Madonna Workshop

Morgan State University
The Pennsylvania State University
University of Maryland
University of Virginia
Virginia Polytechnic Institute & State University
West Virginia University

The Pennsylvania State University
The Thomas D. Larson Pennsylvania Transportation Institute
Transportation Research Building ◆ University Park, PA 16802-4710
Phone: 814-865-1891 ◆ Fax: 814-863-3707
www.mautc.psu.edu
1. **Report No.**
 VT-2013-05

2. **Government Accession No.**

3. **Recipient’s Catalog No.**

4. **Title and Subtitle**
 MADONNA’s Decision Support System and User Interface Enhancement for Workshops and Professional Development

5. **Report Date**
 Sept 14, 2014

6. **Performing Organization Code**

7. **Author(s)**
 Montasir Abbas and Milos Mladenovic

8. **Performing Organization Report No.**

9. **Performing Organization Name and Address**
 Virginia Polytechnic Institute and State University
 Charles E. Via, Jr. Department of Civil and Environmental Engineering
 301-H, Patton Hall
 Blacksburg, VA 24061

10. **Work Unit No. (TRAIS)**

11. **Contract or Grant No.**
 DTRT12-G-UTC03

12. **Sponsoring Agency Name and Address**
 US Department of Transportation
 Research & Innovative Technology Admin
 UTC Program, RDT-30
 1200 New Jersey Ave., SE
 Washington, DC 20590

13. **Type of Report and Period Covered**
 Final Report 8/1/13 – 8/31/14

14. **Sponsoring Agency Code**

15. **Supplementary Notes**

16. **Abstract**
 Transportation agencies need to go through a hard decision-making process while selecting the traffic signal controller that corresponds to the needs of their future signal systems. The complexity of this problem originates from the current level of controller standardization, market-driven competition, responsibility for long-term operation, and scale of investment. This report presents the results of a MAUTC-funded project to enhance and develop a user-friendly user interface for the Multi Attribute Decision-making Optimizer for Next-generation Network-upgrade and Assessment (MADONNA) framework, which emerged during a research project conducted to address upgrade needs raised by Virginia Northern Region Operations. The MADONNA framework is a tool for system-engineering assessment and upgrade of control hardware/software to improve the overall signal system performance. In this project, a decision-support system (DSS) for selecting traffic signal controllers based on an analytical hierarchy process was developed as an application in MS Excel. The main improvement in this DSS system compared to the authors’ previous work is the component for expert knowledge acquisition during the assignment of criteria weights. The graphical user interface and supporting analytical engine are based on fuzzy logic and were developed to enhance the expert knowledge acquisition. The application interface and the analytical engine are presented and are made available for VDOT on-demand workshops.

17. **Key Words**
 MADONNA, decision support system, analytical hierarchy process

18. **Distribution Statement**
 No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. **Security Classif. (of this report)**
 Unclassified

20. **Security Classif. (of this page)**
 Unclassified

21. **No. of Pages**
 26

22. **Price**
# Table of Contents

**INTRODUCTION**.......................................................................................................................................................... 1

Previous Projects and Research Need............................................................................................................................... 1

**DECISION-SUPPORT SYSTEM FOR CONTROLLER SELECTION** .................................................................................. 2

The Role of Expert Knowledge in DSS.............................................................................................................................. 3

**DECISION-SUPPORT METHODOLOGY** ............................................................................................................................ 4

Multi-Attribute Decision Making ........................................................................................................................................ 4

Analytic Hierarchy Process................................................................................................................................................ 5

Establishment of Evaluation Criteria................................................................................................................................... 5

Hierarchical Decomposition of Evaluation Criteria and Attributes..................................................................................... 6

Criteria Scores and Weights.................................................................................................................................................. 7

**MADONNA-DSS**............................................................................................................................................................... 7

Graphical User Interface for Expert Knowledge Acquisition............................................................................................... 8

**ASSIGNMENT OF CRITERIA WEIGHTS**............................................................................................................................ 9

