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Sustainability-informed multi-criteria decision support framework for ranking and prioritization of pavement sections

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ABSTRACT

Ranking and prioritizing pavement infrastructure for maintenance and rehabilitation have become major undertakings for several departments of transportation around the globe. This is a complex decision-making problem because multiple and conflicting criteria can contribute to the assessment. Multi-criteria decision analysis (MCDA) techniques evaluate the trade-off between several quantitative and qualitative criteria and facilitate complex decision-making. This research introduces a framework based on MCDA to support pavement management decision making, while quantifying emerging sustainability-related factors such as safety, noise, and pollution in the decision-making process. The framework features include 1) identifying pavement management main decision elements: objectives, criteria, and attributes by detailing the problem with a five-level hierarchy structure; 2) employing combined analytic hierarchy process and multi-attribute utility theory to develop representative set of utility functions; and 3) ranking and prioritizing large networks of pavement sections while incorporating sustainability-related criteria. Data used to assess the decision criteria and develop the utility functions is extracted by means of a questionnaire survey completed by professionals working in the field of pavement management. The proposed method is applied to a case study consisting of ten pavement sections extracted from the long-term pavement performance database, wherein the sections are ranked based on their attributes. Sensitivity analysis is performed to evaluate the impact of the different criteria on the ranking process. The proposed method has shown potential in ranking pavement networks based on the identified criteria. Future work can test the performance of the proposed methodology with a full-scale pavement network and apply it to other civil infrastructure assets to evaluate its performance with different types of projects.

Key Words: Pavement; Management; Multi-criteria; Sustainability; Ranking; Prioritizing

1. Introduction

Pavement management system (PMS) consists of a set of tools and methods to support an agency's decisions on optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time (AASHTO, 1993). Pavement management can be implemented primarily at three levels: strategic, network, and project. The main objective of a network-level PMS is to develop short and long-term budget requirements and produce a list of potential projects that will ensure safety and serviceability of the network. Due to limited budgets available for pavement maintenance operations, ranking and prioritizing processes are usually incorporated in PMSs to choose sections with high priority and find an optimal solution for the allocation of available funds while meeting the needs of the pavement network (Moazami et al., 2011). Available prioritization methods can be divided into optimization and priority setting models (Shah et al., 2014). Optimization models are typically based on solving the mathematical formulation of an objective function that aims to maximize network conditions under a limited budget constraint. These models can be applied after identifying the highest priority sections in a network. The objective of optimization is to develop a work program that addresses the needs of the most important sections without exceeding the available budget. Priority setting models typically focus on incorporating expert judgments and experience in the decision-making process (Flintsch et al., 1998). Moreover, specific distresses such as extent of rutting and cracking and specific failure indicators such as number of failures per mile are used in prioritizing projects (Abu Dabous and Al-Khayyat, 2018; Dessouky et al., 2011).

Ranking and prioritization of pavement sections in a network are vital steps in pavement management. In practice, several performance indicators are used to prioritize pavement sections, including present serviceability index, riding comfort index, pavement condition index, condition score, and ride score (Abu Dabous et al., 2019; Gurganus, 2011; Haas et al., 2001; Terzi, 2006). One main limitation of ranking pavement sections based on condition rating or a service indicator is the potential of excluding important criteria, which can affect users and the environment. To overcome this limitation, other important parameters must be considered, including user impact (Dessouky et al., 2011; Flintsch et al., 1998; Haas et al., 2001; Šelih et al., 2008), road functional classification (Moazami et al., 2011), traffic volume and truck loads (Gurganus, 2011), pavement noise (Haas et al., 2001), and climate and operational factors (Abu-Samra et al., 2017). The inclusion of multiple criteria in priority decisions related to transportation assets can produce plans that are more balanced, effective, rational, and justifiable (Sinha et al., 2009). The use of multi-criteria decision analysis (MCDA) in civil infrastructure management is gradually spreading all over the world. The construction sector has notably evolved in considering multiple and conflicting criteria while making decisions. Environmental and social aspects have become increasingly important in the decision-making process due to their contribution to success of any work or procedure, and MCDA has raised broadminded clairvoyance in decision makers (Jato-Espino et al., 2014).

Our literature review indicates that MCDA has been widely applied in the prioritization process of different civil infrastructure assets such as bridges (Bukhsh et al., 2018; Abu Dabous et al., 2017; Penadés-Plà et al., 2016; Sabatino et al., 2015) and utility assets (Abu-Samra et al., 2017; El Chanati et al., 2015; Kaddoura et al., 2017) in the trade-off analysis in transportation asset management (Bai et al., 2015, 2012). Zavadskas et al. (2017) reviewed sustainable decision-making in the field of civil engineering. However, it is noted that relatively limited number of researches focused on sustainable MCDA in pavement management. Most of the published work in this area aim toward selecting maintenance and rehabilitation strategies to optimize cost and distribute limited budget to pavement sections in a network. Recent literature published on MCDA in pavement management is summarized in Table 1 and briefly discussed in the following paragraphs.

Insert Table 1: Summarized literature review of the application of MCDA in pavement management

Cafiso et al. (2002) developed an analytic hierarchy process (AHP)-based method for pavement maintenance management. AHP was selected because it facilitates the analysis by performing simple comparisons between decision elements. Five decision criteria were chosen, namely comfort, environment, safety, road agency cost, and road user cost. It was concluded that road maintenance prioritization based on MCDA could distribute the budget more effectively than the traditional economic priority settings. Ouma et al. (2015) utilized fuzzy AHP and fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) to prioritize maintenance and rehabilitation of pavement sections based on the following criteria: road safety, pavement surface preservation, road operational status and standards, and road aesthetics. They pointed out that fuzzy AHP and fuzzy TOPSIS are preferred over crisp AHP because the former are deemed more appropriate for subjective analysis. However, fuzzy-based analysis increases the complexity and judgment elicitation compared to the intuitive procedure embedded in traditional AHP. Another study assimilated fuzzy AHP with the VIKOR method to optimize decision making considering pavement condition index, traffic congestion, pavement width, improvement and maintenance costs, and operation time (Babashamsi et al., 2016). Other models developed for pavement maintenance or management systems include the MACBETH method and nondominated sorting genetic algorithm (Khiavi and Mohammadi, 2018; Marcelino et al., 2019).

Santos et al. (2017) focused on addressing the sustainability objectives in pavement management by developing a decision support system consisting of a multi-objective optimization module, cradle-to-grave life-cycle cost, an environmental assessment module, and a decision support module. An optimal maintenance strategy was selected by determining an alternative, which reduced the present value of the total life-cycle highway agency and user costs and yielded the best results in terms of life-cycle greenhouse gas emissions. Lee and Madanat (2017) proposed an algorithm based on Lagrangian relaxation and dynamic programming to reduce greenhouse gas emissions during pavement management. Other sustainable pavement management frameworks utilizing a logistic regression model (Kim et al., 2018), mechanistic-empirical pavement design guide, and life-cycle assessment methods (Chong and Wang, 2017) can be found in literature.

Incorporating sustainability-related criteria in infrastructure management systems under MCDA is paramount, and it has been receiving attention worldwide. Therefore, further research is required to facilitate integrating sustainable pavement management decision-making methods in practice, while including multiple criteria to assess large pavement networks in a systematic way. This research introduces a multi-criteria ranking and prioritizing framework capable of ranking and prioritizing a large network of pavement sections while including multiple objectives and criteria in the process. The focus of the framework is sustainability-related criteria. Further, this study introduces a method for extracting and utilizing expert judgments in the ranking process systematically, which is absent in the existing literature. The framework enables a decision maker to select the decision criteria and provides flexibility in assigning weights and specifying intensities of the different objectives and criteria. Once the decision parameters are defined, the proposed framework can systematically rank pavement sections of pavement networks or a subset of a network and identify the highest priority sections based on the decision criteria. To attain these requirements, the AHP and multi-attribute utility theory (MAUT) are utilized within the proposed framework to rank and prioritize large networks of pavement sections under sustainability-related criteria. Future work can build on the current research to select optimized maintenance and rehabilitation strategies of the identified highest priority pavement sections.

2. Research methodology

A research methodology is designed to study the pavement management decision-making problem and develop a decision support framework to rank and prioritize large networks of pavements while including multiple criteria. The main steps of this research methodology are as follows:

1) Select appropriate MCDA methods to be utilized in the pavement management decision-making problem.
2) Analyze the pavement management decision-making problem to understand its main elements and identify the decision objectives, criteria, and attributes.
3) Develop a multi-criteria decision support framework to rank and prioritize pavement sections based on the decision elements identified in Step 2.
4) Test the proposed method and illustrate its performance with a case study of a network of pavement sections currently in service.

The following sections discuss the implementation of the proposed research methodology.

