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DEVELOPMENT OF A COMPOSITE SUSTAINABILITY INDEX FOR ROADWAY INTERSECTTION DESIGN ALTERNATIVES IN THE UAE

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering

Under the Supervision of Professor Munjed Maraqa

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Declaration of Original Work

I, Maryam Juma Al-Kaabi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Development of a Composite Sustainability Index for Roadway Intersection Design Alternatives in the UAE*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Munjed Maraqa, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

Many studies had been carried out to evaluate the sustainability of transportation systems, but little attention was given in these studies for the design of roadway intersections. The objective of this study was to define a framework to assess intersection sustainability from a road-user perspective and to develop a visual tool that helps decision-makers to support a more sustainable design of roadway intersections. Suitable sustainability indicators that would serve as elements in the built framework at the strategic and early planning level were extracted from the literature. The extracted indicators were utilized with relative weights to develop basic dimensional indices that would be further combined into a Composite Sustainability Index (CSI) tool. The application of the CSI tool was demonstrated in four case studies of existing intersections in Al Ain City, UAE. For each case study, the sustainability of fifteen design alternatives was evaluated for different scenarios of traffic volume and operational speed. Indices representing the individual dimensions of sustainability (economic, environmental, and social) and the overall CSI were determined for each alternative using the Multi-Criteria Decision Making (MCDM) method and Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) technique. For each scenario, the most sustainable design alternative and its dimensional tradeoffs were determined. A sensitivity analysis was carried out to study the impact of weight assignment that reflects stakeholders' interests and priorities on the sustainability assessment of the proposed intersection designs. Results indicated that traffic volume had a significant impact on sustainability ranking between single intersection design alternatives, while the effect of operational speed was insignificant. Moreover, sensitivity analysis proved that weight assignment had an effect on determining the most sustainable design alternative. Whereas, alternatives that rank highest in the dimension of the major weight, would result in being the most sustainable. However, if an alternative performs exceedingly well in another dimension, other than the one with the heaviest weight, it may still have the highest contribution to the overall CSI. The developed methodology would assist decision-makers in other cities to assess and implement sustainable roadway intersection projects that correspond to their regional visions and goals.

Keywords: Sustainable Transport Planning, Road Intersections Design, Multi Criteria Decision Making, United Arab Emirates (UAE).

Title and Abstract (in Arabic)

تطوير مؤشر استدامة مركب للتصاميم المتنوعة لتقاطعات الطرق في دولة الامارات العربية المتحدة

الملخص

تم إجراء العديد من الدراسات لتقييم استدامة أنظمة النقل، ولكن لم يتم إيلاء اهتمام كبير في هذه الدراسات لتصميم تقاطعات الطرق بشكل خاص. كان الهدف من هذه الدراسة هو تحديد إطار لتقييم استدامة تقاطعات الطرق من منظور مستخدم الطريق وتطوير أداة بصرية تساعد صانعي القرار على دعم تصميم أكثر استدامة لهذه التقاطعات. تم استخراج مؤشرات الاستدامة المناسبة التي ستكون بمثابة العناصر المكونة لإطار تقييم الإستدامة للتقاطعات على مستوى التخطيط الاستراتيجي والمبكر. تم استخدام المؤشرات المستخرجة مع الأوزان النسبية لتطوير مؤشرات الأبعاد الأساسية التي سيتم دمجها في أداة مؤشر الاستدامة المركبة (CSI). تم عرض تطبيق أداة الـ CSI في أربع دراسات حالة للتقاطعات الحالية في مدينة العين في دولة الإمارات العربية المتحدة. لكل دراسة حالة، تم تقييم استدامة خمسة عشر بدائل تصميم للتقاطعات لسيناريوهات مختلفة من حجم حركة المرور وسرعة الطريق الموضوعة. تم تحديد المؤشرات التي تمثل الأبعاد الأساسية للاستدامة (الاقتصادية والبيئية والاجتماعية) ومؤشر الـ CSI الكلي لكل بديل باستخدام طريقة اتخاذ القرار متعدد المعايير (MCDM) وتقنية تفضيل الترتيب عن طريق التشابه مع الحل المثالي TOPSIS. لكل سيناريو، تم تحديد بديل التصميم الأكثر استدامة ومفاضلات أبعاد الإستدامة المقترنة به. تم إجراء تحليل الحساسية لدراسة تأثير تخصيص الوزن الذي يعكس اهتمامات أصحاب المصلحة ومتخذي القرار وأولوياتهم على تقييم الاستدامة لتصاميم التقاطع المقترحة. أشارت النتائج إلى أن حجم حركة المرور كان له تأثير كبير على ترتيب الاستدامة بين بدائل تصميم التقاطع الواحد، في حين أن تأثير سرعة الطريق الموضوعة كان ضئيلا. علاوة على ذلك، أثبت تحليل الحساسية أن تخصيص الوزن كان له تأثير كبير على تحديد بديل تصميم التقاطع الأكثر استدامة. حيث أن البدائل التي تحتل المراتب العليا في البعد ذو الوزن الكبير، قد تؤدي إلى كونها الأكثر استدامة. ومع ذلك، إذا كان أداء بديل جيدًا للغاية في بُعد آخر، بخلاف البعد الذي له أعلى وزن، فقد يكون لا يزال لديه أعلى مساهمة في قيمة الـ CSI الكلي. ستساعد المنهجية المطروحة صناع القرار في مدن أخرى على تقييم وتنفيذ مشاريع تقاطع الطرق المستدامة التي تتوافق مع رؤاهم وأهدافهم الإقليمية.

كلمات البحث الرئيسية: التخطيط المستدام للنقل، تصميم تقاطع الطرق، صنع القرار متعدد المعايير، الإمارات العربية المتحدة.

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Dedication

To my beloved parents and family

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List of Abbreviations

AASHTO	The American Association of State Highway and Officials
ADSRRS	Abu Dhabi Sustainable Roadways Rating System
AED	Arab Emirates Dirham
AHP	Analytical hierarchy process
CEEQUAL	Civil Engineering Environmental Quality Assessment and Awards Scheme
CFC	Chlorofluoro-carbons
CST	Center for Sustainable Transportation
CSI	Composite Sustainability Index
CO	Carbon monoxide
CO_2	Carbon dioxide
DMA	Department of Municipal Affairs
DoT	Department of Transport
EAD	Environment Agency- Abu Dhabi
Eco	Economic dimension
Env	Environmental dimension
FA	Factor analysis
FHWA	Federal Highway Administration
GHG	Greenhouse gases
GNI	Gross national income
Green LITES Sustainability	Green Leadership in Transportation and Environmental
$GtCO_2e$	Giga-tons of carbon dioxide equivalent
IEA	International Energy Agency
IS	Infrastructure Sustainability rating scheme

I-LAST	Illinois Livable and Sustainable Transportation
INVEST	Infrastructure Voluntary Evaluation Sustainability Tool
MAUT	Multi-attribute utility theory
MCDM	Multi criteria decision making
$MtCO_2e$	Metric tons of carbon dioxide equivalent
NC Dot	North California Department of Transportation
NO_x	Nitrogen oxides
O-RA	Overpass paired with a roundabout
O-SRA	Overpass paired with a signalized roundabout
$O\text{-}S(R_T)$	Overpass paired with a signalized intersection with short exclusive right-turn lanes
$O\text{-}S(R_T, L_T)$	Overpass paired with a signalized intersection with short exclusive right- and left-turn lanes
$O\text{-}S(R_T, L_T, U_T)$	Overpass paired with a signalized intersection with short exclusive right-, left- and U-turn lanes
OECD	Organization for Economic Cooperation and Development
PCA	Principle component analysis
PROSPECTS	Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems
RA	Roundabout
SLAs	Statistical local areas
Soc	Social dimension
SPF	Safety performance function
SRA	Signalized roundabout
$S(R_T)$	Signalized intersection with short exclusive right-turn lanes
$S(R_T, L_T)$	Signalized intersection with short exclusive right- and left-turn lanes
$S(R_T, L_T, U_T)$	Signalized intersection with short exclusive right-, left- and U-turn lanes

TAC	Transportation Association of Canada
TISP	Transportation Index for Sustainable Places
TOPSIS	Technique of Order Preference by Similarity to Ideal Solution
TSRSs	Transportation Sustainability Rating Systems
VHT	Vehicle hours traveled
VMT	Vehicle miles traveled
U-RA	Underpass paired with a roundabout
U-SRA	Underpass paired with a signalized roundabout
U-S(R_T)	Underpass paired with a signalized intersection with short exclusive right-turn lanes
U-S(R_T, L_T)	Underpass paired with a signalized intersection with short exclusive right- and left-turn lanes
U-S(R_T, L_T, U_T)	Underpass paired with a signalized intersection with short exclusive right-, left- and U-turn lanes
UAE	United Arab Emirates
US	United States
USD	United States Dollar

Chapter 1: Introduction

1.1. Background

With the breakthrough of "industrial revolution" in recent years, the economic and industrial sectors undertook fast developments. Unfortunately, some of these developments were at the expense of a lot of natural and social equity aspects. Air pollution, excessive land consumption, and the use of non-renewable natural resources are some examples of the resulting environmental impacts that affect the welfare of human beings. These negative consequences made decision-makers more aware of the situation, leading to the introduction of a new concept of "Sustainable development". Sustainable development can be defined as the 'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs', which reflects the three aspects of environment, economy, and social equity (Brundtland, 1987).

The transportation sector is one of the main parts of urban development. Transportation activities and projects should be carried out in a careful manner. In general, they contribute to the release of harmful gases into the atmosphere, adding up to one-fifth of the total carbon dioxides (CO_2), one-third of the chlorofluoro-carbons (CFCs), and 50% of the nitrogen oxides (NOx) (OECD, 2008). Moreover, the International Energy Agency (IEA) claims that transport activities are responsible for emitting approximately 8 $GtCO_2e$ in 2016, which equals about a quarter of the total global greenhouse gas (GHG) emissions. With such an amount, the transport sector represents the second-largest source of GHG emissions after electricity and heat generation in 2016 (IEA, 2017).

Poor air quality also has a significant impact on socio-economic wellbeing. Increased air pollution would lead to an increase in healthcare expenses and loss in working days due to health-related illnesses, as well as a decrease in productivity levels in both public and private companies (Environment Agency-Abu Dhabi, 2017). In this regard, a definition of sustainable transport is provided by the Organization for Economic Cooperation and Development (OECD) as the “transportation that does not endanger public health or ecosystems and meets the needs for access” (EA, 1999). Therefore, achieving sustainability of transportation is a huge step in obtaining urban sustainable development. If the transportation system contributes to the economic growth and provides the mobility needs of citizens in an eco-friendly manner, it can be labeled as “Sustainable” (Bueno et al., 2015; Litman and Burwell, 2006).

In the United Arab Emirates (UAE) and especially in the Emirate of Abu Dhabi, sustainable transportation plays an essential role in the achievement of Abu Dhabi’s Vision 2030. In 2017, the Environment Agency- Abu Dhabi (EAD) published an environmental report that stated a contribution of about 19.32 $MtCO_2e$ to the atmosphere from the transportation sector in Abu Dhabi, with around 97% of the total direct GHG emissions from road vehicles (Environment Agency-Abu Dhabi, 2017). In this regard and alongside other economic and social needs, the Abu Dhabi Urban Planning Council envisioned and initiated an Urban Structure Framework Plan for the evolution of the city of Abu Dhabi. It has a timeframe of about a quarter-century period from the year 2007 to the year 2030. The “Plan Abu Dhabi 2030” aims to help respond to current and future development needs, establish a planning culture and introduce strong guiding principles for new development in a sustainable way (Abu Dhabi Urban Planning Council, 2010).

As one of the efforts to realize the vision, the Department of Transport (DoT) of Abu Dhabi, directs its long-term strategies and operations towards the attainment of a sustainable transportation system. Abu Dhabi's economic growth and diversification targets can be enhanced by integrating the transportation sector into the urban and economic planning. Likewise, a transportation system that is effectively aligned with the Emirate's environmental strategy would be of high necessity. Three main aspects are introduced by DoT as the meaning of sustainability to Abu Dhabi, which are:

1. Integrated planning with the government and the private sector.
2. Economic growth and diversification.
3. Environment, health, and safety.

Moreover, DoT represents the meaning of sustainability in four main dimensions as follows (DoT of Abu Dhabi, 2010):

1. Effective, inclusive, and expanding public transport system.
2. Main road development and safety.
3. Enhanced customer experience.
4. Intelligent and strategic traffic management.

This aligns well with the definition presented by the European Union of Sustainable Transport System as the one that (Council of the European Union, 2001):

- Allows the basic access and development needs of individuals, companies, and societies to be met safely and in a manner consistent with human and ecosystem health, and promises equity within and between successive generations;

- Is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development; Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise.

This definition clearly exhibits the social/cultural, economic and environment-friendly nature of sustainability.

As one of the efforts towards sustainable transportation, Abu Dhabi Department of Municipal Affairs (DMA) developed a rating system called Abu Dhabi Sustainable Roadways Rating System (ADSRRS). It is a system that helps identifying best practices for applying sustainability to road projects. It is a score-based system with a specific weighting scheme that gives an overall rating for the road project, taking into account the road type under consideration (Abu Dhabi DMA, 2015). Although such an initiative gives a good approximation of the overall performance of the road with respect to sustainability, it requires a considerable amount of input data about the project which makes it difficult to apply on projects at the strategic level. As such, a need still exists for a tool that allows decision makers to evaluate road projects at a macroscopic scale where most of the project details are not readily available.

An essential part of road projects is the construction of intersections. Intersections in the UAE vary by kind and size. Abu Dhabi city itself has more than

460 roundabouts (Dabbour et al., 2018). Intersections are classified as at-grade intersections or grade separated (also known as interchanges). They could be also classified according to the number of lanes/approaches intersecting; such as three-way, four-way, five-way, or six-way intersection. Moreover, intersections differ based on the control sign or signal. Mainly, it can be either an uncontrolled intersection where the right of way is for vehicles on the major road, or a controlled intersection usually by traffic signs, traffic signals or as roundabouts.

Since intersections are considered to be one of the main elements of any urban road network, a good design of these intersections that takes into consideration how well they contribute to sustaining the environment and enhancing the economic and social wellbeing would be a huge step towards achieving sustainable development.

1.2. Research Questions

At the current time, there exist a lack of a standard and defined framework for transportation systems sustainability and in particular those related to intersections. The questions that would be raised in this study is what elements are needed to be included in a framework to assess the sustainability of road intersections at the strategic level and from a road-user perspective? Could a composite sustainability index be developed for comparing the sustainability of intersection design alternatives? How could different road intersection design affect sustainability? What is the impact of varying the factors of traffic volume and roadway operational speed on the sustainability of intersection? Does weight assignment on different sustainability dimensions affect the overall sustainability of the design alternatives? Is the design of intersections in the UAE driven by sustainability?

This research would pursue to answer all these questions by carrying out four different case studies in Al-Ain city within the Emirate of Abu Dhabi, UAE.

1.3. Objectives

This study aims to develop a tool that allows decision makers to choose the most sustainable alternative from a road-user perspective out of a set of proposed road intersection designs. This study takes into consideration the lack of detailed information about the design while still at the planning and strategic level. The specific objectives of this study are as follows:

- Extraction of a framework of suitable sustainability indicators through literature review.
- Development of the so-called Composite Sustainability Index (CSI) for roadway intersection design. Sub-indices would represent sustainability in social, environmental and economic aspects.
- Carry out detailed case studies on existing intersections (roundabouts) in Al-Ain city of Abu Dhabi Emirate to assess the validity of the proposed CSI approach and to determine the best design alternative.

1.4. Scope of Work

The three dimensions of sustainability covered in this study are the economic, environmental and social dimensions. Sustainability is specifically defined from a road-user perspective. The developed CSI is envisioned to be utilized at the early planning stages of road projects, with very little details on the design/operation aspects being available for decision makers. Since detailed information of the project would not be available at early stages (e.g. exact overall cost, detailed geometric design, in-depth structural details of the design, etc.), a macroscopic approach would be considered. Such an approach would be appropriate for decision-makers who would use this index for planning at the strategic level. Used indicators would be extracted from literature taking into consideration the applicability and availability of the required data.

Four case studies would be used to showcase the tool application. They are intersections in the form of roundabouts but are planned to be transformed to signalized intersections in Al Ain city; namely, Asharej, Al Markhaniya, Al Ahliya, and Al Dewan roundabouts. These selected roundabouts differ in size, geometric details, and traffic demand. Several scenarios of different vehicle volumes (demand) and road speeds would be considered for each study case in order to determine any effect of such variations on the final ranking of the CSIs. The volume scenarios would cover the present volume (the year 2018) obtained from DoT records. Two other volumes would be generated for ten years back and ten years later (2008 and 2028) using an appropriate growth factor. This ten-year period will allow to check whether the decision made based on a traffic volume in the past was justifiable and whether that design is still suitable for current and future traffic volumes or it might change to another design alternative. The speed variation would be applied on two cases only (Al Ahliya and Al Dewan roundabouts) since they have uniform speeds on all four-lane approaches, unlike the other two roundabouts (Asharej and Al Markhaniya roundabouts) which have varying speeds between the North-South approach and the East-West approach. Two speeds would be used; 80 km/h and 100 km/h. Even though the CSI tool would be used on case studies in Al-Ain, it is aimed that this tool would be applicable to any other region.

This study scope would be limited to the design of individual intersections. It will not account for the overall network configuration or design, as this would require combining the individual intersection designs and studying all combinatorial possibilities, which is outside the scope of this study.

1.5. General Approach

The framework of the methodology followed in this thesis begins with a literature review to extract sustainability indicators for intersection design. The indicators are then refined into a smaller set based on applicability and availability of data. After determining the final set of indicators, a multi-criteria decision making (MCDM) method called TOPSIS is applied to the chosen indicators. TOPSIS uses a weighting system and some mathematical algorithms to rank several alternatives based on the corresponding values of the indicators for each alternative. The weighting system chosen in this study is equalized for the three dimensions of sustainability and for the individual indicators within each dimension. However, the weights can be modified in order to meet the requirements of the decision makers.

After the development of the ranking system of the CSIs, it is applied to four roundabouts as case studies. Design alternatives of the intersections are generated in a program called SIDRA Intersection. Data collection is carried out for each case study using SIDRA, AutoCAD and qualitative assessment based on literature. The data collected serves as input in the TOPSIS-based ranking system alongside the equal weights to finally get the CSI rankings as outputs of the model. The system evaluates the alternatives and determines the best option based on the values of the indicators for each alternative and its weight. The effect of weights variation on the final ranking is showcased for each roundabout, whereas 80% of the weight is assigned to one specific dimension alternatively (first the economic then the environmental and finally the social dimension) and the remaining 20% is divided equally on the other two dimensions.

1.6. Thesis Structure

This thesis begins with Chapter 1 titled “Introduction”; it gives some basic background information related to this study. Chapter 2 follows as the “Literature Review”, which goes in-depth through past research and studies about transportation sustainability pillars, road intersections, sustainability indicators and MCDM – TOPSIS analysis. Chapter 3 focuses on the development of a framework to assess the CSI of road intersections. This chapter identifies the considered sustainability dimensions and indicators, shows the MCDM - TOPSIS analysis and its weighting scheme and suggests a way to present results using a tool called the “spider-graph” or “radar-graph”. The system developed in Chapter 3 would be showcased in Chapter 4, “Case Studies”, where a detailed application of the system would be undertaken mainly using a simulation program for data collection called SIDRA Intersection. Finally, the findings of the thesis are concluded in Chapter 5.

Chapter 2: Literature Review

2.1. Definition of Transportation Sustainability

The negative impacts on the environment and society have been increased due to transportation activities, hence, the incorporation of sustainability in the design of transportation systems has become of high importance to the planners and decision-makers (Haghshenas and Vaziri, 2012). Sustainable development is typically defined as the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (WCED, 1987). Applying such definition to the transportation sector can help in reaching a sustainable transportation system.

In the literature, a definition for a sustainable transportation system has not been standardized, however, it can be seen that a common definition goes around three main aspects. First, a sustainable transportation system must meet the needs of equity and safe access for its users in an effective and efficient manner. Second, it should enhance and support the economic growth of society. Third, it should minimize the harmful effects of transportation activities on the environment (Jeon and Amekudzi, 2005). For instance, the Organization for Economic Cooperation and Development (OECD) defined environmentally sustainable transportation as the "Transportation that does not endanger public health or ecosystems and that meets needs for access consistent with (a) use of renewable resources at below their rates of regeneration, and (b) use of non-renewable resources below the rates of development of renewable substitutes” (OECD, 1998).

A more detailed definition from the Transportation Association of Canada (TAC) elaborates on the three main aspects. For the *natural environment*, the transportation system should: “limit emissions and waste (that pollute air, soil, and water) within the urban area's ability to absorb/recycle/ cleanse; provide power to vehicles from renewable or inexhaustible energy sources (such as solar power in the long run); and recycle natural resources used in vehicles and infrastructure (such as steel, plastic, etc.)”. For the second aspect related to *society*, the system should: “provide equity of access for people and their goods, in this generation and in all future generations; enhance human health; help support the highest quality of life compatible with available wealth; facilitate urban development at the human scale; limit noise intrusion below levels accepted by communities; and be safe for people and their property”. The final aspect which is the *economy*, the system should: “be financially affordable in each generation, be designed and operated to maximize economic efficiency and minimize economic costs, and help support a strong, vibrant and diverse economy” (TAC, 1999).

From a similar point of view, a simpler definition of a sustainable transportation system is provided by the California Department of Transportation in 2001 as the system that meets the basic mobility and accessibility needs of current and future generations (Zhang and Wei, 2013).

Another working definition adopted by the Center for Sustainable Transportation (CST) of Canada states that a sustainable transportation system allows access needs for both individuals and societies in a safe manner for present and future generations, efficient, affordable, enhances the economic growth of the region and minimizing emissions, waste, land consumption and noise pollution that may affect the environment (Gilbert et al., 2003).

An initiative carried out in Europe called “Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems (PROSPECTS) has defined a sustainable urban transport and land use system as the one that provides efficient access to goods and services for the citizens of urbanized area, protect the environment and ecosystems for the current generation and ensures for future generations the same level of environmental welfare and cultural heritage as that of the current generation (May et al., 2003). Moreover, more than 40% of the state Departments of Transportation in the United States, currently include sustainability either directly or indirectly in their mission statements (Jeon et al., 2006). Hence, it can be seen that while there is no standard definition for sustainable transportation systems, there are three common dimensions in the literature that sustainable transportation must consider, which are the environment, economy and overall social welfare (Force, 1991).

2.2. Frameworks for Evaluating Transportation Sustainability

Evaluating transportation sustainability has been a highly discussed topic throughout the years. Currently, a common state-of-practice for measuring sustainability in transportation is by matrices of performance indicators. The use and development of indicator systems in measuring the progress toward transportation system sustainability is a rapidly growing practice within more organizations around the world (Jeon et al., 2006). The framework for developing such indicators varies from one agency to another with respect to the visions and goals they intend to achieve.

An extensive literature review, carried out by Jeon and Amekudzi (2005), reviewed around sixteen different initiatives on sustainability indicators. They concluded that while a framework for evaluating transportation sustainability has not been standardized, current evaluation frameworks move at least in one of three main directions; either:

- Linkage-based frameworks, which capture the relationships between the causal factors, impacts, and corrective actions related to achieving sustainability;
- Impact-based frameworks, which focus on the nature and extent of various kinds of economic, environmental, and social impacts that determines the overall sustainability of a system (with or without determining causal factors and corrective actions) and;
- Influence-oriented frameworks, which considers the relative levels of influence that an agency or organization has on specific activities that affect progress toward achieving sustainability.

In another attempt to evaluate the sustainability of transportation infrastructure, an innovative Sustainability Indicator Prism was introduced by Zegras (2006), as shown in Figure 1. This kind of framework creates performance indicators around specific themes or goals. The prism represents the hierarchal order of goals, indices, indicators, and raw data along with the multidimensional structure of the performance measures. Building up from raw data at the bottom to the performance indicators or variables level, then to another level of sub-indices of the main aspects of sustainability, leading to the top of the pyramid which represents the sustainability goals of a society. It can be noticed that Zegras took ‘System Effectiveness’ as a separate aspect of sustainability along with the three major ones.

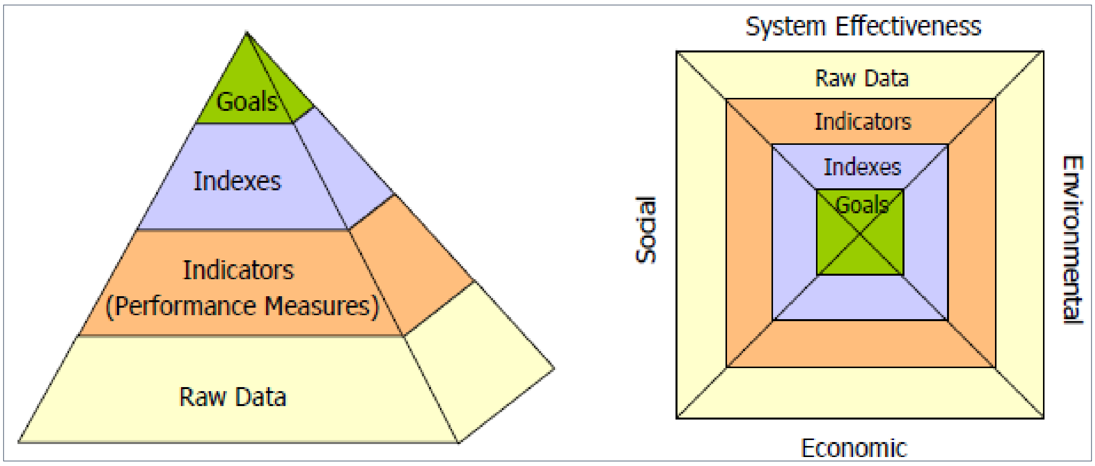


Figure 1: Sustainability indicator prism (Zegras, 2006; Meyer and Miller, 2001).

In this study, a similar approach to Zegras (2006) would be used as a guideline in developing a framework for transportation sustainability indicators.

2.3. Sustainability Indicators

Measurement of sustainability by developing and implementing suitable related indicators is considered a challenge in urban transportation design (Litman, 2012). Some traditional indicators, represented by vehicle mobility and travel time, lack the ability to determine which transportation system gives sustainable outcomes. However, sustainability indicators can be utilized to aggregate complex concepts into a simple data format that can be easily and efficiently interpreted (Castillo and Pitfield, 2010).

In practice, creating a composite index from individual sets of indicators to be used as a tool to compare and analyze different designs and scenarios is a widely used method (Mansourianfar and Haghshenas, 2018). However, despite the vast use of such composite indices, two opposite perspectives about them exist. Opposing parties claim that composite indices are not reliable because of their subjective construction (Cherchye et al., 2007). Furthermore, one single index is not enough to answer all the questions, hence there is a need for multiple indicators (Jollands et al., 2003). On the other hand, some researchers are confident that such indices are valuable assertion tools, since they summarize the available information, making comparison an easier and quicker task for stakeholders and decision makers (Freudenberg, 2003). These contrary ideas, are both sides of the same coin, and it can be concluded that if clear assumptions and methodology are used, and if the index can be broken down into its original components, the development of a composite index can be regarded as a successful approach (Jollands et al., 2003).

Among the sources of sustainability indicators are the rating system tools, which are developed to appraise projects with respect to their sustainability. Most of the rating systems considered civil infrastructure in general, but they gradually become more applicable to transportation systems (McVoy et al., 2010). Usually, transportation sustainability rating systems (TSRSs) rank and evaluate infrastructure projects depending on how sustainable they are through different award levels, such as Gold, Silver, and Bronze. Some examples of widely used TSRSs are: BE2ST-In-Highways, Envision, Greenroads, the Civil Engineering Environmental Quality Assessment and Awards Scheme (CEEQUAL), the Infrastructure Sustainability rating scheme from Australia (IS), Illinois Livable and Sustainable Transportation (I-LAST) and Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) (Bueno et al., 2015; Clevenger et al., 2013; Simpson, 2013).

Abu Dhabi City Municipality developed a sustainable road rating system based on Greenroads rating system (CH2MHILL, 2015). The system is designed as a weighted system, in which points were earned in a gradual manner in most credits. The goal of weighing is to make the point value for each credit corresponds with its potential to affect sustainability in terms of span, duration, and magnitude of the impact.

A study conducted by Zheng et al. (2013) provided basic guidelines to develop performance measures to assess the sustainability of transportation systems at the macro-scale level. To represent a set of indicators in environmental, social and economic domains, twenty-two variables were introduced. Some of the indicators under the environmental domain are energy consumption, infrastructure materials consumption, land use, GHG emissions, pollution, and waste production. The social domain included indicators such as health, traffic safety, community involvement, social equity, and accessibility. Moreover, the indicators representing the economic domain were affordability, mobility, financial security, and economic vulnerability.