Fuzziness of Criteria Weights.............................................................................................................................................. 9

**PAIRWISE QUALITATIVE CRITERIA COMPARISON**........................................................................................................ 11

Synthetic Quantitative Comparison Matrix....................................................................................................................... 11

**CONCLUSION AND FUTURE WORK**.............................................................................................................................. 12

**REFERENCES**................................................................................................................................................................. 14

**APPENDIX 1. MADONNA-DSS USER MANUAL** ............................................................................................................ 16

User Selection..................................................................................................................................................................... 16

Pairwise Comparison of Criteria Weight............................................................................................................................ 16

Generating the Report.......................................................................................................................................................... 19
List of Figures

Figure 1: General representation of decision matrix .......................................................... 4
Figure 2: Hierarchical DSS structure .................................................................................. 7
Figure 3: Weight assignment window .................................................................................. 9
Figure 4: Membership functions of linguistic variables used in the framework .................. 10
Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation’s University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.
INTRODUCTION

Conventional traffic signal controllers are one of the most direct control components of modern traffic control systems and have a crucial role in the operation of transportation systems. The development of traffic signal controllers across the world, although with very similar operational goals in safety constraints and basic phase structure, had different paths of development. One path, mainly in Europe, resulted in the interval-based controllers with flexible stage sequencing and without wider standardization across countries [1]. On the other side, mainly in North America, controllers are mainly based on ring-barrier control structure with several generations of standards starting from the early 1970s [2]. The latest standardization effort, named the Advanced Transportation Controller (ATC) standard, is a combination and upgrade of all the previous North American operational and hardware standards (NEMA TS1, NEMA TS2, 170, 179, 2070, etc.) [2, 3]. This standard primarily defines signal cabinet and controller elements.

Contrary to the high level of hardware standardization, the development of signal control software in the United States was mostly unconstrained, except for general recommendations accepted mainly from earlier NEMA controllers. This premise was giving the opportunity for agencies to purchase controller hardware and software separately as third-party vendors developed signal control software according to agencies’ customized needs. However, this increased flexibility in software customization resulted in a multitude of signal-control software versions and their programmable parameters. Nowadays, there are over ten companies with several versions of ATC controller software, frequently having over 200 control parameters [1, 4]. As a result, transportation agencies are facing increased decision-making concerns in selecting their optimal future traffic signal controller. The decision-making is additionally burdening considering that the choice of the particular controller would mean having to commit to this choice for the next 15 to 20 years. Finally, although frequently underestimated, traffic signals are an asset worth $82.7 billion of public investment for over 310,000 traffic signals in the United States alone [5].

Previous Projects and Research Need

Several previous research studies and practical projects have focused on the decision-making for the procurement of traffic signal controllers [6-9]. Considering this previous research and practice developed for selecting future signal controllers, it is noticeable that their focus was not
primarily on controller software. The focus was primarily on cabinet-controller compatibility and establishing some base level requirements. These requirements were primarily related to device compatibility, equipment life, ability to generate reports, and some operational functions. A survey of agencies across the United States, performed by the authors, confirmed that there were very limited practical specifications for acquiring new traffic control equipment (e.g., the maturity of technology, compatibility with central traffic management software and communication standards) [10].

The research presented here was originally initiated in 2008 to help the Northern Region Operations (NRO) of Virginia Department of Transportation (VDOT) in the selection of their future controllers [10, 11]. NRO has over 1,600 signalized intersections under its purview. The existing system was primarily based upon type 170 controllers, installed in the previous century. These controllers were reaching the limit of their operational effectiveness due to changing traffic patterns and volumes in this densely populated region. In addition to the constraint that NRO will need to operate the new controllers for the next 20 years, the scale of the investment itself introduced additional pressure for improved decision-making. Considering that none of the previous research had developed a complete procedure or tool for evaluating traffic signal controllers, there was an apparent need for a robust, analytically based decision-making tool. The work conducted on this project focused on improvements to the previously developed decision-support system (DSS) concept [11], including improvements to the analytical procedure underlying the knowledge-acquisition process of criteria weights, and the development of a graphical user interface to facilitate the use of this application.