3. Selection of an MCDA method for pavement ranking and prioritizing

Since its inception by Saaty (1980), AHP has been widely used as a multi-criteria decision-making theory in several engineering applications because of its intuitive and efficient approach in extracting judgments. Expert judgments are extracted through pairwise comparisons between elements and sub-elements of a decision problem. The levels of relative importance are defined with standard terms proposed by Saaty (1980), known as scale of relative importance. Torres-

Machí et al. (2015) studied methods that can integrate multiple criteria related to technical, user, and environmental aspects with the potential of enhancing the sustainable management of pavement infrastructure. They concluded that AHP is a suitable method to produce robust results, but highlighted the fact that AHP can be used only when the number of alternatives is small. When the number of alternatives is large, pairwise comparison becomes difficult. Saaty (1980) recognized this limitation and recommended that the number of alternatives compared in pairs should not exceed nine. In pavement management, a network of pavement sections can include thousands of sections, making it impossible to estimate the relative importance of these sections simultaneously. To overcome this limitation, this research attempts to implement the principle of utility along with AHP. MAUT provides the basis of assessing performance based on measurable attributes of a system and represents degree of satisfaction with these attributes in terms of utility scores. This approach offers a logical and traceable means to assess trade-offs among conflicting objectives (Keeney and Raiffa, 1993). The theory evaluates the available alternatives based on the attributes and uses utility functions to depict preferences of experts by assigning utility values for different levels of the attributes. The utility function assigns a utility score (typically between 0 and 100) to each value of the attribute ranging from the least to the most desirable value. The proposed method (integrated AHP and MAUT) has the following advantages:

1. The intuitive pairwise comparison procedure embedded in AHP can facilitate the development of a representative set of utility functions.
2. The produced utility functions can reflect the decision maker’s attitude toward risk (risk prone, risk averse, or risk neutral).
3. The method is flexible and allows for revising its parameters. It enables revising the utility functions by simply resubmitting the pairwise comparisons.

4. Once the utility functions are developed and the decision element weights are assigned, any number of alternatives can be evaluated and ranked immediately.

4. Analysis of pavement management decision problem

Based on a thorough review of literature and pavement management current practices, the complex pavement management decision problem is analyzed in this research by breaking it into five levels, using a work breakdown structure (WBS), to identify the decision elements. WBS is developed by first identifying the top level and subsequently moving down to identify more detailed components. Priority ranking of pavement sections for maintenance is the overall goal of this decision-making process; hence, this overall goal is assigned as the first level in the hierarchy structure. The decomposition of the decision problem proceeds until all the decision elements have been identified. Figure 1 shows the work breakdown structure developed in this research and the decision elements.

Insert Figure 1: Breakdown structure for pavement network ranking problem

As can be seen in Figure 1, the main goal of the decision-making process is the ranking and prioritizing of a network of pavement sections for intervention(s). The decision matrices in this breakdown are selected to achieve the department of transportation (DOT) objectives of prioritizing important and deficient sections in a sustainable manner. The second level of the WBS includes the main objectives required to achieve the main goal, and the third level comprises of the criteria selected to assess each pavement section's level of attainment with respect to the related objective. The objectives and criteria are selected to incorporate important sustainability-related aspects. One objective is to prioritize important sections. The criteria selected to measure the level of achievement on this objective are those that prioritize significant and busy pavement sections serving high traffic volume. Hence, traffic volume and road classification are selected for this purpose. The second objective is to incorporate the impact on environment and society by prioritizing pavement sections with high community and society impacts. The third objective is to prioritize sections with performance drop or deterioration due to prominent surface deterioration and structural degradation, thereby causing serviceability and safety concerns. Each objective and criterion is assigned a specific weight to reflect its relative importance among the different decision elements. These weights are identified based on the results of a questionnaire survey conducted in the course of this research. The design of the survey and analysis of its results are presented in the data analysis section. These weights are developed and integrated in the proposed framework as the original assessment of the decision elements. Moreover, the proposed framework provides flexibility to adjust the weights of the decision elements if required.

The fourth level contains the pavement attributes that can be used to assess the important features of each pavement section. In the following section, we discuss the pavement section attributes selected to quantify the level of attainment of a section based on the different criteria. The pavement sections that need to be ranked and prioritized for intervention are added at the lowest level of the structure.

4.1 Selection of decision attributes

Specific attributes of a pavement section can be used to evaluate the level of attainment of the section based on the different evaluation criteria. For example, a pavement section with high traffic volume has higher priority than a section with low traffic volume. The section traffic volume is typically estimated with a specific measure known as equivalent single axle load (ESAL). Hence, ESAL is an attribute of any pavement section, which can be used to assess the importance of the section in terms of traffic volume. Pavement section attributes are collected by DOTs and populated in databases to facilitate pavement management. Long-term pavement performance

(LTPP) is a major pavement performance research program collecting data from more than 2,500 pavement sections. The Federal Highway Administration (FHWA) maintains a resource website for pavement data *(*http://www.trb.org/LTPPProgram/LTPPProgram.aspx*)*. The LTPP database stores data related to structure, performance, traffic, climate, and traffic and pavement inventory made available to researchers. The decision attributes (fourth level in Figure 1) of the proposed framework are consistent with the data available in the LTPP database. Some of the attributes are provided directly in the database, while others are not. LTPP provides parameters related to the attributes, which can be used to estimate the attribute value. In this case, specific models from literature are selected to estimate these attributes. The following subsections discuss the decision attributes and selected models from the literature to quantify attributes that are not directly provided in the LTPP database.

4.1.1 Equivalent single axle load

ESAL is a concept developed based on analyzing data collected by the American Association of State Highway Officials Road Test to define a damage relationship for comparing the effects of axles carrying different loads (AASHTO, 1993). Design ESAL is a cumulative traffic load summary statistic reflecting a mixed stream of traffic configurations and axle loads anticipated over the analysis or design period and subsequently converted into an equivalent number of receptions of a reference single axle load of 18,000 lb with dual tires. For flexible pavements, ESAL is calculated using either an equivalent single load factor or a truck factor. More details about the design ESAL calculations can be found in the AASHTO guide for the design of pavement structures (AASHTO, 1993).

4.1.2 Functional classification of roadways

The concept of functional classification describes the role that a particular roadway segment plays in serving the flow of traffic through a network. A roadway is assigned to one of several functional classifications within a hierarchy according to the service level that the roadway is intended to provide. There are two basic hierarchies of the roadway functional classification system according to the area setting: urban and rural (U.S. Department of Transportation, 2013). For urban areas, there are four roadway functional classifications: principle arterial, minor arterial, collector, and local. For rural areas, there are five roadway functional classifications: principle arterial, minor arterial, major collector, minor collector, and local. The classification of urban areas is considered in the proposed method.

4.1.3 Traffic noise

One direct assessment of community impact is the noise associated with each section. Traffic noise pollution is one of the main problems worldwide, especially in urban areas with high population density and high volumes of commuter traffic. Chronic exposure to traffic noise can affect human health by varying degrees both physiologically and psychologically (Tsunokawa and Hoban, 1997). There are four main sources of traffic noise: engines, exhausts, aerodynamics, and tire/pavement interactions. Pavements with well-maintained and smooth surfaces are expected to produce less tire/pavement interaction noise. Traffic noise is measured in decibels (dBA), which is a logarithmic function of the square of the ratio of sound pressure over reference pressure. Because traffic noise levels often fluctuate with time, a single value such as L_{eq} or L_{50}, which can reflect an equivalent continuous sound level, is used, where L_{eq} is defined as the steady sound pressure level with the same total energy over a given time.

Several traffic noise prediction models have been developed for the prediction of sound pressure levels at roadsides (Garg et al., 2017; Steele, 2001). Most current models assume point sources, while some models assume line sources in which sound emission levels are expressed as a function of vehicle type, flow, speed, road surface, and other aspects. Recent models incorporate a propagation section to calculate the outdoor sound attenuation. Simple and representative highway noise prediction methods are useful for urban planning and verification models. In this study, a simple yet comprehensive traffic noise model is proposed. Contributing factors of the proposed model are available in the LTPP database and can be extracted to assess the noise level of each pavement section. The model is given by Equation 1 (Galloway et al., 1969).

$$L_{50} = 20 + 10 \log (V.S^2/D) + 0.4 (T), \quad (1)$$

where

L_{50} = equivalent continuous sound level in dBA;

V = traffic volume in vehicles per hour;

S = mean vehicle speed in mph;

D = distance from the traffic lane in feet (50 feet according to the FHWA model); and

T = percentage of heavy trucks.

4.1.4 Traffic CO_2 emission

The environmental impact of civil infrastructures can be linked and assessed by the amount of CO_2 released into the environment due to their operation and maintenance. Road transportation is one of the major greenhouse gas (GHG) emission sources and therefore a large contributor to global climate change (Chapman, 2007). It is estimated that a third of America's CO_2 emissions originate from moving people and goods, and 80% of these emissions are from cars and trucks (Barth and Boriboonsomsin, 2009). There have been few attempts to incorporate GHG emissions from different sources in sustainable PMS at both the project- and network-level through their life-cycle assessment cost models (Zhang, 2009). Two main GHG emission sources are typically considered: material and construction emissions and vehicle emissions. In this study, only vehicle GHG emissions are considered for project-level analysis because material and construction GHG emissions are more important at the project level for deciding among different designs and rehabilitation strategies. Transportation agencies and researchers have been implementing different techniques in developing vehicle CO_2 emission models because 95% of transportation GHG emissions are in the form of CO_2 (U.S. Environmental Protection Agency, 2009).

