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16. Abstract


The Texas Department of Transportation has been experiencing maintenance budget fluctuations recently. The budget shortage has a negative impact on the agency's maintenance strategies and results in the undesirable deterioration of highway conditions, increasing the risk for both road users and the agency. This project aims to develop a methodology to minimize the impact of budget fluctuation by quantifying the risk of not performing a maintenance activity and identifying the priority of maintenance activities based on the quantified risk.

With the help of maintenance experts from TxDOT, 4 maintenance objectives and 16 maintenance function groups were identified and a hierarchy structure was developed based on the objectives and function groups. Four pilot districts were selected to represent the different demographic and climatic regions in Texas and maintenance experts were selected from the four districts to participate in the workshop. The overall relative weights of the 16 maintenance function groups were determined based on the individual evaluator's judgments using the Analytical Hierarchy Process. To determine whether the 4 pilot districts varied in assigning relative importance to the 4 defined objectives and priority to the 16 maintenance groups, statistical analyses were conducted with the 4 sets of values, 1 for each of the 4 pilot districts, using Kruskal-Wallis test.

Lastly, a web-based prototype system was developed to assist users in generating the list of maintenance projects under budget constraints. Exposure factors, ADT, and truck volume were applied in the system to factor in the impact of traffic on the maintenance strategy. Users of this system can choose to use the weights and parameter values from the pilot district that they think is most comparable to their own district, or use the state average values that have proved to be applicable to all the districts in Texas.


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# An AHP-based Approach to Prioritizing Resources for Highway Routine Maintenance

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Toribio Garza, Jr., P.E., Director, MNT (Retired)
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Ted Moore, P.E., Director of Maintenance, LBB
Karl Bednarz, P.E., Director of Operations, SJT
Joseph Lindsey, Maint. Crew Chief, ELP
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# Chapter 1: Introduction

The Texas Department of Transportation (TxDOT) is responsible for maintaining over 190,000 lane miles of highways. This highway network is as vast and diverse as Texas itself. It covers the whole spectrum in terms of traffic and ranges from rural two-lane highways carrying a few hundred vehicles per day to major interstate eight-lane highways carrying well over 200,000 ADT (Average Daily Traffic) [1]. This highway network represents a monumental investment in infrastructure that is vital to the safety, well-being, and economic prosperity of all Texans.

TxDOT is not only obligated to preserve the pavements in good condition—it must also maintain the roadside and all roadway fixtures in a functional and acceptable condition. These roadside fixtures include signs, barriers, drainage structures, traffic signals, illumination fixtures, and rest areas, just to name a few. This presents a major challenge for the agency as it tries to balance the need between preserving pavements and maintaining non-pavement assets. To add to this already difficult task, the agency has experienced funding fluctuations that can disrupt the timing of scheduled maintenance work resulting in unstable highway conditions. Funding fluctuations occurring over several consecutive years will not only expose motorists to unfavorable conditions, but may also result in highway network condition dropping below the threshold of restoration by routine and preventive maintenance treatments. The cost of deferring certain maintenance treatments can consume a considerable amount of future revenue that could otherwise be dedicated to system improvements. The Federal Highway Administration (FHWA) estimates that every dollar invested in maintenance saves $6 in reconstruction costs [2].

In addition to the higher costs, the demand or strain placed on the highway system will continue to increase as the state's population is projected to surpass 33 million by the year 2030, an increase of almost 60 percent from the year 2000 [3]. This situation has forced TxDOT to look for new and innovative maintenance strategies that are aligned with its needs and requirements. To accomplish this, TxDOT must reevaluate its current method of ranking and prioritizing maintenance needs and projects.

## 1.1 The Need for Highway Maintenance Prioritization

Deferred maintenance activities resulting from budget fluctuations can lead to deteriorated pavement conditions and expose road users to a higher level of risk. As a result, there is a need for methods that can help select the most cost-effective maintenance projects to control and minimize the risk for road users under current budget constraints. By doing so, the agency can select and implement the most cost-effective projects within the budget constraints and revise their maintenance plans to accommodate budget fluctuations.

Analytical Hierarchy Process (AHP) is one of the most commonly used methodologies to evaluate and quantify subjective judgment. This report proposes the use of AHP to quantify the risk of not performing a particular maintenance activity based on the judgment of experienced engineers. A web-based prototype system was developed to demonstrate how the developed method can assist highway agencies in prioritizing maintenance projects based on the results from a workshop and budget constraints.

## 1.2 Importance of Performing Routine Maintenance

During the planning and design stages, highways are developed to incorporate all the necessary safety criteria to ensure safe and comfortable driving under all weather conditions. As these facilities begin to deteriorate under normal use, a good maintenance strategy has been proven to be the most effective tool to ensure that the facilities continue to operate as originally intended and to provide the desired level of service. In addition, a good maintenance strategy will lessen the impacts of deterioration or consumption and extend the service life of the facility, allowing resources that would otherwise be expended to reconstruct or rehabilitate the facility to be used for other purposes.

The FHWA defines routine maintenance as any maintenance activity that “consists of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service” [2]. Perhaps the best way to understand this statement is to explain the limitations of routine maintenance in relation to construction, reconstruction, and other types of maintenance activities. As shown in Table 1, routine maintenance is not designed to increase capacity, increase strength, or even reduce aging; its main purpose is to restore serviceability. This is the only function routine maintenance is designed to accomplish [2].

A good example of a routine maintenance activity is sealing cracks on pavements, commonly referred to as *crack sealing*. This activity does not increase the capacity or strength and does not reduce pavement damage. It does, however, prevent premature pavement damage by preventing moisture infiltration into the pavement structure. Another example is grass mowing. It appears to most people as an aesthetics issue, but if the grass is not mowed for a period of time, animals can hide in the tall grass and may be startled when vehicles approach, causing serious accidents. It can also affect the structure strength of the pavement when the grass roots spread into and damage the pavement structure.

**Table 1: Pavement Preservation Guidelines Pavement Preservation Guidelines**

| Type of Activity | Increase Capacity | Increase Strength | Reduce Aging | Restore Serviceability |
|---|---|---|---|---|
| New Construction | X | X | X | X |
| Reconstruction | X | X | X | X |
| Major (Heavy) Rehabilitation | | X | X | X |
| Structural Overlay | | X | X | X |
| Minor (Light) Rehabilitation | | | X | X |
| Preventive Maintenance | | | X | X |
| Routine Maintenance | | | | X |
| Corrective (Reactive) Maintenance | | | | X |
| Catastrophic Maintenance | | | | X |

# Chapter 2: Literature Review

A thorough literature review was conducted to assess what other state, national, and even international departments of transportation (DOT) or highway agencies are doing to address funding fluctuations. In addition to the state of the practice, a review was conducted of existing methodologies that could be used to prioritize or rank maintenance activities and projects.

## 2.1 Current State of Practice

After conducting an exhaustive literature review on different state, national, and international DOTs or highway agency procedures, it was discovered that budget fluctuations are not unique to TxDOT. However, the methods to address them are quite varied. Similarly to TxDOT, many highway agencies allocate the vast majority of their budgets to pavement preservation and many have adopted asset management principles and techniques to assist with their maintenance operations.

### 2.1.1 Domestic Departments of Transportation

Several state DOTs' current practices of prioritizing maintenance activities and projects were researched, but few had actual adopted guidelines and procedures in place to address this issue. Many simply rely on ad-hoc methods to develop their routine maintenance strategy.

#### *2.1.1.1 Florida Department of Transportation*

The Florida Department of Transportation (FDOT) developed and implemented the Maintenance Rating Program (MRP) in April 1985 as a formal method to make policy decisions on the desired level of service of its highway maintenance program [4]. The previous maintenance strategy used by the agency did not provide the consistency or uniformity in the condition of their highway system that the agency was striving for.

Over the years, these inconsistencies in the maintenance strategy resulted in an overall reduced level of service. The MRP was designed to evaluate the current condition of the highway system and serve as a design support tool for agency administrators to set maintenance goals based on the funding level. Florida's MRP focuses on all areas of highway maintenance including pavement, roadside, traffic services, drainage and vegetation needs.

#### *2.1.1.2 Ohio Department of Transportation*

The Ohio Department of Transportation (ODOT) has divided its highway network into a three-tier system composed of priority, urban, and general. The priority tier is made up of interstate and four lane-divided highways and accounts for 26 percent of the total highway system, but carries 57 percent of total vehicular traffic and 75 percent of total truck traffic. The urban and general tiers make up 12 and 62 percent of the highway network respectively [5].

The ODOT implements an asset management system to help address maintenance needs on the network and has identified eight characteristics of highway maintenance: 1) drainage obstruction, 2) guardrail, 3) litter, 4) pavement marking, 5) pavement deficiency, 6) pavement drop-off, 7) sign deficiencies, and 8) vegetation obstructions. Data is collected on the entire highway network and used to develop maintenance work programs [5].

#### *2.1.1.3 Washington State Department of Transportation (WSDOT)*

The Washington State Department of Transportation (WSDOT) implemented a similar system called Maintenance Accountability Process (MAP). This process is aligned with the department's strategic planning, budget and maintenance service delivery. In essence, MAP provides the necessary tools to evaluate the effectiveness and accountability of the state's maintenance program. The program basically relies on random evaluations of selected sample locations, where field surveys results are compared against established benchmarks and a level of service is determined. This level of service is then plotted and a historic performance trend is obtained [6].

MAP's most important and significant tool is its Priority Matrix. This Priority Matrix ranks the maintenance activities according to their contribution towards the maintenance program objectives. These objectives include the following [6]:

- Safety of traveling public and employees
- Operation of the highway system (Highway System, keeping the road open)
- Meeting environmental responsibilities
- Maintaining the infrastructure
- Addressing legal mandates other than environmental (including torts)
- Contributing to comfort, aesthetics, and or convenience

Each maintenance activity is then assigned a value between 0 and 9 (9 being the highest impact) in terms of its impact on the maintenance objectives identified earlier. A cumulative score is then obtained that essentially becomes the priority value or rank. The maintenance activities are then ranked in the order of descending priority values. The MAP also serves as a communication tool among all the stakeholders. The Washington state government, transportation commission, and taxpaying public are kept informed of the impact of policy and budget decisions on the program service delivery [6].

#### *2.1.1.4 New York State Department of Transportation (NYSDOT)*

The New York State Department of Transportation (NYSDOT) adopted a Maintenance and Operations First Strategy (MOF). The first step of MOF is to obtain a yearly analysis and inventory on existing infrastructure. This information is compiled, and trend lines are plotted against the condition and performance of the infrastructure. This helps identify rapid deterioration levels, triggering maintenance and rehabilitation activities through prioritizing projects. Asset preservation is the top priority on all major trade and intercity corridors [7].

Another benefit obtained from the MOF strategy is development of maintenance activities guidelines. These guidelines allow the department to develop timing intervals for certain maintenance activities, though it is understood that this type of system may not result in the most efficient use of resources [7].

### 2.1.2 International Transportation Agencies

International highway agencies are not immune to the effects of budget fluctuations. In some European countries, highway agencies are conducting research to help identify possible solutions to reduce the impact of budget fluctuations on their highway conditions.

#### *2.1.2.1 Highway Agency*

The United Kingdom's (UK) Highway Agency (HA) is currently conducting research in three methodologies that include 1) Value Management Process, 2) Effective Asset Management, and 3) Risk Assessment Methodologies. The outcomes of these methodologies are unknown since they are in the early research stages.

The Value Management (VM) process aims at establishing a risk approach to prioritizing highway maintenance. Some of its anticipated benefits include the greater transparency and understanding of risks in the prioritization of maintenance schemes. It will assist decision makers in understanding the consequences of funding or not funding certain maintenance works, and it will also allow the HA to assess the value of the benefits obtained by funding specific maintenance programs. Finally, this methodology will unify assessment across diverse asset types.

The Effective Asset Management methodology will implement a whole life costing (WLC) approach to obtain the risk of delayed or deferred maintenance. On the other hand, the Risk Assessment methodology proposes a framework for operational decision making and will establish possible ways of addressing inconsistency in decision making by implementing monetary based multi-criteria analysis (MCA).

#### *2.1.2.2 VICROADS*

VICROADS is responsible for the development, construction, and maintenance of highways for the State of Victoria in Australia. The agency conducts road condition surveys to identify their pavement and resurfacing projects. In addition to the data collection, the agency implements a structural maintenance project that identifies risk as the product of the probability of failure and the consequence of failure. This approach takes into account the importance of the highway in the maintenance strategy decision making process [8].

In terms of its roadside maintenance strategy, the agency has identified three objectives or goals: 1) Safety, 2) Environmental and Cultural Heritage Values, and 3) Amenity and Access. These three goals represent the agency's top priorities for their roadside maintenance strategy [8].

## 2.2 Risk Assessment and Quantification Methodologies

A literature review was made to identify existing methodologies for assessing and quantifying risk. These methodologies ranged from the typical risk assessment process to more sophisticated methodologies such as Probabilistic Approach to Quantifying Risk, Priority Numbers, and the Analytical Hierarchy Process.

### 2.2.1 Risk Assessment Process

The risk assessment process involves implementation of seven key steps:

Step 1) Define Limits and Scope of Analysis

Step 2) Identify Tasks and Hazards

Step 3) Risk Assessment

Step 4) Limit Risk

Step 5) Residual Risk Assessment

Step 6) Decision Making Process

Step 7) Document Results

One of the most important aspects of this method is that the scope of analysis must be defined prior to the analysis being conducted. The tasks must be clearly defined and controlled to prevent them from overwhelming the analysis process. This method can require multiple iterations when the residual risk exceeds the tolerable or acceptable level [9].

### 2.2.2 Probabilistic Approach to Quantifying Risk

The probabilistic approach involves identifying the probability or frequency estimation based on predefined events. For example, Qiang Meng et al. developed a method to estimate work zone crash frequency using this approach. Seven factors were considered for this model: age (A), crash unit (CU), vehicle type (VT), alcohol (AL), light condition (LC), crash type (CT), and severity (S). One disadvantage of this approach is that, for intermediate events, the uncertainty increases and thereby any results obtained become questionable [10].

### 2.2.3 Priority Numbers

Risk priority numbers have been used to quantify risks of different failure modes. For example, Zaifang Zhang et al. used this same methodology to quantify the different failure modes for a drilling machine [11]. This methodology assessed the risk of each alternative in terms of severity, occurrence, and detection. Severity is a measure of the impact of failure. The more severe the impact, the higher the risk will be. Occurrence is a function of the frequency of failure or failure rate. Detection evaluates the likelihood a problem can be identified before the task is completed.

This particular methodology has been widely implemented for its simplicity. Its downside, however, is that it only captures risk as a function of these three criteria, which may lead to underrepresented risk values.

### 2.2.4 Analytical Hierarchy Process (AHP)

AHP has been successfully used in different fields and disciplines. Its ability to handle both qualitative and quantitative data makes AHP an ideal methodology for some prioritization problems. There has been extensive research on prioritization problems using the AHP method.

The fundamental logic of AHP is to decompose a large complex task into smaller, manageable subtasks. In essence, AHP enables users to create different levels or hierarchies depending on the complexity of the problem. Furthermore, the prioritization is based on pairwise comparison assessments. Each pairwise comparison assessment is obtained by comparing two alternatives at a time, and a relative value is assigned to each pair. Using AHP, a priority vector of the alternatives is developed from the synthesis of the pairwise comparisons.

There have been many variations of AHP since it was first used in prioritization. The AHP described earlier is the additive AHP (AAHP), which is the most commonly used. To address the lack of ability to deal with extreme cases, multiplicative AHP (MAHP) was proposed to give a more balanced result. Apart from the traditional 1–9 scale system proposed by Saaty [12], many other scale systems have been developed, such as the inverse linear scale system proposed by Ma and Zheng to address more delicate differences between preferences [13], as well as the power scale system and logarithmic scale system to address non-linear cases.

Because of the many successful applications and its simplicity, the additive AHP was selected as the methodology for this research; AHP is explained in further detail in the following chapter.

# Chapter 3: Expert Work Group

## 3.1 Expert Work Group (EWG) Membership and Experience

The EWG was selected by TxDOT to provide a diverse background and experience in highway maintenance operations. This group is composed of administrative as well as field operations personnel. This expert panel will provide key support and advice to the researchers and will be instrumental to the success of this research project. The EWG is shown in Table 2.

**Table 2: Expert Work Group Membership and Experience**

| Participant | Title | Office/Dist. | Years of Experience in Maintenance | Area of Specialty |
|---|---|---|---|---|
| Tammy Sims, P.E. | Special Program Engineer | MNT | 23 | Management & Operations |
| Pedro R. Alvarez, P.E. | Director of Maintenance | PHR | 4 | Management & Operations |
| Jenny Li, Ph.D | Engineer | CST | 4 | PMIS |
| Billy W. Williams | Maint. Section Supervisor | PAR | 29 | Maintenance |
| Byron Hicks, P.E. | Engineer | MNT | 10 | Management & Operations |
| Ted Moore, P.E. | Director of Maintenance | LBB | 25 | Management & Operations |
| German Claros, P.E., Ph.D | Research Engineer | RTI | 25 | Maintenance & Pavements |
| Karl Bednarz, P.E. | Director of Operations | SJT | 23 | Routine, Preventive and Rehabilitation of Roadways and Bridges |
| Joseph Lindsey | Maint. Crew Chief | ELP | 24 | Budgeting, Inventory, Maint. Contracts, Incident Management |
| Michael Lee, P.E. | Area Engineer | LFK | 3 | Management & Operations |

## 3.2 Identifying Maintenance Objectives

Over the years, TxDOT's maintenance personnel have developed a keen understanding of their maintenance objectives. For this research, four objectives that were identified in cooperation with TxDOT's EWG: 1) Safety, 2) System Preservation, 3) System Operation, and 4)

Aesthetics. It is very important to understand that these four maintenance objectives are not independent of each other and in some cases strong relationships exists among them. For example, potholes on highways are not only an eyesore but can significantly affect the safety of the motorists. Potholes also affect the operational capability of the highway and, if left untreated, will accelerate other types of pavement distress. Therefore, it is the combined effect that these four maintenance objectives have on the overall maintenance strategy that is sought.

Safety is considered one of the most important objectives, and is at the core of virtually every maintenance strategy adopted by TxDOT. It is so important that it is part of the agency's mission statement, which reads in part as *"providing safe, effective and efficient movement of people and goods."* This not only demonstrates TxDOT's continued commitment to safety but also implies a legal responsibility as well.

Not only does TxDOT have a legal responsibility to ensure the safety of the traveling public, but it must also act as a good steward of the public's resources. The over 190,000 lane miles of highways, 50,019 bridges, and numerous roadside facilities represent a significant financial investment that should be maintained and preserved to ensure it meets the current and future needs of all Texans [1]. This vast transportation network is vital to the state's continued and future economic growth.

System preservation is therefore another key objective in TxDOT's overall maintenance strategy. Being able to perform the required routine, preventive, and rehabilitation activities at the appropriate intervals not only restores and or preserves the functional capability of the facility, but also reduces the overall cost of maintaining the highway network. Studies indicate that every dollar invested in routine and preventive maintenance saves $6 in rehabilitation costs [2].

System operation is yet another key objective identified by the EWG and can be defined as a measure of how well the system is meeting its intended purpose. For example, a high speed highway segment may be structurally sufficient with little evidence of distress, but may have a poor ride quality that prevents motorists from traveling through this section of highway at the posted speed limits. Because motorists are not able to safely traverse the highway at the posted speed limit, this highway does not meet its intended purpose and therefore provides a reduced operational level of service. Another example could be a bridge that has not been properly maintained and, as a result, is no longer capable of supporting its original design load. Both of these examples demonstrate that not performing the required maintenance treatments can downgrade a facility's operational capabilities or level of service.

Aesthetics is also considered an important objective for the department and therefore merits consideration in this research project. Aesthetics provides a "first impression" of the highway condition to the traveling public and this first impression is what most people will use to judge the effectiveness of the agency's maintenance strategy. Texans have come to expect a high level of service from their transportation system; aesthetics is a big part of satisfying that expectation.

## 3.3 Selecting the Most Relevant Maintenance Functions

TxDOT has over 120 different maintenance activities that are further grouped into 5 categories based on the type of function they serve: 1) Pavement, 2) Roadside, 3) Bridge, 4) Traffic Operations, and 5) Emergency related maintenance activities. For this research project, bridge and emergency related maintenance activities were not considered due to the nature of these functions. Maintenance activities that fall into these two categories have to be performed on a periodic basis as in the case of bridge related maintenance activities and on an as needed basis as in the case of the emergency related maintenance activities.

The maintenance functions belonging to the 3 remaining categories were identified as potential candidates for this research. However, due to the large number of maintenance activities and a high degree of similarity between some of these activities, the first step was to combine similar maintenance activities into sub-categories. Each sub-category may contain only one or multiple maintenance activities that are closely related in function and benefits gained from performing the activity. For example, the sub-category Surface Treatments consists of five different maintenance activities: 231 – Seal Coat, 232 – Strip or Spot Seal Coat, 233 – Fog Seal, 235 – Micro Surfacing, and 265 Treat Bleeding, as shown in Figure 2. All these activities require similar efforts and tend to produce similar results. Tables 3 to 5 represent the grouped functions along with their corresponding costs and total group expenditures. Figure 1 shows the expenditure breakdown by category.