DECISION-SUPPORT SYSTEM FOR CONTROLLER SELECTION

The complex situation described in the previous section made apparent that there was an essential need for normative decision analysis that can help finding the most desirable future controller. Had this been a single-criterion problem, the decision making would be intuitive [12, 13]. However, considering that there are several alternative controllers, multiple criteria (controller features), preference dependence, etc., there was apparently a need for more sophisticated evaluation methods. In the complex decision environment, as it is the one for selecting traffic signal controllers, traditional informal judgment cannot fulfill the decision-
making requirements. There was a need for a decision-support system that would aid agencies
during the procurement of the new generation of traffic signal controller.

According to its definition, DSS is an interactive computer-based information system that uses
data and models to help solve semi-structured or unstructured problems, and support managerial
judgment [14]. Important characteristics of a DSS are its flexibility, ability to incorporate both
data and models, and the capability to provide a range of alternative solutions. Overall, DSS is
intended for improving the quality of information on which a decision is based, and extending
the range of decision processes. In transportation engineering, the DSS was primarily used for
scheduling and managing trains, fleets, or crews [15, 16]. However, there has been previous
research in fields other than signal control, where the DSS was used for equipment replacement
decision [17] and equipment selection [18-20].

The framework for selection from available alternative controllers required the following:

- Analytically-based comparison of alternatives
- Transparency and cross-referencing to relevant sources of information
- Adaptation to change and transferability among agencies
- Enabling performance measurement as the responsibility of a group of experts
- Utilization as a communication medium between experts and a wider audience

In order to fulfill the framework requirements, the selection process needed to be based on a set
of criteria. This is the reason Multi-Criteria Decision Making (MCDM) was selected as the core
of DSS. The framework for this DSS was developed utilizing a top-down approach, based on the
three main DSS components: criteria, criteria weights, and attribute scores.

The Role of Expert Knowledge in DSS

The controller selection problem presented previously is a semi-structured decision problem,
which cannot be solved by existing classic mathematical models. The decision primarily relies
on human intuition [21]. In this situation, DSS is a tool intended to support, rather than replace,
traffic signal experts’ role in choosing future signal controllers. Signal operation engineers and
traffic signal technicians with different training levels have extensive expert knowledge and trial-
and-error experience in specific parts of controller programming and fine-tuning. This dispersed
knowledge base has a potential to be effectively integrated and organized [2] for selecting the future signal controller. In addition, DSS provides flexibility to collect the knowledge of other experts, such as traffic center operators and traffic engineers.

**DECISION-SUPPORT METHODOLOGY**

**Multi-Attribute Decision Making**

Multi-Criteria Decision Making (MCDM) is a decision theory approach and set of techniques that aids in a coherent ordering of options [22]. A specific implementation of MCDM is Multi-Attribute Decision Making (MADM) [23]. The decision space of MADM is discrete. In the field of transportation, MADM has been used in problems such as planning purposes [24], highway asset management [25, 26], or macro-level evaluation of signal infrastructure [27]. Each MADM evaluation model [28] is defined by the set of alternatives, the set of criteria or attributes for evaluation, and the decision matrix. A finite set of alternatives is a choice set denoted as $A = \{A_1, A_2, ..., A_m\}$. Each alternative $A_i \in A$ is evaluated by a single element $x(a)$ of an attribute $X \subseteq R$. A pure ordinal scale used for evaluation is defined as:

$$\forall a, b \in A_i \{a P b \leftrightarrow x(a) > x(b) \} \{a I b \leftrightarrow x(a) = x(b) \}$$

where $a P b$ means “$a$ is preferred to $b$” and $a I p$ means “$a$ is indifferent to $b$”. A decision matrix or performance table expresses performance of $m$ alternative relative to $n$ attributes considered:

