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Improved Decision-Support Making for Selecting Future Traffic Signal Controllers using Expert-Knowledge Acquisition

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Abstract — **Transportation agencies are facing the decision-making problem while selecting traffic signal controller that corresponds to the needs of their future signal system. 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 paper presents an improvement of methodology and a decision-support system (DSS) for selecting traffic signal controllers. DSS bases upon Analytical Hierarchy Process, and is developed as an application in MS Excel. The main improvement is the component for expert knowledge acquisition for assignment of criteria weights. The graphical user interface and supporting analytical engine based on fuzzy logic are developed to enhance the expert knowledge acquisition. Paper presents application interface and analytical engine with an example. Possibilities for further research should provide potential for greater flexibility of this application to aid in decision-making for other equipment selection.**

I. Introduction

CONVENTIONAL traffic signal controllers are one of the most direct control components of modern traffic control systems and they 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, safety constraints and basic phase structure, had different paths. One path of the development, 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 base upon ring-barrier control structure with several generations of standards starting from the early 1970s [2]. The latest standardization effort, named 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, besides some 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 agency's customized needs. However, this increased flexibility in software customization resulted in the 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 the choice of the particular controller assumes the responsibility of having to operate with it in 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 United States alone [5].

A. *Previous projects and research need*

There were several previous research and practical projects focusing on the decision-making for the procurement of traffic signal controllers [6-9]. Considering this previous research and practice developed for selecting future signal controller, 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 just some operational functions. A survey of agencies across United States, performed by the authors, confirmed that there are 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 initiated for helping the Northern Region Operations (NRO) of Virginia Department of Transportation (VDOT) in the selection of their future controllers [10, 11]. NRO has over 1600 signalized intersections under their 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 with the new controllers in the next 20 years, the scale of the investment itself introduced additional pressure for improved decision-making. Considering none of the

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previous research has developed a complete procedure or tool for evaluating traffic signal controllers, there was an apparent need for improved and analytically-based decision-making. This paper will focus on presenting the improvements on the previously developed decision-support system (DSS) [11]. These improvements focus on the improved analytical procedure underlying knowledge-acquisition process of criteria weights, and development of graphical user interface to accommodate this application.

II. Decision-Support System for Controller Selection

The complex situation described in the section above has made apparent the essential need for normative decision analysis that can help finding the most desirable future controller. In the case this was a single criterion problem, decision making would be intuitive [12, 13]. However, considering that there are several alternative controllers, multiple criteria (controller features), preference dependence, etc., there is a need more sophisticated evaluation methods. In the complex decision environment, as it is the one for selecting traffic signal controllers, traditional informal judgment cannot fulfill 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 capability to provide a range of alternative solutions. In overall, DSS is intended for improving the quality of information on which decision is based, and extending the range of decision processes. In transportation engineering, DSS were primarily used for scheduling and managing trains, fleet, or crew [15, 16]. However, there has been previous research in fields other than signal control, where DSS were used for equipment replacement decision [17] and equipment selection [18-20].

The framework for selection among the 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 group of experts
- Utilization as a communication medium between experts and wider audience

In order to fulfill the framework requirements, selection needed to base upon 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 top-down approach, based on the three main DSS components: criteria, criteria weights, and attribute scores.

A. *The role of expert knowledge in DSS*

The controller selection problem presented above 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 controller. 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.

III. Decision-Support Methodology

A. *Multi-attribute 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 decision matrix. A finite set of alternatives is a choice set denoted as $A = \{A_1, A_2, \dots, A_m\}$. 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:

$$\forall a, b \in A, \begin{Bmatrix} a\ P\ b \leftrightarrow x(a) > x(b) \\ a\ I\ b \leftrightarrow x(a) = x(b) \end{Bmatrix} \tag{1}$$

where *a P b* means "a is preferred to b" and *a I p* means "a is indifferent to b". Decision matrix or performance table, expresses performance of *m* alternative relative to *n* attributes considered (Fig. 1). Usually, there is a measure of relative importance of criteria/attribute, expressed as weight vector $w = (w_1, w_2, \dots, w_n)$.

	a_1	a_2	...	...	a_j	...	...	a_n
A_1	a_{11}	a_{12}	...	...	a_{1j}	...	...	a_{1n}
A_2	a_{21}	a_{22}	...	...	a_{2j}	...	...	a_{2n}
.	.	.			.			.
.	.	.			.			.
.	.	.			.			.
A_i	a_{i1}	a_{i2}	...	...	a_{ij}	...	...	a_{in}
.	.	.			.			.
.	.	.			.			.
.	.	.			.			.
A_m	a_{m1}	a_{m2}	...	...	a_{mj}	...	...	a_{mn}
w	w_1	w_2	...	...	w_i	...	...	w_n

Fig. 1: General representation of decision matrix

B. *Analytical Hierarchy Process*

A specific MADM technique chosen for the proposed DSS is 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]. AHP procedure has 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 reciprocal matrix.
3) Organize 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, that are finally aggregated to obtain global ratings.