**Table 3: Pavement Related Functions**

| Routine Highway Maintenance Functions Prioritizing Using Delphi Process | | | | |
|---|---|---|---|---|
| Pavement Related Functions (Series 100, 200, 300, and 400) | | | | |
| 2008-2010 AVERAGE FUNCTION CODE, WORK UNITS AND COST | | | | PERCENT COST USE |
| FUNCTION CODE | FUNCTION CODE DESCRIPTION | UNIT | AVG. TOTAL COST | |
| 211-214 | LEVELING/OVERLAY | SY | $169,616,993.63 | 16.9910 |
| 231-232 | SEAL COAT & STRIP/SPOT SEAL | SY | $47,928,253.37 | 21.7921 |
| 110 | BASE REMOVAL/REPLACEMENT | CY | $38,551,266.92 | 25.6539 |
| 120 | BASE IN PLACE REPAIR | CY | $30,647,483.72 | 28.7239 |
| 225 | SEALING CRACKS | LM | $17,109,497.30 | 30.4378 |
| 270 | EDGE REPAIR | LF | $16,460,070.77 | 32.0867 |
| 360 | FULL DEPTH REMOVAL/REPLACEMENT | SY | $15,096,316.22 | 33.5989 |
| 252-253 | MILLING/PLANING & SPOT MILLING | SY | $14,198,690.25 | 35.0212 |
| 245 | ADDING/WIDENING PAVEMENT | SY | $12,549,110.51 | 36.2783 |
| 241-242 | POTHOLES, SEMI-PERMANENT & PERMANENT REPAIR | EA | $9,640,181.71 | 37.2440 |
| 455 | RESHAPING UNPAVED SHOULDERS | SY | $8,563,017.14 | 38.1018 |
| 233 | FOG SEAL | SY | $4,167,535.08 | 38.5193 |
| 480 | SIDE ROAD APPROACHES/CROSSOVER/TURNOUTS | SY | $3,639,962.47 | 38.8839 |
| 345 | REPAIR SPALLING | SY | $2,539,415.61 | 39.1383 |
| 488 | CONCRETE APPURTENANCE INSTALLATION/MAINTENANCE | SY | $1,870,903.41 | 39.3257 |
| 235 | MICROSURFACING | SY | $1,677,707.38 | 39.4937 |
| 325 | CLEANING/SEALING JOINTS & CRACKS | LF | $1,652,598.54 | 39.6593 |
| 315 | SLAB STABILIZATION/JACKING | *** | $1,289,924.23 | 39.7885 |
| 265 | TREAT BLEEDING PAVEMENT | SY | $817,729.34 | 39.8704 |
| 495 | PARKING AREA MAINTENANCE | SY | $639,092.19 | 39.9344 |
| 145 | UNPAVED ROAD MAINTENANCE | SY | $544,901.47 | 39.9890 |
| 330 | BLOWUPS AND STRESS RELIEF | *** | $474,387.32 | 40.0365 |
| 135 | INSTALL/MAINTAIN UNDER-DRAINS | LF | $91,664.03 | 40.0457 |
| | Sub-Total (Pavement Related Functions): | | $399,766,702.61 | |

## Table 4: Roadside Related Functions

| Routine Highway Maintenance Functions Prioritizing Using Delphi Process | | | | |
|---|---|---|---|---|
| Roadside Related Functions (Series 500) | | | | |
| 2008-2010 AVERAGE FUNCTION CODE, WORK UNITS AND COST | | | | PERCENT COST USE |
| FUNCTION CODE | FUNCTION CODE DESCRIPTION | UNIT | AVG. TOTAL COST | |
| 511-513 | MOWING & SPOT MOWING | AC | $50,297,905.26 | 5.0385 |
| 521-524 | LITTER & SPOT LITTER | AC | $26,620,298.69 | 7.7051 |
| 522 | ROUTINE STREET SWEEPING | MI | $23,522,143.47 | 10.0614 |
| 532-533 | REST AREA MAINTENANCE & THRU REGIONAL CONTRACTS | *** | $21,665,775.08 | 12.2317 |
| 540-545 | HAND & CHEMICAL VEG. CONTROL | *** | $21,272,228.28 | 14.3626 |
| 595 | GUARD FENCE | LF | $19,703,214.40 | 16.3363 |
| 523 | DEBRIS | MI | $18,825,403.58 | 18.2221 |
| 570 | CULVERT AND STORM MAINTENANCE | *** | $18,308,309.58 | 20.0561 |
| 552 | TREE AND BRUSH CONTROL | *** | $16,491,891.62 | 21.7082 |
| 561 | DITCH MAINTENANCE | CY | $12,976,482.73 | 23.0080 |
| 596 | GUARDRAIL END TREATMENT SYSTEMS | EA | $11,574,622.61 | 24.1675 |
| 531 | PICNIC AREA MAINTENANCE | *** | $7,830,893.14 | 24.9519 |
| 562 | RESHAPING DITCHES | LF | $5,437,527.33 | 25.4966 |
| 591 | UTILITIES/DRIVEWAY INSPECTION | *** | $5,227,009.53 | 26.0202 |
| 597 | MAILBOX INSTALLATION/MAINT. | EA | $4,187,057.19 | 26.4397 |
| 551 | LANDSCAPING | *** | $4,186,420.55 | 26.8590 |
| 560 | RIPRAP INSTALLATION AND MAINTENANCE | SY | $3,470,150.35 | 27.2066 |
| 563 | SLOPE REPAIR / STABILIZATION | SY | $2,513,883.32 | 27.4585 |
| 571 | STORM WATER PUMP STATION MAINT | *** | $2,076,260.28 | 27.6665 |
| 593 | CABLE MEDIAN BARRIER | LF | $1,904,997.80 | 27.8573 |
| 594 | CONCRETE BARRIER | LF | $1,896,049.73 | 28.0472 |
| 585 | DRIVEWAY INSTALL/REMOVAL&MAINT | SY | $1,210,231.00 | 28.1684 |
| 525 | ADOPT-A-HIGHWAY | *** | $997,279.59 | 28.2683 |
| 527 | HAND SWEEPING | *** | $867,874.07 | 28.3553 |
| 558 | STORM WATER POLLUTION PROTECT | *** | $862,904.70 | 28.4417 |
| 530 | REMOVAL OF GRAFFITI | SF | $723,327.85 | 28.5142 |
| 580-581 | REMOVAL OF ILLEGAL SIGN (TEMP)&(PERM) | EA | $559,905.64 | 28.5703 |
| 536 | CENTRAL TURNPIKE SYSTEM OPS | *** | $467,078.53 | 28.6171 |
| 548 | SEEDING/SODDING/HYDROMULCHING | SY | $377,607.54 | 28.6549 |
| 526 | SWEEPING ICE ROCK | EA | $367,380.88 | 28.6917 |
| 535 | MAINTENANCE OF SPECIALTY FACILITIES | *** | $361,459.79 | 28.7279 |
| 520 | ILLEGAL DUMPSITE REMOVAL/DISPOSAL | CY | $272,853.82 | 28.7552 |
| 598 | BOAT RAMP MAINTENANCE | *** | $187,746.63 | 28.7740 |
| 582 | REMOVAL OF ENCROACHMENTS, OTHER THAN SIGNS | *** | $178,596.37 | 28.7919 |
| 538 | PEST CONTROL | *** | $57,046.96 | 28.7976 |
| | Sub-Total (Roadside Related Functions): | | $287,479,817.89 | |

## Table 5: Traffic Operation Related Functions

| Routine Highway Maintenance Functions Prioritizing Using Delphi Process | | | | |
|---|---|---|---|---|
| Traffic Operations Related Functions (Series 700) | | | | |
| 2008-2010 AVERAGE FUNCTION CODE, WORK UNITS AND COST | | | | PERCENT COST USE |
| FUNCTION CODE | FUNCTION CODE DESCRIPTION | UNIT | AVG. TOTAL COST | |
| 731-733 | INSTALL/REINSTALL SMALL, LARGE & VANDALIZED SIGNS | EA | $47,219,820.78 | 4.7301 |
| 799 | TRAFFIC CONTROL PLAN | *** | $35,532,590.43 | 8.2895 |
| 712 | HIGH PERFORMANCE STRIPING | LF | $30,182,173.94 | 11.3130 |
| 743-744 | MAINT OF ISOLATED & COORDINATED TRAFFIC SIGNALS | *** | $28,793,800.58 | 14.1973 |
| 742 | ILLUMINATION | *** | $26,351,921.07 | 16.8371 |
| 745 | TRAFFIC MANAGEMENT SYSTEM | *** | $15,502,334.21 | 18.3900 |
| 711 | PAINT & BEAD STRIPING | LF | $9,672,764.73 | 19.3589 |
| 721 | DELINEATORS | EA | $8,858,670.52 | 20.2463 |
| 713 | SPECIALTY MARKINGS | *** | $7,449,011.92 | 20.9925 |
| 738 | INSTALL/MAINT FLASHING BEACON | *** | $7,147,206.87 | 21.7085 |
| 750 | INSTALL/REMOVAL PAVEMENT MARKERS | EA | $6,701,234.36 | 22.3797 |
| 725 | VEHICLE ATTENUATORS | *** | $6,511,589.34 | 23.0320 |
| 790 | MISCELLANEOUS TRAFFIC SERVICES | *** | $3,566,164.76 | 23.3893 |
| 724 | ROADWAY ACCESS CONTROL | *** | $1,322,394.52 | 23.5217 |
| 715 | REMOVAL OF PAVEMENT STRIPING | *** | $374,183.71 | 23.5592 |
| | Sub-Total (Traffic Operations Functions): | | $235,185,861.75 | |

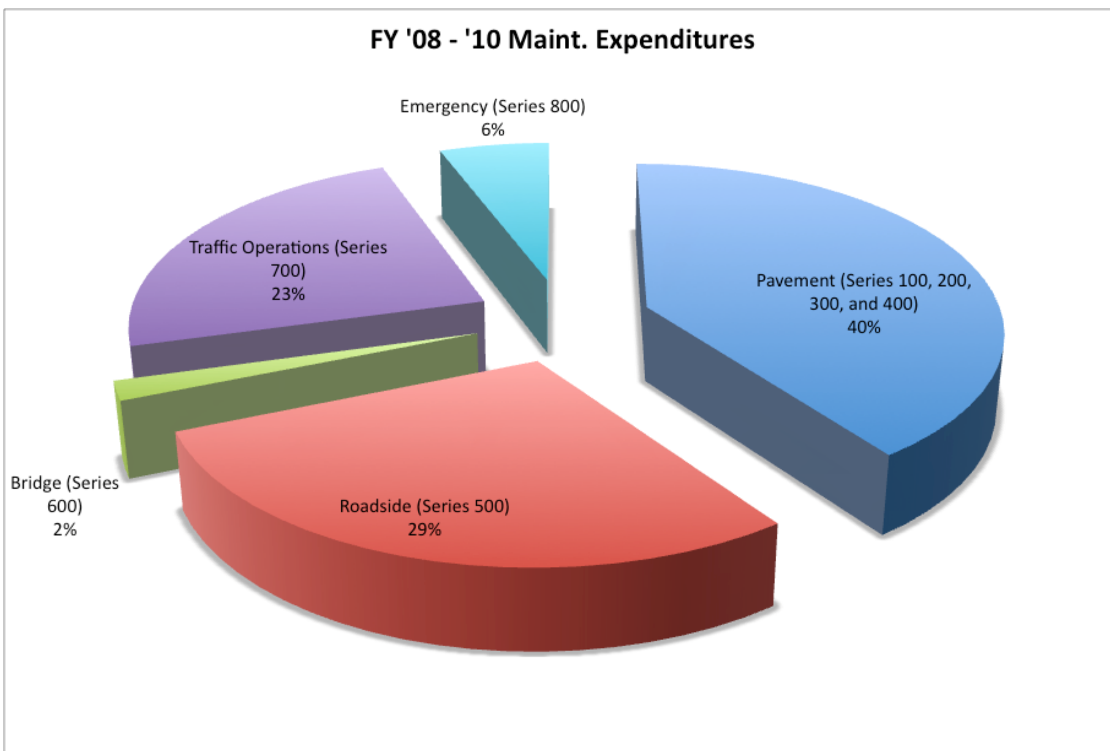


*Figure 1: Total Maintenance Expenditure by Function Categories*

After grouping the maintenance activities into sub-categories, the next step involved selecting the most relevant maintenance sub-categories. This was accomplished with the help of TxDOT's EWG. EWG members were asked to identify the most important and most frequently used maintenance sub-categories to be included in the research project. Sixteen maintenance sub-categories were identified by the EWG and used in this research along with the individual maintenance functions that make up each sub-category. To ensure that the selected maintenance sub-categories truly represented a significant portion of TxDOT's maintenance work, the combined annual expenditures for the 16 maintenance sub-categories were tabulated and found to account for an average of 76.3 percent of TxDOT's annual maintenance expenditures for fiscal years 2008–2010. Table 6 shows the maintenance activities that make up the 16 maintenance sub-categories along with the percentage breakdown of the annual maintenance expenditures obtained from data provided by TxDOT's maintenance division.

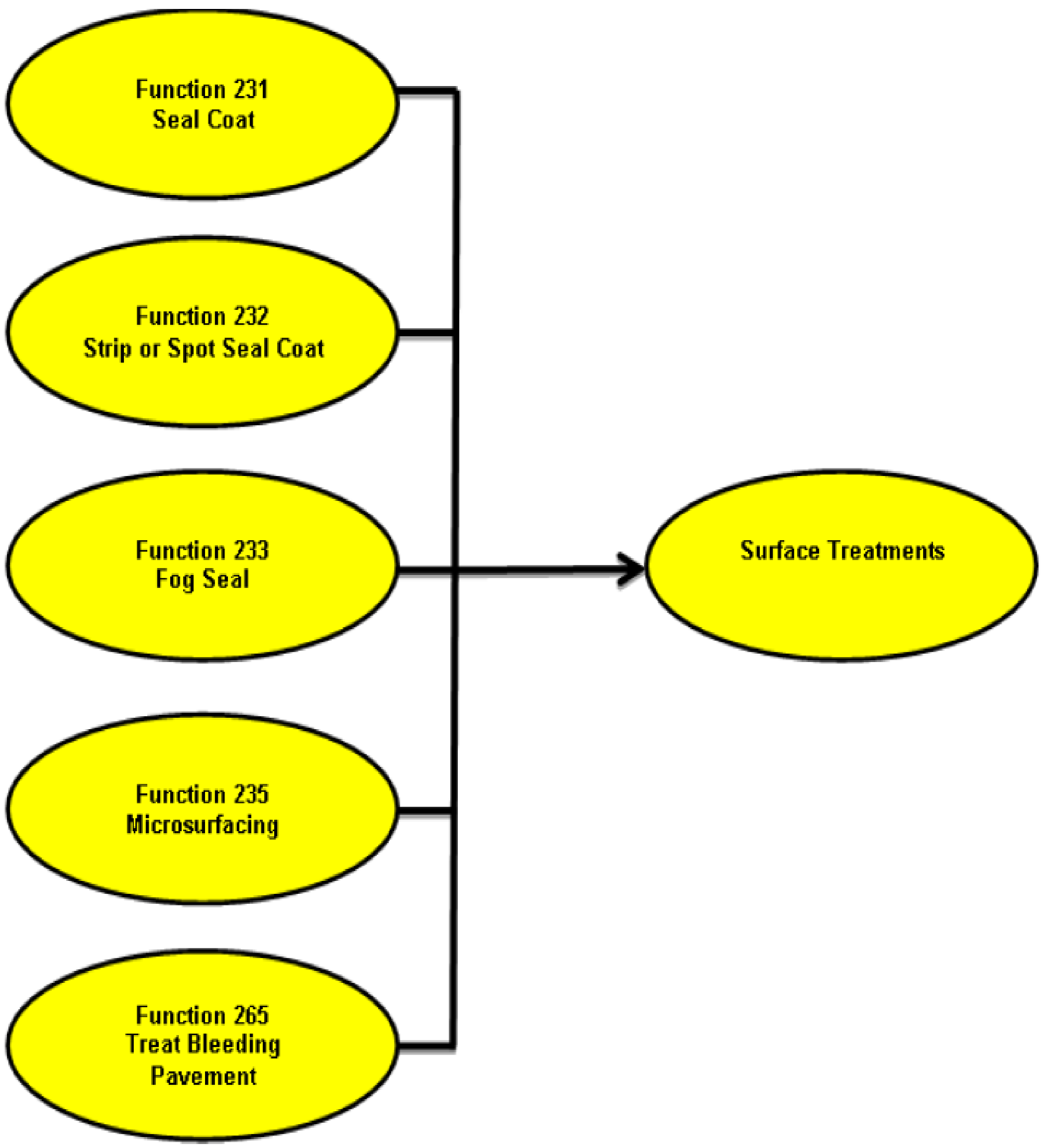


*Figure 2: Maintenance Category: Surface Treatments*

## Table 6: Maintenance Expenditures by Category

| Maintenance Expenditures by Sub-Category | | | | |
|---|---|---|---|---|
| **Pavement Related Functions** | | **Percent of Total Expenditure** | | |
| **Function No.** | **Sub-Category** | **2008** | **2009** | **2010** |
| 110, 120 | Base Repair | 7.68 | 6.11 | 6.98 |
| 211, 212, 213, 214 | Pavement Leveling/Overlay | 16.19 | 15.83 | 18.89 |
| 225, 325 | Crack Seal | 1.82 | 1.73 | 2.08 |
| 231, 232, 233, 235, 265 | Surface Treatments | 4.29 | 5.38 | 6.71 |
| 241, 242 | Pothole Patching | 0.84 | 0.75 | 1.31 |
| 252, 253 | Milling | 1.53 | 1.33 | 1.39 |
| 270, 455 | Edge Maintenance | 2.52 | 2.81 | 2.18 |
| **Sub-Total:** | | **34.87** | **33.94** | **39.54** |
| **Roadside Related Functions** | | | | |
| **Function No.** | **Sub-Category** | **2008** | **2009** | **2010** |
| 511, 513 | Mowing | 6.09 | 4.83 | 4.17 |
| 520, 521, 522, 523, 524, 525, 527 | Debris/Litter/Sweeping | 7.33 | 7.06 | 6.94 |
| 538, 540, 541, 542, 544, 545 | Vegetation Control and Pest Control | 2.06 | 2.19 | 2.14 |
| 135, 561, 562, 570, 571 | Drainage System Maintenance | 4.67 | 3.84 | 3.16 |
| **Sub-Total:** | | **20.15** | **17.92** | **16.41** |
| **Traffic Operations Related Functions** | | | | |
| **Function No.** | **Sub-Category** | **2008** | **2009** | **2010** |
| 593, 594, 595, 724 | Safety Barrier Maintenance | 2.56 | 2.45 | 2.45 |
| 711, 712, 713, 715, 750 | Pavement Markings/Markers | 5.67 | 5.51 | 5.13 |
| 596, 725 | Crash Attenuators | 1.71 | 1.81 | 1.91 |
| 580, 581, 597, 721, 731, 732, 733 | Sign Maintenance | 6.70 | 5.95 | 5.60 |
| 738, 742, 743, 744 | Flashing Beacons, Traffic Signals and Illumination (Install/Maintain) | 6.15 | 6.05 | 6.50 |
| **Sub-Total:** | | **22.79** | **21.77** | **21.59** |
| **Total** | | **77.81** | **73.63** | **77.54** |
| **Average Expenditures for FY '08, '09, '10** | | **76.33** | | |

# Chapter 4: Conceptual Framework

A conceptual framework was prepared by the research team based on the literature review and the workshop comments provided by the TxDOT experts. The conceptual framework lists and explains the various components of the whole risk assessment procedure when certain routine maintenance activities or projects are removed under a budget cut, serving as the basis for optimizing resource allocations. Figure 1 presents the proposed conceptual framework. The maintenance objectives were defined and selected by TxDOT EWG as safety, system preservation, aesthetics and system operations. This conceptual framework has the flexibility of accommodating projects that have a single routine maintenance activity and those that have multiple routine maintenance activities.

## 4.1 Analytic Hierarchy Process

Dr. Thomas L. Saaty developed the Analytic Hierarchy Process (AHP) in the 1970s while working for the Department of Defense [12]. Some of the main advantages of the AHP are that it provides a framework for decomposing and structuring complex problems where decision makers are faced with Multiple Criteria Decision Making (MCDM). By decomposing and structuring these types of problems, the decision makers often gain a better understanding of the problem and the relationships of the individual criteria or attributes.

Another key advantage of AHP is that it can synthesize the ranking of alternatives or options based on different criteria. This process has been used extensively in numerous fields and applications with a high degree of success. For example, it has been used by the US Military to determine the location of Army Bases and in the development of high-tech weapon systems. Many Fortune 500 companies have used AHP when developing new products or entering a new market or in determining strategic locations for their overseas manufacturing facilities [14].

Now that we have been briefly introduced the AHP and know that it is very versatile and has been used extensively in a wide range of applications, let's address how it actually works. The AHP provides a framework for solving complex and unstructured problems through explicit logical analysis. It uses three natural analysis principles to help structure the problem: 1) the principle of constructing hierarchies, 2) the principle of establishing priorities, and 3) the principle of logical consistency. In addition to these principles, the AHP provides many other advantages that make it an ideal method for solving complex and unstructured problems in an individual as well as a group environment [15]. In order to gain a better appreciation for AHP and the benefits it can provide, it is necessary to understand some of the key characteristics that separate AHP from other methods. Perhaps its most important characteristic is the ability to decompose a rather large and complex task or problem into smaller, more manageable tasks or sub-problems. Most problems can be more easily understood and solved if they can be broken up into smaller parts.

### 4.1.1 Advantages of the Analytical Hierarchy Process

Oftentimes, major decisions require input and consensus from individuals with varying degrees of experience, technical knowledge, expertise, and even rank within an organization. These types of scenarios present both an opportunity as well as a problem. One of the advantages of having such a group is that it will typically lead to a more complete and deeper understanding of the problem by ensuring that all possible issues have been addressed. This is especially true if the group is able to brainstorm and gets involved in the development of the hierarchy, criteria, and alternatives [15].

However, this situation may also present a unique challenge to the success of the analysis. In a group environment, it may be easy for some individuals to be intimidated, manipulated, or kept from expressing their own ideas by more vocal or powerful group members. The AHP is useful in this type of setting since it allows individual group members to state their preferences without being confrontational. Furthermore, it does not force group members to reach a consensus, but rather it synthesizes a representative outcome based on individual judgments [15]. In other words, each group member will influence the final weights or ranking of the criteria and alternatives by his or her preferences.

Another advantage of the AHP is the concept of tradeoffs. This concept allows evaluators the freedom to choose or select the best option or alternative based on their unique perspective of the goal or objective. For example, an individual may not only choose between different criteria and alternatives, but also determine the relative strength or preference of his or her judgments. These and other advantages of AHP are shown in Figure 3 [15].

### 4.1.2 Principle of Constructing Hierarchies

The principle of constructing hierarchies is the first of the AHP's natural principles and introduces the concept of hierarchies. This concept of hierarchies is fundamental to the human mind. It requires a unique process that involves the following steps: first, the individual must identify the elements of the problem. Secondly, he or she must group these elements into homogeneous sets. Finally, these homogeneous sets must be arranged into different levels or tiers [12]. Figure 4 shows a typical three-tier hierarchy structure where Tier I describes the ultimate goal that is being pursued, and Tier II describes the criteria that will be used to judge or compare the alternatives identified in Tier III.

Hierarchies can be further classified as structural or functional based on their arrangement and purpose. As humans, we possess a natural ability to not only recognize hierarchies, but also to distinguish between the two types. The AHP then follows our natural or default way of decomposing large unstructured problems into smaller more manageable sub-parts. This characteristic makes the AHP extremely versatile and easily adaptable, allowing us to better understand and solve a wide array of problems in many different fields and disciplines [15].

A structured hierarchy can be described as one where a complex system is arranged or structured into constituent parts in descending order. A good example of a structured hierarchy is perhaps the list of commissioned officers in the United States Army. This list, arranged in descending order, includes the General of the Army: General: Lieutenant General: Major General: Brigadier General: Colonel: Lieutenant Colonel: Major: Captain: First Lieutenant: and Second Lieutenant. This type of hierarchy is perhaps the most closely associated with how our brains naturally decompose complex systems to facilitate understanding.

