Development and use of Critical Functional Requirements for Controllers upgrade Decisions.

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ABSTRACT

Modern traffic signal controllers usually have to adopt to local transportation agency requirements. The standardization of controller hardware under Advanced Transportation Controller standard provided the flexibility for customized development of controller software. This resulted in a multitude of market controller software features that are challenging to evaluate. This paper presents a decision-support system based on a Multi-Criteria Decision Making (MCDM) technique for evaluation of traffic signal controllers. The method to evaluate the controllers is based on the set of Critical Functional Requirements for signalized intersections. The method was developed for a signal system under purview of Virginia Department of Transportation (VDOT). The critical functional requirements were developed through discussion with professionals in the field of signal system operations across North America. Criteria for scoring the controller features were developed from the information obtained from the controller manuals, vendors, software-in-the-loop and hardware-in-the-loop testing, survey of agencies, etc. A presentation of the proposed framework, with evaluation for three different controllers is included. In addition, presented are accompanying decision-support visualization aids. Alternate methods were also suggested for evaluation purpose, leaving opportunities for further research.

INTRODUCTION

Traffic signal controllers are one of the most important components of the signal control infrastructure, and play a crucial role in the operation of signalized intersections. Evaluation and upgrade of traffic signal controllers at intersections has been a conventional task for over eight decades. Electro-mechanical controllers were the first devices used to control traffic in the early 1930s [1, 2]. However, the use of these electro-mechanical devices has become almost obsolete due to the development of microprocessor-based technology that can better handle increasing traffic demand. With the wider implementation of microcontroller devices, the focus of development was on creating customized controller and signal cabinet equipment for application in traffic signal control.

The North American controller market bases on ring-barrier control (RBC) structure. North America had several generations of standards for traffic signal microcontrollers starting from the early 1970s. The Institute of Transportation Engineers, the National Electrical Manufacturers Association (NEMA), and the American Association of State and Highway Transportation Officials carried out the majority of the standardization effort [3]. The latest effort, named 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) [4]. This standard defines signal cabinet elements such as traffic signal controller, power supply and detector rack, malfunction management unit, back panel, etc. In addition to this, this standard defines all the controller elements, such as chassis, central processing unit, controller bus, field input/output, serial communication and modem units, power supply, front panel, and NEMA interface module. In addition, this standard defines operating system (OS9 or Linux) that deals with procedure startup, device, clock, and file management.

The ATC standard introduced a high level of hardware standardization, giving the opportunity for third-party vendors to develop signal control software according to customized agency's needs or through the competitive market development. Separated software and hardware development has allowed for increased flexibility and software customization. However, this separation also resulted in the multitude of signal-control software versions. Today, there are over ten different companies developing signal controller software for the North American market, often with several versions of signal controller software. These companies are producing traffic signal controller software that often has over 200 (frequently non-standard) control parameters.

The multitude and complexity of software options introduced decision-making issues in selecting an optimal solution for an upgraded signal-control system. This concern is even greater when the upgrade is planned for a signal control system with a large number of signalized intersections. In addition, the concern is increased by the fact that traffic agencies usually assumes the responsibility of having to operate with the selected traffic signal controller in the next 15 to 20 years. This complex situation has made apparent the essential need for improved and analytically based decision-making in selecting the optimal controller for procurement.

The research presented here was developed to help the Northern Region Operations (NRO) of Virginia Department of Transportation (VDOT) in the selection of their future controllers [5]. NRO operates and maintains more than half the traffic signals under VDOT's purview, with around 1560 traffic signals, 136 flashers, 14 intersection control beacons, 24 lane control signals, 5 emergency/fire signals, and 27 auxiliary control devices. The existing system was primarily based upon type 170 controllers, with most of the infrastructure reaching the limit of its operational effectiveness and capabilities due to changing traffic patterns and volumes in the region. The main objective of the research was therefore to develop a flexible decision-support system, implementable in NRO and statewide.

Nationwide state-of-the-practice

Previous projects revealed some of the experience and requirements that Departments of Transportation (DOTs) across the United States have obtained while purchasing controllers for their future control system. The Federal Highway Administration published a basic approach for the successful procurement of traffic signals and suggested location-specific identification of requirements [6]. This document identifies the functional needs for an integrated platform for signals and other ITS systems or devices, longer equipment life, the ability to generate reports, and the need for a particular controller type.