Each indicator was further represented by a specific variable that can be quantified (e.g. CO_2 emissions per capita representing GHG emissions, Transportation fatalities per 100,000 people representing traffic safety and the percentage of household income spent on transportation representing affordability). However, some of these variables were impractical and hard to obtain at the statewide level. Nonetheless, an overall tool for assessing sustainable transportation, called Transportation Index for Sustainable Places (TISP), was developed based on the available data they could obtain (Zheng et al., 2013). Similarly, Reisi et al. (2014)

attempted to develop a method for obtaining a composite sustainability index for Melbourne statistical local areas (SLAs) in Australia. The index was also based around the three main aspects of sustainability: environmental, social and economic aspects. The environmental aspect considered depletion of non-renewable resources, GHG emissions (in terms of $CO_{2\text{-}e}$), other air pollutants (CO, NO_2, PM_{10}) and land consumption. The social indicators covered accessibility, fatalities, injuries related to traffic accidents and mortality effects of air pollutants. In addition, the economic aspect was represented by vehicular costs and general costs of accidents.

This study differs from others in considering the importance of each individual indicator in the weighting process. To adjust for the subjectivity issue and avoid biased measures of transportation sustainability, the principle component analysis/factor analysis (PCA/FA) was applied for weighting the indicators. Furthermore, the developed index can be utilized in evaluating the effect of policies issued by policymakers which are related to transportation sustainability.

Mansourianfar and Haghshenas (2018) carried out a study to assess the sustainability of infrastructure projects on urban transportation systems in Azadi district in Isfahan city, Iran. Nine scenarios to improve the traffic situation in the district were proposed, and their sustainability was evaluated using a CSI. This index was aggregated from ten quantitative indicators relevant to the three main dimensions of sustainability (environmental, social, and economic). Data needed were directly and indirectly obtained through the simulation of the scenarios in AIMSUN 8.0 environment. The main finding of their study was that their system favored public transportation projects as the most compliant scenarios with the defined principles of urban sustainability in the situation they had in hand. The final set of indicators that they derived is provided in Table 1.

Table 1: Sample of sustainable transportation indicators

Sustainability Dimension	Area	Indicator	Unit
Environmental indicators	Air Pollution	1) CO, HC and NO_x emissions	Kg
	Consumption of natural resources	2) Land consumption for transport	m^2
		3) Green spaces destruction	m^2
		4) Fuel consumption	Liter
Social indicators	Safety	5) Average crash frequency based on Highway Safety Manual (HSM)	Accident/km
	Noise pollution	6) Exposure to noise level above 65 dB	m^2
	Public satisfaction	7) Average travel time	Second /person
	Non-motorized promotion	8) The impact on non-motorized transport	Like-art-scale (-1, 0, +1)
Economic indicators	Operator costs	9) Capital costs	Dollar
		10) Maintenance and repair costs	Dollar

The development of indicators is not necessarily constrained by only three dimensions. For instance, an initiative carried out in Atlanta Metropolitan Region, U.S. considered four dimensions to represent transportation sustainability (Jeon et al., 2013). Transportation system effectiveness was added as a main dimension of sustainability alongside the three common dimensions of environmental, social and economic dimensions. Jeon et al. utilized some regional data related to sustainability issues to determine fifteen performance indicators. The system effectiveness dimension included two performance measures which are the average freeway speed and vehicle miles traveled (VMT) per capita. The indicators under the environmental dimension are CO_2, VOC, NO_x emissions and land consumption. Moving towards the economic indicators, they included vehicle hours traveled (VHT) per employee, land consumed by retail/service and employment. Finally, they defined exposure to VOC and NO_x emissions and the equity of exposure to VOC and NO_x emissions separated by geography and income levels as performance measures for the social dimension. Those indicators were incorporated into one CSI by multiple criteria decision analysis (MCDA) method. This index is used to assess alternatives of transportation systems and land use in the planning phase and identify the dominant dimension that each alternative contributes to.

- Safety at intersections

Safety at intersections is a very controversial topic. Hence, a thorough literature review on safety at intersections was explicitly conducted to explore the previously considered methods to assess safety. One method for quantifying safety is by obtaining the rate of accidents occurring on the intersection in a specific period of time. Another approach is by comparing two different types of intersections. This can be done by carrying out a before and after study of converted intersections (from one type to another) for a certain period of time and assessing the number and severity of accidents on each type and how did the accident rate change after the conversion. However, such a method cannot be applied for cases where the design alternatives are hypothetical and no real data can be obtained. For these cases, a qualitative approach may be more appropriate. Two combined methods could be used to rank the alternatives in terms of safety. The first one would be by considering the conflict points (defined in section 3.3.3), when applicable, whereas the design having less traffic conflict points would be regarded as the safest design. The other method would be based on findings in the literature, where a safety comparison between different types of intersections has been conducted.

A point worth mentioning is the fact that such studies are rarely done in the UAE due to lack of required data of traffic counts and accidents in the past years. Hence, studies of other regions would be used. Another issue that may arise from using results obtained for a geographical location in a different country is the difference in road users' behavior that may exist and can affect the outcome of the safety assessment. Nevertheless, for the specific purpose of this research, developing and demonstrating a methodology for evaluating sustainability of intersections, the qualitative combined method is within reason.

The following findings in literature would be used as bases to assess the safety of the developed design alternatives of intersections that would be showcased later on in section 4.3:

- Safety comparison between roundabouts and signalized intersection

The Federal Highway Administration (FHWA) Office of Safety has identified roundabouts as "a Proven Safety Countermeasure" since they are able to substantially reduce the types of serious injury or loss of life crashes. They are also designed to improve safety for all intersection users, including pedestrians and bicycles. The American Association of State Highway and Officials (AASHTO) highway safety manual shows that roundabouts reduce the type of crashes resulting in severe injuries or fatalities by 78-82% in comparison to conventional stop-controlled and signalized intersections (Manual, 2010).

Moreover, in a study conducted in Canada by the Insurance Institute for Highway Safety on 24 stop sign and signal controlled intersections that were converted into roundabouts, showed a reduction in all crash severities combined by a 38%, a reduction of 76% of serious injury crashes, and an estimated reduction of 89% for fatal and incapacitating injury crashes (Retting et al., 2001). This study estimated potential reductions in motor vehicle crashes and injuries associated with the use of roundabouts as an alternative to signal and stop sign control at intersections in the United States. An empiric Bayes procedure was used to estimate changes in motor vehicle crashes following conversion of 24 intersections from stop sign and traffic signal control to modern roundabouts. There were highly significant reductions of 38% for all crash severities combined and a decrease of 76% for all injury crashes. Reductions in the numbers of fatal and incapacitating injury crashes were estimated at about 90%. Results are consistent with numerous international studies and suggest that roundabout installation should be strongly promoted as an effective safety treatment. These pros of the roundabout are mainly due to a well-design that regulates the traffic flow in a simple, independent and efficient manner. The consistency of a roundabout provides for the vehicles, whereas all of the vehicles enter the roundabout by making a right turn, helps in reducing the number of conflict points. A roundabout has eight conflict points, while a signalized intersection has 32, thus having less potential crashes. Moreover, since vehicles merge into the roundabout at low angles, instead of perpendicular angles, the chances of occurring of the dangerous T-bone crashes are virtually eliminated (Eshragh, 2011).

Wadhwa and Thomson (2006) studied the relative safety of different intersection types in Townsville, Australia, taking in consideration the corresponding conflict points. Table 2 shows the number of conflict points and a paired fatality rate for varying types of intersections. These authors observed an increase in fatality rates with the increase of the number of conflict points of an intersection. They concluded that the roundabout is the safest form of intersection compared to signalized and un-signalized T-intersections and cross intersections. The corresponding number of fatalities per 1000 crashes for roundabouts was 1.46, while the T-intersections and cross intersections had a rate of 6.32 and 5.83, respectively (Wadhwa and Thomson, 2006). Based on the above, roundabout alternatives would be considered as *safer* than signalized intersections.

Table 2: Number of crossing conflict points paired with the fatality rates for different types of intersections

Intersection Type	Number of crossing conflict points	Number of intersections in Townsville	Fatality rate
Roundabout	0	128	0.191
Signalized T-intersections	1	37	0.438
Signalized cross intersections	2	46	0.532
Un-signalized T-intersections	3	2129	0.878
Un-signalized cross intersections	16	408	1.05

- Safety comparison between traditional roundabouts and metered roundabouts

With the development of roundabouts in the United States as an effective form of traffic control, Robinson et al. (2000) suggested introducing signalized and metered roundabouts as a method to relieve congestion and provide safer access for pedestrians and cyclists. In addition, Natalizio (2005) conducted a study to compare between a conventional roundabout and a metered roundabout in several aspects. One of the considered aspects was safety with respect to drivers' control and its effect on pedestrian's movement. The author found out that metered roundabouts leans on the safer side than conventional roundabouts since it provides more control for the driver and gives a chance for pedestrians to cross safely. A summary of Natalizio's comparison is shown in Table 3.

Table 3: A comparison between conventional roundabouts and metered roundabouts

Criteria	Conventional RA	Metered RA
Safety / Control	The need for weaving and merging can provide difficulties at particular entry approaches.	Signals can better regulate traffic patterns, reduce the need for merging and reduce speeds.
Pedestrian Facilities	Lack of control can make it difficult for pedestrians to cross approaches.	Signals can render it safer and more positive.

Moreover, since 1997, the County Surveyors Society conducted a survey in England on 49 road authorities regarding the installation of metered roundabouts. They found out several reasons justifying the use of signals on roundabouts, such as (Natalizio, 2005):

- Queue control

- Increased capacity
- Accident reduction
- Links with adjacent signal sites
- Other reasons

Hence, for this case study, metered/signalized roundabout alternatives would be considered as *safer* than conventional roundabouts.

- Safety comparison between metered roundabouts and signalized intersections

Robinson and Rodegerdts (2000) stated that even though a signal installed at a roundabout may affect the main benefit of a roundabout (gaining greater capacity and having lower delays), a signalized roundabout is still far better than regular signalized intersections. They justify this by the benefits of improved safety that the metered roundabouts offer over the signalized intersections by eliminating right angle collisions, providing safer merging conditions and reducing entry and exit speed. Moreover, the reduction of speed gives drivers the time to react to possible crashes, hence reducing crash severity. This considered and the fact that it was shown previously that a metered roundabout is safer than a conventional roundabout and a conventional roundabout is actually safer than a regular signalized intersection, it can be decided for this study, that a metered roundabout is *safer* than a regular signalized intersection.

- Improved safety of signals by adding left-turn lane, right-turn lane or both

Harwood et al. (2003) carried out a before-after study of the safety effects of providing left- and right-turn lanes for at-grade intersections. The study covered a total of 280 improved intersections and 300 similar unimproved intersections in the evaluation period. Geometric design, traffic control, traffic volume and crash data were collected for a mean before period of 6.9-years and a mean after period of 3.9-years. For added left-turn lanes, it was found out that they are effective in improving safety at signalized and un-signalized intersections in both rural and urban areas. A 10% reduction of accidents was expected when installing a left-turn lane on one approach of a four-leg urban signalized intersection. Moreover, adding right-turn lanes proved effective in improving safety at signalized and un-signalized intersections in both rural and urban areas. Accidents were reduced on individual approaches to four-leg intersections by 18% at urban signalized intersection due to the installation of a right-turn lane (and 4% reduction with respect to the whole intersection). Finally, the evaluation of projects involving added left- and right-turn lanes for four-leg intersections shows a reduction of 7% in all crashes.

Another justification for adding exclusive turn lanes was stated by the Federal Highway Administration (2016). Turn lanes cause an improvement of safety and operations of U-turn opportunities and typical left- and right-turn maneuvers by separating the turning traffic volume from the through traffic along the main line of way. Moreover, the provision of an exclusive left-turn reduces the total crashes from 7-44% and fatal and injury crashes from 6-55% at rural and urban stop-sign controlled and signalized intersections. Therefore, it could be concluded that the more exclusive lanes added in an intersection the *safer* the design alternatives would be considered.

- Safety comparison of at-grade and grade-separated intersections

Over the last decades, grade separated intersections were applied as an innovative solution for traffic calming. The vertical separation of roadways resulted in a reduction of crossing conflict points. The route transferring was provided with ramps in order to remove any grade crossing conflicts and accommodate any other intersection maneuvers of vehicles due to diverging, merging and weaving at low speeds. Hence, the provided grade separated intersections have the ability to result in less dangerous situations and delay than grade intersections (Mathew, 2017). Moreover, Shokry et al. (2017) stated that due to the flexible designs of overpass and underpass intersections, they exhibit enhanced traffic performance.

Maze et al. (2004) used a safety performance function (SPF) and crash data of 5 years (1996-2000) in order to assess the safety of two grade-separated, two-way, stop-controlled intersections in Iowa, United States. The expected crash severity rate was estimated when these intersections were at-grade and stop-controlled, and the expected value of the at-grade intersection was compared with the actual value. It was found that with the same volume, the actual safety performance of the grade-separated was about three times better than the expected safety performance of a conventional intersection.

According to He et al. (2016), mobility and safety increases with grade separation. Possibilities of collision reduce due to the removal of the crossing stream of vehicles. Moreover, pedestrians have greater protection since there will be less traffic movements to cross and more refuge points at several locations.

In addition, the Highway Safety Manual of AASHTO (2010) stated that a reduction of 57% in injury crashes results from converting an at-grade, 4-leg intersection into a grade separated interchange, and a 28% reduction can be achieved by changing a signalized intersection into a grade-separated interchange. Thus, the design alternatives of grade separated intersections are considered *safer* than at-grade intersections.

- Safety considerations of grade-separated intersections

There was no clear literature comparing the safety between underpass paired intersections and overpass paired intersection. However, a reasonable factor that may be considered in such comparison is the effect of possible flooding on an underpass-paired intersection, making them less safe than overpasses. Another logical situation is overturning on overpasses, however due to the safety measurements and constrains, the hazardous impact may be much lower than flooding. As such, the overpass is considered *safer* than an underpass design alternative of the intersections.

2.4. MCDM in Transportation Sustainability

Since the planning process in transportation includes many different objectives and usually conflicting interests of a wide range of varying stakeholders, a method that incorporates such multiple objectives should be used in the assessment of transportation projects (Teng and Tzeng, 1996). One of the most common research techniques to assess transit performance is the MCDM (Hassan et al., 2013). The main advantage of this method is its ability to account for a wide range of different, yet relevant criteria, unlike single-objective methods, such as the cost-benefit analysis. Another disadvantage of the cost-benefit analysis is the fact that the data needs to be in monetary values, on the contrary with the MCDM method, that can use raw values and even qualitative measures such as ranking and priorities (Nijkamp and van Delft, 1977).

Another method called the Multi-Attribute Utility Theory (MAUT) methodology is considered a broader field of MCDM that handles some multi-objective trade-offs and involves several attributes that should be considered in the decision-making process (Hwang and Yoon, 1981). MUAT can evaluate several designs in the different required objectives and rank those designs in a quantifiable manner.

Zietsman et al. (2003) carried out a quantitative application of the MCDM for assessing the sustainability of different corridor-level scenarios. The authors integrated a sustainability evaluation process alongside the decision making approach. They based their study on the MAUT technique and combined several chosen performance measures under a single index representing transportation sustainability. They used a microscopic simulation model, called CORSIM, to quantify the sustainability of selected scenarios at the corridor-level. Their study demonstrated the usefulness of indexes while applying the MCDM process in sustainability evaluation and showed that such an approach is highly applicable.

The use of the MCDM methodology in decision making can be conducted using different mathematical techniques that can be used based on the study objectives and data types available. For instance, Zak (2011) applied the MCDM methodology to solve some decision problems of varying categories related to mass transit systems in Poland, using two different analysis techniques. He demonstrated the method by analyzing two real-life case studies in medium-size public transit systems. In the first case study, Zac used the common method of ELECTRE III to rank different solutions to the transit system to determine the best improvement. For the second case study, graphical facilities, called Light Beam Search, were incorporated with the MCDM process to optimize the transit vehicle assignment problem.

In another study conducted by Campos et al. (2009), an index-based weighted multiple criteria procedure was utilized in order to assess sustainable mobility in urban areas. A group of specialists determined the weights for the criteria under the three dimensions of sustainability; environmental, economic and social dimensions. The weighting scheme helped to incorporate the opinions of stakeholders in the relevant definition of sustainability. The developed methodology was validated by applying it to the city of Belo Horizonte, State of Minas Gerais, Brazil.

The evaluation process of the MAUT methodology is implemented by assigning relative scores based on either single or multiple criteria for each alternative. MAUT uses a special technique to normalize the numerical values of the indicators (attributes) into a scale of 0 to 1, with “0” representing the worst option and “1” representing the ideal. This unification enables direct comparison of alternatives that have criteria of different corresponding units.

MAUT has several acknowledged and commonly used models, such as the Analytical Hierarchy Process (AHP) suggested by Saaty (1988) and the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) by Hwang and Yoon (1981). The AHP method applies a pairwise comparison on a scale of 1 to 9 in order to obtain relative weights of indicators, which would be essential in the performance evaluation process. Although this method may be valuable for the assessment of alternatives including subjective criteria, it has several main drawbacks. Guzman (2001) criticized the potential internal inconsistency of this method, the bases of the rigid 1 – 9 scale and the fact that “rank reversal” may occur when introducing a new alternative to the analysis. In comparison, the TOPSIS model compares relative scores of the alternatives in hand based on a single criterion or multiple criteria. Moreover, assessment can be in an objective, subjective, quantitative and qualitative manner (Hawas et al., 2012). TOPSIS estimates the best and worst relative solution and the geometric distance of how close or far they are from the ideal best solution in a way that helps the decision makers determine a suitable course of action. Additional detailed concepts and formulation of the mathematical procedures of TOPSIS are provided by Hwang and Yoon (1981). In this study, TOPSIS analysis would be used as part of the multi-criteria decision-making method, since it is the best fit for the available data in a way that would represent them the best to help decision makers compare between different design alternatives.

Chapter 3: Methodology

The aim of this study is to develop a methodology for evaluating transportation sustainability of intersections using an index-based multiple criteria decision-making technique. The resulting tool generates an index for each design alternative, called the Composite Sustainability Index (CSI), representing its overall sustainability. This methodology is directed towards the strategic planning of road intersections. This chapter shows the main steps for developing such a tool.

3.1. General Approach

The first step in developing the CSI tool was to define the sustainability dimensions under consideration. Then, for the determination of the indicators framework, a review of related previous studies in the literature was conducted. Indicators that reflect the three major sustainability aspects (socio-cultural equity, economic development, and environmental sustainability) from a road-user perspective were extracted. After that, the MCDM technique was used to enable the evaluation of the proposed intersection design alternatives based on the chosen set of indicators. Specific weights were assigned to the indicators as part of the TOPSIS analysis of the MCDM method. The incorporation of the weights enables the determination of the CSI index for the specific design alternatives in TOPSIS analysis. Figure 2 shows the framework of the proposed methodology. The basic element of this framework is the combination of the CSI tool with the MCDM process.

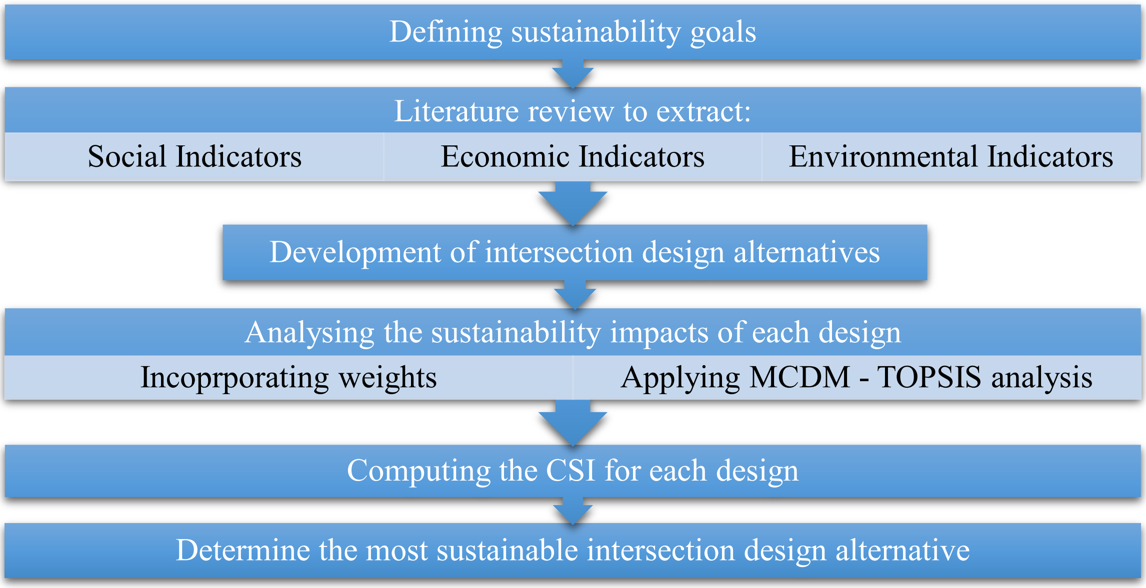


Figure 2: Proposed methodology framework

A practical support tool can be represented by a profile radar graph showing the impacts of the design on the three dimensions of sustainability. This tool can be used by stakeholders and decision makers to visually compare between several design alternatives while still keeping track with the occurring trade-offs. A full triangular shape is considered the solution with the maximum contribution to sustainability based on the sustainability goals. The graphs are shown in Figures 3 and 4. Finally, the tool was applied to four case studies of roundabouts in Al Ain city.

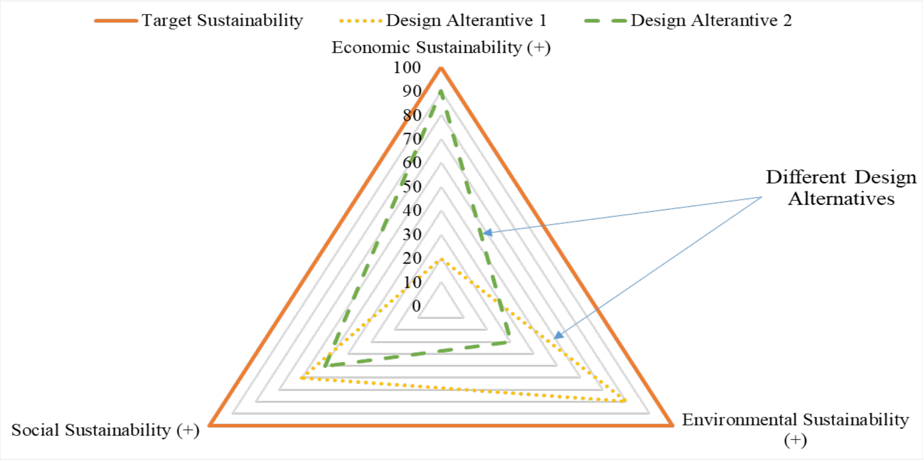


Figure 3: Visual Composite Sustainability Index (CSI) Tool in the three dimensions of sustainability

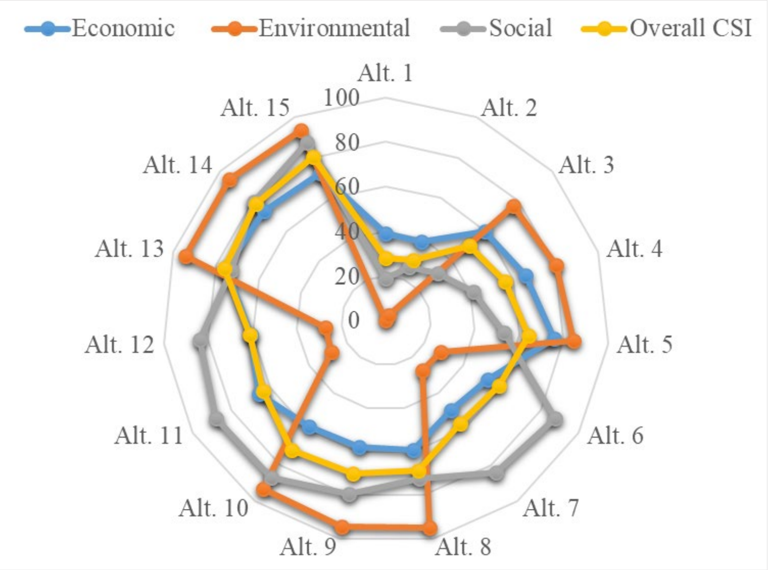


Figure 4: Spider/radar-graph tool for presenting the intersection sustainability assessment of different design alternatives

3.2. Sustainability Definition and Dimensions

This study defines transportation sustainability as the transport that:

- provides equity and safe access for its users;
- enhances the economic efficiency of road users; and
- minimizes the harmful effects of transportation activities on the environment.

Hence, the three main pillars of transportation sustainability which are considered in this study are the economic, environmental and social dimensions. Incorporating an economic dimension serves the main goal of having an efficient transportation system for the movement of people and goods in a way that enhances the economic efficiency of the road intersection users. The aim of considering the environmental aspect is to minimize transportation facilities' impact on ecological systems and consumption of natural resources. Since global warming is a highly regarded issue nowadays, minimizing GHG emissions at the smaller scale of an intersection level will be of good service for the greater global benefit. The social dimension plays an essential role in bringing equity to the community's welfare. It regulates the process of meeting access needs in a way that is consistent with human health and safety. Moreover, a good design that incorporates public and stakeholders input can help promote social equity and interaction. The combination of all of these dimensions aligns well with the 2030 Plan of Abu Dhabi that has the vision of achieving sustainability in the long-term for current and future generation of their citizens.

3.3. Indicators Identification

After determining the main aspects of sustainability that are within the scope of this study, the set of indicators representing those aspects were chosen. A common method for choosing the indicators is to check their adherence to certain criteria. This study will focus on some of the common criteria that were suggested by Castillo and Pitfield (2010), namely:

i. Measurability: The indicator should be measurable in a way that is theoretically sound, reliable and simple to understand.

ii. Ease of availability: The data for the indicator should be available for collection at a reasonable cost and effort. If the data were obtained using a model, the model should be reliable and theoretically acceptable.

iii. Interpretability: The indicator value should provide clear information that all the stakeholders can understand with ease.

Moreover, for this specific research, the indicators would focus on the perspective of the road-user and will have a *macroscopic dimension* that will be more of use for strategic purposes in the early planning stages. A comprehensive list of indicators that were extracted from the literature is shown in Table 4.

Table 4: A comprehensive list of sustainable transportation indicators from literature

Sustainability Dimension	Indicator	Performance measure/Variable	Reference
Economic Sustainability	Operator cost	-Initial cost -Maintenance cost	Lautso et al., 2002; Mansourianfar and Haghshenas, 2018
	Affordability and household expenditure allocated to transport	- Percent of household income spent on transportation -Cost of parking -Fuel price -Point-to-point travel cost	Litman, 2008; Zheng et al., 2013 ; Jeon et al., 2013; Tafidis et al., 2017
	Economic efficiency	-Total time spent in traffic -User welfare changes	Jeon et al., 2013
	Promotion of economic development	-Induced employment -Land consumed by retail/service	Jeon et al., 2013; Sakamoto, 2014;
Environmental Sustainability	Energy consumption	-Vehicle kilometer traveled -Passenger kilometer traveled by public transport -Fuel consumption	Jeon et al., 2013; Mansourianfar and Haghshenas, 2018
	Air pollutants	-VOC emissions -CO emissions -NOx emissions	Mansourianfar and Haghshenas, 2018; Haghshenas and Vaziri, 2012; Litman, 2008;
	GHG emissions	-CO_2 and ozone emissions per capita	Zheng et al., 2013; Jeon et al., 2013

Table 4: A comprehensive list of sustainable transportation indicators from literature (Continued)

Sustainability Dimension	Indicator	Performance measure/Variable	Reference
Environmental Sustainability	Noise pollution	- Exposure to noise level above 65 dB -Decrease in traffic volume (%) -Average speed	Mansourianfar and Haghshenas, 2018; Litman, 2008; Puodziukas et al., 2016
	Land consumption for transport	-Land use mix -Length of railways, main road, cycling and walking pass -Green spaces destruction	Litman, 2008; Mansourianfar and Haghshenas, 2018
Social Sustainability	Mobility	-Level of service (LOS) -Freeway/arterial congestion -Total vehicle-miles traveled -Total passenger-miles traveled -Travel time -Average speed of private vehicles	Gudmundsson, 2001; Litman, 2008; Jeon et al., 2013; Mansourianfar and Haghshenas, 2018; Tafidis et al., 2017
	Accessibility to facilities and public transport	-Railway and main road length -Proportion of residents with public transit services within 500 m -Percent of children walking to school -Percent commuting to work via non-automobile means -Access to activity centers and major services -Access to health care center -Number of accessible facilities	Geurs and Ritsema van Eck, 2001; Jeon et al., 2013; Mansourianfar and Haghshenas, 2018
	Health	-Pedestrian and bicycle mode share -EPA Air Quality Index	Zheng et al., 2013
	Traffic safety	-Fatality and injuries of traffic accident per capita -Bicyclist and pedestrian fatalities per capita	Zheng et al., 2013
	Public satisfaction	- Average travel time -Mode split -Quality of pedestrian and bicycle environment	Litman, 2008; Mansourianfar and Haghshenas, 2018; Winata and Rarasati, 2018
	Social equity	-Average income of population using transit relative to average state income -Equity of exposure to noise and emissions	Zheng et al., 2013; Jeon et al., 2013; Mansourianfar and Haghshenas, 2018

The extracted list of indicators was refined with respect to the previously mentioned criteria. The selected economic, environmental, and social indicators are shown in Figure 5. The percentage of chosen indicators from the comprehensive list, ranges from 22-38% for the three dimensions, which ensures a fair relative selection process of the sustainability indicators. The following sections define the performance measures in more detail in reference to this specific research.