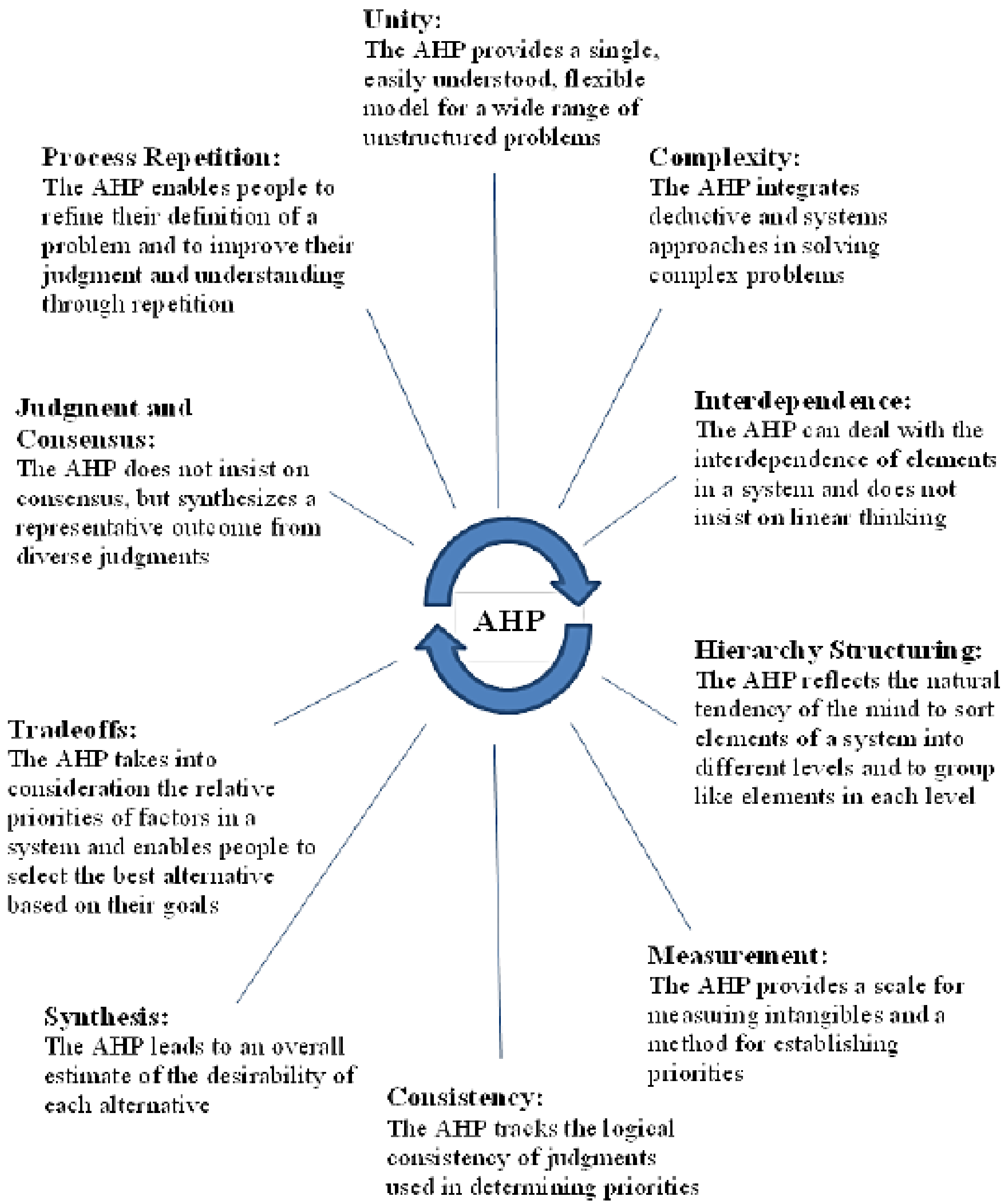


*Figure 3: Advantages of the Analytical Hierarchy Process*

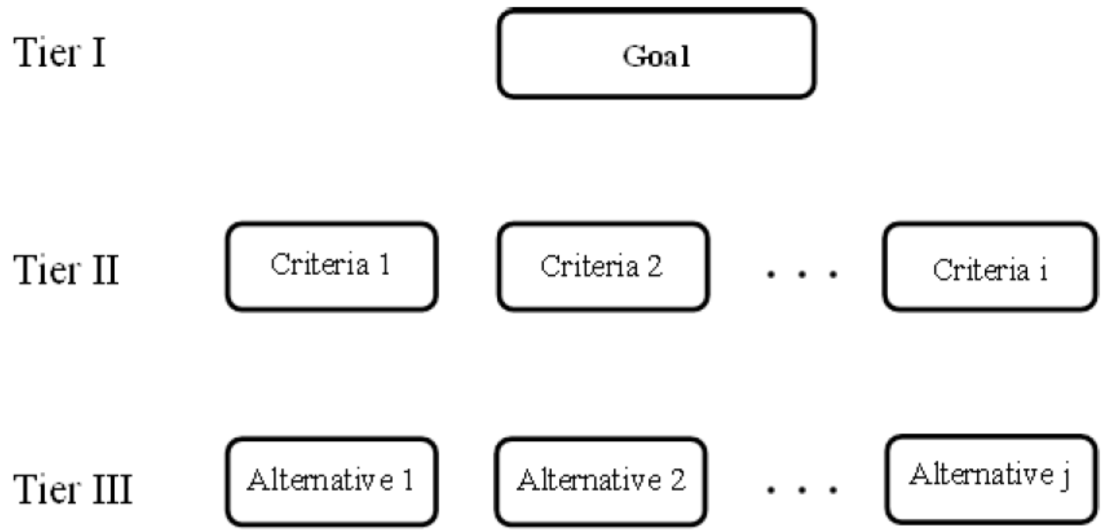


*Figure 4: AHP Tier Hierarchy Structure*

In contrast to the structured hierarchy, the functional hierarchy is more concerned with decomposing a complex system or problem into its constituent parts based on their interactions or relationships. A good example is our very own bodies. Our bodies can be divided up into systems based on their functions and interactions with other systems. Our nervous, skeletal, digestive, respiratory, and muscular systems, just to name a few, have unique functions that separate them from one another but must depend on and interact with each other for the body to function properly.

This example of a very complex system provides an ideal opportunity to explain the structural hierarchy. Imagine a pharmaceutical company developing a new drug. They are obviously concerned with the patients' overall health, but must gain a detailed understanding of how the drug will affect each of the body's systems and their interactions with other systems. To do so, it may be useful to decompose the body into its different systems. By decomposing this huge and intricate problem into hierarchies, it is possible to gain a better understanding of the fundamental issues and relationships that are at the core of the problem and are able to arrive at a more meaningful solution.

### 4.1.3 Principle of Establishing Priorities

The second natural principle of the AHP is the principle of establishing priorities. This principle allows us the ability to perceive and recognize relationships through observation. By recognizing these relationships, it allows us to distinguish and determine the intensity of our preference between two choices. From this, we can ultimately deduce which alternative we most prefer. The AHP does nothing more than provide a framework to this already inherent capability. It is for this reason that AHP has been applied in numerous applications with a great deal of success [15].

### 4.1.4 Principle of Logical Consistency

The third and final natural principle of the AHP is the principle of logical consistency. Having the ability to establish relationships among ideas and objects and organize these relationships in logical and coherent patterns based on our understanding and observations is certainly helpful. However, for this human quality of establishing relationships to be of any significant value, it must be implemented consistently. Therefore, it is also important to have a clear definition and understanding of consistency and how it exists before the AHP can be applied effectively [15].

Consistency as it relates to the AHP exists in two different forms. First, consistency exists in the form of homogeneity and relevance. This means we have the ability to group things or objects by establishing criteria. For example, if we select automobiles as our criteria, then a compact car, sedan, minivan, and even a pickup truck belong in the same homogeneous set. However, if the criteria changes to sports cars, these four objects no longer belong in the same homogeneous set.

The second manner in which consistency exists is in the form of intensities of relevance. Consider the example of judging food for spiciness: Indian food is judged to be three times spicier than Chinese food and Chinese food is judged to be twice as spicy as American food. In order to be consistent with the intensity of our judgments, Indian food would need to be judged six times spicier than American food. Any deviation from this value would constitute an inconsistency in the judgment. This concept may be more readily applicable when strictly quantitative values are being evaluated, but may be harder to implement when qualitative data is being used. However, since the AHP is capable of handling both quantitative as well as qualitative data, it has a built-in mechanism to accommodate a fair degree of inconsistencies when more qualitative data is being evaluated.

When Dr. Saaty first developed the AHP, he devised it so it would be capable of handling both quantitative as well as qualitative data. To accommodate qualitative data and the fact that human judgments are not always consistent, he designed the AHP to tolerate a reasonable amount of inconsistencies in the user judgments and preferences. Dr. Saaty introduced several concepts that help determine and quantify the consistency of the user judgments. These concepts include the maximum or principle eigenvalue ($\lambda max$), consistency index (CI), and the random index (RI) [12]. The algorithms of calculating these two indices will be discussed later in this chapter.

## 4.2 Components and Relationship among Them

The conceptual framework lists and explains the various components of the whole risk assessment procedure when certain routine maintenance activities or projects are removed due to a budget cut, serving as the basis for optimizing resource allocations. The key components and the relationships among them are illustrated along with information on how they are defined or analyzed in Figure 5. Following are these key components:

1) **Maintenance functions**: These maintenance activities are used in practice, and a complete list of them was obtained from TxDOT's routine maintenance manual. Projects can have one or multiple maintenance activities. In the pilot study, 15 of the most frequently used functions were selected as the alternatives to be ranked using AHP.

2) **Risk with respect to maintenance objectives**: The risk with respect to each of the maintenance objectives when a routine maintenance activity is not performed. For example, if the “Sign Repairing” is not performed, it will result in a significant risk for “Safety,” some risk for “Aesthetics,” and no risk for “Pavement Preservation.” These risks can be quantified by using the AHP. The total risk for a maintenance objective can be determined by adding the individual risks of the maintenance activities with respect to the objective.

3) **Maintenance objectives**: These can be defined as the individual districts routine maintenance program’s desired outcome. These objectives should be identical for all districts. For example, the maintenance objectives could be to preserve the pavements, ensure safety, maintain ride quality, and protect highway aesthetics. As mentioned, the maintenance objectives are: safety, system preservation, aesthetics and system operations.

4) **Relative weights of maintenance objectives**: These reflect the relative importance of a maintenance objective. The relative weights are quantified by using the AHP.

5) **Project risk**: This is defined as the total risk of the project in terms of all the maintenance objectives if the specified maintenance activities are not performed. It is determined by the weighted sum of the risks for each maintenance objective, using the total risk for a maintenance objective and the relative weight of the maintenance objective.

6) **Risk impact**: This is the relative impact of the project risk by considering the level of its exposure. For example, for the same project risk, its impact on a highway segment with a higher ADT will be greater than that on a highway with a relative lower ADT. The risk impact is determined by using the exposure factors such as ADT as multipliers.

   Once the risk impact is determined for a project, it is used as an index to rank all of the projects in a routine maintenance program in terms of the potential risk if a project is removed from the program because of a budget cut. When a budget cut occurs, starting with the project having the lowest risk index impact, projects will be removed from the maintenance program in ascending order until the total maintenance program cost fits the available budget.

| System Component | Maintenance Activity | Risk with Respect to Maintenance Objectives | Maintenance Objectives | Relative Weights of Maintenance Objectives | Project Risk | Project Risk Impact |
|---|---|---|---|---|---|---|
| **Information Source or Analysis Method** | To be obtained from TxDOT Maintenance Manual | To be determined with Analytic Hierarchy Process (AHP) | To be defined by working with the project PMC and EWG | To be determined with Analytic Hierarchy Process (AHP) | To be determined by weighted sum | To be determined by using exposure factors as multipliers |

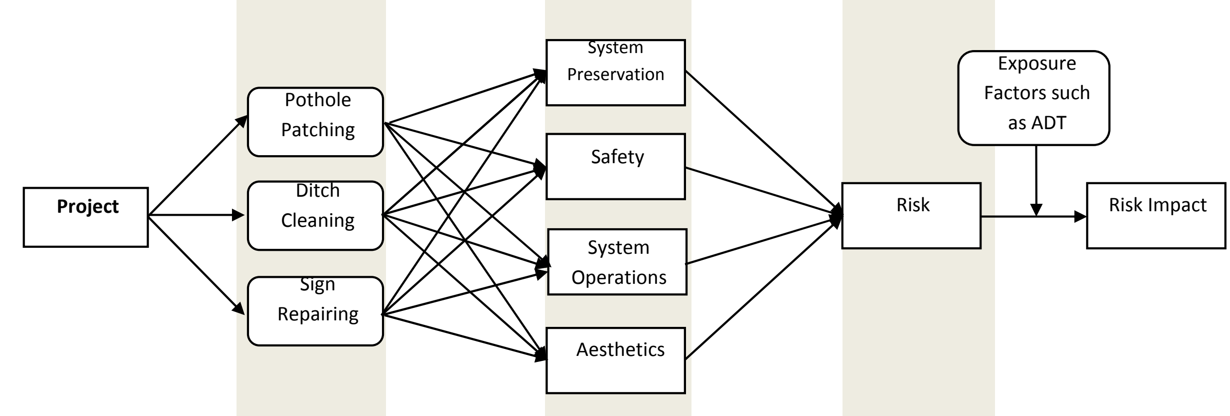


*Figure 5: Conceptual Framework of Routine Maintenance Optimizing Resource Allocation*

## 4.3 Domino Effect of Not Performing Maintenance Functions

It is important to understand the relationship between each maintenance sub-category (alternative) and the maintenance objectives (criteria). In most cases each maintenance alternative has a component of each maintenance criteria. For example, Mowing can appear to serve a purely Aesthetic objective. However, under closer evaluation, we can determine that it has significant Safety, System Operation, and System Preservation components.

For example, if the grass is not mowed for an extended period of time, wildlife and or livestock can hide in the tall grass and as vehicles approach they may get startled and run across the street and collide with the vehicle or cause the motorist to swerve into an adjacent or opposing traffic lanes to avoid colliding with the animal. Another scenario may involve a stranded or disabled vehicle on a road with no paved shoulders. The disabled vehicle may not be able to pull off the road due to the tall grass, thus impacting the traffic flow and safety of the traveling public. Yet another example can involve grass that is tall enough to affect a motorist's visibility or line of sight as he or she enters the highway at a driveway, intersection, or crossover. These are examples that help explain that Mowing not only improves the Aesthetics of the highway, but also improves Safety, System Operation, and Preservation as well. Figure 6 shows these relationships in a graphical representation. Similar diagrams were developed for each of the 16 different maintenance sub-categories. These diagrams served to stimulate the evaluator's judgments when performing the pair-wise comparisons.

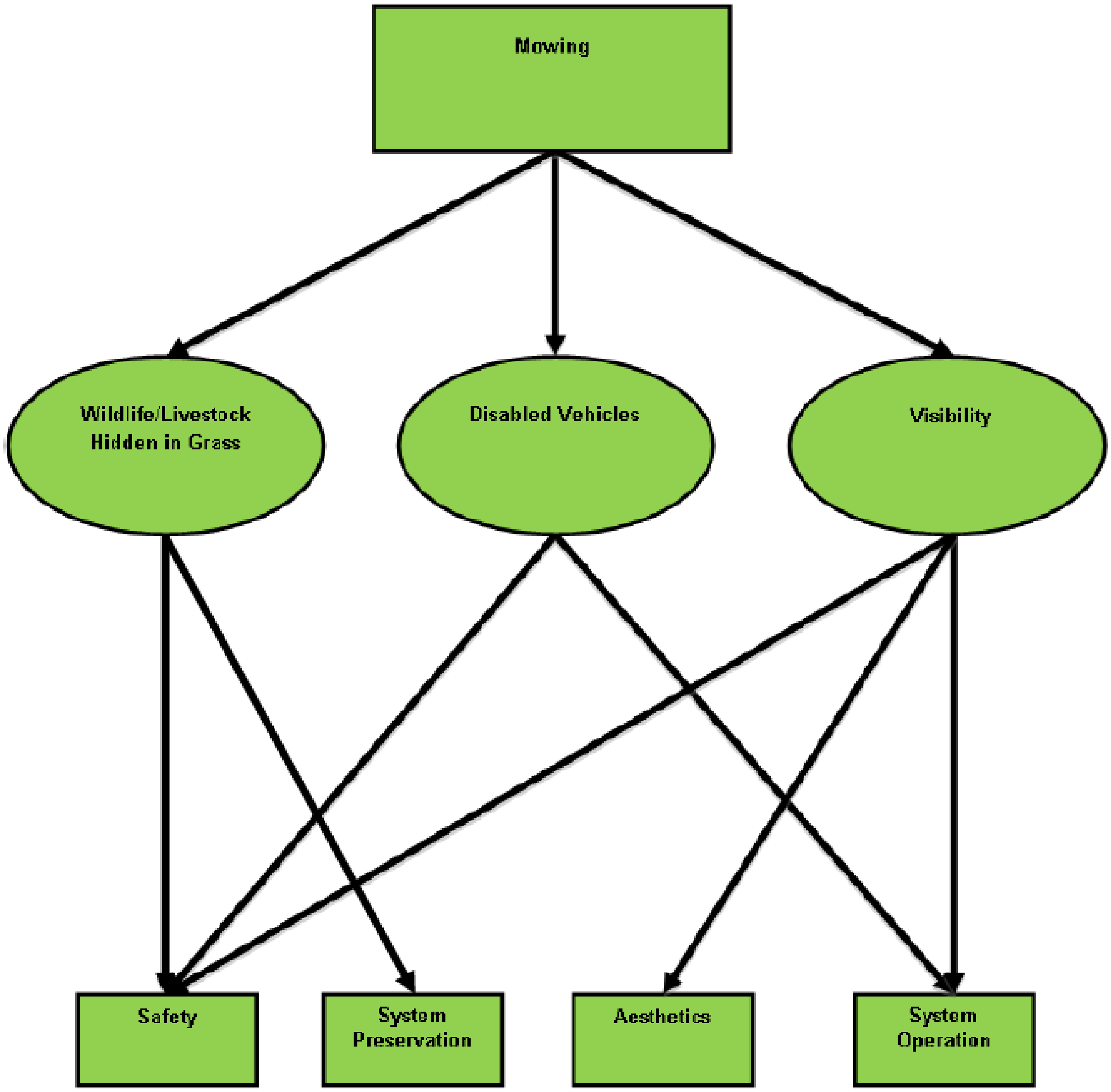


*Figure 6: Domino Effects of Maintenance Sub-Category: Mowing*

## 4.4 Developing the Hierarchy Structure

After identifying and selecting the maintenance goals and the most relevant maintenance sub-categories, the next step involves organizing the hierarchy structure for the AHP. To accomplish this task, it is important to focus on the ultimate objective of this research project. TxDOT, like many other transportation agencies, is always looking for ways to provide a superior service by improving its operations and better administering its limited resources. Therefore, computing each maintenance sub-category's Overall Relative Weight (ORW) will allow maintenance personnel to make decisions of whether to perform certain maintenance activities based on those activities' contribution to the four maintenance objectives.

Maintaining a highway network the size of Texas's not only requires an enormous amount of resources, but it also requires maintenance supervisors, engineers, and administrators with the foresight to be able to distinguish between maintenance activities that have a relatively higher impact on the maintenance goals and maintenance activities that have little or no impact. This will allow the maintenance personnel to reduce the impact of budget fluctuations on the highway condition by knowing which maintenance functions or activities to reduce or suspend in order to meet budget constraints without adversely affecting the overall highway system condition.

Therefore, to properly rank or weight each maintenance sub-category it is important to determine each alternative's contribution toward each maintenance objective. The ORW for each maintenance sub-category is therefore the ranking index obtained from the AHP. The hierarchy structure developed for this analysis consists of three tiers with Tier I being the overall relative weight or the risk this activity would pose if not performed. Tier II is made up of the 4 different maintenance objectives while Tier III is made up of the 16 different maintenance alternatives. Figure 7 shows the relationship between the different tiers and how each maintenance objective impacts each maintenance alternative's ORW and ranking.

## 4.5 Performing Pair-wise Comparison

Once the hierarchy structure has been developed, and a clear understanding of the concepts of establishing priorities and consistency have been obtained, the next step involves assigning the relative weights to the different options at each tier or hierarchy level. To do so, a scale must be established. Significant research has been performed on the topic of determining the most appropriate scale of measurement. The one-to-nine scale has been preferred over other scales since it most closely resembles our natural ability to distinguish strengths of dominance or preferences between objects [11]. Table 7 shows Dr. Saaty's *Intensity of Importance Scale* along with the definition and an explanation of what each value represents.

Once an appropriate scale has been selected, the evaluator performs the judgments and preferences using a concept called *pair-wise comparisons*. This concept allows the AHP users the ability to evaluate multiple criteria and or alternatives by simply comparing two criteria or alternatives at a time and can be best described by Figure 8. This approach simplifies the evaluation process by focusing the evaluator's attention to the two choices at hand.

Therefore, the process requires that all combinations of criteria and alternatives be compared for each tier using this concept of pair-wise comparisons. Equation 1 can be used to calculate the number of pair-wise comparisons for an $n \times n$ sized matrix. For example, for a 10x10 matrix, the evaluator would be required to make 45 pair-wise comparisons. During this process, the evaluator must decide between two options and determine the intensity of his or her preference one pair at a time, no other criteria or alternatives are relevant during the process. The process is repeated until all combinations of the criteria or alternatives have been compared to one another. The AHP keeps track of the evaluator's judgments and synthesizes a ranking of all the criteria or alternatives based on these pair-wise comparison judgments.

$$Number\ of\ Pair-wise\ Comparison = \frac{n \times (n-1)}{2} \qquad \textbf{Equation 1}$$

Where,
$n$ = Size of Square Matrix.

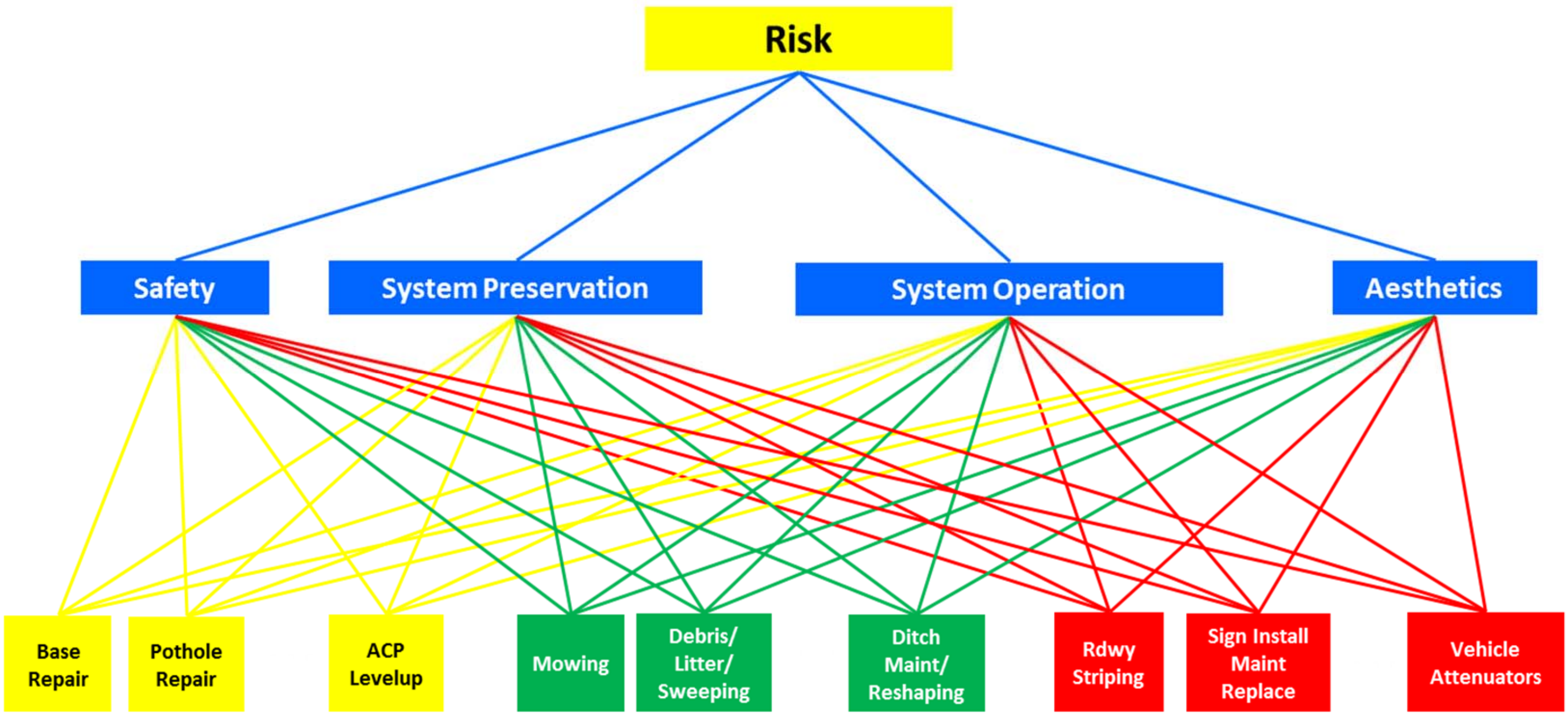


*Figure 7: Three-tier Hierarchy Structure of AHP*

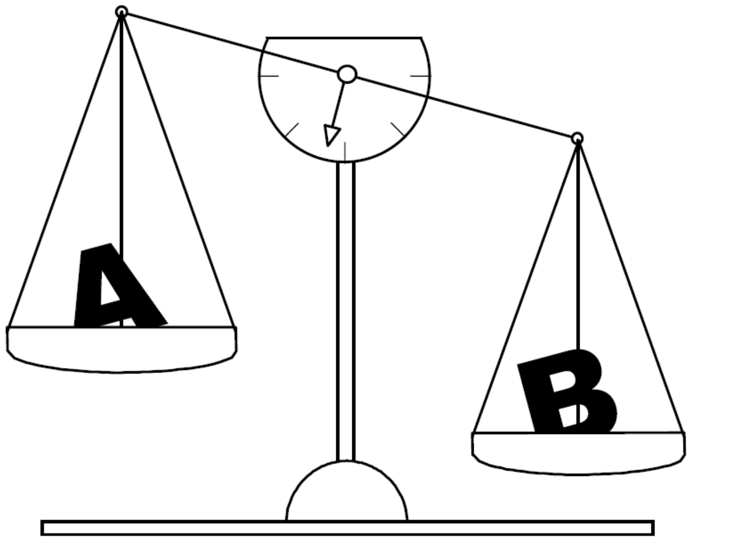


*Figure 8: Illustration of Pair-wise Comparison*

**Table 7: Intensity of Importance Scale**

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance or preference of both elements | Two elements contribute equally to the objective |
| 3 | Moderate importance or preference of once element over another | Experience and judgment slightly favors one element over another |
| 5 | Strong importance or preference of one element over another | Experience and judgment strongly favors one element over another |
| 7 | Very strong importance or preference of one element over another | An element is strongly favored and its dominance is demonstrated in practice |
| 9 | Extreme or absolute importance or preference of one element over another | The evidence favoring one element over another is one of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values | Used when compromise is needed |
| Reciprocals of above nonzero numbers | If one element ***i*** is given a nonzero value when compared to element ***j***, then ***j*** has the reciprocal value when compared to ***i***. **(*a*ij = 1/aij)** | |

## 4.6 Combining Individual Judgments

After each individual evaluator has specified his or her preferences for each pair-wise comparison, it must then be combined with the other group members' preferences. This will incorporate all the individual's unique judgments into a single representative value for each combination of different criteria and alternatives and a new matrix incorporating all the individual's pairwise comparisons is created. Equation 2 demonstrates the algorithm of how each individual evaluator's pair-wise comparisons are combined into a single value using the geometric mean.

$$a_{ij} = \left(\prod_{k=1}^{N} a_{ij}^{k}\right)^{1/N} \quad \textbf{Equation 2}$$

Where,
$i,j$ = Alternatives in pair-wise comparison;
$a_{ij}$ = Combined judgment for alternative *i* over alternative *j*;
$a^{k}_{ij}$ = Evaluator k's judgment for alternative *i* over alternative *j*;
$N$ = Number of evaluators participated.