Emission models are mainly categorized as macroscopic and microscopic, depending on vehicle parameters (vehicle technology, fuel type, loaded mass, class, engine capacity, mileage, gear shift pattern, number of wheels, and tire diameter), traffic and road-related parameters (average speed, traffic volume, traffic composition, truck percentage, paving material, surface roughness, and longitudinal slope), activity data (travel demand and access management), and driver-related parameters (rate of acceleration and driving behavior) (Mamarikas et al., 2015). One way to reduce traffic CO_2 emissions would be to maintain smooth road surfaces. This would help to maintain traffic flow and speed in addition to reducing vehicle fuel consumption rate and noise level. As part of this study, the available literature was reviewed to select a practical CO_2 emission model with parameters that can be quantified and stored in a PMS database. The CO_2 emission model developed by Abou-Senna and Radwan (2014), as shown in Equation (2), is considered here. The model predicts the quantity of CO_2 emissions in kilogram per mile.

$$Ln\ (CO_2) = 10.407 - 0.268\ (V^2) + 0.073\ (S^2) + 0.55\ (V) - 0.084\ (S) + 0.31\ (T) + 0.298\ (G) + 0.057\ (S \times G) + 0.054\ (T \times G) \quad (2)$$

where

V reflects traffic volume (vehicles per hour) = {(Volume – 4500) / 2500};

S reflects traffic speed (mph) = {(Speed – 45) / 25};

T reflects percentage of trucks = {(Truck% – 0.075) / 0.075}; and

G reflects percentage of longitudinal grade = {(Grade% – 0.025) / 0.025}.

The above parameters should be utilized with the following specifications:

V (from 2,000 to 7,000 vehicles per hour);

S (from 20 to 70 mph);

T (from 0% to 15%); and

G (from 0% to 5%).

4.1.5 Pavement structural capacity index

Pavement structural capacity is the ability of a road to carry traffic loads without excessive deterioration and can be expressed through several structural capacity indexes (Mack, 2013). Recently, many agencies and different state DOTs have implemented structural capacity indicators at the network-level into PMS and decision-making processes, such as structural condition index (SCI) for the Texas DOT, modified structural index for the Virginia DOT, structural strength index for the Indiana DOT, and structural health index for the Louisiana DOT (Bryce et al. 2013; Elbagalati et al. 2016; Flora, 2009; Zhang et al. 2003; Zhang and Yang., 2011).

In this study, SCI was selected to reflect the pavement structural performance. It was developed for the Texas DOT using falling weight deflectometer data. It is expressed as the ratio of the effective AASHTO structural number (SN_{eff}) to the design AASHTO structural number (SN_{des}) and based on estimated 20-year ESAL values assuming an annual traffic growth rate of 3 %. A modified model for SCI estimation was developed by Bryce et al. (2013), as presented in Equations (3) and (4).

$$SCI = \frac{SN_{Eff}}{SN_{Des}} = \frac{0.4728 \times (D_0 - D_{1.5Hp})^{-0.4810} \times Hp^{0.7581}}{0.05716 \times \left(\log\left(ESAL\right) - 2.32 \times \log(M_R) + 9.07605\right)^{2.36777}} , \quad (3)$$

$$M_R = \frac{0.33 \times 0.24 \times P}{D_r \times r}, \qquad (4)$$

where

SN_{eff} is effective structural capacity determined by deflection testing;

SN_{Des} is design structural capacity determined by traffic and resilient modulus data;

D_0 is deflection at center of load at 68 ºF (in);

$D_{1.5Hp}$ is deflections at an offset of 1.5 times the pavement depth (in);

Hp is depth of the pavement (in);

M_R is subgrade resilient modulus (psi);

P is falling weight deflectometer load (lb);

D_r is deflection at radius r (in); and

r is radius (in).

Using an effective structural number value of 6 and a resilient modulus of 10,000 psi, the SCI was reported to range roughly from 1.6 to 0.6 considering low, intermediate, and high traffic levels (Bryce et al. 2013).

4.1.6 Friction number

The tire-pavement friction of roads is a crucial safety parameter for vehicles. Hence, friction number (FN) is chosen as an attribute for the safety criteria. US studies show that between 15 and 18 % of crashes occur on wet pavements due to the loss of surface friction (FHWA, 1980; Wambold et al., 1986). Pavement friction is primarily a function of surface texture, including both microtexture (texture less than 0.5 mm—an aggregate characteristic to provide higher frictional resistance) and macrotexture (0.5 to 50 mm texture—an overall asphalt mixture characteristic for draining surface water fast) (Masad et al., 2009). Many other factors influence the level of friction on a paved road, such as the age of the road surface, seasonal variation, traffic intensity, aggregate properties, and road geometry (Chelliah et al., 2003).

Many devices and methods have been developed around the world to measure the friction and texture of paved road surfaces (Hall et al. 2009). Moreover, several friction indexes have been in use as indicators for road surface texture, such as FN, earlier known as skid number, to replace the coefficient of friction, and the international friction index (IFI). FN values are normally designated by the speed at which the test is performed and the type of tire used (smooth or ribbed). Trigger FN values ranging from 25 to 37 have been used by different agencies as an indication of friction deficiency (Hall et al. 2009). IFI is a recent index designed to calculate the coefficient of friction at any traffic speed and developed to harmonize friction and texture measurements by means of different test methods (Wambold and Antle, 1995). It consists of an FN value at 60 km/h (F_{60}) and a speed constant (S_P) and is reported as IFI (F_{60}, S_P). In this study, FN is used to describe the surface friction of pavement sections, thereby reflecting their safety.

4.1.7 International roughness index

Pavement roughness is a term used to express irregularities on a pavement surface, which adversely affect the ride quality of a vehicle. International roughness index (IRI) was developed by the World Bank in the 1980s as a profile-based statistic obtained from longitudinal road profiles to quantify surface roughness (Sayers et al., 1986). This index is typically expressed in inches per mile or meters per kilometer. Higher IRI values generally represent rough roads, while lower IRI values mean smooth roads. The US national standard of IRI thresholds for all road classifications range from 1.5 to 2.7 m/km (95 to 170 in/mi), indicating “acceptable” road segments. An IRI value of less than 1.5 m/km (95 in/mi) is considered to represent “good” road segments and that more than 2.7 m/km (170 in/mi) is considered to be poor (Arhin et al., 2015). However, several states are reviewing their strategic repair and rehabilitation programs based on IRI values, local conditions, and functional classification of roadways. Within the framework of the proposed method, IRI is selected to range between 40 and 300 in/mi, covering most of the possible values.

5. Development of the proposed AHP-MAUT framework

This research investigates the integration of MAUT with AHP. To implement MAUT, a set of concrete and measurable attributes are required, which are representative of the main features of each alternative (pavement section in our case). Levels of attainment at different values of an attribute are measured using a utility function. Hence, preparing utility functions is the core of MAUT. The proposed framework in this research includes the main elements required for pavement management decision making, including pavement section attributes, utility functions and weights of the decision elements (criteria and objectives), while providing flexibility to adjust these elements to reflect specific or different requirements of a network. Figure 2 shows a flowchart of the main elements of the ranking method developed in this research. A decision maker can adjust the selected criteria, attributes, and their corresponding weights if required. In addition, decision makers can submit their own judgments to develop a revised set of utility functions.

Insert Figure 2: Flowchart for the developed ranking method

5.1 Development of utility models

Implementation of the AHP-MAUT integrated method requires the development of a representative set of utility functions. A procedure to capture expert judgments through AHP is developed in this research to build the required utility functions. These functions can be used to estimate utility scores, typically between 0 and 100, based on the attribute value of each section. The utility scores can subsequently be combined using a utility model to produce an overall assessment of the section utility reflecting the significance of each section based on multiple criteria. The utility function development procedure is based on intuitive pairwise comparisons required for the AHP methodology. The steps to be implemented to develop the utility function are as follows:

1. Select attribute values that correspond to the lowest and highest possible utilities:
    - Define a minimum value for attributes such that any pavement section with this attribute value is considered with the least priority.
    - Define a maximum value for attributes, which represents *absolute* importance compared to the minimum value. Any pavement section with this attribute value is considered with the highest priority.
2. Select an attribute value with *weak* importance over the attribute value of the lowest utility. This relative importance between the two attribute values can be translated to 3 (Saaty, 1980). If a judgment indicates that the selected attribute's relative importance is more or less than 3, then the decision maker has the flexibility to use 2 or 4 to reflect the relative importance.
3. Select an attribute value with *demonstrated* importance over the attribute value of the lowest utility. This strong relative importance between the two elements can be translated to 7 (Saaty, 1980). If a judgment indicates that the selected attribute's relative importance is more or less than 7, then the decision maker has the flexibility to use 6 or 8 to reflect the relative importance.
4. Develop a reciprocal matrix for the relative intensities extracted during the previous steps.
5. Estimate the eigenvector, reflecting the relative weights for the attribute values.
6. Normalize the weights by assigning a utility value of 100 to the maximum attribute value, and the remaining weights are normalized at the same rate.

As a sample demonstration of the above procedure, utility function for the ESAL attribute is discussed here. ESAL is one standard approach in pavement management used to quantify traffic volume (discussed later). Assuming that the lowest ESAL value is selected as 0.01 million (a section with the lowest utility) and the highest ESAL value is selected as 30 million (a section with the highest utility), and assuming that the decision maker selects an ESAL value of 0.3 million to have slightly more importance compared to 0.01 million and an ESAL value of 3 million to have much more importance compared to the ESAL value of 0.01 million. Based on these judgments, the pairwise matrix can be developed as shown in Figure 3a, and the eigenvector is estimated and normalized to represent the utility points. Figure 3b shows the utility function linking ESAL values with the corresponding utility points estimated as per the above procedure.