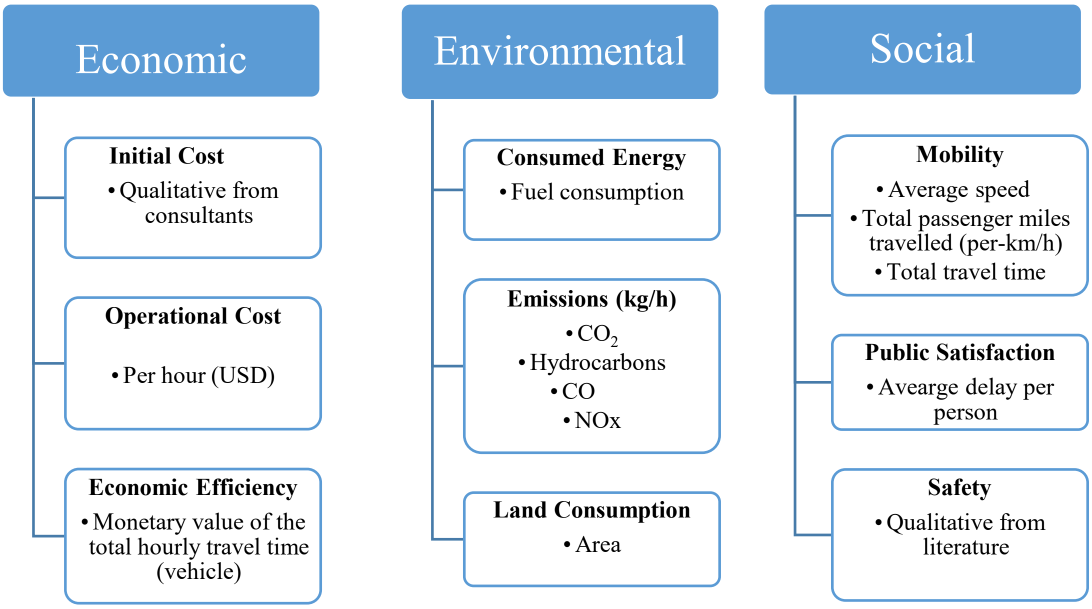


Figure 5: Selected performance measures categorized by sustainability dimensions

3.3.1. Economic indicators

Initial cost, operational cost, and economic efficiency are the indicators representing the economic dimension of sustainability. The initial or capital cost is necessary for decision makers who care about finding equity in the financial state, and it gives a direct way of comparison for a set of alternatives serving the same objective (e.g. a four-way intersection). Since this tool is used for evaluating alternatives in the early stages of transport planning, an exact or even an estimate cost may not be available. Nevertheless, this tool allows the ranking of alternatives as a mean of comparison instead of using real values. The mathematical algorithms used in TOPSIS measures the geometric distance between alternatives after normalizing the scores of each criterion (Hassan et al., 2013), hence counting for the effect of ranks within the specific indicator.

The operational cost reflects the cost of fuel for operating all the vehicles in addition to the time cost of the passengers occupying those vehicles. In a study conducted by Alzard et al. (2019) to compute the road carbon footprint in Abu Dhabi city, more than 90% of the GHG emissions were produced in the operation phase of a road lifecycle, hence including the operational cost might be of high benefit. While the initial cost and operational cost can be measured directly, the economic efficiency, however, is further represented by a performance measure of the monetary value of the total hourly time traveled. This measure uses the time value factor in order to directly present the value of the traveled time per vehicle. In several previous studies (Jeon, 2007; Haghshenas and Vaziri, 2012; Hickman et al., 2012; Smith et al., 2013), the total time spent in traffic was suggested as a surrogate measure for economic efficiency. This research will further convert the time traveled into a monetary value in order to make it easier to understand by stakeholders as an economic indicator.

3.3.2. Environmental Indicators

The environmental dimension has an undeniable part in sustainable development. Protecting the mother-nature preserves more natural resources for future generations. Developing a set of indicators that assess the impact of an urbanized project on the environment helps in the process of controlling or managing the impacts on the environment. Another feature that can be utilized for the environmental indicators is that they have significant ties with the economic and social indicators.

Environmental indicators give an indirect assessment of some social and economic conditions, such as health improvement, reduction of cost for health infrastructure and lower expenses due to lower incidence of traffic congestion (Wilheim, 2013).

The selected environmental dimension covers three main indicators; energy consumption, GHG emissions, and land consumption. Energy consumption has the fuel consumed per vehicle as a performance measure. The GHG emissions also contribute to the harmful effect on the environment, hence this factor was included to quantify the impact of the alternatives on sustainability. The emissions considered are CO_2, hydrocarbons, CO and NO_x, expressed in kg per hour per vehicle. The last selected environmental indicator is the so-called land consumption (the exact area needed for the intersection and approaches). The land consumed for the project can be considered as a direct measure to quantify the extent of the consumption of natural resources. Minimizing the area consumed would achieve higher scores for sustainable development.

3.3.3. Social Indicators

The selected indicators to represent the social dimension in the sustainability assessment of intersections are mobility, public satisfaction, and safety. The chosen performance measures for mobility are the vehicles average speed (km/hr), the total passenger miles traveled per hour (mi/hr), and the total travel time of vehicles (hr). The average speed represents that of vehicles in the peak hour of the day with the peak demand on the intersection. This gives an indication of how the vehicles maneuver through the intersection and the level of service it can provide. For the total passenger miles traveled, while it considers the passengers occupying the vehicles, it also includes the miles traveled by pedestrians crossing the intersection. This takes into account the mobility of pedestrians as a social performance measure. The *total time traveled* for each vehicle may seem like a repetition of the average speed, however, inclusion of the effect on all the vehicles shows the effect on mobility from another point of view. Hence, the mobility indicator has three performance measures that complement each other to give a clear indication of the impact that occurs.

The second social indicator is public satisfaction. Public satisfaction can be quantified indirectly by obtaining the average hourly delay per person. The delay includes both passengers of the vehicles and pedestrians crossing the intersection. The lesser the delay, the more satisfied the users would be with the service (of the intersection).

The third and last indicator of the social dimension of sustainability is safety. According to the FHWA, more than 50% of fatal and injury crashes between 2010 and 2014 occurred in the vicinity of intersections (Megat-Johari et al., 2018). Quantifying safety in the early stages of intersection planning can be quite tricky. Common safety assessment methods deal with quantifying the accidents that occurred on the transport facility within a certain period of time. However, such a method cannot be applied in the planning stage when the facility does not exist yet. Lack of data requires coming up with another method that goes around this issue. The suggested method used in this study is the assessment of safety qualitatively. Instead of quantifying the safety of each design alternative for the intersection (e.g. number of accidents), a ranking procedure is introduced. Many studies have been conducted on existing intersections that compare the safety of different designs. Practical results can be used to justify the ranking.

However, a valid issue can arise while using this method. The ranking can fluctuate based on the region or time period of the conducted study. Differences in road users' behavior and perception of local citizens exist between different countries. Thus, a ranking of intersection safety that may be found in one place may not apply when comparing it to another place. An example of this is the ranking between whether a roundabout or a signalized intersection is safer. Despite the fact that many international studies had concluded that a roundabout is safer than a signalized intersection, a study prepared by Abou-Kassem (2017) conducted a survey on road users in the UAE revealed that the drivers' perception of safety of signalized intersections is higher than their perception of safety of roundabouts. This conclusion was also supported by some crash data that indicated experiences of severe crashes and fatalities at several roundabouts in the UAE (Al Ain city).

Nevertheless, this method (reviewing previous literature) seems good enough for the purpose of this study since it can help standardize the procedure for ranking. Then again, the purpose of this study is not to obtain the exact ranking of alternatives (as it may differ actually from one country to another), it is more about developing the methodology for strategic sustainability assessment and showcasing the obtained tool. Customized ranking using the opinions of a specialist panel can be considered when applying this tool in real life on the specific proposed project designs.

Another method for ranking the alternatives objectively is by considering the conflict points for each design as safety measures. *Traffic conflict* is defined in the National Cooperative Highway Research Program Project 17-3 by the Transportation Research Board as follows: “A traffic conflict is a traffic event involving two or more road users, in which one user performs some atypical or unusual action, such as a change in direction or speed, that places another in jeopardy of a collision unless an evasive maneuver is undertaken.” (Parker and Zegeer, 1988). The study and observations of conflict points at intersections can be used to identify operational and roadway characteristics that contribute to safety problems (Garber and Smith, 1996). Having more conflict points for a certain intersection design makes the intersection less safe. For this study, those two methods are combined to assess and rank the safety of the different design alternatives of the intersections.

3.4. MCDM Method

After determining the set of sustainability indicators, the proposed intersection design alternatives can be evaluated using the MCDM method. This study focuses on the incorporation of the developed CSI tool with the MCDM. Since this method allows for the observation of trade-offs in each individual sustainability dimensions, stakeholders can have a better understanding of the impacts regarding each design alternative.

3.4.1. TOPSIS Analysis and the CSI

TOPSIS analysis is a technique under the MCDM method. It allows the evaluation of the criteria in an individual and collective manner using various relative weights for dimensions, criteria and indicators. Data for each indicator and its assigned weight are required to apply TOPSIS analysis. Varying weights can be considered by TOPSIS depending on how each indicator affects the overall sustainability in the opinion of the stakeholders. For this study, the evaluation of the three dimensions of sustainability (economic, environmental and social) would be conducted individually by determining an index for each dimension and collectively as an overall CSI for each design alternative of the study cases. The so-called *TOPSIS scores* represent those indices. A brief explanation of the algorithm used is provided next.

- *Structure of the decision matrix*

To evaluate an alternatives set of multi-attribute decision making problem with the alternatives defined by A = (A1, A2, …, Am), the criteria set defined by C = (C1, C2, …, Cn), and the jth criteria's value in the ith alternative is x_{ij}; then the decision matrix can be presented as $X=[x_{ij}]_{m\times n}$.

- *Normalization of the decision matrix*

Eliminating the effect of the different criteria units and their varying range on the sustainability evaluation would require normalization across the values of the original matrix. This would ensure the equivalency of all the existing attributes and that they have the same format. Hence, the normalized decision matrix is $R=[r_{ij}]_{m\times n}$, which is calculated by Equation (1).

$$r_{ij} = {x_{ij}}\Big/{\sqrt{\sum_{j=1}^{m} x_{ij}^2}}, (i = 1, \dots, m; j = 1, \dots, n) \tag{1}$$

- Determination of the weighted decision matrix (V)

In order to determine the weighted decision matrix, the specified criteria weights are multiplied by the normalized decision matrix as shown in Equation (2).

$$v_{ij} = w_i r_{ij}, (i = 1, \dots, m; j = 1, \dots, n) \tag{2}$$

- *Determination of the ideal best and ideal worst solution*

The ideal best solution is composed of the optimal value of every attribute from the weighted decision matrix V and shown by (3), and the ideal worst solution is composed of the worst value of every attribute from the weighted decision matrix V and shown by (4).

$$V^{+} = (V_1^{+}, V_2^{+}, \dots, V_m^{+}) \tag{3}$$

$$V^{-} = (V_1^{-}, V_2^{-}, \dots, V_m^{-}) \tag{4}$$

Whereas, the ideal best value and ideal worst value are determined by (5) and (6) respectively.

$$V_j^{+} = \begin{cases} \max v_{ij} & , the\ positive\ criteria \\ \min v_{ij} & , the\ negative\ criteria \end{cases} \tag{5}$$

$$V_j^{-} = \begin{cases} \max v_{ij} & , the\ negative\ criteria \\ \min v_{ij} & , the\ positive\ criteria \end{cases} \tag{6}$$

- *Calculation of the distance*

The distance of every possible solution from the ideal best solution and the ideal worst solution are computed respectively by (7) and (8).

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{+}\right)^2}, (i = 1, \dots, m; j = 1, \dots, n) \tag{7}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{-}\right)^2}, (i = 1, \dots, m; j = 1, \dots, n) \tag{8}$$

- *Calculation of the relative degree of approximation (CSI)*

The relative degree of approximation is calculated by Equation (9).

$$CSI_i = {S_i^-}\big/_{(S_i^+ + S_i^-)}, (0 \leq CSI_i \leq 1; i = 1, 2, \dots m) \tag{9}$$

The object of evaluation, which is sustainability in this study, is ranked according to the value of the relative degree of approximation. The relative degree of approximation is coded as “CSI” to conveniently represent the composite sustainability index used in this study. The higher the value the better the sustainability of the alternative.

In a basic statement, the TOPSIS scores (indices) are obtained by normalizing the values of the indicators relative to the “ideal” value while incorporating their corresponding weight. In this study, the ideal value is considered to be the “minimum” value for each indicator except for the Mobility indicator of *average speed* performance measure; whereas the ideal value is considered to be the maximum. Moreover, the score of each indicator would have a real value between 1 (best performance) and 0 (worst performance). An overall performance index of each alternative can be computed using a weighted average of the three sub-indices of the sustainability dimensions (Kobryń and Prystrom, 2016). The final ranking of the design alternatives would be determined by comparing the overall CSI where the highest index would be ranked first as the optimal solution. Also, another type of comparison between the individual dimensions of sustainability can be applied, and the separate trade-offs can be observed.

3.4.2. Weighting Scheme

Relative weights show how much an indicator contributes to the concept of sustainability as a whole and with respect to its relevant dimension of sustainability (environmental, economic or social).

A straightforward procedure suggested by Hwang and Yoon (1981) which is based on a linear and discrete 1-5 point scale, can be utilized to assign relative weights to the indicators. This method is simple and requires less effort when compared to other methods such as Analytic Hierarchical Process (AHP). The numbers 1 to 5 respectively correspond to a linguistic scale of importance: ‘Very Low’, ‘Low’, ‘Medium’, ‘High’, and ‘Very High’; a case of ‘Not Applicable’ is also available. After the collection of the numeric data from the surveys of a specialist panel, they can be normalized across the complete list of indicators underneath each aspect of sustainability to generate relative weights on a scale from 0 to 1. Relative weights of the major sustainability aspects (environmental, economic and social) will be also assigned in the same way. A CSI value can be extracted using these set of weighted indicators.

Conducting surveys on specialists in order to generate the specific weighting of dimensions, criteria and indicators is out of the scope of this study. However, another approach would be taken in order to showcase the effect of different weights on the final ranking of alternatives. The first weighting attempt would be to equalize the weights across the three dimensions of sustainability and within the set of indicators. The second attempt would be to introduce variations in the main weight distribution of the three dimensions of sustainability. A major part of the weight (80%) would be placed on one dimension of sustainability, while the other two dimensions would share the remaining minor weight (20%). This variation would alternate through the three dimensions (economic, environmental and social aspects) and the difference in the final ranking of the alternatives would be observed. This demonstrates how the interests of specific stakeholders can produce a change in the sustainability direction.

A case study of four existing intersections in Al Ain city was conducted to showcase the CSI tool. Different design alternatives were developed and evaluated to determine their contribution to sustainability. Data collection was carried out, and relevant data for each indicator was collected for all the proposed designs. Data collection methods varied from using simulation models (e.g. *SIDRA Intersection Simulation Model*), qualitative assessment through literature review, consulting contractors and direct measuring; depending on the most suitable and efficient way for each specific indicator. Moreover, Figure 6 shows some suggested methods to obtain the required data.

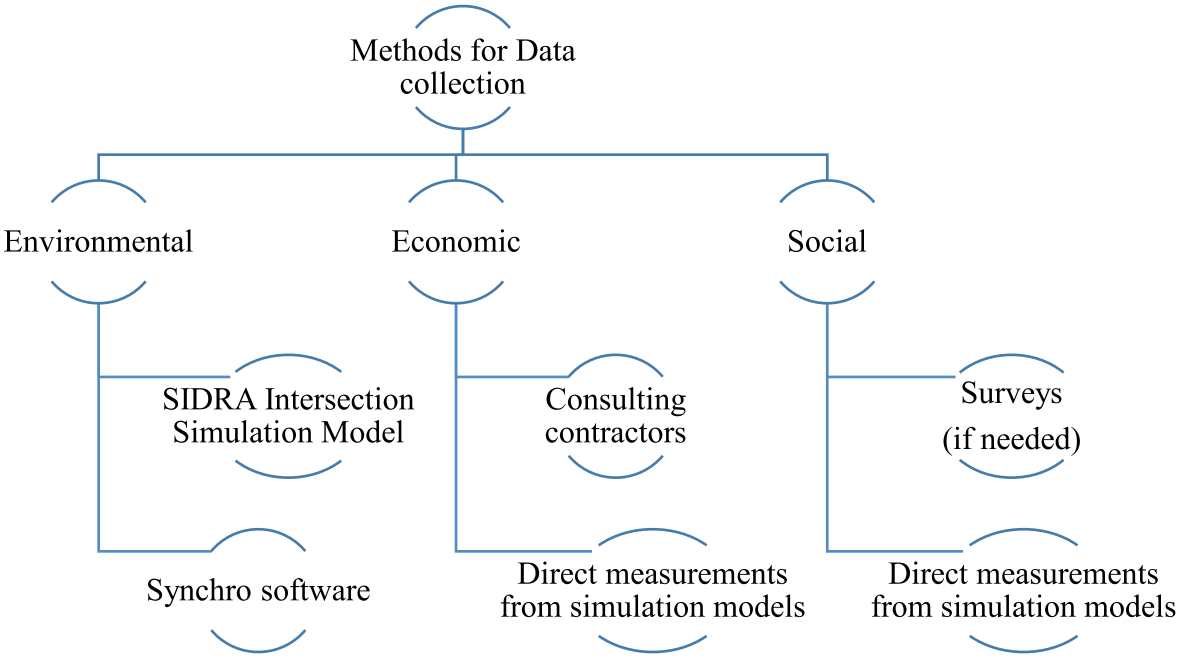


Figure 6: Proposed methods for data collection

Chapter 4: Case Studies Application

The previously developed framework was demonstrated in four case studies in Al Ain city, UAE. Four roundabouts, namely, Asharej Roundabout, Al-Markhaniya Roundabout, Al-Ahliya Roundabout, and Al-Dewan Roundabout; were considered for the case studies. For each roundabout, fifteen design alternatives were developed. The alternatives were evaluated by TOPSIS while introducing variations in the volume and the operational speeds. The best design alternative with respect to sustainability was determined alongside any existing trade-offs within the individual sustainability dimension. A sensitivity analysis was conducted by varying the weights of the sustainability dimensions and observing the changes in the final ranking.

4.1. Description of Case Studies

The roundabouts are located in Al-Ain city within the Abu Dhabi Emirate, UAE. Abu Dhabi is considered to be the largest emirate in the UAE covering around 87% of the country's area with a population of around 2,900,000 capita in 2016 (SCAD, 2017). Al Ain city is the second largest city in the Emirate of Abu Dhabi, after the capital itself. It is known as the garden city due to its extensive green and landscape areas. The city is located approximately 160 km east of the Abu Dhabi capital, adjacent to the border with the Sultanate of Oman. The city is an attractive tourist destination, with many forts and archaeological sites. The topography of the city is generally flat but rises in elevation from North-East to South-West.

Rapid development has taken place in Al Ain over the past 30 years. For instance, a new industrial city was established in the West of Al Ain and many development projects were constructed such as hotels, malls, and new urban settlements. Nonetheless, the majority of the city is composed of three to four-story buildings and the main streets are quite wide with dual three lanes.

Abu Dhabi Emirate has more than 460 roundabouts, most of which are multi-lane roundabouts with three entry/circulatory/exit lanes (Dabbour et al., 2018). Specifically, Al-Ain city was mainly operated by roundabouts until the early 2000's. The considered part of Al-Ain city in this study is mainly a mixed of residential and commercial areas. A recent trend happening is the conversion of most of these roundabouts into signalized intersections. There is no published official study that justifies such a conversion. This is happening despite the fact that several research studies showed a reduction in crash frequency and severity when comparing the performance of a roundabout with that of a signalized intersection (e.g. Troutbeck, 1993; Schoon and van Minnen, 1994; Persaud et al., 2001; Elvik, 2003; Rodegerdts et al., 2007).

The developed tool in this study can benefit in assessing the appropriateness of a chosen design of an intersection in Al-Ain with respect to the specific sustainability dimensions. The chosen roundabouts are directly connected to each other. Figure 7 shows a map overview of their location.

Figure 7: Location of studied roundabouts in Al-Ain City (Google Maps, 2019)

The four considered roundabouts are Asharej, Al-Markhaniya, Al-Ahliya and Al-Dewan roundabouts. They are connected by four main streets which are Sheik Khalifa Bin Zayed Street, Hazzaa Bin Sultan Street, Shakhboot Bin Sultan Street and Zayed Al Awwal Street. All of the roundabouts have four arms with three lanes for each approach, exit and circulating lanes. Asharej and Al-Ahliya roundabouts have an operational speed of 80 km/h on all four arms while Al-Markhaniya and Al-Dewan roundabouts have varying operational speeds of 80 km/h and 100 km/h.

Traffic data for the four roundabouts was obtained from the Department of Transportation of Abu-Dhabi. The traffic volume was taken for the A.M. peak hour (7:15-8:15) volume count on 08/12/2015. Figure 8 shows the four roundabouts with a code for each arm and Table 5 shows the corresponding attributes for each arm of Asharej roundabout. The data attributes of the remaining roundabouts are shown in Tables A1-A3 of Appendix A.

The reason behind choosing four roundabouts of case studies is because of some distinct features that each roundabout has that distinct it from the other. For instance, Al-Dewan roundabout differs slightly from the other case studies by the fact that it originally has an underpass, while the other roundabouts are originally at-grade. Also, Al-Ahliya roundabout was recently converted into a signalized intersection. Thus, the developed tool can determine if such a conversion is justified or not. While Asharej and Al-Markhaniya may appear to have big similarities, the geometric design of Asharej roundabout is that of an ellipse while the other is more of a circle.

Having several case studies may also help in catching any kind of unaccounted for variations that are related to the nature of the roundabouts and the purposes of the road users to enter that specific roundabout on that specific road. Moreover, these four roundabouts are located adjacent to each other, hence it would help in future research concerning the accumulating impacts on sustainability for a network of intersections instead of only limiting the study to individual intersections.

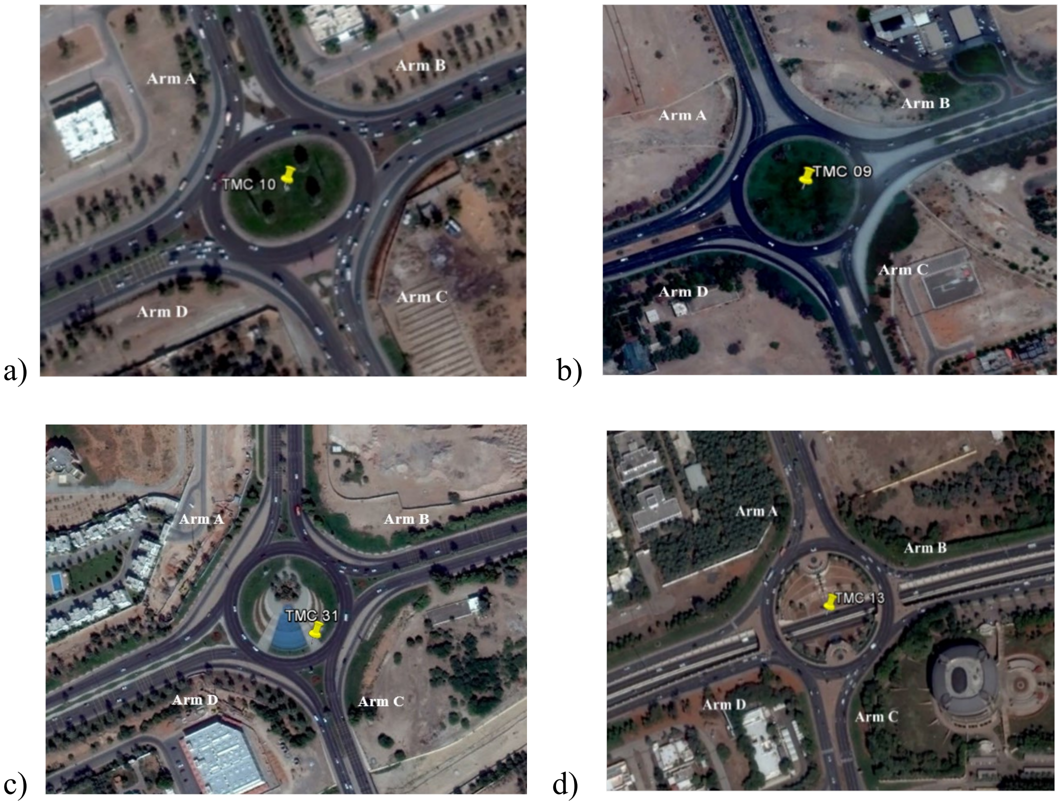


Figure 8: The roundabout case studies: a) Asharej, b) Al-Markhaniya, c) Al-Ahliya, d) Al-Dewan.

Table 5: Traffic data attributes for Asharej roundabout (2015)

	ARM A				ARM C			
Links	A-D	A-C	A-B	A-A	C-C	C-D	C-A	C-B
% Heavy Vehicles	1%	6%	3%	8%	0%	2%	5%	5%
Peak Hour Factor	0.90	0.88	0.79	0.81	0.50	0.90	0.90	0.79
Vehicles Per Hour	287	1126	333	26	6	461	1123	148
	ARM B				ARM D			
Links	B-A	B-D	B-C	B-B	D-D	D-A	D-B	D-C
% Heavy Vehicles	4%	4%	7%	23%	2%	0%	4%	4%
Peak Hour Factor	0.82	0.89	0.63	0.58	0.60	0.74	0.93	0.92
Vehicles Per Hour	262	1032	407	30	41	237	1057	373

4.2. Development of Intersection Design Alternatives

For each roundabout, fifteen design alternatives were developed using SIDRA Intersection 7.0 Software. The alternatives can be grouped in three main intersection categories; at grade intersections, grade separated intersections with an underpass, and grade separated intersections with an overpass. The alternatives have the same properties of the original roundabouts except for some variations in the control type (e.g. metered roundabout, signals) and the number of exclusive short lanes (right-, left- and U-turn lanes).

- Group 1 Description

There are five design alternatives for the at-grade intersections group. The first design alternative is a regular three-lane roundabout with short right lanes in every arm (Figure 9a). The second design is a signalized (metered) roundabout with the same properties of the previous roundabout design (Figure 9b). The third design moves to a signalized intersection with all the arms having a short right lane (Figure 9c). The fourth alternative is a signalized intersection with short exclusive right and left lanes (Figure 9d). The final design alternative for this group is a signalized intersection with short exclusive right-, left- and U-turn-lanes at each arm (Figure 9e).