The traffic signal requirements for a new system, developed by the City of Lakeland, FL [7], described some requirements on general traffic control, preemptor, time-of-day, status display, detectors, logging, telemetry, protocols, and configuration of controller software. These requirements emphasized the interoperability of the new systems with the existing infrastructure, due to budgetary constraints. The general features of the new systems are to be compatible with the 170, NEMA, or ITS cabinets and with all 2070, 170, 170E, NEMA TS1 and TS2 – Type 1 or 2 applications. The communication is required to be compatible with TS2 Type Synchronous Data Link Control and multi-system protocol support, including National Transportation Communications for ITS Protocol (NTCIP) and AB3418 protocol. Communication should also be fully compatible with the traffic management system, including easy and fast software installation using serial port on a standard personal computer or laptop, and the advanced TSP options. In addition to these specifications, the system was required to include fully mappable Input/Output (I/O) operations.

Another project conducted by the Denver Regional Council [8] has outlined the base-level requirements, which included automatic synchronization to Universal Coordinated Time, upload/download of timing/coordination parameters, real-time monitoring of system and intersection operation, error detection and automatic reporting, back-up time-based coordination operation, and remote access to system databases. The agency also emphasized having a reliable communication network in signal systems, good detection technology, and coordination capabilities. Apart from the requirements, the agency also stated interest in testing technologies such as Transit Signal Priority (TSP).

The key functional requirements for future signal control equipment in the New York City [9] were ease of maintenance and installation, along with minimization of custom development. The details considered were the size of the cabinet, plug-and-play installation and maintenance, 6 or 12 load switches, four input slots, and communication capabilities. During this project, it was concluded that the NEMA TS2 – Type 1 was the most cost-effective cabinet, with additional constraints on the form and function of the cabinet. However, controller architecture, such as processor and memory was left for vendors to decide. In addition, the vendor was required to provide the controller's source code with license rights given to the City. Finally, a 16-bit address card for USB connection and reading the data was also defined as a deliverable.

In all the previous projects, a significant focus was not on controller software, but primarily on cabinet-controller compatibility, especially for 33x and NEMA cabinets. There is a need for recommended set of guidelines or procedures to help in evaluating signal controller software, quantifying their capabilities. Additional survey of agencies across nation, which was performed by the authors, showed very limited specifications for acquiring new equipment used in practice (e.g., the maturity of technology, compatibility with central traffic management software and NTCIP). These were the reasons that the authors decided to develop both critical functional requirements for the future system and a decision-support system [3]. The Multi-Criteria Decision Making technique is selected for implementation in the decision-support system, as a technique for evaluation and ranking of different traffic signal controllers.

MULTI-CRITERIA DECISION MAKING

Background

Multi-Criteria Decision-Making (MCDM) is a decision theory approach and set of techniques that aids in a coherent ordering of options. MCDM is generally divided into Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM) [10]. These two methodologies share common MCDM characteristics, such as conflicting options, incommensurable units, and difficulties/need for selection of alternatives. However, they are differentiated by their decision space. MADM decision space is discrete and each candidate alternative can be evaluated using a combination of analytical tools. MODM decision space is continuous and alternatives are not pre-determined. Each MCDM evaluation model [11] is defined by:

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

A finite set of alternatives is a choice set denoted as $A = \{A_1, A_2, \ldots, A_m\}$. 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:

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

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

	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

FIGURE 1: General depiction of Decision Matrix

The usual MCDM analysis steps [12], that have been followed in this research are:

1. Establish the decision context
2. Identification of the options for appraisal
3. Identification of criteria
4. Scoring the expected performance of options against criteria
5. Weighting of criterions based on relative importance
6. Deriving the overall value for each option
7. Examining the results
8. Conducting sensitivity analysis

Simple Additive Weighting

There are many MCDM techniques implemented in practice (e.g., Linear Assignment Method, ELECTRE, TOPSIS, PROMETHEE, etc.). One of the most well-known and widely implemented is Simple Additive Weighting (SAW). SAW is a MADM technique whose evaluation principle is to select an alternative having the largest utility [10]. Each attribute has assigned importance weights (as coefficients to the variable). The total score for each alternative is calculated 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, …, 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 outcome of the i[th] alternative about the j[th] attribute with a numerically comparable scale.

