4-32 displays the corresponding scores of each alternative on this criterion.

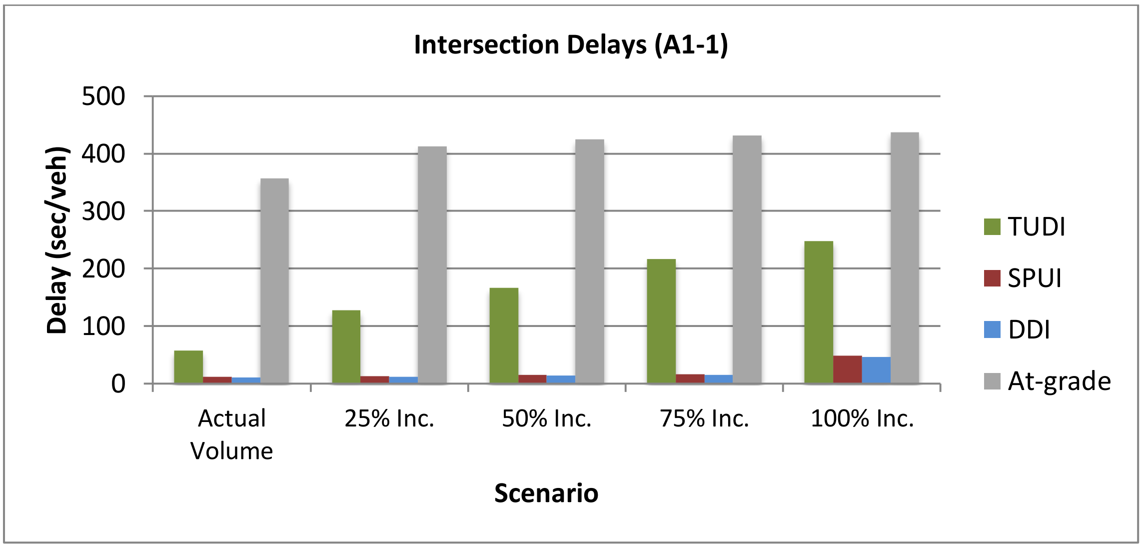

Figure 4-35: Sensitivity of increasing volumes on intersection delays

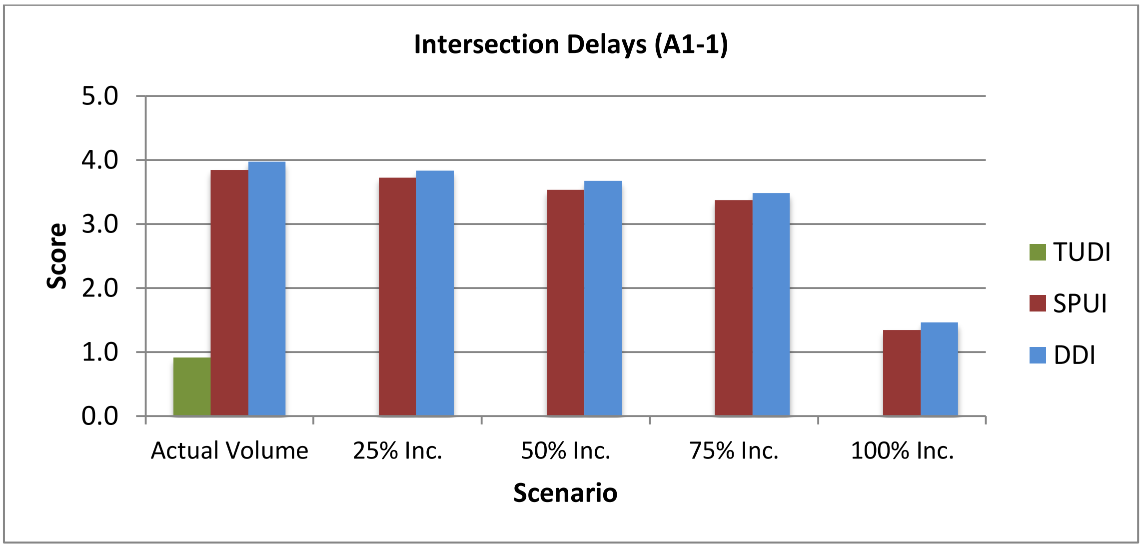

Figure 4-36: Impact of increasing volumes on scoring (A1-1)

4.8.1.1.2 Impact on Average Delay for All Left-Turning Movements (A1-2)

In this section, the impact of increasing traffic volumes is examined on the average delays for all left-turning movements. The figures below display a noticeable increase in delays for TUDI whereas the SPUI and DDI experienced relatively acceptable delays. As in criterion (A1-1), the DDI performed best at high volumes and the SPUI ranked second in order.

Figure 4-33 shows the average delays for all left-turning movements for all scenarios. Figure 4-34 displays the corresponding scores of each alternative on this criterion.

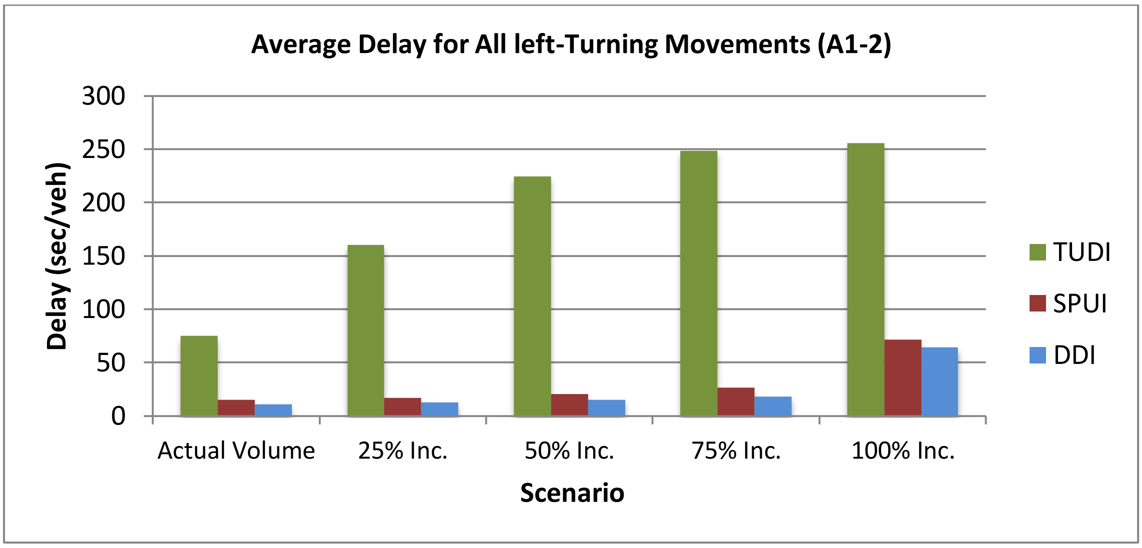

Figure 4-37: Sensitivity of increasing volumes on delays for left-turning movements

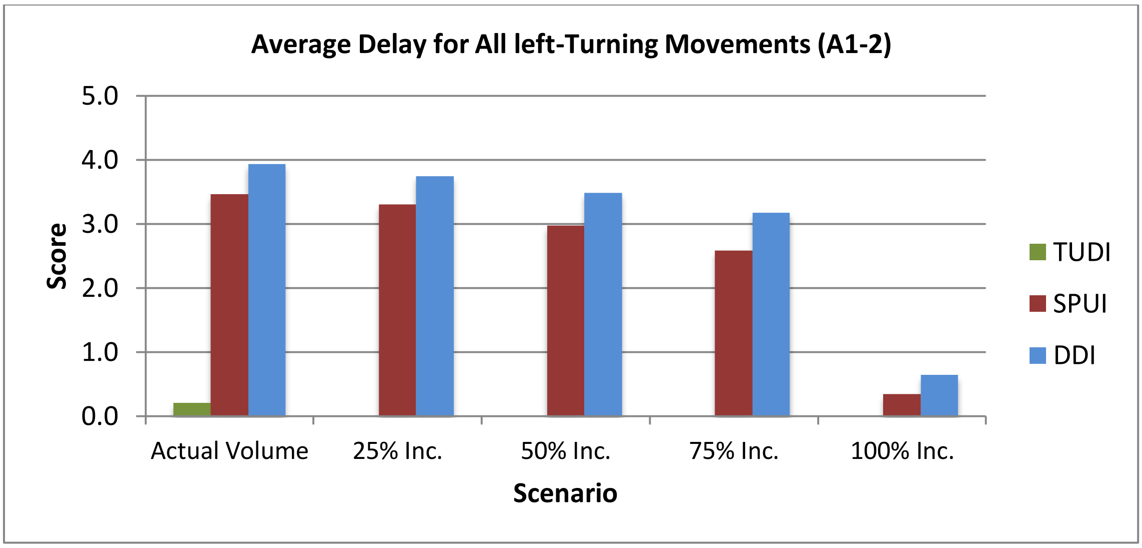

Figure 4-38: Impact of increasing volumes on scoring (A1-2)

4.8.1.1.3 Impact on the percentage of Stops (A2)

In this section, the effect of increasing the volume levels on the percentage of vehicular stops is demonstrated. By referring to the figures below, the increase in traffic volumes imposes a significant increase in the percentage of stops for the TUDI configuration. On the other hand, the figures display a general, yet slight, increasing trend for the SPUI and DDI from the actual case study volumes up to the 75% increase scenario. The increase is more pronounced under the 100% scenario. In general, the

SPUI experienced the lowest percentage of stops followed closely by the DDI and then by the TUDI.

Figure 4-35 depicts the percentage of stops as experienced at all tested scenarios. Figure 4-36 displays the corresponding scores of each alternative on this criterion.

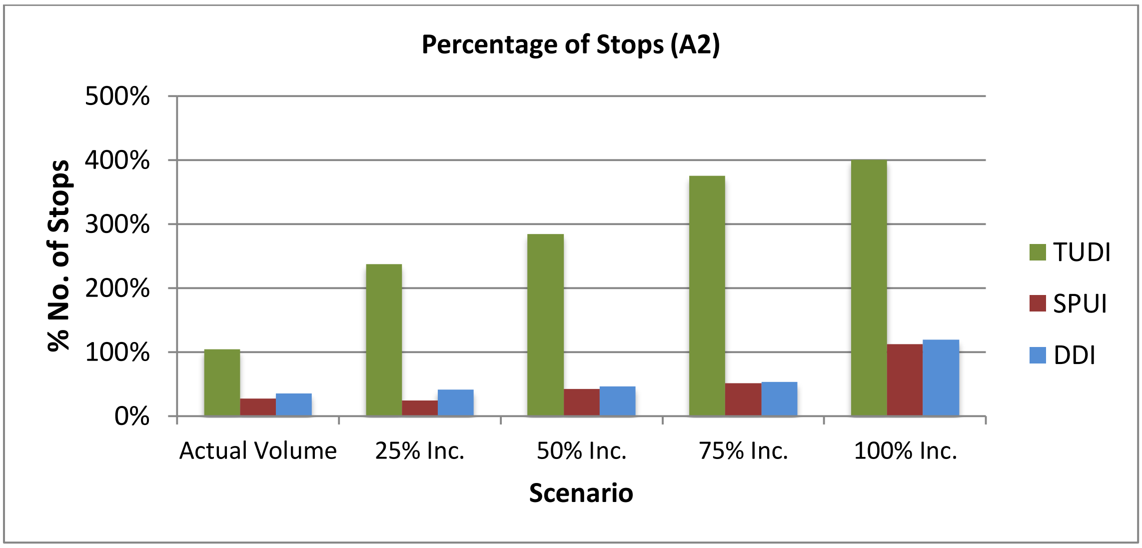

Figure 4-39: Sensitivity of increasing volumes on percentage of stops

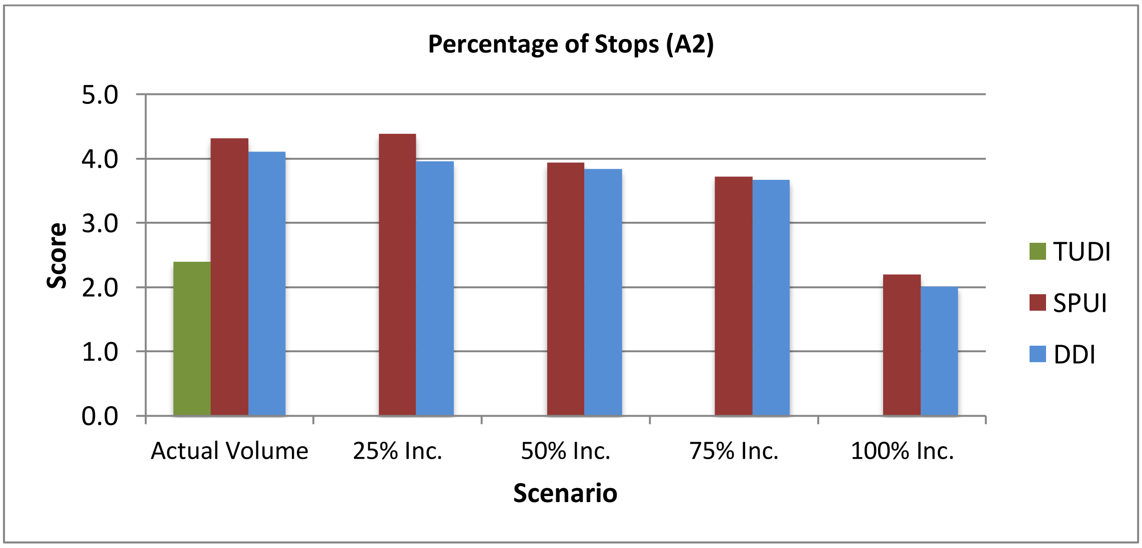

Figure 4-40: Impact of increasing volumes on scoring (A2)

4.8.1.1.4 Impact on the maximum queue length (A3)

The impact of increasing the traffic volumes on the maximum queue lengths was also tested for all three interchanges. Referring to the below figures, the TUDI witnessed the highest queue lengths as the traffic levels increased to double at the 100% increase scenario. As for the SPUI and DDI, the maximum queue length increased at a slower pace between the actual case study volumes and the 75% increase than it did for the 100% increase volume scenario. For all tested scenarios, the DDI was the most preferred interchange alternative offering the lowest queue lengths followed by the SPUI and TUDI respectively.

Figure 4-37 depicts the maximum queue length observed at each interchange for all tested scenarios. Figure 4-38 displays the corresponding scores on this criterion.

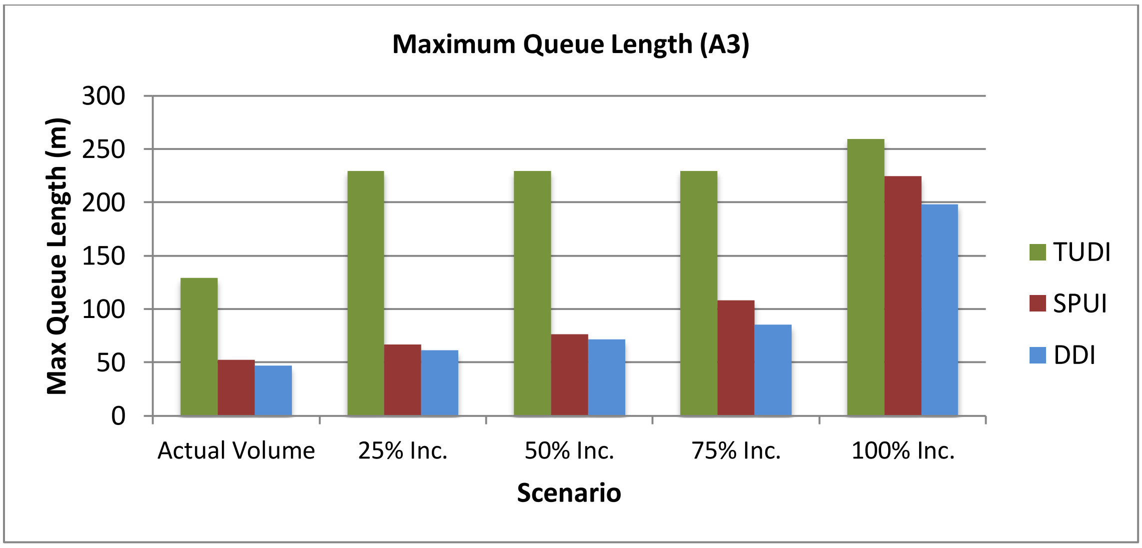

Figure 4-41: Sensitivity of increasing volumes on maximum queue length

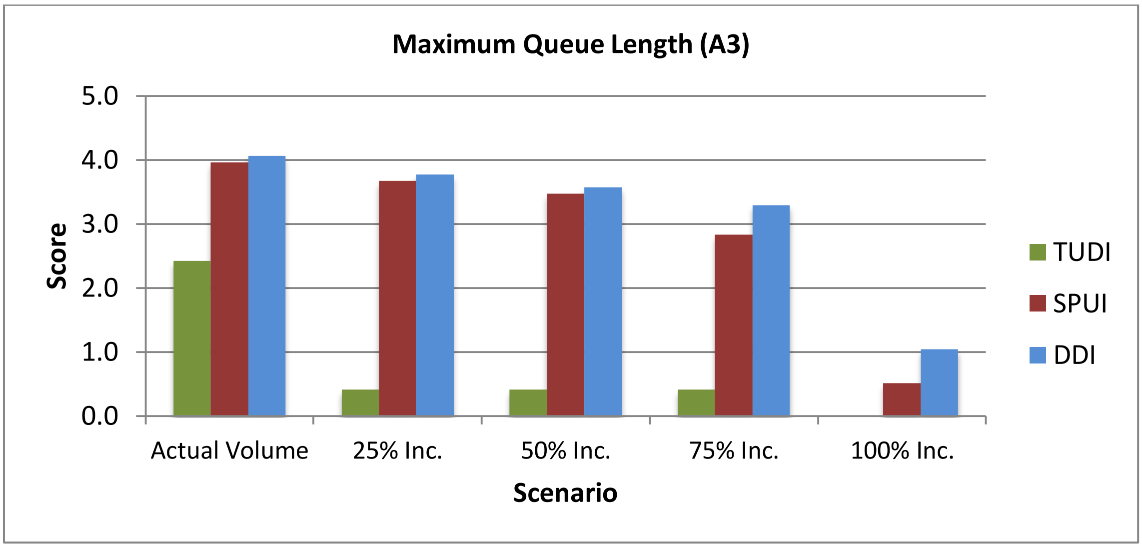

Figure 4-42: Impact of increasing volumes on scoring (A3)

4.8.1.1.5 Impact on the presence of conflicting protected traffic (A4-2)

The accommodation of pedestrian crossings was also addressed in increasing the traffic volumes through checking the presence of the conflicting protected traffic. All interchange types were sensitive to the increasing volumes in a similar manner. The DDI experienced the highest volume of conflicting protected traffic and consequently ranked last, whereas the TUDI ranked first.

Figure 4-39 shows how much the protected traffic varies with increasing the traffic volumes. Figure 4-40 displays the corresponding scores of each alternative on this criterion.

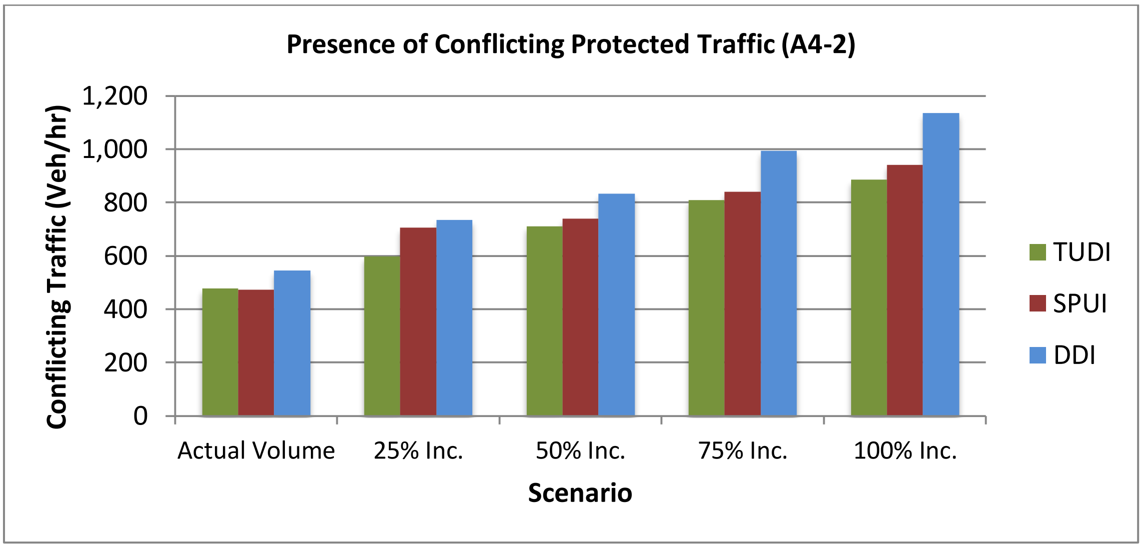

Figure 4-43: Sensitivity of increasing volumes on conflicting traffic volumes

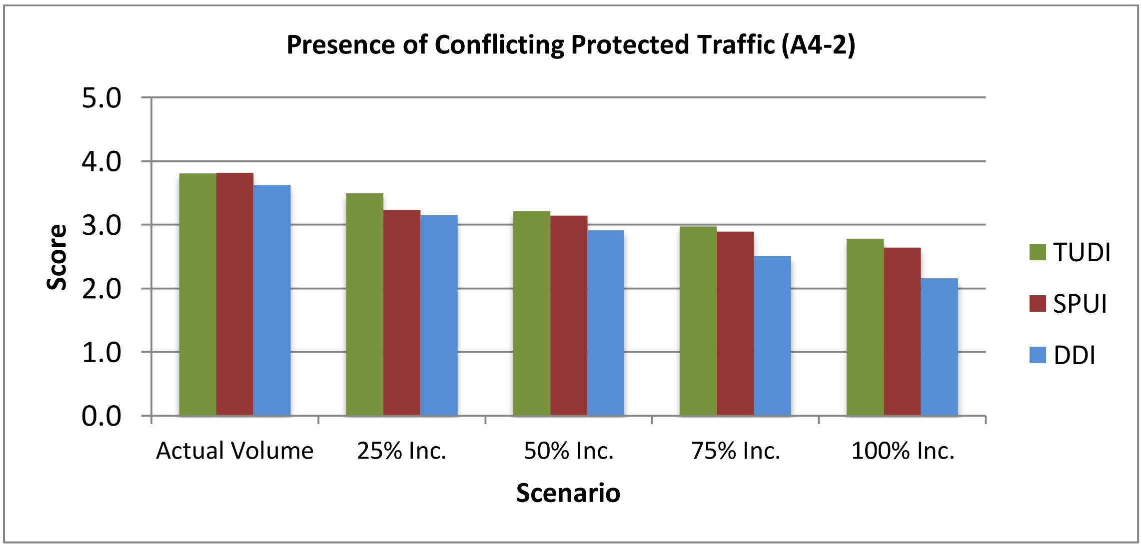

Figure 4-44: Impact of increasing volumes on scoring (A4-2)

4.8.1.1.6 Impact on the noise levels (B2)

This section describes the impact of increasing the traffic volumes on the generated noise levels. As inferred from the below figures, the increase in traffic volumes increases the generated noise levels and consequently the sensitivity to noise requirements becomes more evident. Noticeably, the TUDI experienced the lowest noise levels and was ranked first. On the other hand, the DDI generated higher noise levels and was the least preferred. This is possibly due to its compact intersection area, high speed, and high traffic throughput.

Figure 4-41 illustrates the percentage of area having noise levels exceeding the international requirements for interchange under all scenarios. Figure 4-42 displays the corresponding scores of each alternative on this criterion.