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>...</th>
<th>$a_j$</th>
<th>...</th>
<th>$a_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>$a_{11}$</td>
<td>$a_{12}$</td>
<td>...</td>
<td>$a_{1j}$</td>
<td>...</td>
<td>$a_{1n}$</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$a_{21}$</td>
<td>$a_{22}$</td>
<td>...</td>
<td>$a_{2j}$</td>
<td>...</td>
<td>$a_{2n}$</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>$A_i$</td>
<td>$a_{i1}$</td>
<td>$a_{i2}$</td>
<td>...</td>
<td>$a_{ij}$</td>
<td>...</td>
<td>$a_{in}$</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>$A_m$</td>
<td>$a_{m1}$</td>
<td>$a_{m2}$</td>
<td>...</td>
<td>$a_{mj}$</td>
<td>...</td>
<td>$a_{mn}$</td>
</tr>
<tr>
<td>$w'$</td>
<td>$w_1$</td>
<td>$w_2$</td>
<td>...</td>
<td>$w_j$</td>
<td>...</td>
<td>$w_n$</td>
</tr>
</tbody>
</table>

**Figure 1**. Usually, there is a measure of relative importance of criteria/attribute, expressed as weight vector $w = (w_1, w_2, ..., w_n)$. 

4
Figure 1: General representation of decision matrix

Analytic Hierarchy Process
A specific MADM technique chosen for the proposed DSS is the analytical hierarchy process (AHP). AHP was developed to model subjective decision-making processes based on multiple attributes in a hierarchical system. AHP structures process through a hierarchical decomposition, reducing complex problems into sub-problems [29]. The AHP procedure has the following steps:

1) Establish decision context and decompose a problem into an interrelated hierarchy of goal, criteria, sub-criteria, and alternatives.

2) Collect data from the experts or decision makers as a pairwise qualitative comparison of criteria to create a reciprocal matrix.

3) Organize the pairwise criteria comparison into a square quantitative matrix.

4) Evaluate matrix consistency.

5) Multiply the weights of the criteria with the score for each attribute and then aggregate to obtain local ratings with respect to each criterion, which are finally aggregated to obtain global ratings.

Establishment of Evaluation Criteria
The decision context of this methodology focuses on the choice between alternative controllers. A well-defined set of decision criteria is important because it allows each of the alternatives to be quantifiable and easily evaluated [30]. In addition, choosing a future controller that does not meet user requirements would be a failure, whatever other merits appear. The evaluation criteria were developed through a series of interviews with VDOT traffic signal experts about the desired
future traffic signal control system [10]. In addition, the list of evaluation criteria was based on the surveyed opinions of experts in signal control across North America. The final list of evaluation criteria contained the following:

- **Controller Hardware and Software** - Controller features directly related to hardware and software components (not including programming options), such as the availability of an LCD display with 8 lines and 40 characters, the ability to upload/download to/from laptop, compatibility with VDOT's Traffic Management Software, and the availability of controller software code in C programming language.

- **General Traffic Operation** - Basic operational functions, such as the number of phases, conditional phase service and re-service, detector switching capabilities, queue detection actions, left-turn trap protection options, etc.

- **Coordination and Plan Selection** - Coordination and time of day/schedule options related to cycle length, offset, transition algorithms, holiday/events functions, traffic responsive plan selection capabilities, etc.

- **Preemption (PE) and Transit Signal Priority (TSP)** - Primarily transitioning options from/into PE or TSP, including options for resolving the issue of “double preemption,” options for maintaining progression during PE or TSP, programming options for light rail vehicles control, etc.

- **Pedestrian & Bike** - Options, such as pedestrian overlap, pedestrian phase reservice, walk extension, along with additional capabilities, available only in some controllers (e.g., early walk, pedestrian scramble, bike timing, etc.).

- **Reports, Data Archiving, Communications, and Maintenance Requirements** - Includes capabilities in saving data, logging a higher number of parameters, compatibility with the database in the central TMS, availability of multiple polling and communication rates, the availability of alarms for reporting different hardware or software issues, etc.