Insert Figure 3: a) Pairwise comparison matrix, eigenvector, and utility points. b) Developed utility function

Utility functions are used to estimate the utility points of any attribute value. A utility model is required to aggregate the utilities of the different attributes into one overall value, reflecting the degree of satisfaction with the pavement section. Two models are typically used to aggregate the utilities, namely additive and multiplicative. An additive model is best used when the decision elements are independent, while the multiplicative form is selected when dependencies between the decision elements exist and can be quantified (Keeney and Raiffa, 1993). The overall utility estimated by the additive model is expressed as follows:

$$U(x_1, x_2, \dots \dots \dots x_n) = \sum_{i=1}^{n} k_i \, u_i(x_i), \quad (5)$$

where $U(x_1, x_2, \dots, x_n)$ is the total utility; k_i is the scaling weight in the range of 0 to 1, representing the relative importance of each of the *n* attributes; $\sum_{i=1}^{n} k_i = 1$; and $u_i(x_i)$ is the utility value when the attribute value is x_i. The multiplicative model reflects the dependence between attributes where $\sum_{i=1}^{n} k_i \neq 1$. The multiplicative model is represented as follows:

$$1 + kU(x_1, x_2, ..., x_n) = \prod_{i=1}^{n} [1 + kk_i u_i(x_i)], \quad (6)$$

where k is known as "common k" and is represented as an additional scaling constant. The scaling constant is related to the trade-off rate, which reflects the concept of offsetting gains in some criteria compared to losses in the other. Keeney and Raiffa (1976) proposed a trading off procedure between consequences to estimate the scaling constant. If the scaling constant is estimated to be zero, then Equation 6 reduces to the additive form given in Equation 5.

5.2 Data collection and analysis

To collect the data required for the framework implementation, a questionnaire survey was designed and distributed. The main objectives of the survey are 1) to estimate the weights of the decision criteria, and 2) to develop utility functions for the proposed framework. The survey was sent by email to 41 professionals working in the area of civil infrastructure management. Of these, 32 professionals completed and returned the survey. The respondents are involved in infrastructure management and their specializations are as follows: 19 respondents (59%) work directly in the industry and 13 (41%) are researchers. The survey was designed using Microsoft Excel, and the instruction and all parts of the survey were included on one sheet to facilitate the process of completing it. The survey was designed to be visual and interactive to extract the required judgments in an easy and efficient manner. The first part of the questionnaire survey included instructions and information to the respondents, mainly a brief description of the survey purpose, the problem breakdown structure (Figure 1), and the AHP scale of relative importance (Saaty, 1980). After the instructions, the survey had two main parts. The first part was designed to assess the weights of the different decision elements, where the experts were requested to submit their judgments in three matrices. These judgments were mainly the pairwise relative importance between the different decision criteria based on the AHP scale of relative importance.

AHP requires a consistent review of the submitted judgments to ensure that the submitted relative weights comply with the following two equations: 1) $w_{ij} = 1/w_{ji}$ and 2) $w_{ij} = w_{ik} \times w_{kj}$, where wij is the relative weight when element i is compared to element j. The process allows for limited inconsistency. A consistency index (CI) can be estimated for this purpose, where a small value of CI reflects a limited acceptable deviation from absolute consistency. CI can be estimated as follows:

$$CI = \frac{\lambda_{max} - N}{N - 1} \tag{7}$$

where λ_{max} is the maximum eigenvalue and N is the number of elements compared in the reciprocal matrix. Consistency ratio (CR) is subsequently calculated as CI/RI, where RI is a random consistency index derived from a large sample of randomly generated reciprocal matrices. Pairwise comparisons are considered adequately consistent if the corresponding CR is less than 10% (Saaty, 1980). The consistency check was completed on the results collected from every respondent and all the judgments were consistent. Visual nature of the matrices provided in the survey questionnaire and the limited number of pairwise compared elements (three or two) helped the respondents to submit consistent judgments.

A normalized eigenvector is estimated as per the AHP methodology to evaluate the weights of the decision elements in each reciprocal matrix. The priority vectors showed close agreement between the different respondents in assessing the weights of the decision elements. The estimated priority vectors for the three main decision goals show that 25 of the participants (78%) considered maximizing the effectiveness of investments to achieve the highest priority and impact on the overall goal, 4 participants (13%) selected community and environmental impacts, and 3 participants (9%) opted for maximizing condition preservation and safety as the highest priority. The average weight of each objective and criterion is estimated to represent the weights of these decision elements as shown in Table 2.

Insert Table 2: Weights based on results of Part 1 of the survey

The second part of the questionnaire survey was designed to extract expert judgments required to develop the utility functions as per the procedure described in the previous section. For each attribute, the respondents were requested to provide the attribute value that represented the least and most desirable values. The least desirable value was assigned as the lowest value of the attribute and the most desirable value was assigned as the highest value of the attribute. Subsequently, the respondents were requested to provide the attribute values with relatively *weak* and *demonstrated* importance compared to the least desirable value. Using the average value of expert judgments, reciprocal matrices were developed and utility functions were derived. The definitions of the used relative importance terms such as *weak* and *demonstrated* are based on the standard scale of relative importance developed and validated by Saaty (1980). These definitions were provided with the questionnaire survey form. Figure 4 shows the utility function of the different attributes developed based on the results of the questionnaire survey.

Insert Figure 4: Developed utility functions of the selected attributes

The collected results were tested to check the values' reliability using Cronbach's α test to estimate the reliability of the questionnaire results. This index has a range from 0 to 1, where values close to 1 reflect consistent and reliable results (Wei et al., 2007). The reliability test was performed with the aid of Microsoft Excel calculator to estimate the Cronbach's α values for the different attributes. The obtained Cronbach's α factors proved that the results collected through the survey were consistent and reliable. The factors are provided in Table 3.

Insert Table 3: Results of the reliability test of the survey

6. AHP-MAUT method implementation and analysis

To demonstrate the proposed method, a case study of a pavement network with 10 pavement sections is used. The 10 sections and their parameters are extracted from the LTPP database and listed in Table 4.

Insert Table 4: Data of the 10 pavement sections used in the case study directly extracted from the LTPP database

Specific attributes are directly extracted from the LTPP database. The values of these attributes can be directly input into their specific utility functions (Figure 4) to assess the utility points corresponding to each attribute value. These direct attributes are cumulative ESAL, functional classification, IRI, and FN. Other attributes that are not directly provided in the LTPP are noise level, CO_2 emission, and SCI. However, these attributes can be assessed using the models discussed in Section 4.1.3, 4.1.4, and 4.1.5, respectively. Equations 1, 2, and 3 are used to assess these three attributes based on data available in the LTPP database. Subsequently, the estimated attribute values are input into the corresponding utility functions to estimate the utility points. The directly extracted and estimated attributes along with each attribute's utility point are shown in Table 5. Once all the utility points are estimated, they can be aggregated into an overall utility score using the additive utility model given by Equation 5. The weights of the criteria and the objectives are estimated based on the questionnaire survey results. The estimated overall utility of each section is shown at the bottom of Table 5. As an illustration of estimating the overall utility using the additive utility model, following is the detailed calculation for Section 1. Similar calculations are performed for the remaining nine sections.

Overall utility of Section 1 = ((34.37 × 0.77) + (100.00 × 0.23)) × 0.61 + ((95.1 × 0.72) + (35.2 × 0.28)) × 0.28 + ((43.40 × 0.58) + (37.7 × 0.28) + (71.4 × 0.14)) × 0.11 = 57

Insert Table 5: Estimated utility value for each attribute and overall utility of each pavement section

Based on the results shown in Table 5, Section 3 has the highest priority, with a total utility of 78, and Sections 7 and 10 have the lowest utility of 38. Section 3 received the highest utility points in terms of ESAL and relatively high utility points on the remaining attributes. Although Section 10 is a principal arterial, it received relatively low utility points in terms of ESAL and other criterion, which clearly indicates that this section has not received its capacity and thus does not require immediate attention compared to the other sections. As a result, this section received the lowest priority among the 10 sections. The 10 sections can be ranked using the overall utility values. Among the 10 analyzed sections, Sections 4 and 9 attained the highest utility points on the CO_2 emission rating, with utility scores of 66.1 and 61.9, respectively. In terms of noise pollution, the results provided by the experts indicated that the maximum allowed noise level is 63 dBA, and any section with noise levels beyond this value must be assigned the full utility value of 100 on the noise pollution criterion. The method has captured this significant impact with respect to social and environmental aspects and prioritized Section 4 for the necessary intervention. Meanwhile, Section 7 attained the lowest utility points on the CO_2 emission and sound pollution attributes. In terms of ESAL and the other attributes, it also received relatively low utility points. As a result, its impact was low and received the lowest utility.

Thus, this analysis demonstrated that the proposed method is capable of capturing several attributes that reflect the important criteria, especially criteria related to sustainability, and prioritizing sections with the highest impact. Simultaneously, the method assigned less priority to sections with relatively lower impact on society and environment. It is important to study the sensitivity of the proposed method.

6.1 Sensitivity analysis

The purpose of sensitivity analysis is to aid the understanding of the extent to which a change in the decision factors may influence the outcomes related to a decision. The topic of sensitivity analysis has been prominently covered in literature. Insua and French (1991) discussed the application of sensitivity analysis in multi-objective decision-making problems and scrutinized prior work in the field of sensitivity analysis. Butler et al. (2001) examined a ranking and selection criteria to contrast various systems with numerous performance measures. More information and details on sensitivity analysis can be found in the works of Dyer et al. (1998) and Jiménez et al. (2003).