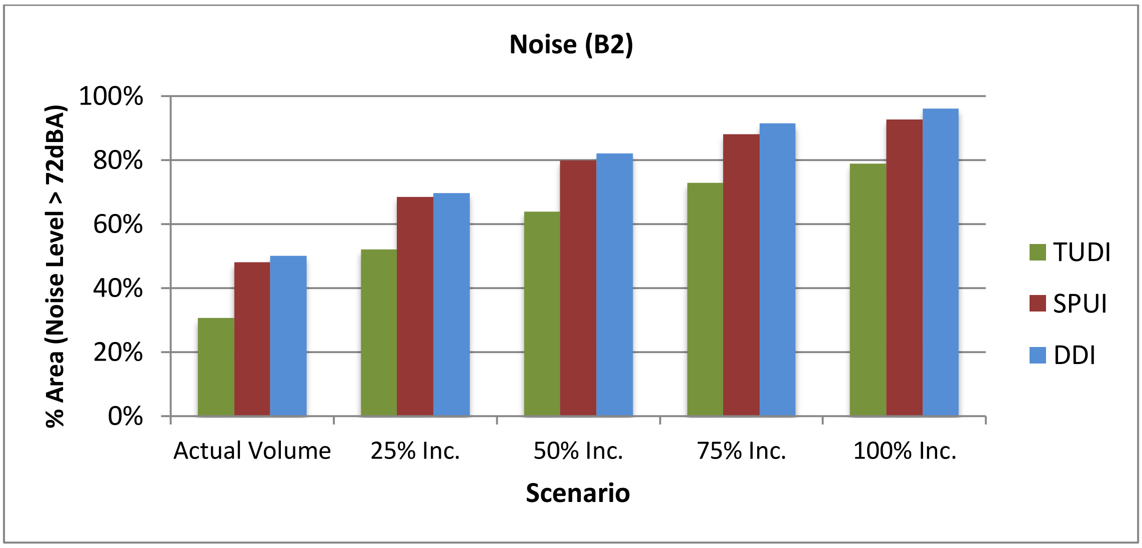

Figure 4-45: Sensitivity of increasing volumes on generated noise levels

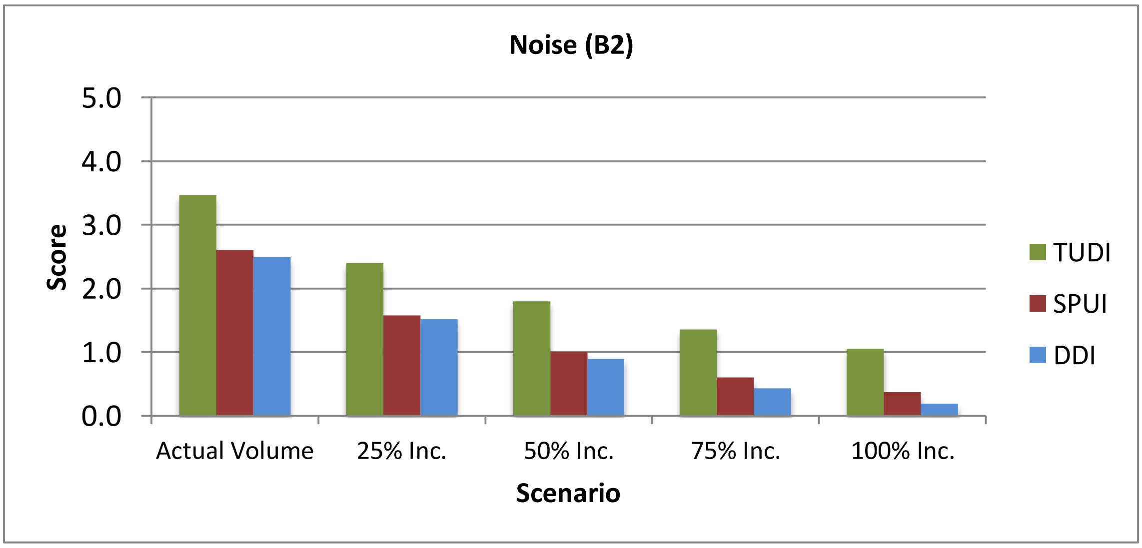

Figure 4-46: Impact of increasing volumes on scoring (B2)

4.8.1.1.7 Impact on the vehicle emissions (B3)

The impact of increasing traffic volumes on the generated vehicle emissions was also tested. In general, the higher the traffic volume, the more greenhouse gases are generated. It is noteworthy that the TUDI was found the most sensitive to vehicular emissions (both HC and CO gases). The figures below demonstrate the effect increasing the traffic volumes has on HC and CO emissions. The DDI ranked first for generating the lowest amount of gases. On the other hand, TUDI ranked third.

Figures 4-43 and 4-44 demonstrate the greenhouse gases (HC and CO respectively) generated at each interchange. Figure 4-45 displays the corresponding scores on this criterion.

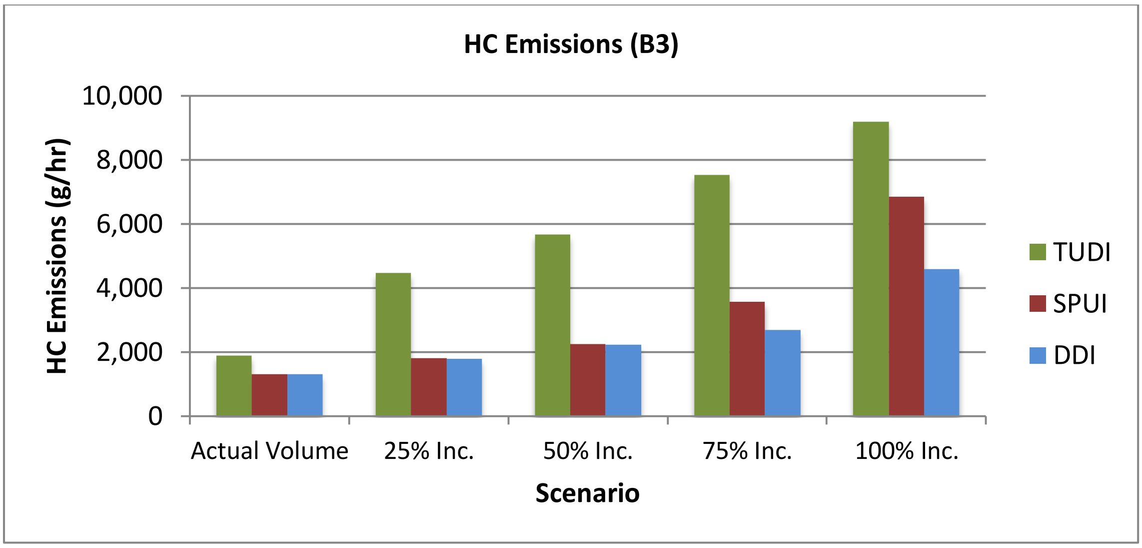

Figure 4-47: Sensitivity of increasing volumes on HC emissions

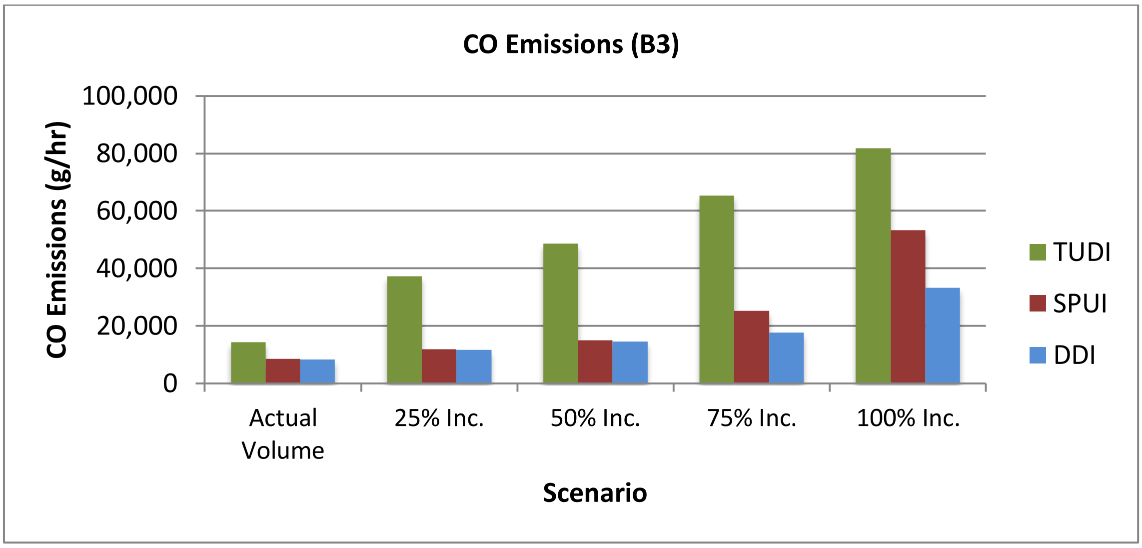

Figure 4-48: Sensitivity of increasing volumes on CO emissions

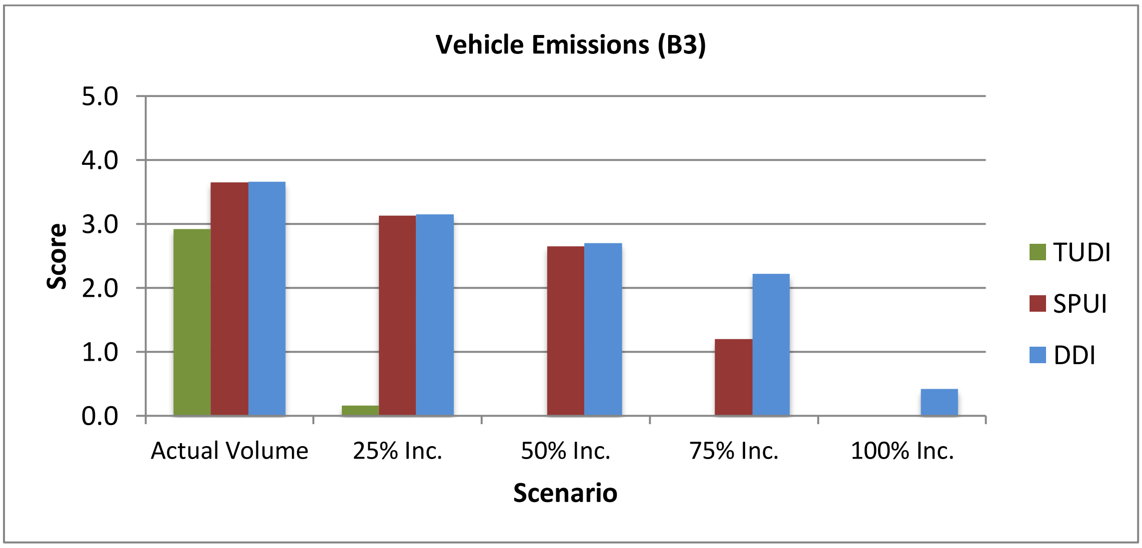

Figure 4-49: Impact of increasing volumes on scoring (B3)

4.8.1.1.8 Impact on the VOC reductions (C1-2)

It was also interesting to identify the effect changing the traffic volumes has on reducing the vehicle operating costs. As expected, the increase in traffic volumes decreases the reductions of vehicle operating costs. These reductions were found higher for TUDI than for DDI configuration. Consequently, the TUDI ranked first on this criterion, followed by the SPUI and the DDI, respectively.

Figure 4-46 illustrates the reductions in VOCs for all interchanges. Figure 4-47 displays the corresponding scores on this criterion.

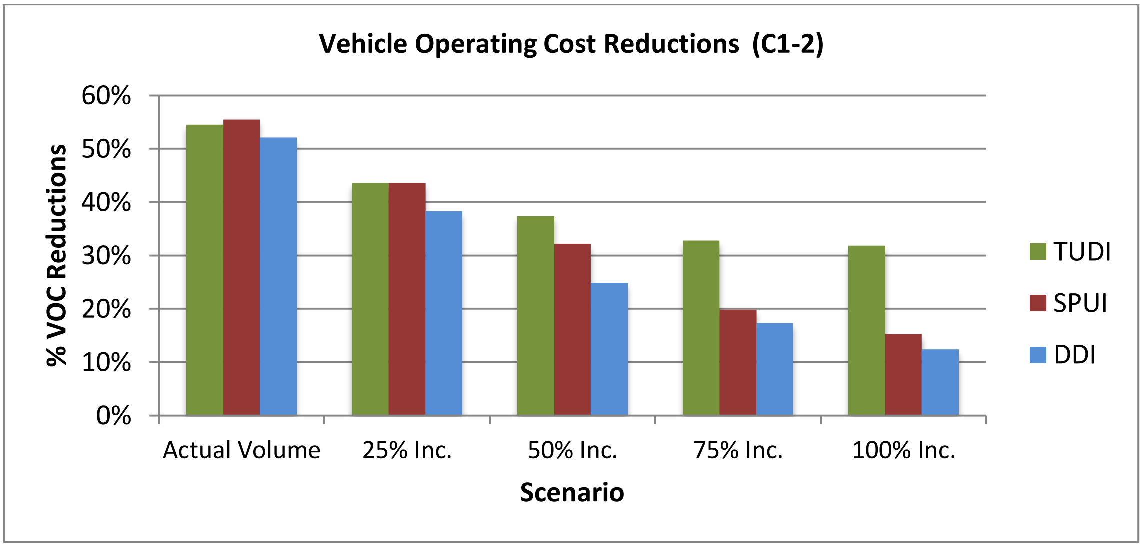

Figure 4-50: Sensitivity of increasing volumes on VOC reductions

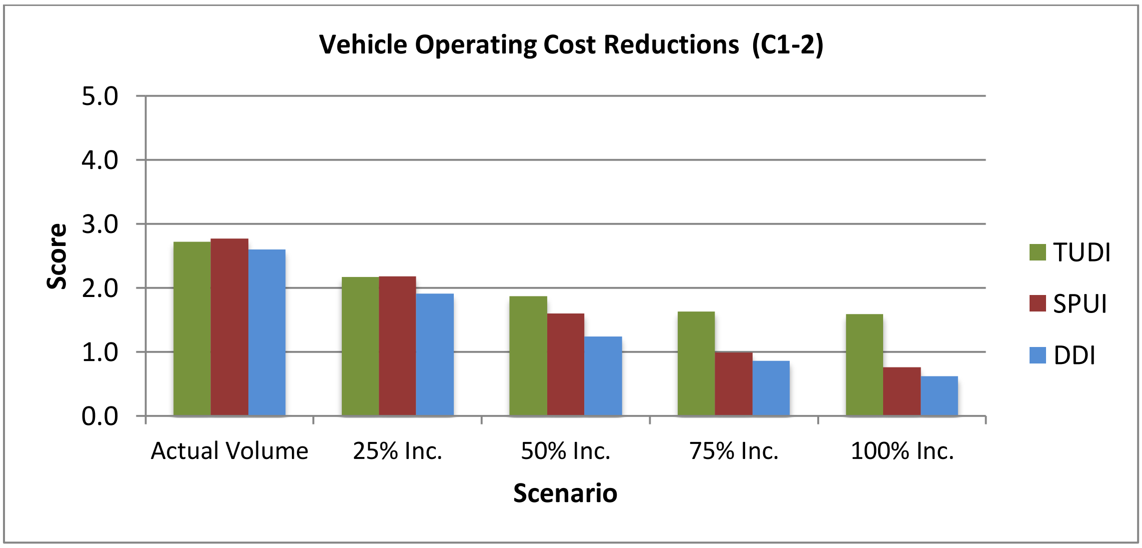

Figure 4-51: Impact of increasing volumes on scoring (C1-2)

4.8.1.1.9 Impact on the overall ranking

After considering the impacts of increasing the demand volumes on the criteria presented above and after determining the weighted scores, it was interesting to identify if there were any possible changes to the overall ranking. As displayed in Figure 4-48, the DDI configuration remained the most preferred alternative for all tested scenarios. Similarly, SPUI ranked second in all scenarios whereas the TUDI ranked last.

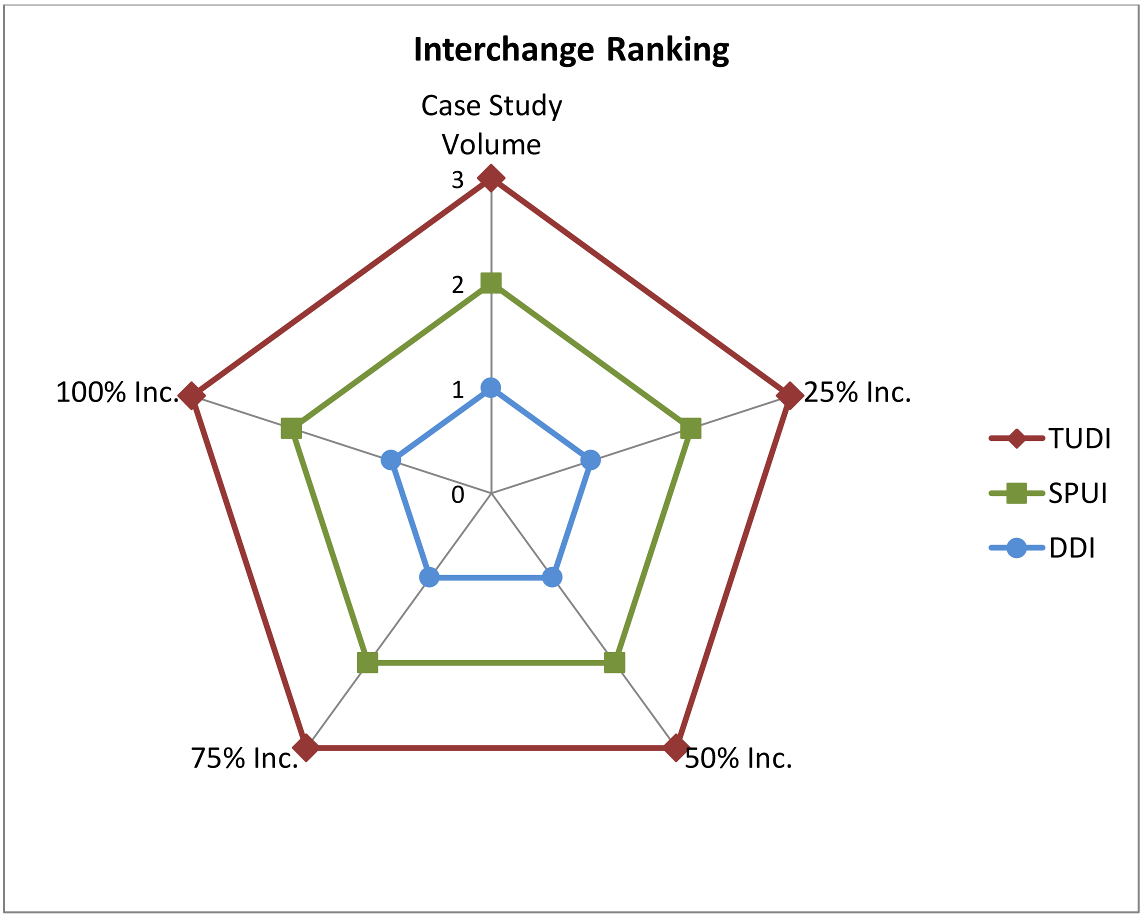

Figure 4-52: Impact of increasing volumes on the overall ranking

Nevertheless, it is worthy to note that the large margin of the total weighted score between the SPUI and TUDI for the actual case study volumes was greatly reduced after increasing the volumes by an additional 100%, as shown in figure 4-49. Regardless of this reduction, the SPUI remained second in ranking and the TUDI the least preferred alternative. Table 4-40 shows total weighted score of each alternative for the different scenarios.

Table 4-40: Sensitivity of changing volumes on the overall weighted scores

Scenario	Total Weighted Score		
	TUDI	**SPUI**	**DDI**
Case Study Volumes	1.917	2.456	2.702
25% Increase	1.236	2.345	2.578
50% Increase	1.221	2.239	2.488
75% Increase	1.142	1.948	2.298
100% Increase	1.106	1.121	1.462

Figure 4-53: Impact of increasing volumes on the total weighted score

4.8.1.2 Impact of using unbalanced volume scenarios

It was also interesting to analyze the performance of interchanges at unbalanced volume scenarios. As such, the sensitivity of delays to the change of volumes for the left-turning movements was tested. In this section, two traffic scenarios were analyzed to consider the impact of increasing only the left-turning movements by 25% and 50%. The following subsections describe the impact of using unbalanced volume scenarios on the overall intersection delays and the delays for the left-turning movements only.

4.8.1.2.1 Impact on Intersection Delays (A1-1)

This section demonstrates the impact of using unbalanced volume scenarios on the overall intersection delays. The below figures depict that the TUDI is more sensitive to the increasing volumes as compared to SPUI and DDI. The latter, DDI, ranked first as it offered the lowest intersection delays. SPUI ranked second and TUDI was the least preferred.

Figure 4-50 illustrates the overall intersection delays observed for the considered scenarios. Figure 4-51 displays the corresponding scores of each alternative on this criterion.

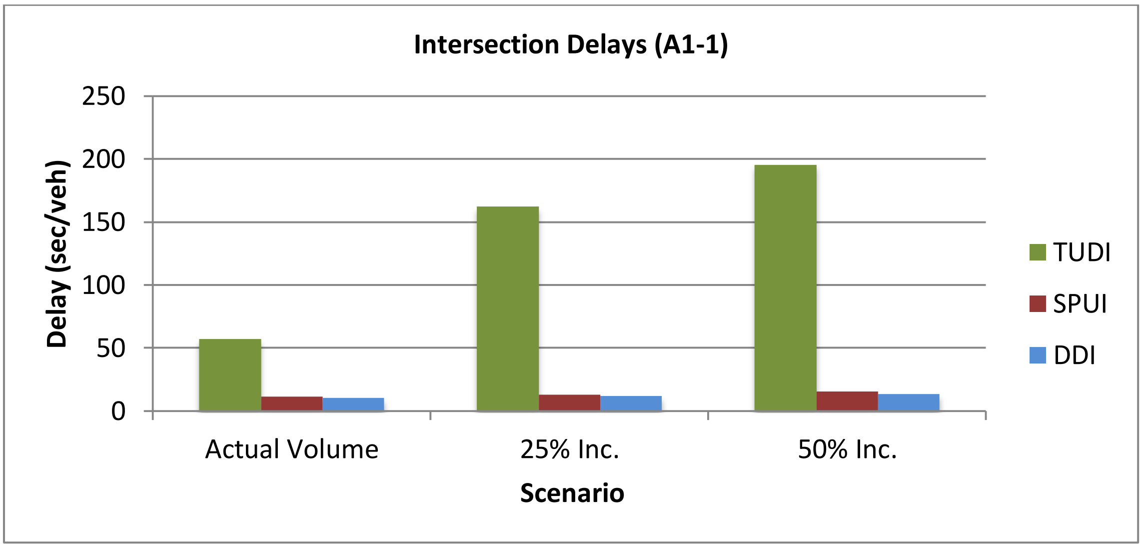

Figure 4-54: Sensitivity of using unbalanced volume scenarios on Intersection Delays

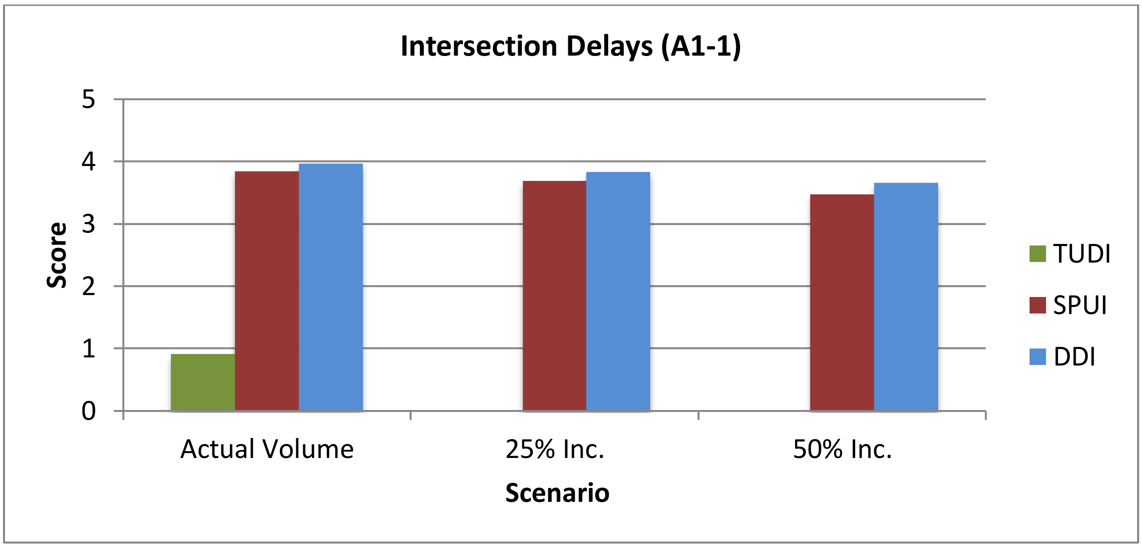

Figure 4-55: Impact of using unbalanced volume scenarios on scoring (A1-1)

4.8.1.2.2 Impact on Average Delay for All Left-Turning Movements (A1-2)

Similar to the overall intersection delays, the impact of using unbalanced volume scenarios on the average delay for all left-turning movements was considered. The below figures demonstrate that the TUDI is highly sensitive to the increasing volumes. The delays increased from 55sec/veh to around 200 sec/veh with 50% increase in traffic volumes. With regards to ranking, the DDI is most preferred, SPUI ranks second and TUDI the worst.

