Decision-Support System for Assessment of Alternative Signal Controllers using Expert Knowledge Acquisition

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ABSTRACT

The standardization of controller hardware under the Advanced Transportation Controller standard provided the flexibility for customized development of controller software. However, a multitude of controller software features on the market presents a challenge for the assessment when purchasing future system. This paper presents a decision-support application based on Analytic Hierarchy Process technique for the assessment of traffic signal controllers. The method to evaluate the controllers is based on the set of criteria derived from market controller features. The application consists of knowledge, model, data, and dialog management components. It was developed in MS Excel, along with supporting MS Access database. The application is highly dependent on the expert knowledge acquisition. It provides weighted Performance Index along with the decision-support visualization aids. The application was developed using previous research originally developed for a signal system under the purview of Virginia Department of Transportation (VDOT). However, the framework and application are transferable among agencies, and can be potentially used for evaluation of other signal infrastructure.
INTRODUCTION
Traffic signals are one of the vital elements of traffic control systems under the purview of any Department of Transportation (DOT). In the current practice, Traffic Signal Engineers and Traffic Signal Field Technicians in DOTs are often facing pressure for extracting additional benefits from existing signal control equipment, influenced by evident increase in demand and changing traffic patterns. In addition, these engineers and technicians have to evaluate and upgrade traffic signal controllers, once they reach the limit of their operational features. Their evaluation concerns are increased by the fact that DOTs usually assumes the responsibility of having to operate with the selected traffic signal controller in the next 15 to 20 years.

The recent efforts under the Advanced Transportation Controller standard are introducing additional complexity for controller evaluation. Advanced Transportation Controller (ATC) standard, is a combination and improvement of all the previous North American operational and hardware standards (NEMA TS1, NEMA TS2, 170, 2070) [1, 2]. This standard introduced a high level of hardware standardization, defining signal cabinet elements, controller elements, operating system, etc. However, this standard does not have a significant focus on controller software. This gave the opportunity for third-party vendors to develop signal control software according to customized agency’s needs or simply driven by the competitive-market development. Nowadays, North American market consists of over ten companies developing signal controller software, which frequently has over 200 control parameters [3, 4].

The multitude and complexity of software options introduced decision-making issues in selecting an optimal solution for a future agency’s signal controller. Considering previous research and practice [5-8] 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 are primarily related to device compatibility, equipment life, ability to generate reports, and some operational functions. However, there is no complete procedure or tool that would help DOTs to evaluate signal controller software. Literature [2] suggests that there has been previous research in evaluation of signal infrastructure. However, the alternatives were evaluated from a macro perspective and the evaluation procedure did not consider the actual features of the controllers.

DSS FOR EQUIPMENT SELECTION
The complex situation described above has made apparent the essential need for improved and analytically-based decision-making in selecting the optimal controller for procurement. In the case this was a single criterion problem, decision making would be intuitive [9]. However, considering that there are several alternative controllers, multiple criteria (multiple controller features), preference dependence, etc., there is a need more sophisticated evaluation methods.
In addition, DOTs across US have many Signal Operation Engineers and Traffic Signal Field Technicians with different training levels. These engineers and technicians have extensive expert knowledge and trial-and-error experience in specific parts of controller fine-tuning. This dispersed knowledge base has a potential to be effectively integrated and organized into a decision-support system (DSS) [2] for selecting the future signal controller. In addition, considering that the controller selection is a semi-structured decision problem, the problem cannot be solved by existing classic mathematical models, but the decision primarily relies on human intuition [10].

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 [11]. 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. As such, DSS is ideal to support, rather than replace, traffic signal experts’ role in choosing future signal controller.