Use this algorithm to combine the individual judgments of maintenance objectives and maintenance alternatives and obtain two combined matrix for maintenance objectives and maintenance alternatives.

## 4.7 Calculating the Priority Vector of the Combined Matrix

The priority vector of the combined matrix is the relative weights for maintenance objectives and alternatives. The priority vector can be calculated by the process described later. We illustrate the process using a given 3×3 matrix [A].

- The first step is to normalize the matrix. To do this, first obtain the column totals for the original matrix [A], shown in Table 8.
- The second step is to divide each entry in the matrix by its corresponding column total.
- After the matrix has been normalized, the third step is to sum the total for each row.
- The last step is to divide the row totals by *n* which corresponds to the size of the square matrix [A]. In this particular example, *n = 3* for the 3×3 matrix as shown in Table 9.

**Table 8: Example Matrix A**

| Criteria | | Alternatives A | B | C |
|---|---|---|---|---|
| Alternatives | A | 1 | 1/2 | 1/3 |
| | B | 2 | 1 | 1/2 |
| | C | 3 | 2 | 1 |
| Column Total | | 6 | 7/2 | 11/6 |

**Table 9: Normalized Matrix, Row Sums, and Priority Vector**

| Criteria | | Alternatives A | B | C | Row Sums | Average Row Sum | Priority Vector |
|---|---|---|---|---|---|---|---|
| Alternatives | A | 1/6 | 1/7 | 2/11 | 0.491 | 0.491/3 = 0.164 | 0.164 |
| | B | 2/6 | 2/7 | 3/11 | 0.892 | 0.892/3 = 0.297 | 0.297 |
| | C | 3/6 | 4/7 | 6/11 | 1.617 | 1.617/3 = 0.539 | 0.539 |

This step may need to be repeated for several iterations to fine tune the vector of priorities. Once the values for the priority vector no longer change with respect to the values of its previous iteration, then the values have converged and the priority vector have been obtained.

After this step the local weights for maintenance objectives and maintenance alternatives can be obtained.

## 4.8 Calculating the Consistency Ratio

AHP can tolerate a reasonable amount of inconsistencies in the user judgments and preferences. The maximum or principle eigenvalue ($\lambda max$) is used to measure the consistency of the user judgments. $\lambda max$ is obtained by dividing the product of the original input matrix and the vector of priorities for the given matrix by the vector of priorities. The average of the resulting vector is the $\lambda max$.

Continuing with the example above, $\lambda max$ can be obtained from the priority vector. Set the priority vector obtained in the example as matrix [B]. The product of [A] and [B] will result in a new 3x1 matrix [C]. This new matrix will be used to determine the Right eigenvector and ultimately $\lambda max$ . This process is shown in Table 10. When multiplying matrices, a fundamental rule must be followed that requires the number of columns in matrix [A] must equal the number of rows in matrix [B]. This will produce a new matrix that will have the same number of rows as [A] and the same number of columns as [B].

Dividing each entry in matrix [C] by its corresponding value of the priority vector will yield the Right Eigenvector. Once the Right Eigenvector has been computed, the $\lambda max$ is simply the average or mean value for the right eigenvector. It is important to mention that these values are obtained using the normalized version of the original matrix [A].

Table 10 shows the λmax = 3.009 for the original matrix [A] used in this example. When several iterations are required for the priority vector to converge on a solution, the λmax is obtained using Equation 3.

$$\lambda_{max} = \left(\frac{\sum_{i=1}^{n} Right\ Eigenvalues}{n}\right)^{1/r} \qquad \textbf{Equation 3}$$

Where,
*λmax* = Maximum or Principle Eigenvalue
*n* = Size of Square Matrix
*r* = number of iterations (1 for 1st, 2 for 2nd , 3 for 3rd …… and so on)

**Table 10: Calculating Maximum Eigenvalue (λmax)**

| Criteria | | Alternatives | | | Row Sums | Priority Vector | [C] | Right Eigenvector |
|---|---|---|---|---|---|---|---|---|
| | | A | B | | | | | |
| Alternatives | A | 1/6 | 1/7 | 2/11 | 0.491 | 0.164 | 0.492 | 3.004 |
| | B | 2/6 | 2/7 | 3/11 | 0.892 | 0.297 | 0.894 | 3.008 |
| | C | 3/6 | 4/7 | 6/11 | 1.617 | 0.539 | 1.625 | 3.015 |
| | | | | | | | λmax (avg) | 3.009 |

The consistency of user judgments is the controlling factor in determining the effectiveness of the synthesized results obtained from the AHP. The greater the consistency, the more meaningful and reliable the results will be. The λmax is used to determine the consistency of the judgments or inputs into the AHP matrix. The closer the λmax value is to the size of the square matrix the more consistent the evaluator has been with his or her judgments. As mentioned previously, human judgment is not free of inconsistencies and that understanding led Dr. Saaty to define the Consistency Index (CI) as a measure of the consistency of the evaluator's judgments. Equation 4 describes how the λmax value is used to compute the CI for an $n \times n$ sized matrix.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \textbf{Equation 4}$$

Where,
*CI* = Consistency Index
*λmax* = Maximum or Principle Eigenvalue
*n* = Size of Square Matrix

The Consistency Ratio (CR) is the ratio of the consistency index for a matrix where an evaluator used his or her knowledge, experience, and intuition to make both qualitative and quantitative pair-wise comparison judgments to a same sized matrix whose input values have all been randomly assigned. The CR's maximum value of 10% allows the evaluator some flexibility in his or her judgments while still retaining a relatively high degree of consistency producing more reliable results. A CR value higher than 10% distorts the weights and may lead to inaccurate conclusions. Equation 5 is used to compute the CR. Random Index (RI) can be determined from Table 11.

$$CR = \frac{CI}{RI} \qquad \textbf{Equation 5}$$

Where,
$CR$ = Consistency Ratio
$CI$ = Consistency Index
$RI$ = Random Index

**Table 11: Random Index (RI) Using Monte Carlo Simulation Method**

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R.I. | 0.00 | 0.00 | 0.55 | 0.94 | 1.14 | 1.28 | 1.37 | 1.43 | 1.48 | 1.51 | 1.54 | 1.56 | 1.54 | 1.59 | 1.60 | 1.61 |

## 4.9 Calculating the Overall Relative Weights (ORW)

After the final judgment matrices are obtained for criteria and alternatives, the next step is to obtain the priority vector of criteria and alternatives from the matrices and calculate the ORW.

The ORW is defined as the sum of the products of each objective weight and its corresponding alternative weight with respect to the same objective. The process of obtaining the priority vector from the pair-wise comparison matrix is called aggregation. Many aggregation methods have been discussed by different researchers. The most commonly used one is still the eigenvector proposed by Saaty. This method is straightforward to use. The first step is to obtain the column total for each column in the matrix. The next step is to normalize the matrix by dividing each entry in the matrix with its corresponding column total. After the normalization is completed, the next step is to obtain the row total of each row. The final step is to divide each row total by the number *n*, which stands for the size of the square matrix, yielding the priority vector. Several iterations may be needed until no more changes in the values of the priority vector are observed when compared to the previous iteration. Then the values have converged and the true weights of each criterion and alternative have been obtained.

The results obtained from the above computations are in essence the priorities or rankings for the individual alternatives with respect to different criteria. Once this process is completed for all the matrices at each hierarchy level, the ranking can be obtained by simply adding together the products of alternative weights with its corresponding criteria weights, yielding a benefit ranking of each alternative based on the selected criterion and the relative weights assigned to each criterion and alternative. In this report, $X = (X_1, X_2, \ldots, X_m)'$ is the relative weights matrix of all the alternatives with respect to each of the $m$ criteria, and $X_l = (X_{l1}, X_{l2}, \ldots, X_{ln})'$ are the relative weights for all the alternatives with respect to the $l$th criterion, and $W = (w_1, w_2, \ldots, w_m)'$ is the criteria weighting vector. As such, the ORW can be calculated with Equation 6.

$$ORW_i = \sum_{l=1}^{m} w_l X_{li}$$ **Equation 6**

Where,
$ORW_i$ = Overall relative weight for *i*th alternative;
$w_l$ = Weight of *l*th objective;
$X_{li}$ = Weight of *i*th alternative with respect to *l*th objective.

## 4.10 Calculating the Ranking Index

The final step of this process is to take certain exposure factors into consideration. The ORW obtained from the previous step is the priority of each alternative solely based on expert judgments without considering other potential influencing factors. How to determine the priority of projects with the same maintenance function will require consideration of additional factors.

Traffic is a major factor affecting pavement distress and deterioration. This report proposes taking Annual Daily Traffic (ADT) into consideration to reflect the impact of traffic on maintenance. For two maintenance projects needing the same maintenance function but with different ADTs, it is obvious the one with higher ADT should be given a higher priority. Thus, once the maintenance functions are prioritized with AHP based on the level of risk to the public and liability to the department, ADT is adopted as an exposure factor to differentiate maintenance projects with identical maintenance functions.

In addition to ADT, truck load can be another major cause for distress and deterioration of pavements since pavement damage will increase exponentially with the increase of axle load. Truck traffic can cause much more severe damage to the pavement structure than passenger cars. In other words, for maintenance work related to pavement structure, truck volume may become a more important factor than ADT to consider in the risk assessment.

Once the ORWs are computed for all maintenance activities, the exposure factor can be considered by assigning ADT or truck volume values to the corresponding activities. Since directly using the ADT or truck volume values in the ORW calculation will yield ORW values in an un-scaled range, the normalized ADT or truck volume should be used so that the ORW values produced will fall into a range with a scale that can be easily managed and interpreted. More specifically, the normalized ADT is the ADT divided by the maximum of the ADTs under consideration. The normalized truck volume can be calculated by the same process. The final ranking index can be calculated as shown in Equation 7 and 8.

$$RI = ORW \times \frac{ADT_i}{Max\{ADT_i\}} \times 100$$ **Equation 7**

or

$$RI = ORW \times \frac{Truck_i}{Max\{Truck_i\}} \times 100$$ **Equation 8**

Where,
$RI$ = Ranking Index used to prioritize projects;
$ORW$ = Overall Relative Weight of a specific maintenance alternative;
$ADT_i$ = Annual Daily Traffic for project *i*;
$Truck_i$ = Truck volume for project *i*.

# Chapter 5: Data Acquisition

## 5.1 Selecting Pilot Districts

TxDOT is composed of 25 individual districts within 4 regional offices. Each district is responsible for the design, construction, and maintenance of on-system highways within a defined geographic area. Each district consists of a district office and has multiple area offices, where an area or resident engineer oversees the design, construction, and maintenance operations of the office. Each area office may include one or several maintenance offices that perform in-house routine maintenance activities and manage maintenance related contracts.

The purpose of selecting pilot districts was not only to evaluate the practicality of the proposed framework, but also to gain insight into the similarities and differences that exist between different geographic locations and across district boundaries. To obtain a representative sample of the various maintenance needs that exist not only within but also across district's boundaries, four pilot districts were selected in cooperation with TxDOT's Project Director (PD): the Austin, Lubbock, Paris, and Pharr Districts. These Districts were selected from distinct geographical areas of the state and have different climate and soil characteristics. The different climate and soil characteristics of each district may also influence the evaluator's judgments. Therefore, using these four Districts provides an opportunity to document the varying maintenance needs in different parts of the state, and also gather insights into how the maintenance priorities are affected by local conditions.

For example, the western part of the state receives significantly less rainfall than the eastern or coastal part of the state. Therefore, Mowing, Vegetation Control, and even Drainage System Maintenance may not be as important in the western part of the state as it is in the eastern part. Also, the eastern part of the state has different soil characteristics that include high plasticity clays that may require more Base Repair work than 48 other locations. The northern part of the state may experience freeze-thaw cycles, while the southern part of the state does not. In addition to the differing climate and soil characteristics, these districts have different travel demands that can have an impact on the type of maintenance activities performed. Therefore, the local conditions should influence the evaluator's judgments. Table 12 shows the statistics for each of the pilot districts. Figure 9 shows the division of the four different climatic regions in Texas and the four pilot districts.

**Table 12: Pilot District Statistics**

| Pilot Districts Statistics | | | | |
|---|---|---|---|---|
| Statistic | Austin | Lubbock | Paris | Pharr |
| Classification | Metro | Rural | Rural | Urban |
| Geographic Location | Central | West | East | South |
| Registered Vehicles | 1,687,081 | 408,758 | 389,584 | 837,601 |
| Daily Vehicle Miles Traveled | 34,182,360 | 8,980,440 | 9,664,543 | 19,294,290 |
| Population (2009) | 1,822,072 | 446,231 | 359,709 | 1,247,368 |
| Maintenance Offices | 16 | 18 | 9 | 8 |
| Maintenance Employees | 299 | 270 | 185 | 173 |
| Centerline Miles | 3,359.86 | 5,270.91 | 3,302.41 | 2,339.84 |
| Lane Miles | 9,207.37 | 12,132.46 | 7,148.62 | 6,140.71 |
| FY ’10 Maintenance Expenditures | | | | |
| In-House | $40,423,773.05 | $30,772,989.17 | $27,060,273.09 | $20,765,175.09 |
| Contracted | $148,830,656.27 | $70,797,816.30 | $59,661,324.05 | $72,255,439.29 |
| Total | $189,254,429.32 | $101,570,805.47 | $86,721,597.14 | $93,020,614.38 |

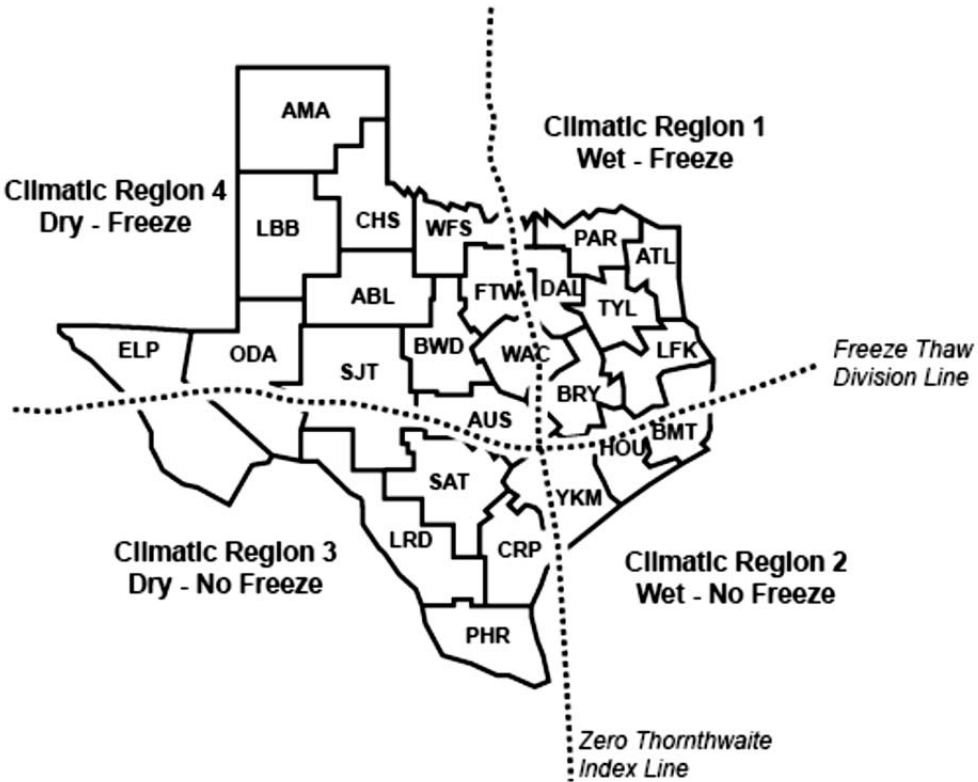


*Figure 9: Division of Climatic Regions in Texas*

## 5.2 Make-It-Rational Software

To ensure the integrity of the expert's judgments and preferences, it was important for the data acquisition method to be as simple and straightforward as possible. Simplicity would ensure that the evaluators' true judgments and preferences were captured and any inconsistencies in the data were only due to the different perspectives of the evaluators and not due to any misinterpretations attributed to the data acquisition method. To accomplish this task, several Multiple Criteria Decision Analysis (MCDA) software products were evaluated for functionality, versatility, and user interface. In addition to these factors, the software needed to be implemented with relative ease and have the capability to accommodate multiple projects and evaluators. In addition, the software needed to have an excellent graphical user interface that would virtually eliminate any possible source of confusion for the evaluators.

The Make-It-Rational Software was ultimately selected as the data acquisition method from a wide range of possible choices for the following reasons. First, it uses an online platform, and only requires internet access. This feature was a tremendous advantage since evaluators were located in different parts of the state. Second, the software must only require basic computer skills. Since it was not possible to know the computer skill level of the participants, it was necessary that use of the software was simple and straightforward. Finally, the software provided an excellent graphical user interface. This would eliminate any possible sources of bias due to confusion or misunderstandings.

The Make-It-Rational software provided all the necessary features to successfully collect the data from the evaluators. Each evaluator was provided a unique internet link to access the software. After logging in into the program, each evaluator was asked to complete each of the five sections by simply selecting the strength of their judgment or preference in favor of a certain objective or alternative.

## 5.3 Guideline of Performing Pair-wise Comparisons

Pair-wise comparison is the first step evaluators need to do in the framework. They will be asked to compare two alternatives at a time. First they will give their judgments to maintenance objectives. Then they will give their judgments to maintenance alternatives under each objective. The Make-It-Rational software is used to help conducting the procedure.

### 5.3.1 Scale System

A 1–9 scale system was selected as the measurement system. The first step is to clarify the meaning of the scale to evaluators. It is important because the results have to capture the real preferences of evaluators. Table 13 defines and explains the values.

**Table 13: Intensity of Importance Scale**

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance or preference of both elements | Two elements contribute equally to the objective |
| 3 | Moderate importance or preference of once element over another | Experience and judgment slightly favors one element over another |
| 5 | Strong importance or preference of one element over another | Experience and judgment strongly favors one element over another |
| 7 | Very strong importance or preference of one element over another | An element is strongly favored and its dominance is demonstrated in practice |
| 9 | Extreme or absolute importance or preference of one element over another | The evidence favoring one element over another is one of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values | Used when compromise is needed |
| Reciprocals of above nonzero numbers | If one element ***i*** is given a nonzero value when compared to element ***j***, then ***j*** has the reciprocal value when compared to ***i. (a*ij = 1/aij)** | |

### 5.3.2 Pair-wise Comparison of Maintenance Objectives

The second step is to perform the pair-wise comparisons of maintenance objectives. Four maintenance objectives were identified in the previous task: Safety, System Preservation, System Operation, and Aesthetics. Six pair-wise comparisons will be performed in this step. Figure 10 shows the interface of comparing maintenance objectives in Make-It-Rational software. Two sets of blue arrows point towards two maintenance objectives in opposite directions. Evaluators select the arrow pointing towards the objective that they think is more important and click on the value that they think can best represent the intensity of importance. Figure 10 shows an evaluator selecting "7" pointing towards Safety, meaning they think Safety has a very strong importance over Aesthetics.

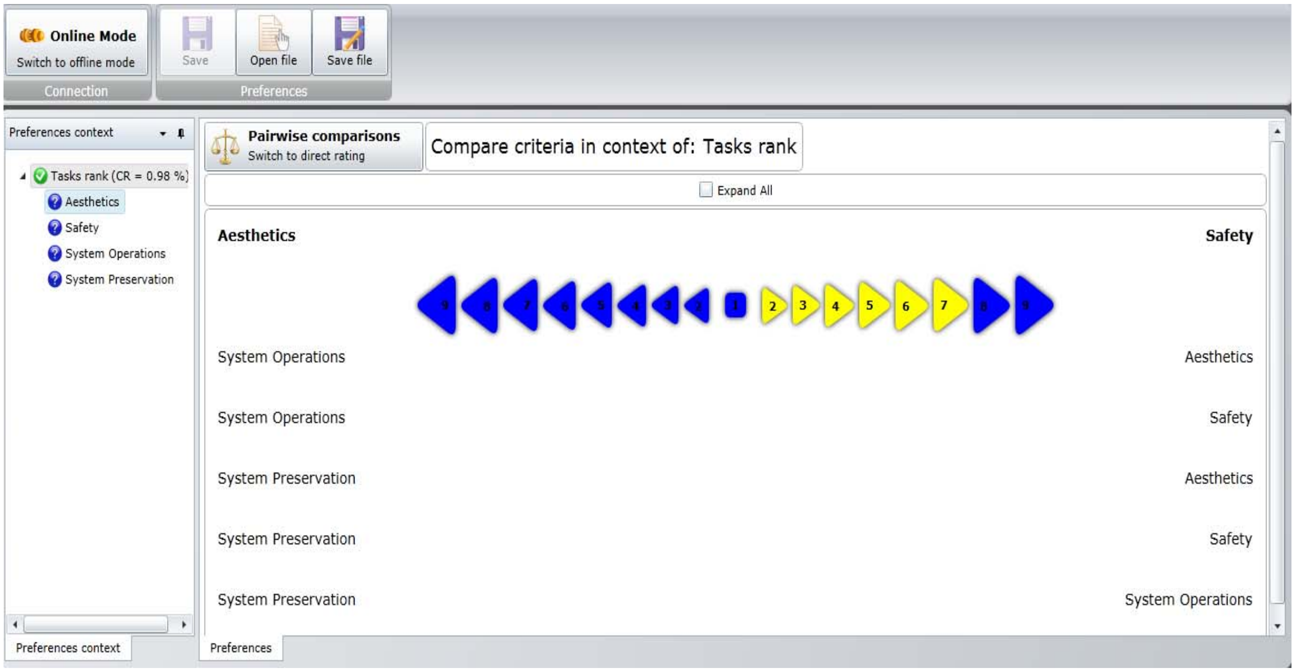


*Figure 10: Interface of Comparing Maintenance Objectives*

After finishing the comparisons, the Consistency Ratio (CR) has to be checked before proceeding to the next step. Figure 11 shows how to check the consistency ratio in the software. If the CR is less than 10% and there is a green check mark before each section, then the comparisons in this section are finished.