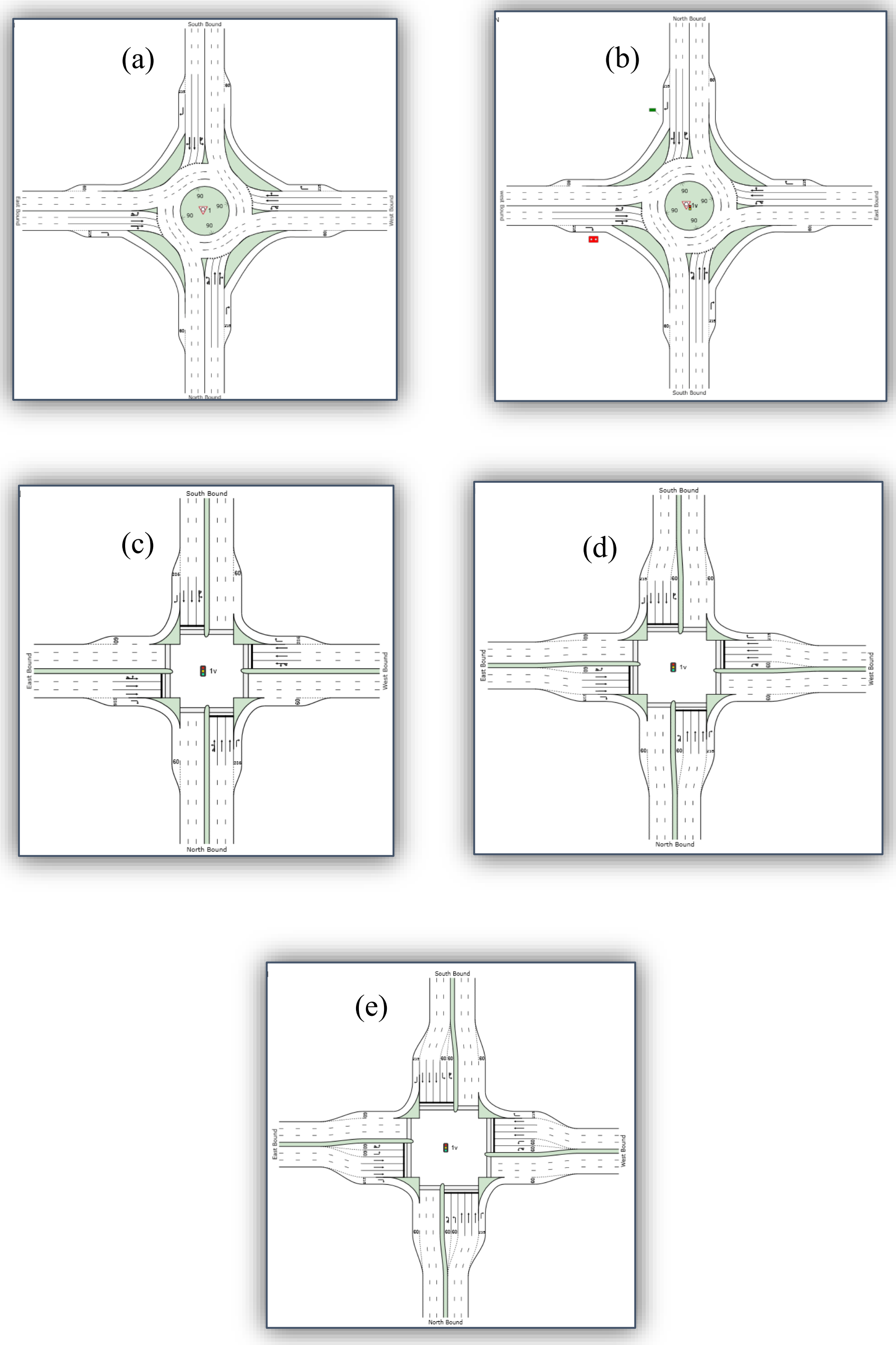


Figure 9: Group 1 of the developed design alternatives a) 3-lane roundabout, b) 3-lane metered roundabout, c) signalized intersection with right-turns, d) signalized intersection with right- and left-turns, e) signalized intersection with right-, left- and U-turns

- Group 2 Description

The design alternatives for Group 2 are the same of those in Group 1 except that they have an additional underpass to the at-grade intersections. The underpass is stationed in the direction of the heaviest traffic load. The through volume of the underpass was roughly assigned to be equal to 97% of the original volume, and the remaining 3% of the volume was assigned to the through movement of the paired at-grade intersection. The underpass and the paired at-grade intersection were modelled separately in SIDRA Intersection Software (more details about the simulation model are provided in section 4.3). The additional underpass is shown in Figure 10 alongside the paired intersections of Group 1. The number of design alternatives for this group is also five.

- Group 3 Description

Group 3 of the design alternatives has the exact same description of Group 2, except that it has an additional overpass instead of an underpass. It is also paired with the designs of Group 1 as shown in Figure 10. Hence, with the additional five designs of Group 3, the total number of alternatives for a single scenario of the case studies equals fifteen design alternatives.

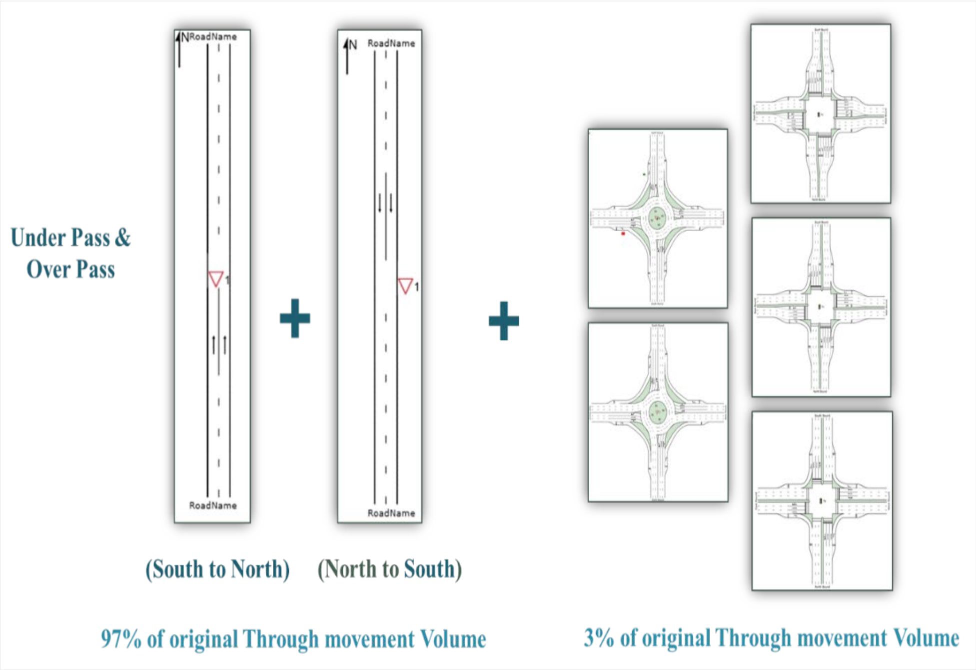


Figure 10**:** Group 2 and Group 3 of the design alternatives

A brief description of each alternative for a single scenario of a case study and its coding (ID) are shown in Table 6.

It should be noted that even though Al Dewan roundabout case study originally has an underpass, the same set of alternatives were developed for it. The traffic volume on the underpass was combined with the through volume of the paired roundabout to give the total through volume on the at-grade intersections alternatives.

Table 6: Description of the design alternatives with their corresponding ID's

No.	ID	Intersection Type	Interchange Type	Turning Lanes		
				Right (R_T)	Left (L_T)	(U_T)
1	RA	Roundabout	-	√	-	-
2	SRA	Signalized Roundabout	-	√	-	-
3	S(R_T)	Signals	-	√	-	-
4	S(R_T, L_T)	Signals	-	√	√	-
5	S(R_T, L_T, U_T)	Signals	-	√	√	√
6	U-RA	Roundabout	Underpass	√	-	-
7	U-SRA	Signalized Roundabout	Underpass	√	-	-
8	U- S(R_T)	Signals	Underpass	√	-	-
9	U-S(R_T, L_T)	Signals	Underpass	√	√	-
10	U- S(R_T, L_T, U_T)	Signals	Underpass	√	√	√
11	O-RA	Roundabout	Overpass	√	-	-
12	O-SRA	Signalized Roundabout	Overpass	√	-	-
13	O-S(R_T)	Signals	Overpass	√	-	-
14	O-S(R_T, L_T)	Signals	Overpass	√	√	-
15	O-S(R_T, L_T, U_T)	Signals	Overpass	√	√	√

- Volume Variations

The fifteen alternatives mentioned previously were repeated for different volume scenarios for each roundabout. The volumes used would be present volume of the year 2018, past volume of year 2008 and future volume of year 2028. Since the data in hand is for the year 2015, forecasting and backtracking techniques would be used in order to get the required volumes. An annual growth factor of 2-3% is recommended by the North California Department of Transportation (NCDOT) to use for intersections (Cunningham et al., 2016). An annual growth factor of 3% is commonly used by the DoT –Abu Dhabi in other studies and as such it is used in this study. The addition of this variation would benefit in observing the effect of traffic volume in choosing the best sustainable alternative.

- Operational Speed Variations

Another factor that would be tested is the operational speed of the roads. However, only two cases where the roundabouts have the same operational speeds in the four arms would be included. The specified roundabouts are, Al-Ahliya and Al-Dewan roundabouts. The operational speeds would be varied between the speeds 80 km/h and 100 km/h. The effect of changing the operational speed on the sustainability ranking of alternatives will be observed.

- Summarized scenarios

This study demonstrates the use of the developed methodology for four case studies which have three traffic volume variations each and two operational speed variations for only two roundabouts (Al-Ahliya and Al-Dewan). Hence, fourteen different scenarios were considered. Within each scenario, a set of fifteen different design alternatives were evaluated using the developed CSI tool. Figure 11 shows a summary of the considered scenarios for the four case studies.

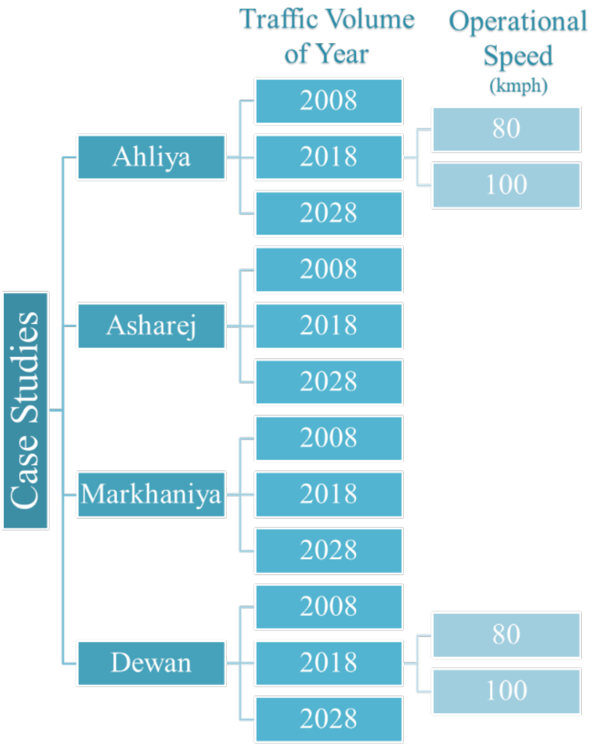


Figure 11: Summary of the scenarios under consideration

4.3. Data Sources and Collection

Data collection methods for this study varies with respect to the type of data needed. The required input data used in TOPSIS analysis are qualitative and quantitative in nature. The following sections describe the data source and collection method for each indicator.

- Methods for collecting data of the Quantitative Indicators

1. SIDRA Intersection 7.0 Software:

SIDRA Intersection is a powerful software used for designing, modelling and evaluating individual intersections and networks of intersections. It can be used to analyze many kinds of intersections, such as: un-signalized and signalized intersections (fixed-time / pre-timed and actuated), signalized and un-signalized pedestrian crossings, roundabouts (un-signalized), roundabouts with metering signals, stop sign and give-way/yield sign control, single point interchanges (signalized) and freeway diamond interchanges (Akçelik, 2016). For this study, the performance measures that were extracted from the simulation program SIDRA are: the operational cost, fuel consumption, emissions of air pollutants in kg/h (CO_2, NOx, CO, hydrocarbons), average speed, total passenger miles travelled (person-km/h), total travel time, and the average delay per person.

- SIDRA Intersection Application and Parameters:

In order to get the previously mentioned output from SIDRA Intersection software, certain input parameters and settings should be entered and defined. Most of the settings used for this study were the original defaults of the software. However, certain parameters were adjusted to suit this study. The parameters' adjustments are mentioned below.

  - Operational Cost

In order to adjust the cost parameters, the Gross National Income (GNI), which represents the average income of the country divided by the population, is required. The GNI for the UAE at the end of 2017 is equal to 150551.614 AED/capita/year (The World Bank, 2018). The GNI value is converted into US dollars to be consistent with the units used in SIDRA Intersection software, hence a value of 40987.68 $/capita/year is obtained. Moreover, the normal working hours for the private sector is identified by article 65 of the UAE Labour Law to be as 8 hours per day (The Official Portal of the UAE Government, 2018), which would be used to input the GNI value in SIDRA as follows:

$$40987.68\ \frac{\$}{year} \times \frac{1\ year}{365\ days} \times \frac{1\ day}{8\ hours} = 14.037\ \$/h$$

Due to lack of relative data for the UAE, the time value factor would be taken similar to the one used by the US (0.4) (American Association of State Highway and Transportation Officials, 2010).

- Fuel Price

Adjustment of the fuel prices in SIDRA is necessary to reflect the conditions of the UAE. Table 7 shows how fuel prices change monthly throughout the year of 2018 (UAE Ministry of Energy and Industry, 2018). The prices of Unleaded Gasoline 98, Unleaded Gasoline 95 and Unleaded Gasoline 91 were averaged for each month. The average value, which is 2.36 AED/L, was chosen as the representative value for the fuel price of light vehicles. While the fuel price for heavy vehicles would be the average of the diesel prices of the year 2018, which is 2.59 AED/L. The units of the fuel prices of the light vehicles and the heavy vehicles were converted into US dollars resulting in 0.64 $/L and 0.71 $/L, respectively.

Table 7: Fuel prices (AED) for UAE – 2018

Month	Unleaded Gasoline 98	Unleaded Gasoline 95	Unleaded Gasoline 91	Diesel	Average Price (AED/L)
December	2.25	2.15	2.05	2.61	2.10
November	2.57	2.46	2.38	2.87	2.47
October	2.61	2.5	2.41	2.76	2.51
September	2.59	2.48	2.4	2.64	2.49
August	2.57	2.46	2.38	2.63	2.47
July	2.56	2.45	2.37	2.66	2.46
June	2.63	2.51	2.44	2.71	2.53
May	2.49	2.37	2.3	2.56	2.39

Table 7: Fuel prices (AED) for UAE – 2018 (Continued)

Month	Unleaded Gasoline 98	Unleaded Gasoline 95	Unleaded Gasoline 91	Diesel	Average Price (AED/L)
April	2.33	2.22	2.14	2.40	2.23
March	2.33	2.22	2.14	2.43	2.23
February	2.36	2.25	2.17	2.49	2.26
January	2.24	2.12	2.05	2.33	2.14
			Average:	2.59	2.36

2. Direct measurement:

- Land consumption: Direct measurement of the area of the intersection was conducted using the AutoCAD software. The geometric features of the intersections would be drawn and the area would be computed.
- The monetary value of the total hourly travel time (vehicle): The economic indicator for the efficiency, would be indirectly computed by multiplying the total hourly travel time from SIDRA with the average income (14.037 $/h) and the time value factor (0.4) that was recommended by the American Association of State Highway and Transportation Officials (2010).

- Qualitative Indicators

The second type of data was determined qualitatively based on the opinions of academic experts and the literature. The qualitative indicators are mentioned below.

- Initial Cost

Determination of an exact cost in early planning stages for the design alternatives is not possible. Thus, qualitative assessment would be conducted in order to obtain a cost ranking of the alternatives. Since TOPSIS analysis can incorporate ranks instead of actual values, this would not introduce any issue. To further check whether using ranks or actual values for the cost has an effect on the results (choosing the best sustainable alternative), a test run was carried out on one of the scenarios. Two trials were run for the same scenario, one trial used ranks and the other used some estimated values for the cost. The values for all of the other criteria were the same in both trials. The final ranking of the alternatives was the same for the first five best sustainable alternatives in both trials. This being said, if a more specific way to estimate the actual costs of the design alternatives does exist, using it would be more desirable. However, for the scope of this study, qualitative ranking was appropriate.

The qualitative ranking of the initial cost was done reasonably. Group 1 of the design alternatives has the lowest cost since it is at-grade, whereas the other two groups are off-grade. Group 2, the paired underpass, has a higher cost than Group 3, the overpass, when considering the cost of excavation. The ranking within each group would be done based on the type of intersection. A roundabout usually costs more than a signalized intersection since it needs a lot of earth work and excavation done and it also needs a very large area relative the signals in order to contain the circulation lanes. For the signalized roundabout when compared to a regular roundabout, it also has some added technology cost for the signals, hence it has a higher cost. Finally, for ranking within the signalized intersections, added lanes means added cost, hence the highest cost would be for the alternative with the three exclusive lanes then to the ones with two and one lanes in sequence. The best alternative (rank =1) relative to the cost is the one that costs the minimum amount of money. The final qualitative ranking of the design alternatives for the initial cost is shown in Table 8.

Table 8: Initial cost ranking of the design alternatives

ID	Initial cost rank
RA	4
SRA	5
$S(R_T)$	1
$S(R_T, L_T)$	2
$S(R_T, L_T, U_T)$	3
U-RA	14
U-SRA	15
U- $S(R_T)$	11
U-$S(R_T, L_T)$	12
U- $S(R_T, L_T, U_T)$	13
O-RA	9
O-SRA	10
O-$S(R_T)$	6
O-$S(R_T, L_T)$	7
O-$S(R_T, L_T, U_T)$	8

- Safety

Safety ranking was based on all the previous reasoning in Chapter 2. A final ranking of the fifteen design alternatives of the intersections for this specific study is presented in Table 9. The best alternative with respect to safety is given the minimum rank of 1, while the worst has the maximum rank of fifteen.

Table 9: Ranking of the intersection design alternatives with respect to safety

ID	Intersection Safety
RA	12
SRA	11
S(R_T)	15
S(R_T, L_T)	14
S(R_T, L_T, U_T)	13
U-RA	7
U-SRA	6
U- S(R_T)	10
U-S(R_T, L_T)	9
U- S(R_T, L_T, U_T)	8
O-RA	2
O-SRA	1
O-S(R_T)	5
O-S(R_T, L_T)	4
O-S(R_T, L_T, U_T)	3

4.4. TOPSIS Evaluation of Intersection Design Alternatives

TOPSIS analysis was carried out using equations (1-9) mentioned in section 3.4.1. Sustainability assessment for the different scenarios within the case studies, resulted in three indices in the three dimensions of sustainability and a fourth index of the overall CSI for each design alternative. The corresponding radar/spider-graphs show the indices for all the fifteen design alternatives with the ideal (best) alternative being closer to the 100% mark.

4.4.1. Results of Equal Criteria Weights

The first part of the results focuses on the case where the weight was equalized for the three main dimension (one-third each) and furthermore equalized within the criteria of each dimension. The observations would be stated under each graph. The radar graph in Figure 12a shows the four indices for all the fifteen design alternatives for Asharej roundabout (2008) scenario with the ideal (best) alternative closer to the 100% mark. The best design alternative based on the overall CSI has a value of 75.65 is O-RA (Figure 12a), which is the overpass alternative with a paired roundabout. The worst design alternative is $S(R_T)$, which is the at-grade signal with an exclusive right-turn lane, having an overall CSI of 34.49 (Figure 12a). Figure 12b shows the final ranking of each design alternatives for this scenario in a line-graph, while Figure 12c shows the sustainability trade-offs for the most sustainable design alternative (O-RA) for Asharej (2008) scenario. From Figure 12b and Figure 12c, it can be seen that the best design alternative has a tendency towards the social dimension when compared to the other design alternatives. An excel sheet of the sample calculation for this scenario is provided in Appendix D.

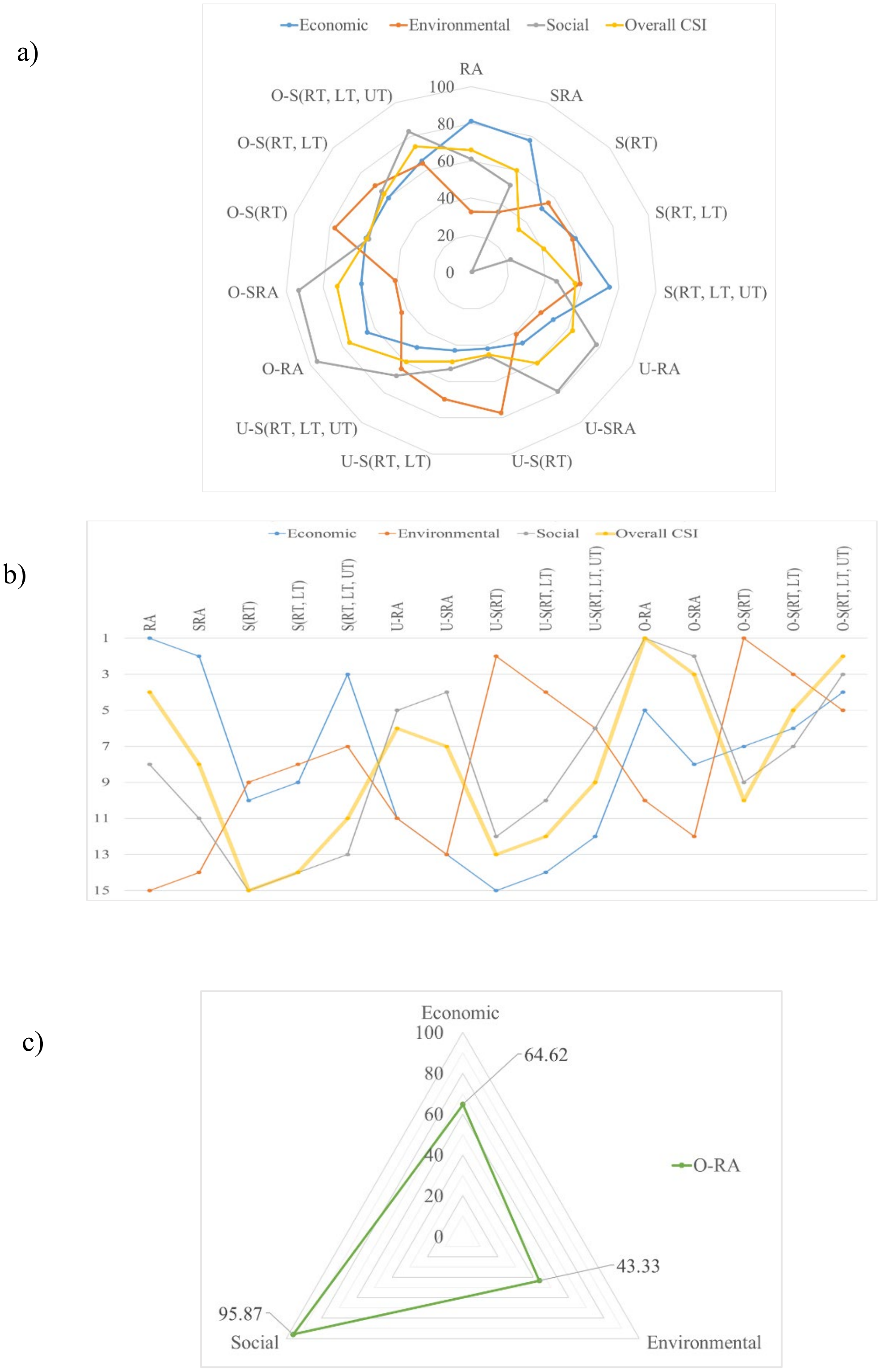
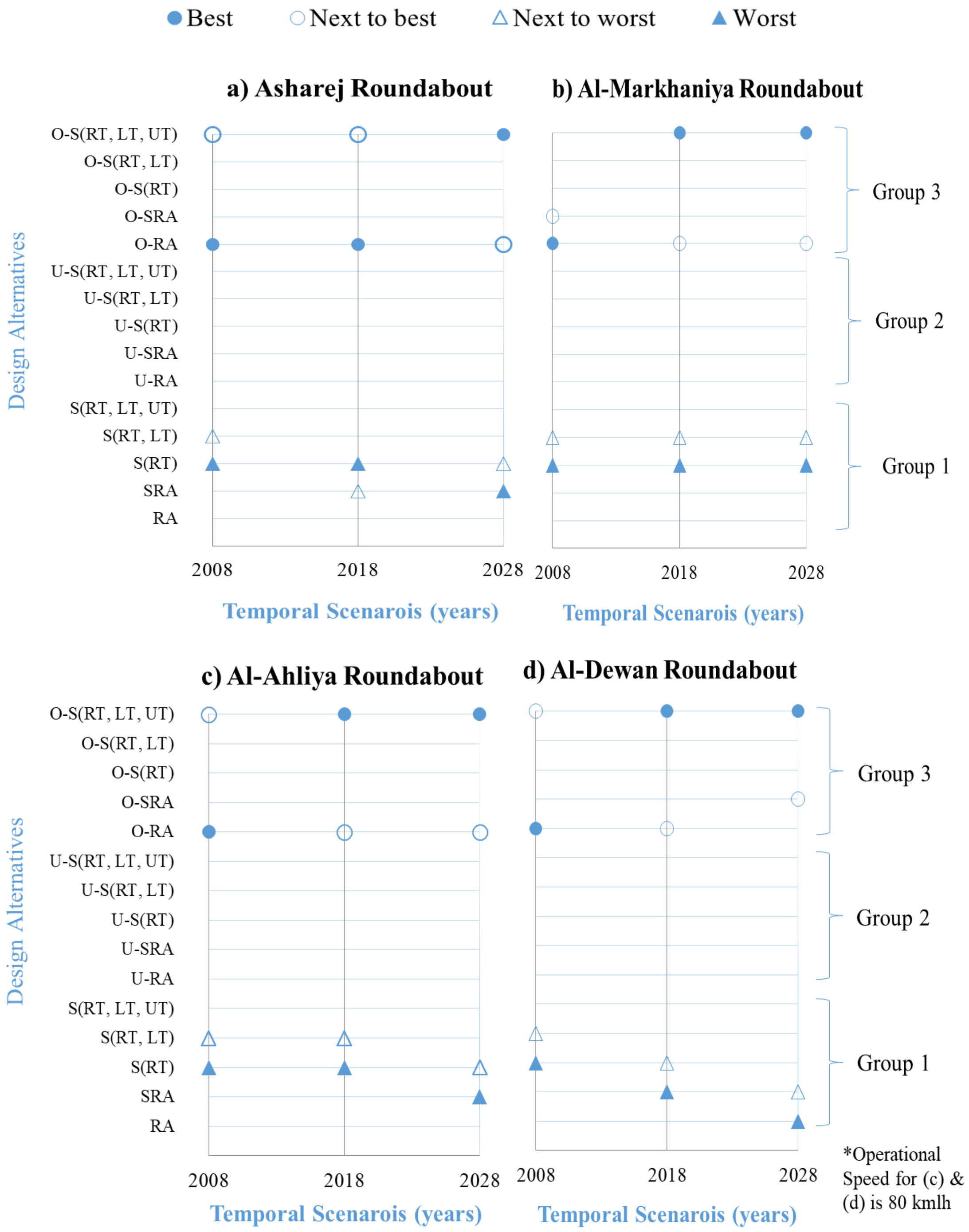


Figure 12: Sustainability assessment of Asharej roundabout (2008) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

The previous analysis was repeated for the remaining spatial and temporal scenarios of the four roundabouts. The generated radar-, line-graphs and the sustainability trade-offs of the most sustainable design for each scenario are presented in Appendix B. It should be noted that for the specific case of Asharej roundabout (2028) in Figure B2, the indicators' values that were extracted from SIDRA intersection software for the roundabout alternative, had a different volume setting. The traffic volume factor for the year 2028 has a 34% increase compared to the year 2018 when using a growth factor of 3%. However, when applying this volume increase on the roundabout alternative (RA), the software gave unreasonable results since the demand exceeded the roundabout capacity to the point where the software could not accommodate. Hence, an iterative process of reducing the traffic volume to the point where the program can give reasonable results has been carried out. The iterative process resulted in choosing an increase in traffic volume of 20% instead of 34% for the at-grade roundabout alternative for the year 2028 of Asharej case study.

- Effect of traffic volume and operational speed variation

Regarding the research question on how the traffic volume and speed factors affect the sustainability, and which factors affect it the most, the effect of varying the assigned traffic volume on the different case studies has been studied while controlling the operational speed. Three different traffic volume scenarios have been generated for the four case studies of the four roundabouts. Al-Ahliya and Al-Dewan roundabouts have two extra scenarios where the operational speed was varied while controlling for the traffic volume. The sustainability assessment for each scenario of the four case studies with traffic volume and operational speed variation are shown in Figures 13 and 14, respectively.