In transportation engineering, DSS were primarily used for scheduling and managing trains, fleet, or crew [12, 13], without any research on equipment selection. However, there has been previous research in other fields, using DSS for equipment replacement decision [14] and equipment selection [15-17]. With this in mind, the research presented is considered being an initial research, focusing on developing a flexible decision-support application for selecting future traffic signal controllers. This DSS, named Decision-Support System for Advanced Transportation Controller selection (DSS-ATCS), is partially developed from research intended to help the Northern Region Operations (NRO) of Virginia Department of Transportation (VDOT) in the selection of their future controllers [18]. The complete evaluation procedure developed in that research is presented in a separate paper. The focus of this paper is on the DSS application and its generalized and flexible procedure for evaluating future traffic signal controllers.

**DSS-ATCS CONCEPTUAL MODEL**

Considering that DSS-ATCS is intended to help decision-making in selecting future traffic signal controllers, it needs to be able to rank and compare traffic signal controllers. This comparison bases on controller’s programmable features and their correspondence to agency’s functional requirements. Considering that expert knowledge of DOT’s traffic engineers is very valuable in this decision-making process, DSS-ATCS is designed to perform expert knowledge acquisition [19]. That knowledge database is used further in the decision-making process. DSS-ATCS is designed to provide the flexibility in collecting and analyzing the expert knowledge, in order to achieve the optimal solution for all the stakeholders. 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. DSS-ATCS consists of knowledge, model, data, and dialog management. In addition, DSS-ATCS has relations with external data, and system user. A conceptual model for DSS-ATCS is presented on the following FIGURE 1. The description of each of the components will be presented in the following sections.

![Conceptual model of DSS-ATCS](image)

**FIGURE 1: Conceptual model of DSS-ATCS**

**MODEL MANAGEMENT**

Considering that this DSS is primarily concerned with alternative choice selection, a typical model choice for this type of DSS issue are Multi-Criteria Decision Making (MCDM) techniques [20]. In addition, MCDM is selected because:

- It is transparent and cross-referenced to other sources of information,
- Allows analytical input to be a responsibility of group of experts, and
- Evaluation of the results can be delivered in a multifaceted form, helping decision-makers to increase their understanding about the choices made.

As defined, MCDM is a decision theory approach and set of techniques that helps in coherent ordering of conflicting options [9]. DSS-ATCS classifies as Multi-Attribute Decision Making (MADM), since decision space is discrete and each candidate alternative can be evaluated using a combination of analytical tools. Each MADM evaluation model is defined by [21]:

- a set of alternatives
- a set of criteria or attributes for evaluation
- a decision matrix

MADM has been used in decision-making problems in transportation, for planning purposes [22] or for planning in highway asset management [23, 24].
Analytic Hierarchic Process

There are many MADM techniques implemented in practice (e.g., Simple Additive Weighting, ELECTRE, TOPSIS, PROMETHEE). Essentially, all MCDM techniques are similar, since they base on the criteria weights and scores. However, the evaluation procedure and the emphasis for using each technique are different. For example, Simple Additive Weighting is the simplest technique, using the addition of weighted criteria scores. This is the reason this technique is the most general one, but is not always the best one. On the opposite, technique such as ELECTRE bases on the relative comparison and elimination of alternatives. This technique is applicable to choosing, ranking, and sorting problems [21].

For the proposed DSS, the research team chose to use Analytical Hierarchy Process (AHP) technique [25]. AHP was developed to model subjective decision-making processes based on multiple attributes in a hierarchical system, and structures process as a hierarchical decomposition, reducing complex problems into sub-problems [26]. AHP procedure has five steps, which will be described in the context of DSS-ATCS:

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.