Figure 4-52 shows the average delays for all left-turning movements for the considered scenarios. Figure 4-53 displays the corresponding scores of each alternative on this criterion.

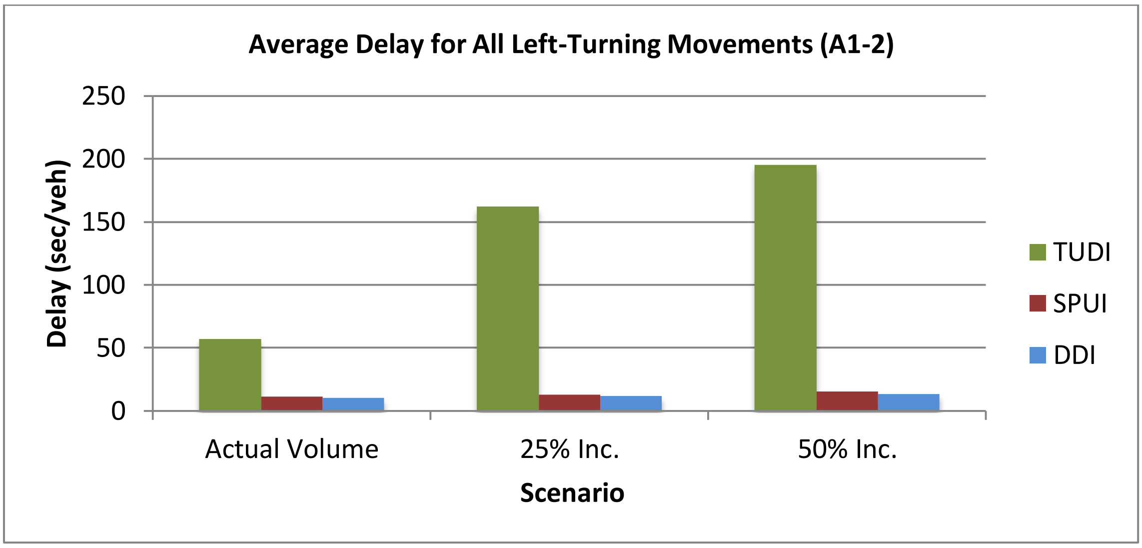

Figure 4-56: Sensitivity of using unbalanced volume scenarios on the Average Delay for All-left turning movements

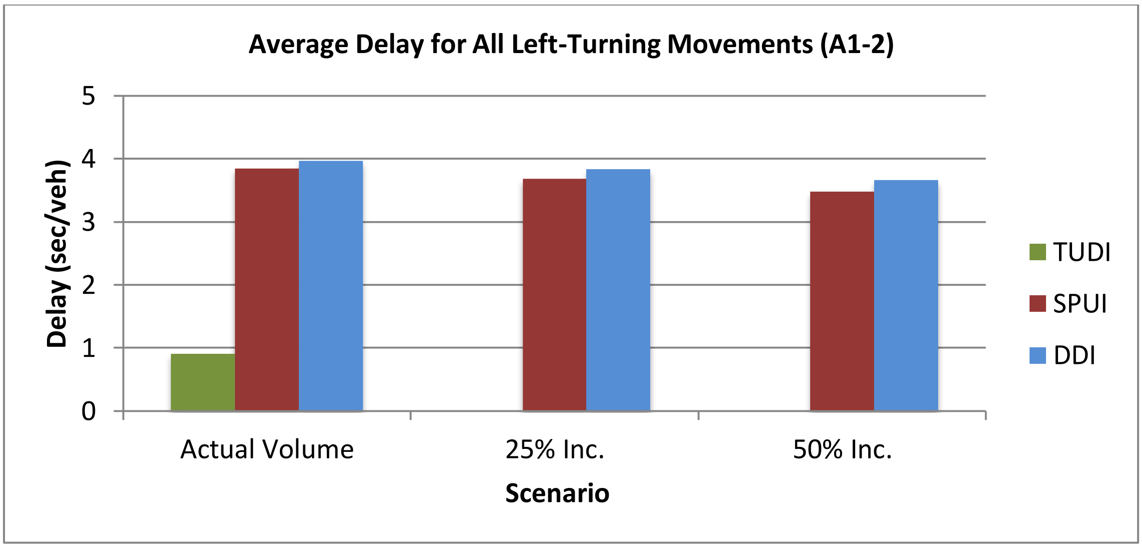

Figure 4-57: Impact of using unbalanced volume scenarios on scoring (A1-1)

4.8.2 Sensitivity with respect to changing scoring functions

In addition to the sensitivity that was carried out to determine the impacts of changing the traffic volumes on the prioritization of interchanges, it is also important to determine the robustness of the proposed scoring functions that were used in the study. As discussed in section 4.4, many of the scoring functions were developed with reference to international standards and regulations. However, several others were proposed based on professional judgment. This section identifies the reliability of these judgments by changing the scoring functions and analyzing the associated impact on the total weighted score and the ranks accordingly. Three criteria were considered in this analysis, namely: Presence of Conflicting Protected Traffic (A4-2), Accessibility Impact on Existing Economic Activities (B1), and Vehicle Emissions (B3).

4.8.2.1 Presence of Conflicting Protected Traffic (A4-2)

In this analysis, the sensitivity of changing conflicting traffic range was tested by increasing the range of protected traffic to reach 4,000 veh/hr instead of the 2,000 veh/hr that was used in the scoring functions. The results showed that the overall interchange ranking remained the same, the scoring changed slightly as the impacts were slightly more sensitive to TUDI and SPUI than DDI. As such, it was concluded that changing the scoring function of criterion (A42) had minimal impacts and the results of the study are reliable.

4.8.2.2 Accessibility Impact on Existing Economic Activities (B1)

Similarly, it was interesting to determine the robustness of the model by changing the scoring functions of criterion (B1). Accordingly, the sensitivity of changing the scoring split of the two considered schemes was tested. As such, scheme 1 that focuses on the accommodation of through traffic received a maximum score of “3” instead of “2”, and the opposite was applied for scheme “2”. The results of this analysis showed that the overall interchange ranking remained the same. The TUDI and DDI were more sensitive than SPUI towards this change; however, changing this scoring function had a minimal impact and the model is robust with respect to this change.

4.8.2.3 Vehicle Emissions (B3)

In this section, the sensitivity of changing the scoring function of HC and CO gas emissions was tested. It was interesting to determine whether the ranking of interchanges can change by reducing the range of HC and CO emissions to reach 3,000 g/hr and 30,000 g/hr respectively. Similar to the previous result, interchange ranking remained the same and the impacts were slightly higher for DDI and SPUI than TUDI. So it was concluded that changing the scoring functions of this criterion were not significant as the interchange ranking remained the same; hence the model is robust.

4.8.3 Other tested scenarios

In addition to testing the sensitivity of increasing the traffic volumes and changing the scoring functions, several additional scenarios were considered to reflect any susceptible changes that might affect the scoring of several criteria such as Noise (B2), Construction Costs (C2-1), and Crash Frequency Experience (D1).

4.8.3.1 Impact of traffic composition on Noise (B2)

This section describes the impacts of changing the traffic composition on the generated noise levels. In addition to the 2% of Trucks that was considered in the case study, another scenario was examined by increasing this percentage to 5%. By referring to the below figure, one notices that the increase in the percentage of trucks had considerable impacts on the generated noise levels. These levels increased drastically such that almost 70% of the considered zone breached the federal highway noise requirements. The DDI remained the interchange generating the highest levels of noise and the TUDI remained the best interchange alternative on this criterion.

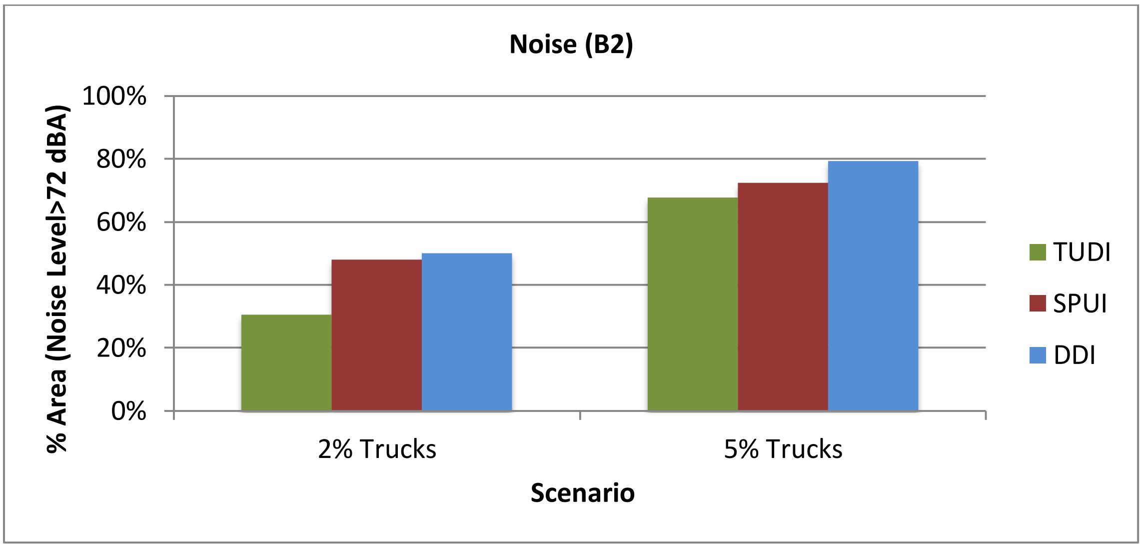

Figure 4-58: Impact of traffic composition on noise levels

4.8.3.2 Impact of using new technologies for reducing Construction Costs (C2-1)

Given that the construction costs had severe impacts on the scoring of the SPUI configuration, it was interesting to analyze the impact of this criterion (C2-1) on the overall scoring and the corresponding interchange ranking. Accordingly, we have considered a scenario in which a new technology is introduced and which would have a direct impact on reducing the construction cost of SPUI specifically. The results of this analysis demonstrated that even with assigning a score of "5" to SPUI, the overall ranking of interchanges remained the same, hence the results are reliable.

4.8.3.3 Analyzing the impact of Crash Frequency Experience (D1) on the overall ranking

Given that the criterion "*Crash Frequency Experience (D1)*" has the highest weight (0.207) among all criteria and that no data was available to quantify it and assign relative scores for each interchange, it was essential to conduct sensitivity analysis to determine the impact of changing the scores on this criterion on the overall ranking. Two main scenarios were considered; the first analyzes the potential scores of TUDI on this criterion and demonstrates the corresponding influences on the overall ranking, while the second uses similar analysis but for the SPUI configuration.

Due to the high weight that is assigned for this criterion, it was considered that each of the alternatives could rank first. The following demonstrates the conditions for the TUDI and SPUI to rank first.

<u>For TUDI to rank 1st (Scenario 1):</u>

Score of TUDI on (D1) > Score of SPUI on (D1 + 2.607 out of 5) (4-11)

Score of TUDI on (D1) > Score of DDI on (D1 + 3.795 out of 5) (4-12)

<u>For SPUI to rank 1st (Scenario 2):</u>

Score of SPUI on (D1) > Score of DDI on (D1 + 1.188 out of 5) (4-13)

Considering scenario 1, TUDI is unlikely to rank first since the difference in score needed on this criterion for the TUDI to overcome the DDI is relatively high (3.795 out of 5). In addition, to elaborate on the safety performance of these interchanges in more detail, the FHWA performed an accident analysis at the French DDI in Versailles and compared it to a similar location in the United States. The results showed that the DDI experienced significant decrease in accident rate and severity than the TUDI configuration (Bared et al., 2007). Similarly, Chilukuri et al. (2011) evaluated the safety of a recently implemented DDI in Missouri by comparing the crash data one year after its operation with the five-year period before executing the interchange. Chilukuri et al. (2011) found that the total crashes were down by 46% when compared to the previous tight diamond interchange. Based on the above, one perceives that the DDI performs better than TUDI from a safety perspective and consequently the possibility of TUDI to rank first is unrealistic.

Considering Scenario 2, for the SPUI alternative to rank first it should score 1.188 higher than the DDI on this criterion. Although this sounds reasonable, and is more likely to happen than scenario 1, according to a crash analysis study that compared 13 SPUI sites with a newly developed DDI crash model, no significant difference in the number of crashes was revealed between the two types. On the other hand, the observed injury/fatality rate of SPUIs compared to corresponding expected injury/fatality rate of DDIs did reveal significant difference as the rate of the latter was found to be higher than the SPUI (Bared et al., 2005). So there is still a possibility for SPUI to rank first; however, the final verdict can be made upon the availability of crash data for all of the considered interchanges.

4.8.4 Sensitivity with respect to Weights

In addition to testing the sensitivity of changing the traffic volumes and scoring functions, additional tests are needed to explore the effects of changing the weights on the overall results. Since many groups are involved in the decision making, each would contribute to different results and consequently a sensitivity analysis is needed to check the adequacy of the overall results and to resolve, if possible, any conflicts among the judgments of the decision-makers.

This section includes testing the sensitivity of weights with respect to each of the decision groups in addition to an in-depth analysis for the main criteria groups of the aggregate results.

4.8.4.1 Impact of decision-maker group weights on the overall ranking

This section demonstrates the set of weights that were obtained for each stakeholder group for the prioritization of arterial/freeway interchange types. The below figures portray the relative weights at the top level of the hierarchy and the overall results for each decision-maker group. In addition, these figures display the weighted scores computed for the whole group (Aggregate) and each decision-maker group.

These weighted scores are determined for each of the alternatives (TUDI, SPUI, and DDI) on each criteria group.

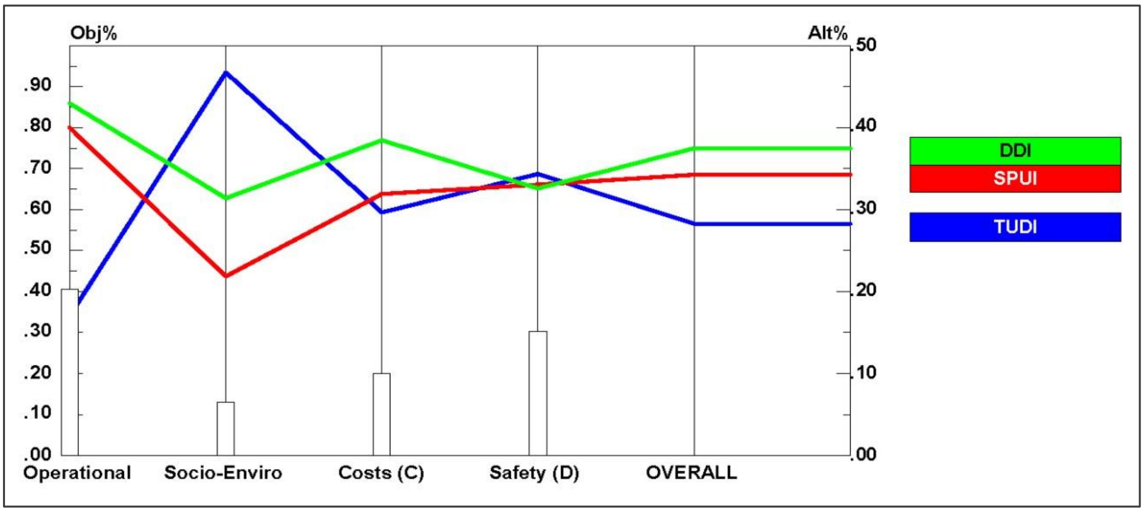

Figure 4-59: Impact of Aggregate group weights on the prioritization of interchanges

Figure 4-55 above shows the impacts of aggregate group weights on the prioritization of interchanges. The figure displays the criteria weights in bars and the weighted scores in colored lines. The left axis (Obj%) represents the weights of the main criteria groups (Framework Objectives) whereas the right axis (Alt%) represents the prioritization of each alternative in percentage.

As previously mentioned the results of the Aggregate decision group showed that the operational performance was considered the most important criteria group for prioritizing the different interchange configurations. Safety ranked second followed by costs and socio-environmental impacts, respectively. As for the overall weighted scores, the DDI was the most preferred interchange and TUDI the least. However, when analyzing each criteria group separately, the DDI ranked first on the “Operational Performance (A)” and “Costs (B)” criteria groups followed by the SPUI and TUDI, respectively. As for the “Socio-Environmental Impacts (B)”, the TUDI was the most preferred followed by SPUI and DDI, respectively. In addition, almost all interchanges performed equally on “Safety (D)” and scored the same with a small preference for the TUDI configuration.

The below two figures (4-56 and 4-57) display the weights of two decision groups (Junior and Senior Engineers) and their corresponding impacts on the prioritization of the interchange types. Similar to the results of aggregate group, operational performance was found as the most important criteria group followed by safety, costs, and socio-environmental impacts, respectively. In addition, the weighted scores of all criteria groups reveal the same interchange preferences as compared to those of the aggregate group; this adds more to the reliability of the results and prevents any conflicts in the prioritization of interchange types among these decision-maker groups.

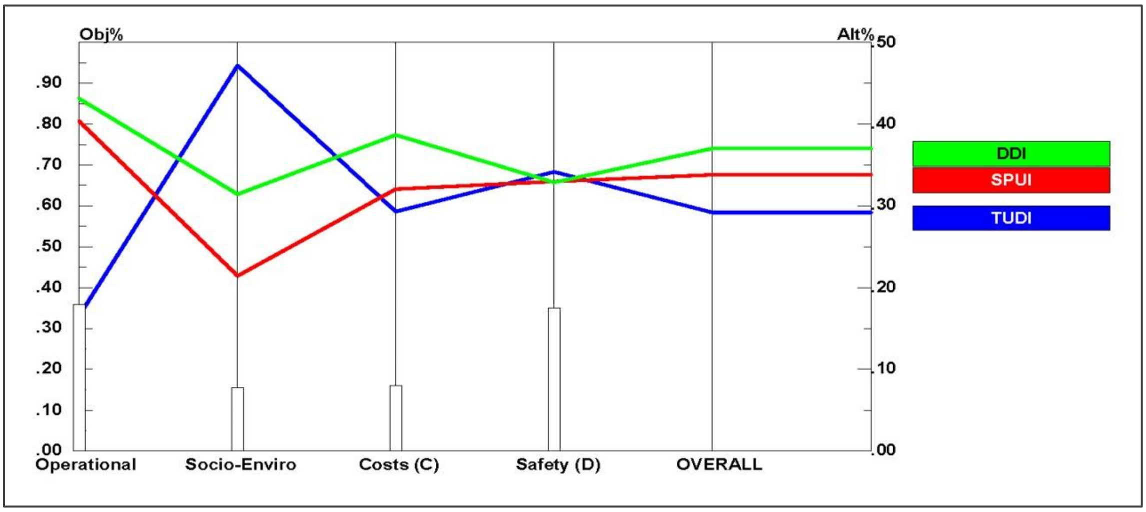

Figure 4-60: Impact of Junior Engineer group weights on the prioritization of interchanges

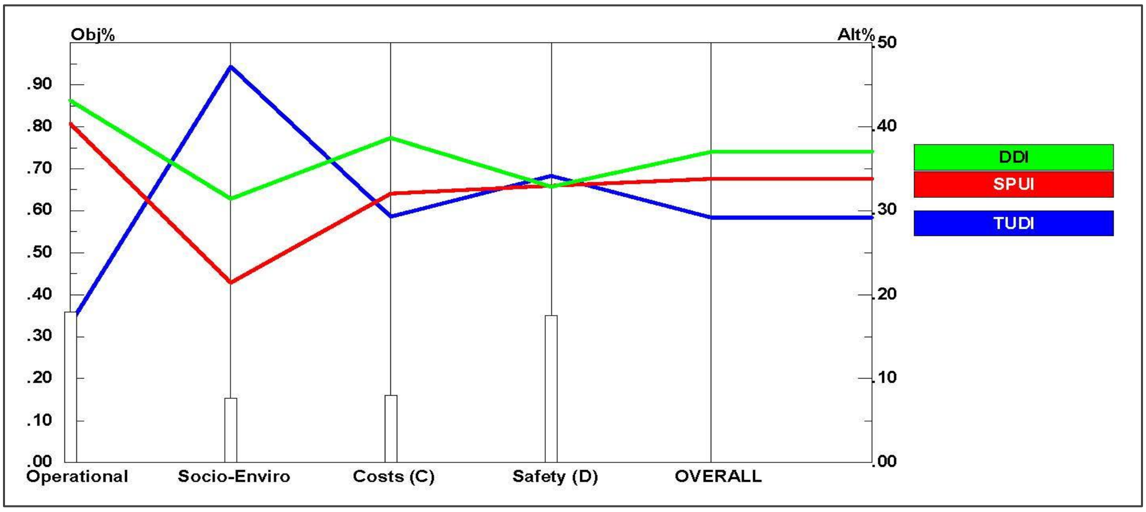

Figure 4-61 Impact of Senior Engineer group weights on the prioritization of interchanges

Figure 4-58 below displays the weights of the Professor decision-group and shows the corresponding impacts on the prioritization of the interchange types. Similar to the results of aggregate group, operational performance was found as the most important criteria group followed by safety, costs, and socio-environmental impacts respectively. In addition, the weighted scores of all criteria groups reveal the same interchange preferences as compared to those of the aggregate group except for the costs whereby the SPUI and TUDI scored almost the same. Despite this small change, no conflicts in the prioritization of interchange types are expected among the decision-maker groups as the results are robust with respect to the first preferences.

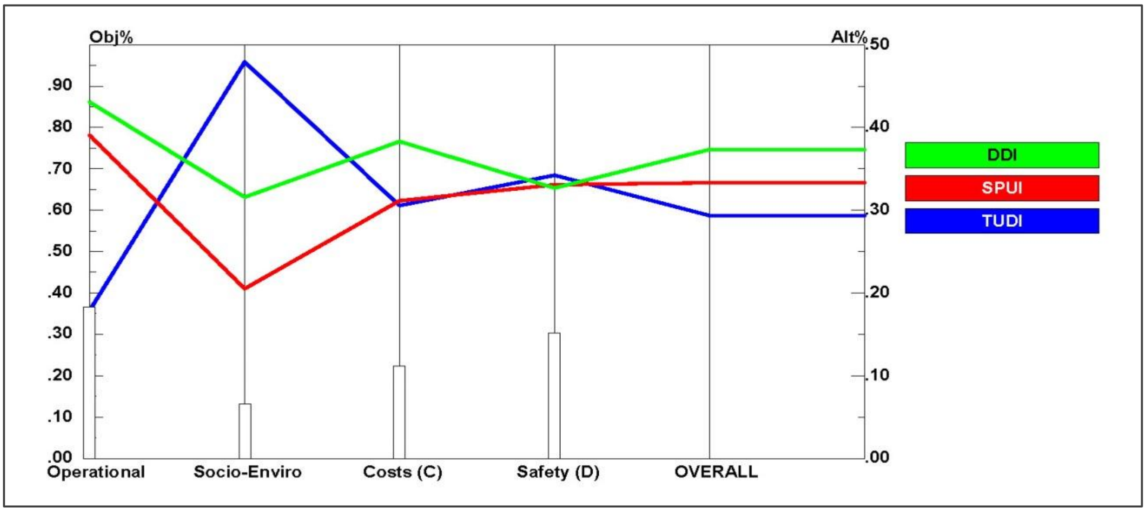

Figure 4-62: Impact of Professor group weights on the prioritization of interchanges

Figure 4-59 below displays the weights of the Stakeholder decision-group and shows the corresponding impacts on the prioritization of the interchange types. Similar to the results of aggregate group, operational performance was found as the most important criteria group followed by safety, costs, and socio-environmental impacts respectively. In addition, the weighted scores of all criteria groups reveal the same interchange preferences as compared to those of the aggregate group except for the costs whereby the SPUI's score on this criterion has decreased as compared to the other two interchanges. Despite this small change, no conflicts in the prioritization of interchanges are expected as the results are robust with respect to the first preferences.