*Operational Speed for (c) & (d) is 80 kmlh

Figure 13: Sustainability assessment of the four roundabouts with traffic volume variation (a) Asharej b) Al-Markhaniya c) Al-Ahliya d) Al-Dewan)

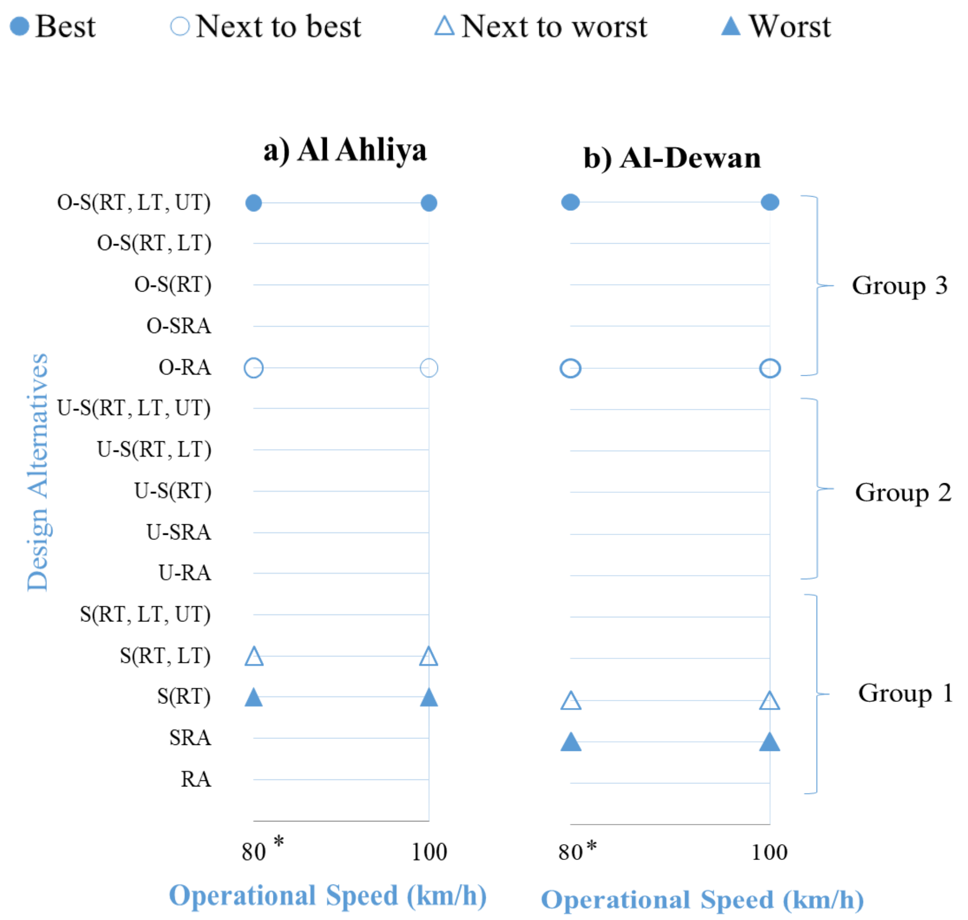


Figure 14: Sustainability assessment with operational speed variation for a) Al-Ahliya roundabout (2018) and b) Al-Dewan roundabout (2018). (* the original operational speed)

Regarding the research question on observable trends in sustainability assessment while varying the volume and the speed factors, a trend that can be noticed from the traffic volume variation is that the best alternatives for the lower volumes have a paired roundabout design, while for the higher volumes, the signal paired designs with added exclusive turning lanes are more likely to be more sustainable. This may be due to the flexible capacity a roundabout provides for low traffic and the organization a signal provides for higher traffic to function/flow/maneuver. This goes well with previous studies such as the one conducted by Sisiopiku and Oh (2001) where it was found that signalized intersections were found to perform better than the roundabouts in terms of delay and capacity when having three-lane approaches accommodating heavy traffic volume.

The speed variation did not have a noticeable effect on the final sustainability ranking of the design alternatives. This may be due to the fact that this study focused on single intersections instead of a whole network of intersections. Hence, the effect of varying the operational speed may have been insignificant on the performance of the individual intersections. Future research may expand the scope of the study to include the accumulating effect of several factors on sustainability when studying a whole network of intersections. It should be noted that the effect of speed variation was not specifically emphasized in previous studies.

A question that was raised earlier about the nature of the most sustainable design alternative was answered in an observation that the most sustainable design for all the volumes has an overpass grade-separated design, while the least sustainable designs are at-grade intersections. This may be due to the fact that the traffic volume gets separated into two sections in the overpass-alternatives, providing smoother flow of traffic with less conflict points (safety-wise), hence, not only enhancing the social aspects but also reducing the harmful effect on the environment due to less congestion.

It can also be remarked that the most sustainable design is not necessarily the most expensive design. The most expensive designs are the designs incorporating an underpass, however, they did not rank as the most sustainable designs when the assessment was conducted with equal weight scheme. This can act as a bonus when stakeholders decide to take sustainability into consideration with a limited budget or just even to save money to utilize in another beneficial cause.

4.4.2. Results of Sensitivity Analysis

A sensitivity analysis was conducted where 80% of the weight in TOPSIS analysis was assigned for only one dimension of sustainability, while the remaining 20% was assigned equally to the other two dimensions. The effect of varying the weight of the sustainability dimension on the ranking of the alternatives was observed for some of the case studies' scenarios. Table 10 and 11 show the results of the sustainability assessment with the corresponding CSI values and the dimensional tendency for equal weight scheme and the sensitivity analysis, respectively.

Table 10: Sustainability assessment of the case studies' scenarios with equal weights scheme

Case Study	Year	Best Design Alternative	Best CSI (%)	Worst CSI (%)	Tendency dimension (%) (for best alternative)
Asharej Roundabout	2008	O-RA	75.65	34.49	Social (95.87)
	2018	O-RA	75.78	34.05	Social (95.41)
	2028	O-S(R_T, L_T, U_T)	76.13	34.12	Social (89.69)
Al-Markhaniya Roundabout	2008	O-RA	73.89	35.94	Social (95.95)
	2018	O-S(R_T, L_T, U_T)	76.02	34.77	Social (86.64)
	2028	O-S(R_T, L_T, U_T)	77.73	35.79	Social (90.81)
Al-Ahliya Roundabout	2008	O-RA	76.90	32.57	Social (96.35)
	2018_80 [a]	O-S(R_T, L_T, U_T)	72.88	31.51	Social (88.55)
	2018_100 [a]	O-S(R_T, L_T, U_T)	79.68	30.87	Social (88.93)
	2028	O-S(R_T, L_T, U_T)	91.25	12.88	Social (91.91)
Al-Dewan Roundabout	2008	O-RA	77.34	32.28	Social (95.84)
	2018_80 [a]	O-S(R_T, L_T, U_T)	76.58	30.25	Social (85.70)
	2018_100 [a]	O-S(R_T, L_T, U_T)	76.75	30.30	Social (86.12)
	2028	O-S(R_T, L_T, U_T)	81.28	24.85	Social (90.56)

[a] The value after the underscore mark (_) represents the corresponding operational speed in km/h.

An important research question regarding any noticed trend in the tendency dimension and CSI values with equal weights analysis was answered as can be seen in Table 10. Whereas by equalizing the weights of the three aspects of sustainability and equalizing the weights within the criteria, all the scenarios have a tendency towards the social dimension. This implies that the impact on the overall CSI for the most sustainable design alternative comes from the social dimension. In other words, the most sustainable design alternative performs exceedingly well in the social dimension when compared to the other two dimensions of sustainability. This may be due to the fact that the design alternatives exhibit a large variation in performance with respect to the social dimension. Whereas the most sustainable design alternative performs outstandingly well in all the criteria under the social dimension resulting in being the closest alternative to the ideal situation. And vice versa, the least sustainable design alternative performs poorly in all the criteria under the social dimension, hence becoming the closest design alternative to the absolute worst situation. This results in a very high score for the most sustainable design alternative and similarly a very low score for the least sustainable design alternative. Another reasoning for such consistent performance in the social dimension for a single design alternative is the possibility of having a correlation between the criteria of this dimension. This does not invalidate the results, since every criteria reflects a different aspects of sustainability despite their correlation. However, a more thorough study in the future that focuses on the interaction between those criteria may give a clearer picture of the effect of each criteria on sustainability.

This being said, the other two dimensions of sustainability (economic and environmental) have a narrower range for their corresponding indices. Which means that even the most sustainable design alternative in those two dimensions does not perform exceedingly well in all the criteria under that specific dimension, hence being quite far from the ideal situation despite ranking first as the most sustainable design alternative in that dimension.

Another observation can be seen in the CSI values when equalizing/controlling for the weight assignment. The overall CSI values are relatively close to each other throughout the years and even when varying the operational speeds. However, a slight increase in the CSI values can be noticed for the high traffic volume of 2028. On the contrary to the idea that more vehicles could cause less sustainable impacts, this may be due to the enhanced utilization of the built facilities when higher volumes are present. Moreover, it should be noted that the sustainability assessment concerns the design alternative itself and how it can contribute to sustainability, not the condition of the situation caused by the existence of a specific quantity of vehicles.

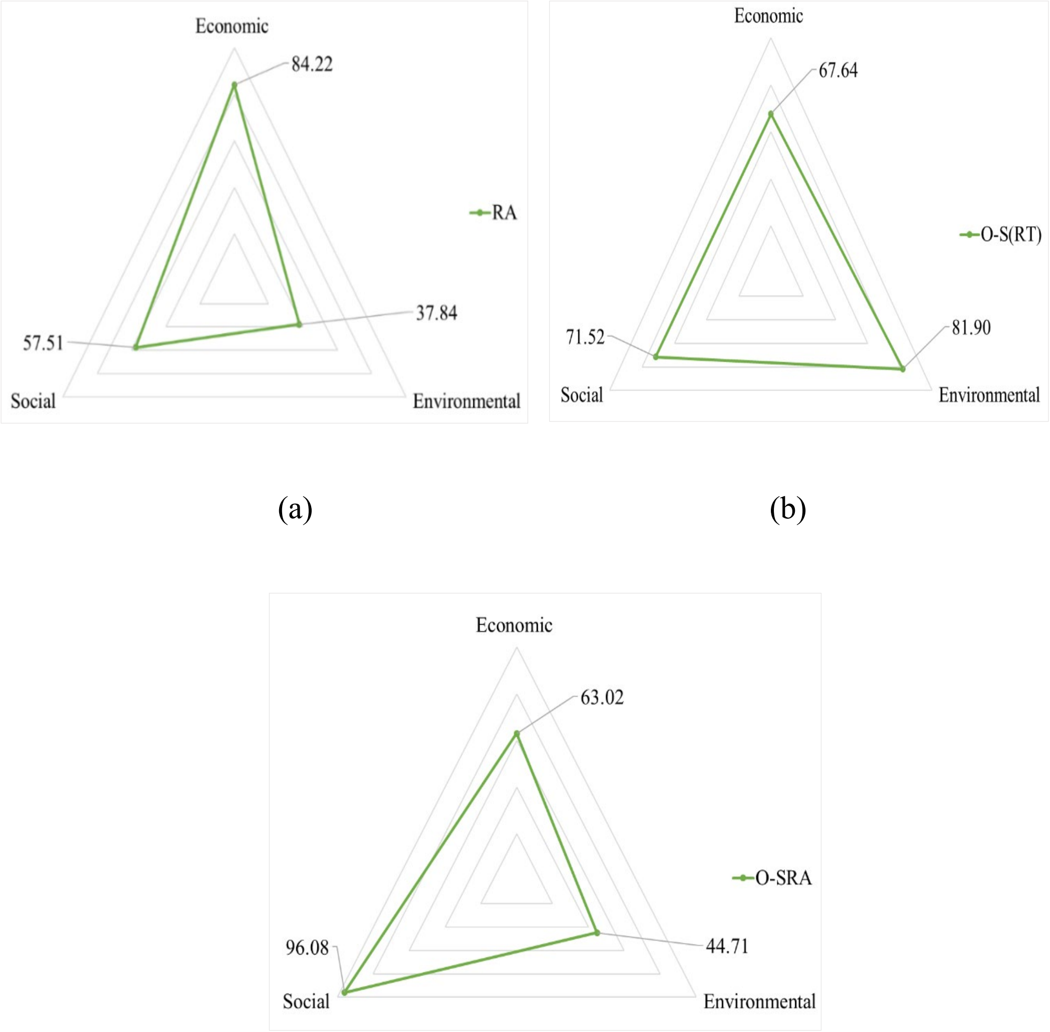
Table 11: Sustainability assessment of the case studies' scenarios with sensitivity analysis

Case study	80% of weight	Best design alternative	Best CSI (%)	Worst CSI (%)	Tendency dimension (by CSI %) (for best scenario)	Tendency dimension (by rank) (for best scenario)
Asharej Roundabout (2018)	Eco.	O-S(R_T, L_T, U_T)	68.98	43.56	Soc. (86.22)	Eco. (2)
	Env.	O-S(R_T, L_T, U_T)	70.64	27.35	Soc. (86.22)	Eco. (2)
	Soc.	O-RA	93.44	7.55	Soc. (95.41)	Soc. (1)
Al-Markhaniya Roundabout (2028)	Eco.	RA	83.04	47.20	Eco. (84.22)	Eco. (1)
	Env.	O-S(R_T)	78.52	28.58	Env. (90.81)	Env. (1)
	Soc.	O-SRA	93.08	8.05	Soc. (96.08)	Soc. (1)
Al-Ahliya Roundabout (2028)	Eco.	O-S(R_T)	75.35	38.50	Env. (87.58)	Eco. & Env. (2)
	Env.	O-S(R_T)	84.87	15.88	Env. (87.58)	Eco. & Env. (2)
	Soc.	O-S(R_T, L_T, U_T)	91.25	12.88	Soc. (91.91)	Soc. (1)
Al-Dewan Roundabout (2008)	Eco.	O-RA	70.76	43.08	Soc. (95.84)	Eco. & S. (1)
	Env.	O-S(R_T, L_T, U_T)	71.84	35.52	Soc. (83.64)	Env. (1)
	Soc.	O-RA	93.94	7.10	Soc. (95.84)	Eco. & Soc. (1)

*Eco.: economic dimension, Env.: environmental dimension, Soc.: social dimension.

Regarding the research question about the observed effect in the tendency dimension by the CSI value and rank when applying the sensitivity analysis, it can be clearly seen in Al Markhaniya roundabout (2028) scenario. The best design alternative when equalizing the weights within the sustainability dimensions, was the O-S(R_T, L_T, U_T) alternative (Table 10). However, after assigning the majority of the weight (80%) to each sustainability dimension alternatively, the most sustainable design alternative changed correspondingly (Table 11).

When assigning the majority of the weight to the economic dimension, the best design alternative changed to the at-grade roundabout alternative. It can be seen from Figure 15a that the RA design alternative has a large impact on the economic dimension, hence it ranked as the most sustainable design when the majority of the weight was assigned to the economic dimension. Another observation can be seen when assigning 80% of the weight to the environmental dimension. Since the O-S(R_T) design alternative, which is the overpass alternative paired with a signalized intersection and exclusive right-turn lanes, tends to have the biggest impact in the environmental aspect (Figure 15b), it ranked first for the 80% environmental weight. Whereas for the last case of assigning 80% to the social dimension, the O-SRA alternative which is an overpass with a paired signalized roundabout, ranked as the most sustainable design since it has the largest impact in that dimension as shown in Figure 15c. The same reasoning applies for the least sustainable design alternatives, where the worst design alternative is the one with the poorest performance in the dimension with the major weight.



(a) (b)

(c)

Figure 15: Most sustainable design alternative for Al-Markhaniya roundabout (2028) with 80% weight variation assigned to the a) economic b) environmental and c) social dimension

However, another observation can be seen in other scenarios, whereas the major impact of a dimension on the overall CSI may not be of the dimension that has the major weight. For instance, when alternating 80% of the weight between the three sustainability dimensions of Al-Dewan roundabout (2008) scenario (Table 11), the dimension that contributes the most to the overall CSI is the social dimension regardless of the weight-dominating dimension. Whereas, the best design alternative throughout the sensitivity analysis has a tendency towards the social dimension.

One of the main research questions was concerned about the effect of the weighting scheme on the sustainability assessment of the roadway intersections, and what would be the best way to observe such an effect. The effect of sensitivity analysis on the tendency dimension of the most sustainable design alternative was observed earlier using the CSI value, however, another way to study this effect is by observing the dimensional tendency using the highest rank. For example, when assigning 80% of the weight to the environmental dimension in Al-Dewan roundabout (2008) scenario (Figure 16), the social dimension appears to have the majority of the impact since its index has the largest value (83.64). However, when examining the ranks within each dimension, it can be seen that the environmental dimension ranks the highest. Thus, this design alternative ranks as the most sustainable design in the environmental aspect, while it ranks the second and third most sustainable design for the economic and social aspects, respectively. Moreover, since 80% of the weight is assigned to the environmental dimension and this design alternative ranks the highest in the environmental dimension, it also ranked the highest when computing the overall CSI. This implies that for implementing a sensitivity analysis on the assessment of sustainability, considering the index value alone without including the rank of the alternative may give misleading interpretations of the results.

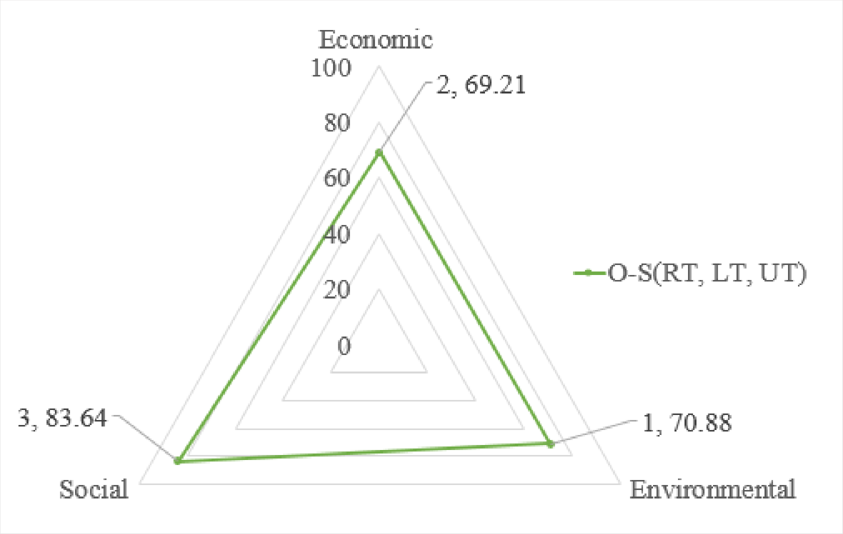


Figure 16: Sustainability trade-offs for the most sustainable design alternative for Al-Dewan roundabout (2008) scenario (rank, sub-index)

Another approach of sensitivity analysis to observe the effect of weight assignment on sustainability assessment was explored. It was conducted by using a weight ratio on the three dimensions of sustainability that is commonly used by various transportation rating systems. This approach may reflect how current sustainability views may affect the choice of the most sustainable design alternative. A study conducted by Simpson (2013) reviewed different rating systems and found out that most of them assigned around 60% to the environmental dimension, about 30% to the social dimension and around 10% to the economic dimension. This ratio (60%:30%:10%) was tested out on Asharej (2018) scenario and the results were compared to the equal weights and the 80% majority weight schemes. It was found out that the most sustainable design alternative was the overpass paired with exclusive turning lanes (CSI: 69.30%). The dimensional trade-offs by ranks and CSI values came out as 2-68.78, 1-80.31 and 3-83.41 for the economic, environmental and social dimensions respectively (rank-CSI value). Since the weighting scheme favored the environmental dimension, it ranked as the best alternative in that dimension. However, the social dimension had a slightly higher contribution to the overall CSI.

Hence, sustainability assessment is highly affected by weight assignment. In another way, the importance of weighting can be stated by "what you value most, heavily influences your choices". Whereas the higher the weight assigned to a specific dimension of sustainability, the higher the chance that a design alternative that performs well in that dimension would be considered as the most sustainable design in the overall sustainability assessment. However, the direct impact on the CSI does not necessarily come from the dimension of the highest weight. If the design alternative performs outstandingly in a specific dimension, it still can have the highest direct contribution to sustainability regardless of its weight. Sustainability trade-offs for the remaining scenarios are presented in Appendix C.

This finding is consistent with the literature, whereas Jeon (2007) conducted an extensive sensitivity analysis for assessing the sustainability of different transport plans for Atlanta region, and concluded that weight assigning plays a huge role in determining the most sustainable plan with respect to the visions and priorities of the region while examining any existing trade-offs in the sustainability dimensions.

Another study by Umer et al. (2016) that developed a roadway sustainability assessment framework based on fuzzy synthetic evaluation (FSE) technique, revealed that weight assignment that reflects the opinions of decision makers can alter the final determination of the most sustainable design.

Finally, a main research question is concerned about how the developed tool differ than the previously developed tools. The developed tool for assessing sustainability has some features that may surpass the previous tools. It should be noted that this tool was specifically developed for intersections, while almost all the other tools were developed at the corridor/link-level or for regional transport planning. Hence, the level of applicability on intersections is higher for this tool than any others.

Although this tool is narrowed in criteria for intersections, it still has a macro-scale nature that allows planners to utilize while still in the strategic planning stage. The required amount of data can be acquired from the early phases of planning, technical and detailed data that usually needs a thorough study are not needed for this tool. Unlike other tools that demand the existence of carefully calculated data.

Another point that differs from other previous studies is the nature of assigning the values of the selected indicators. Some studies rely totally on quantifying the data. While on the other extreme, some studies take a total qualitative approach to assign relative values for the indicators based on the opinions of specialized experts. However, this tool combines both ways in order to bring out the best out of each one of them.

Quantifying the data enables getting quite accurate representation of the indicators value. However, taking a fully quantified approach may raise some issues. For some indicators, data does not readily exist. Hence, models and programs may be developed in order to generate some surrogate measures. Such models are usually limited to a specific region and were developed under certain conditions which if were to be utilized in another region or different conditions, further calibration should be carried out if possible. The way around such issue is taking the qualitative approach. Where tricky data can be assessed and ranked based on literature or experts' opinions. Then again, a fully qualitative approach may result in loosing valuable direct data than can be computed or measured instead of assessing them qualitatively. Hence, unlike others, this tool utilized both approaches for determining the indicators data with the most appropriate and suitable way.

Moreover, this research explicitly studied the effect of varying several factors within each case study and determined its effect on the overall sustainability assessment. However, many other studies took the effect of varying the base condition as a collective change (e.g. land use), hence being unable to extract the impact of a certain factor (e.g. operational speed, traffic volume) on the assessment of sustainability. On the other hand, some studies considered the variation of the values of the sustainability indicators only, without controlling for a base factor or checking the effect of changing this factor on the overall sustainability (Mansourianfar and Haghshenas, 2018). Other studies went to the extent of conducting an extensive sensitivity analysis on each individual indicator to determine the impact on the overall sustainability (Jeon, 2007).

On a final note, this tool aims to compare the level of sustainability of different design alternatives. The absolute CSI value of a design alternative does not have a meaning by itself as an exact magnitude. Decision making based on sustainability comparisons of design alternatives is the basic benefit of this tool.

4.5. Summary

The developed CSI tool was applied to four case studies of existing roundabouts in Al Ain City, UAE. Fourteen different scenarios of traffic volume and operational speed were evaluated for the four roundabouts. For each scenario, fifteen design alternatives were developed in order to assess their sustainability in the economic, environmental and social aspects and as an overall composite sustainability. Indices representing each aspect and the overall CSI were determined for each design alternative using MCDM method and TOPSIS technique. The best design alternative for each scenario of traffic volume and operational speed was determined.

Moreover, the effect of varying the assigned traffic volume on the different case studies has been studied while controlling for the operational speed. Three different volume scenarios have been generated for the four case studies of the four roundabouts, which are the present volume of the year 2018, the volume of ten years back (2008), and the volume of ten years to the future (2028). The three years were specifically chosen to check whether the current design alternative was justified ten years ago and considered as the best option, and if it can still be considered as the best design option with the existing (current year) and growing demand after ten years to the future. The results showed that with lower traffic volumes, the best design alternatives tend to be grade-separated with an overpass and paired with a conventional roundabout. Whereas, as the volume increases the best design alternatives shift towards signalized intersections with exclusive turning lanes. At-grade intersections mainly ranked as the worst design alternatives for all the traffic volumes. Hence, based on this study, introducing an overpass paired with signals and exclusive turning lanes to the current roundabout designs may give better impacts on sustainability for future generations. Nevertheless, the weighting scheme should be thoroughly studied taking into consideration the opinions of different stakeholders and the main objectives that should be accomplished in order to determine the best design alternative. The operational speed is another input variable that was tested in order to check for any significant impact on the outputs. The speed was alternated between 80 km/h and 100 km/h for only two roundabout case studies, which are Al-Ahliya and Al-Dewan

Roundabouts. To control for the traffic volume variable, it was held constant at the present year of 2018. The results showed that a very subtle change was found in the ranking of the best and worst design alternatives. Since the effect of varying the operational speed on a single intersection was not obvious, further study should be carried out to observe the effect of varying the operational speed on a network of intersections.

The indices mentioned previously were based on equal weights for all of the indicators within all the criteria under the three pillars of sustainability (economic, environmental and social pillars). However, a sensitivity analysis where different weights were assigned to the three main dimensions of sustainability was conducted. The sensitivity analysis depended on a weighting scheme where a weight of 80% was assigned alternatively to the three dimensions of sustainability. It was observed that the weight assignment had a significant effect on the final rankings of the design alternatives. The ranks of the design alternatives changed depending on how much of an effect it has on the dimension of sustainability that has the highest weight. For instance, a design alternative that performs well in the social dimension, has a high chance of being the best design alternative when the social dimension has 80% of the weight. And vice versa, a design alternative that performs poorly in the social dimension, has a high chance of being the worst design alternative when the social dimension has 80% of the weight. This implies the importance of adequately assigning the weights for the criteria relative to the goal in mind.

Chapter 5: Conclusion and Recommendations

5.1. Conclusion

The research questions that were presented in section 1.2 were answered successfully. The developed framework of road intersections sustainability was built after a thorough literature review. Transportation sustainability in general was defined as the transport that enhances the economic efficiency of the road intersection users, causes minimum harmful effects on the environment and provides social equity for the users. And going down the same track, a final set of sustainability indicators specific for intersections was extracted in a way that reflects the economic, environmental, and social dimensions. This set of indicators outlines a framework that helps in assessing intersection sustainability. The set of indicators were defined from a road-user perspective and supported a macroscopic point of view, whereas they can be utilized in early stages of strategic planning where detailed input about the project may not be available.

After defining the framework for assessing intersection sustainability, this study answered another research question by developing a tool that generates a composite sustainability index (CSI) for intersection design alternatives using a multi-criteria decision making (MCDM) method. This tool helps decision makers in determining the best sustainable intersection design from a set of alternatives taking in consideration different criteria in the economic, environmental, and social dimensions.

Four case studies of roundabouts in Al-Ain city have been used to demonstrate the applicability of the CSI tool and at the same time explore if the existing intersections in Al-Ain, UAE are driven based on sustainability. Different design alternative for different scenarios of traffic volume and operational speeds variables were generated and evaluated with respect to sustainability. These variations were introduced in order to study how these two factors of traffic volume and operational speed impact the sustainability assessment. The evaluation of the design alternatives was conducted using the MCDM method incorporating TOPSIS technique. The sources of input data used in TOPSIS varied from qualitative and quantitative measures. The qualitative measures included ranking based on literature and consulting academic experts. The quantitative data were extracted using direct measurement and by a simulation program called SIDRA intersection software.

The effect of varying the traffic volume was showcased by using the current traffic volume, past traffic volume of ten years back and future volume after ten years as different scenarios for the four roundabout case studies. These specific years were used in order to determine if the best design that was chosen based on a certain volume can be still considered as the best design alternative for another different scenario of traffic volume. For instance, a design choice can be determined whether it was justified in the past and whether it is still considered as the best option for current and future volumes. It was found out that different design alternatives ranked as the most sustainable design for each volume scenario. However, a trend can be seen where the overpass grade-separated designs were the most sustainable in all the volume scenarios, a paired roundabout design was more appropriate for lower volumes of traffic and as the volume increased the paired signals with exclusive turning lanes were dominant. This implies the significance of considering the growth of traffic volume when determining the most sustainable design alternative of an intersection.

Adding a variation in the operational speed variable had an insignificant impact on the final ranking of the most sustainable design alternatives. A suggestion can be made to further investigate the effect of varying the operational speed when studying the sustainability of a whole network of intersections instead of an individual intersection.

Results of this study further imply that the current designs of the four case studies are not the best option. Since all the case studies are at-grade roundabouts, the results of ten years back show that having these roundabout being paired with an overpass would give more sustainable performance. And for the current and future volumes, not only a paired overpass would be enough, a conversion to a signalized intersection with exclusive turning lanes would enhance the sustainability of the intersections. The step taken in Al-Ahliya roundabout which was the conversion into a signalized intersection appears to be quite justifiable, although adding an overpass would have been more appropriate. This being said, the choice of the most sustainable design may change dramatically when considering the whole network of intersections. Future research should focus on the accumulating effect of the sustainability of the intersections network.

Another main part of the evaluation was applying a sensitivity analysis. Since incorporation of weights in TOPSIS analysis plays a huge role in determining the best design alternative, the sensitivity analysis specifically tested the impact of assigning different weights on the final ranking. An equal set of weights for all of the criteria within all of the dimensions was applied, then the majority of the weight was alternated between the three dimensions of sustainability. It was found out that the effect of assigning the majority of the weight to a specific dimension tends to rank the best alternatives towards that specific dimension.

It can be concluded that when the stakeholders and decision makers wants to achieve some specific objectives or have certain constraints that direct their project, they should reflect such requirements in the weights of the criteria. Since what they value most, heavily influences the final decision. Moreover, the definition of sustainability may vary from one perspective to another for different stakeholders. One stakeholder may perceive the environmental dimension as the one with the highest impact on sustainability since it directly connects to the environment (e.g. environmental agencies). Another may be more interested in the social equity that the project can provide to the public (e.g. municipalities and public associations). In addition, the economic situation of the country or even of the sponsor may be critical for providing the required fund and may be restricted to a certain amount that should be considered when choosing the design. Even though this study defined sustainability for intersections as the design that incorporates and supports all of the three dimensions, the unique interests of the decision makers in real life can be reflected in the weighting process of the suggested criteria.