- **Advanced Controller Features** - Any additional controller features that were not immediately identified as previously mapped CFR groups, but that could have potential future applications, as the system develops.
• **User Survey Ranking** - This evaluation criterion is based on the additional insight about the overall controller performance obtained from the survey of previous agencies’ field experiences.

**Hierarchical Decomposition of Evaluation Criteria and Attributes**

After determining the criteria and sub-criteria, the decision problem was decomposed into goal, criteria, sub-criteria, and alternatives relationships. This AHP hierarchic structure is presented in Figure 2.

![Hierarchical DSS structure](image)

**Figure 2: Hierarchical DSS structure**

**Criteria Scores and Weights**

Special attention needs to be dedicated to determining a score for each sub-criterion. These scores need to be determined after a meticulous testing and analysis. Procedures for determining analytical scores for valid decision-making are presented in the previous research [1, 4, 31]. They include procedures based upon techniques such as Petri Net modeling and software-in-the-loop simulation. In addition to criteria scores that can be analytically determined, criteria weights primarily depend on expert opinions. Considering that the assignment of weights can
significantly influence the final scores of alternatives, this is identified as a critical component and a focus area of the DSS presented here.

**MADONNA-DSS**

The developed DSS application is an integral part of the Multi-Attribute Decision-making Optimizer for Next-generation Network-upgrade and Assessment (MADONNA). MADONNA consisted of a database of alternate controller features and scores, a GIS module for spatial upgrade time scheduling, a multi-objective optimizer, and the DSS system. MADONNA-DSS was developed as a Microsoft Excel-based application, designed to provide the flexibility in collecting and analyzing the traffic signal expert’s knowledge. The DSS system was developed in this format to facilitate knowledge transfer through on-demand workshops. Using MADONNA-DSS, DOT’s decision-makers should have the opportunity to do a "what-if" alternative analysis, include any preferences not initially expressed into the decision process, and have supporting graphical representation for improved decision-making. A part of MADONNA-DSS is an external database developed in Microsoft Access. This database contains criteria scores and stores user input.

**Graphical User Interface for Expert Knowledge Acquisition**

Graphical User Interface (GUI) for MADONNA-DSS was developed through a task matching process [32] between user interface and user’s tasks. Although the expert input is primarily used for assigning the criteria weights, task specification also included input of user identification information and generation of report/alternative comparison. This is the reason application tasks are devised in a three-step linear path, matched to three applications’ windows in the following order of appearance:

1. User identification and previous input selection
2. Pairwise comparison of criteria weight
3. Report generation and analysis

The GUI was developed for the experts that understand the decision context – primarily signal control engineers and technicians. The small number of application steps and menu option for retrieving previous user input were developed assuming infrequent use. These options are
intended to support the ease of use and relearning, in order to reduce the cognitive workload of the user, thus allowing focusing on the assignment of weights.

MADONNA-DSS has dynamical graphical and written feedbacks, designed to support the weight assignment process. An error management system provides error calculation and immediate feedback before the result generation. The weights assignment process is based upon Eigenvector calculations, along with calculating a consistency ratio for determining the logical consistency of assigned weights. Finally, the equation for the calculation of a weighted performance index of each controller determines its global ranking among alternative controllers. The details of these analytical procedures are presented in the next section. The main GUI window for weight assignment is presented in the red ellipse in Figure 3.

Figure 3: Weight assignment window

ASSIGNMENT OF CRITERIA WEIGHTS

Fuzziness of Criteria Weights

MADONNA-DSS is highly dependent on knowledge acquisition from signal control experts. The expert opinion of traffic engineers and traffic signal technicians is a base for the establishment of criteria weights. It is reasonable that all the criteria should not necessarily have
equally weighted importance. For example, a certain corridor might require both transit- and pedestrian-related controller features, but transit functional requirements may be more important than the functional requirements for pedestrian operation for that particular corridor.