C. Establishment of Evaluation Criteria

The decision context of this methodology is focusing 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 future controller that does not meet user requirements will 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 a 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 higher number of parameters, compatibility with database in the central TMS, availability of multiple polling and communication rates, the availably of alarms for reporting different hardware or software issues, etc.
- *Advanced Controller Features* - Any additional controller features that were not immediately identified as mapped previous CFR groups, but that could have potential future applications, as the system develops.
- *User Survey Ranking* - This evaluation criteria bases on the additional insight about the overall controller performance obtained from the survey of previous agency's field experience.

D. 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 on the Fig. 2.

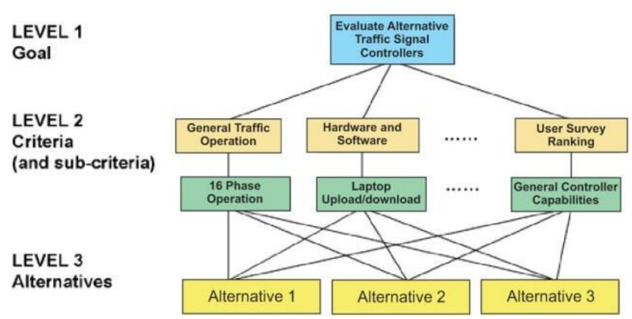

Fig. 2: Hierarchical DSS structure

E. Criteria scores and weights

Special attention needs to be dedicated to determining score for each sub-criteria. 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.

IV. DSS-ATCS

Developed DSS application for evaluation of future signal controllers is named Decision-Support System for Advanced Transportation Controller selection (DSS-ATCS). DSS-ATCS is a Microsoft Excel-based application, designed to provide the flexibility in collecting and analyzing the traffic signal expert's knowledge. Using DSS-ATCS, 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 DSS-ATCS is an external database developed in Microsoft Access. This database contains criteria scores and stores user input.

A. Graphical User Interface for expert knowledge acquisition

Graphical User Interface (GUI) for DSS-ATCS 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 three-step linear path, matched to three application's 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

GUI has been 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 are developed assuming infrequent use. These options are intended to support ease of use and ease of relearning, in order to reduce cognitive workload of the user, thus allowing focusing on the assignment of weights.

DSS-ATCS has dynamic graphical and written feedback, designed to support the weight assignment process. Error management system provided error calculation and immediate feedback before the result generation. The weights assignment process bases upon Eigenvector for calculation, along with calculating 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 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 eclipse in the Figure 3.

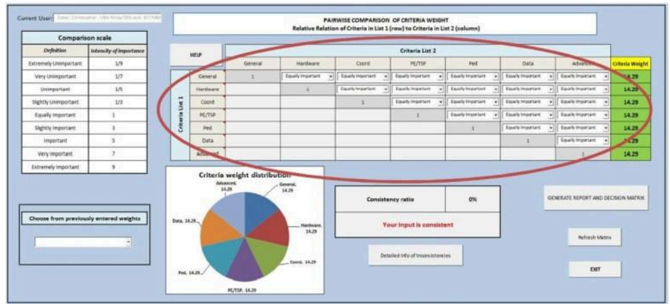

Fig. 3: Weight assignment window

V. Assignment of Criteria Weights

A. Fuzziness of criteria weights

DSS-ATCS is highly dependent on the 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 an equal importance weights. 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.

Although AHP has substantive capability in dealing with the defined type of a decision-making problem, converting 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 DSS-ATCS 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 there is imprecision and the sense of vagueness in linguistic expressions, the subject linguistic variables can be defined by corresponding membership function and fuzzy interval [22]. In DSS-ATCS, the linguistic variables are used for pairwise comparison of criteria in 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), that 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:

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

Table 1: Values of fuzzy numbers from linguistic scale

Extremely strong	Very strong	Strong	Marginally strong	Equal	Marginally strong	Strong	Very strong	Extremely strong
LAb	LVs	LEs	LWk	Eq	Wk	Es	Vs	Ab
$\tilde{9}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	$\tilde{7}$	$\tilde{9}$