In this research, sensitivity analysis is used to determine variations in the ranking of the pavement sections as a function of the utility values fluctuating within some sensible range and test the robustness of the optimal solution. Based on the results generated by the AHP-MAUT integrated method, the rank of the 10 sections has been identified mainly based on the expert judgments used in building the utility functions. However, it is necessary to carry out sensitivity analysis to examine the robustness of the results. Two types of sensitivity analysis were conducted. One was performed to study the sensitivity of all attributes concurrently, and the second was performed to study the sensitivity of individual attributes. The first approach was based on the concurrent alterations of all the attributes simultaneously and performed by applying Monte Carlo simulations to assess different combinations of attributes at different levels defined within specific boundaries from the assigned attribute values. With the aid of Microsoft Excel, 10 runs of Monte Carlo simulation were performed, during which values of the different attributes were randomly generated from the range of plus and minus 10% of the attribute's value. The average overall utility of each section was estimated in each run using the generated attribute values and attribute weights. The average overall utility of the 10 runs were estimated and compared to the original utility values as shown in Table 6.

Insert Table 6: Simulation results of the utilities

In general, slight impact on the overall utility has been identified as shown in the percentage change presented in Table 6. In terms of ranking, only Sections 2 and 8 switched positions after the 10 runs of simulation. This can be attributed to the fact that Sections 2 and 8 originally had very close overall utility values of 66.58 and 65.38, respectively. When the simulation was performed, the average overall utility of these sections changed to 65.90 and 66.10, giving very small preference to Section 8 compared to that given to Section 2.

To analyze the results of each simulation, the overall utility obtained for each section from each run of the simulation is prepared in graphical format, as shown in Figure 5. It is clear from the figure that the 10 sections can be clustered into 5 levels of priorities. The first level has the highest priority and consists of Sections 3 and 4. They exchange the highest priority and the second highest over the 10 runs of simulation. The second cluster consists of Sections 2, 8, and 6 at the second level of priority. The third cluster includes Section 1 and 9, while the fourth cluster includes Section 5 only. At the lowest level of priority, Sections 7 and 10 received close values of overall utility over the 10 runs of simulation, as can be seen in Figure 5.

Insert Figure 5: Results of the 10 simulation runs

In the second type of sensitivity analysis, each attribute was analyzed individually to assess its sensitivity. Two sets of simulations were carried out. One was performed by generating random attribute values from the range between the original attribute and an increment of 10 %, while the second was performed by generating random values from the range between the original attribute value and a reduction of 10%. These random values were used to estimate an average overall utility for the section. Then, a percentage of change in overall utility value was calculated to assess impact of varying the attribute as provided in Table 7. For example, in the case of ESAL for Section 1, random values were generated between its original utility value of 34.37 and 10% increment, i.e., 37.81. The average overall utility for Section 1 was subsequently calculated by varying ESAL during the 10 runs of the simulation, while retaining the original utilities of the other parameters. The generated average overall utility is subsequently compared to the original overall utility value. Similar analysis is carried out for 10% reduction of the utility to perform the sensitivity analysis. The same analysis is repeated on all pavement sections in the case study. From the analysis results, it is evident that noise level is the most sensitive parameter followed closely by ESAL, whereas IRI is the least sensitive parameter.

Insert Table 7: Attribute sensitivity based on 10% increment

7. Summary and conclusions

Decision problems that entail several objectives and need to satisfy multiple criteria, such as the pavement management problem, are complex in nature. MCDA is a decision support tool, which can consider several criteria and factors and enable quantitative assessment of the decision variables by combining the level of attainment of several criteria into one overall evaluation. It is especially beneficial in incorporating multiple criteria and evaluating the trade-off between these decision criteria. The MCDA has gained acceptance in the area of civil infrastructure management in general and pavement management in particular. The main challenge in applying MCDA is defining and quantifying decision criteria, objectives, and their weights while incorporating the decision maker's judgment and experience in the process.

This research presents a network-level framework for ranking and prioritizing pavement sections with special focus on sustainability-related criteria. The framework includes all the decision parameters required to rank a network of pavement sections and provides flexibility to the decision maker to adjust these parameters. The embedded methods within the framework are based on AHP and MAUT principles utilized to rank any-size network of pavement sections in a systematic way. The methods benefit from the intuitive judgment extraction of the AHP through pairwise comparisons to develop a representative set of utility functions. These functions are used to quantify levels of attainment on the different criteria based on the attribute values of each pavement section. This eliminates the limitation on the number of alternatives that can be ranked and prioritized. The ranking and prioritizing decision-making process is analyzed by breaking the decision problem into a five-level hierarchy structure, which facilitates identifying the main decision parameters: objectives, criteria, and decision attributes. A set of representative attributes are selected, and models from the literature are integrated within the developed framework to quantify these attributes. A representative set of utility functions are developed based on the results of a questionnaire survey. These utility functions reflect the decision maker's degree of satisfaction at different levels of attainment of the different decision attributes and criteria. The utility functions are applied to any number of pavement sections to assess their utilities in a systematic way. The additive utility model is used to aggregate the different utilities into one overall utility value, which is used to rank and prioritize pavement sections for intervention.

The framework includes all the decision parameters required for ranking and prioritizing pavement sections in a network. These parameters are identified based on a comprehensive literature review and assessed based on the results of a questionnaire survey distributed among experts and practitioners in pavement management. The results of the questionnaire survey are used to estimate the relative importance of the different decision elements and their weights. The survey results indicate that high priority should be given to important pavement sections with high traffic volume. The estimated weight of prioritizing an important section is 0.61, while the weight of community and environmental impact is 0.28. The proposed ranking method provides flexibility in terms of using the decision parameters estimated from the survey as embedded in the framework or if required, adjusting them based on specific requirements of the DOT.

The proposed method is demonstrated with a case study using the LTPP database. Sensitivity analysis was performed to evaluate the results under varying conditions and scenarios. The analysis produced clusters of pavement sections with close priorities, which facilitated management and decision-making regarding maintenance priorities and fund allocation. The results show the potential of the proposed method in assessing pavement section priority and benefitting practitioners and managers. The method can facilitate the complex process of prioritizing the most deserving pavement sections for maintenance and improvement programs while incorporating multiple criteria.

The proposed framework attempted to identify generally accepted decision objectives and criteria related to pavement management, which can incorporate globally emerging sustainability requirements. Direct agency cost related to maintenance and rehabilitation is not included in the framework to maintain the focus on ranking and prioritizing the network based on sustainability-related criteria. The next stage of the decision-making process can focus on the highest priority sections identified by the proposed framework, estimate their direct cost, and optimize budget allocation. Hence, a natural extension of the current work is by applying cost optimization techniques to distribute limited budget over the identified highest priority pavement section. Future work can further review the decision objectives and criteria and study if additional decision elements need to be incorporated in the decision-making process. The performance of the proposed ranking method can be assessed using data extracted from different pavement networks other than the LTPP database. Moreover, the proposed method can be evaluated with different types of civil infrastructure assets such as underground utility networks by identifying relevant attributes to the new application area and assessing the performance of the ranking and prioritizing process.

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Table 1: Summarized literature review of the application of MCDA in pavement management

Publication	Application	MCDM Method(s) Applied	Criteria	Type	Finding(s)	Limitation(s)
Torres-Machí et al., (2015)	Sustainable pavement management	Cost-Effectiveness, WS, MA, and AHP	Technical (effectiveness), Economic (total cost), and Environmental (emissions)	Network level	AHP, WS and MA approach resulted in consistent rankings. AHP is advantageous for establishing priorities on the basis of paired comparisons among the criteria.	Pair comparison and the calculation of AHP matrices become difficult when the number of criteria and alternatives under evaluation is large. WS is recommended in such a scenario
Chong & Wang, (2016)	Pavement design and management decisions	ME-PDG, LCA, regression model	Energy consumption and GHG emissions	Project Level	Well suited to analyze the quantitative relationships between major pavement decisions and environmental impacts	Traffic volume could be considered as a continuous variable instead of a discrete variable. The impacts of asphalt mixture types on pavement performance and life cycle environmental impacts could be incorporated. Only one type of maintenance technique (resurfacing) is considered.
Babashamsi et al. (2016)	Pavement maintenance activities	Fuzzy AHP with the VIKOR method	PCI, traffic congestion, pavement width, improvement and maintenance costs, and the time required to operate	Network level	PCI is the most important criterion for experts, followed by operational time, traffic congestion, operational cost and pavement width.	It is suitable for situations in which the decision maker wants to achieve maximum profit and the risk of the decision is less important
Santos et al., (2017)	Sustainable pavement management	Pareto optimality, LCC-LCA, augmented weighted Tchebycheff method	Performance, LCC and LCA	Project Level	Efficient in the incorporation of environmental and road user-related considerations in the sustainable decision-making process of pavement management. Simultaneously accounts for several lifetime metrics of sustainability, while also providing the possibility of visualizing, and thereby understanding more deeply their relationships and eventual trade-offs	Decision level considered only for the project level. Computational limitations associated with solving MaOO problems
Lee & Madanat, (2016)	Pavement management	Computationally efficient bottom-up solution algorithm built on Lagrangian Relaxation and Dynamic Programming	GHG emissions	Project Level	Possibility of reduction in GHG emissions by 20% through increasing the total budget by 35% on the Pareto frontier	Do not account for functional or economic interdependence among pavement segments in networks.
Khiavi & Mohammadi, (2018)	Pavement management system	NSGA-II	Economic	Network level	Less weight was assigned to the agency costs objective function; NSGA-II algorithm is has the ability to solve complex nonlinear optimization problems.	Focus on economic criteria only