Decision context

Establishing a decision context by decompose a problem into an interrelated hierarchy of goal, criteria, and alternatives, we have the following:

- Goal: selecting an optimal traffic signal controller
- Criteria:
  - Controller hardware and software
  - General traffic operation
  - Coordination and plan selection
  - Signal Preemption (PE) and Transit Signal Priority (TSP)
  - Pedestrian and bike operation
  - Reports, data archiving needs, and communications requirements
  - Advanced controller features
- Alternatives: different market ATC
A well-defined set of criteria is important because it allows each of the criteria to be quantifiable and easily evaluated [27]. The decision criteria for DSS-ATCS were developed in the previous research by the authors [18]. The decision criteria related directly to the features of traffic signal controller hardware and software. Decision variables are presented as sub-criteria in the lowest hierarchical level on the Figure 2. These criteria were developed by gathering interview and survey input from signal control experts across Northern America. In addition, the authors used highly detailed information about the actual controller features available on the market. During this research, over 50 specific controller features were identified. These features were clustered together, into groups that are mapped to distinguished groups [28], which became the decision criteria. This clustering was intended to ease the calculation of weights in MADM application and to facilitate the importance of high-level views on issues with related trade-offs. The derivation of criteria and relative weights is performed according to a hierarchical system [9]. Decomposing a problem of selecting an optimal signal controller into a hierarchy of interrelated elements is presented on the following FIGURE 2: Hierarchical structure of criteria and sub-criteria. This figure presents sub-criteria for the seven decision criteria, that were developed in the previous research [18] by the authors.

**FIGURE 2: Hierarchical structure of criteria and sub-criteria**

**Pairwise criteria comparison**

As a second step in AHP, we need to collect data from the traffic signal experts, as a pairwise qualitative comparison of criteria to create reciprocal matrix. The weighting process is usually based on the explicit conversion of expert knowledge obtained through interviews of signal control experts. Linguistic variables are used for pairwise comparison of criteria in the second AHP step [29]. A transformation of qualitative expert estimates into the quantitative ones, and the approach uses the standard 9-point Saaty’s scale [29] (FIGURE 3) based on linguistic variables:
By changing the weights of criteria, according to their priority to future control system, analyst can affect the final scores of mutual assessment of controllers. For example, a certain corridor might require both Transit and pedestrian facilities but the Transit features may be more important than the pedestrian requirements. This relative importance can be well represented in the reciprocal matrix. As each linguistic variable has a corresponding numerical value, we first calculate Relative Value Vector. This is performed by multiplying the entries in each row of the weight matrix, then calculating the $n^{th}$ root of that product, and finally summing the $n^{th}$ roots results in the normalized eigenvector elements that add to one. Having organized pairwise criteria comparison into a square quantitative matrix, this completes the third AHP step.

**Evaluating matrix consistency**

The weights assigned by the expert are consistent if they are transitive. However, since human judgment is usually not consistent, AHP process requires the comparison of expert judgments to purely random judgments. There are several methods for assessing consistency of weights, including the use of Eigenvector, Weighted Least Square, Entropy method, etc. In this particular case, the weights are assessed using Eigenvector method [17, 30]. The relative weights from the previous step are given as the right eigenvector ($w$), corresponding to the largest eigenvalue ($\lambda_{max}$), as:

$$Aw = \lambda_{max}w$$

If the pairwise comparisons are completely consistent, the matrix $A$ has rank value of one and $\lambda_{max}$ is equal to $n$. The consistency is defined by the transitivity between the entries in the matrix $A$, as $a_{ij} \times a_{jk} = a_{ik}$. In order to determine matrix consistency, we need to calculate Consistency Ratio (CR). However, before CR, we need to determine the Consistency Index (CI) as

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Finally, CR is calculated as a ratio of CI and Random Index (RI). RI is the value of CR for purely random weight matrix. In the case a matrix has seven elements (as the number of criteria in DSS-ATCS) this value is 1.32. The value of 0.1 is the acceptable upper limit for CR. In the case final CR exceeds this value, the input of weights comparison need to be repeated. This completes fourth AHP step, evaluating matrix consistency, and having importance weights
assigned to each criteria. An example of eigenvector and CR calculation for hypothetical weights of four criteria is presented in the Table 1. The RI obtained from Saaty’s list of random values was 0.9, since there are four criteria (n=4).