Hence, the CSI tool can be utilized to support and enhance future strategic planning and decision-making of stakeholders by adequately comparing between a set of different intersection design alternatives while balancing between the three dimensions of sustainability. Moreover, even though the CSI tool was applied on case studies in Al-Ain, it is applicable to assess intersection sustainability in any other region.

5.2. Limitations of the Study

One of the limitations that faced this study was acquiring some specific data that would have supported the sustainability assessment. The initial cost data for each specific design alternative were roughly ranked since specific technical details were not available. However, when a real project is conducted, a full cost study would be conducted by experts for a smaller set of alternatives and the data may be used in the evaluation.

Another data set that was difficult to collect was under the safety criteria. Quantifying safety was a challenging task especially that for the environment of Al-Ain, safety of different designs may be perceived differently due to the existing road user behavior. That is, what may be quantified as the safest option, can be perceived as the least safe design in the public's opinion. The best way to quantify safety was by conducting a before-and-after study of different design alternatives. However, traffic volume and accident data for a decent period of time does not exist for Abu Dhabi Emirate. When the related data does exist, safety can be assessed in a better manner. Moreover, the inclusion of freight data would have covered another aspect of transport sustainability, but a useful quantity of data does not exist at the current time.

5.3. Recommendations

More research is required to further develop the CSI tool to incorporate the design of a whole network of intersections in the evaluation of the transport sustainability of the region. However, research for more and different indicators may be required in order to adequately assess the overall sustainability of the intersections network.

Moreover, the developed tool was applied on case studies in Al-Ain where most intersections have 3-lane arms. However, another aspect would be to conduct a study to evaluate the sustainability of roadway intersections taking into consideration the number of lanes as another explicit factor. Whereas, CSI values of 2-lane intersections may be compared to the values of 3-lane intersections.

Finally, another interesting approach that may add to the value of this study, is considering sustainability from public and neighbors' perspective instead of only focusing on the road intersection users' point-of-view. For instance, art/aesthetics, culture, wayfinding, community acceptance, context sensitive design, landscaping, most things regarding construction techniques and materials use, lighting, storm water, ground/water pollution, runoff flow control, soil management, preferred ecological location, durability, etc. This may add a different dimension to the developed tool in a way that would enrich its ability to assess road intersection sustainability.

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Appendix A: Traffic Data Attributes for the Study Cases

Table A1: Traffic data attributes for Al-Markhaniya roundabout (2015)

ARM A					ARM C			
Links	A-D	A-C	A-B	A-A	C-C	C-D	C-A	C-B
% Heavy Vehicles	3%	5%	5%	14%	12%	3%	4%	5%
Peak Hour Factor	0.82	0.95	0.90	0.69	0.90	0.81	0.94	0.83
Vehicles Per Hour	486	893	130	36	130	298	1148	267
	ARM B				ARM D			
Links	B-A	B-D	B-C	B-B	D-D	D-A	D-B	D-C
% Heavy Vehicles	2%	2%	5%	10%	25%	4%	3%	4%
Peak Hour Factor	0.86	0.91	0.81	0.53	0.50	0.86	0.95	0.89
Vehicles Per Hour	107	589	421	21	4	549	639	286

Table A2: Traffic data attributes for Al-Ahliya roundabout (2015)

ARM A					ARM C			
Links	A-D	A-C	A-B	A-A	C-C	C-D	C-A	C-B
% Heavy Vehicles	3%	4%	3%	17%	8%	7%	3%	4%
Peak Hour Factor	0.76	0.91	0.98	0.64	0.65	0.94	0.93	0.88
Vehicles Per Hour	237	1734	413	36	52	507	1323	428
ARM B					ARM D			
Links	B-A	B-D	B-C	B-B	D-D	D-A	D-B	D-C
% Heavy Vehicles	4%	3%	2%	0%	17%	3%	2%	5%
Peak Hour Factor	0.83	0.85	0.77	0.38	0.60	0.86	0.87	0.91
Vehicles Per Hour	209	400	167	6	12	244	734	726

Table A3: Traffic data attributes for Al-Dewan roundabout (2015)

ARM A						ARM B			
Links	A-D	A-C	A-B	A-A	B-A	B-D	UB-D	B-C	B-B
% Heavy Vehicles	4%	4%	4%	11%	7%	42%	4%	6%	8%
Peak Hour Factor	0.90	0.89	0.75	0.77	0.86	0.68	0.82	0.79	0.68
Vehicles Per Hour	226	1898	634	71	411	19	1409	389	49
ARM C					ARM D				
Links	C-C	C-D	C-A	C-B	D-D	D-A	UD-B	D-B	D-C
% Heavy Vehicles	17%	3%	3%	2%	17%	3%	4%	18%	4%
Peak Hour Factor	0.64	0.86	0.89	0.89	0.64	0.74	0.90	0.61	0.78
Vehicles Per Hour	23	145	1467	175	23	416	2055	44	56

Appendix B: TOPSIS Evaluation

Case: Asharej Roundabout 2018

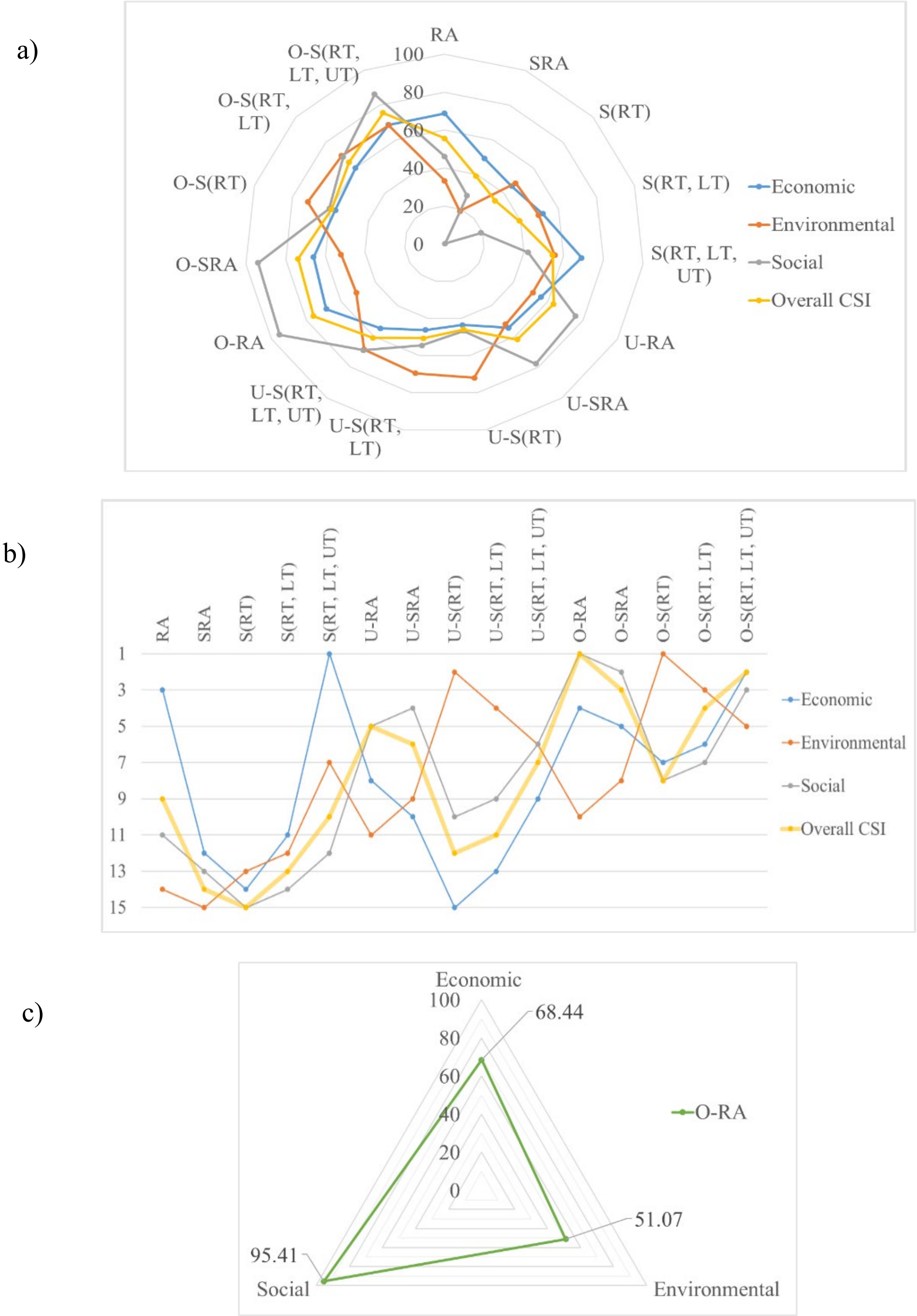


Figure B1: Sustainability assessment of Asharej roundabout (2018) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Asharej Roundabout 2028

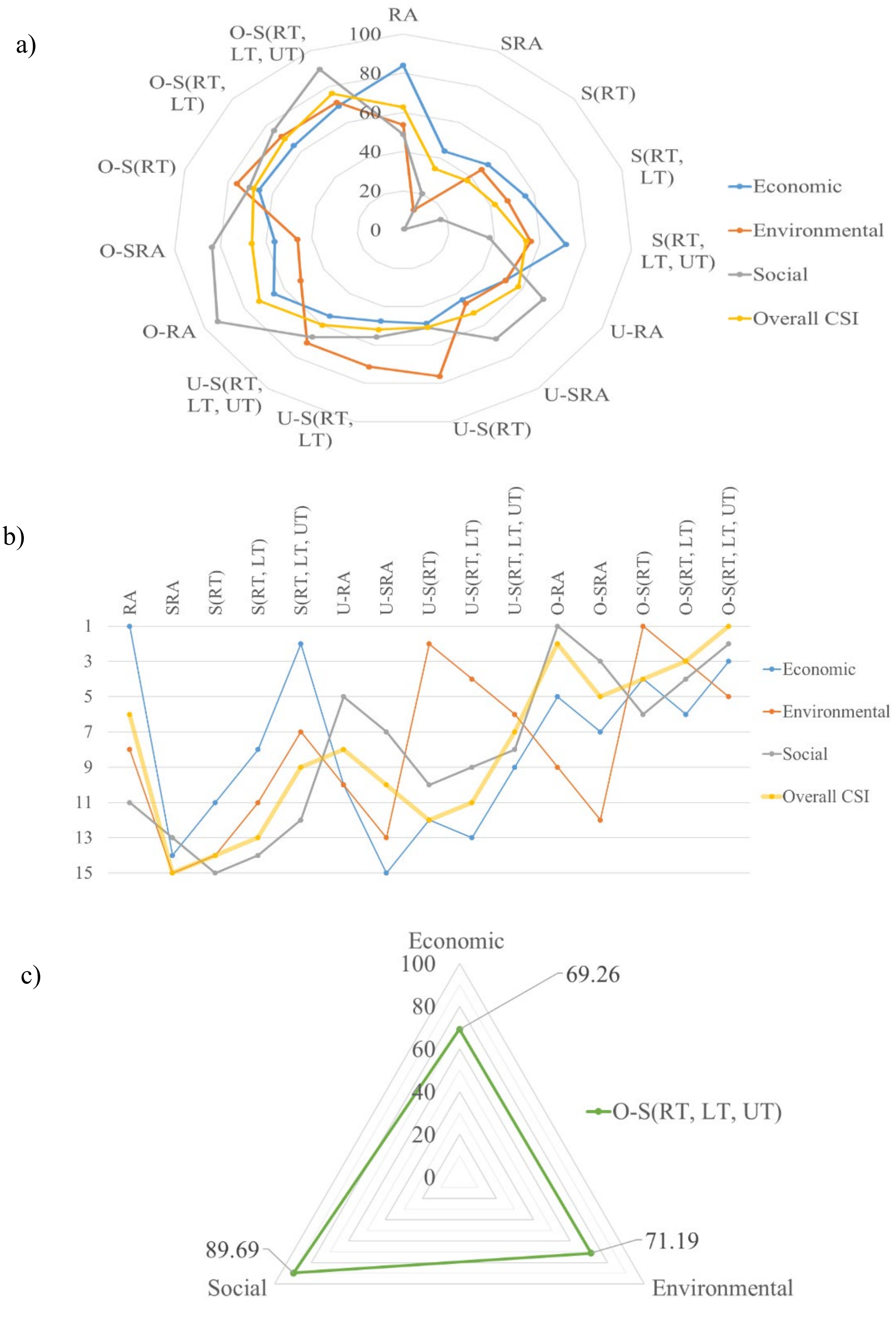


Figure B2: Sustainability assessment of Asharej roundabout (2028) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Markhaniya Roundabout 2008

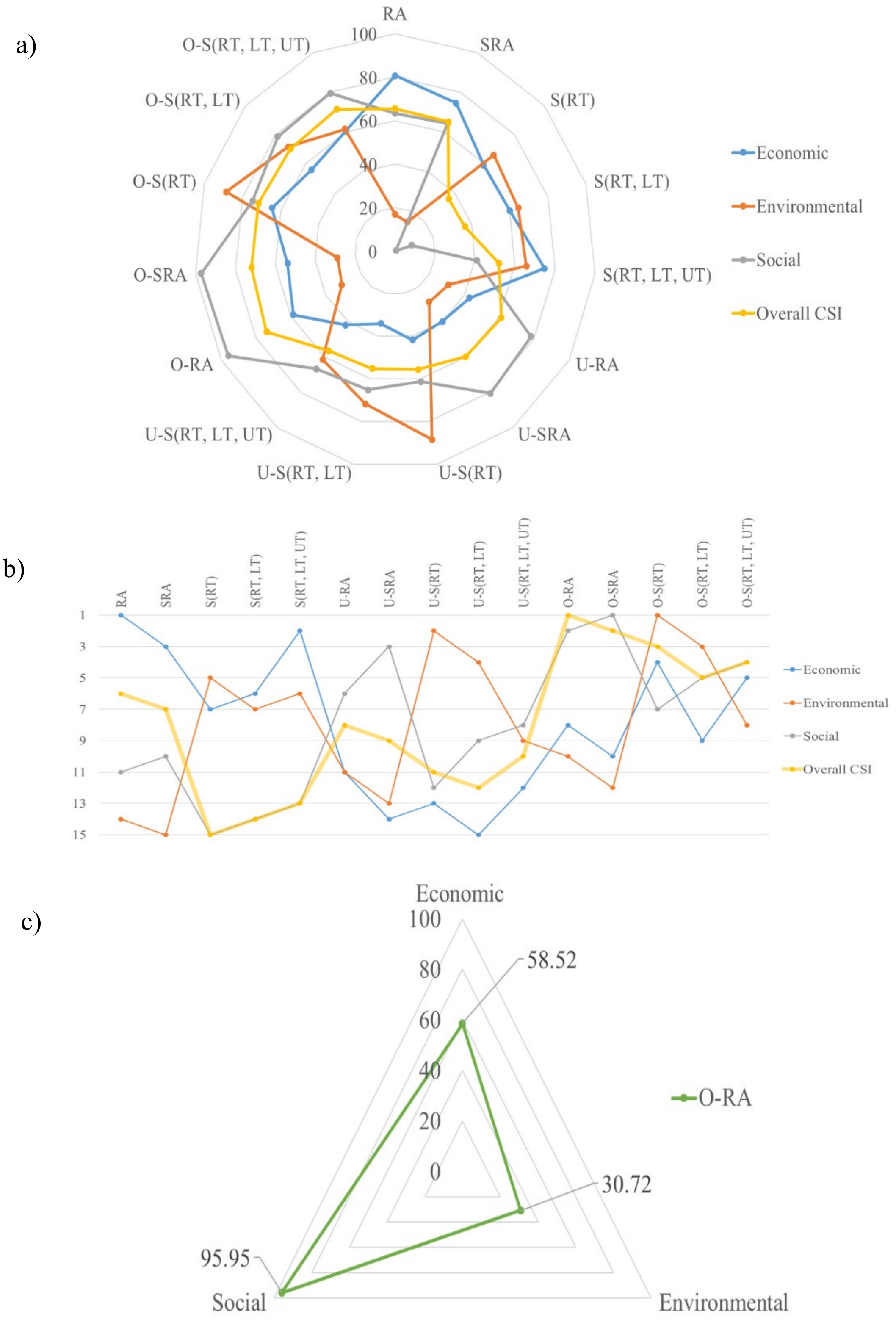


Figure B3: Sustainability assessment of Al-Markhaniya roundabout (2008) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Markhaniya Roundabout 2018

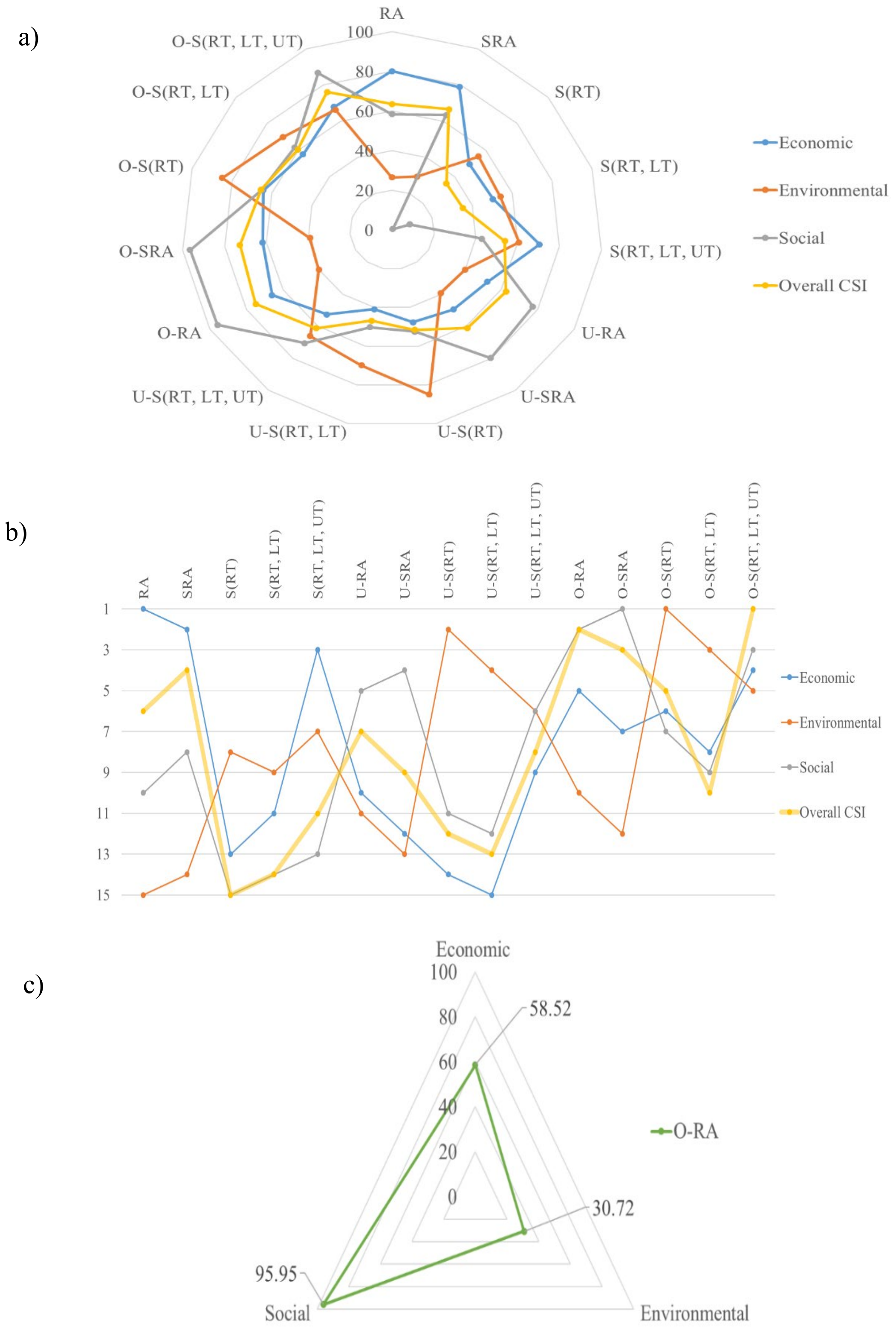


Figure B4: Sustainability assessment of Al-Markhaniya roundabout (2018) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Markhaniya Roundabout 2028

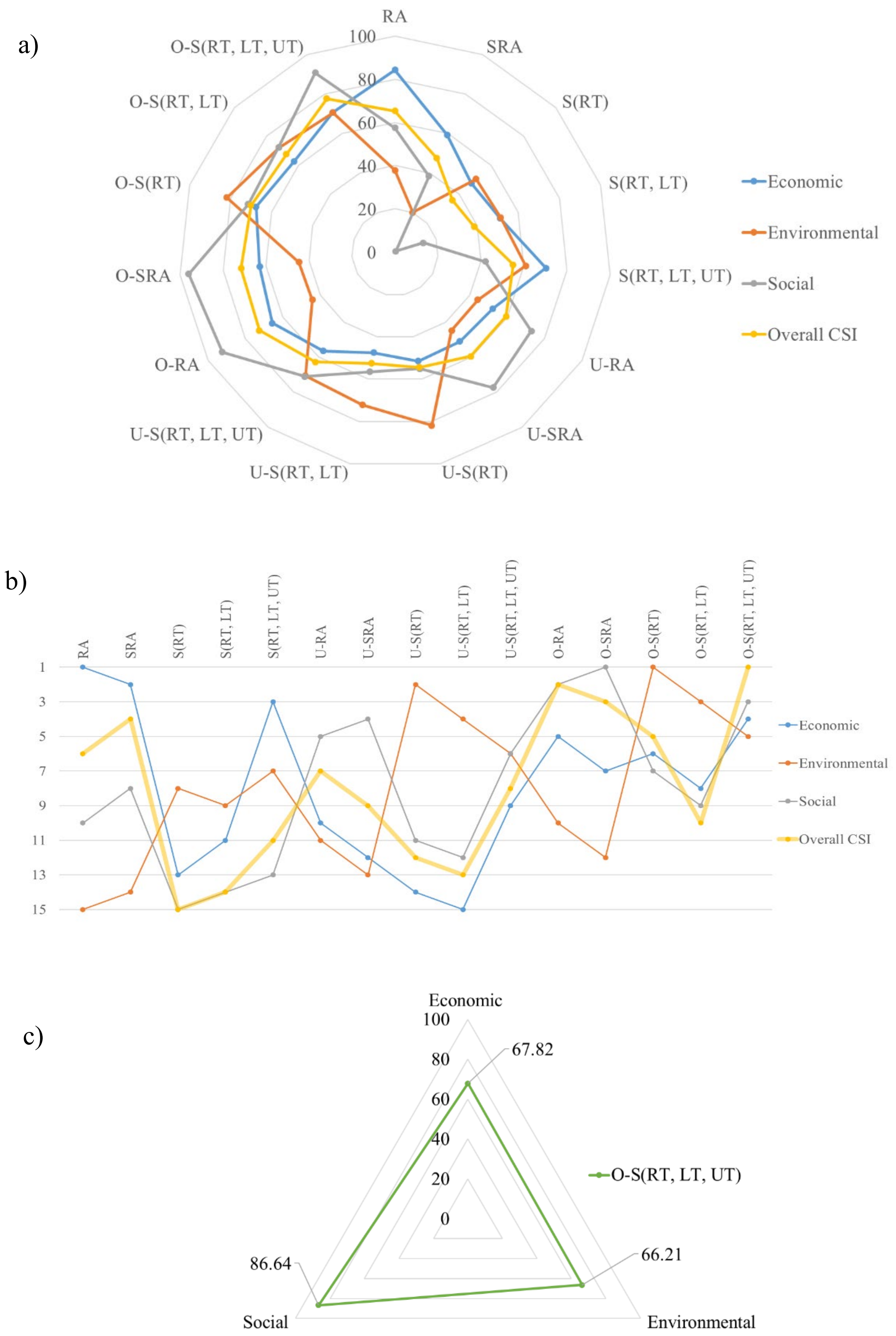


Figure B5: Sustainability assessment of Al-Markhaniya roundabout (2028) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Ahliya Roundabout 2008

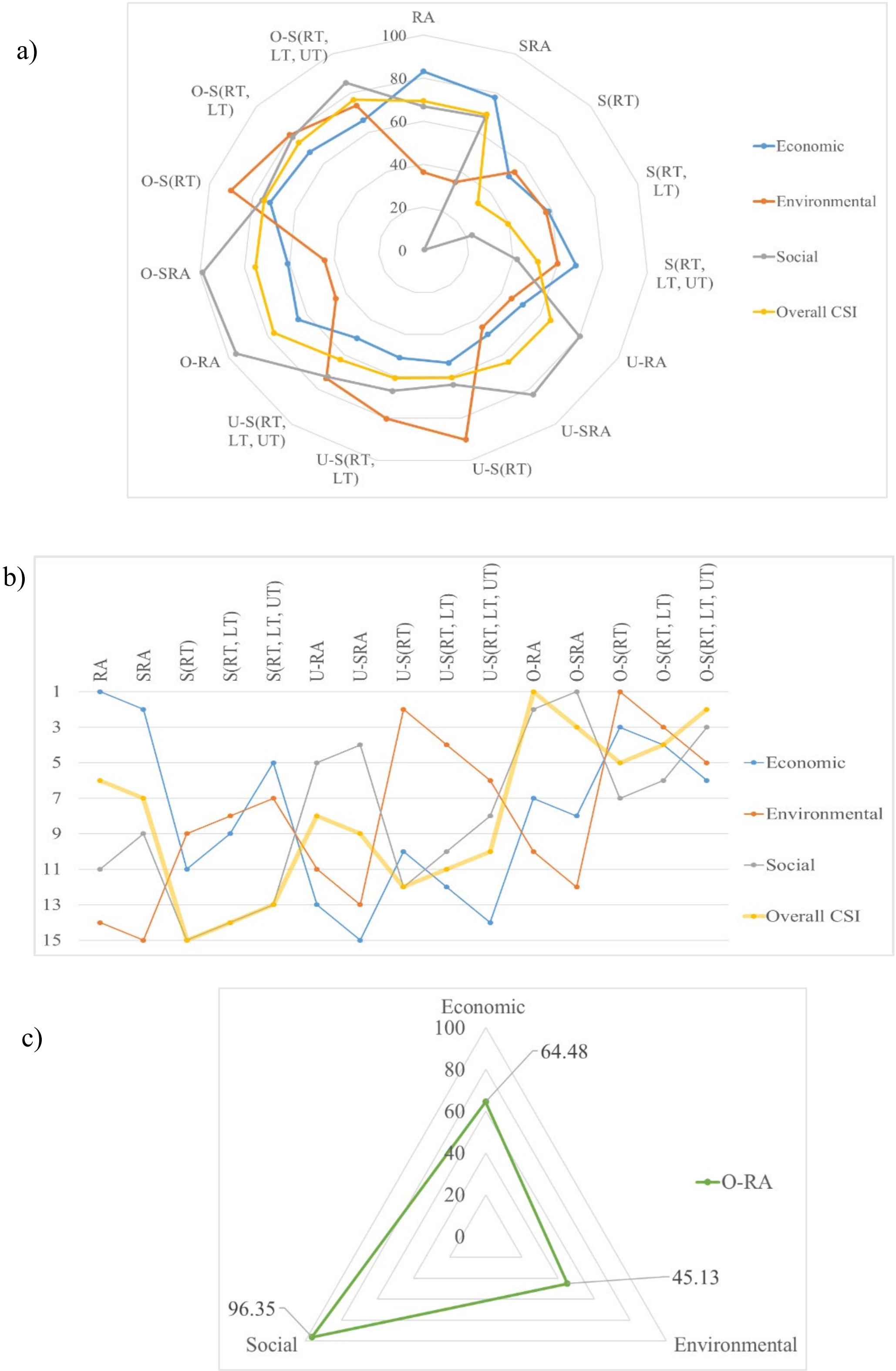


Figure B6: Sustainability assessment of Al-Ahliya roundabout (2008) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Ahliya Roundabout 2018_80