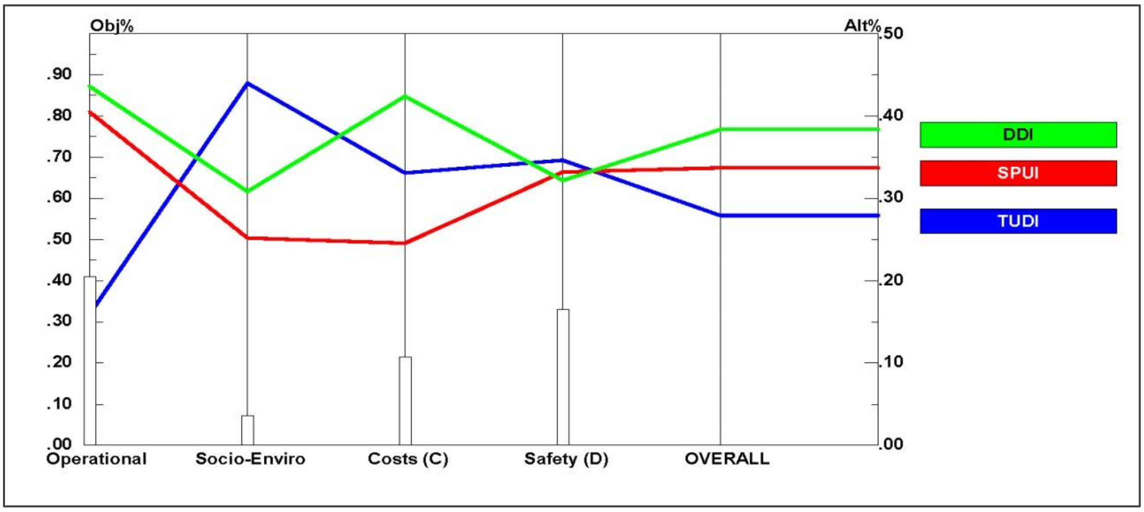

Figure 4-63: Impact of Stakeholder group weights on the prioritization of interchanges

In general, one notices that the weights of the "*Operational Performance (A)"* criterion ranked first among all decision-maker groups with an average weight of around 40%. Similarly, "*Safety (D)"* ranked second followed by the *"Costs (C)"* and "*Socio-Environmental Impacts (B)"*. It was also inferred that the weights were consistent among the different decision groups. In addition, when considering the weighted scores of the interchanges among all groups, the DDI outranked all of its counterparts, the SPUI ranked second followed by the TUDI. Accordingly, one perceives that there should be no significant conflicts in the prioritization of interchange types among all decision-makers. Furthermore, the presented figures depict the final weighted scores of each criteria group for all decision-maker groups. In general, it can be inferred that the DDI ranked first in the operational performance and cost considerations, the TUDI was the most preferred in terms of its socio-environmental impacts, and safety was almost equal among all interchanges.

4.8.4.2 Impact of criteria group weights on the overall ranking

In this section, the effect of changing the criteria weights on the ranking of interchanges is analyzed thoroughly.

Figure 4-60 displays the sensitivity of rankings with respect to the weight of the operational performance criterion. Using the computed weight (0.396) of the aggregate group for “Operational Performance (A)” criteria group, the DDI ranked first followed by the SPUI and TUDI, respectively. As shown in the below plot, the higher the weight that is assigned to the operational performance, the higher the composite score of DDI and SPUI whereas TUDI’s composite score becomes lower. Based on the figure, the DDI retains the first rank whenever the weight of criterion (A) is above 10%, the SPUI ranks second for weights above 20%, whereas the TUDI could rank first for an assigned weight less than 10%.

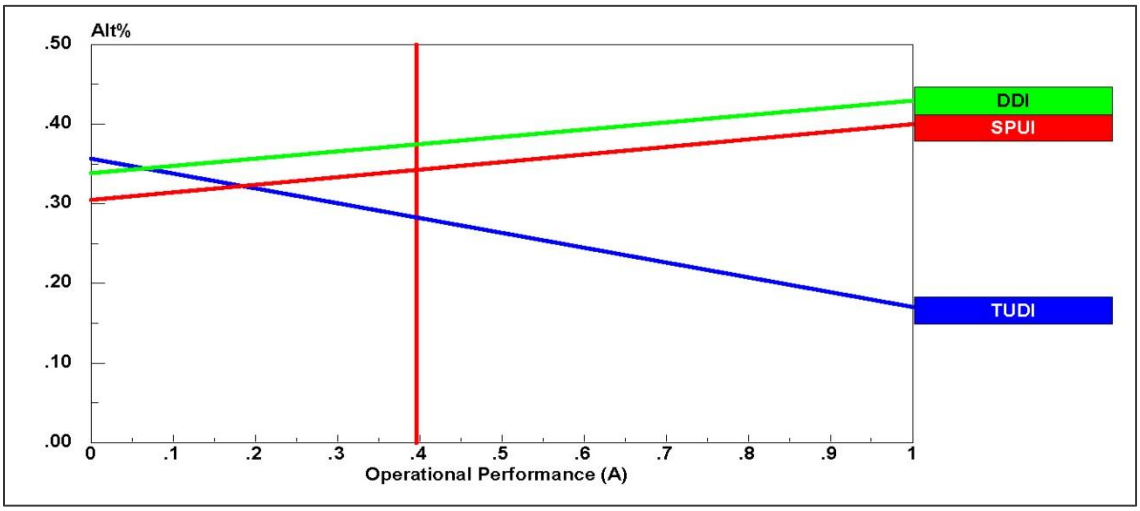

Figure 4-64: Impact of “Operational Performance” criteria group weights on the prioritization of interchanges

Figure 4-61 portrays the sensitivity of rankings with respect to the weight of the socio-environmental impacts criterion. Using the computed weight (0.120) of the aggregate group for “Socio-Environmental Impacts (B)” criteria group, the DDI ranked first followed by the SPUI and TUDI, respectively. As shown in the below plot, the higher the weight that is assigned to the socio-environmental impacts, the higher the composite score of TUDI whereas the DDI and SPUI’s composite scores become lower. Based on the below figure, the DDI retains the first rank whenever the weight of criterion (B) remains below 43%. On the other hand, the TUDI overtakes the ranking of its interchange counterparts when the weight assigned to this criterion exceeds 43%. As for the SPUI, its rank remains second for all weights below than 28% on this criterion; beyond this weight the SPUI becomes the least preferred interchange type.

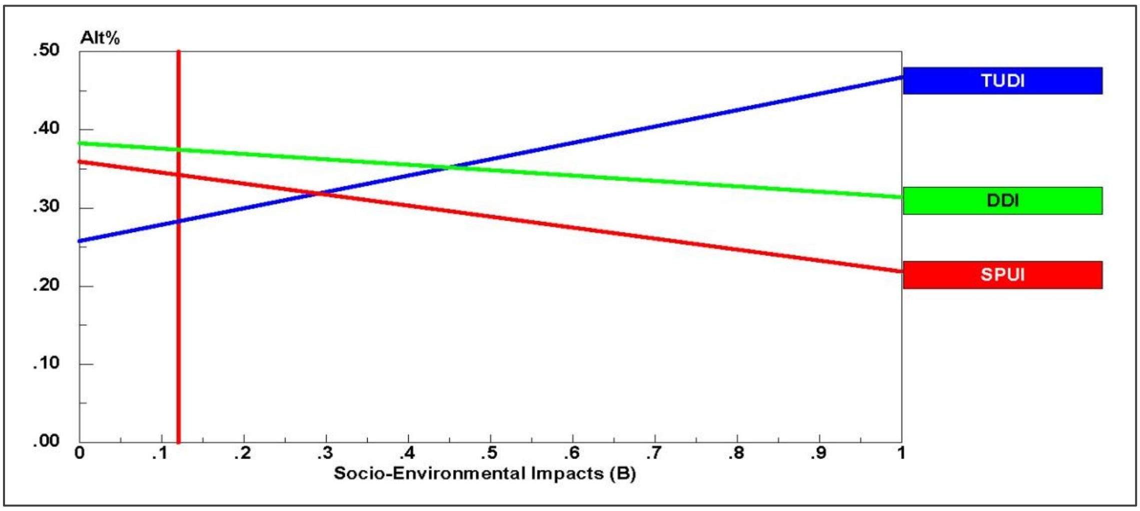

Figure 4-65: Impact of “Socio-Environmental Impacts” criteria group weights on the prioritization of interchanges

Figure 4-62 portrays the sensitivity of rankings with respect to the weight of the costs criterion. Using the computed weight (0.190) of the aggregate group for “Costs (C)” criteria group, the DDI ranked first followed by the SPUI and TUDI, respectively. As shown in the below plot, the higher the weight that is assigned to the costs, the higher the composite score of DDI and TUDI whereas SPUI’s composite score becomes lower. In addition, it is worthy to note that all three interchange types retain all their rankings regardless of the weight assigned on this criterion. The DDI remains the preferred interchange type whereas the TUDI ranks the lowest.

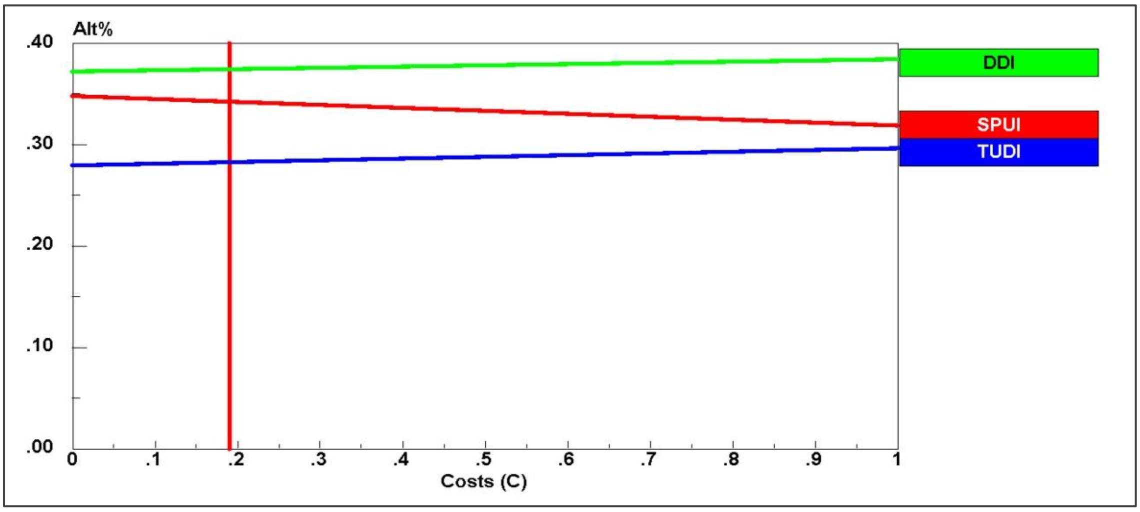

Figure 4-66: Impact of “Costs” criteria group weights on the prioritization of interchanges

Figure 4-63 shows the sensitivity of rankings with respect to the weight of the safety criterion. Using the computed weight (0.294) of the aggregate group for “Safety (D)” criteria group, the DDI ranked first followed by the SPUI and TUDI, respectively. As shown in the below plot, the higher the weight that is assigned to the safety, the higher the composite score of TUDI whereas the DDI and SPUI’s composite scores become lower. According to the below figure, all interchange types retain their rankings whenever the weight assigned on this criterion remains below 86%. Beyond this value, the DDI ranks third, the TUDI becomes the most preferred interchange configuration while the SPUI remains second.

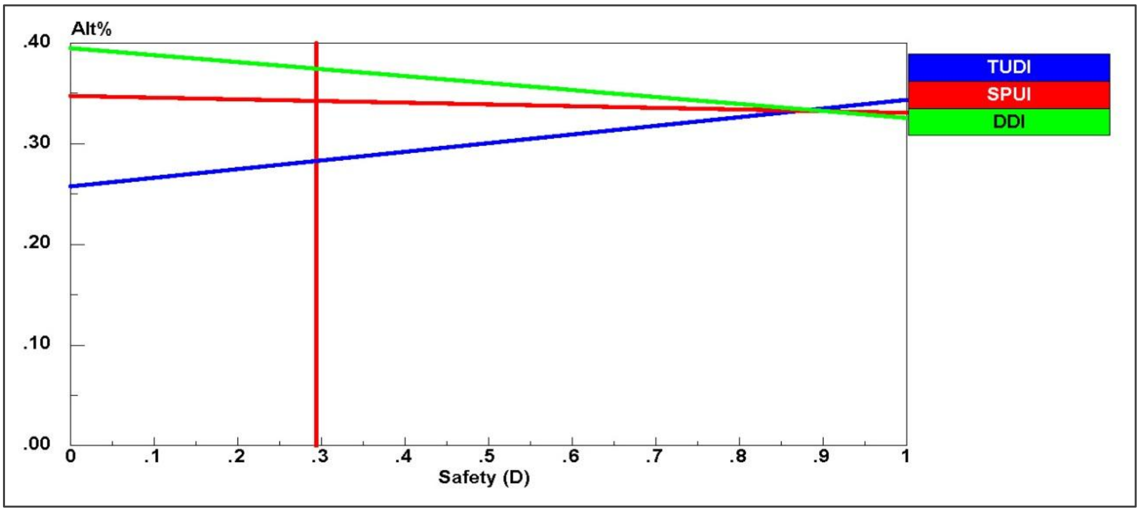

Figure 4-67: Impact of "Safety" criteria group weights on the prioritization of interchanges

4.5 Summary

The proposed interchange prioritization framework was applied for a case study in Riyadh, KSA. The performance of three types of interchanges (TUDI, SPUI, and DDI) was evaluated based on which a score was assigned using the proposed scoring functions. Consequently, and after applying the criteria weights, an overall score was determined for each alternative and the DDI was found as the preferred interchange configuration, followed by the SPUI and TUDI, respectively. Finally, sensitivity tests were explored to examine the effects of changing several factors on the overall ranking. These tests comprise changing the traffic volumes, scoring functions and even the weights to analyze their impacts on the overall ranking. These tests revealed the robustness of the case study results as the interchange prioritization remained the same at different tested scenarios and among the different groups.

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CHAPTER 5

CONCLUSIONS

5.1 Contributions

This research presented a framework for prioritizing Arterial/Freeway interchange types using multi-criteria analysis. Compared to previous studies, this research makes the following major contributions:

1. This research comprehensively reviewed previous studies pertaining to the operational performance, socio-environmental impacts, costs, and safety of three Arterial/Freeway interchanges (TUDI, SPUI, and DDI). Based on this review, several performance measures were identified and compared with the results of this study.
2. This research pointed out the advantages and disadvantages of each of these interchange types and presented a summary of the evaluation metrics that were used in earlier research studies. In addition, this research presented a summary of the different microscopic simulation tools that were used in other research studies and identified the type of analysis conducted in each study.
3. In prioritizing the arterial/freeway interchange types, this research adopted a multi-criteria analysis rather than the conventional assessment approach that was used in other research efforts, such as the cost-benefit analysis. Accordingly, several weighting methodologies were considered and evaluated following which the AHP/Eigenvector

method was found the most appropriate method and was used in this research.

4. Through an online questionnaire, the judgments of several decision-makers were elicited based on which the relative importance of different criteria was determined. The corresponding weights that were assigned for each of the 17 criteria were used in the prioritization framework and were helpful in determining the overall ranking.
5. This research developed several scoring functions that were helpful in computing the scores of interchanges on the different criteria.This research proposed a case study at the intersection of Sheikh Jaber road and Prince Bandar Bin Abdulaziz road in the city of Riyadh, KSA. This case study compared three arterial/freeway interchange types using the proposed prioritization framework. The results of the study showed that the DDI outperformed the other interchange types and was also the most preferred after conducting several sensitivity tests. The SPUI ranked second, followed by the TUDI that was least preferred.
6. Finally, this research demonstrated the robustness of the model results based on several sensitivity tests in different areas of the model namely in the measurement of performance of the options on each criterion, in the form of the scoring functions, and in the weights.

5.2 Findings

This research aimed to develop a framework for prioritizing Arterial/Freeway interchange types using Multi-Criteria analysis. A case study was used to illustrate the proper implementation of the developed prioritization framework. The key findings of this research are provided below:

1. Among the four main criteria groups, "*Operational Performance (A)*" had the highest weight (0.396) reflecting its importance as perceived by the different decision-maker groups. Following the operational performance of interchanges, "*Safety (D)"* ranked second in importance (weight = 0.294) followed by "*Costs (C)"* with a weight of (0.190) and "*Socio-Environmental Impacts (B)"* as the least important (weight = 0.120).
2. Under the Operational Performance criteria group, "*Level of Service (A1)*" was found to be the most important primary criterion having a weight of (0.506) within its own segment. Similarly, "*Accessibility Impact on Existing Economic Activities (B1)*" was found as a key criterion under the socio-environmental impacts group. Likewise, *"Economic Costs (C1)"* and *"Crash Frequency Experience (D1)"* were found to be the most influential criteria within the Costs (C) and Safety (D) criteria groups, respectively.
3. Out of the 17 criteria that were used in the framework, the five criteria that have the highest impact on the prioritization of interchanges are listed in order below:
    a. D1: Crash Frequency Experience (weight = 0.207)

    b. A1-1: Intersection Delays (weight = 0.153)
    c. C1-1: Total Travel Time Savings (weight = 0.101)
    d. A2: Average Number of Stops (weight = 0.063)
    e. B1: Accessibility Impact on Existing Economic Activities (weight = 0.061)

4. Through a case study implemented at the intersection of Sheikh Jaber road and Prince Bandar Bin Abdulaziz road in the city of Riyadh, three different interchange types (TUDI, SPUI, and DDI) were prioritized using multi-criteria analysis. In general, no single interchange outperformed the other types on all criteria thus no preference was directly perceived. Each interchange configuration performed better on certain criteria and consequently scored higher on these criteria. The following demonstrates the criteria on which each interchange performed the best:
    a. <u>TUDI</u>
        i. ***A4-3: Pedestrian Crossing Distance*** due to geometric design and the interchange configuration.
        ii. ***B1: Accessibility Impact on Existing Economic Activities*** due to the accommodation of through traffic and the low distance imposed by the interchange whereby no access to local activities is allowed.
        iii. ***B2: Noise*** due to the geometric design of this interchange and the roadway configuration in between the ramp terminals.

        iv. ***D2-1: Potential Driver Confusion*** due to the defined path, direct traffic movement direction, and compact intersection area.

    b. SPUI

        i. ***A2: Average Number of Stops*** due to the stoppage of vehicles at only one signalized intersection.
        ii. ***A4-2: Presence of Conflicting Protected Traffic*** due to geometric configuration of this interchange as only two locations were identified for traffic conflicting with the crossing of pedestrians.
        iii. ***C1-2: Vehicle Operating Cost Reductions*** due to the speed and volume of vehicles.

    c. DDI

        i. ***A1-1: Intersection Delays*** due to the highest level of service achieved.
        ii. ***A1-2: Average Delay for All Left-Turning Movements*** due to the free flow movements for the left-turning traffic after crossing over to the opposite side of the intersection.
        iii. ***A3: Maximum Queue Length*** due to the short cycle length needed at the signalized intersections and consequently the low number of vehicles that may stop and remain in queue.
        iv. ***A4-1: Average Pedestrian Waiting Time at Signalized Intersection*** due to the need for only two phases for the signalized intersections.
        v. ***B3: Vehicle Emissions*** due to the high speed of vehicles.

    vi. ***C1-1: Travel Time Savings*** due to the low delays observed at the interchange as compared to the at-grade intersection.
    vii. ***C2-1: Construction Costs*** due to the smaller bridge structure needed to span the intersection.
    viii. ***C2-2: Right-of-Way Costs*** due to the geometric design of the interchange and the number of lanes needed in between the signalized intersections.
    ix. ***D2-2: Potential Number of Conflict Points*** due to the geometric configuration resulting in the lowest potential number of merging, diverging and crossing conflict points.
5. Using a linear additive model, the weighted scores of each alternative are computed. The results of the study showed that the DDI outranked its interchange counterparts and was chosen as the most preferred interchange configuration for the case study. The SPUI ranked second while the TUDI was least preferred.
6. This research presented the procedures used in the different models that were helpful in scoring the criteria. These models comprise: (i) the VISSIM traffic model, (ii) the Traffic Noise Model (TNM), and (iii) the vehicle emissions model.
7. Sensitivity tests were also considered in this research to explore the effects of changing several factors on the overall ranking. These tests demonstrated the reliability of the results through considering the following scenarios:
    a. <u>Increasing traffic volumes</u>

    i. TUDI was found to be more sensitive than other configurations in terms of *"Intersection delays (A1-1)"* and "*Average delay for all left-turning movements (A1-2)*".
    ii. TUDI experienced a high number of stops with increasing traffic volumes. SPUI retained first rank among all scenarios.
    iii. Regarding the queue lengths, both SPUI and DDI experienced lower queues than TUDI. The DDI retained the first rank on all tested scenarios.
    iv. TUDI outperformed its counterparts on the generated levels of noise and VOC reductions, whereas the DDI retained its first rank on vehicle emissions.
    v. In general, the DDI configuration remained the most preferred alternative under all volume scenarios. The SPUI ranked second followed by the TUDI.

b. <u>Using unbalanced volume scenarios</u>
    i. Under unbalanced volume scenarios, the DDI outperformed the other types and ranked first on *"Intersection delays (A1-1)"* and "*Average delay for all left-turning movements (A1-2)*".
    ii. The SPUI ranked second followed by the TUDI that was the least preferred.

c. <u>Other tested scenarios</u>
    i. The use of 5% of trucks rather than 2% increased drastically the generated levels of noise. Consequently, around 70% of the defined area breached the international regulations; thus,

on this criterion all interchanges were sensitive to traffic composition.

   ii. Regardless of any new technology that might reduce the construction costs of interchanges, the SPUI, being the most expensive, retained its second rank overall.
   iii. Due to the unavailability of crash data statistics, additional scenarios were tested to determine the possibility of any change in the overall ranking. The results showed that the possibility of TUDI ranking first was found to be unrealistic and the possibility of SPUI ranking first was unlikely to happen.

d. Sensitivity with Respect to Criteria Weights
   i. It was concluded that the ranking of interchanges was the same among all decision-maker groups. In other words, regardless of the nature of the decision-makers, the same preferences are made; this reinforces the robustness of the results regarding the selection of the preferred interchange type.
   ii. Considering the weights of each criteria group separately, all interchange types retained their overall ranking. The DDI remained the most preferred interchange type when analyzing the operational performance, socio-environmental impacts, safety, and costs separately of all interchanges. In addition, the DDI was found to retain its first rank under each of the following situations:

1. Operational Performance (A): for all weights greater than 10%.
2. Socio-Environmental Impacts (B): for all weights less than 43%.
3. Costs (C): for all assigned weights.
4. Safety (D): for all weights less than 86%.

5.3 Future Research

Although this research made a comprehensive analysis of the three different Arterial/Freeway interchange types and examined their performances on an actual case study, several areas can be studied further. Some areas for further research are recommended as outlined below:

1. This research presented a methodology for prioritizing three types of Arterial/Freeway interchange types, namely: TUDI, SPUI, and DDI. However, this study did not comprehensively examine other in-use similar interchange configurations, such as roundabout diamond interchanges.
2. Similarly, the prioritization framework provided in this research could be expanded to include all interchange classifications, such as: Arterial/Arterial interchanges, Freeway/Freeway interchanges, and the like. Accordingly, the proposed scoring functions should be examined thoroughly to include all performance measure ranges.
3. The design concepts studied in this research should be further expanded to accommodate a wider range of geometrical interchange configurations. In other words, each of the three types can still be

analyzed according to different options such as providing the signalized intersection at-grade whereas the through movements along the highway can cross freely as an underpass or overpass. Alternatively, the intersection can be elevated over the at-grade highway. These feasible scenarios have substantial impacts on the scoring of different criteria, such as: "*Accessibility Impacts to Existing Economic Activities (B1")*, "*Noise (B2)", "Construction Costs (C1-2)"*, and *"Right-of-Way Costs (C2-2);* hence, they should be considered in future studies.

4. Despite conducting the analyses using a large set of traffic volume scenarios, care should be taken to analyze the interchange as a part of the adjacent road network. In other words, any improvement on the road geometry along this interchange would have impacts on the nearby intersections. Consequently, the most preferred interchange type should be determined taking into account its impacts on the overall road network.
5. In determining the relative importance of criteria and the corresponding weights, it would be interesting to elicit judgments from decision-makers of different cultures and contexts and determine whether there are any differences in the computed results.
6. Upon the availability of crash data statistics for the three interchange types, the relative scores of each on this criterion should be determined using the proposed scoring functions. The overall scoring and the corresponding ranking are to be examined to identify if there is any change in the prioritization of interchanges.

7. Future research should focus on evaluating the performance of interchanges according to the generated vehicular emissions for all greenhouse gases and not just HC and CO gas emissions. Accordingly, the effect of NOx, $CO_{2,}$ and other greenhouse gases should be examined in future studies.
8. Utilize driving simulator experiments to examine the driving behavior at all interchanges and consequently quantify potential driver confusion.
9. Consider the total construction costs of interchanges rather than focusing only on the concrete and steel structural works. Although this might not change the interchange preferences, it would be always beneficial, especially from a client’s perspective, to determine the total construction costs.