**Table 1: Example of CR calculation**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>nth root of product of criteria weights</th>
<th>Eigenvector (normalized value)</th>
<th>Sum of products of criteria weight and eigenvector value</th>
<th>Division of sum of products and eigenvector</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00</td>
<td>0.33</td>
<td>0.11</td>
<td>0.20</td>
<td>0.29</td>
<td>0.06</td>
<td>0.25</td>
<td>4.05</td>
<td>0.06</td>
</tr>
<tr>
<td>B</td>
<td>3.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.32</td>
<td>0.27</td>
<td>1.12</td>
<td>4.12</td>
<td>CR</td>
</tr>
<tr>
<td>C</td>
<td>7.00</td>
<td>1.00</td>
<td>1.00</td>
<td>3.00</td>
<td>2.14</td>
<td>0.44</td>
<td>1.81</td>
<td>4.10</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>7.00</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>1.09</td>
<td>0.22</td>
<td>1.01</td>
<td>4.49</td>
<td>0.07</td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.84</td>
<td>1.00</td>
<td>MEAN (λmax)</td>
<td>4.19</td>
<td></td>
</tr>
</tbody>
</table>

**Calculation of Performance Index**

As the last AHP step, analyst needs to calculate Performance Index (PI). This value is used to compare decision alternatives. Weighted PI is obtained by multiplying the attribute value by the importance weight and then summing over all attributes. Assuming a set of importance weights as \( w = \{w_1, w_2, \ldots, w_n\} \), the most preferred alternative \( A^* \) is selected as

\[
A^* = \{A_i \mid \max_i \sum_{j=1}^n w_j x_{ij} / \sum_{j=1}^n w_j \}
\]

where \( x_{ij} \) is the score of the i\(^{th}\) alternative about the j\(^{th}\) attribute. Usually the weights are normalized as \( \sum_{j=1}^n w_j = 100 \), in order to obtain mutually comparable scores. Therefore, in the maximization case, the best alternative is the one that corresponds to the largest PI. By using the above formula, the PI values can be calculated for each controller, thus creating a global comparison numerical scale. That PI value is a measurement of the controller performance and represents the score/benefit of alternate systems.

**KNOWLEDGE MANAGEMENT**

Knowledge management in DSS-ATCS is introduced to include the expert knowledge of Signal Technicians and Traffic Signal Engineers. This component is intended primarily for tacit knowledge acquisition [19] considering criteria weights and evaluation scores. In addition, the knowledge acquisition is enhanced by extensive use of graphical presentations. These presentations will be presented in the dialog management component of DSS-ATCS. A conceptual presentation of the expert knowledge acquisition process is presented in FIGURE 4. The main sub-process is expert weight input, which takes top-down approach, starting with DOT operational goals. This input can be gathered from senior Traffic Engineers. Usually these goals are safety, mobility, and environmental protection, but they directly influence the importance of
specific controller features. Consequently, this relates to relative weight importance of specific
criteria for future signal controller (e.g. Coordination and plan selection or Pedestrian and bike
controller features). The sub-process of expert weight input is performed by Signal Technicians
and Traffic Signal Engineers, and is directly related to its consistency check sub-process. The
analytical procedure for weight-matrix consistency check was described in the previous paper
section, and this is the first level of assessment of expert input. These two elements of the expert
knowledge acquisition process are further directly related weight visualization. Weight
visualization is the second level of expert input assessment. Finally, expert weight input is also
related to evaluation visualization, which is a third level of expert input assessment.

In addition to criteria weights, scores for all the alternative controller features are an external
input to expert knowledge acquisition process. The procedure and scoring can be obtained using
controller manual, user and vendor survey, modeling and testing of controller features (for
further details see [3, 4, 31-34]). Each controller feature can receive a score according to the
level it satisfies technical requirements. The scoring of controller capabilities is done in integer
values. The scoring of alternative controller features can be performed by DOT or by external
contractor. Depending if or up to what level the controller feature is satisfying technical
requirements, that feature receives a score. All the scores are normalized to be in the range of
zero to one. In DSS-ATCS, these values are stored in MS Access database, which is a data
management component.