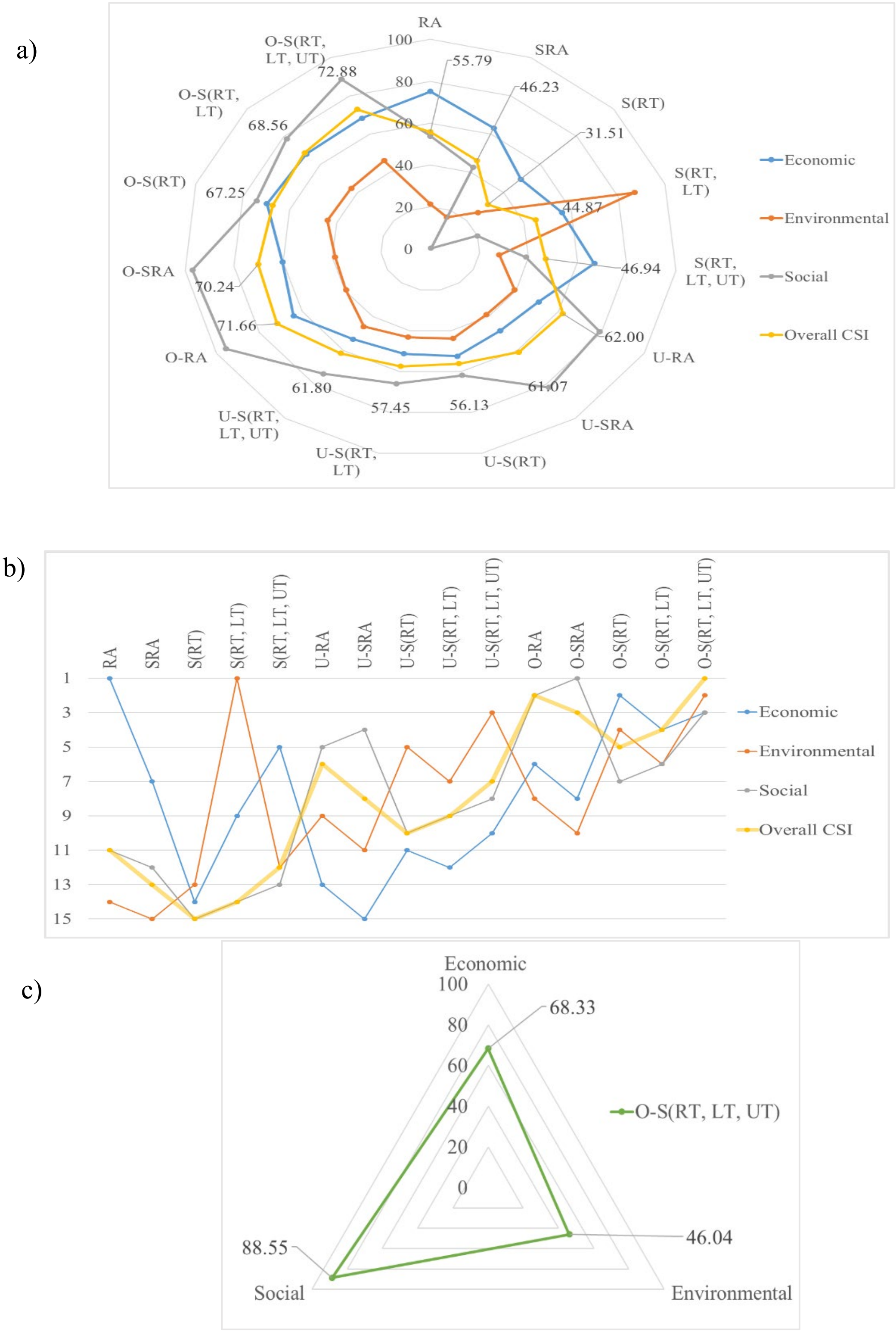


Figure B7: Sustainability assessment of Al-Ahliya roundabout (2018_80) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Ahliya Roundabout 2018_100

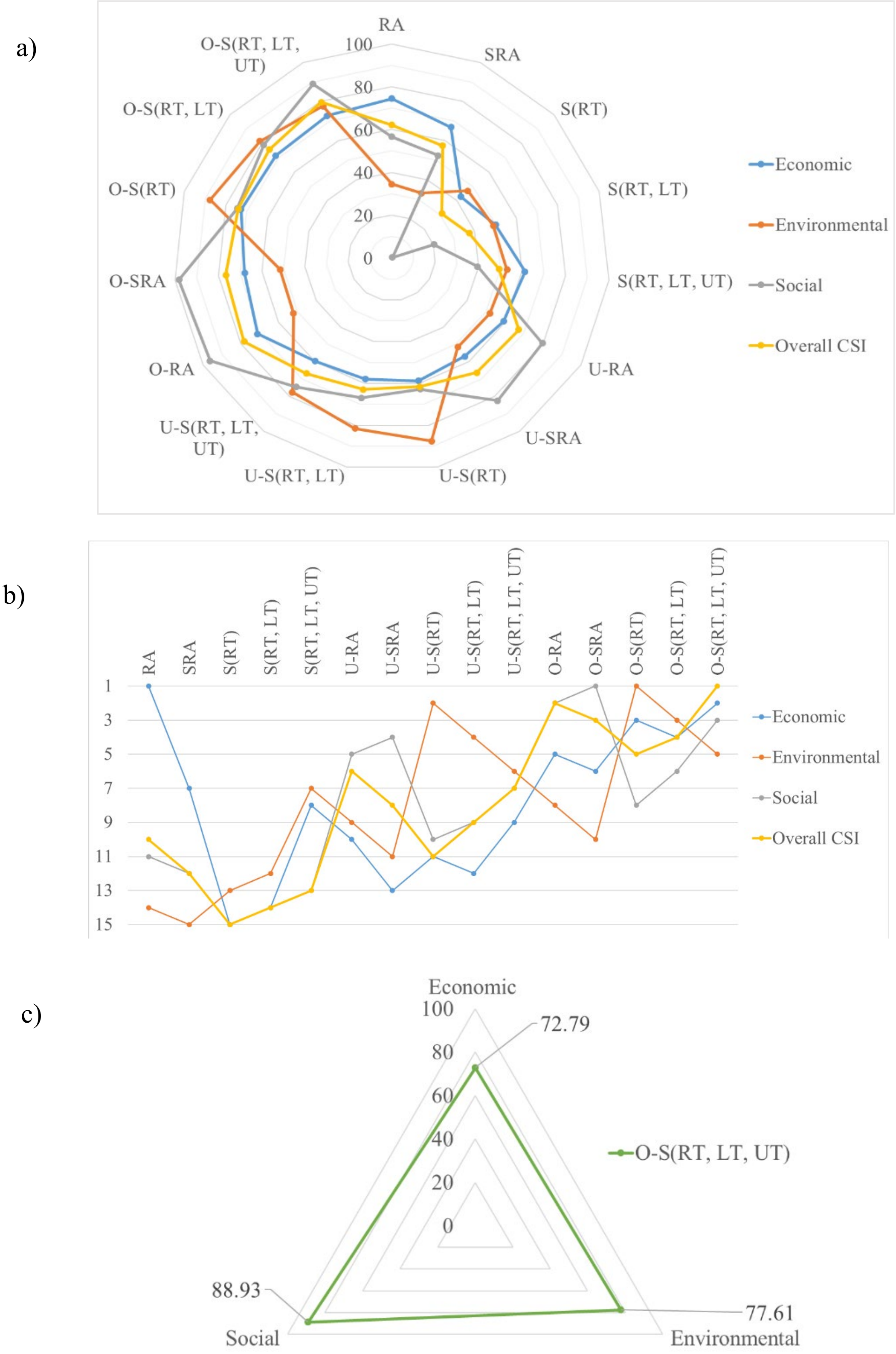


Figure B8: Sustainability assessment of Al-Ahliya roundabout (2018_100) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Ahliya Roundabout 2028

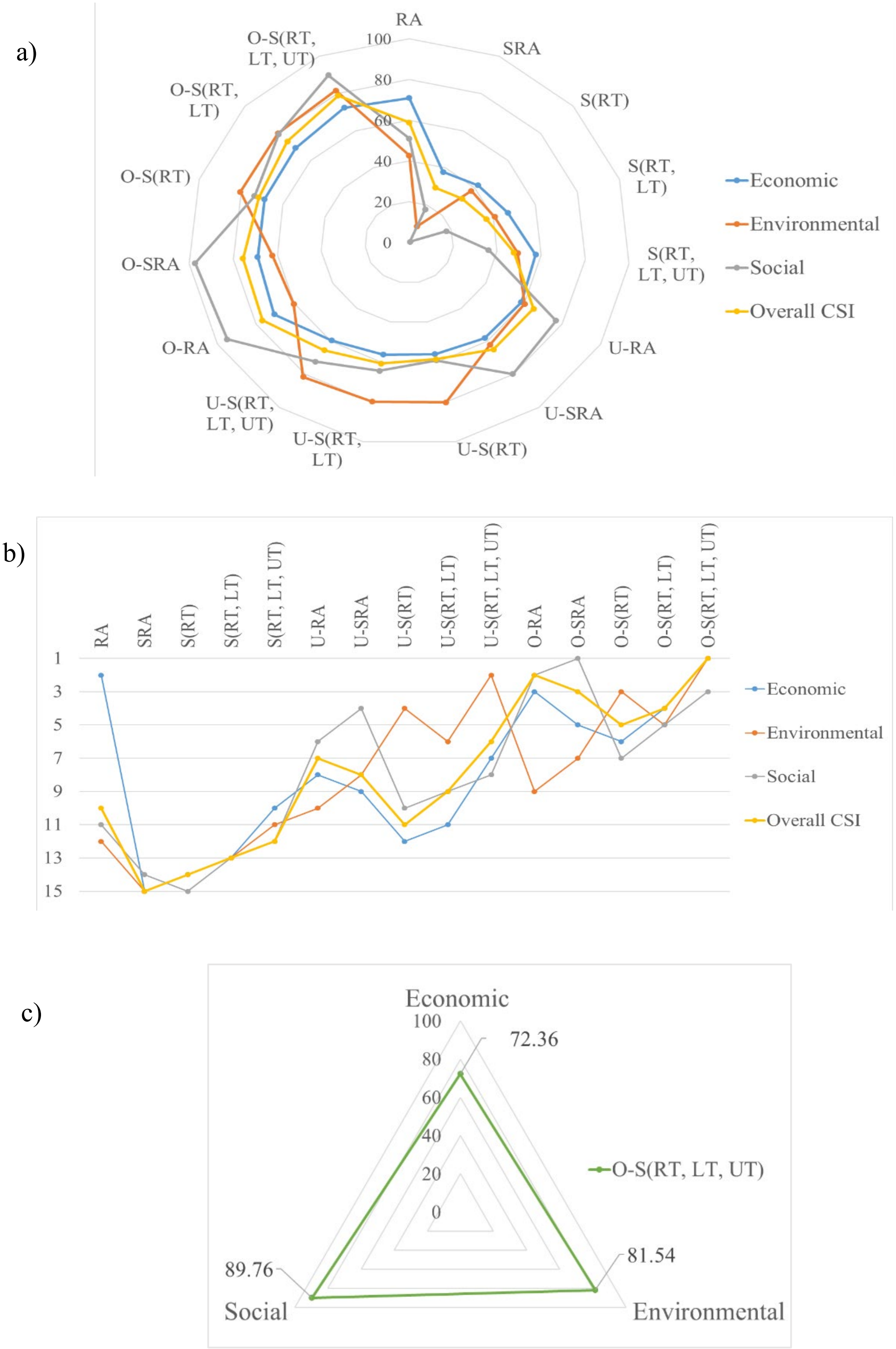


Figure B9: Sustainability assessment of Al-Ahliya roundabout (2028) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Dewan Roundabout 2008

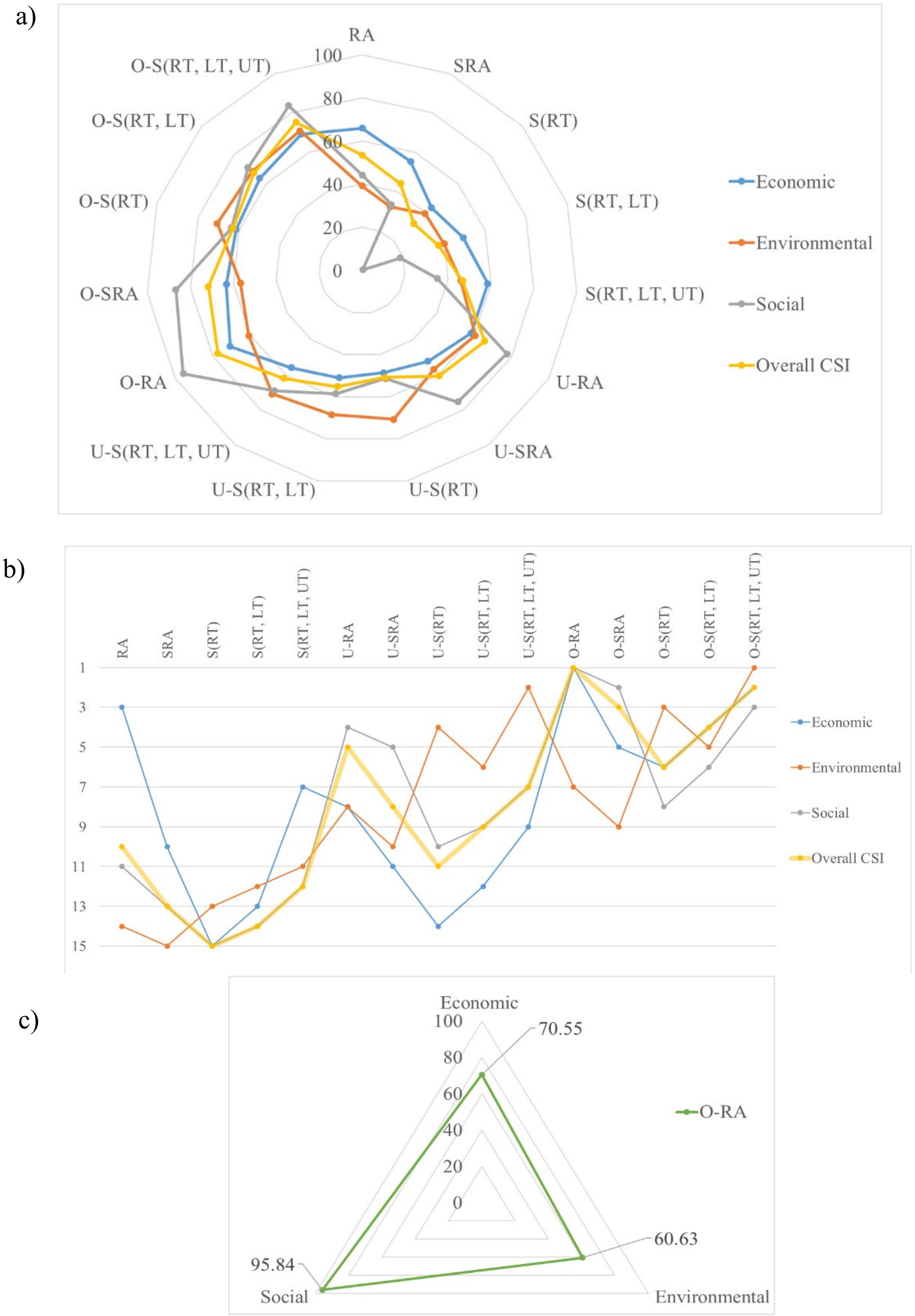


Figure B10: Sustainability assessment of Al-Dewan roundabout (2008) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Dewan Roundabout 2018_80

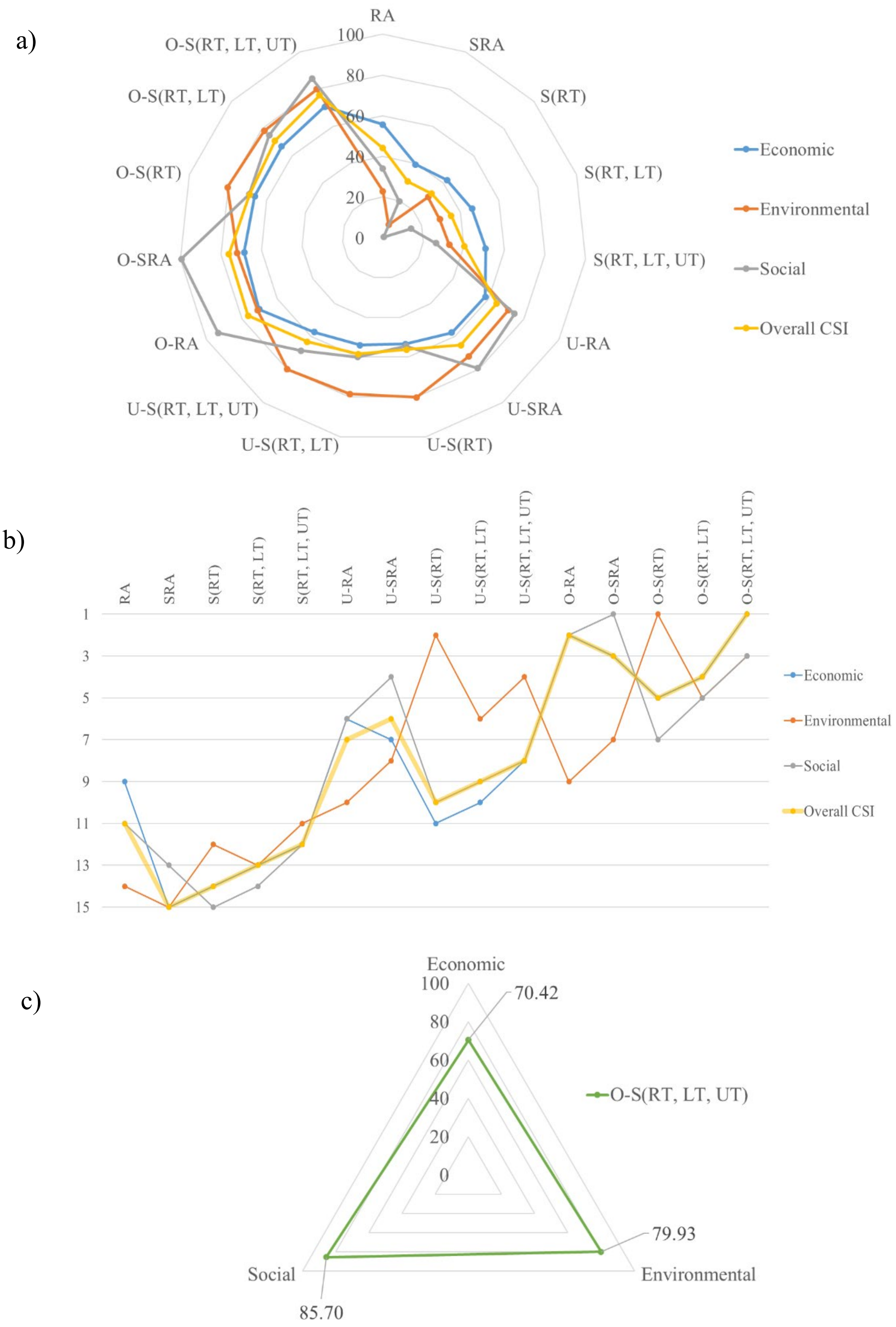


Figure B11: Sustainability assessment of Al-Dewan roundabout (2018_80) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Dewan Roundabout 2018_100

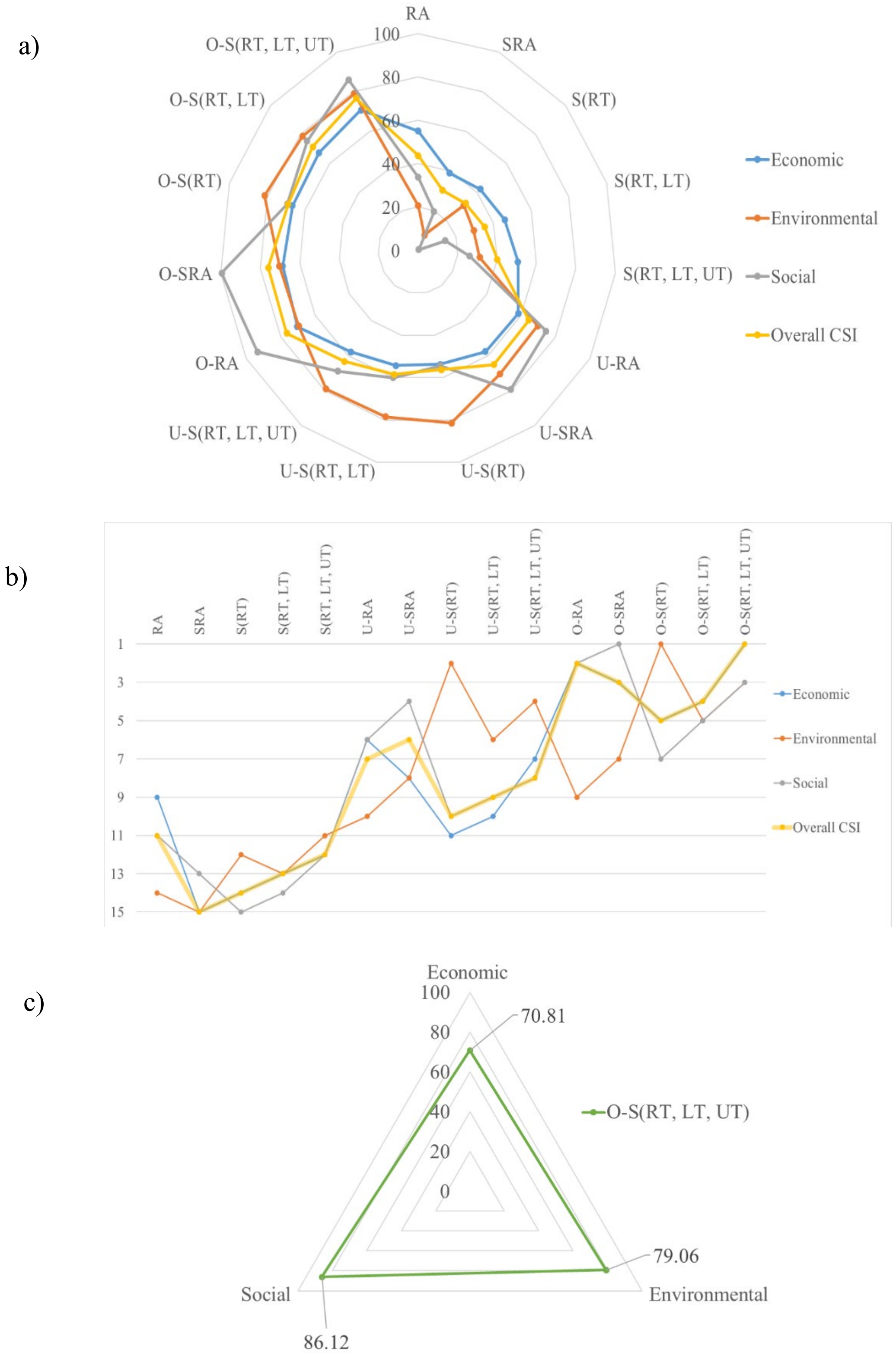


Figure B12: Sustainability assessment of Al-Dewan roundabout (2018_100) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Case: Al-Dewan Roundabout 2028

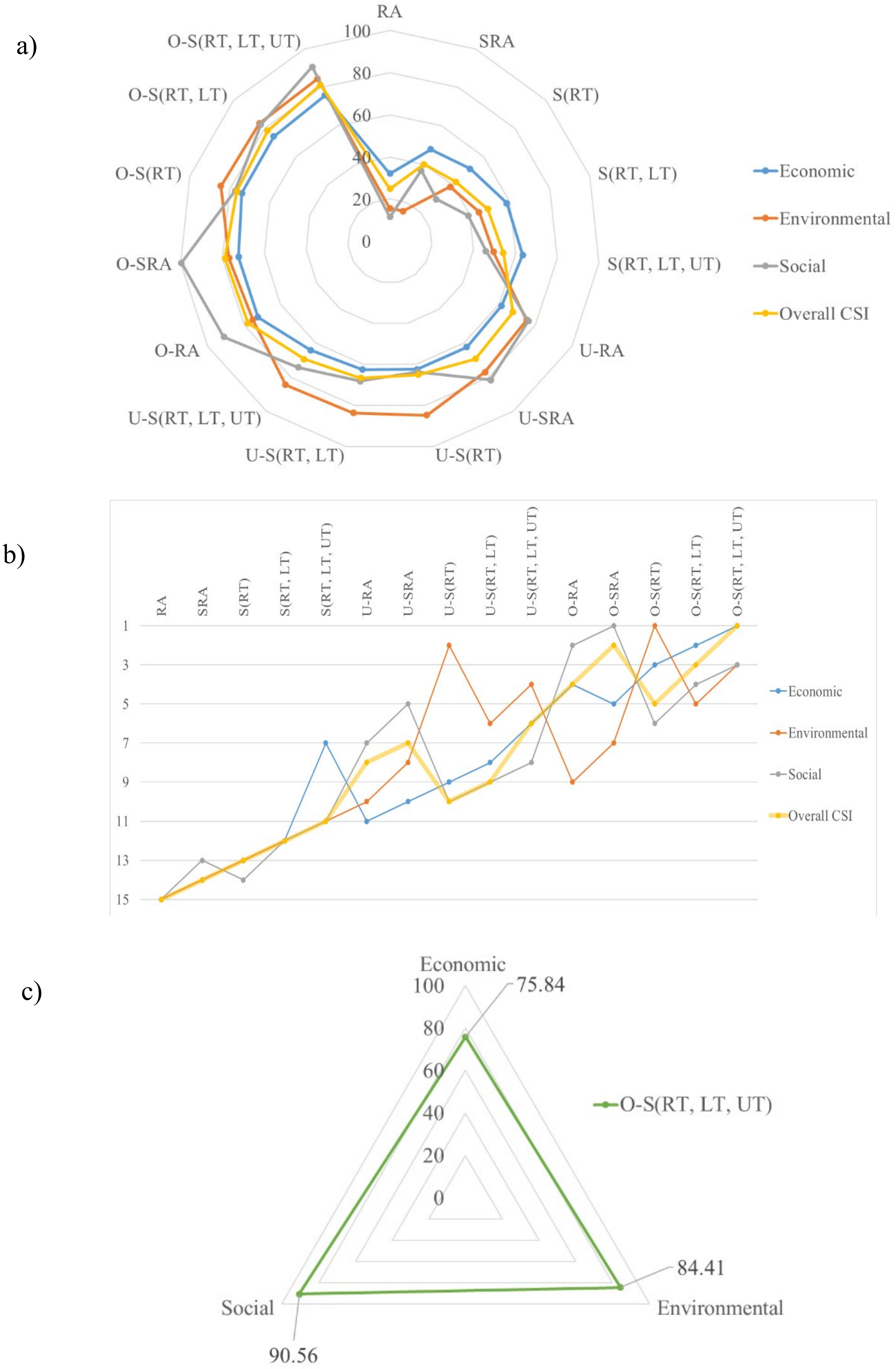
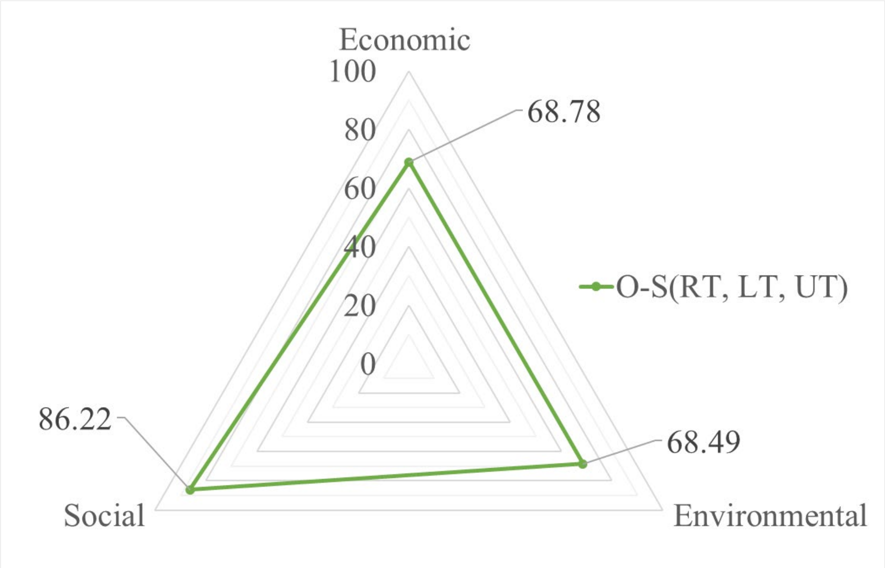
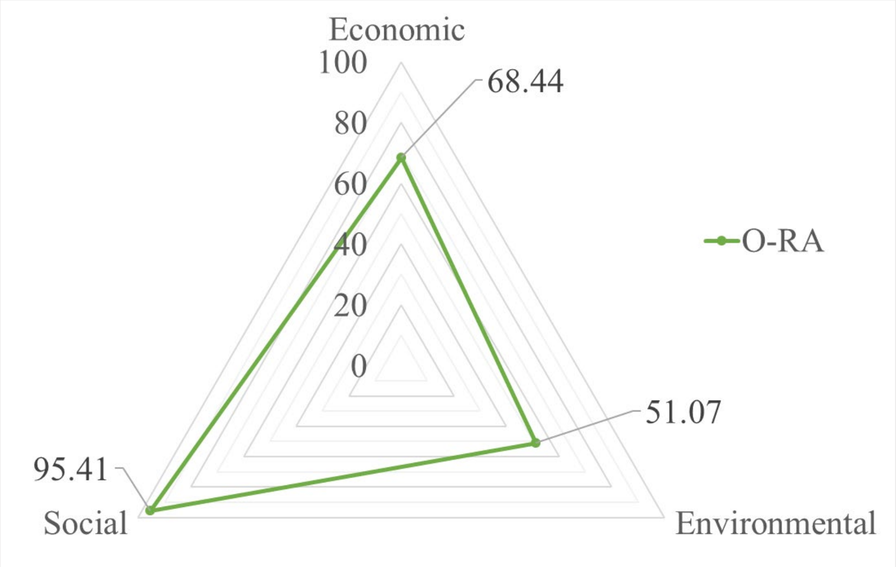