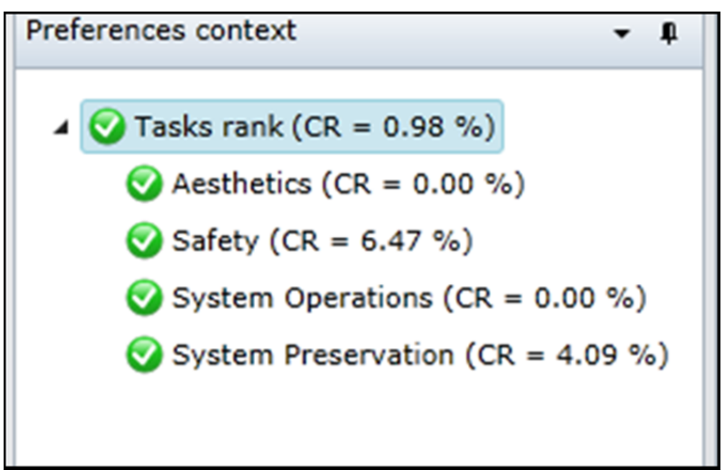


*Figure 11: Consistency Ratio Check*

### 5.3.3 Pair-wise Comparison of Maintenance Alternatives

After finishing the pair-wise comparisons of maintenance objectives, evaluators can click on the maintenance objectives on the left column and proceed with the pair-wise comparison of maintenance alternatives using the same procedure defined to compare maintenance objectives. Figure 12 shows the interface of comparing maintenance alternatives under Aesthetics. Under each maintenance objective, 120 pair-wise comparisons will be performed, meaning 480 pair-wise comparisons will be performed in this step.

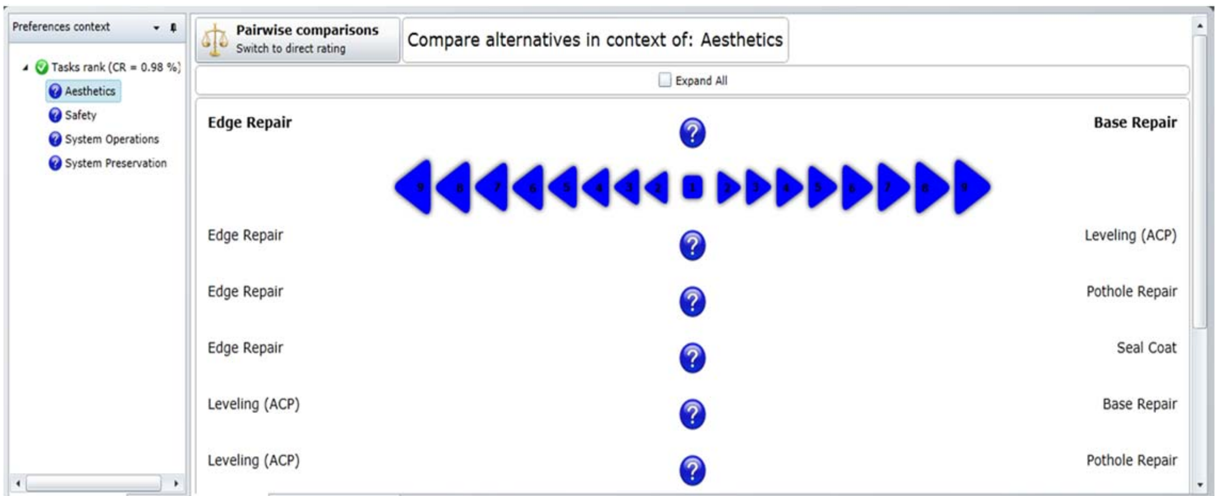


*Figure 12: Interface of Comparing Maintenance Alternatives*

# Chapter 6: Results

The evaluators' judgments were analyzed independently to ensure consistency in their judgments. Once the consistency was confirmed, the judgments of each evaluator from a particular district were combined to obtain district-wide weights for each maintenance objective and alternative. This process was also extended to obtain a comprehensive or statewide set of weights and rankings for the criteria and alternatives. This was accomplished by combining the four combined district pair-wise judgments into a single set of representative pair-wise judgments using the geometric mean method described earlier.

## 6.1 District Maintenance Objective Weights

The maintenance goals for each district were obtained by combining the judgments of each evaluator from a particular district into a single representative value using the geometric mean method. This process is demonstrated in Table 14, which shows the pair-wise judgments for each of the Pharr District evaluators and the combined judgments for the district using Equation 5.

The numerical values in this table correspond to the criteria on the left versus the criteria on the right using Dr. Saaty's Intensity of Importance Scale shown in Table 13. A value greater than one implies that the criteria on the left is preferred over the criteria on the right. A value less than one means the criteria on the right is actually preferred over the criteria on the left by the inverse of the value. For example, for Aesthetics versus Safety, Table 14 shows a 0.11 value for evaluator number 2. Since this value is less than one, this evaluator actually prefers Safety over Aesthetics with a value of 1/0.11 or 9 to 1. This indicates an absolute preference or dominance of Safety over Aesthetics. In the case of Safety versus System Operations, the table shows a value of 7 for evaluator number 3. This means that this evaluator prefers Safety over System Operations 7 to 1, indicating a very strong preference of Safety over System Operations.

**Table 14: Pharr District: Maintenance Objectives Pair-Wise Comparison Judgments**

| Pharr District: Maintenance Objectives | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Objectives | | Evaluator | | | | | | | | | | Geometric Mean |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| Aesthetics | Safety | 0.14 | 0.11 | 0.33 | 0.50 | 0.14 | 0.11 | 0.50 | 0.11 | 0.11 | 0.25 | $a_{12} = 0.19$ |
| Aesthetics | System Operations | 0.20 | 0.20 | 2.00 | 2.00 | 0.20 | 0.50 | 0.33 | 4.00 | 0.25 | 0.33 | $a_{13} = 0.53$ |
| Aesthetics | System Preservation | 0.20 | 0.20 | 0.50 | 0.50 | 0.33 | 0.50 | 0.33 | 6.00 | 0.13 | 0.33 | $a_{14} = 0.41$ |
| Safety | System Operations | 4.00 | 5.00 | 7.00 | 2.00 | 3.00 | 9.00 | 2.00 | 0.25 | 9.00 | 3.00 | $a_{23} = 3.17$ |
| Safety | System Preservation | 1.00 | 7.00 | 3.00 | 1.00 | 3.00 | 9.00 | 2.00 | 2.00 | 1.00 | 3.00 | $a_{24} = 2.42$ |
| System Operations | System Preservation | 0.33 | 2.00 | 0.33 | 0.50 | 2.00 | 1.00 | 0.50 | 0.50 | 0.33 | 0.50 | $a_{34} = 0.63$ |

After combining the evaluator's individual pairwise judgments into a district-wide representative value, these new values were entered as the district-wide preference judgments into the AHP matrix (shown in Table 15) to compute each district's maintenance objective weights.

**Table 15: AHP Matrix: Pharr District Maintenance Objectives**

| **Objectives** | Aesthetics | Safety | System Operation | System Preservation |
|---|---|---|---|---|
| Aesthetics | 1.00 | $a_{12}$ | $a_{13}$ | $a_{14}$ |
| Safety | 1/ $a_{12}$ | 1.00 | $a_{23}$ | $a_{24}$ |
| System Operation | 1/ $a_{13}$ | 1/ $a_{23}$ | 1.00 | $a_{34}$ |
| System Preservation | 1/ $a_{14}$ | 1/ $a_{24}$ | 1/ $a_{34}$ | 1.00 |

The statewide maintenance objective weights were computed in a similar manner—the only difference is that instead of using each district's evaluators, each district's combined pair-wise judgments were used.

These new statewide pair-wise judgment values were entered into the AHP matrix to produce the comprehensive or statewide maintenance objective weights. Table 16 shows the maintenance objective weights along with the ranking for each district as well as the comprehensive statewide weights. It is important to understand that the weights for each of the maintenance objectives will vary, since they are a compilation of each evaluator's unique perspective and are a function of his or her experience, knowledge and intuition. However, there is an important trend in the maintenance objective weights and rankings between the four pilot districts. Each district ranked Safety as the number one or most important maintenance objective while Aesthetics was ranked the least important. The Lubbock, Paris, and Pharr Districts ranked System Preservation to be more important than System Operation, while only the Austin district considered System Operation to have a higher priority than System Preservation.

**Table 16: District and Statewide Maintenance Objective Weights and Ranks**

| **Objectives** | **Austin** | | **Lubbock** | | **Paris** | | **Pharr** | | **Statewide** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Weight (%)** | **Rank** | **Weigh t (%)** | **Rank** | **Weight (%)** | **Rank** | **Weight (%)** | **Rank** | **Weight (%)** | **Rank** |
| Aesthetics | 5.83 | 4 | 6.80 | 4 | 6.30 | 4 | 9.27 | 4 | 7.00 | 4 |
| Safety | 50.38 | 1 | 52.13 | 1 | 58.06 | 1 | 51.60 | 1 | 53.42 | 1 |
| System Operation | 24.57 | 2 | 14.32 | 3 | 12.81 | 3 | 16.03 | 3 | 16.57 | 3 |
| System Preservation | 19.22 | 3 | 26.75 | 2 | 22.83 | 2 | 23.10 | 2 | 23.02 | 2 |

Figure 13 provides a clear picture of the similarities and variability among the four districts. The weights of safety and aesthetics are almost the same for all four pilot districts.

Although there are differences in system preservation and system operation between Austin and the other three districts, the differences are insignificant as can be seen from Figure 13.

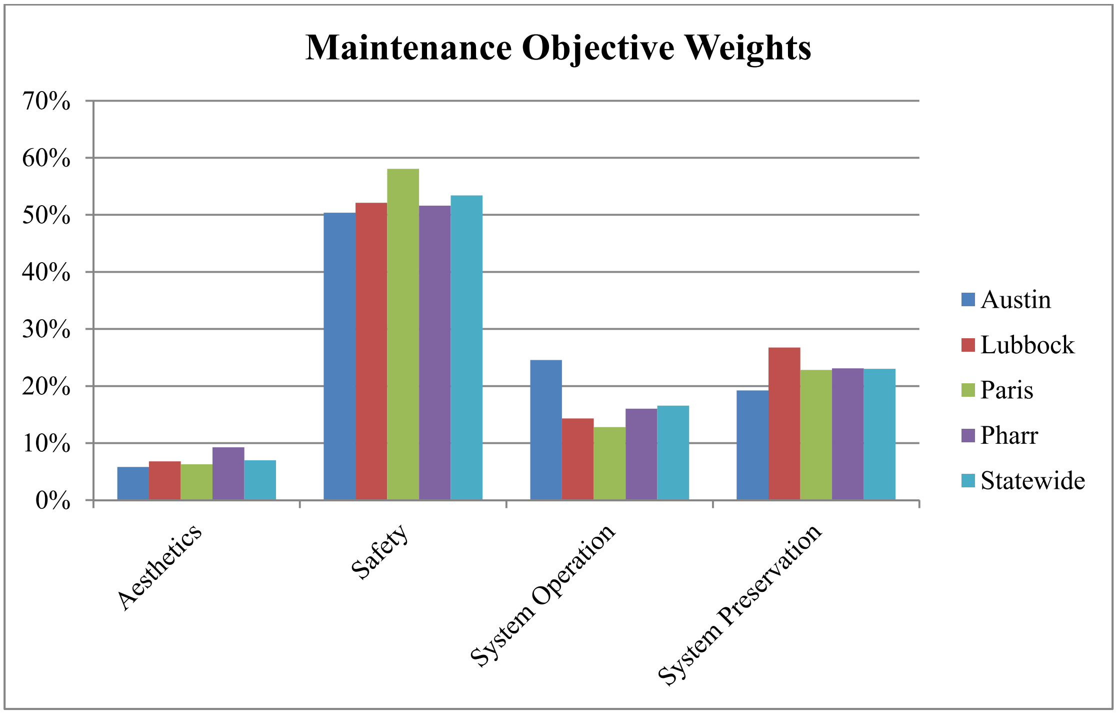


*Figure 13: Comparison among Pilot Districts and Statewide Weights*

## 6.2 District Maintenance Alternative Weights

The same process was repeated to obtain the maintenance alternative weights and rankings for the four pilot districts and the statewide average. After the local alternative weights were obtained, the Overall Relative Weight (ORW) was computed using the method described earlier.

### 6.2.1 Local Alternative Weight

The local weights represent the unadjusted or true contribution from each maintenance objective toward each maintenance alternative's total weight. The local weights do not reflect the effect of the maintenance objectives. Tables 17, 18, 19, and 20 give the local alternative weights and rankings with respect to the four different objectives for the four pilot districts. Table 21 presents the statewide results.

The weights and rankings for alternatives are different among all the four pilot districts. Although the top-three and the bottom-three maintenance activities for different districts are not exactly the same, the categories to which those activities belong are the same. All four districts selected pavement-related maintenance activities as their top-three activities and roadside-related maintenance activities as their bottom-three activities. Furthermore, three out of four pilot districts selected pothole patching as their most important maintenance activity; only the Paris District selected edge repair as their most important activity.

**Table 17: Austin District Maintenance Alternative Weights and Ranks**

| Alternative | Total Weights (%) | Rank | Aesthetics (%) | Safety (%) | System Operation (%) | System Preservation (%) |
|---|---|---|---|---|---|---|
| Base Repair | 24.50 | 8 | 2.65 | 2.83 | 5.22 | 13.80 |
| Crack Seal | 21.99 | 10 | 2.68 | 1.90 | 3.06 | 14.35 |
| Crash Attenuators | 28.11 | 7 | 4.83 | 13.63 | 6.59 | 3.06 |
| Debris/Litter/Sweeping | 20.69 | 13 | 12.67 | 3.06 | 2.84 | 2.11 |
| Drainage System Maintenance | 11.83 | 16 | 2.52 | 1.87 | 2.76 | 4.68 |
| Edge Repair | 31.93 | 3 | 3.59 | 12.90 | 7.56 | 7.88 |
| Flashing Beacons/Traffic Signals/Illumination | 30.31 | 5 | 6.75 | 9.92 | 11.47 | 2.17 |
| Milling | 12.43 | 15 | 2.43 | 2.49 | 3.68 | 3.85 |
| Mowing | 21.20 | 12 | 12.53 | 4.17 | 2.66 | 1.84 |
| Pavement Leveling/Overlay | 21.63 | 11 | 4.32 | 3.89 | 5.07 | 8.35 |
| Pavement Markings/Markers | 36.35 | 2 | 8.96 | 11.33 | 13.53 | 2.53 |
| Pothole Patching | 37.79 | 1 | 7.49 | 8.16 | 9.64 | 12.49 |
| Safety Barrier Maintenance | 24.03 | 9 | 4.84 | 10.32 | 6.53 | 2.34 |
| Signs Maintenance | 28.56 | 6 | 9.64 | 6.15 | 9.80 | 2.98 |
| Surface Treatments | 30.36 | 4 | 6.76 | 4.20 | 5.74 | 13.66 |
| Vegetation Control | 18.28 | 14 | 7.35 | 3.18 | 3.84 | 3.92 |

**Table 18: Lubbock District Maintenance Alternative Weights and Ranks**

| Alternative | Total Weights (%) | Rank | Aesthetics (%) | Safety (%) | System Operation (%) | System Preservation (%) |
|---|---|---|---|---|---|---|
| Base Repair | 31.76 | 5 | 7.00 | 7.73 | 7.95 | 9.09 |
| Crack Seal | 23.61 | 7 | 6.01 | 4.15 | 5.19 | 8.26 |
| Crash Attenuators | 19.59 | 9 | 5.38 | 6.33 | 3.91 | 3.96 |
| Debris/Litter/Sweeping | 14.77 | 16 | 3.84 | 3.90 | 4.03 | 3.01 |
| Drainage System Maintenance | 17.45 | 12 | 4.19 | 4.50 | 4.40 | 4.36 |
| Edge Repair | 32.85 | 4 | 7.54 | 8.77 | 7.64 | 8.89 |
| Flashing Beacons/Traffic Signals/Illumination | 21.56 | 8 | 5.38 | 6.15 | 6.31 | 3.71 |
| Milling | 26.33 | 6 | 6.86 | 5.71 | 6.82 | 6.95 |
| Mowing | 16.01 | 14 | 4.63 | 4.25 | 3.73 | 3.40 |
| Pavement Leveling/Overlay | 35.67 | 3 | 8.81 | 8.25 | 9.00 | 9.61 |
| Pavement Markings/Markers | 17.09 | 13 | 3.92 | 4.89 | 5.49 | 2.80 |
| Pothole Patching | 48.30 | 1 | 11.03 | 12.58 | 13.03 | 11.66 |
| Safety Barrier Maintenance | 19.52 | 10 | 5.43 | 6.24 | 4.14 | 3.71 |
| Signs Maintenance | 17.46 | 11 | 5.29 | 4.16 | 4.57 | 3.45 |
| Surface Treatments | 42.99 | 2 | 9.93 | 8.89 | 10.36 | 13.81 |
| Vegetation Control | 15.03 | 15 | 4.78 | 3.49 | 3.43 | 3.33 |

**Table 19: Paris District Maintenance Alternative Weights and Ranks**

| Alternative | Total Weights (%) | Rank | Aesthetics (%) | Safety (%) | System Operation (%) | System Preservation (%) |
|---|---|---|---|---|---|---|
| Base Repair | 34.76 | 5 | 5.65 | 7.07 | 11.27 | 10.77 |
| Crack Seal | 22.53 | 7 | 5.91 | 2.60 | 5.12 | 8.90 |
| Crash Attenuators | 15.38 | 15 | 3.47 | 6.11 | 3.00 | 2.81 |
| Debris/Litter/Sweeping | 17.51 | 13 | 5.42 | 2.98 | 3.70 | 5.42 |
| Drainage System Maintenance | 15.64 | 14 | 6.30 | 2.36 | 2.91 | 4.07 |
| Edge Repair | 46.56 | 1 | 8.58 | 13.70 | 13.12 | 11.17 |
| Flashing Beacons/Traffic Signals/Illumination | 18.04 | 11 | 3.91 | 5.75 | 4.72 | 3.66 |
| Milling | 17.54 | 12 | 4.40 | 4.87 | 3.70 | 4.57 |
| Mowing | 20.02 | 10 | 5.84 | 3.91 | 4.69 | 5.57 |
| Pavement Leveling/Overlay | 37.78 | 3 | 7.92 | 11.66 | 10.57 | 7.61 |
| Pavement Markings/Markers | 24.72 | 6 | 6.42 | 9.24 | 5.17 | 3.89 |
| Pothole Patching | 35.92 | 4 | 7.33 | 10.63 | 9.72 | 8.25 |
| Safety Barrier Maintenance | 12.74 | 16 | 4.76 | 2.70 | 2.89 | 2.39 |
| Signs Maintenance | 20.57 | 8 | 6.16 | 3.89 | 6.16 | 4.36 |
| Surface Treatments | 39.83 | 2 | 12.56 | 7.14 | 7.88 | 12.24 |
| Vegetation Control | 20.46 | 9 | 5.38 | 5.39 | 5.36 | 4.33 |

**Table 20: Pharr District Maintenance Alternative Weights and Ranks**

| Alternative | Total Weights (%) | Rank | Aesthetics (%) | Safety (%) | System Operation (%) | System Preservation (%) |
|---|---|---|---|---|---|---|
| Base Repair | 34.33 | 2 | 7.00 | 7.56 | 9.36 | 10.41 |
| Crack Seal | 24.84 | 7 | 5.53 | 3.21 | 5.95 | 10.15 |
| Crash Attenuators | 22.45 | 9 | 4.38 | 8.17 | 5.72 | 4.18 |
| Debris/Litter/Sweeping | 16.49 | 14 | 7.58 | 3.28 | 3.09 | 2.54 |
| Drainage System Maintenance | 14.56 | 15 | 4.02 | 3.61 | 3.32 | 3.60 |
| Edge Repair | 30.74 | 3 | 6.12 | 9.84 | 6.31 | 8.47 |
| Flashing Beacons/Traffic Signals/Illumination | 21.26 | 11 | 3.41 | 10.15 | 4.85 | 2.85 |
| Milling | 22.27 | 10 | 4.47 | 5.73 | 5.79 | 6.28 |
| Mowing | 18.98 | 13 | 7.38 | 3.82 | 3.68 | 4.10 |
| Pavement Leveling/Overlay | 28.19 | 5 | 7.21 | 6.21 | 7.16 | 7.62 |
| Pavement Markings/Markers | 29.27 | 4 | 8.00 | 7.10 | 9.31 | 4.86 |
| Pothole Patching | 49.64 | 1 | 9.64 | 11.54 | 14.43 | 14.03 |
| Safety Barrier Maintenance | 20.54 | 12 | 5.16 | 6.95 | 5.35 | 3.08 |
| Signs Maintenance | 24.63 | 8 | 6.51 | 6.49 | 7.14 | 4.49 |
| Surface Treatments | 27.37 | 6 | 7.05 | 3.90 | 5.93 | 10.49 |
| Vegetation Control | 14.44 | 16 | 6.54 | 2.45 | 2.59 | 2.86 |

**Table 21: Statewide Maintenance Alternative Weights and Ranks**

| Alternative | Total Weights (%) | Rank | Aesthetics (%) | Safety (%) | System Operation (%) | System Preservation (%) |
|---|---|---|---|---|---|---|
| Base Repair | 31.02 | 4 | 5.46 | 6.08 | 8.43 | 11.06 |
| Crack Seal | 23.21 | 7 | 5.01 | 2.97 | 4.88 | 10.36 |
| Crash Attenuators | 21.41 | 10 | 4.66 | 8.46 | 4.76 | 3.53 |
| Debris/Litter/Sweeping | 17.07 | 15 | 6.96 | 3.45 | 3.52 | 3.13 |
| Drainage System Maintenance | 14.90 | 16 | 4.22 | 3.01 | 3.43 | 4.24 |
| Edge Repair | 35.85 | 2 | 6.42 | 11.61 | 8.61 | 9.20 |
| Flashing Beacons/Traffic Signals/Illumination | 22.70 | 9 | 4.88 | 8.09 | 6.63 | 3.09 |
| Milling | 19.46 | 11 | 4.44 | 4.65 | 5.00 | 5.37 |
| Mowing | 18.84 | 13 | 7.34 | 4.21 | 3.76 | 3.53 |
| Pavement Leveling/Overlay | 30.75 | 5 | 7.12 | 7.26 | 7.97 | 8.40 |
| Pavement Markings/Markers | 26.50 | 6 | 6.80 | 8.14 | 8.06 | 3.50 |
| Pothole Patching | 43.74 | 1 | 9.11 | 11.09 | 11.99 | 11.55 |
| Safety Barrier Maintenance | 19.00 | 12 | 5.27 | 6.15 | 4.68 | 2.89 |
| Signs Maintenance | 23.06 | 8 | 7.02 | 5.24 | 6.94 | 3.86 |
| Surface Treatments | 35.22 | 3 | 9.12 | 5.95 | 7.50 | 12.66 |
| Vegetation Control | 17.26 | 14 | 6.17 | 3.64 | 3.82 | 3.62 |

Some variability is expected among the pilot districts and this is perhaps more evident in Figures 14, 15, 16, and 17. These figures indicate that some districts favor certain maintenance functions over others in terms of the four objectives. For example, per Figure 14 the Austin district evaluators consider Debris/Litter/Sweeping and Mowing to have significantly higher local weights in the context of Aesthetics than any other district. Although there is more variability among the evaluators among the sub-category contribution to Aesthetics, Safety, and System Operation, Figure 17 makes clear that most evaluators are able to agree in each maintenance sub-category's contribution to System Preservation. Figure 18 compares the overall local weights for each maintenance sub-category, illustrating that pavement related maintenance activities are at the top and include Pothole Patching, Edge Repair, Surface Treatments, and Base Repair.