Although AHP has substantive capability in dealing with the defined type of decision-making problem, converting a decision-maker’s expert intuition into numbers that can be openly questioned by other stakeholders is still an issue. This is the reason the research team decided to expand the proposed MADONNA-DSS with the concept of fuzzy numbers. Fuzzy numbers are a fuzzy subset of real numbers, introduced to deal with subjective uncertainty that comes from using linguistic variables to represent problems [33]. Fuzzy numbers represent the expansion of the confidence interval idea. In classic decision-making models, the components are usually crisp functions. However, considering that there is imprecision and the sense of vagueness in linguistic expressions, the subject linguistic variables can be defined by corresponding membership function and fuzzy intervals [22]. In MADONNA-DSS, the linguistic variables are used for pairwise comparison of criteria in a second GUI window. In a transformation of qualitative expert estimates into the quantitative ones, the approach uses the 9-point Saaty’s scale based on linguistic variables: equal, marginally strong, strong, very strong, and extremely strong. The assigned linguistic variables are then transformed into triangular fuzzy numbers (Table 1), which are defined as $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, with $l_{ij}$ as the lower and $u_{ij}$ as the upper limit, while $m_{ij}$ is the point where membership function $\mu(x) = 1$. The membership function of linguistic variables (Figure 4) for measuring the value of criteria weights is defined as:

$$\mu(x) = \begin{cases} \frac{x-l}{m-l}, & x \in [l, m], \\ \frac{u-x}{u-m}, & x \in [m, u], \\ 0, & otherwise \end{cases} \quad (2)$$

<table>
<thead>
<tr>
<th>Extremely strong</th>
<th>Very strong</th>
<th>Strong</th>
<th>Marginally strong</th>
<th>Equal</th>
<th>Marginally strong</th>
<th>Strong</th>
<th>Very strong</th>
<th>Extremely strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAb</td>
<td>LVs</td>
<td>LES</td>
<td>Lwk</td>
<td>Eq</td>
<td>Wk</td>
<td>Es</td>
<td>Vs</td>
<td>Ab</td>
</tr>
<tr>
<td>~9.4</td>
<td>~7.4</td>
<td>~5.4</td>
<td>~3.4</td>
<td>~1</td>
<td>~3</td>
<td>~5</td>
<td>~7</td>
<td>~9</td>
</tr>
</tbody>
</table>

Table 1: Values of fuzzy numbers from linguistic scale
PAIRWISE QUALITATIVE CRITERIA COMPARISON

Expert data acquisition is used to create a pairwise qualitative comparison of criteria. The comparison of criteria can develop on different network levels, depending on the perspective and goals of the decision-maker. In addition, the expert’s background (e.g., control, maintenance, design) can influence the assignment of criteria weights. The aggregation of pairwise comparisons among all the criteria from VDOT engineers is presented in the pairwise linguistic comparison matrix (Table 2). This matrix represents the relationship between criteria in each column compared to the criteria in each row, respectively.

Table 2: Pairwise linguistic comparison matrix

<table>
<thead>
<tr>
<th></th>
<th>General</th>
<th>Hardware</th>
<th>Coord</th>
<th>PE/TSP</th>
<th>Ped</th>
<th>Data</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 Wk</td>
<td>Wk</td>
<td>Wk</td>
<td>LWk</td>
<td>LWk</td>
<td>Es</td>
<td>Wk</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>LEs</td>
<td>LVs</td>
<td>LVs</td>
<td>Wk</td>
<td>LWk</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>LEs</td>
<td>LEs</td>
<td>Wk</td>
<td>Wk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Eq</td>
<td>Es</td>
<td>Wk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td></td>
<td>Es</td>
<td>Wk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>LEs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
**Synthetic Quantitative Comparison Matrix**

After the linguistic variables are assigned to the weights in the pairwise comparison matrix, the DSS converts them into fuzzy numbers using the linguistic scale from Table 1. This creates a pairwise comparison matrix with fuzzy numbers (Table 3) that have triangular membership functions.