Ouma et al. (2015)	Pavement Maintenance Prioritization	Comparison of Fuzzy AHP and Fuzzy TOPSIS	Road safety, pavement surface preservation, road operational status and standards, and road aesthetics	Not mentioned	Fuzzy TOPSIS performed slightly better than fuzzy AHP. The fuzzy AHP tended to overestimate the prioritization ranking process.	Automated distress surveys and measurements should be considered. Developments on pavement maintenance prioritization approach that can enable decision makers to quantify and minimize the total risk due to canceling or deferring maintenance functions during budget cuts should also be considered in the prioritization process.
Marcelino et al. (2019)	Pavement maintenance and rehabilitation prioritization	MACBETH approach	Average annual daily traffic, friction coefficient, quality index, number of maintenance and rehabilitations interventions in the last 10 years	Network level	Prioritization of interventions according to the maximization of the benefit/cost relationship results in greater benefit than the prioritization according only to the benefit.	Process described in this work is limited to network-level decisions, in which project-level inputs are provided.

where AHP - Analytic Heirarchy Process, WS - Weighting-Sum, MA - Multi-Attribute, ME-PDG - Mechanistic-Empirical Pavement Design Guide, LCA - Life Cycle Assessment, LCC - Life Cycle Cost, GHG - GreenHouse Gas, PCI - Pavement Condition Index, MaOO - Many-Objective Optimization, TOPSIS - The Technique for Order of Preference by Similarity to Ideal Solution, MACBETH - Measuring Attractiveness Through Categorical-based Evaluation Technique, NSGA - Nondominated Sorting Genetic Algorithm

Table 2: Weights based on results of Part 1 of the survey

Objectives	Objective weight	Criteria measuring the objective	Criteria weight	Number of respondents considered the criterion as the highest priority
1. Prioritize important sections	0.61	1. Traffic volume	0.77	23
		2. Load classification	0.23	9
2. Incorporate community and environmental impacts	0.28	1. Community impact	0.72	19
		2. Environmental Impact	0.28	13
3. Prioritize sections with deteriorated conditions and reduced performance	0.11	1. Structural condition	0.58	18
		2. Safety	0.28	9
		3. Surface condition	0.14	5

Table 3: Results of the reliability test of the survey

Attribute	Cronbach’s α	Reliability
ESAL	0.786	High
Functional classification	0.871	High
Traffic noise	0.767	High
CO_2 Emission	0.728	High
Structural Capacity Index	0.835	High
Friction Number	0.814	High
International Roughness Index	0.878	High

Table 4: Data of the 10 pavement sections used in the case study directly extracted from the LTPP database

Section Number	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9	Section 10
	16-1021	18-2009	23-1012	32-7000	17-1003	20-0902	26-1001	29-1005	35-1022	53-1501
Pavement Age (Years)	5	15	13	18	4	7	19	25	8	9
Functional Classification	Principal Arterial	Minor Arterial	Principal Arterial	Principal Arterial	Principal Arterial	Principal Arterial	Minor Arterial	Principal Arterial	Principal Arterial	Principal Arterial
Cumulative ESAL (millions)	1.22	4.68	7.89	5.86	0.20	2.04	0.32	3.13	0.52	0.14
Average Daily Traffic	3,912	5,657	13,428	1,883	2,900	2,503	850	5,508	3,634	421
Design Speed (mph)	70	60	70	70	70	70	60	70	70	70
Average Daily Truck Traffic	532	521	1530	759	212	757	40	688	909	42
Percentage of Heavy Tuck (%)	13.60	9.21	11.39	40.31	7.31	30.24	4.71	12.49	25.01	9.98
IRI (in/mile)	79.0	144.2	49.8	73.5	59.7	62.2	66.6	50.4	48.5	64.0
Friction Number	51.00	42.00	43.00	55.00	50.00	43.50	56.00	40.00	41.00	55.00
Speed at Friction Number (mph)	63	64	64	64	64	64	64	64	64	64
Total Pavement Thickness, (in)	11.20	25.50	52.30	15.20	24.20	17.00	13.10	12.80	16.90	16.41
Thickness of Asphalt Layer (in)	5.90	2.90	1.30	3.90	1.30	1.80	2.20	1.00	5.50	4.30
Subgrade Resilient Modulus (psi)	9,534	5,667	5,053	4,500	2,728	4,579	3,929	5,227	3,538	31,069
Longitudinal Grades (%)	1.50	2.00	1.00	2.50	2.00	1.00	1.40	1.50	2.10	3.20
Pavement Surface Temperature (ºF)	98.60	86.00	86.00	98.60	86.00	86.00	86.00	86.00	95.00	86.00
FWD Load (lb)	5,966	5,593	16,067	10,770	16,605	6,493	5,944	5,911	12,360	6,076

D_0 at Surface Temperature (in)	0.00602	0.00665	0.01472	0.01201	0.00941	0.00449	0.01161	0.00602	0.01634	0.01539
Deflection at 12 (in)	0.00264	0.00390	0.00886	0.00709	0.00780	0.00303	0.00524	0.00406	0.01213	0.00913
Deflection at 18 (in)	0.00165	0.00295	0.00685	0.00421	0.00705	0.00248	0.00346	0.00307	0.00957	0.00598
Deflection at 24 (in)	0.00110	0.00224	0.00531	0.00319	0.00642	0.00205	0.00252	0.00240	0.00760	0.00374
Deflection at 36 (in)	0.00067	0.00146	0.00315	0.00165	0.00504	0.00146	0.00157	0.00209	0.00472	0.00197
Deflection at 60 (in)	0.00043	0.00063	0.00122	0.00087	0.00327	0.00094	0.00091	0.00110	0.00213	0.00067

Table 5: Estimated utility value for each attribute and overall utility of each pavement section

Section Identifier	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9	Section 10
	16-1021	18-2009	23-1012	32-7000	17-1003	20-0902	26-1001	29-1005	35-1022	53-1501
Cumulative ESAL(millions)	1.22	4.68	7.89	5.86	0.20	2.04	0.32	3.13	0.52	0.14
Utility Value	34.37	57.48	77.88	65.36	14.07	39.86	16.78	47.17	21.21	12.73
Functional Classification	Principal Arterial	Minor Arterial	Principal Arterial	Principal Arterial	Principal Arterial	Principal Arterial	Minor Arterial	Principal Arterial	Principal Arterial	Principal Arterial
Utility Value	100.00	77.77	100.00	100.00	100.00	100.00	77.77	100.00	100.00	100.00
IRI (in/mile)	79.0	144.2	49.8	73.5	59.7	62.2	66.6	50.4	48.5	64.0
Utility Value	30.8	71.4	16.4	28.1	21.3	22.5	24.7	16.7	15.7	23.4
Friction Number	51.0	42.0	43.0	55.0	50.0	43.5	56.0	40.0	41.0	55.0
Utility Value	37.7	67.0	63.7	27.7	41.0	62.1	25.5	73.5	70.2	27.7
Noise Level, L50 (dBA)	81.3	79.8	85.8	88.8	77.5	86.0	69.7	82.3	85.5	70.1
Utility Value	95.1	90.7	100.0	100.0	83.9	100.0	57.5	98.1	100.0	59.0
Temperature Correction Factor	1.25	1.25	1.25	1.22	1.24	1.24	1.24	1.24	1.26	1.28
Corrected D_0 at 68 ºF	0.00751	0.00834	0.01846	0.01463	0.01164	0.00555	0.01441	0.00745	0.02054	0.01967
$r_x = 1.5 \times Hp$ (in)	16.80	38.25	78.45	22.80	36.30	25.50	19.65	19.20	25.35	24.61
M_R (psi)	19,980	12,785	18,965	17,826	7,312	9,946	9,406	7,739	8,356	13,059
SN_{eff}	2.07	4.46	4.81	2.72	6.63	4.25	1.96	2.71	3.05	2.08
SN_{Des}	3.30	6.10	5.70	3.20	7.20	5.60	1.60	4.10	4.20	2.80
SCI	0.63	0.73	0.84	0.85	0.92	0.76	1.23	0.66	0.73	0.74
Utility Value	43.4	55.7	68.9	69.7	77.8	58.9	89.8	47.4	55.2	57.0
V	-0.235	0.463	3.571	-1.047	-0.640	-0.799	-1.460	0.403	-0.346	-1.632
S	1.0	0.6	1.0	1.0	1.0	1.0	0.6	1.0	1.0	1.0

T	0.8	0.2	0.5	4.4	0.0	3.0	-0.4	0.7	2.3	0.3
G	-0.4	-0.2	-0.6	0.0	-0.2	-0.6	-0.4	-0.4	-0.2	0.3
CO_2 (kg/mile)	31,172	39,427	7,159	53,245	19,065	33,889	6,338	41,213	50,192	8,031
Utility Value	35.2	46.8	13.1	66.1	23.7	39.0	12.4	49.3	61.9	13.9
ESAL+ROAD CLASSIFICA-TION	49.5	62.1	83.0	73.3	33.8	53.7	30.8	59.3	39.3	32.8
NOISE INTENSITY +CO_2 EMMISION	78.3	78.4	75.7	90.5	67.1	82.9	44.9	84.4	89.3	46.4
SCI+FN+IRI	40.1	61.0	60.1	52.1	59.6	54.7	62.7	50.4	53.9	44.1
Overall Utility	**57**	**67**	**78**	**76**	**46**	**62**	**38**	**65**	**55**	**38**