DATA MANAGEMENT

DSS-ATCS data management component is a collection of interrelated data structure organized
to share the information. This component is represented by a MS Access database, which enables
storage of expert knowledge from different experts and at different points in time. The database
itself contains four tables: Criteria, Char, User, and Weight (FIGURE 5). Table Criteria contains
field Criteria ID, which is identification number for decision criteria, and field Criteria, which contains all the decision criteria (seven in this DSS). This table allows the change of decision criteria for further customizable development of DSS-ATCS. Table Char is related to table Criteria. This table has fields Characteristic ID, Criteria ID, CharacteristicName, ControllerScore, and Scoring System. Field Characteristic ID and CharacteristicName are related to the list of all the controller features that belong to each of the seven decision criteria in DSS-ATCS (e.g., 16-phase operation, phase reservice during Free and Coordinated operation, number of offsets per plan, 4 seconds early Walk, etc.). ControllerScore and Scoring System fields contain the information on the score each controller feature has, along with the description of the scoring procedure. Criteria and Char table have one-to-one relation using CriteriaID, and are primarily populated through external data. User table contains several fields, which are intended to store information on all the experts that were a part of the knowledge acquisition. The fields in this table store name, title, organization, and date related information. Weight table is related to User table in one-to-many relationship, and contains all the expert input for weight relationships. This enables storage of all the expert inputs, which can later be retrieved and compared. This way, the system is able to compare multiple users’ importance pairwise comparison matrix at once. The MS Access database developed is related to MS Excel application, where DSS-ATCS is developed.

![FIGURE 5: MS Access database relationships](image)

**DIALOG MANAGEMENT**

Dialog management component of the DSS-ATCS application is designed to allow step-by-step user input while allowing backward progression through application menu. Some DSS experts feel that the user interface is the most important component because many of the distinguishing characteristics of DSS (such as power, flexibility, and ease-of-use) are derived from this component [13, 31]. According to the presented framework, the research team developed an application based on MS Excel, using Visual Basic for Applications (VBA) [35]. Each of the DSS application menus is described below.
User Selection
User Selection (FIGURE 6) is 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 can be 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 DSS application.

FIGURE 6: User Selection menu

Pairwise Comparison of Criteria Weight
The second menu (FIGURE 7) in the decision-making process is primarily directed towards collecting expert knowledge from agency’s traffic engineers. In this menu, the expert traffic engineer is supposed to decide on the relative importance between decision-making criteria. These criteria are provided in the central matrix, encircled in the red ellipse on the FIGURE 7. The user can see additional information on each decision criteria by holding a cursor above specific criteria. The expert is expected to perform relative comparison as relation of criteria from list 1 (rows) to criteria from list 2 (columns). The comparison of criteria bases on the Saaty’s comparison scale, which is provided on the left side of the menu. The relative comparison is performed using linguistic parameters on a scale from Extremely Unimportant up to Extremely Important. Each linguistic parameter is having corresponding numerical intensity from 1/9 to 9. By selecting a linguistic parameter from combo box in the comparison matrix the expert decides on the relative importance or non-importance of criteria in list 1 with respect to criteria in list 2. The Help button provides additional instructions and examples for relative comparison of criteria. In addition, the user has the option to retrieve previous weights selection using the combo box in the left lower corner of this menu interface.
While the user is assigning relative importance between criteria, the pie chart below the matrix is showing criteria weight distribution on a hundred-point scale. This dynamic graphical feature enables expert traffic engineer to perceive the absolute importance each criteria will have in the decision-making process afterwards. In addition to this weight distribution pie chart (FIGURE 8), this menu shows consistency ratio in percent.