<table>
<thead>
<tr>
<th>Table 3: Pairwise comparison matrix with fuzzy numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
</tr>
<tr>
<td>General</td>
</tr>
<tr>
<td>Hardware</td>
</tr>
<tr>
<td>Coord</td>
</tr>
<tr>
<td>PE/TSP</td>
</tr>
<tr>
<td>Ped</td>
</tr>
<tr>
<td>Data</td>
</tr>
<tr>
<td>Advanced</td>
</tr>
</tbody>
</table>

From the fuzzy comparison matrix, the DSS obtains the fuzzy weights of dimensions, using the geometric mean method with fuzzy product:

\[
\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in})^{1/n}
\]  

(3)

The weights of each dimension can be obtained using fuzzy addition and product:

\[
\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1}
\]  

(4)

Since the result of the previous fuzzy synthetic decisions are fuzzy numbers, those numbers need to be defuzzified into crisp values. The center of area method is used for computing the best non-fuzzy performance (BNP) value of the fuzzy weights, following the formula:

\[
BNP_{w_i} = \frac{[(Uw_i-Lw_i)+(Mw_i-Lw_i)]}{3} + Lw_i
\]  

(5)

The BNP values, normalized into a 100-point scale for the provided example, are presented in Table 4: Values of the best non-fuzzy performance of the fuzzy weights. As can be seen from the weights for PE/TSP and pedestrian features in this table, these are considered to be the most important.

<table>
<thead>
<tr>
<th>Table 4: Values of the best non-fuzzy performance of the fuzzy weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
</tr>
</tbody>
</table>

12
With the final weights calculated, the procedure of expert knowledge acquisition is completed. These weights are then presented on a pie chart graph that has a 100-point scale (similar to the pie chart in Figure 3). The pie chart is intended to change as the user performs each input, thus providing constant feedback on the expert’s input. This dynamism enables expert traffic engineers to perceive the absolute importance each criterion will have in the decision-making process.

CONCLUSION AND FUTURE WORK

The research presented here was initiated by the need of transportation agencies to select traffic signal controllers for their future traffic signal systems. Considering that there are several alternative controllers, multiple criteria (multiple controller features), preference dependence, responsibility for long-term operation and large-scale investment, etc., there is a need for analytically based evaluation methods. To the authors’ knowledge, this research pioneers the provision of a complete procedure or tool for evaluating traffic signal controllers. This research has focused on developing a decision-support application that can fulfill the transportation agencies’ need for improved decision-making. The research presented here focused on the decision-support application itself and its capabilities in expert knowledge acquisition. Previous research has established the complete evaluation methodology, development of evaluation criteria, and the provision of procedures for assignment of scores to sub-criteria.

MADONNA-DSS was developed as a three-step analytical application in Microsoft Excel, with a supporting database in Microsoft Access to facilitate tech transfer through workshop presentations. The focus of the improvement was primarily on the procedure collecting user expertise in assigning criteria weights. A GUI of the application was developed to support the expert knowledge acquisition – enabling their focus on the task of assigning weights, while reducing the cognitive workload. The computation, based on fuzzy logic, was performed in the background. In addition, the application can generate detailed reports and enable comparison among inputs between different experts or from different times. This enables the analytically based comparison of alternatives, transparency, adaptability, and utilization as a communication medium between experts and a wider audience. Finally, future research can focus on collecting
further feedback from different transportation agencies and validation of its operation. This should provide a potential for greater flexibility of this application to aid in the decision-making process for other traffic signal control equipment selection (e.g., detection, communication, emergency power supply, etc.).

REFERENCES


12. Tzeng, G.H. and J.J. Huang, Multiple attribute decision making: Methods and applications2011: CRC Press.


APPENDIX 1. MADONNA-DSS USER MANUAL

The MADONNA-DSS module is designed to allow step-by-step user input while allowing backward progression through the application menu. The following is a description of the application menus, their options and capabilities. The description is provided in the form of a complete step-wise decision-making procedure.