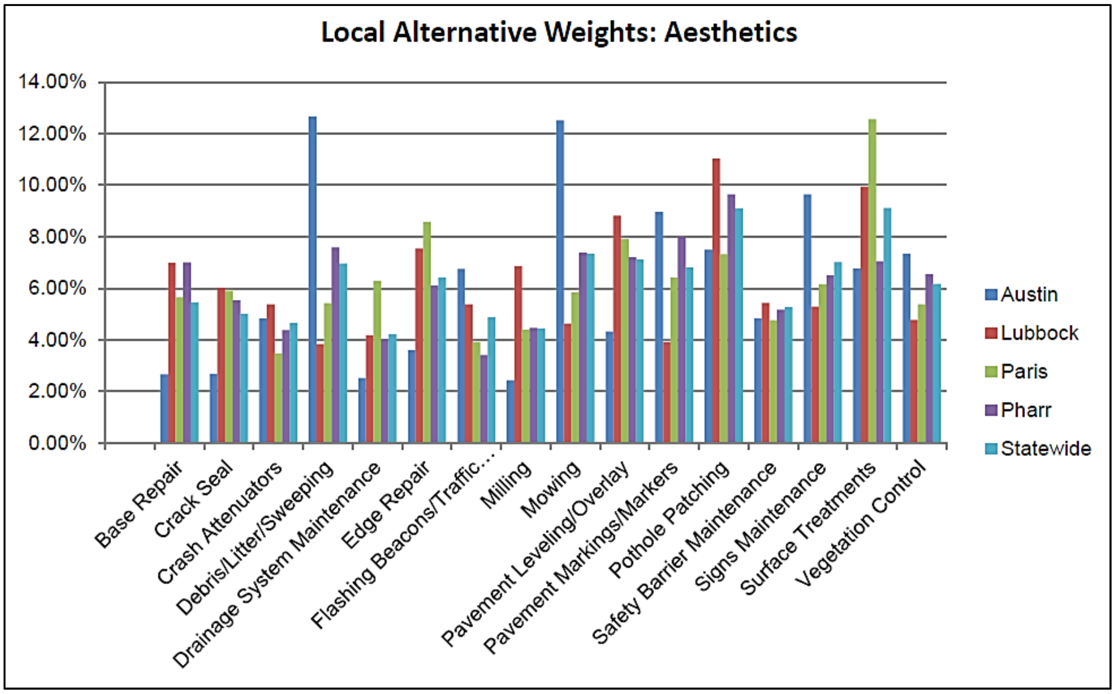


*Figure 14: Local Alternative Weights Comparison: Aesthetics*

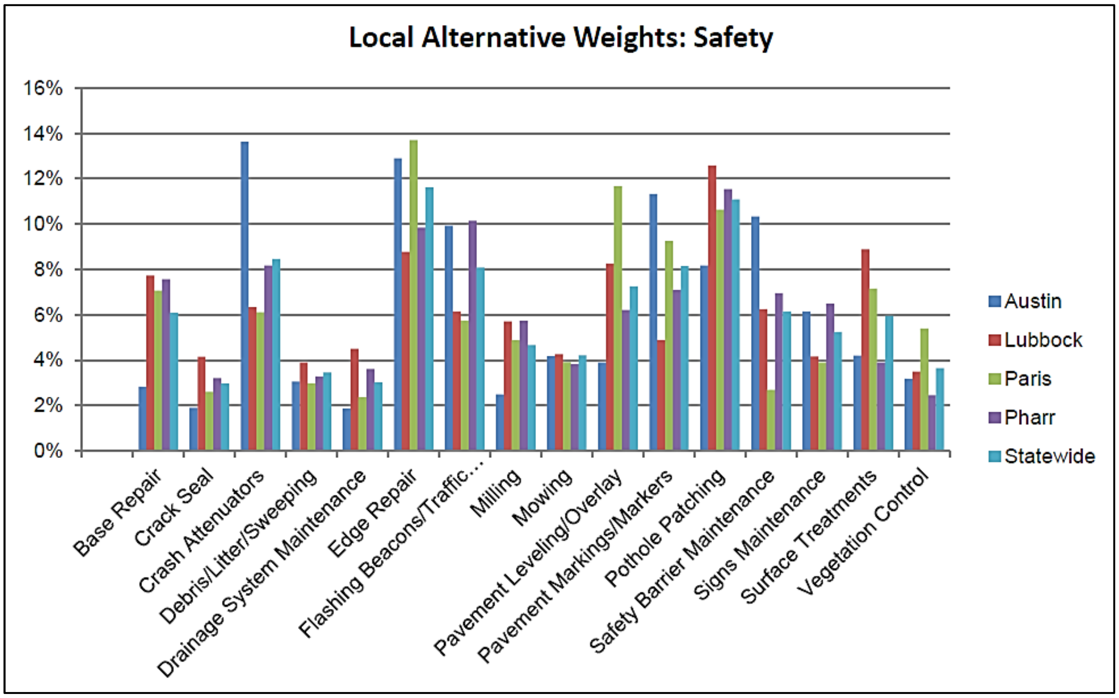


*Figure 15: Local Alternative Weight Comparison: Safety*

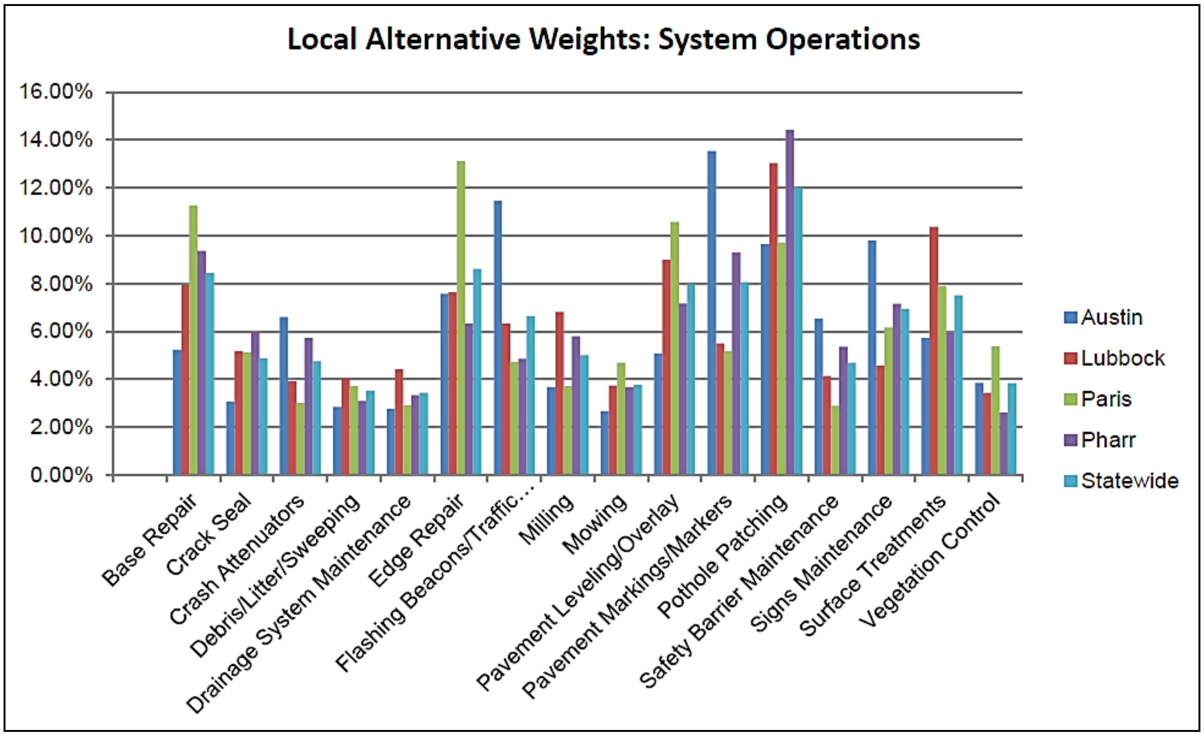


*Figure 16: Local Alternative Weight Comparison: System Operations*

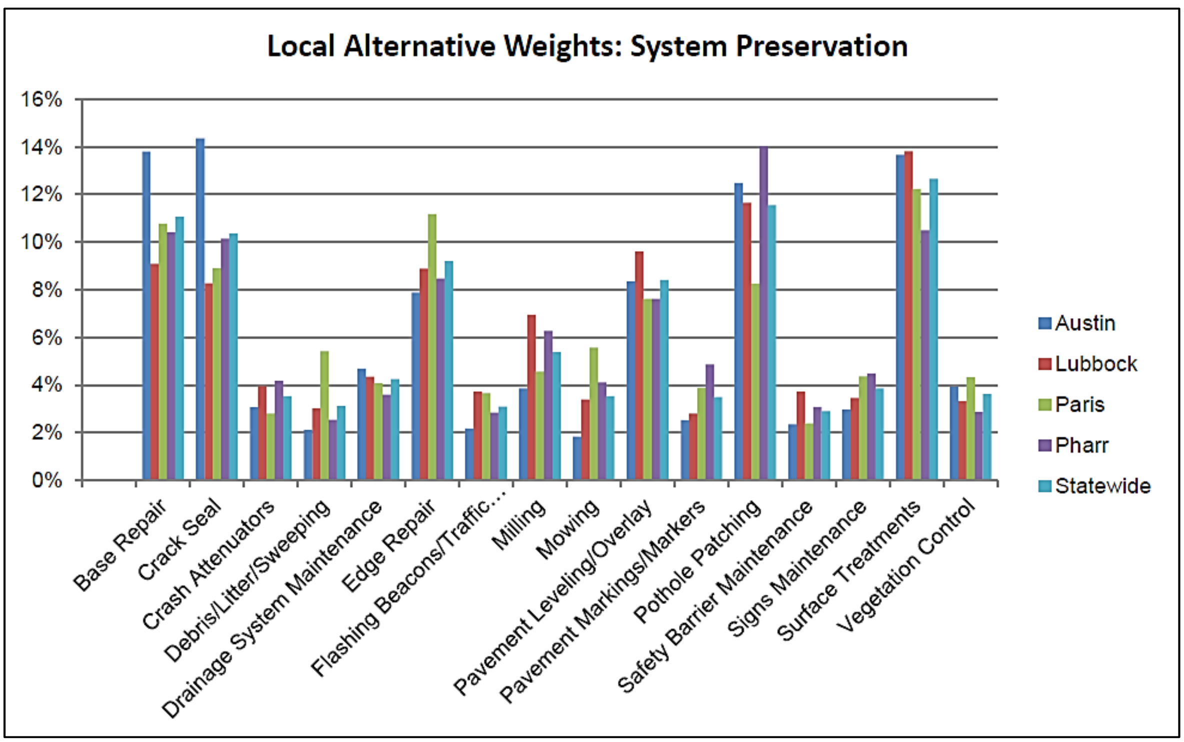


*Figure 17: Local Alternative Weight Comparison: System Preservation*

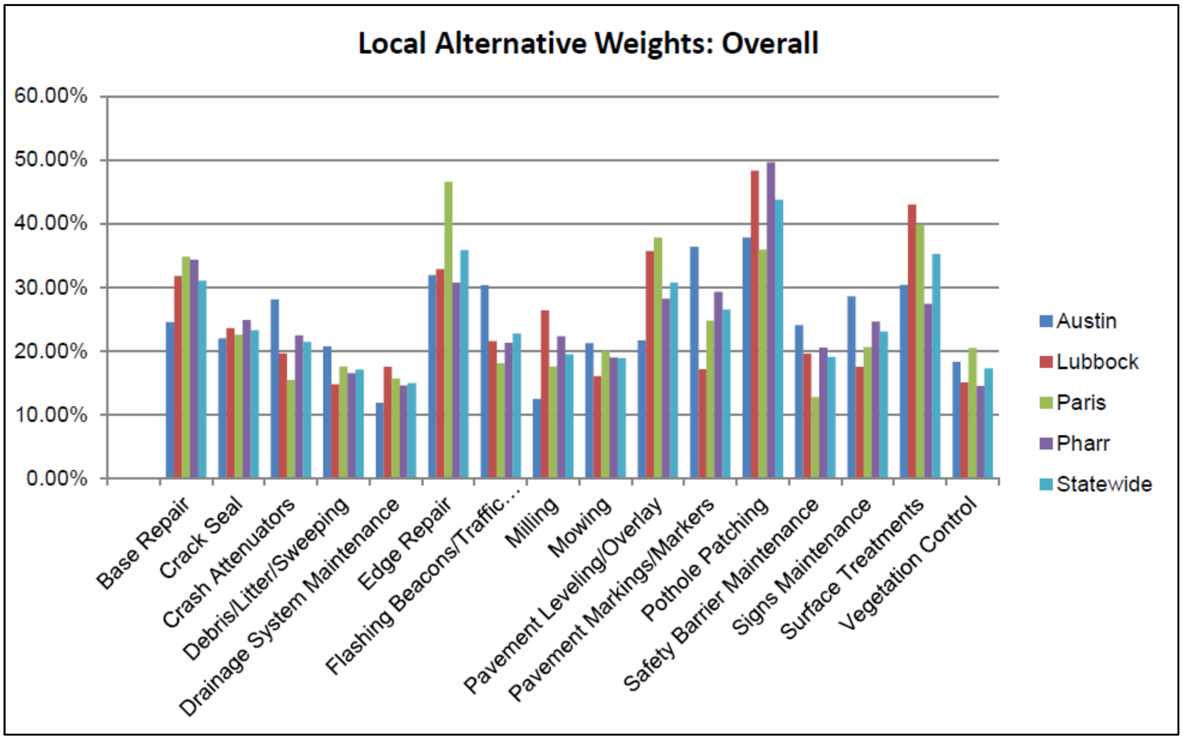


*Figure 18: Local Alternative Weight Comparison: Overall*

### 6.2.2 Overall Relative Weight

The global weight or ORW reflects the influence of the maintenance objectives in the weight or rank of each maintenance or alternative. It is computed as the product of the maintenance objective and each maintenance sub-category's corresponding weight and therefore captures the importance of each maintenance objective. Earlier, the maintenance objective weights were computed and indicated that Safety was given the highest weight. Therefore, the global values will tend to be dominated by the Safety component for each of the four pilot districts. The opposite is true for the Aesthetics component since in most cases it contributes the least toward the ORW because of the Aesthetics objective's relatively small weight.

Although the global weights and ranking of the maintenance alternatives have changed when compared to the local weights, the global weights still tend to favor pavement-related maintenance activities. From Figures 19 through 22 the top three maintenance sub-categories for each pilot district represent pavement-related maintenance activities, while the lower three maintenance sub-categories represent roadside-related maintenance activities.

The same variability that existed in the local weights is also evident in the global weights and can be observed in Figures 19 through 22. Aesthetics appears to have the greatest variability among the maintenance objectives with no clear maintenance sub-category dominating. In terms of Safety, the focus appears to be in pavement and traffic operations related maintenance functions with Edge Repair, Pothole Patching, Pavement Markings/Markers, Crash Attenuators, and Flashing Beacons/Traffic Signals/Illumination ranking in the top five, respectively. For System Operation and System Preservation, the top three and top five alternatives are pavement related maintenance functions respectively. For the ORW, pavement-related maintenance functions ranked higher than traffic operations and roadside functions, as shown in Figure 23 and Table 22.