In the case the user input is inconsistent and 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 potential logical inconsistencies. The button Refresh Matrix resets the relative weights among criteria. Finally, the button GENERATE REPORT AND DECISION MATRIX in the bottom right corner leads the decision-maker into the final decision-making menu.
The last menu in the decision-making procedure is used for generating the report. The FIGURE 9 and FIGURE 10 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 the 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 has assigned red color. The radar graph at the bottom of the default report menu gives an opportunity to the decision-maker to select alternative set or absolute criteria weights. The selection of alternative absolute criteria weights can be performed using combo boxes on the lower right, encircled in green on the FIGURE 10. The user can also re-enter relative weights in the comparison matrix by clicking Re-Enter Comparison Matrix button, or exit the application by clicking the EXIT button.

The button View Decision Matrix (marked in the red ellipse on the FIGURE 9) generates a decision matrix for the defined controller weights. This enables 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 expanded and collapsed view in the option buttons below View Decision Matrix button. An example of the collapsed view is presented on the following FIGURE 11, where criteria name and weight are in yellow cells, while light blue cells show respective scores per criteria.
FIGURE 10: Lower part of the Decision Matrix and Radar Graph menu

<table>
<thead>
<tr>
<th>Controller capabilities - adjusted weights</th>
<th>Controller 1</th>
<th>Controller 2</th>
<th>Controller 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Traffic Operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controller hardware and software</td>
<td>128.6</td>
<td>125.9</td>
<td>100.0</td>
</tr>
<tr>
<td>Traffic coordination and plan selection</td>
<td>114.3</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Signal Preemption/Transit Priority</td>
<td>100.0</td>
<td>142.9</td>
<td>96.4</td>
</tr>
<tr>
<td>Pedestrians and bikes</td>
<td>125.7</td>
<td>105.7</td>
<td>114.3</td>
</tr>
<tr>
<td>Reports, Data Archiving Needs, Communications</td>
<td>57.1</td>
<td>35.7</td>
<td>64.3</td>
</tr>
<tr>
<td>Advance Controller Features</td>
<td>42.9</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Score</td>
<td>Score</td>
<td>Score</td>
<td>Score</td>
</tr>
<tr>
<td>SUM</td>
<td>41.8</td>
<td>43.07</td>
<td>41.25</td>
</tr>
</tbody>
</table>

FIGURE 11: Collapsed view of decision-matrix and PIs
Interpretation of the results

As the final output, DSS-ATCS calculates the weighted PI for each controller, resulting in pure ordinal scale with relative ranking. This enables the decision-maker to conclude which controller provides the highest satisfaction of established criteria for the future control system. In addition, the decision-maker can observe controllers that have advanced or missing capabilities in some of the groups of required features. The radar graphs in previous Figures FIGURE 9 and FIGURE 10 enable a comparison of capabilities per criteria for the best three controllers.

FINDINGS FROM THE TOOL DEVELOPMENT AND TESTING

Considering that DSS-ATCS is the first application for evaluating signal controllers, the findings from tool development and testing are also important. The tool testing has been performed using data from the project “Evaluation of Merits and Requirements of Next-Generation Traffic-Control Systems for VDOT's Northern Region Existing Infrastructure” [18]. One of the focuses of this project was evaluation of market controllers for future VDOT signal control system. The data on controller scores created during that project has been used for operational testing of DSS-ATCS. Although this application development has not focused on determining scores for controller features, the authors emphasize that special attention needs to be dedicated to this. Analytical scores for valid decision-making need to be determined during a meticulous testing and analysis, as described in the previous research [3, 4, 31-34].