Table 6: Simulation results of the utilities

Section	Overall Utility	Simulation Results			
		Minimum Utility	Average Utility	Maximum Utility	% Change
1	56.51	55.57	57.40	59.51	0.71
2	66.58	62.21	65.90	69.30	-1.65
3	78.41	74.85	77.32	81.90	-0.87
4	75.80	72.23	75.83	80.03	-0.23
5	45.97	44.23	45.70	46.99	-0.65
6	61.99	58.14	61.87	65.63	-0.21
7	38.26	36.79	38.38	39.75	1.01
8	65.38	62.67	66.10	69.29	1.70
9	54.93	53.23	54.72	55.78	-0.51
10	37.84	36.12	37.61	39.18	-1.03

Table 7: Attribute sensitivity based on 10% increment

Section No.		1	2	3	4	5	6	7	8	9	10	
Original Utilities		57	67	78	76	46	62	38	65	55	38	
Varying ESAL	Simulated Overall Utilities	57.47	68.21	80.37	77.74	46.29	62.98	38.66	66.23	55.31	38.10	
	% Change	1.71	2.46	2.50	2.55	0.69	1.59	1.04	1.31	0.69	0.70	Average = 1.52
Varying IRI	Simulated Overall Utilities	56.53	66.63	78.42	75.83	45.98	62.01	38.27	65.39	54.94	37.87	
	% Change	0.04	0.08	0.01	0.04	0.02	0.03	0.04	0.02	0.03	0.09	Average = 0.04
Varying Fricti-on No.	Simulated Overall Utilities	56.58	66.68	78.51	75.84	46.03	62.08	38.30	65.51	55.02	37.88	
	% Change	0.12	0.16	0.13	0.05	0.12	0.14	0.10	0.20	0.16	0.12	Average = 0.13
Varying Noise Level	Simulated Overall Utilities	57.18	67.55	79.35	77.06	46.72	63.13	38.86	66.40	55.74	38.64	
	% Change	1.19	1.46	1.19	1.66	1.63	1.84	1.58	1.57	1.48	2.12	Average = 1.57
Varying SCI	Simulated Overall Utilities	56.63	66.78	78.61	76.04	46.25	62.18	38.57	65.53	55.12	38.02	
	% Change	0.22	0.30	0.25	0.31	0.61	0.30	0.82	0.24	0.35	0.48	Average = 0.39
Varying CO_2	Simulated Overall Utilities	56.77	66.76	78.48	76.32	46.15	62.15	38.35	65.75	55.37	37.88	
	% Change	0.46	0.28	0.08	0.68	0.38	0.26	0.23	0.58	0.79	0.12	Average = 0.39

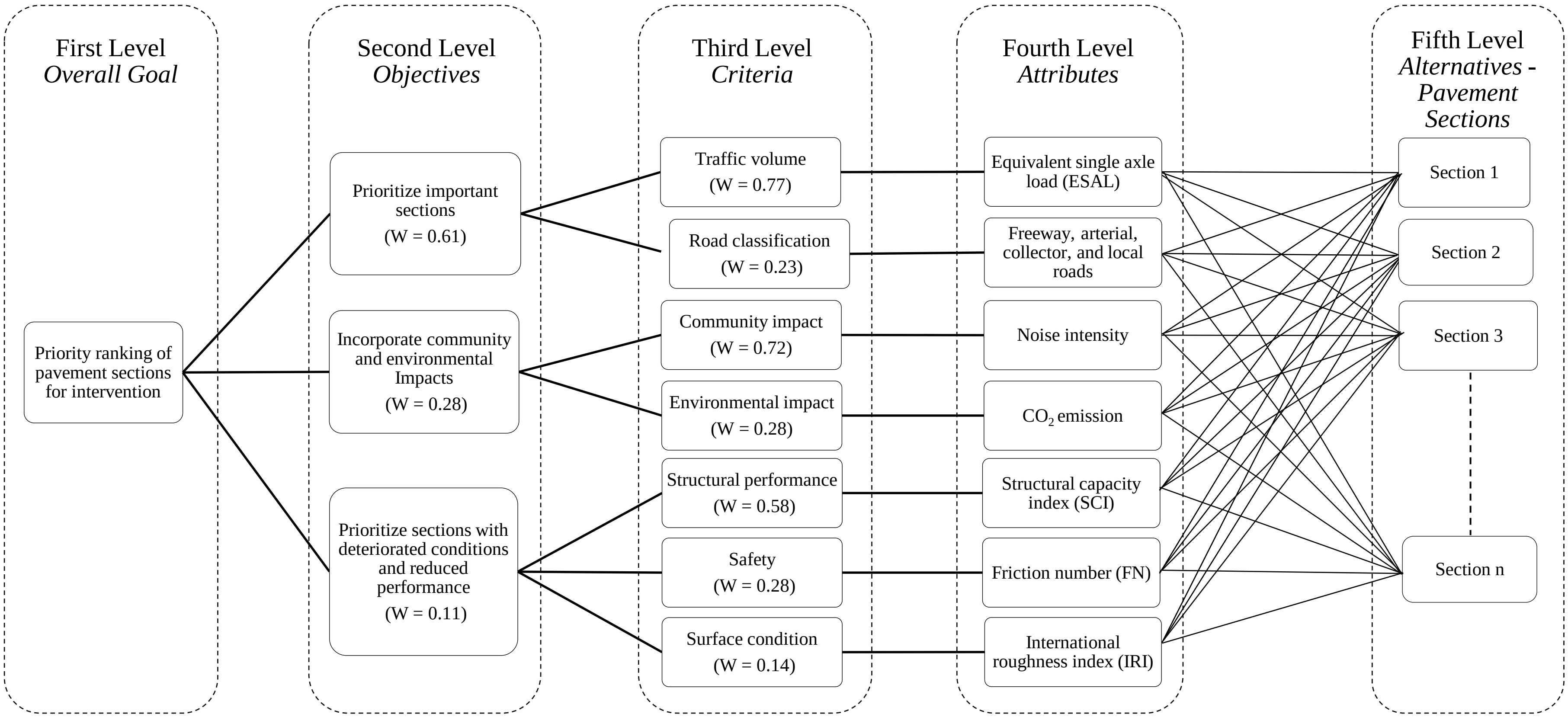

Figure 1: Breakdown structure for pavement network ranking problem.

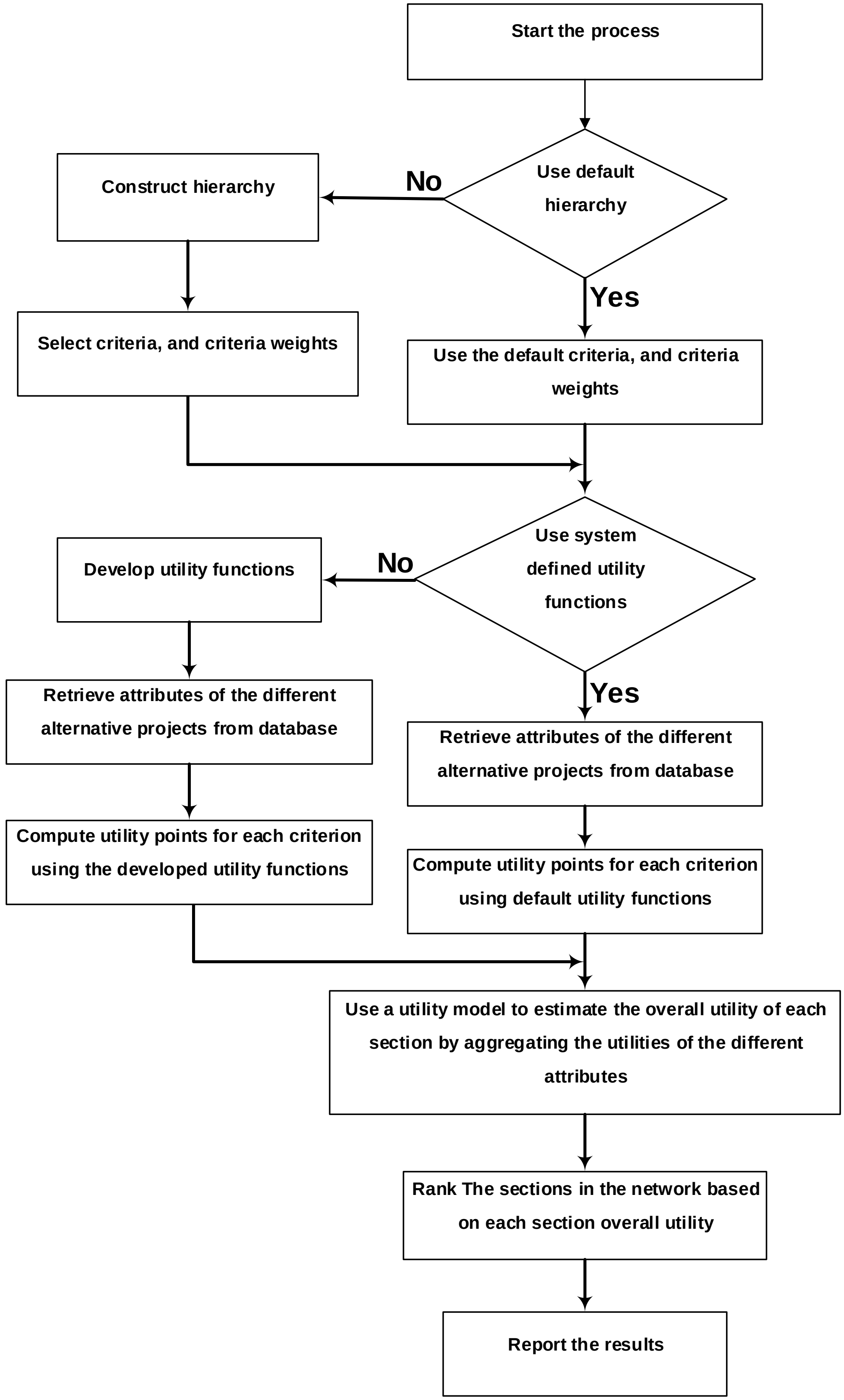

Figure 2: Flowchart for the developed ranking method.