BIBLIOGRAPHY

Abbyad, R., & Kaysi, I. (2011). Prioritization of national road projects in saudi arabia: Weighting of multiple criteria. *The Sustainable World,* , 501.

Afshar, A. M., Bared, J. G., Wolf, S., & Edara, P. K. (2009). Traffic operational comparison of single-point and diverging diamond interchanges. *Transportation Research Board 88th Annual Meeting(no. 09-2939).* 21p.

Amer, A. (2009). Tight diamond interchange versus single point urban interchange: Pedestrians prospective. *Paper Submitted to the Student Paper Competition of the 2nd International Symposium on Freeway and Tollway Operations.,*

American Association of State Highway and Transportation Officials. (2004). *A policy on geometric design of highways and streets*. Washington, D.C: American Association of State Highway and Transportation Officials.

Anderson, M., Schroer, B., & Moeller, D. (2012). Analyzing the diverging diamond interchange using discrete event simulation. *Modelling and Simulation in Engineering, 2012*(47) doi:10.1155/2012/639865

Arab News. (2014). Metro work will disrupt traffic, governor tells riyadh residents. Retrieved from http://www.arabnews.com/news/619571

Arriyadh Development Authority. (2004). Arriyadh city population estimates. Retrieved from http://www.arriyadh.com/Eng/Ab-Arriyad/Content/getdocument.aspx?f=/openshare/Eng/Ab-Arriyad/Content/AboutArRiyadh_21.doc_cvt.htm

Avineri, E., Prashker, J., & Ceder, A. (2000). Transportation projects selection process using fuzzy sets theory. *Fuzzy Sets and Systems, 116*(1), 35-47.

Ballestero, E., Antón, J. M., & Bielza, C. (2003). Compromise-based approach to road project selection in madrid metropolitan area. *Journal of the Operations Research Society of Japan-Keiei Kagaku, 46*(1), 99.

Baltussen, R., Stolk, E., Chisholm, D., & Aikins, M. (2006). Towards a multi-criteria approach for priority setting: An application to ghana. *Health Economics, 15*(7), 689-696.

Bared, J. G., Edara, P. K., & Jagannathan, R. (2005). Design and operational performance of double crossover intersection and diverging diamond interchange. *Transportation Research Record,* (1912), 31.

Bared, J. G., Powell, A., & Kaisar, E. (2003). Traffic planning models for single-point and tight diamond interchanges. *Transportation Research Record, 1847*((1)), 52.

Bared, J. G. (2009). *Double crossover diamond interchange.* (No. FHWA-HRT-09-054). McLean, VA: Tech Brief.

Bared, J. G., Granda, T., & Zindeddin, A. (2007). *Drivers' evaluation of the diverging diamond interchange.* (No. FHWA-HRT-07-048). McLean, VA: Tech Brief.

Bared, J. G., Powell, A., Kaisar, E., & Jagannathan, R. (2005). Crash comparison of single point and tight diamond interchanges. *Journal of Transportation Engineering, 131*(5), 379. doi:10.1061/(ASCE)0733-947X(2005)131:5(379)

Berechman, J., & Paaswell, R. E. (2005). Evaluation, prioritization and selection of transportation investment projects in new york city. *Transportation, 32*(3), 223-249.

Butt, M. F. (2012). *A Practical Perspective on the Benefits of Combined Traffic Assignment and Control Models,*

Chatterjee, A. (1997). *Improving transportation data for mobile source emission estimates* Transportation Research Board.

Chaudhary, N. A., & Chu, C. (2000). *Guidelines for timing and cordinating diamond interchanges with adjacent traffic signals.* (No. TX-00/4913-2).Texas Transportation Institute, Texas A & M University System.

Chilukuri, V., Siromaskul, S., Trueblood, M., & Ryan, T. (2011). *Diverging diamond interchange: Performance evaluation (I-44 and route 13).* (No. OR 11-012). Jefferson City, MO: HDR Engineering and MODOT.

Chlewicki, G. (2003). New interchange and intersection designs: The synchronized split-phasing intersection and the diverging diamond interchange. *2nd Urban Street Symposium: Uptown, Downtown, Or Small Town: Designing Urban Streets that Work,* Anaheim, CA.

Chlewicki, G. (2010). Operational effects of diverging diamond interchange. *89th Transportation Research Board Annual Meeting DVD,* Washington, D.C. 15p.

Chlewicki, G. (2012). *Learning from six (plus) operational DDIs in the US. 2012 ITE Midwestern District Conference and TRB 4th Urban Street Symposium, 2012,*

Chlewicki, G. (2011). Should the diverging diamond interchange always be considered a diamond interchange form? *Transportation Research Record,* (2223), 88.

CORSIM User's Manual. (2012). . Colorado Springs, CO: ITT Systems & Sciences Corporation.

Department of Communities and Local Governments. (2009). Multi-criteria analysis: A manual. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf

Diakoulaki, D., & Grafakos, S. (2004). Multicriteria analysis, ExternE-pol (externalities of energy: Extension of accounting framework and policy applications), final report on work package 4Directorate general external relations, directorate general development, joint évaluation unit (2006). *Évaluation Methods Far Thè European Union's External Assistance.Methodological Bases Far Evaluation,*

Dorothy, P. W., Maleck, T. L., & Aylsworth-Bonzelet, L. (1997). Field analysis of operation and design of single-point urban interchanges. *Transportation Research Record,* (1579), 11.

Douligeris, C., & Pereira, I. (1992). An analytical hierarchy process approach to the analysis of quality in telecommunication systems. *Network, 101,* 121.

Dowling, R., Skabardonis, A., & Alexiadis, V. (2004). Traffic analysis toolbox volume III: Guidelines for applying traffic microsimulation modeling software.

European Commission. (1988). A methodology for policy analysis and spatial conflicts in transport policies. *Edited by Euro Beinat, Report no. R98/08 of 31/07/98,*

Expert Choice. (2014). Expert choice for collaborative decision making. Retrieved from http://expertchoice.com/about-us/our-decision-making-methodology/

Fang, F. C., & Elefteriadou, L. (2005). Some guidelines for selecting microsimulation models for interchange traffic operational analysis. *Journal of Transportation Engineering, 131*(7), 535-543. doi:10.1061/(ASCE)0733-947X(2005)131:7(535)

Federal Highway Administration.Traffic noise model. Retrieved from http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/

Galletebeitia, B. (2011). *Comparative analysis between the diverging diamond interchange and partial cloverleaf interchange using microsimulation modeling* (Degree of Masters of Science).

Garber, N. J., & Fontaine, M. (1999). *Final report-guidelines for preliminary selection of the optimum interchange type for a specific location.* (No. VTRC 99-R15). VDOT: Virginia Transportation Research Council.

Garber, N. J., & Smith, M. J. (1996). *Comparison of the operational and safety characteristics of the single point urban and diamond interchanges.* (No. FHWA/VA-97-R6).Virginia Transportation Research Council.

Guerrieri, M., & Corriere, F. (2013). An international review on one and two level innovative unconventional intersection and interchange. *ARPN Journal of Engineering and Applied Sciences, 8*(12), 1059-1070.

Hankard, M., Cerjan, J., & Leasure, J. (2006). Evaluation of the FHWA traffic noise model, TNM, for highway traffic noise prediction in the state of colorado.

Hiroyuki, T. (2000). Decision analysis. in: Handbook of industrial automation., 369-376.

Hu, P. (2013). *Advanced signal control strategies and analysis methodologies for diverging diamond interchanges* (Doctor of Philosophy in Civil Engineering).

Hughes, W., Jagannathan, R., Sengupta, D., & Hummer, J. E. (2010). *Alternative intersections/interchanges: Informational report (AIIR).* (No. FHWA-HR-09-060). McLean, VA: USDOT.

Hush, D., & Albeck, J. (2001). *Synchro user guide*. AC: Trafficware, Albany.

Jones, E. G., & Selinger, M. J. (2003). A comparison of operations of single-point and tight urban diamond interchanges. *Transportation Research Record,* (1847), 29.

Kaysi, I., Al-Hathlool, H., Darwish, F., & Sayour, M. (2013). Prioritization of national road projects in saudi arabia: Framework and implementation. *17th International Road Federation (IRF) World Meeting and Exhibition 2013,*

Kulkarni, R. B., Miller, D., Ingram, R. M., Wong, C., & Lorenz, J. (2004). Need-based project prioritization: Alternative to cost-benefit analysis. *Journal of Transportation Engineering, 130*(2), 150-158.

Liberatore, M. J., & Nydick, R. L. (2008). The analytic hierarchy process in medical and health care decision making: A literature review. *European Journal of Operational Research, 189*, 194-207.

Maji, A., Mishra, S., & Jha, M. K. (2013). Diverging diamond interchange analysis: Planning tool. *Journal of Transportation Engineering, 139*(12), 1201.

Martinez, J. A., & Cheu, R. L. (2012). Double crossover versus conventional diamond interchanges both with frontage roads. *Journal of Transportation of the Institute of Transportation Engineers, 4*(1)

Menge, C., Rossano, C., Anderson, G., & Bajdek, C. (1998). FHWA traffic noise model: Technical manual. *FHWA Traffic Noise Model, Version 1: Technical Manual, Federal Highway Administration, US Department of Transportation,*

MoDOT. (2010). *Missouri's experience with a diverging diamond interchange* - *lessons learned.* (No. OR 10-021). Jefferson City: MO.

Olsson, L. (1994). Motor vehicle air pollution control in sweden. *Science of the Total Environment, 146*, 27-34.

Ongprasert, S., & Todoroki, T. (2003). Recommendations of multi criteria analysis under multi actor decision condition in transport project evaluation. *Proceedings of the Eastern Asia Society for Transportation Studies, , 4*

Planung Transport Verkehr (AG). (2000). *ViSSIM user manual*. Germany:

Quartieri, J., Mastorakis, N., Iannone, G., Guarnaccia, C., D'Ambrosio, S., Troisi, A., & Lenza, T. (2009). A review of traffic noise predictive models. *Proceedings of the 5th WSEAS Int. Conf. on "Applied and Theoretical Mechanics"(MECHANICS'09), Puerto De La Cruz, Canary Islands, Spain,* 72-80.

Qureshi, M., Spring, G., Lasod, R., & Sugathan, N. (2004). *Design of single point urban interchanges.* (No. RDT 04-011). Jefferson City: MODOT.

Ressel, N. R. (2012). *Insights into the first three diverging diamond interchanges in missouri* (Masters of Science).

Saaty, T. L. (1980). The analytic hierarchy process, paperback edition. RWS Publications.

Saaty, T. L., & Alexander, J. M. (1989). *Conflict resolution: The analytic hierachy approach* RWS Publications.

Saaty, T. L., & Vargas, L. G. (2001). The seven pillars of the analytic hierarchy process. *Models, methods, concepts & applications of the analytic hierarchy process* (pp. 27-46) Springer.

Saaty, T. L. (2006). *Fundamentals of decision making and priority theory with the analytic hierarchy process*. Pittsburgh, Pa: RWS Publications.

Saaty, T. L., & Kearns, K. P. (1985). *Analytical planning: The organization of systems*. Oxford: Pergamon Press.

Saaty, T. L., & Vargas, L. G. (. G. (2012). *Models, methods, concepts & applications of the analytic hierarchy process*. New York: Springer.

Sadek, S., Bedran, M., & Kaysi, I. (1999). GIS platform for multicriteria evaluation of route alignments. *Journal of Transportation Engineering, 125*(2), 144-151.

Sadek, S., Kaysi, I., & Bedran, M. (2000). Geotechnical and environmental considerations in highway layouts: An integrated GIS assessment approach. *International Journal of Applied Earth Observation and Geoinformation, 2*(3), 190-198.

Salley, J., & Christo, A. (2012). Easing congestion in a new way – the first diverging diamond interchange in chicagoland. *2012 ITE Midwestern District Conference and TRB 4th Urban Street Symposium, 2012,* Chicago, IL.

Salmeron, J. L., & Herrero, I. (2005). An AHP-based methodology to rank critical success factors of executive information systems. *Computer Standards & Interfaces, 28*(1), 1-12.

Sbayti, H., El-Fadel, M., & Kaysi, I. (2002). Effect of roadway network aggregation levels on modeling of traffic-induced emission inventories in beirut. *Transportation Research Part D: Transport and Environment, 7*(3), 163-173.

Sharma, S., & Chatterjee, I. (2007). Performance evaluation of the diverging diamond interchange in comparison with the conventional diamond interchange. *2007 Transportation Scholars Conference,*

Sharp, W. H., & Selinger, M. J. (2000). Comparison of SPUI and TUDI interchange alternatives with computer simulation modeling. *ITE Annual Meeting Compendium of Technical Papers,* Washington, D.C.

Shefer, D., & Tsubari, V. (1990). Tribute plan evaluation method: An essay in memory of morris (moshe) hill. *Journal of Planning Education and Research, 10*(1), 5-14. doi:10.1177/0739456X9001000103

Siromaskul, S., & Speth, S. B. (2008). A comparative analysis of diverging diamond interchange operations. *ITE 2008 Annual Meeting and Exhibit,*

Stanek, D. (2007). Innovative diamond interchange designs: How to increase capacity and minimize cost. *Institute of Transportation Engineers Annual Meeting and Exhibit 2007,*

Survey Monkey. (2009). Survey monkey brand perception survey. Retrieved from https://www.surveymonkey.com/mp/aboutus/

Transportation Simulation System (TSS). (2002). In Version 4.1 (Ed.), *AIMSUN user manual*. Barcelona, Spain:

Tsamboulas, D. A. (2007). A tool for prioritizing multinational transport infrastructure investments. *Transport Policy, 14*(1), 11-26.

Tudela, A., Akiki, N., & Cisternas, R. (2006). Comparing the output of cost benefit and multi-criteria analysis: An application to urban transport investments. *Transportation Research Part A: Policy and Practice, 40*(5), 414-423.

UK Department of Communities and Local Government. (2009). DTLR multi-criteria analysis manual. Retrieved from http://www.communities.gov.uk/documents/corporate/pdf/146868.pdf

Vaughan, C., Cunningham, C., Schroeder, B., & Hummer, J. E. (2012). Early findings on the operational impacts of double crossover diamond interchanges. *ITE 2012 Annual Meeting & Exhibit,*

Wasil, E., & Golden, B. (2003). Celebrating 25 years of AHP-based decision making. *Computers and Operations Research, 30*(10), 1419-1420. doi:10.1016/S0305-0548(02)00184-3

Xiao, H., Ambadipudi, R. i., Hourdakis, J., & Michalopoulos, P. (2005). Methodology for selecting microscopic simulators: Comparative evaluation of AIMSUN and VISSIM.

Xu, H., Liu, H., Tian, Z., & Zhang, W. (2011). Control delay calculation at diverging diamond interchanges. *Journal of the Transportation Research Board, 2257*(1), 121.

Zhou, H., Zhao, J., Fries, R., & Pour Rouholamin, M. (2014). Statistical characteristics of wrong-way driving crashes on illinois freeways. *93rd Annual Meeting of Transportation Research Board,* Washington, DC. 14p.

Zura, M., & Lipar, P. (1995). The road and traffic environmental impact assessment and optimal room layout selection. *The Road and Traffic Environmental Impact Assessment and Optimal Room Layout Selection, ESRI User Conference 1995 Proceedings,*

APPENDIX A: ONLINE QUESTIONNAIRE

Questionnaire

Objective of Questionnaire

Research is being pursued at the Civil Engineering Department in the American University of Beirut (AUB) for prioritizing several highway interchange types using Multi-Criteria Analysis (MCA). The objective of this questionnaire is to help determine the relative weights of the criteria to be used in the multi-criteria analysis of the Arterial/Freeway Interchange type. It is very important for the assignment of criteria weights to be based on the judgment of key players (engineers, experts, and academics) who are familiar with this domain (interchange types) and therefore your input is highly appreciated.

You will be presented with a summary of the performance for each criterion including the best and worst expected performances. A detailed explanation of each criterion is also available to give you a better understanding of the research and facilitate the task of specifying your preferences and concluding the relative weights of the different criteria.

To do so, you will be asked to compare criteria in pairs in the section “YOUR PAIRWISE COMPARISONS” which has been designed specifically for the Multi-Criteria Analysis of the Arterial/Freeway Interchange type selection.

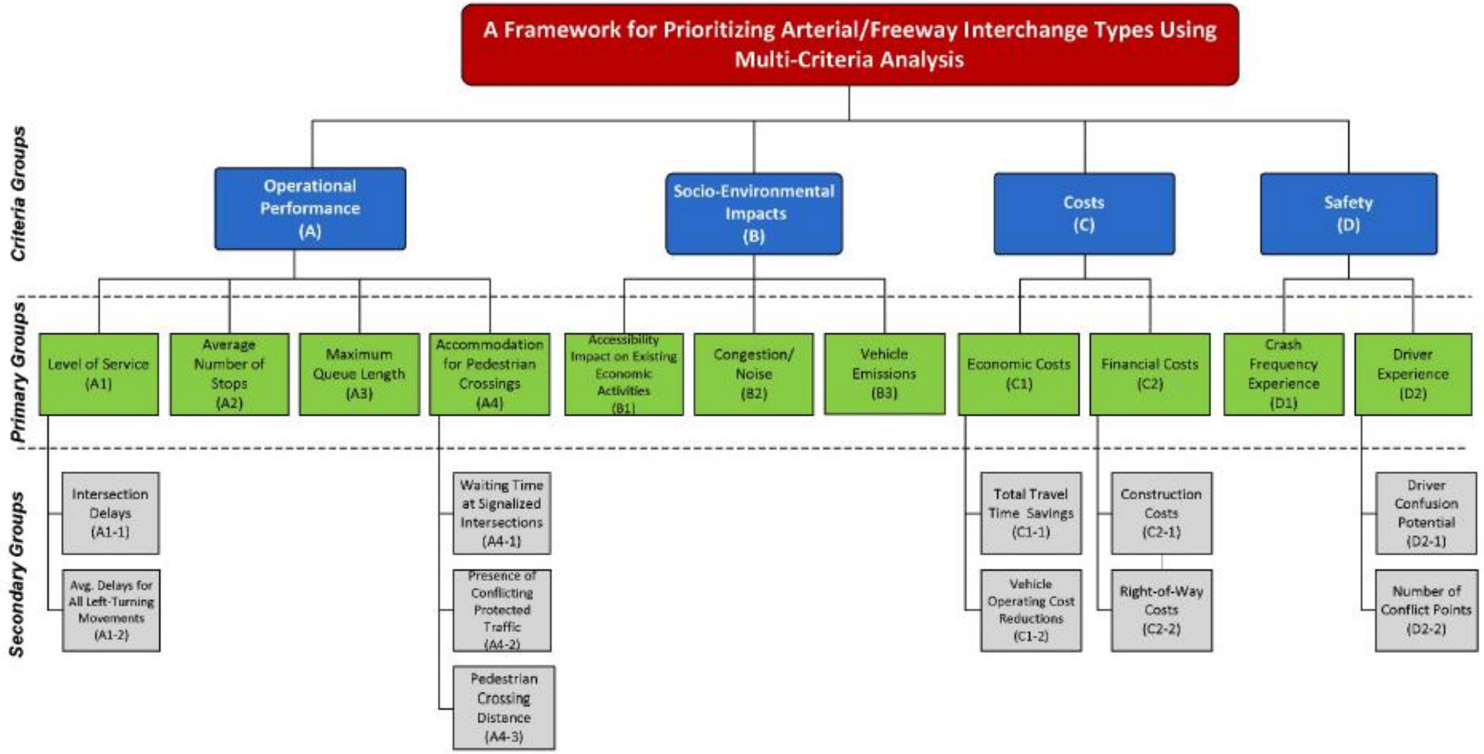
Questionnaire

Evaluation Framework

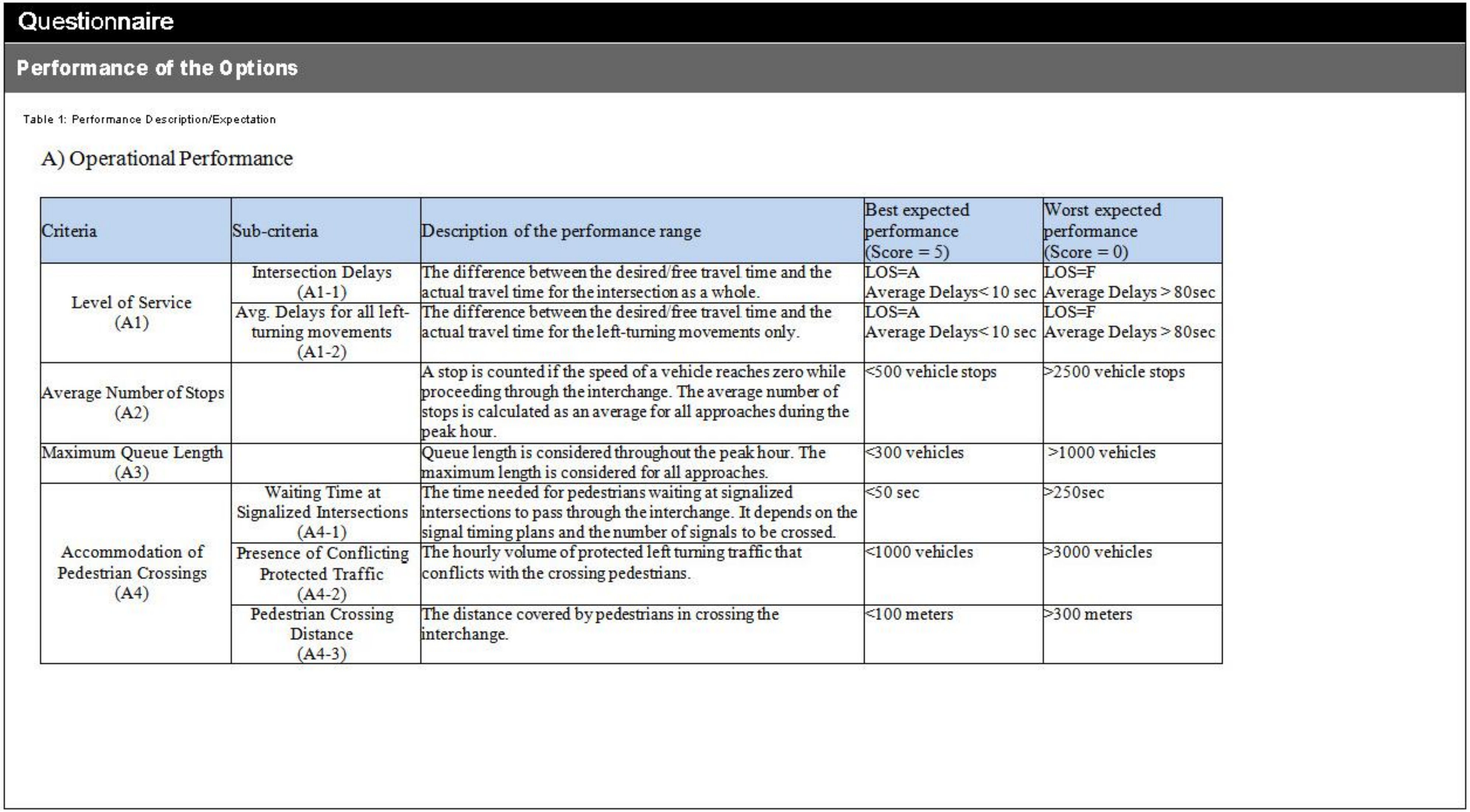
The prioritization of Arterial/Freeway Interchange types depends on several criteria that play a major role in determining the preferred interchange configuartion. A framework for prioritizing the interchange types has been developed based on the different criteria, as shown in the below Figure.

This framework depends on four main criteria groups. These groups include primary and secondary criteria as shown below. The main criteria groups include:
1. Operational Performance
2. Socio-Environmental Impacts
3. Costs
4. Safety

Questionnaire



For proper identification of the relative weights, it is important to be fully aware of the expected performance of the different options for each criterion. The best and worst performances expected are given in Table 1 below. The table also includes a description of the performance range for each criterion.