Figure B13: Sustainability assessment of Al-Dewan roundabout (2028) scenario, a) radar graph of CSI values, b) line-graph of CSI ranks, c) dimensional trade-offs of the most sustainable design alternative

Appendix C: Dimensional Tradeoffs of the most Sustainable Alternatives

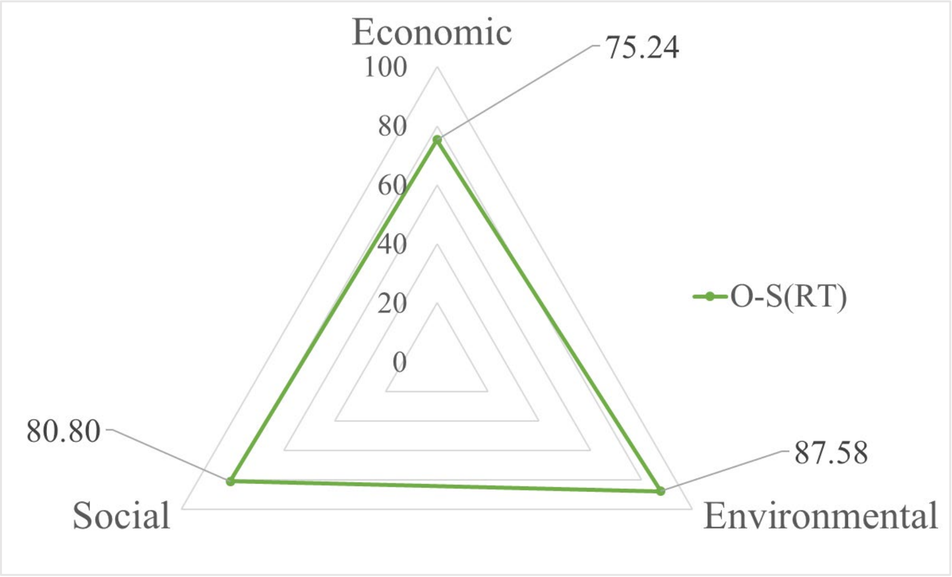


(a)

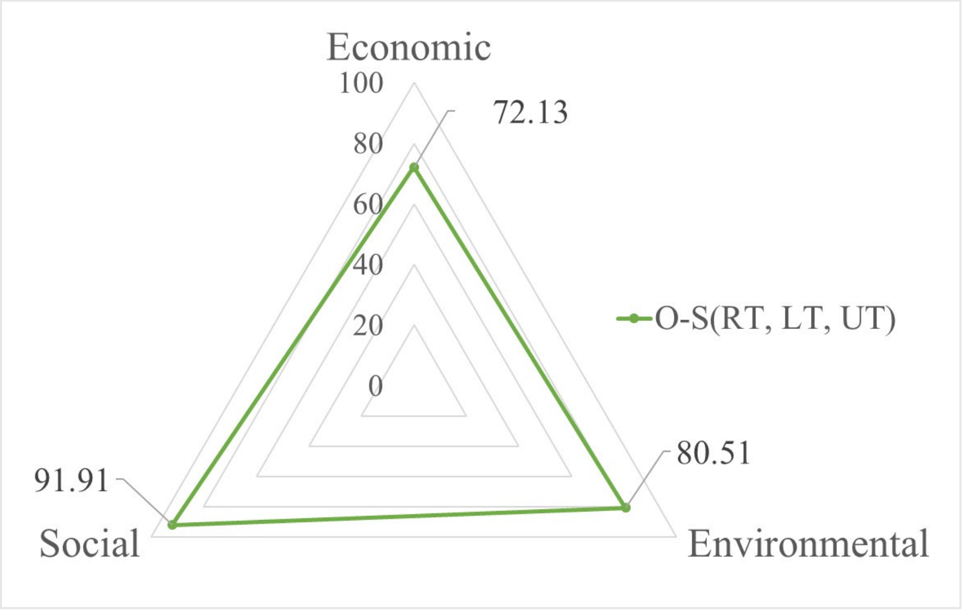


(b)

Figure C1: Dimensional trade-offs of the most sustainable design alternative for Asharej roundabout (2018) with 80% weight assigned to the a) economic and environmental and b) social dimension

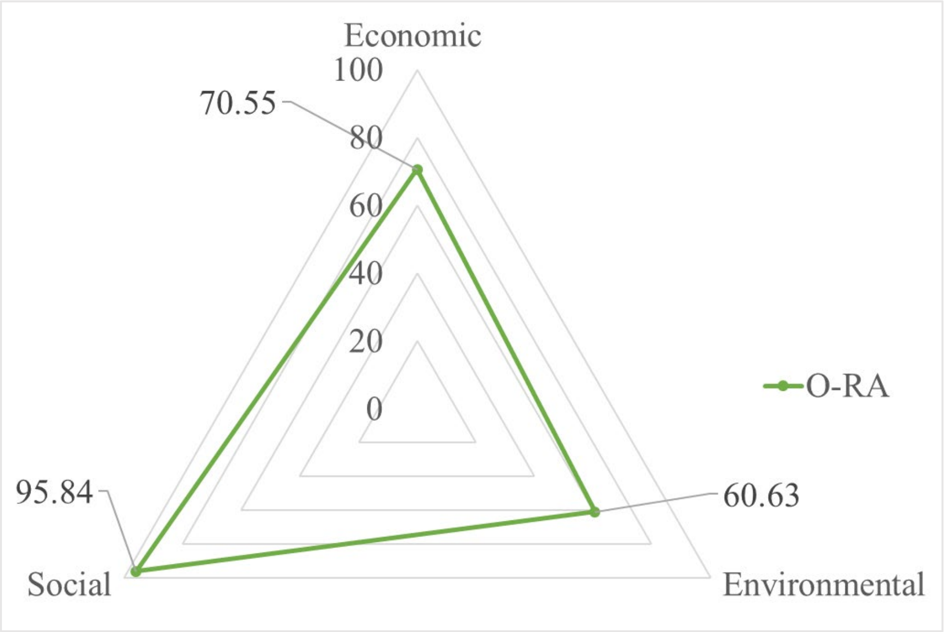


(a)

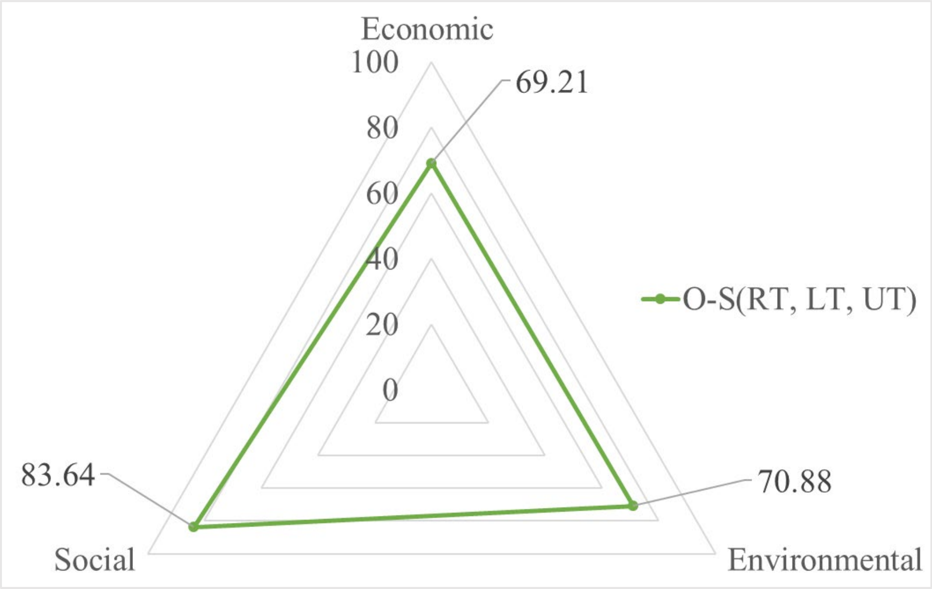


(b)

Figure C2: Dimensional trade-offs of the most sustainable design alternative for Al-Ahliya roundabout (2028) with 80% weight assigned to the a) economic and environmental and b) social dimension



(a)



(b)

Figure C3: Dimensional trade-offs of the most sustainable design alternative for Al-Dewan roundabout (2008) with 80% weight assigned to the a) economic and social and b) environmental dimension

Appendix D: TOPSIS Sample Calculation for Asharej (2008) Scenario

* The equations used are referenced from section 3.4.1.

Table D 1 TOPSIS Sample Calculation for Asharej (2008) Scenario

A	**Asharej Roundabout** **Speed = 100 km/h - 2008** **Sustainability Dimensions** **Indicator Area**		**Economic**	
		Initial Cost	**Operational Cost**	**Economic Efficiency**
ID	**Alternative**	(Qualitative)	Per Hour (USD)	Monetary Value of the Total Hourly Travel Time
1	**RA**	4	2516.24	1080.29
2	**SRA**	5	2455.30	1076.36
3	**S(R_T)**	1	4668.79	2621.55
4	**S(R_T, L_T)**	2	3890.88	2098.81
5	**S(R_T, L_T, U_T)**	3	2939.73	1464.90
6	**U-RA**	14	1961.08	904.54
7	**U-SRA**	15	2163.93	1027.51
8	**U-S(R_T)**	11	3059.17	1724.31
9	**U-S(R_T, L_T)**	12	2834.62	1581.13
10	**U-S(R_T, L_T, U_T)**	13	2167.57	1147.67
11	**O-RA**	9	1995.23	904.54
12	**O-SRA**	10	2198.08	1027.51
13	**O-S(R_T)**	6	3093.32	1724.31
14	**O-S(R_T, L_T)**	7	2868.77	1581.13
15	**O-S(R_T, L_T, U_T)**	8	2201.72	1147.67
	Square root of Sum of Squares:	35.21	10955.25	5935.37
	Weights	0.11	0.11	0.11

Normalized Data **rij**	**Equation (1)**		**Economic**	
		Initial Cost	**Operational Cost**	**Economic Efficiency**
ID	**Alternative**	(Qualitative)	Per Hour (USD)	Monetary Value of the Total Hourly Travel Time
1	**RA**	0.1136	0.2297	0.1820
2	**SRA**	0.1420	0.2241	0.1813
3	**S(R_T)**	0.0284	0.4262	0.4417
4	**S(R_T, L_T)**	0.0568	0.3552	0.3536
5	**S(R_T, L_T, U_T)**	0.0852	0.2683	0.2468
6	**U-RA**	0.3976	0.1790	0.1524
7	**U-SRA**	0.4260	0.1975	0.1731
8	**U-S(R_T)**	0.3124	0.2792	0.2905
9	**U-S(R_T, L_T)**	0.3408	0.2587	0.2664
10	**U-S(R_T, L_T, U_T)**	0.3692	0.1979	0.1934
11	**O-RA**	0.2556	0.1821	0.1524
12	**O-SRA**	0.2840	0.2006	0.1731
13	**O-S(R_T)**	0.1704	0.2824	0.2905
14	**O-S(R_T, L_T)**	0.1988	0.2619	0.2664
15	**O-S(R_T, L_T, U_T)**	0.2272	0.2010	0.1934

Weighted Normalized Data **Vij**	**Equation (2)**		**Economic**	
		Initial Cost	**Operational Cost**	**Economic Efficiency**
ID	**Alternative**	(Qualitative)	Per Hour (USD)	Monetary Value of the Total Hourly Travel Time
1	**RA**	0.0126	0.0255	0.0202
2	**SRA**	0.0158	0.0249	0.0201
3	**S(R_T)**	0.0032	0.0474	0.0491
4	**S(R_T, L_T)**	0.0063	0.0395	0.0393
5	**S(R_T, L_T, U_T)**	0.0095	0.0298	0.0274
6	**U-RA**	0.0442	0.0199	0.0169
7	**U-SRA**	0.0473	0.0219	0.0192
8	**U-S(R_T)**	0.0347	0.0310	0.0323
9	**U-S(R_T, L_T)**	0.0379	0.0287	0.0296
10	**U-S(R_T, L_T, U_T)**	0.0410	0.0220	0.0215
11	**O-RA**	0.0284	0.0202	0.0169
12	**O-SRA**	0.0316	0.0223	0.0192
13	**O-S(R_T)**	0.0189	0.0314	0.0323
14	**O-S(R_T, L_T)**	0.0221	0.0291	0.0296
15	**O-S(R_T, L_T, U_T)**	0.0252	0.0223	0.0215
Ideal best (V+) / worst (V-) Value				
Eq. 5	**V+**	0.0032	0.0199	0.0169
Eq. 6	**V-**	0.0473	0.0474	0.0491

Table D1: TOPSIS Sample Calculation for Asharej (2008) Scenario (Continued)

A	Asharej Roundabout Speed = 100 km/h - 2008 Sustainability Dimensions Indicator Area	Consumed Energy	Environmental (Emissions) (kg/h)				Land Consumption
ID	**Alternative**	Fuel Consumption	CO_2	Hydro Carbons	CO	NOx	Area (m^2)
1	**RA**	1857.60	4409.90	0.52	9.52	9.09	21642.50
2	**SRA**	1819.20	4318.90	0.51	9.44	8.81	21642.50
3	**S(R_T)**	2160.80	5128.40	0.64	10.06	9.83	14933.18
4	**S(R_T, L_T)**	2019.00	4795.40	0.59	9.84	9.38	16340.12
5	**S(R_T, L_T, U_T)**	1863.20	4428.40	0.54	9.59	9.00	17764.99
6	**U-RA**	1598.10	3796.50	0.46	9.08	7.09	23042.38
7	**U-SRA**	1643.60	3904.00	0.48	9.16	7.26	23042.38
8	**U-S(R_T)**	1734.50	4119.00	0.52	9.30	7.30	16555.37
9	**U-S(R_T, L_T)**	1687.70	4009.40	0.51	9.24	7.13	17889.43
10	**U-S(R_T, L_T, U_T)**	1576.50	3747.50	0.47	9.07	6.83	19137.66
11	**O-RA**	1597.90	3793.40	0.46	9.08	7.09	23042.38
12	**O-SRA**	1643.40	3900.90	0.48	9.16	7.26	23042.38
13	**O-S(R_T)**	1734.30	4115.90	0.52	9.30	7.29	16555.37
14	**O-S(R_T, L_T)**	1687.50	4006.30	0.51	9.24	7.13	17889.43
15	**O-S(R_T, L_T, U_T)**	1576.30	3744.40	0.47	9.07	6.83	19137.66
	Square root of Sum of Squares:	7842.97	15547.11	1.99	36.20	30.55	76071.79
	Weights	0.11	0.03	0.03	0.03	0.03	0.11

Normalized Data rij	Equation (1)	Consumed Energy	Environmental (Emissions) (kg/h)				Land Consumption
ID	**Alternative**	Fuel Consumption	CO_2	Hydro Carbons	CO	NOx	Area (m^2)
1	**RA**	0.2368	0.2836	0.2612	0.2629	0.2977	0.2845
2	**SRA**	0.2320	0.2778	0.2561	0.2607	0.2884	0.2845
3	**S(R_T)**	0.2755	0.3299	0.3211	0.2779	0.3217	0.1963
4	**S(R_T, L_T)**	0.2574	0.3084	0.2974	0.2719	0.3069	0.2148
5	**S(R_T, L_T, U_T)**	0.2376	0.2848	0.2707	0.2648	0.2945	0.2335
6	**U-RA**	0.2038	0.2442	0.2325	0.2509	0.2322	0.3029
7	**U-SRA**	0.2096	0.2511	0.2395	0.2530	0.2376	0.3029
8	**U-S(R_T)**	0.2212	0.2649	0.2617	0.2569	0.2388	0.2176
9	**U-S(R_T, L_T)**	0.2152	0.2579	0.2551	0.2553	0.2334	0.2352
10	**U-S(R_T, L_T, U_T)**	0.2010	0.2410	0.2360	0.2505	0.2237	0.2516
11	**O-RA**	0.2037	0.2440	0.2325	0.2508	0.2321	0.3029
12	**O-SRA**	0.2095	0.2509	0.2395	0.2530	0.2375	0.3029
13	**O-S(R_T)**	0.2211	0.2647	0.2617	0.2569	0.2388	0.2176
14	**O-S(R_T, L_T)**	0.2152	0.2577	0.2551	0.2552	0.2333	0.2352
15	**O-S(R_T, L_T, U_T)**	0.2010	0.2408	0.2360	0.2504	0.2237	0.2516

Weighted Normalized Data Vij	Equation (2)	Consumed Energy	Environmental (Emissions) (kg/h)				Land Consumption
ID	**Alternative**	Fuel Consumption	CO_2	Hydro Carbons	CO	NOx	Area (m^2)
1	**RA**	0.0263	0.0079	0.0073	0.0073	0.0083	0.0316
2	**SRA**	0.0258	0.0077	0.0071	0.0072	0.0080	0.0316
3	**S(R_T)**	0.0306	0.0092	0.0089	0.0077	0.0089	0.0218
4	**S(R_T, L_T)**	0.0286	0.0086	0.0083	0.0076	0.0085	0.0239
5	**S(R_T, L_T, U_T)**	0.0264	0.0079	0.0075	0.0074	0.0082	0.0259
6	**U-RA**	0.0226	0.0068	0.0065	0.0070	0.0065	0.0337
7	**U-SRA**	0.0233	0.0070	0.0067	0.0070	0.0066	0.0337
8	**U-S(R_T)**	0.0246	0.0074	0.0073	0.0071	0.0066	0.0242
9	**U-S(R_T, L_T)**	0.0239	0.0072	0.0071	0.0071	0.0065	0.0261
10	**U-S(R_T, L_T, U_T)**	0.0223	0.0067	0.0066	0.0070	0.0062	0.0280
11	**O-RA**	0.0226	0.0068	0.0065	0.0070	0.0064	0.0337
12	**O-SRA**	0.0233	0.0070	0.0067	0.0070	0.0066	0.0337
13	**O-S(R_T)**	0.0246	0.0074	0.0073	0.0071	0.0066	0.0242
14	**O-S(R_T, L_T)**	0.0239	0.0072	0.0071	0.0071	0.0065	0.0261
15	**O-S(R_T, L_T, U_T)**	0.0223	0.0067	0.0066	0.0070	0.0062	0.0280
Ideal best (V+) / worst (V-) Value							
Eq. 5	V+	0.0223	0.0067	0.0065	0.0070	0.0062	0.0218
Eq. 6	V-	0.0306	0.0092	0.0089	0.0077	0.0089	0.0337

Table D1: TOPSIS Sample Calculation for Asharej (2008) Scenario (Continued)

A	**Asharej Roundabout**					
	Speed = 100 km/h - 2008					
	Sustainability Dimensions	**Social**				
	Indicator Area	**Mobility**			**Safety**	**Public Satisfaction**
ID	**Alternative**	Avg. Speed (km/h)	Total Hourly Travel Time	Total passenger miles travelled (per-km/h)	Safety (Qualitative/for Veh.)	Avg. Delay (Per Person)
1	**RA**	72.30	192.40	16699.90	12	26.10
2	**SRA**	72.60	191.70	16699.90	11	65.50
3	**S(R_T)**	28.80	466.90	16142.20	15	156.80
4	**S(R_T, L_T)**	36.00	373.80	16164.20	14	116.20
5	**S(R_T, L_T, U_T)**	51.60	260.90	16186.60	13	66.40
6	**U-RA**	86.34	161.10	16488.80	7	10.70
7	**U-SRA**	77.75	183.00	16488.80	6	22.43
8	**U-S(R_T)**	54.58	307.10	16059.40	10	81.41
9	**U-S(R_T, L_T)**	57.23	281.60	16073.50	9	70.87
10	**U-S(R_T, L_T, U_T)**	70.01	204.40	16088.00	8	37.36
11	**O-RA**	86.34	161.10	16488.80	2	10.70
12	**O-SRA**	77.75	183.00	16488.80	1	22.43
13	**O-S(R_T)**	54.58	307.10	16059.40	5	81.41
14	**O-S(R_T, L_T)**	57.23	281.60	16073.50	4	70.87
15	**O-S(R_T, L_T, U_T)**	70.01	204.40	16088.00	3	37.36
	Square root of Sum of Squares:	254.16	1024.31	63081.89	35.21	273.49
	Weights	0.04	0.04	0.04	0.11	0.11

Normalized Data		**Social**				
rij	**Equation (1)**	**Mobility**			**Safety**	**Public Satisfaction**
ID	**Alternative**	Avg. Speed (km/h)	Total Hourly Travel Time	Total passenger miles travelled (per-km/h)	Safety (Qualitative/for Veh.)	Avg. Delay (Per Person)
1	**RA**	0.2845	0.1878	0.2647	0.3408	0.0954
2	**SRA**	0.2856	0.1871	0.2647	0.3124	0.2395
3	**S(R_T)**	0.1133	0.4558	0.2559	0.4260	0.5733
4	**S(R_T, L_T)**	0.1416	0.3649	0.2562	0.3976	0.4249
5	**S(R_T, L_T, U_T)**	0.2030	0.2547	0.2566	0.3692	0.2428
6	**U-RA**	0.3397	0.1573	0.2614	0.1988	0.0391
7	**U-SRA**	0.3059	0.1787	0.2614	0.1704	0.0820
8	**U-S(R_T)**	0.2148	0.2998	0.2546	0.2840	0.2977
9	**U-S(R_T, L_T)**	0.2252	0.2749	0.2548	0.2556	0.2591
10	**U-S(R_T, L_T, U_T)**	0.2754	0.1995	0.2550	0.2272	0.1366
11	**O-RA**	0.3397	0.1573	0.2614	0.0568	0.0391
12	**O-SRA**	0.3059	0.1787	0.2614	0.0284	0.0820
13	**O-S(R_T)**	0.2148	0.2998	0.2546	0.1420	0.2977
14	**O-S(R_T, L_T)**	0.2252	0.2749	0.2548	0.1136	0.2591
15	**O-S(R_T, L_T, U_T)**	0.2754	0.1995	0.2550	0.0852	0.1366

Weighted Normalized Data		**Social**				
Vij	**Equation (2)**	**Mobility**			**Safety**	**Public Satisfaction**
ID	**Alternative**	Avg. Speed (km/h)	Total Hourly Travel Time	Total passenger miles travelled (per-km/h)	Safety (Qualitative/for Veh.)	Avg. Delay (Per Person)
1	**RA**	0.0105	0.0070	0.0098	0.0379	0.0106
2	**SRA**	0.0106	0.0069	0.0098	0.0347	0.0266
3	**S(R_T)**	0.0042	0.0169	0.0095	0.0473	0.0637
4	**S(R_T, L_T)**	0.0052	0.0135	0.0095	0.0442	0.0472
5	**S(R_T, L_T, U_T)**	0.0075	0.0094	0.0095	0.0410	0.0270
6	**U-RA**	0.0126	0.0058	0.0097	0.0221	0.0043
7	**U-SRA**	0.0113	0.0066	0.0097	0.0189	0.0091
8	**U-S(R_T)**	0.0080	0.0111	0.0094	0.0316	0.0331
9	**U-S(R_T, L_T)**	0.0083	0.0102	0.0094	0.0284	0.0288
10	**U-S(R_T, L_T, U_T)**	0.0102	0.0074	0.0094	0.0252	0.0152
11	**O-RA**	0.0126	0.0058	0.0097	0.0063	0.0043
12	**O-SRA**	0.0113	0.0066	0.0097	0.0032	0.0091
13	**O-S(R_T)**	0.0080	0.0111	0.0094	0.0158	0.0331
14	**O-S(R_T, L_T)**	0.0083	0.0102	0.0094	0.0126	0.0288
15	**O-S(R_T, L_T, U_T)**	0.0102	0.0074	0.0094	0.0095	0.0152
Ideal best (V+) / worst (V-) Value						
Eq. 5	**V+**	0.0126	0.0058	0.0094	0.0032	0.0043
Eq. 6	**V-**	0.0042	0.0169	0.0098	0.0473	0.0637

Table D1: TOPSIS Sample Calculation for Asharej (2008) Scenario (Continued)

Si (+)	Eq. (7): Sqrt (Sum{ [Vij - Vj(+)] ^2 })
Si (-)	Eq. (8): Sqrt (Sum{ [Vij - Vj(-)] ^2 })
CSI	Eq. (9): Si(-) / { Si (+) + Si (-) }

ID	Alternative	Economic			
		Si (+)	Si (-)	Ec. CSI	Rank
1	RA	0.0115	0.0501	81.3493	1
2	SRA	0.0140	0.0483	77.5958	2
3	S(R_T)	0.0423	0.0442	51.0977	10
4	S(R_T, L_T)	0.0299	0.0429	58.9453	9
5	S(R_T, L_T, U_T)	0.0158	0.0470	74.8927	3
6	U-RA	0.0410	0.0424	50.8242	11
7	U-SRA	0.0443	0.0392	46.9498	13
8	U-S(R_T)	0.0368	0.0266	41.9541	15
9	U-S(R_T, L_T)	0.0380	0.0285	42.9020	14
10	U-S(R_T, L_T, U_T)	0.0382	0.0380	49.8782	12
11	O-RA	0.0252	0.0461	64.6243	5
12	O-SRA	0.0286	0.0420	59.5190	8
13	O-S(R_T)	0.0248	0.0367	59.6239	7
14	O-S(R_T, L_T)	0.0246	0.0367	59.9268	6
15	O-S(R_T, L_T, U_T)	0.0227	0.0433	65.6248	4

ID	Alternative	Environmental			
		Si (+)	Si (-)	Env. CSI	Rank
1	RA	0.0109	0.0053	32.5941	15
2	SRA	0.0106	0.0058	35.4655	14
3	S(R_T)	0.0094	0.0118	55.7004	9
4	S(R_T, L_T)	0.0075	0.0100	57.2926	8
5	S(R_T, L_T, U_T)	0.0063	0.0090	58.7044	7
6	U-RA	0.0119	0.0091	43.3154	11
7	U-SRA	0.0119	0.0083	41.2152	13
8	U-S(R_T)	0.0035	0.0117	77.2536	2
9	U-S(R_T, L_T)	0.0047	0.0107	69.6761	4
10	U-S(R_T, L_T, U_T)	0.0061	0.0110	64.1425	6
11	O-RA	0.0119	0.0091	43.3279	10
12	O-SRA	0.0119	0.0083	41.2291	12
13	O-S(R_T)	0.0035	0.0117	77.2738	1
14	O-S(R_T, L_T)	0.0047	0.0107	69.6899	3
15	O-S(R_T, L_T, U_T)	0.0061	0.0110	64.1506	5

Table D1: TOPSIS Sample Calculation for Asharej (2008) Scenario (Continued)

ID	Alternative	Social			
		Si (+)	Si (-)	Soc. CSI	Rank
1	RA	0.0353	0.0552	60.9659	8
2	SRA	0.0387	0.0409	51.4060	11
3	S(R_T)	0.0753	0.0003	0.4331	15
4	S(R_T, L_T)	0.0603	0.0172	22.1641	14
5	S(R_T, L_T, U_T)	0.0445	0.0381	46.1312	13
6	U-RA	0.0189	0.0660	77.7020	5
7	U-SRA	0.0165	0.0628	79.1424	4
8	U-S(R_T)	0.0410	0.0351	46.1508	12
9	U-S(R_T, L_T)	0.0357	0.0405	53.1706	10
10	U-S(R_T, L_T, U_T)	0.0248	0.0545	68.7514	6
11	O-RA	0.0032	0.0735	95.8698	1
12	O-SRA	0.0050	0.0713	93.4537	2
13	O-S(R_T)	0.0322	0.0445	58.0604	9
14	O-S(R_T, L_T)	0.0269	0.0499	64.9458	7
15	O-S(R_T, L_T, U_T)	0.0129	0.0626	82.9544	3

ID	Alternative	Composite Sustainability			
		Si (+)	Si (-)	Overall CSI	Rank
1	RA	0.0387	0.0748	65.88	4
2	SRA	0.0425	0.0636	59.96	8
3	S(R_T)	0.0869	0.0457	34.49	15
4	S(R_T, L_T)	0.0677	0.0473	41.13	14
5	S(R_T, L_T, U_T)	0.0477	0.0612	56.21	11
6	U-RA	0.0467	0.0789	62.83	6
7	U-SRA	0.0487	0.0745	60.44	7
8	U-S(R_T)	0.0552	0.0456	45.24	13
9	U-S(R_T, L_T)	0.0523	0.0507	49.21	12
10	U-S(R_T, L_T, U_T)	0.0459	0.0673	59.45	9
11	O-RA	0.0281	0.0872	75.65	1
12	O-SRA	0.0314	0.0832	72.62	3
13	O-S(R_T)	0.0408	0.0588	59.08	10
14	O-S(R_T, L_T)	0.0367	0.0629	63.11	5
15	O-S(R_T, L_T, U_T)	0.0268	0.0769	74.16	2