User Selection

Figure 1 presents the first menu displayed in this application to the potential user. This menu is used for selecting a user that will perform the decision-making procedure itself. The decision-maker is selected from the drop-down combo box. Clicking on the button Proceed, the potential user will be guided to the next menu for knowledge acquisition. In addition, the buttons below the drop-down combo box provide the capabilities to add, change the info, or delete an existing user. The button Exit Application is used for closing the MADONNA-DSS application.

![User Selection Menu](image)

Figure 1: User selection menu

Pairwise Comparison of Criteria Weight

The second step in the decision-making process is primarily directed toward collecting expert knowledge from an agency’s traffic engineers. In this menu (Figure 2), the expert traffic engineer is supposed to decide on the relative importance between decision-making criteria. The criteria
for traffic signal controllers are grouped as General Traffic Operation, Hardware, Coordination, Preemption/Transit Signal Priority, Pedestrian and Bike, Data, and Advanced. These criteria are provided in the central matrix, encircled in the red ellipse in Figure 2. The user can see additional information on each decision criterion by holding a cursor above specific criteria in list 1.

![Figure 2: Pairwise comparison of criteria weight](image)

The expert should perform a relative comparison as a relation of criteria from list 1 (row) to criteria from list 2 (column). The comparison of criteria based on Saaty’s comparison scale is provided in Figure 3. The relative comparison is performed using linguistic parameters on a scale from “extremely unimportant” to “extremely important,” with each linguistic parameter having a corresponding numerical intensity from 1/9 to 9. By selecting a linguistic parameter from the combo box in the comparison matrix, the expert decides on the relative importance or non-importance of criteria in list 1 to criteria in list 2. The Help button can provide additional instructions and examples for relative comparison of criteria. The user has the option to retrieve a previous weights selection using the combo box in the left lower corner of this interface.
While the user is assigning relative importance between criteria, the pie chart below the matrix is showing criteria weight distribution on a 100-point scale. This dynamic graphical feature enables the expert traffic engineer to perceive the absolute importance each criterion will have in the decision-making process. In addition to this criteria weight distribution pie chart, Figure 4 shows the consistency ratio as a percentage, which is a parameter describing a logical consistency of relations of criteria weights. In the case where the user input is inconsistent and an error message is displayed in the box below the consistency ratio, the user can click on the button Detailed Info of Inconsistencies. This will generate a message box showing the specific relations that have logical inconsistencies. The button Refresh Matrix resets the relative weights among criteria. Finally, the button GENERATE REPORT AND DECISION MATRIX leads the decision-maker into the final decision-making step.
Generating the Report

The last step in the decision-making procedure is the generation of the report. Figure 5 presents a default view that shows two radar graphs. The radar graph on the top of the report presents controller capabilities per criteria for the selected relative criteria weights in the previous step. Below this radar graph are three color-coded cells (red, yellow, green) that represent the absolute score for each controller. The green color is assigned to a cell with the highest score, while respectively the cell with the lowest score is assigned the red color. The radar graph at the bottom of the default report page gives the decision maker an opportunity to select an alternative set or absolute criteria weights, thus enabling dynamic “what-if” comparison of alternative weights and consequential alternative solutions. The selection of alternative absolute criteria weights can be performed using the combo boxes on the lower right, encircled in green in Figure 5. The user can also re-enter relative weights in the comparison matrix by clicking the Re-Enter Comparison Matrix button, or exit the application by clicking the EXIT button.

The button View Decision Matrix (marked in the red ellipse in Figure 5) generates a decision matrix for the defined controller weights. This enables the user to see the details of the decision-making scores and procedures, along with respective details on controller capabilities. The user has the option to choose between the expanded and collapsed view in the option buttons below the View Decision Matrix button. An example of the collapsed view is presented in Figure 6, where the criteria name and weight are in yellow cells, while light blue cells show respective scores per criteria.
Figure 5: Comparison of controller capabilities
An example of the expanded view of the decision matrix shows detailed scores for each sub-criterion, and the procedure for scoring is presented in Figure 7.