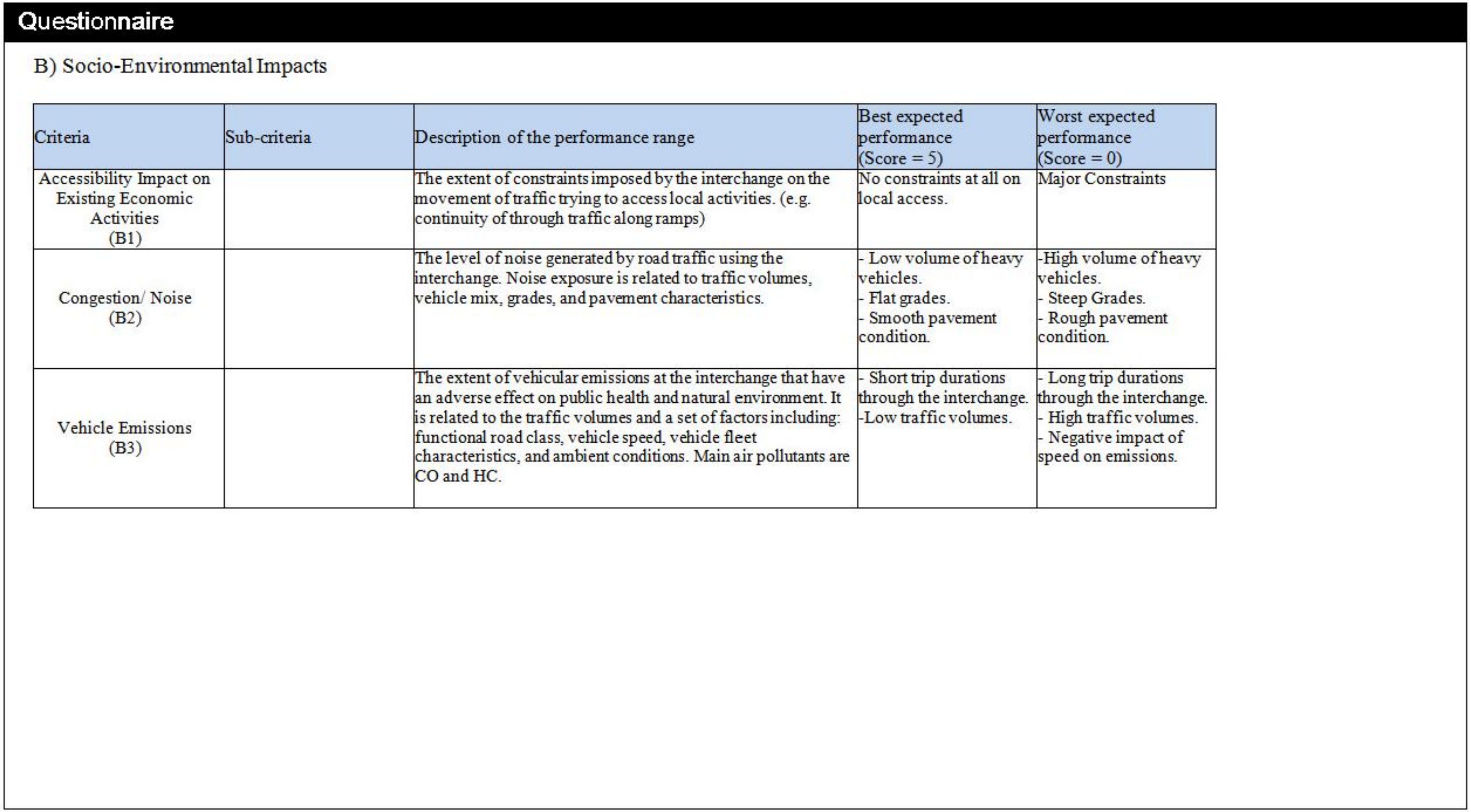
Questionnaire

Performance of the Options

Table 1: Performance Description/Expectation

A) Operational Performance

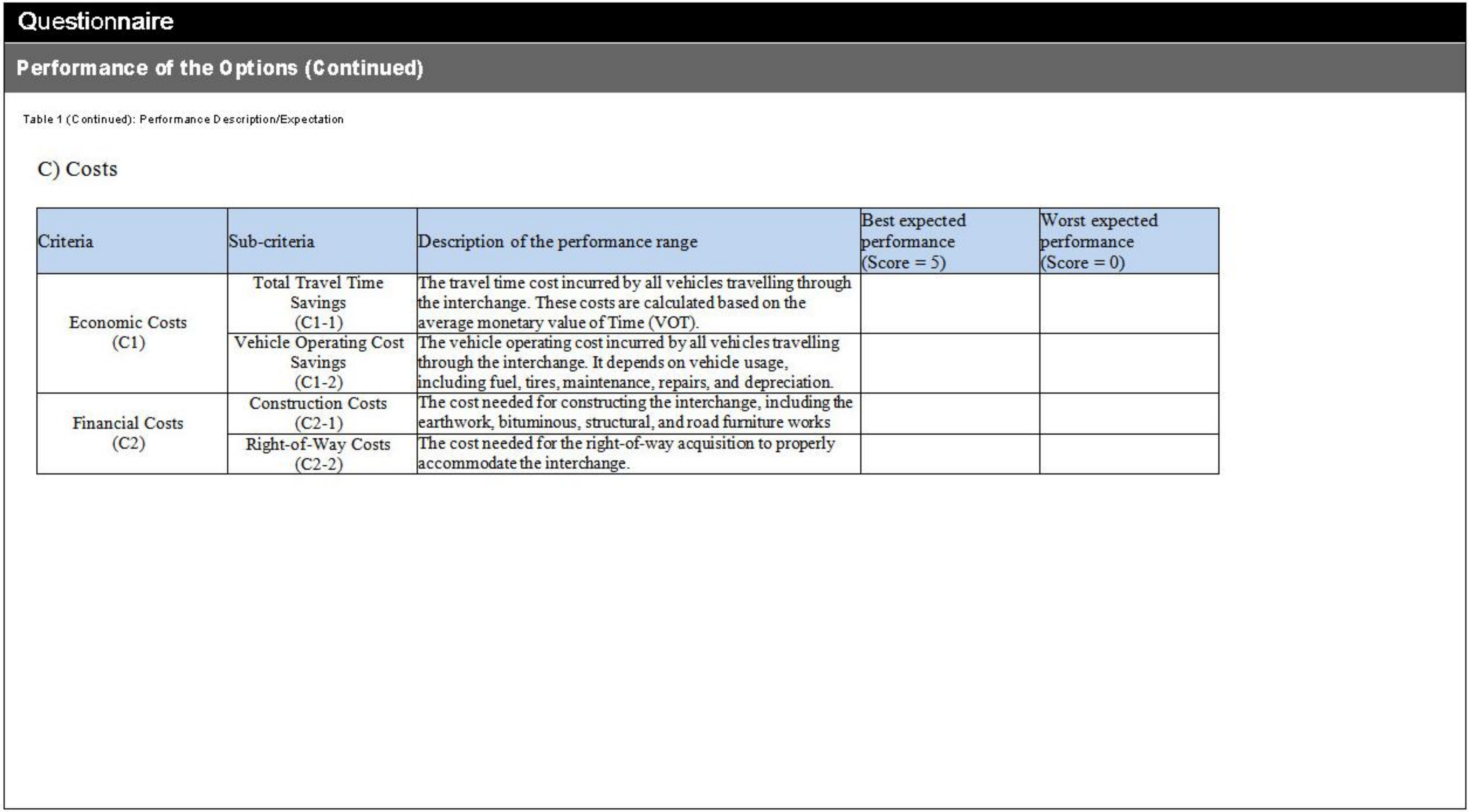
Criteria	Sub-criteria	Description of the performance range	Best expected performance (Score = 5)	Worst expected performance (Score = 0)
Level of Service (A1)	Intersection Delays (A1-1)	The difference between the desired/free travel time and the actual travel time for the intersection as a whole.	LOS=A Average Delays< 10 sec	LOS=F Average Delays > 80sec
	Avg. Delays for all left-turning movements (A1-2)	The difference between the desired/free travel time and the actual travel time for the left-turning movements only.	LOS=A Average Delays< 10 sec	LOS=F Average Delays > 80sec
Average Number of Stops (A2)		A stop is counted if the speed of a vehicle reaches zero while proceeding through the interchange. The average number of stops is calculated as an average for all approaches during the peak hour.	<500 vehicle stops	>2500 vehicle stops
Maximum Queue Length (A3)		Queue length is considered throughout the peak hour. The maximum length is considered for all approaches.	<300 vehicles	>1000 vehicles
Accommodation of Pedestrian Crossings (A4)	Waiting Time at Signalized Intersections (A4-1)	The time needed for pedestrians waiting at signalized intersections to pass through the interchange. It depends on the signal timing plans and the number of signals to be crossed.	<50 sec	>250sec
	Presence of Conflicting Protected Traffic (A4-2)	The hourly volume of protected left turning traffic that conflicts with the crossing pedestrians.	<1000 vehicles	>3000 vehicles
	Pedestrian Crossing Distance (A4-3)	The distance covered by pedestrians in crossing the interchange.	<100 meters	>300 meters



Questionnaire

B) Socio-Environmental Impacts

Criteria	Sub-criteria	Description of the performance range	Best expected performance (Score = 5)	Worst expected performance (Score = 0)
Accessibility Impact on Existing Economic Activities (B1)		The extent of constraints imposed by the interchange on the movement of traffic trying to access local activities. (e.g. continuity of through traffic along ramps)	No constraints at all on local access.	Major Constraints
Congestion/ Noise (B2)		The level of noise generated by road traffic using the interchange. Noise exposure is related to traffic volumes, vehicle mix, grades, and pavement characteristics.	- Low volume of heavy vehicles. - Flat grades. - Smooth pavement condition.	-High volume of heavy vehicles. - Steep Grades. - Rough pavement condition.
Vehicle Emissions (B3)		The extent of vehicular emissions at the interchange that have an adverse effect on public health and natural environment. It is related to the traffic volumes and a set of factors including: functional road class, vehicle speed, vehicle fleet characteristics, and ambient conditions. Main air pollutants are CO and HC.	- Short trip durations through the interchange. -Low traffic volumes.	- Long trip durations through the interchange. - High traffic volumes. - Negative impact of speed on emissions.



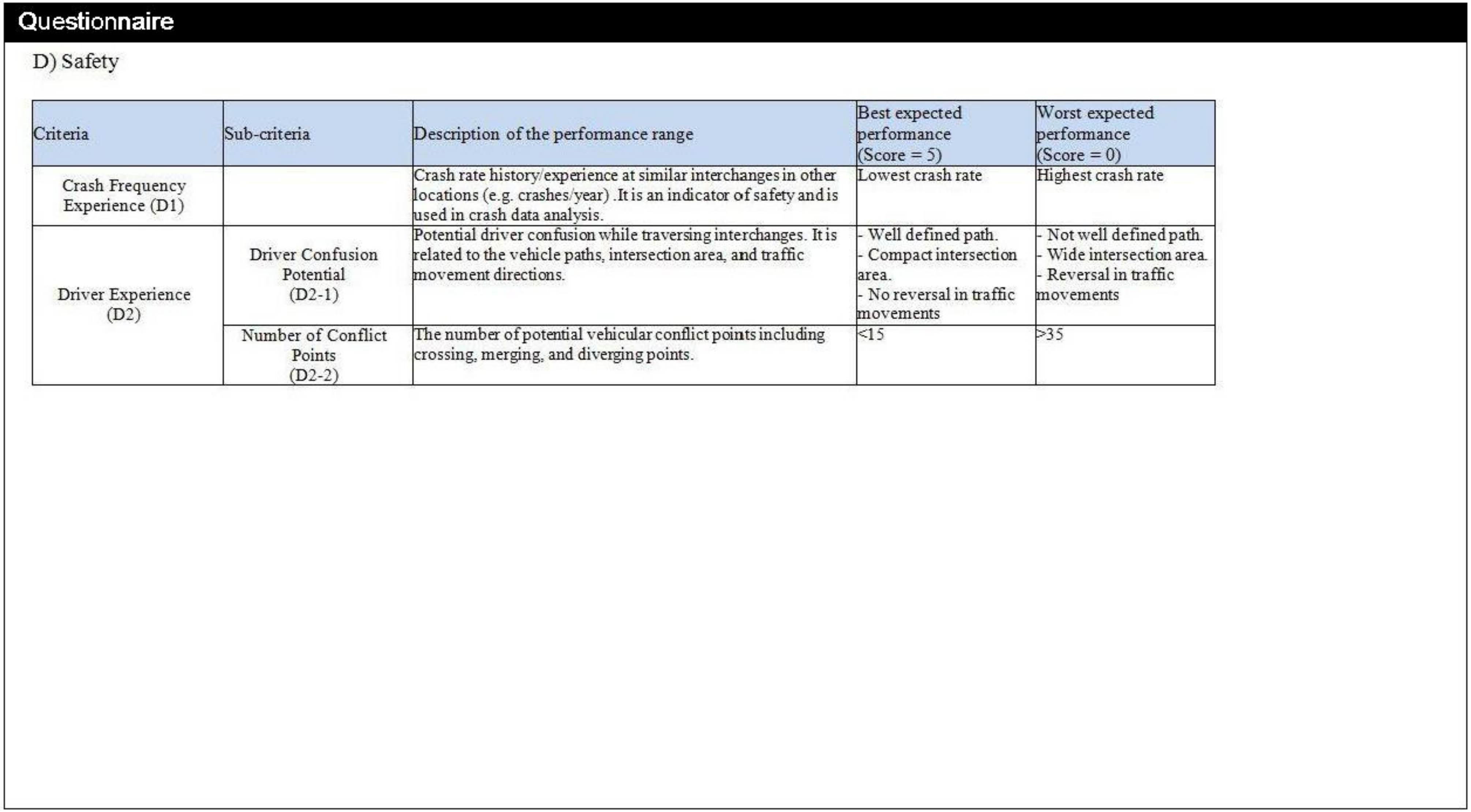
Questionnaire

Performance of the Options (Continued)

Table 1 (Continued): Performance Description/Expectation

C) Costs

Criteria	Sub-criteria	Description of the performance range	Best expected performance (Score = 5)	Worst expected performance (Score = 0)
Economic Costs (C1)	Total Travel Time Savings (C1-1)	The travel time cost incurred by all vehicles travelling through the interchange. These costs are calculated based on the average monetary value of Time (VOT).		
	Vehicle Operating Cost Savings (C1-2)	The vehicle operating cost incurred by all vehicles travelling through the interchange. It depends on vehicle usage, including fuel, tires, maintenance, repairs, and depreciation.		
Financial Costs (C2)	Construction Costs (C2-1)	The cost needed for constructing the interchange, including the earthwork, bituminous, structural, and road furniture works		
	Right-of-Way Costs (C2-2)	The cost needed for the right-of-way acquisition to properly accommodate the interchange.		



Questionnaire

D) Safety

Criteria	Sub-criteria	Description of the performance range	Best expected performance (Score = 5)	Worst expected performance (Score = 0)
Crash Frequency Experience (D1)		Crash rate history/experience at similar interchanges in other locations (e.g. crashes/year) .It is an indicator of safety and is used in crash data analysis.	Lowest crash rate	Highest crash rate
Driver Experience (D2)	Driver Confusion Potential (D2-1)	Potential driver confusion while traversing interchanges. It is related to the vehicle paths, intersection area, and traffic movement directions.	- Well defined path. - Compact intersection area. - No reversal in traffic movements	- Not well defined path. - Wide intersection area. - Reversal in traffic movements
	Number of Conflict Points (D2-2)	The number of potential vehicular conflict points including crossing, merging, and diverging points.	<15	>35

Questionnaire

The Method

To specify your preferences, please go to the section "YOUR PAIRWISE COMPARISON" where you will be asked to indicate the Preliminary Ranking of Criteria after which you will be asked to indicate (on a scale) the position that best describes your judgement regarding the relative importance of each pair of criteria. Please bear in mind that the comparisons need to be transitive i.e. if criterion A is more important than criterion B and Criterion B is more important than Criterion C then A should be more important than criterion C.

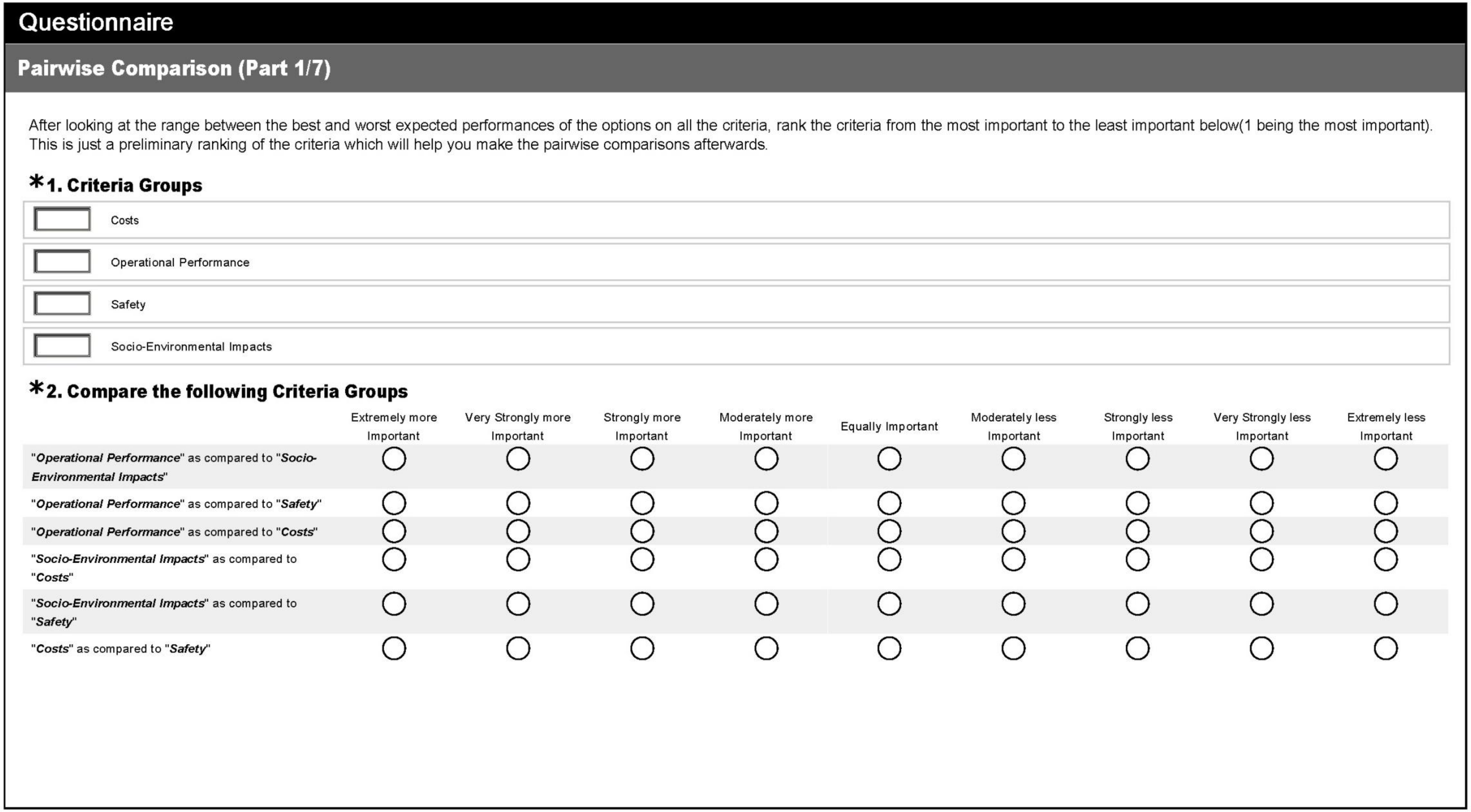
Step 1: Look at the range between the best and worst expected performances for the options on all the criteria. Then rank the criteria from the most important to the least indicating a Preliminary Ranking of Criteria. This will help you make judgements that are transitive.

Step 2: In the section "YOUR PAIRWISE COMPARISONS" look at the first pair of criteria that need to be compared.

Step 3: Look at the performance range for these two criteria by clicking on the provided link to download the performance expectation tables.

Step 4: Place on the scale the position that best describes your judgement. For example, if you think that both criteria are of equal importance, then you should place a tick in the middle of the scale. If you think that one criterion is more important than the other then make sure to select the option/position that best describes the relative importance of a single criterion as compared to another.

Step 5: Continue this process for all the criteria pairs, one after the other, always bearing in mind that the judgements should be transitive.



Questionnaire

Pairwise Comparison (Part 1/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least important below(1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

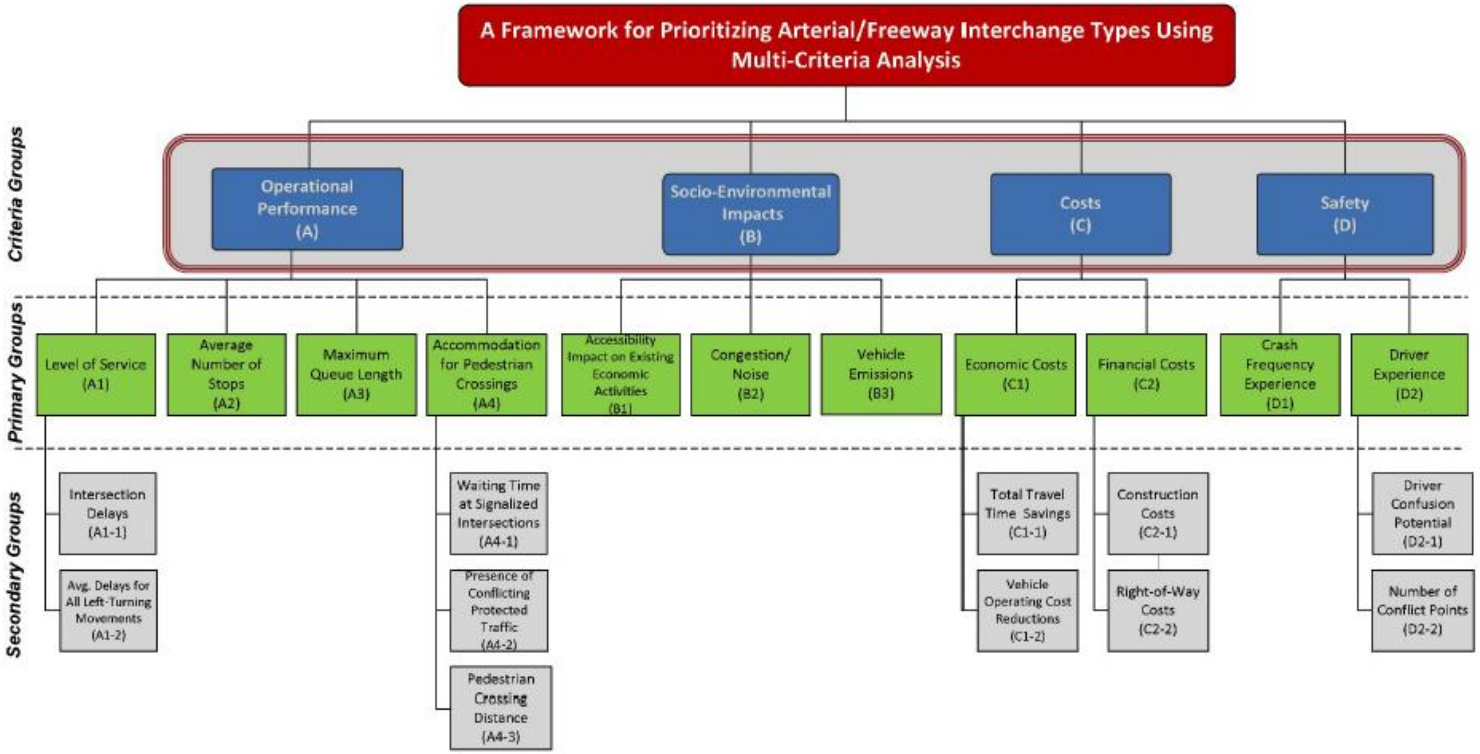
*1. Criteria Groups

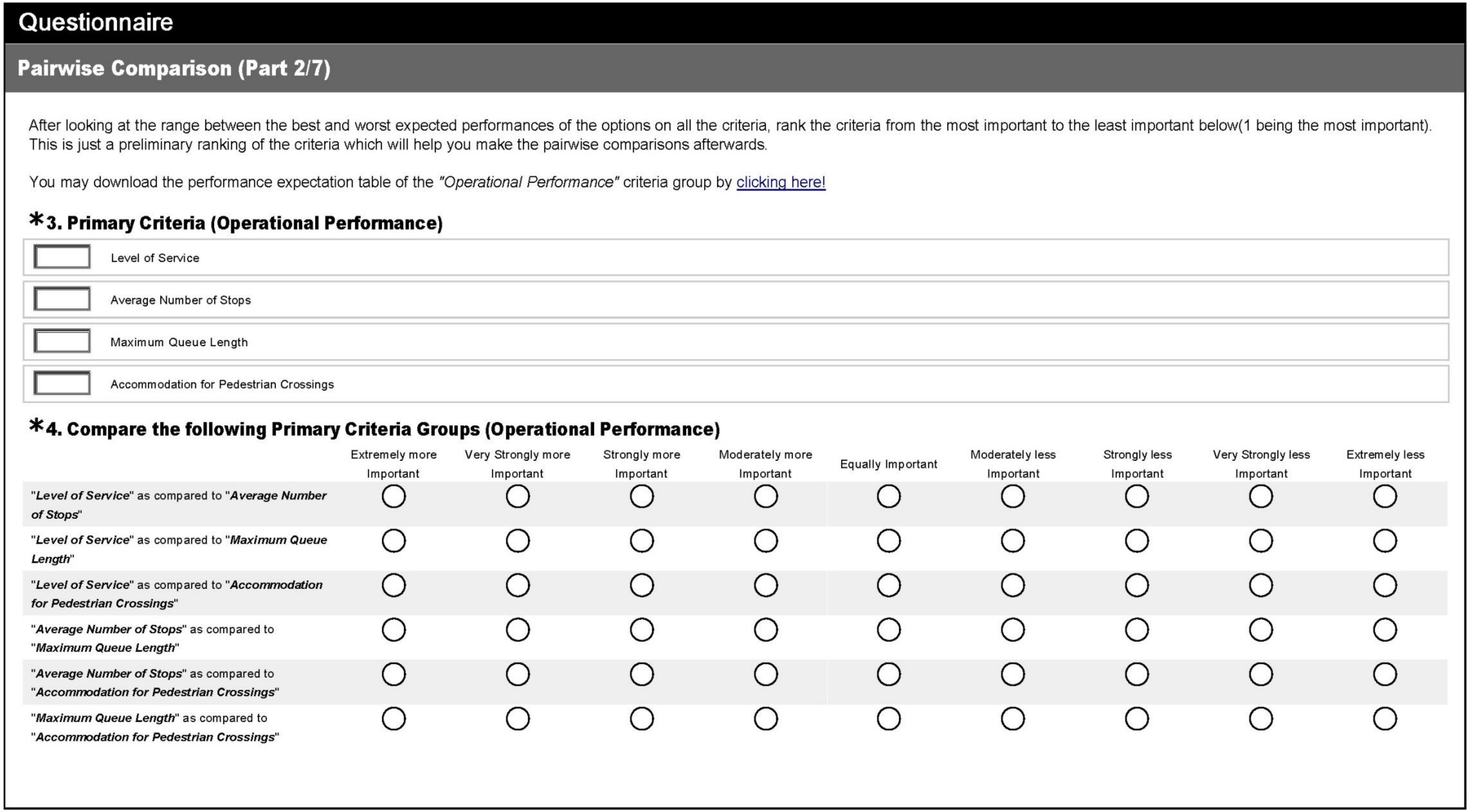
☐ Costs
☐ Operational Performance
☐ Safety
☐ Socio-Environmental Impacts

*2. Compare the following Criteria Groups

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Operational Performance***" as compared to "***Socio-Environmental Impacts***"	○	○	○	○	○	○	○	○	○
"***Operational Performance***" as compared to "***Safety***"	○	○	○	○	○	○	○	○	○
"***Operational Performance***" as compared to "***Costs***"	○	○	○	○	○	○	○	○	○
"***Socio-Environmental Impacts***" as compared to "***Costs***"	○	○	○	○	○	○	○	○	○
"***Socio-Environmental Impacts***" as compared to "***Safety***"	○	○	○	○	○	○	○	○	○
"***Costs***" as compared to "***Safety***"	○	○	○	○	○	○	○	○	○

Questionnaire





Questionnaire

Pairwise Comparison (Part 2/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least important below(1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

You may download the performance expectation table of the *"Operational Performance"* criteria group by clicking here!