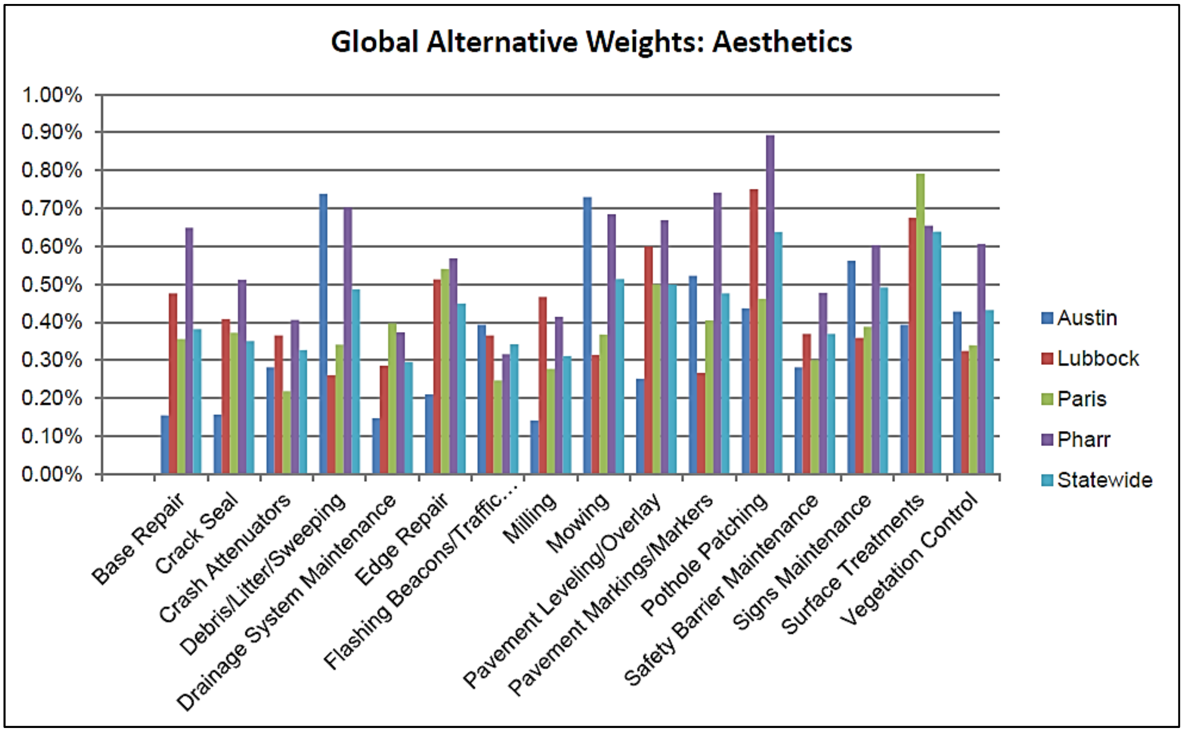


*Figure 19: Global Alternative Weight Comparison: Aesthetics*

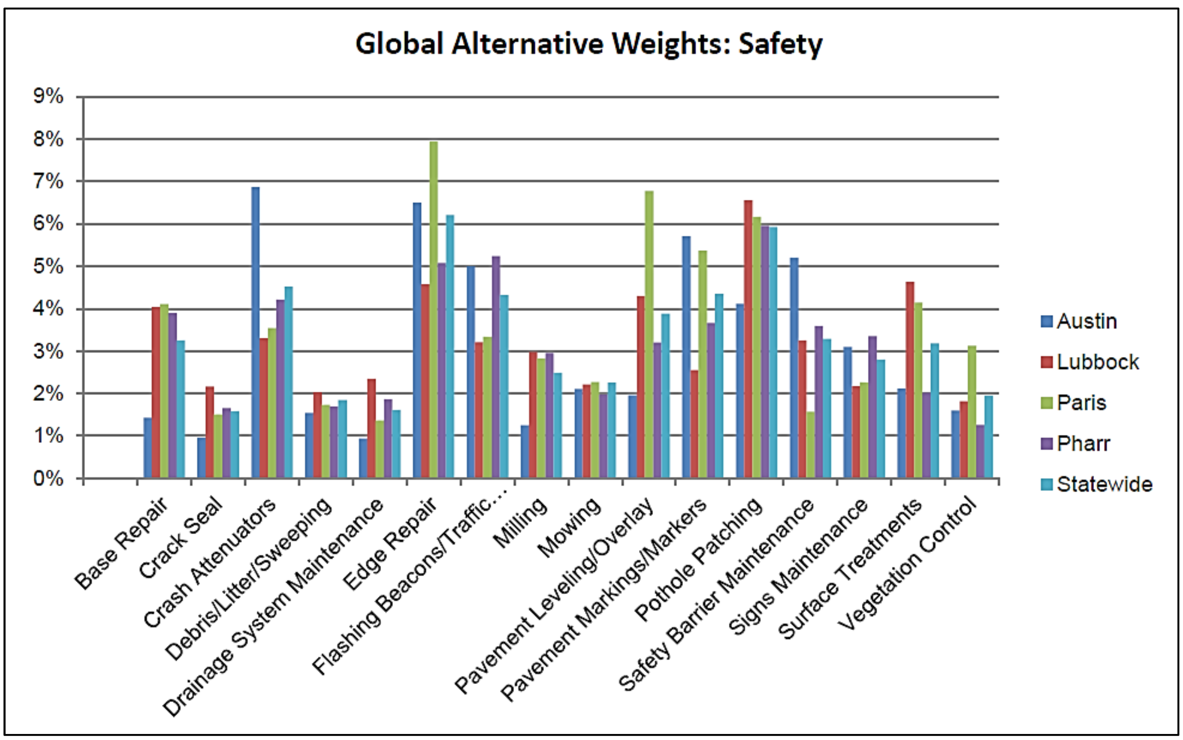


*Figure 20: Global Alternative Weight Comparison: Safety*

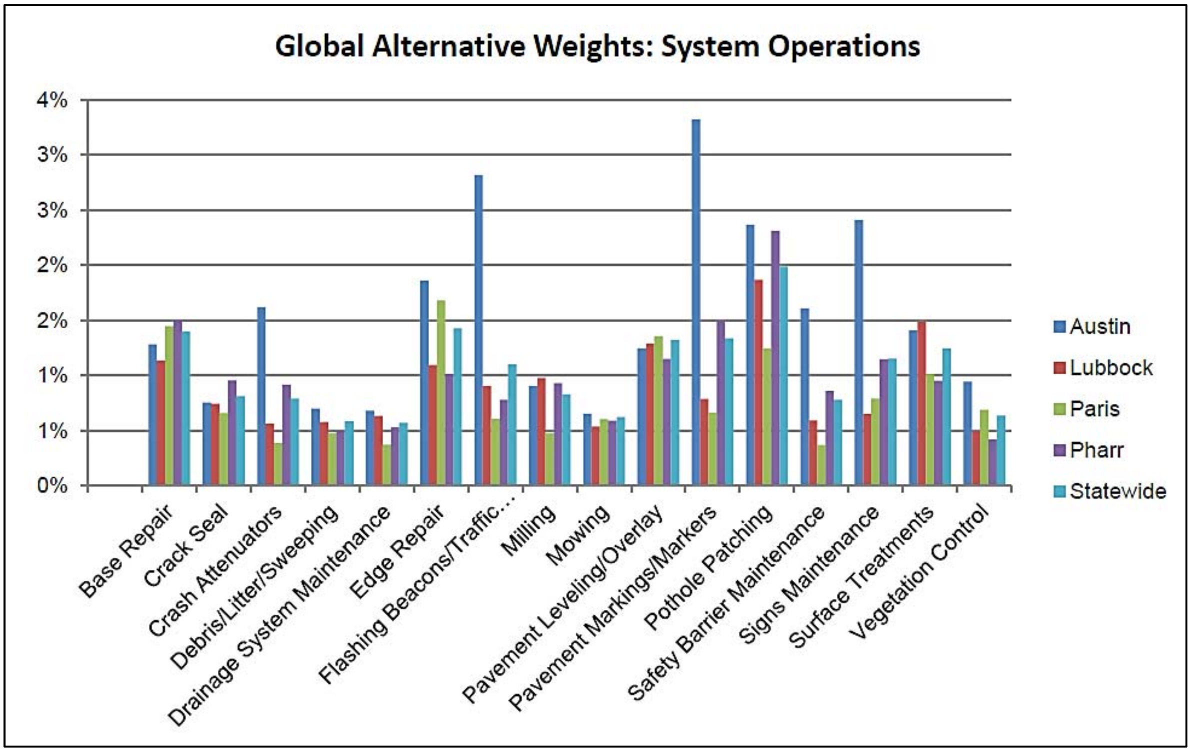


*Figure 21: Global Alternative Weight Comparison: System Operations*

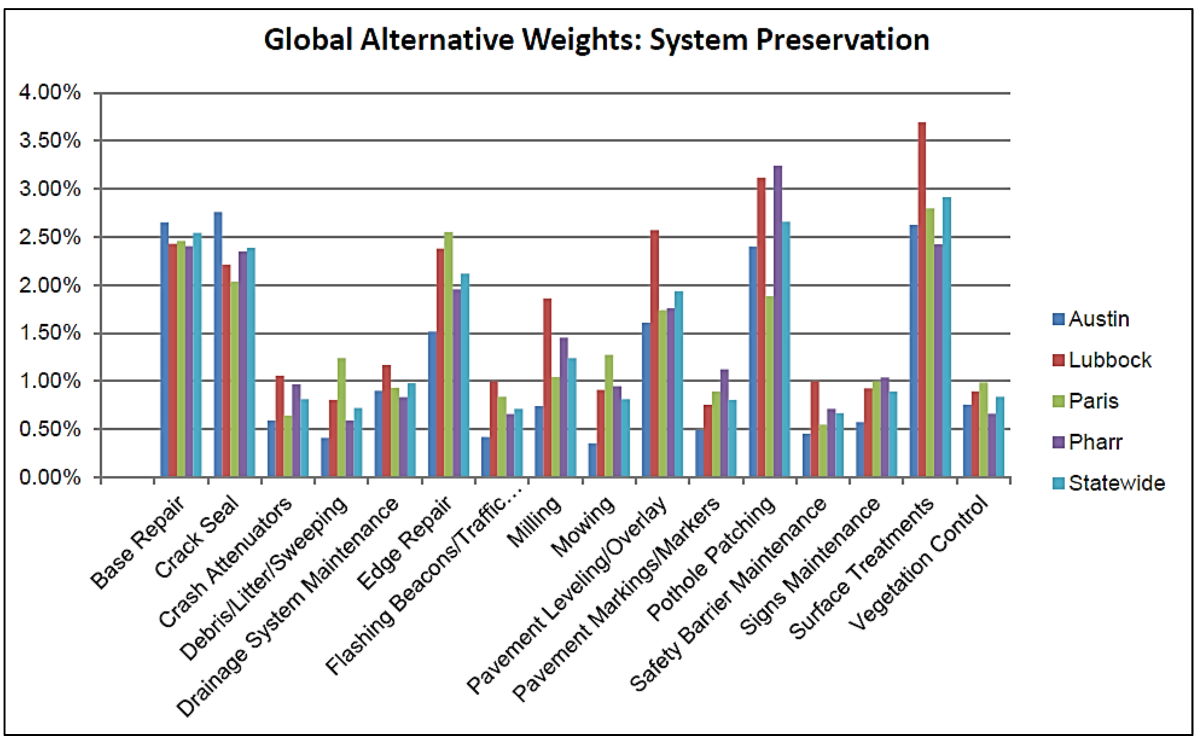


*Figure 22: Global Alternative Weight Comparison: System Preservation*

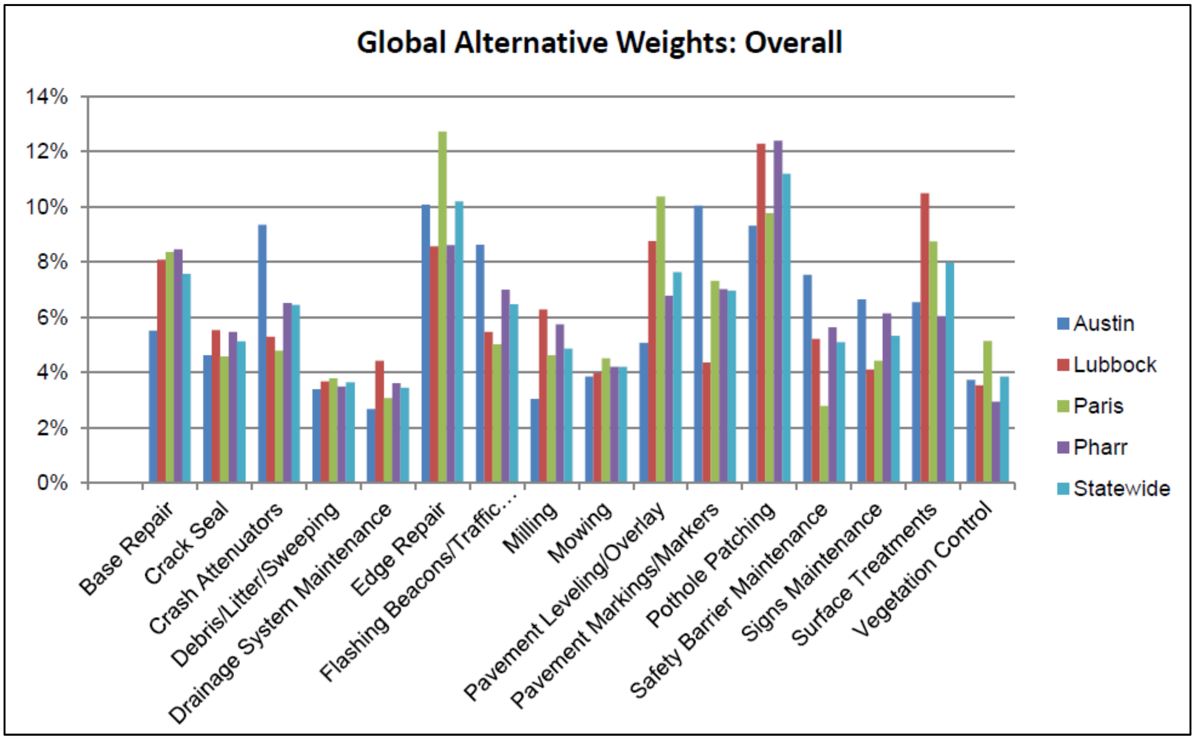


*Figure 23: Global Alternative Weight Comparison: Overall*

**Table 22: Districts and Statewide Maintenance Alternative Weights and Ranks**

| Objectives | Austin | | Lubbock | | Paris | | Pharr | | Statewide | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Weight (%) | Rank | Weigh t (%) | Rank | Weight (%) | Rank | Weight (%) | Rank | Weight (%) | Rank |
| Base Repair | 5.51 | 9 | 8.08 | 5 | 8.36 | 5 | 8.50 | 3 | 7.57 | 4 |
| Crack Seal | 4.62 | 11 | 5.53 | 7 | 4.57 | 11 | 5.50 | 12 | 5.13 | 10 |
| Crash Attenuators | 9.36 | 3 | 5.29 | 9 | 4.79 | 9 | 6.53 | 7 | 6.45 | 7 |
| Debris/Litter/ Sweeping | 3.38 | 14 | 3.67 | 15 | 3.78 | 14 | 3.52 | 15 | 3.64 | 15 |
| Drainage System Maintenance | 2.67 | 16 | 4.43 | 11 | 3.07 | 15 | 3.62 | 14 | 3.45 | 14 |
| Edge Repair | 10.08 | 1 | 8.56 | 4 | 12.72 | 1 | 8.65 | 2 | 10.20 | 2 |
| Flashing Beacons/ Traffic Signals /Illumination | 8.63 | 5 | 5.47 | 8 | 5.02 | 8 | 7.01 | 5 | 6.48 | 6 |
| Milling | 3.04 | 15 | 6.28 | 6 | 4.62 | 10 | 5.78 | 10 | 4.86 | 9 |
| Mowing | 3.84 | 12 | 3.98 | 14 | 4.51 | 12 | 4.24 | 13 | 4.20 | 13 |
| Pavement Leveling/ Overlay | 5.06 | 10 | 8.76 | 3 | 10.36 | 2 | 6.82 | 6 | 7.63 | 5 |
| Pavement Markings /Markers | 10.04 | 2 | 4.35 | 12 | 7.32 | 6 | 7.07 | 4 | 6.96 | 8 |
| Pothole Patching | 9.32 | 4 | 12.29 | 1 | 9.76 | 3 | 12.46 | 1 | 11.21 | 1 |
| Safety Barrier Maintenance | 7.54 | 6 | 5.21 | 10 | 2.78 | 16 | 5.67 | 11 | 5.10 | 11 |
| Signs Maintenance | 6.64 | 7 | 4.10 | 13 | 4.43 | 13 | 6.17 | 8 | 5.33 | 12 |
| Surface Treatments | 6.54 | 8 | 10.49 | 2 | 8.74 | 4 | 6.08 | 9 | 7.97 | 3 |
| Vegetation Control | 3.73 | 13 | 3.53 | 16 | 5.14 | 7 | 2.98 | 16 | 3.85 | 16 |

# Chapter 7: Comparison of Results among Districts

As briefly discussed in the previous chapter, weights and rankings of maintenance objectives and alternatives showed strong similarities among the four pilot districts. However, variability also exists among the results. It is hard to determine whether the variability is statistically significant among the districts without conducting statistical analyses. In other words, statistical analyses are needed to test the similarities among different sets of data. Statistical hypothesis tests are the most effective and commonly-used method to test whether several sets of data are related.

There are two types of statistical tests: parametric and non-parametric tests. Parametric tests are often considered to be more reliable since they assume the data follows a certain probability distribution and meet level of measurement requirements. But this statement is true only when this assumption is correct. If the assumption is incorrect, the results can be misleading. Analysis of Variance (ANOVA) is the most popular parametric test to detect correlations among several sets of data. It requires that the samples entering the test must obey the Gaussian distribution. Because of the nature of the data used in this research, it is difficult to determine whether the data obeys the Gaussian distribution. Under such circumstances, a non-parametric test is more appropriate for testing the similarities among the pilot districts.

Non-parametric tests do not rely on the assumptions that the data are drawn from a given probability distribution; rather, the tests can be conducted with data measured at the ordinal level, i.e., data composed of rankings. Because of their reliance on fewer assumptions, non-parametric tests enjoy a wide range of applications and are more robust. The downside of this test is that it is less powerful when there indeed exists an appropriate parametric test. Kendall's tau test and Kruskal-Wallis test are two commonly-used non-parametric methods of testing whether samples are statistically dependent.

Kendall's tau test is often used as a method to test whether two sets of data are statistically dependent. The most important step in this method is to calculate the Kendall rank correlation coefficient, $\tau$ (tau). First, obtain the ranking for both sets of data. Then, rearrange data sets so that they are in natural order by the first data set ranking. After the data sets are rearranged, consider possible pairs of the second data set rankings and give scores to each pair using these criteria: +1 if the pair is in natural order, and -1 if not. Sum those scores together to obtain the actual total for the given two data sets. Divide the actual total by the maximum possible total to obtain the final coefficient $\tau$. Equation 9 demonstrates the formula to calculate the coefficient [16].

$$\tau = \frac{\Sigma}{\frac{1}{2}N(N-1)} \qquad \textbf{Equation 9}$$

Where,
$\Sigma$ = Actual score of given rankings;
$N$ = Number of observations ranked.

The null hypothesis of the Kendall's tau test is that the two sets of data are statistically independent. And the null hypothesis is rejected when the probability P(CV > $\tau$) is smaller than the confidence level $\alpha$, where CV is the critical value in correspondence to the confidence level.

If $N$ is equal to or larger than 10, then τ is considered distributed normally with a mean equal to zero and a standard deviation computed by Equation 10.

$$\sigma = \sqrt{\frac{2(2N+5)}{9N(N-1)}} \qquad \textbf{Equation 10}$$

However, Kendall's tau test can only test association between two sets of data at a time. If more than two sets of data exist, more tests are needed. Four sets of data were obtained in this research; in order to test the association among those four data sets, six tests should be performed, compromising the reliability of this test. For example, the confidence level for this test is 5 percent, which means the reliability of performing one test is 95 percent. After performing six tests, the reliability of the test will become $(95 \text{ percent})^6$ = 73.5 percent. The reliability is significantly reduced with the increase of number of data sets. In other words, Kendall's tau test is not the most appropriate when dealing with more than two sets of data.

In order to resolve this issue, the Kruskal-Wallis test (also called the *H test*) is introduced to specifically deal with association among more than two sets of data. The null hypothesis for this test is that all the data sets originate from the same distribution. If the null hypothesis is rejected, then it means there is at least one difference existing between two sets of data. But how many differences actually exist and which data sets are different cannot be determined from this test. Other post hoc tests are needed if the test result is significant.

This rank test requires that all the observations be ranked together, and the sum of the ranks of each data set be obtained separately. The greater the observed value, the larger the rank number. Therefore, 1 will be assigned to the smallest value of all the sampled data and N will be assigned to the largest. The test statistic H is computed using Equation 11 if there is no tie (no two observations are equal) [17].

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{C} \frac{R_i^2}{n_i} - 3(N+1) \qquad \textbf{Equation 11}$$

Where,
$C$ = The number of samples;
$n_i$ = The number of observations in the $i$th sample;
$N = \Sigma n_i$, the number of observations in all samples combined;
$R_i$ = the sum of the ranks in the $i$th sample.

If there are ties, each observation is given the mean of the ranks for which it is tied. For example, there are two equal observations which are ranked 6 and 7, instead of ranking them both 6, the mean of 6 and 7 is given to both observations. So both observations will be ranked 6.5. H can be corrected by Equation 12 [17].

$$H = \frac{\frac{12}{N(N+1)} \sum_{i=1}^{C} \frac{R_i^2}{n_i} - 3(N+1)}{1 - \frac{\sum T}{N^3 - N}} \qquad \textbf{Equation 12}$$

Where the summation is over all groups of ties and $T = t^3\text{-}t$ for each group of ties, t being the number of tied observations in the group.

The null hypothesis is rejected if the statistic H is larger than the critical value CV. And if the sample sizes $n_i$ are not too small—say, larger than 5—then H obeys the chi-square distribution with a degree of freedom *C-1*. For those tests that can use appropriate chi-square distributions, *p*-value – P(CV > H) can be calculated and the null hypothesis can be rejected if the *p*-value is less than confidence level α. If the sample sizes are less than 5, then there are probability tables specifically computed for the Kruskal-Wallis test, where the critical value under different confidence levels can be found.

## 7.1 Associations among Maintenance Objectives

First, the associations among maintenance objectives should be checked. Based on Table 16 and Figure 13 there are strong similarities among maintenance objectives of four pilot districts. Little variability exists except that the weights of system operation and system preservation in Austin district are different from the other three districts.

To use the Kruskal-Wallis tests mentioned earlier, the first step is to calculate the ranking of all the observations and sum of ranks obtained by each sample. Table 23 shows the combined rankings of maintenance objectives from the four districts and the sum of each district's rankings.

**Table 23: Weights and Combined Rankings of Maintenance Objectives**

| Objectives \ Districts | Austin (%) | Lubbock (%) | Paris (%) | Pharr (%) | Rank | | | |
|---|---|---|---|---|---|---|---|---|
| **Aesthetics** | 5.83 | 6.80 | 6.30 | 9.87 | 1 | 3 | 2 | 4 |
| **Safety** | 50.38 | 52.13 | 58.06 | 51.60 | 13 | 15 | 16 | 14 |
| **System Operation** | 24.57 | 14.32 | 12.81 | 16.03 | 11 | 6 | 5 | 7 |
| **System Preservation** | 19.22 | 26.75 | 22.83 | 23.10 | 8 | 12 | 9 | 10 |
| | | | | **Sum** | 33 | 36 | 32 | 35 |
| | | | | **Average** | 8.25 | 9 | 8 | 8.75 |

Since there is no tie in the data, Equation 11 is used to compute the test statistic H, with the sample size being 4 for each and the combined sample size being 16.

$$H = \frac{12}{16 \times 17} \times \left( \frac{33^2 + 36^2 + 32^2 + 35^2}{4} \right) - 3 \times 17 = 0.111$$

Because the number of observations of each sample is too small, the chi-square distribution is inapplicable to H. By setting the confidence level at 5 percent and using the probability table, the critical value CV is 7.235. Since H is much less than the critical value at the 5 percent confidence level, the null hypothesis cannot be rejected meaning the four sets of data from the four districts are statistically correlated. Therefore, all four districts share the same preferences in terms of maintenance objectives; this means that the state average can be adopted by all 25 districts to represent their judgments and preferences on maintenance objectives.

## 7.2 Associations among Maintenance Alternatives

Though Tables 17 to 20 indicate that there is greater variability among maintenance alternatives than maintenance objectives; it is still hard to decide whether the four sets of data are correlated with each other. So the same procedure used in the previous section is replicated here to test whether the four districts preferences on maintenance alternatives are statistically the same under different maintenance objectives.

Appendices A.1 to A.4 show the tables of combined rankings for 16 maintenance alternatives under the four maintenance objectives, respectively.

Because the number of observations in each sample is larger than 5, the test statistic H obeys the chi-square distribution. There are four samples in the test, so the degree of freedom for the chi-square distribution is 3. Using Equation 11, H values were calculated for rankings under each objectives and *p*-value were determined using the chi-square distribution. The results are shown in Table 24.

**Table 24: H value and p-value Results**

| | Aesthetics | Safety | System Operation | System Preservation |
|---|---|---|---|---|
| **H** | 0.409 | 0.667 | 0.225 | 1.030 |
| **p-value** | 0.938 | 0.880 | 0.973 | 0.793 |

By setting the confidence level at 5 percent, all the four *p*-values are larger than the confidence level. So the null hypothesis cannot be rejected, meaning that the preferences on maintenance alternatives are statistically correlated under each corresponding maintenance objectives; this suggests that the state average can be adopted to represent the preferences on the maintenance alternatives of the 25 districts.

## 7.3 Associations among ORWs

The statistical dependencies among maintenance objectives and maintenance alternatives under each objective have been demonstrated in the previous sections. This cannot guarantee that the products of these two weights, or the ORWs, are statistically dependent. Since ORWs are the final weights and rankings of each maintenance alternative used in the optimization process, it is important to test whether the state average can be adopted by all the 25 districts.

The same calculation procedure was carried out to test the statistical dependency among the ORWs. Appendix A.5 shows the combined rankings for the ORWs of 16 maintenance alternatives. The H value was calculated using Equation 11, and the chi-square distribution with the three degrees of freedom was chosen to calculate the *p*-value since the sample size is larger than 5. Setting the confidence level $\alpha$ at 5 percent, H can be calculated as follows:

$$H = \frac{12}{64 \times 65} \times \left( \frac{521^2 + 514^2 + 505^2 + 540^2}{16} \right) - 3 \times 65 = 0.119$$

Using the chi-square distribution the *p*-value is 0.989, much larger than the confidence level 0.05. It was concluded that ORWs of the four pilot districts are correlated and the differences among them are small enough that the average could represent any one of the pilot districts. If the 4 pilot districts truly represent the possible range of district values, then the state average can be adopted by all the 25 districts to represent the overall preferences.

# Chapter 8: Prototype System

When each district is making strategic maintenance plans, all the maintenance projects under consideration are already identified. However, only a portion of those projects can be implemented because of the shortage of maintenance funds. In order to assist each district in selecting the most cost-effective maintenance projects and maximize the outcome of the maintenance funding, a prototype system was developed to demonstrate how to optimize resource allocation based on the findings of this research.

This prototype system is a web-based application which can be accessed by all TxDOT personnel from the district or division offices with a computer connected to the internet. It uses the ORWs from the pilot districts as the basic rankings of maintenance activities. Exposure factors, such as ADT and truck volume, can be integrated into the process to adjust the priorities of maintenance projects with different ADTs or truck volumes. After the current maintenance budget has been entered into the system, the system calculates the cost for each of the maintenance projects using the default maintenance activities unit costs and generates the final list of prioritized projects under a given budget constraint.

## 8.1 Main Menu

In the prototype system, all the ORWs for all 4 pilot districts and the state average ORWs can be calculated, even the state average has proved to be applicable to all the 25 districts. There is one thing that needs to be clarified. The results for each of the four pilot districts represent a typical demographic and climatic region in Texas. So when districts other than these four are using the system, they can choose one of the pilot districts most comparable in demography and climate to their own district or the state average.

Figure 24 is the screenshot of the main menu of the prototype system. On the top of the main menu are the project number and title. There are five orange buttons under the title, each representing one of the four pilot districts (Austin, Lubbock, Paris, and Pharr) and the state average. The user from different districts can choose the one most comparable with the corresponding button, leading them to the optimization page that uses the corresponding ORWs.

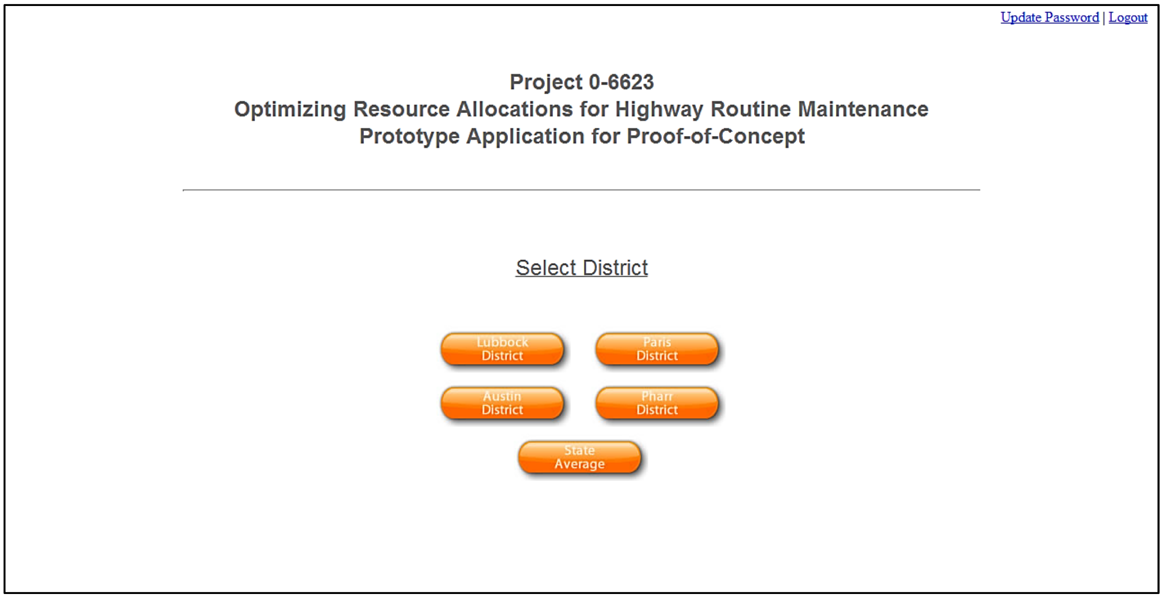


*Figure 24: Screenshot of the Main Menu of Prototype System*

## 8.2 Optimization Page

Once a district is chosen by the user, the optimization page will appear to allow the user to enter the available maintenance budget and run the optimization. In order to run the optimization and generate the final list of maintenance projects, two types of tables have to be uploaded into the system in advance. The first table is the unit cost table for all the maintenance functions. The second table is the project table that contains all the maintenance projects under consideration by the user's district. Table 25 is an example of the unit cost table used in the system, and Table 26 is an incomplete table of future maintenance projects for Pharr district to illustrate the information needed.

The unit costs used in the prototype system are the average unit costs of maintenance functions from 2008 to 2010 in Texas and they can be updated when new cost data is available. All the five options are presented using the same unit costs. The maintenance projects table contains the highway number where maintenance would occur, maintenance function code, description, ADT and truck factor as exposure factors, and work units of projects to calculate the total cost of each project. After all the information is uploaded into the system, it will assign the unit costs to each maintenance project using the function code and the total cost of each project will be calculated. Then the ORW will be assigned to each project and the final Ranking Index (RI) will be calculated using the ORW and the exposure factor chosen by the users. Finally, the budget constraint entered by the user will be applied and the final list of prioritized maintenance projects will be generated.