a)

		ESAL				**Eigen-vector**	**Utility Point**
		0.01	0.3	3	30		
ESAL	0.01	1	1/3	1/7	1/9	0.05	11.11
	0.3	3	1	3/7	3/9	0.15	33.33
	3	7	7/3	1	7/9	0.35	77.77
	30	9	3	9/7	1	0.45	100

b)

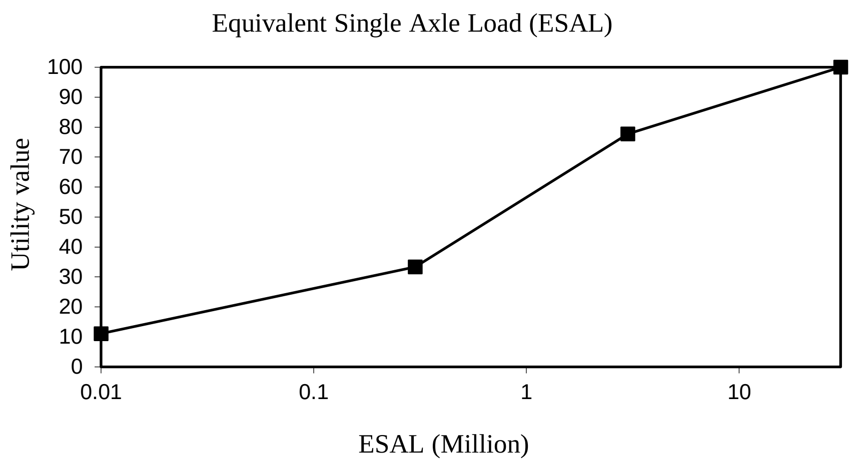

Figure 3: a) Pairwise comparison matrix, eigenvector, and utility points. b) Developed utility function

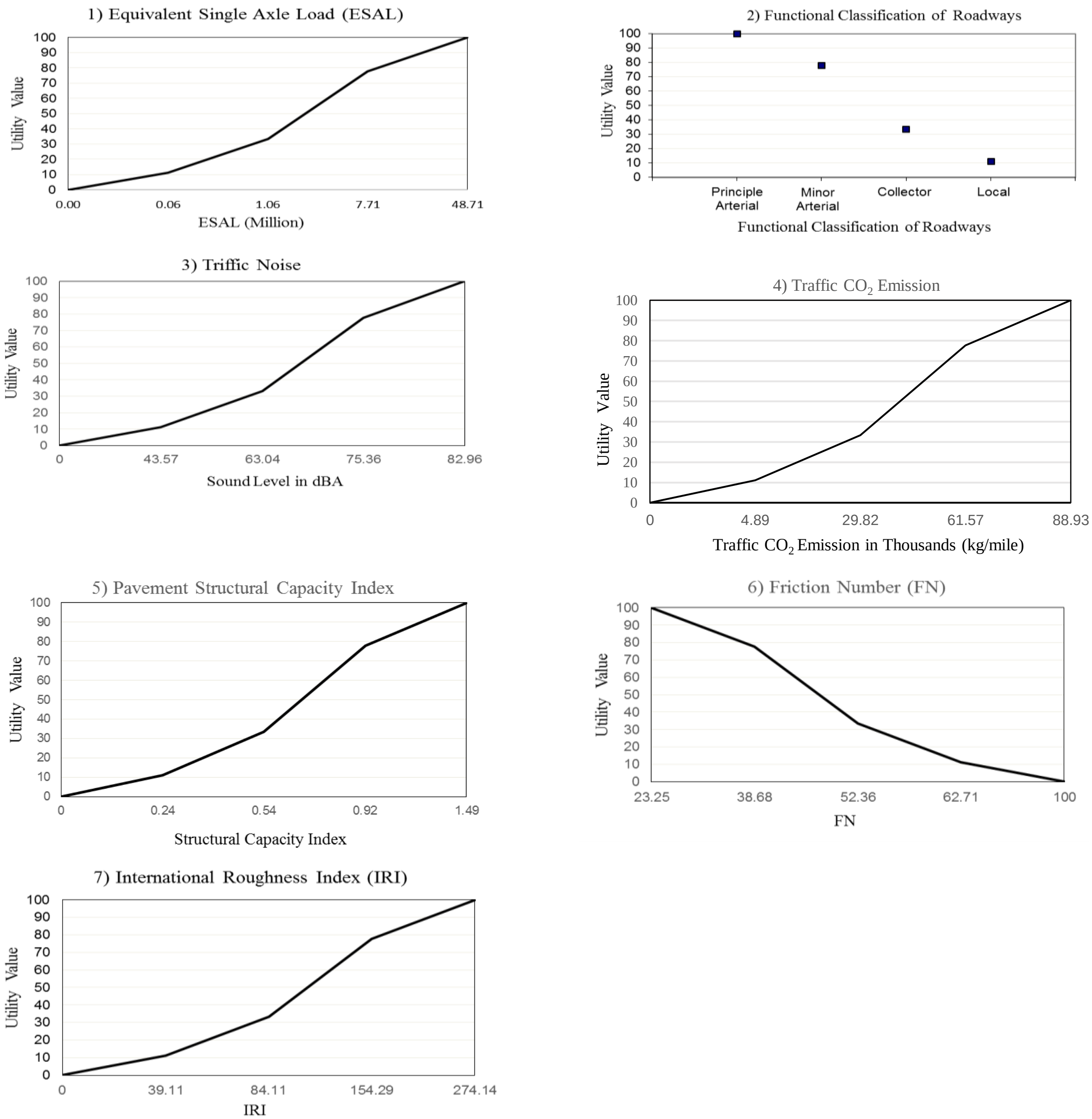

Figure 4: Developed utility functions of the selected attributes.

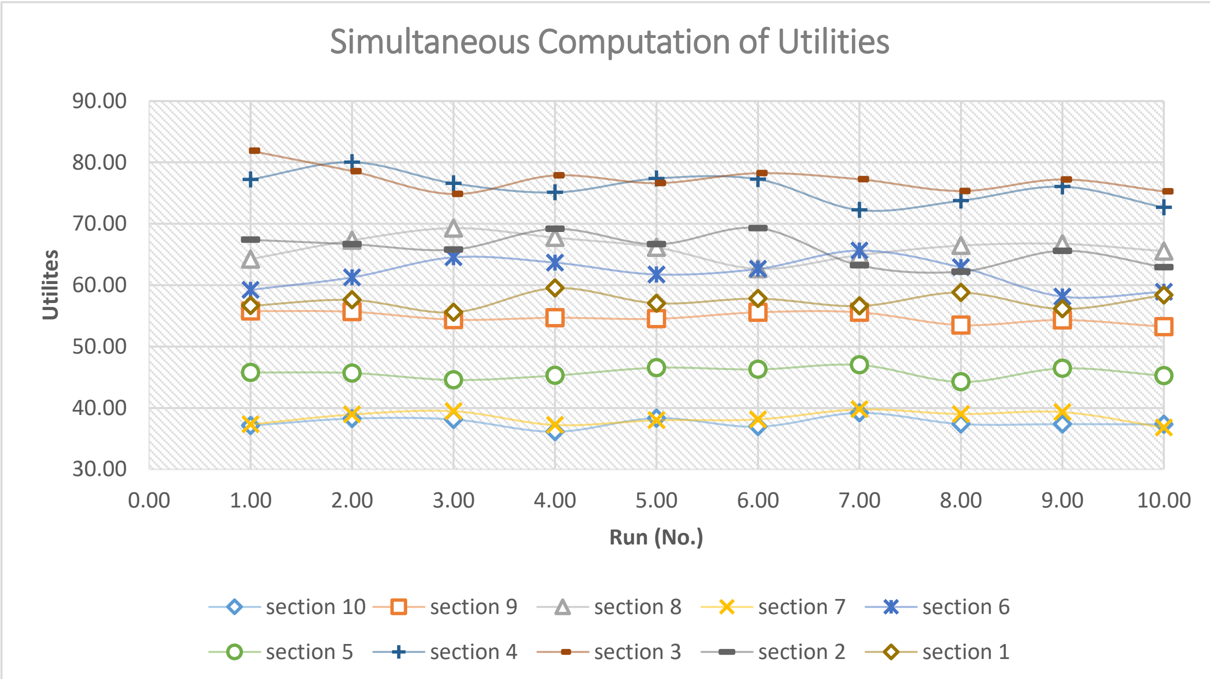

Figure 5: Results of the 10 simulation runs.