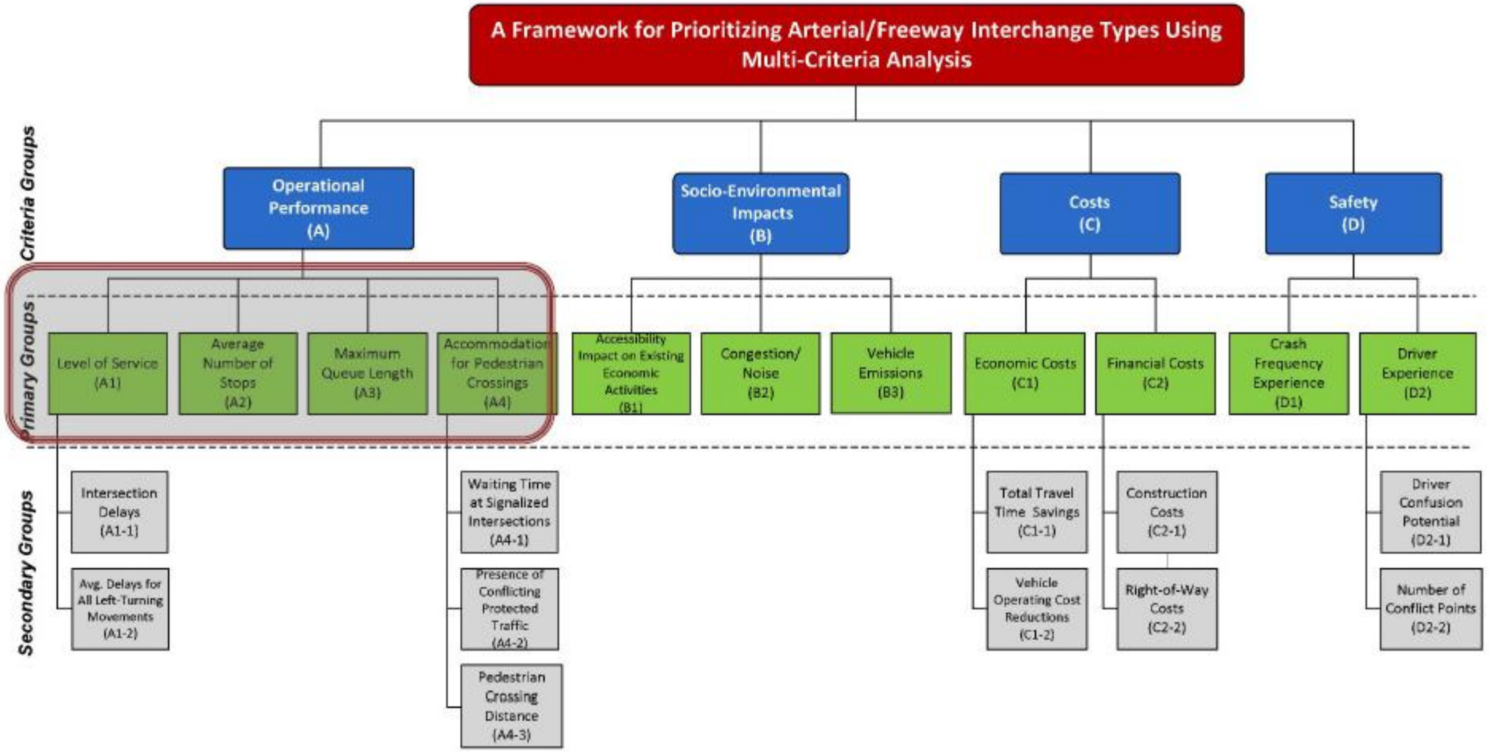
*3. Primary Criteria (Operational Performance)

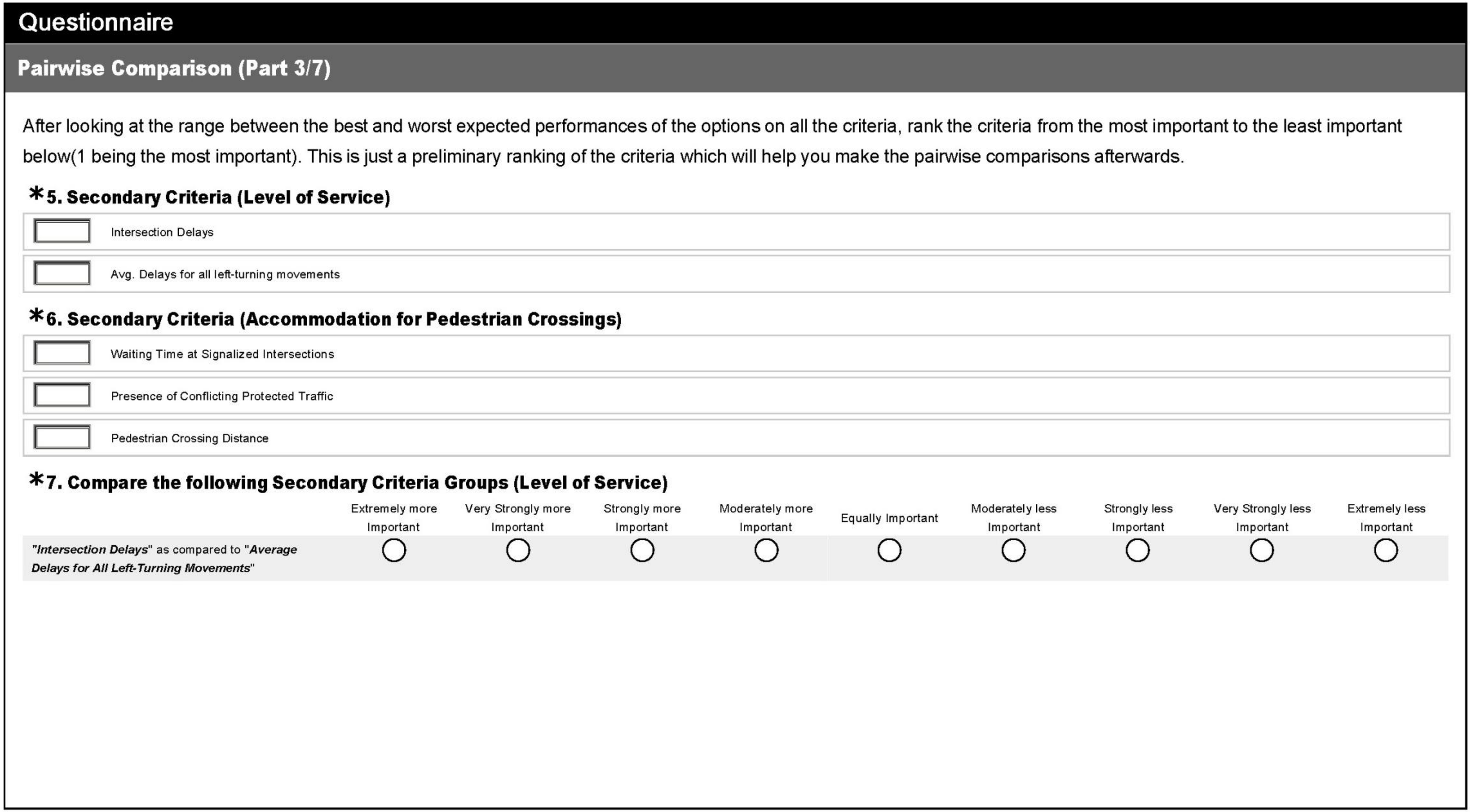
☐	Level of Service
☐	Average Number of Stops
☐	Maximum Queue Length
☐	Accommodation for Pedestrian Crossings

*4. Compare the following Primary Criteria Groups (Operational Performance)

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Level of Service***" as compared to "***Average Number of Stops***"	○	○	○	○	○	○	○	○	○
"***Level of Service***" as compared to "***Maximum Queue Length***"	○	○	○	○	○	○	○	○	○
"***Level of Service***" as compared to "***Accommodation for Pedestrian Crossings***"	○	○	○	○	○	○	○	○	○
"***Average Number of Stops***" as compared to "***Maximum Queue Length***"	○	○	○	○	○	○	○	○	○
"***Average Number of Stops***" as compared to "***Accommodation for Pedestrian Crossings***"	○	○	○	○	○	○	○	○	○
"***Maximum Queue Length***" as compared to "***Accommodation for Pedestrian Crossings***"	○	○	○	○	○	○	○	○	○

Questionnaire





Questionnaire

Pairwise Comparison (Part 3/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least important below(1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

*5. Secondary Criteria (Level of Service)

☐ Intersection Delays

☐ Avg. Delays for all left-turning movements

*6. Secondary Criteria (Accommodation for Pedestrian Crossings)

☐ Waiting Time at Signalized Intersections

☐ Presence of Conflicting Protected Traffic

☐ Pedestrian Crossing Distance

*7. Compare the following Secondary Criteria Groups (Level of Service)

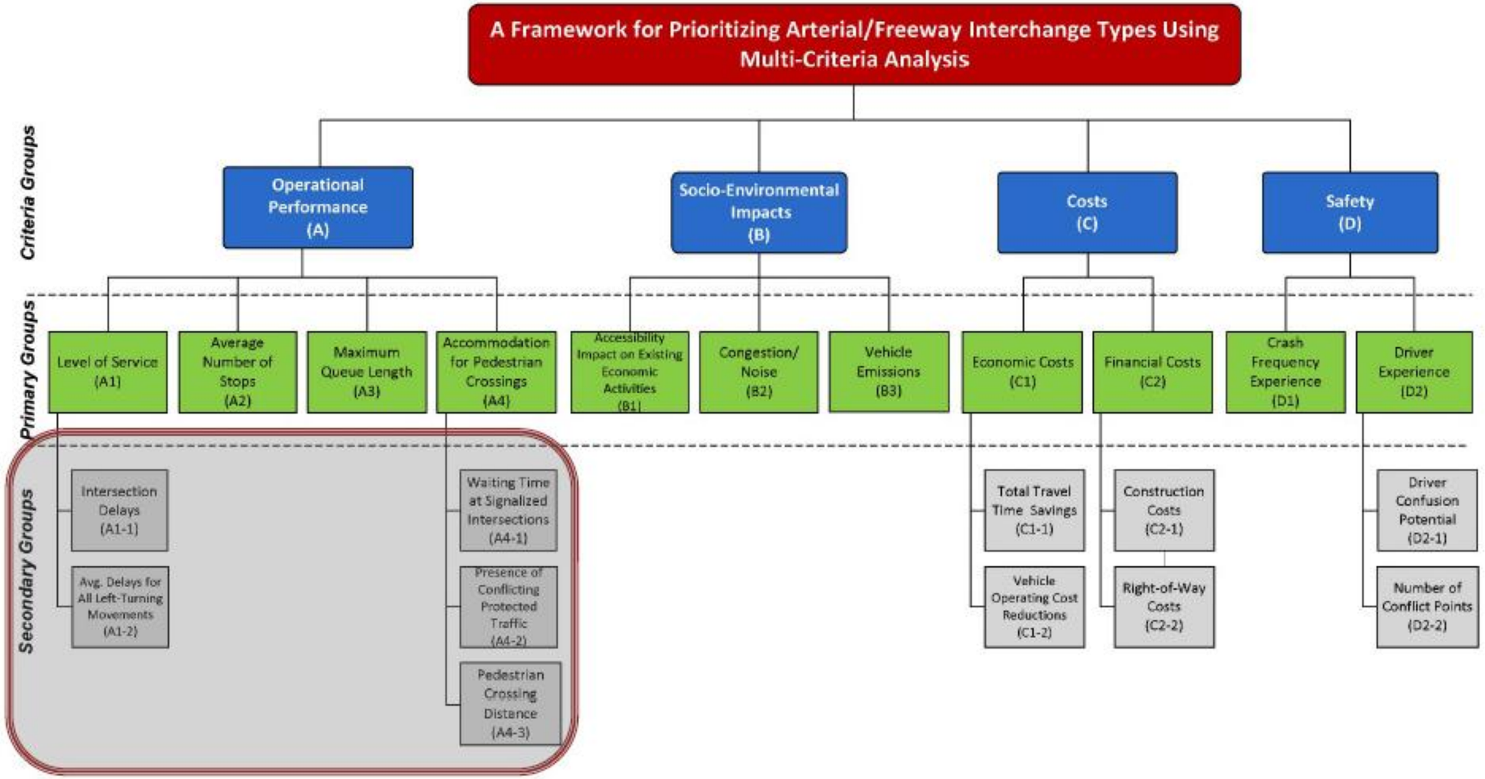
	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Intersection Delays***" as compared to "***Average Delays for All Left-Turning Movements***"	○	○	○	○	○	○	○	○	○

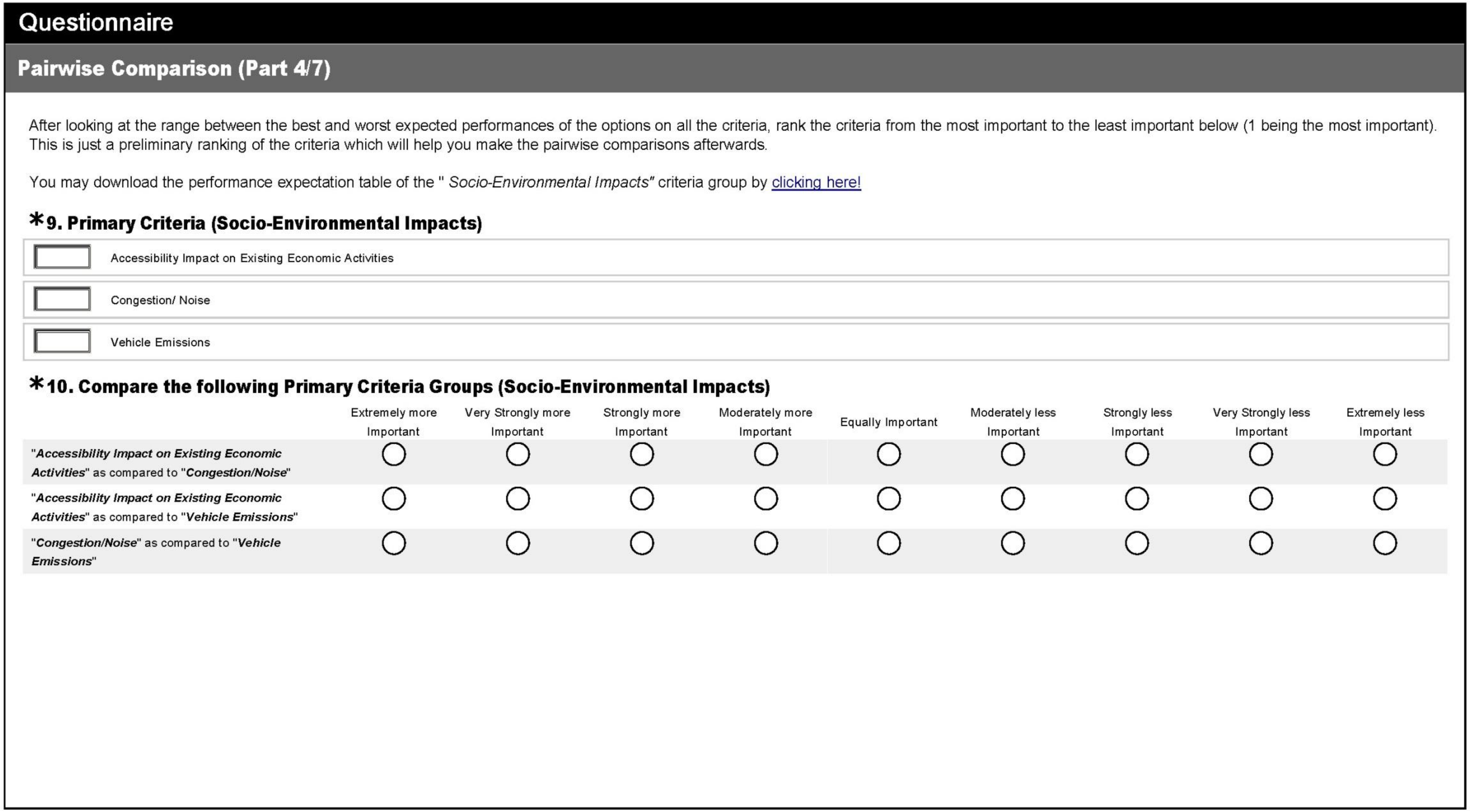
Questionnaire

8. Compare the following Secondary Criteria Groups (Accommodation for Pedestrian Crossings)

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Waiting Time at Signalized Intersections***" as compared to "***Presence of Conflicting Protected Traffic***"	○	○	○	○	○	○	○	○	○
"***Waiting Time at Signalized Intersections***" as compared to "***Pedestrian Crossing Distance***"	○	○	○	○	○	○	○	○	○
"***Presence of Conflicting Protected Traffic***" as compared to "***Pedestrian Crossing Distance"***	○	○	○	○	○	○	○	○	○

Questionnaire





Questionnaire

Pairwise Comparison (Part 4/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least important below (1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

You may download the performance expectation table of the " *Socio-Environmental Impacts"* criteria group by clicking here!

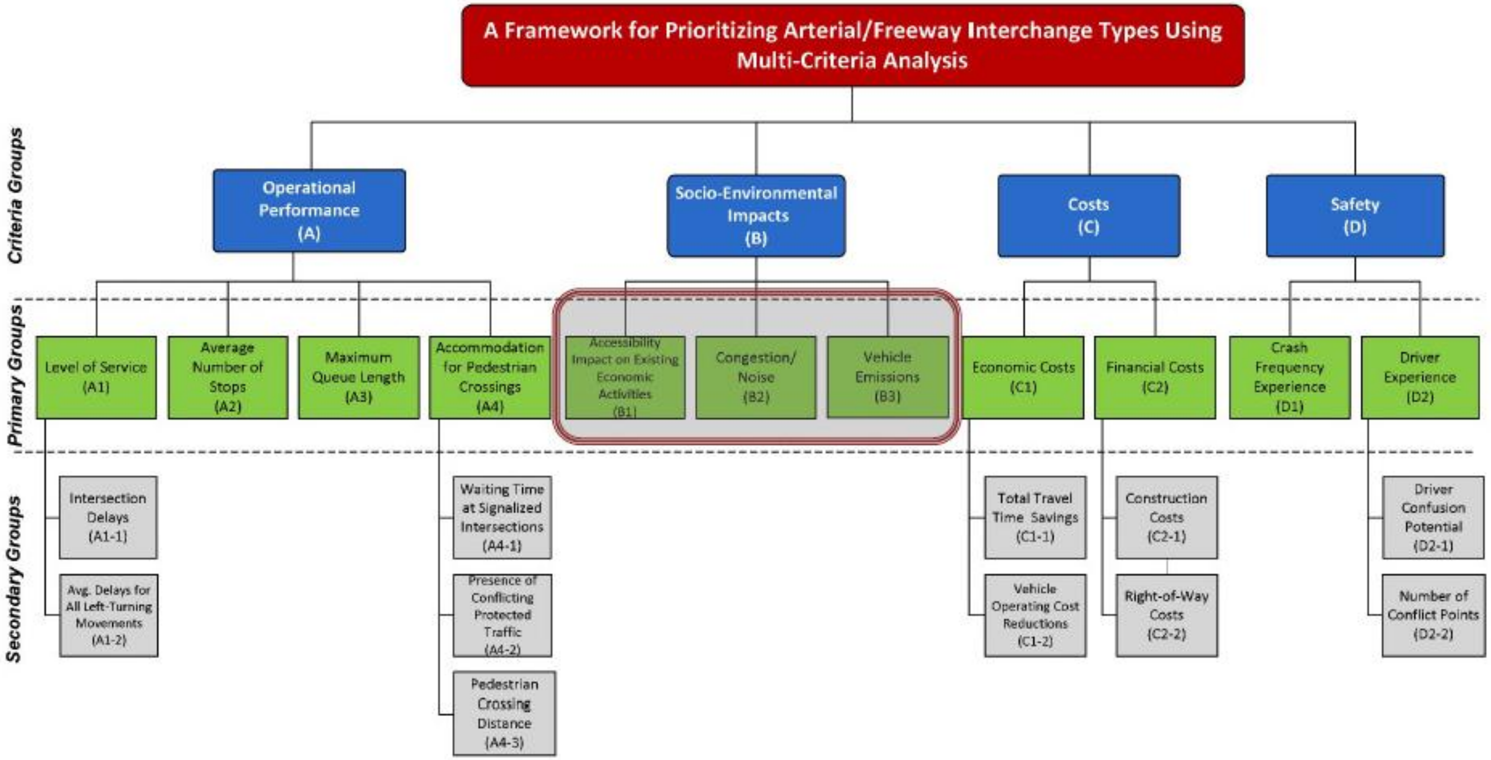
***9. Primary Criteria (Socio-Environmental Impacts)**