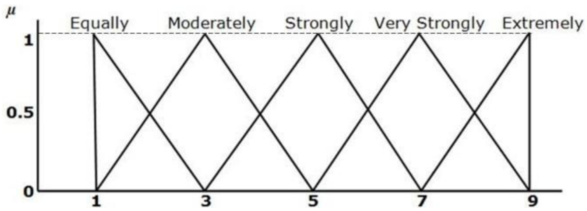

Fig. 4: Membership functions of linguistic variables used in the framework

VI. 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 experts 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

		General	Hardware	Coord	PE/TSP	Ped	Data	Advanced	Survey
1	General	1	Wk	Wk	LWk	LWk	Es	Wk	Ab
2	Hardware		1	LEs	LVs	LVs	Wk	LWk	Wk
3	Coord			1	LEs	LEs	Wk	Wk	Vs
4	PE/TSP				1	Eq	Es	Wk	Ab
5	Ped					1	Es	Wk	Ab
6	Data						1	LEs	Wk
7	Advanced							1	Es
8	Survey								1

A. *Synthetic quantitative comparison matrix*

After the linguistic variables are assigned to the weights in the pairwise comparison matrix, the DSS needs to convert 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 3: Pairwise comparison matrix with fuzzy numbers

		General	Hardware	Coord	PE/TSP	Ped	Data	Advanced	Survey
1	General	1	$\tilde{7}$	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{3}$	$\tilde{9}$
2	Hardware	$\tilde{7}^{-1}$	1	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{3}$
3	Coord	$\tilde{3}^{-1}$	$\tilde{5}$	1	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{7}$
4	PE/TSP	$\tilde{3}$	$\tilde{7}$	$\tilde{5}$	1	$\tilde{1}$	$\tilde{5}$	$\tilde{3}$	$\tilde{9}$
5	Ped	$\tilde{3}$	$\tilde{7}$	$\tilde{5}$	$\tilde{1}$	1	$\tilde{5}$	$\tilde{3}$	$\tilde{9}$
6	Data	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	1	$\tilde{5}^{-1}$	$\tilde{3}$
7	Advanced	$\tilde{3}^{-1}$	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}$	1	$\tilde{5}$
8	Survey	$\tilde{9}^{-1}$	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{9}^{-1}$	$\tilde{9}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	1

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

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ . \ . \ . \otimes \tilde{a}_{in})^{1/n} \quad (3)$$

$$\tilde{r}_1 = (1.196, 2.052, 3.303) \quad \tilde{r}_5 = (2.052, 3.303, 4.833)$$

$$\tilde{r}_2 = (0.281, 0.452, 0.713) \quad \tilde{r}_6 = (0.253, 0.390, 0.706)$$

$$\tilde{r}_3 = (0.705, 1.196, 1.907) \quad \tilde{r}_7 = (0.589, 0.990, 1.990)$$

$$\tilde{r}_4 = (2.052, 3.303, 4.833) \quad \tilde{r}_8 = (0.175, 0.214, 0.344)$$

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

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ . \ . \ . \oplus \tilde{r}_n)^{-1} \quad (4)$$

$$\widetilde{w}_1 = (0.164, 0.172, 0.177) \quad \widetilde{w}_5 = (0.281, 0.277, 0.259)$$

$$\widetilde{w}_2 = (0.038, 0.038, 0.038) \quad \widetilde{w}_6 = (0.035, 0.033, 0.038)$$

$$\widetilde{w}_3 = (0.096, 0.100, 0.102) \quad \widetilde{w}_7 = (0.081, 0.083, 0.107)$$

$$\widetilde{w}_4 = (0.281, 0.277, 0.259) \quad \widetilde{w}_8 = (0.024, 0.018, 0.018)$$

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:

$$BNPw_i = \frac{[(Uw_i - Lw_i) + (Mw_i - Lw_i)]}{3} + Lw_i \quad (3)$$

The BNP values, normalized into a 100-point scale, are presented in the following Table 4: Values of the best non-fuzzy performance of the fuzzy weights. As you can see from the weights for PE/TSP and pedestrian features in this table are considered as the most important However, the weights for data and survey criteria are considered as the least important.

Table 4: Values of the best non-fuzzy performance of the fuzzy weights

General	Hardware	Coord	PE/TSP	Ped	Data	Advanced	Survey
$BNPw_1$	$BNPw_2$	$BNPw_3$	$BNPw_4$	$BNPw_5$	$BNPw_6$	$BNPw_7$	$BNPw_8$
17.1	3.8	10.0	27.3	27.3	3.5	9.0	2.0

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 hundred point scale (similar to the pie chart on the Figure 3). 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 engineer to perceive the absolute importance each criteria will have in the decision-making process.

VII. CONCLUSION AND FUTURE WORK

Research presented here was initiated by the need of transportation agencies to select traffic signal controller for their future traffic signal system. 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. No previous research has provided 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 is focusing 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 provided procedures for assignment of scores to sub-criteria.

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

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