## Table 25: Unit Cost Table in Prototype System

| 2008-2010 Average Function Code Work Units and Cost | | | | | |
|---|---|---|---|---|---|
| FUNCTION CODE | FUNCTION CODE DESCRIPTION | UNIT | Avg Total Cost ($) | Avg Total Work Units | Unit Cost ($) |
| 110 | BASE REMOVAL/REPLACEMENT | CY | $38,551,266.92 | 761020 | $50.66 |
| 120 | BASE IN PLACE REPAIR | CY | $30,647,483.72 | 1456932 | $21.04 |
| 211 | LEVELING/OVERLAY W/ LAYDOWN | SY | $76,609,378.38 | 9629662 | $7.96 |
| 212 | LEVELING/OVERLAY W/ MAINTAINER | SY | $81,126,651.49 | 18720046 | $4.33 |
| 213 | LEVELING BY HAND | SY | $7,635,088.47 | 316391 | $24.13 |
| 214 | LEVELING/OVERLAY WITH DRAG BOX | SY | $4,245,875.29 | 1703002 | $2.49 |
| 231 | SEAL COAT | SY | $35,259,354.60 | 16793293 | $2.10 |
| 232 | STRIP/SPOT SEAL | SY | $12,668,898.77 | 5821494 | $2.18 |
| 241 | POTHOLES, SEMI-PERMANENT REPAIR | EA | $9,103,107.58 | 492369 | $18.49 |
| 242 | POTHOLES, PERMANENT REPAIR | EA | $537,074.14 | 15456 | $34.75 |
| 270 | EDGE REPAIR | LF | $16,460,070.77 | 17451734 | $0.94 |
| 511 | MOWING | AC | $48,902,558.34 | 1604988 | $30.47 |
| 513 | SPOT MOWING | AC | $1,395,346.92 | 20335 | $68.62 |
| 521 | LITTER | AC | $24,212,732.51 | 1808880 | $13.39 |
| 522 | ROUTINE STREET SWEEPING | MI | $23,522,143.47 | 294744 | $79.81 |
| 523 | DEBRIS | MI | $18,825,403.58 | 2619543 | $7.19 |
| 524 | SPOT LITTER | AC | $2,407,566.18 | 129795 | $18.55 |
| 540 | HAND VEGETATION CONTROL | AC | $2,429,118.20 | 0 | $87.75 |
| 541 | CHEMICAL VEG. CONTROL EDGES | AC | $7,198,826.24 | 82038 | $87.75 |
| 542 | CHEMICAL VEG. CONTROL OVERSPRAY | AC | $10,905,658.59 | 266840 | $40.87 |
| 544 | CHEMICAL VEG. CONTROL ROPE-WICK | AC | $121,555.39 | 5948 | $20.44 |
| 545 | CHEMICAL VEG. CONTROL BASAL APP | AC | $617,069.85 | 0 | $38.00 |
| 561 | DITCH MAINTENANCE | CY | $12,976,482.73 | 1876625 | $6.91 |
| 562 | RESHAPING DITCHES | LF | $5,437,527.33 | 18040774 | $0.30 |
| 595 | GUARD FENCE | LF | $19,703,214.40 | 1052873 | $18.71 |
| 596 | GUARDRAIL END TREATMENT SYSTEMS | EA | $11,574,622.61 | 30088 | $384.70 |
| 711 | PAINT & BEAD STRIPING | LF | $9,672,764.73 | 69291483 | $0.14 |
| 712 | HIGH PERFORMANCE STRIPING | LF | $30,182,173.94 | 110592408 | $0.27 |
| 713 | SPECIALTY MARKINGS | EA | $7,449,011.92 | 0 | $256.00 |
| 715 | REMOVAL OF PAVEMENT STRIPING | LF | $374,183.71 | 0 | $1.79 |
| 731 | INSTALL/REINSTALL SMALL SIGN | EA | $34,897,882.08 | 913875 | $38.19 |
| 732 | INSTALL/REINSTALL LARGE SIGN | SF | $10,038,616.76 | 1099759 | $9.13 |
| 733 | VANDALIZED SIGNS | EA | $2,283,321.95 | 51750 | $44.12 |
| 742 | ILLUMINATION | LS | $26,351,921.07 | 0 | $1,155.00 |
| 743 | MAINT OF ISOLATED TRAFFIC SIGNALS | EA | $17,489,633.97 | 0 | $2,700.00 |
| 744 | MAINT OF COORDINATED TRAFFIC SIGNALS | EA | $11,304,166.61 | 0 | $3,600.00 |
| 750 | INSTALL/REMOVAL PAVEMENT MARKERS | EA | $6,701,234.36 | 3653811 | $1.83 |

**Table 26: Part of Maintenance Projects Table of Cameron County in Pharr District**

| ID | COUNTY | YEAR | HWY | FUNC CODE | FUNC_DESCRIPTION | ADT | TRUCK FACTOR | LENGTH | QUANTITY | UNIT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | CAMERON | 2010 | US 77/83 (MAIN LANES) | 595 | GUARD FENCE | 73000 | 25% | 4.516 | 217 | LF |
| 2 | CAMERON | 2010 | US 77/83 (M.L.) | 712 | HIGH PERFORMANCE STRIPING | 73000 | 25% | 4.516 | 119222 | LF |
| 3 | CAMERON | 2010 | US 77/83 (MAIN LANES) | 521 | LITTER | 73000 | 25% | 4.516 | 108 | MI |
| 4 | CAMERON | 2010 | US 77/83 (MAIN LANES) | 523 | DEBRIS | 73000 | 25% | 4.516 | 217 | MI |
| 5 | CAMERON | 2010 | US 77/83 (MAIN LANES) | 540 | HAND VEGETATION CONTROL | 73000 | 25% | 4.516 | 6 | AC |
| 6 | CAMERON | 2010 | US 77/83 (MAIN LANES) | 511 | MOWING | 73000 | 25% | 4.516 | 66 | AC |
| 7 | CAMERON | 2010 | US 77/83 (M.L.) | 595 | GUARD FENCE | 54000 | 20% | 2.365 | 114 | LF |
| 8 | CAMERON | 2010 | US 77/83 (M.L.) | 712 | HIGH PERFORMANCE STRIPING | 54000 | 20% | 2.365 | 62436 | LF |
| 9 | CAMERON | 2010 | US 77/83 (M.L.) | 521 | LITTER | 54000 | 20% | 2.365 | 57 | MI |
| 10 | CAMERON | 2010 | US 77/83 (M.L.) | 523 | DEBRIS | 54000 | 20% | 2.365 | 114 | MI |
| 11 | CAMERON | 2010 | US 77/83 (M.L.) | 542 | CHEMICAL VEGETATION CONTROL, OVERSPRAY | 54000 | 20% | 2.365 | 35 | AC |
| 12 | CAMERON | 2010 | US 77/83 (M.L.) | 511 | MOWING | 54000 | 20% | 2.365 | 36 | AC |
| 13 | CAMERON | 2010 | US 77/83 (FRTG. RD.) | 211 | LEVELING or OVERLAY W/ LAYDOWN MACHINE | 43000 | 25% | 5.803 | 81706 | SY |
| 14 | CAMERON | 2010 | US 77 | 211 | LEVELING or OVERLAY W/ LAYDOWN MACHINE | 40500 | 25% | 2 | 28160 | SY |
| 15 | CAMERON | 2010 | US 77/83 (FRTG. RD.) | 120 | IN PLACE REPAIR | 40500 | 25% | 2.25 | 955 | CY |

Figure 25 is a screenshot of the optimization page using the data obtained from the Pharr district. This page consists of three major sections. The first section shown in Figure 26 is for the user to enter their maintenance budget and the second section as shown in Figure 27 is for the user to choose the exposure factor to be used. The user just needs to check the box before the exposure factor to be used after the total budget is entered. Since it is a single-choice checkbox, it means the user can only choose one factor for the calculation. The third section shown in Figure 28 is to show the weights of maintenance objectives obtained from this district, giving the user a direct understanding of the level of importance of different maintenance objectives. After the budget is entered and the exposure factor is checked, the user should click on the "submit" button below the third section for the final list of maintenance projects to be generated.

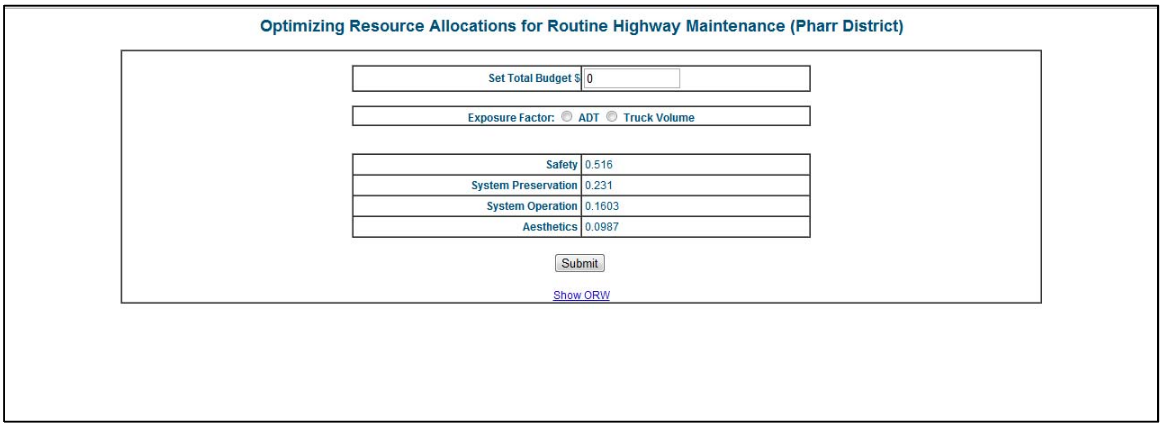


*Figure 25: Optimization Page of Pharr District*

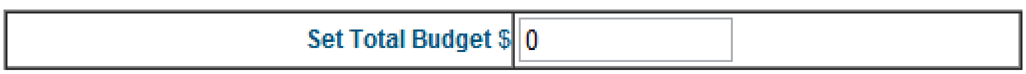


*Figure 26: Budget Entering Section*


*Figure 27: Exposure Factor Choosing Section*

| | |
|---|---|
| Safety | 0.516 |
| System Preservation | 0.231 |
| System Operation | 0.1603 |
| Aesthetics | 0.0987 |

*Figure 28: Maintenance Objective Weights Table*

# Chapter 9: Conclusions

This report presents a methodological framework using the Analytical Hierarchy Process (AHP) for prioritizing routine maintenance projects by quantifying the risk of not performing a highway maintenance activity. This study demonstrates that a systematic approach can in fact be developed for scheduling and prioritizing maintenance activities and projects. The proposed methodology could help improve the consistency of the highway condition by replacing a purely subjective method with a formal decision support framework. In addition, the proposed methodology could help reduce road user's exposure to unfavorable highway conditions while simultaneously reducing a DOT's liability by minimizing the risks induced by budget fluctuations. More specifically, the proposed methodology in this study

1) Enables engineers to assess the maintenance needs of the roadway network and evaluate the implications of budget fluctuations;
2) Provides engineers with a versatile framework that can be adjusted to reflect local conditions and strategies;
3) Facilitates the selection of maintenance programs and strategies that minimize the impact of budget fluctuations on the overall condition of the roadway network; and
4) Allows engineers to better conduct "what-if" analyses of various funding levels which can lead to cost savings.

Some cautions should also be exercised when using this system. If a district wants to develop its own priorities of maintenance activities, the meaning of the scale system has to be carefully explained so that the real preferences of maintenance engineers on maintenance activities can be captured. In addition, the exposure factor has to be carefully chosen in the web-based system since the priorities of maintenance projects can be significantly different when applying different exposure factors in the calculation.

# Appendix A: Kruskal-Wallis Test Calculation Sheets

### A.1 Weights and Combined Rankings of Maintenance Alternatives for Aesthetics

| Objectives \ Districts | Austin (%) | Lubbock (%) | Paris (%) | Pharr (%) | Rank | | | |
|---|---|---|---|---|---|---|---|---|
| **Base Repair** | 2.65 | 7.00 | 5.65 | 7.00 | 3 | 43 | 30 | 44 |
| **Crack Seal** | 2.68 | 6.01 | 5.91 | 5.53 | 4 | 33 | 32 | 29 |
| **Crash Attenuators** | 4.83 | 5.38 | 3.47 | 4.38 | 20 | 25 | 6 | 14 |
| **Debris/Litter/ Sweeping** | 12.67 | 3.84 | 5.42 | 7.58 | 64 | 8 | 27 | 52 |
| **Drainage System Maintenance** | 2.52 | 4.19 | 6.30 | 4.02 | 2 | 12 | 36 | 11 |
| **Edge Repair** | 3.59 | 7.54 | 8.58 | 6.12 | 7 | 51 | 55 | 34 |
| **Flashing Beacons/Traffic Signals/ Illumination** | 6.75 | 5.38 | 3.91 | 3.41 | 40 | 24 | 9 | 5 |
| **Milling** | 2.43 | 6.86 | 4.40 | 4.47 | 1 | 42 | 15 | 16 |
| **Mowing** | 12.53 | 4.63 | 5.84 | 7.38 | 62 | 17 | 31 | 49 |
| **Pavement Leveling /Overlay** | 4.32 | 8.81 | 7.92 | 7.21 | 13 | 56 | 53 | 46 |
| **Pavement Markings/ Markers** | 8.96 | 3.92 | 6.42 | 8.00 | 57 | 10 | 37 | 54 |
| **Pothole Patching** | 7.49 | 11.03 | 7.33 | 9.64 | 50 | 61 | 47 | 59 |
| **Safety Barrier Maintenance** | 4.84 | 5.43 | 4.76 | 5.16 | 21 | 28 | 18 | 22 |
| **Signs Maintenance** | 9.64 | 5.29 | 6.16 | 6.51 | 58 | 23 | 35 | 38 |
| **Surface Treatments** | 6.76 | 9.93 | 12.56 | 7.05 | 41 | 60 | 63 | 45 |
| **Vegetation Control** | 7.35 | 4.78 | 5.38 | 6.54 | 48 | 19 | 26 | 39 |
| | | | | **Sum** | 491 | 512 | 520 | 557 |
| | | | | **Average** | 30.68 | 32 | 32.5 | 34.81 |

## A.2 Weights and Combined Rankings of Maintenance Alternatives for Safety

| Objectives \ Districts | Austin (%) | Lubbock (%) | Paris (%) | Pharr (%) | Rank | | | |
|---|---|---|---|---|---|---|---|---|
| Base Repair | 2.83 | 7.73 | 7.07 | 7.56 | 8 | 46 | 42 | 45 |
| Crack Seal | 1.90 | 4.15 | 2.60 | 3.21 | 2 | 22 | 6 | 12 |
| Crash Attenuators | 13.63 | 6.33 | 6.11 | 8.17 | 63 | 39 | 34 | 48 |
| Debris/Litter/ Sweeping | 3.06 | 3.90 | 2.98 | 3.28 | 10 | 19 | 9 | 13 |
| Drainage System Maintenance | 1.87 | 4.50 | 2.36 | 3.61 | 1 | 27 | 3 | 15 |
| Edge Repair | 12.90 | 8.77 | 13.70 | 9.84 | 62 | 50 | 64 | 53 |
| Flashing Beacons/Traffic Signals/ Illumination | 9.92 | 6.15 | 5.75 | 10.15 | 54 | 36 | 33 | 55 |
| Milling | 2.49 | 5.71 | 4.87 | 5.73 | 5 | 31 | 28 | 32 |
| Mowing | 4.17 | 4.25 | 3.91 | 3.82 | 24 | 26 | 21 | 16 |
| Pavement Leveling /Overlay | 3.89 | 8.25 | 11.66 | 6.21 | 18 | 49 | 60 | 37 |
| Pavement Markings/ Markers | 11.33 | 4.89 | 9.24 | 7.10 | 58 | 29 | 52 | 43 |
| Pothole Patching | 8.16 | 12.58 | 10.63 | 11.54 | 47 | 61 | 57 | 59 |
| Safety Barrier Maintenance | 10.32 | 6.24 | 2.70 | 6.95 | 56 | 38 | 7 | 41 |
| Signs Maintenance | 6.15 | 4.16 | 3.89 | 6.49 | 35 | 23 | 17 | 40 |
| Surface Treatments | 4.20 | 8.89 | 7.14 | 3.90 | 25 | 51 | 44 | 20 |
| Vegetation Control | 3.18 | 3.49 | 5.39 | 2.45 | 11 | 14 | 30 | 4 |
| | | | | Sum | 479 | 561 | 507 | 533 |
| | | | | Average | 29.94 | 35.06 | 31.69 | 33.31 |

## A.3 Weights and Combined Rankings of Maintenance Alternatives for System Operation

| Objectives \ Districts | Austin (%) | Lubbock (%) | Paris (%) | Pharr (%) | Rank | | | |
|---|---|---|---|---|---|---|---|---|
| **Base Repair** | 5.22 | 7.95 | 11.27 | 9.36 | 30 | 50 | 59 | 53 |
| **Crack Seal** | 3.06 | 5.19 | 5.12 | 5.95 | 8 | 29 | 27 | 38 |
| **Crash Attenuators** | 6.59 | 3.91 | 3.00 | 5.72 | 43 | 18 | 7 | 34 |
| **Debris/Litter/ Sweeping** | 2.84 | 4.03 | 3.70 | 3.09 | 4 | 19 | 15 | 9 |
| **Drainage System Maintenance** | 2.76 | 4.40 | 2.91 | 3.32 | 3 | 21 | 6 | 10 |
| **Edge Repair** | 7.56 | 7.64 | 13.12 | 6.31 | 47 | 48 | 62 | 40 |
| **Flashing Beacons/Traffic Signals/ Illumination** | 11.47 | 6.31 | 4.72 | 4.85 | 60 | 41 | 24 | 25 |
| **Milling** | 3.68 | 6.82 | 3.70 | 5.79 | 12 | 44 | 14 | 36 |
| **Mowing** | 2.66 | 3.73 | 4.69 | 3.68 | 2 | 16 | 23 | 13 |
| **Pavement Leveling /Overlay** | 5.07 | 9.00 | 10.57 | 7.16 | 26 | 51 | 58 | 46 |
| **Pavement Markings/ Markers** | 13.53 | 5.49 | 5.17 | 9.31 | 63 | 33 | 28 | 52 |
| **Pothole Patching** | 9.64 | 13.03 | 9.72 | 14.43 | 54 | 61 | 55 | 64 |
| **Safety Barrier Maintenance** | 6.53 | 4.14 | 2.89 | 5.35 | 42 | 20 | 5 | 31 |
| **Signs Maintenance** | 9.80 | 4.57 | 6.16 | 7.14 | 56 | 22 | 39 | 45 |
| **Surface Treatments** | 5.74 | 10.36 | 7.88 | 5.93 | 35 | 57 | 49 | 37 |
| **Vegetation Control** | 3.84 | 3.43 | 5.36 | 2.59 | 17 | 11 | 32 | 1 |
| | | | | **Sum** | 502 | 541 | 503 | 534 |
| | | | | **Average** | 31.38 | 33.81 | 31.44 | 33.38 |

## A.4 Weights and Combined Rankings of Maintenance Alternatives for System Preservation

| Objectives \ Districts | Austin (%) | Lubbock (%) | Paris (%) | Pharr (%) | Rank | | | |
|---|---|---|---|---|---|---|---|---|
| **Base Repair** | 13.80 | 9.09 | 10.77 | 10.41 | 61 | 50 | 55 | 53 |
| **Crack Seal** | 14.35 | 8.26 | 8.90 | 10.15 | 64 | 45 | 49 | 52 |
| **Crash Attenuators** | 3.06 | 3.96 | 2.81 | 4.18 | 14 | 26 | 9 | 29 |
| **Debris/Litter/ Sweeping** | 2.11 | 3.01 | 5.42 | 2.54 | 2 | 13 | 37 | 7 |
| **Drainage System Maintenance** | 4.68 | 4.36 | 4.07 | 3.60 | 35 | 31 | 27 | 19 |
| **Edge Repair** | 7.88 | 8.89 | 11.17 | 8.47 | 43 | 48 | 56 | 47 |
| **Flashing Beacons/Traffic Signals/ Illumination** | 2.17 | 3.71 | 3.66 | 2.85 | 3 | 21 | 20 | 10 |
| **Milling** | 3.85 | 6.95 | 4.57 | 6.28 | 23 | 40 | 34 | 39 |
| **Mowing** | 1.84 | 3.40 | 5.57 | 4.10 | 1 | 17 | 38 | 28 |
| **Pavement Leveling /Overlay** | 8.35 | 9.61 | 7.61 | 7.62 | 46 | 51 | 41 | 42 |
| **Pavement Markings/ Markers** | 2.53 | 2.80 | 3.89 | 4.86 | 6 | 8 | 24 | 36 |
| **Pothole Patching** | 12.49 | 11.66 | 8.25 | 14.03 | 59 | 57 | 44 | 63 |
| **Safety Barrier Maintenance** | 2.34 | 3.71 | 2.39 | 3.08 | 4 | 22 | 5 | 15 |
| **Signs Maintenance** | 2.98 | 3.45 | 4.36 | 4.49 | 12 | 18 | 32 | 33 |
| **Surface Treatments** | 13.66 | 13.81 | 12.24 | 10.49 | 60 | 62 | 58 | 54 |
| **Vegetation Control** | 3.92 | 3.33 | 4.33 | 2.86 | 25 | 16 | 30 | 11 |
| | | | | **Sum** | 458 | 525 | 559 | 538 |
| | | | | **Average** | 28.63 | 32.81 | 34.94 | 33.63 |

## A.5 Weights and Combined Rankings of ORWs

| Objectives \ Districts | Austin (%) | Lubbock (%) | Paris (%) | Pharr (%) | Rank | | | |
|---|---|---|---|---|---|---|---|---|
| Base Repair | 5.51 | 8.08 | 8.36 | 8.50 | 32 | 47 | 48 | 49 |
| Crack Seal | 4.62 | 5.53 | 4.57 | 5.50 | 22 | 33 | 21 | 31 |
| Crash Attenuators | 9.36 | 5.29 | 4.79 | 6.53 | 56 | 29 | 24 | 39 |
| Debris/Litter/ Sweeping | 3.38 | 3.67 | 3.78 | 3.52 | 6 | 10 | 12 | 7 |
| Drainage System Maintenance | 2.67 | 4.43 | 3.07 | 3.62 | 1 | 18 | 5 | 9 |
| Edge Repair | 10.08 | 8.56 | 12.72 | 8.65 | 59 | 50 | 64 | 52 |
| Flashing Beacons/Traffic Signals/ Illumination | 8.63 | 5.47 | 5.02 | 7.01 | 51 | 30 | 25 | 43 |
| Milling | 3.04 | 6.28 | 4.62 | 5.78 | 4 | 38 | 23 | 35 |
| Mowing | 3.84 | 3.98 | 4.51 | 4.24 | 13 | 14 | 20 | 16 |
| Pavement Leveling /Overlay | 5.06 | 8.76 | 10.36 | 6.82 | 26 | 54 | 60 | 42 |
| Pavement Markings/ Markers | 10.04 | 4.35 | 7.32 | 7.07 | 58 | 17 | 45 | 44 |
| Pothole Patching | 9.32 | 12.29 | 9.76 | 12.46 | 55 | 62 | 57 | 63 |
| Safety Barrier Maintenance | 7.54 | 5.21 | 2.78 | 5.67 | 46 | 28 | 2 | 34 |
| Signs Maintenance | 6.64 | 4.10 | 4.43 | 6.17 | 1 | 15 | 19 | 37 |
| Surface Treatments | 6.54 | 10.49 | 8.74 | 6.08 | 40 | 61 | 53 | 36 |
| Vegetation Control | 3.73 | 3.53 | 5.14 | 2.98 | 11 | 8 | 27 | 3 |
| | | | | **Sum** | 521 | 514 | 505 | 540 |
| | | | | **Average** | 32.56 | 32.13 | 31.56 | 33.75 |

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