As initially envisioned in the design, DSS-ATCS has been proved as a flexible decision-support system. DSS-ATCS is able to accommodate any changes in the weights or criteria, based on the specific DOT requirements. Originally, the application was envisioned to be used by signal control experts that should provide their input related to importance of criteria. During the development the user interface of the application has been simplified to be used by any decision-making stakeholder, not necessarily having signal control expertise. However, the evaluation process must include signal control experts, considering their knowledge base is important in finalizing the decision. However, any input from other stakeholders is welcome in the evaluation process, since it can broaden the perspectives. Furthermore, the application interaction with the user is able to provide feedback and help a user during the input. The application can be used even if the user does not have engineering background, or does not have in-depth understanding of the hidden analytical engine. In addition to Help buttons, pop-up windows, and comments, the application has graphical tools that perform input assessment, and provide instant feedback. Matrix consistency check, pie chart for criteria weights visualization, and radar graphs for evaluation visualization are additional tools that support input assessment. The combination of these tools helps the decision-maker to determine the weights and generate different reports, but is limited not to impose additional load to the potential user.
The application’s step-by-step procedure is intended to allow iterative comparison and generation of several reports in brief amount of time. DSS-ATCS gives the opportunity for decision-makers to do a "what-if" alternative analysis, comparing different criteria weights and controller capabilities. This allows inclusion of any preferences not initially expressed into the decision process. The application allows selection of the previous sets of weight too. In addition, graphical representation of the output should increase communication transparency for reaching a consensus among decision-makers. Ideally, each decision-maker should perform the input of desired criteria weights individually, without consultation with others. This should enable unconstrained perspectives and alternative solutions. After these initial evaluations, all the reports can be gathered and discussed during a joint meeting. This would ensure that all different perspectives are included, but that a mutually-agreeable solution is reached.

In addition, there are several more findings related to implementation of MCDM in this DSS. As stated above, MCDM is chosen for this DSS because it is transparent, cross-referenced, allows expert input, and delivers output in a multifaceted form. MCDM does not just help make a decision, but also increases the understanding on the choice made. The selection of a specific MCDM technique is especially important. AHP has been chosen in this case because it is based on hierarchical decomposition and allows calculation of PI, for relative comparison of alternatives. In addition, the assignment of criteria weights is especially important because it has the biggest influence on the final PI values. This is the reason the weight input is the central theme of the application and is supported by several supporting tools that help in input assessment. Either in analysis performed individually or in the group meeting, decision-makers need to be especially attentive to weight assignment. For example, as you can see on FIGURE 10, the controller with the highest PI value is controller 2. However, the radar graph shape on that figure is significantly different than the one on FIGURE 12. FIGURE 12 presents the evaluation output, that has only one criteria weight changed – weight for criteria “Pedestrian and bike controller features” has been changed from “equally important” to “slightly important”. Although this can be considered as a small change, the PI values for controllers are different, with controller 3 having the highest value. This example shows the importance of weight assignment has, since even small changes can have significant impact on the final decision.
CONCLUSION AND RECOMMENDATIONS

This paper presents a DSS application for evaluating traffic signal controllers based on the AHP technique. DSS-ATCS is designed to provide the flexibility in collecting and analyzing the expert knowledge, in order to achieve the optimal solution for all the stakeholders. 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. DSS-ATCS consists of knowledge, model, data, and dialog management. In addition, DSS-ATCS has relations with external data, and system user.

The application is highly dependent on the knowledge acquisition from signal control experts. The expert input is primarily used in determining the criteria weights. The weights assignment process uses Eigenvector for calculation, along with calculating Consistency Ratio for determining the logical consistency of assigned weights. The equation for the calculation of a weighted Performance Index of each controller respects determines global ranking among alternative controllers.

The developed method is applied in the developed MS Excel application and supporting MS Access database. This application allows automating the decision-making process in any DOT. Flexible framework design can accommodate the iterative change of weights according to local conditions and expert input. Each DOT has the flexibility to emphasize or deemphasize certain controller features. In addition to selecting the optimal future controller, the application allows identification of the potential for improvement of controller features.
The presented evaluation method can be enhanced even further by developing a method that
assigns scores based on the Measure of Effectiveness expected from each controller features. In
addition, the application has yet to incorporate the capability of automatic integration of multiple
users’ importance pairwise comparisons matrix into one. The developed method can also be
applied to the evaluation of other signal infrastructure components or to further MADM
evaluation of controllers including all of their advanced features. The framework is considered
transferable to evaluation of other signal infrastructure.

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