Usually the weights are normalized as $\sum_{j=1}^{n} w_j = 1$, in order to obtain mutually comparable scores. Therefore, in the maximization case, the best alternative is the one that corresponds to the largest preference value. The first step is the assignment of numerical values to qualitative attributes in a decision matrix. The seconds step is the calculation of a comparable scale for elements in the decision matrix, as:

$$r_{ij} = \frac{x_{ij}}{x_j^*}$$

where x_{ij} is value of j[th] attribute for i[th] alternative, while x_j^* is the maximum value for a particular attribute for all alternatives. After this, the analyst assigns weights for groups of attributes. Finally, weighted average values for all of the alternatives are obtained as transformation of a vector to an appropriate scalar value. The scoring model selects an alternative with the highest score (i.e., highest utility). Methods for assessing weights can be e.g., Eigenvector, Weighted Least Square, Entropy method, etc. The weighting usually bases on the explicit conversion of expert knowledge obtained through interviews or public surveys.

MADM implementation cases and reasoning for implementation

MADM implementation can be found in many disciplines: urban planning, management, economics, psychometrics, marketing, statistics, environmental engineering, etc. It is used for commodity selection, facility location, personnel selection, project selection, and public facility selection [13-20]. MCDM has been used in problems for planning purposes [21] or for planning in highway asset management, differentiating between competing project candidates [22, 23]. Literature [24] suggests that MCDM analysis has been previously used to evaluate signal infrastructure. However, the alternatives were evaluated from a macro perspective and the evaluation procedure did not consider the features of the controllers. The complexity level of decision-making needed for determining the future signal controllers would require an approach with a higher level of details on controller features.

Using MADM in evaluation of controller features is superior to traditional informal judgment for the following reasons:

- The choice of alternatives, criteria, scores and weight is open to analysis, adaptable to change, and cross-referenced to other sources of information
- Performance measurement can be a responsibility of group of experts, not necessarily the responsibility of decision-making group
- Evaluation of the results can be delivered in a multifaceted form, helping decision-makers to increase their understanding about the choices made
- MADM matrix can be a useful communication medium between experts and wider audience

IDENTIFICATION OF DECISION CRITERIA USING CRITICAL FUNCTIONAL REQUIREMENTS

Framework for development of Critical Functional Requirements

As one of the essential steps during the creation of decision-support system is the development of critical functional requirements for next generation of control system. The approach taken was top-down, staring with agency goals. Usually, signal control systems have safety, mobility, and environmental goals. These are high-level goals, which usually determine if and when to replace the existing system. However, for the actual selection of next generation controller, these general goals are often not detailed enough to aid decision-making on an operational level. The selection should also depend on the critical functional requirements (CFR) for the operation of the next generation system (FIGURE 2). Although experts in the area of signal control often develop CRF, input can be expanded by including politicians or general public opinions. On the other hand, the selection of the next generation system should depend on the highly detailed information about the actual controller features. Information on controllers can be obtained from controller manual, user and vendor survey, modeling and testing of controller features (for detailed examples on modeling and testing refer to [25-30]). The information on these two sides directly relates to creation of decision matrix for controller selection, where attributes for MADM are corresponding CFR.