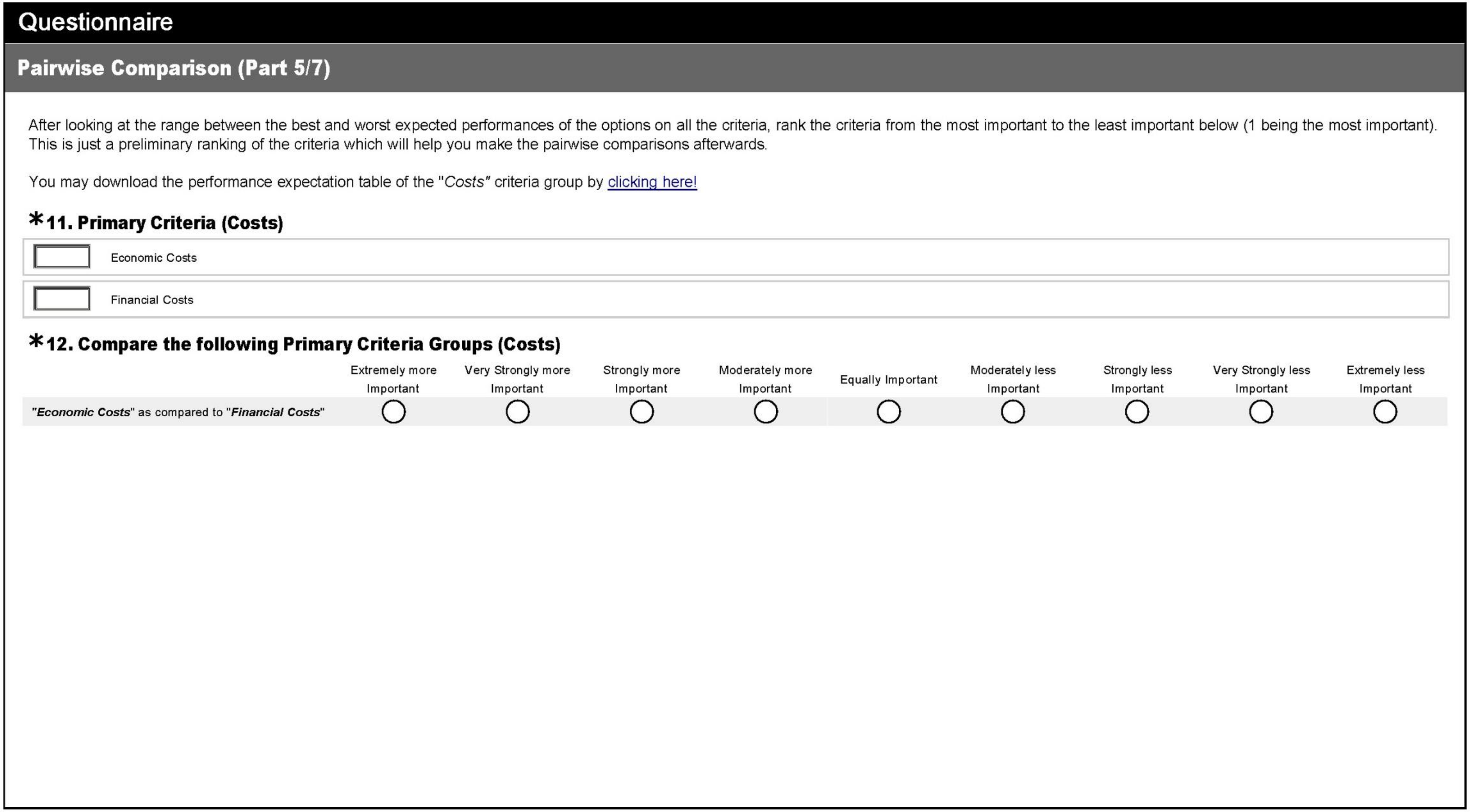
☐	Accessibility Impact on Existing Economic Activities
☐	Congestion/ Noise
☐	Vehicle Emissions

***10. Compare the following Primary Criteria Groups (Socio-Environmental Impacts)**

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Accessibility Impact on Existing Economic Activities***" as compared to "***Congestion/Noise***"	○	○	○	○	○	○	○	○	○
"***Accessibility Impact on Existing Economic Activities***" as compared to "***Vehicle Emissions***"	○	○	○	○	○	○	○	○	○
"***Congestion/Noise***" as compared to "***Vehicle Emissions***"	○	○	○	○	○	○	○	○	○

Questionnaire





Questionnaire

Pairwise Comparison (Part 5/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least important below (1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

You may download the performance expectation table of the "*Costs*" criteria group by clicking here!

*11. Primary Criteria (Costs)

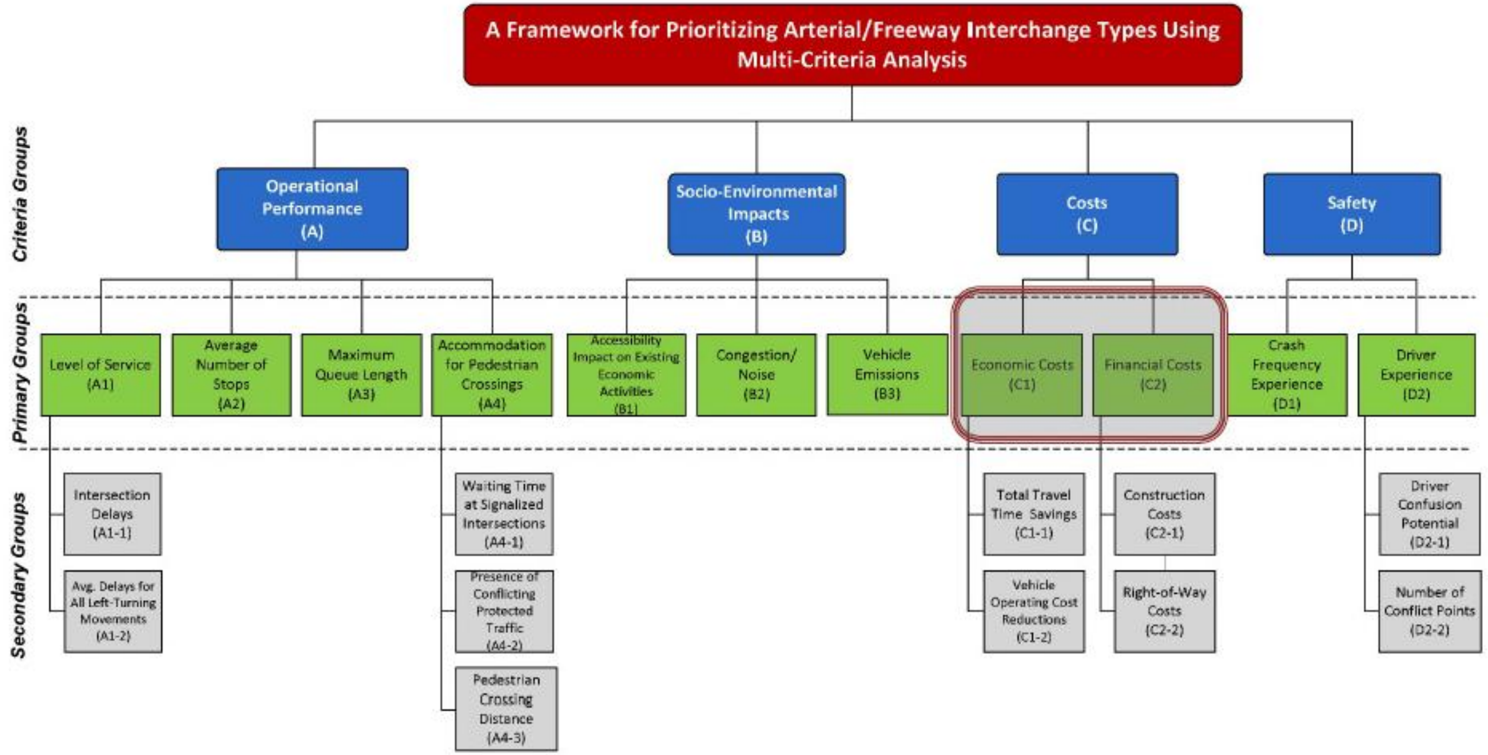
☐ Economic Costs

☐ Financial Costs

*12. Compare the following Primary Criteria Groups (Costs)

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Economic Costs***" as compared to "***Financial Costs***"	○	○	○	○	○	○	○	○	○

Questionnaire



Questionnaire

Pairwise Comparison (Part 6/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least important below (1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

*13. Secondary Criteria (Economic Costs)

☐ Total Travel Time Savings

☐ Vehicle Operating Cost Reductions

*14. Compare the following Secondary Criteria Groups (Economic Costs)

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Total Travel Time Costs***" as compared to "***Vehicle Operating Costs***"	○	○	○	○	○	○	○	○	○

*15. Secondary Criteria (Financial Costs)

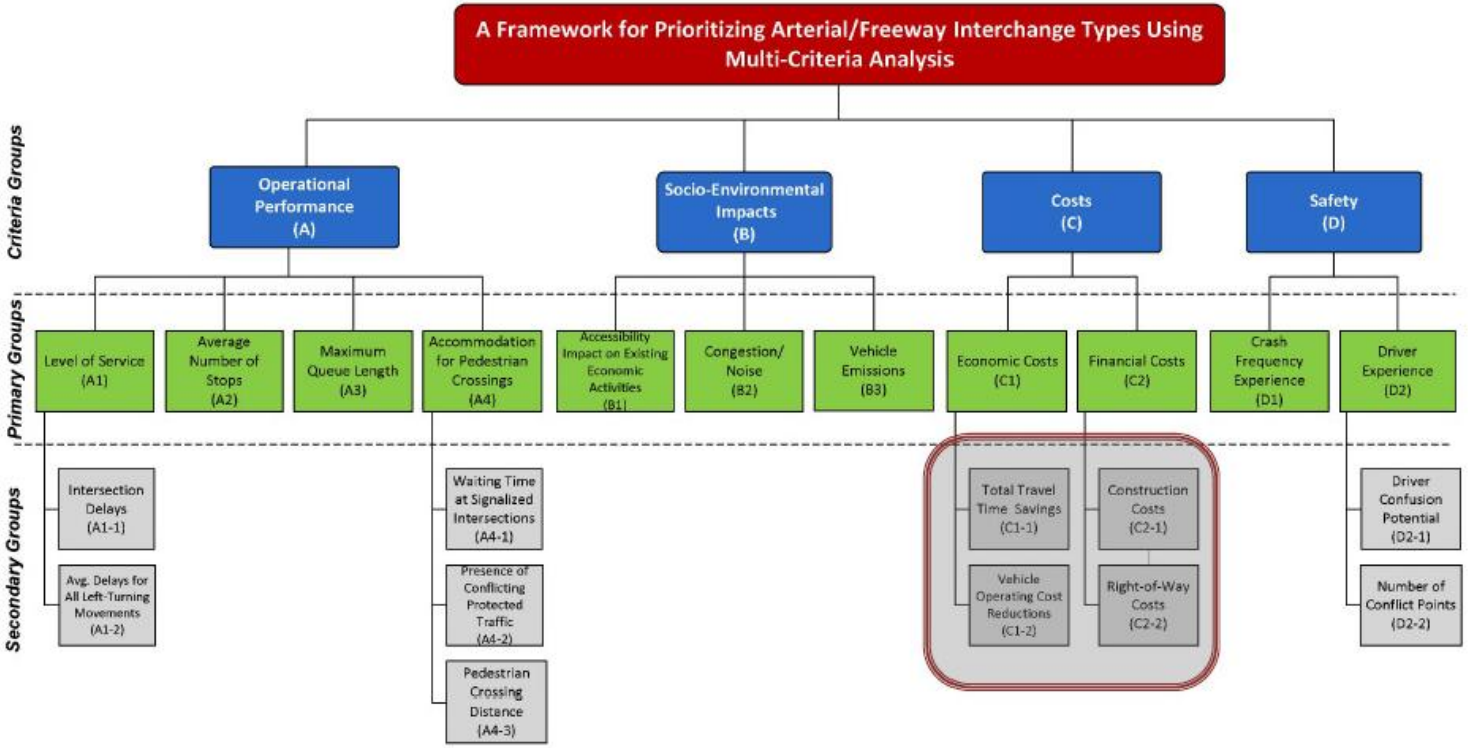
☐ Construction Costs

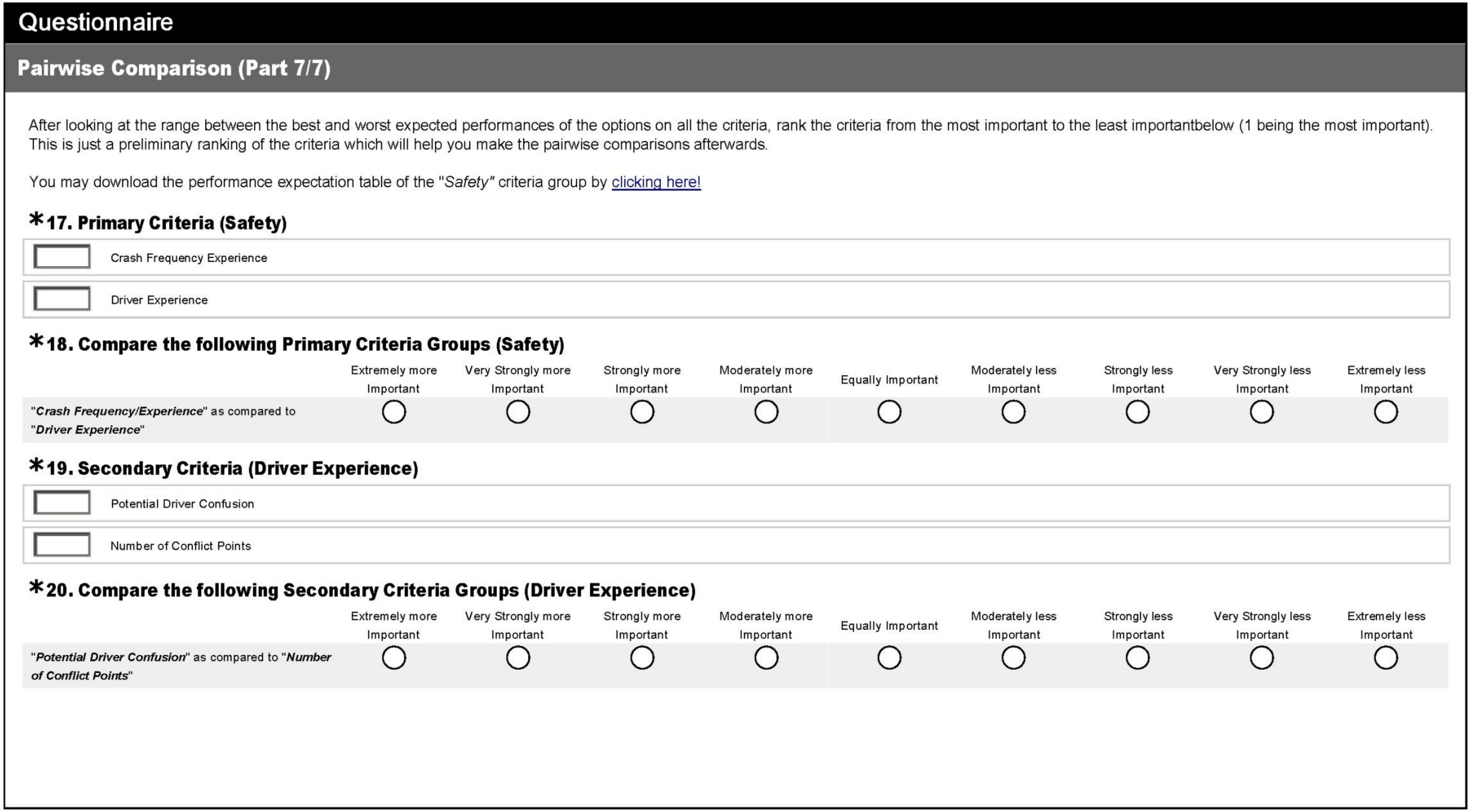
☐ Right-of-Way Costs

*16. Compare the following Secondary Criteria Groups (Financial Costs)

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Construction Costs***" as compared to "***Right-of-Way Costs***"	○	○	○	○	○	○	○	○	○

Questionnaire





Questionnaire

Pairwise Comparison (Part 7/7)

After looking at the range between the best and worst expected performances of the options on all the criteria, rank the criteria from the most important to the least importantbelow (1 being the most important). This is just a preliminary ranking of the criteria which will help you make the pairwise comparisons afterwards.

You may download the performance expectation table of the "*Safety"* criteria group by clicking here!

***17. Primary Criteria (Safety)**

☐ Crash Frequency Experience

☐ Driver Experience

***18. Compare the following Primary Criteria Groups (Safety)**

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Crash Frequency/Experience***" as compared to "***Driver Experience***"	○	○	○	○	○	○	○	○	○

***19. Secondary Criteria (Driver Experience)**

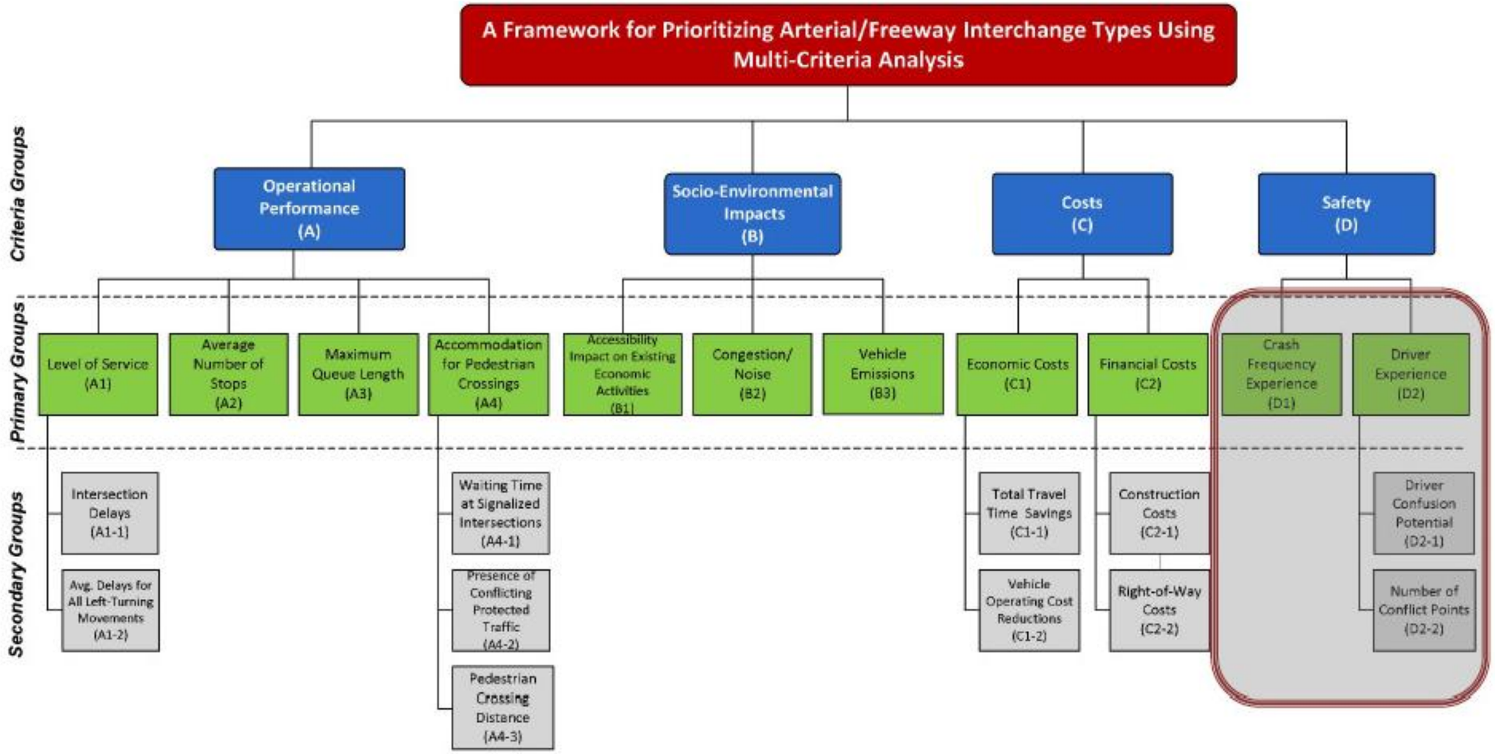
☐ Potential Driver Confusion

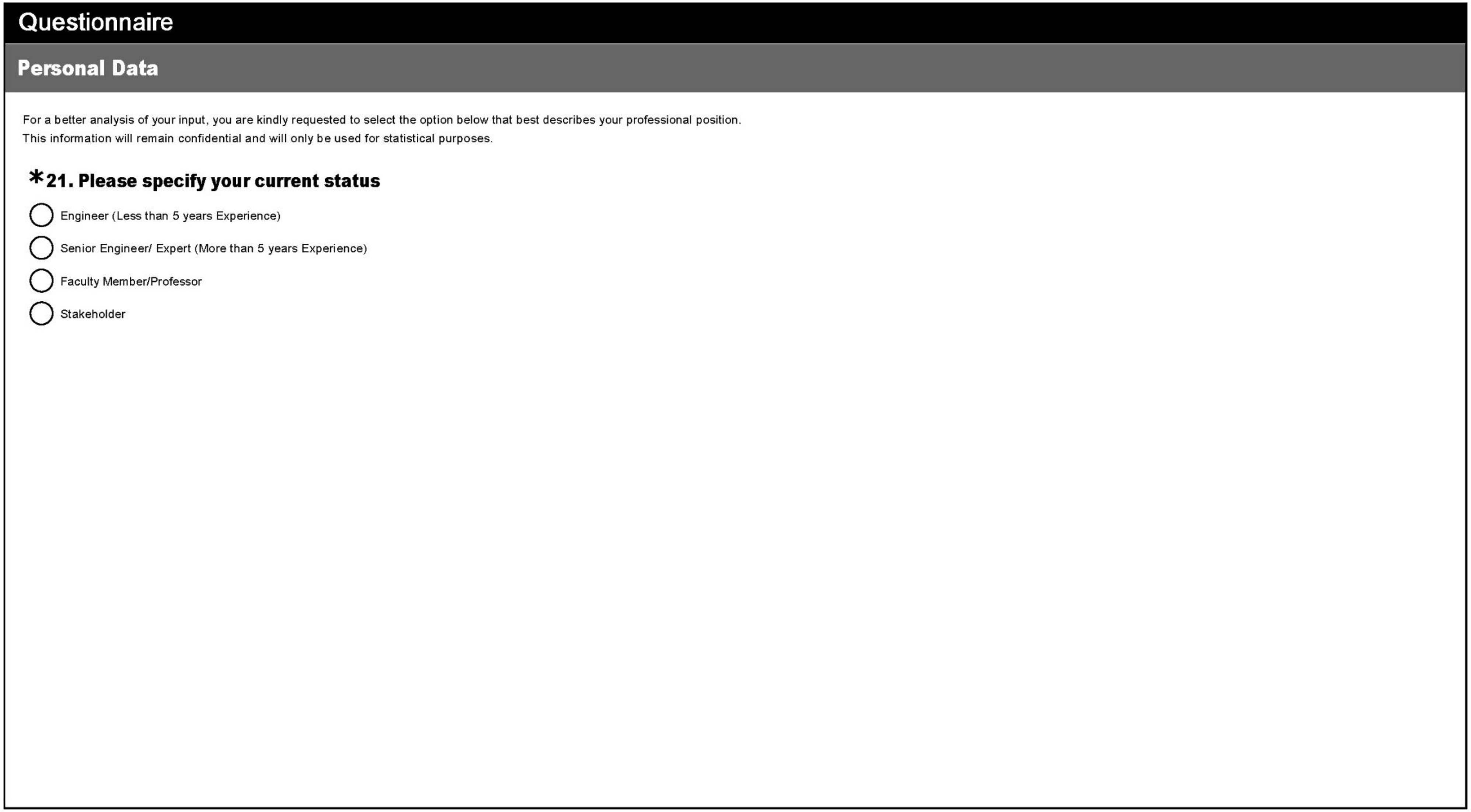
☐ Number of Conflict Points

***20. Compare the following Secondary Criteria Groups (Driver Experience)**

	Extremely more Important	Very Strongly more Important	Strongly more Important	Moderately more Important	Equally Important	Moderately less Important	Strongly less Important	Very Strongly less Important	Extremely less Important
"***Potential Driver Confusion***" as compared to "***Number of Conflict Points***"	○	○	○	○	○	○	○	○	○

Questionnaire





Questionnaire

Personal Data

For a better analysis of your input, you are kindly requested to select the option below that best describes your professional position.
This information will remain confidential and will only be used for statistical purposes.

*21. Please specify your current status

○ Engineer (Less than 5 years Experience)
○ Senior Engineer/ Expert (More than 5 years Experience)
○ Faculty Member/Professor
○ Stakeholder