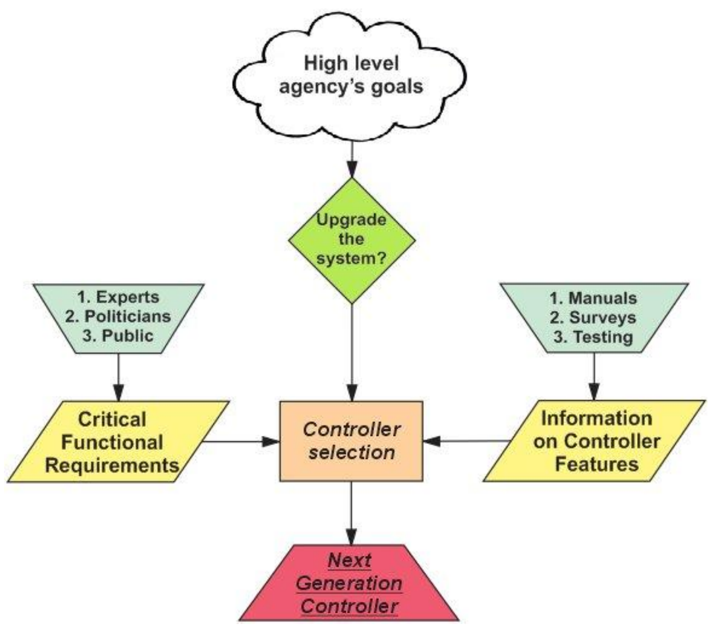

FIGURE 2: Flow of information for next generation controller decision-making

CFR development

A well-defined set of attributes is important because it allows each of the attributes to be quantifiable and easily evaluated [31]. Considering that previous projects have not provided detailed list of functional requirements, this research has developed it, based on the interview and survey of experts across North America. The information on the desired future signal system was initially compiled through a series of interviews with different groups in the VDOT. The information was posted on a web forum (FIGURE 3) at http://www.vt-scores.cee.vt.edu/forum/. This forum was specifically designed to collect input from all of the VDOT districts. System operation objectives discussed with NRO and other VDOT staff included the reduction of system delay, vehicle stops, travel time, fuel consumption, and enhancing safety. Other transportation modes and users, such as pedestrians and bikes, were also discussed to identify the required controller features. These meetings were instrumental in identifying potential gaps in operation capabilities provided by current infrastructure and the user requirements. This was also an opportunity for the research team to acquire knowledge about the specific system characteristics in the NRO and how that system differs from those in other regions of the state.

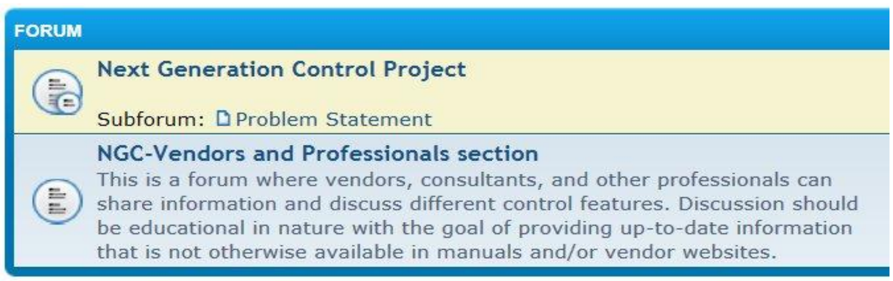

FIGURE 3: NGC web forum screenshot

In addition to the forum, a separate survey was distributed among transportation agencies across United States and Canada. Experts in signal control were rating the importance of various controller features and capabilities. Agencies were also providing accompanying information on their field equipment life span, detection methods in use, techniques for controller testing, and agency's specifications when acquiring new controllers. This information was presented to VDOT engineers in order to obtain the final CFR list and relative weighting for evaluation attributes.

Mapping of Functional Requirements to Technical Requirements and Evaluation Attributes

All the controller attributes for MADM were clustered together, into series that relate to distinguished controller features [12]. This is especially important since the decision structure for traffic controllers in this research has over 50 attributes. The clustering was intended to reduce the complexity during the calculation of weights in a large MADM application and to facilitate the importance of high-level views on issues with related trade-offs. The attributes were clustered into eight categories, as listed and described below:

1. Controller hardware and software

This group of attributes consists of controller features that are directly related to general hardware and software components, not related to software features. Programming options in controller software are not attributes of this group. The group consists of attributes 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 Traffic Management Software, and the availability of controller software code in C or C++. The attributes in this group are mainly based on the constraints and requirements of existing signal control infrastructure, with compatibility issues mainly related to signal control cabinets (i.e. 330, NEMA or ITS).

2. General Traffic Operation

Attributes in this category include basic operational functions available in the controllers. Some of the attributes are number of phases, conditional phase service and re-service, detector capabilities, queue detection actions, etc. The list can be possibly expanded by a particular DOT, including for example gap reduction, recall or dual entry programming options.

3. Coordination and plan selection

Attributes in this group are directly related to coordination and time of day options /schedule options in controller software. Options considered in this study relate to cycle length, offset, transition algorithms, and holiday/events functions. In addition to this, there are many options dealing with transitions during time plan changes [32]. Additional features, such as Traffic Responsive Plan selection [33] are also attributes of this group, especially since they are not available in all of the market controller software.

4. Preemption and Transit Priority

Although similar, Signal Preemption and Transit Signal Priority operation modes have different implementation requirements, and have different programming options (especially transitioning options) [34]. Some attributes in this group include recovery options from PE and TSP, options for resolving the issue of "double preemption", options for maintaining progression during PE or TSP, programming options for Light Rail Vehicle (LRV), etc. PE and TSP settings have the greatest variety in programming options among different controllers.

5. Pedestrian & Bike

Most of the modern controllers offer many new features that can effectively manage the intersection conflicts between vehicular and pedestrian flow. Literature suggests control options such as pedestrian minimum-based control and Walk interval simultaneous activation with protected left turn arrow [35]. In addition to this, evaluation attributes in this group are related to overlap, reservice, Walk extension, etc. Some of the controllers have additional capabilities for pedestrian and bike operation (early Walk, Pedestrian Scramble, dedicated Bike timing, etc.).

6. Reports, Data Archiving, Communications, and Maintenance Requirements

These attributes originate from the relationship of signal controllers and the other agency's elements – transportation management software, features of communication infrastructure, and agency's maintenance capabilities. CFRs related to reports and data archiving aim for higher capabilities in saving data, logging higher number of parameters and compatibility with database in the central TMS. Communication requirements aim for availability of multiple polling and communication rates. Maintenance requirements of controllers are reflected in the availably of proper alarms for reporting different hardware or software issues.

7. Advanced Controller Features

No matter how extensive a CFR list is, not all the controller capabilities can be covered. Some of the controller features may not be identified as immediately needed, but their value might reveal as the system develops. In addition, some of the features might be very applicable but just for specific intersections. Advanced controller features can also be in groups: user interface, coordination, PE, TSP, pedestrian, reports and data logging.

8. User survey

This is a special category of evaluation attributes, which bases on a survey of previous experience with the same controllers in city or state transportation agencies across North America. The survey provided additional insight in the overall performance of controller software already in the field deployment. The survey also requested information on advantages or disadvantages in the matter of hardware, software and operational functions of a specific controller.

After the CFRs are defined and grouped, each one is mapped to technical requirements for controller operation. These technical requirements are later defined as evaluation attributes of a decision matrix. FIGURE 4 bellow depicts this thought process for converting CFR into evaluation attributes.

FIGURE 4: Flow of information for development of Evaluation Attributes

An example of mapping of CFR and technical requirements for three controllers is presented in the TABLE 1. The two examples are from General Traffic Operation and Pedestrian features.

TABLE 1: Example of CFR, relative technical requirements, and evaluation of controller capabilities per attribute

Critical Functional Requirements	Technical Requirements	Controller 1	Controller 2	Controller 3
Need for phase re-servicing, quad re-servicing, etc., during Free or Coordinated operation	Phase re-servicing during Free or Coordinated operation	*Available both in Free and Coordinated operation*	*Available only in Free operation*	*Available only in Free operation*
Different pedestrian times for controller minimum value for pedestrian walk (hold for longer, push for normal)	Different minimum pedestrian walk time	*Not available*	*Not available*	*Available through Internal Logic programming*

SCORING THE EXPECTED PERFORMANCE OF OPTIONS AGAINST CRITERIA

After determining the criteria for evaluation, the process requires the assignment of scores to each of scores to each of controller's capabilities. At this point, the authors would like to emphasize that the paper the paper will limit the presentation of this framework on three market controllers. This is primarily due to primarily due to the readability of the paper, since the actual research compared nine market controller, and controller, and the presentation of that number of controller would be much more complex. According to the According to the scoring procedure, each of the controllers is assigned a score depending on the level it level it satisfies technical requirements. The scoring of controller capabilities is done in integer values and values and saved in the database with information on controller features. Depending if the feature is assessed feature is assessed as non-existing or existing, score can be 0 or 1. In some cases, the score is dependent on dependent on how much requirements are satisfied with particular feature (e.g., 4 out of 5). However, after However, after the normalization, the scores are kept in the range of 0 to 1. Scoring criteria, weights and weights and scores for attributes in each group are presented on following TABLE 2 to

TABLE 8. Scoring procedure is presented for each criterion in textual format, on the far right side of the table. In addition, a weight value for each group is presented in the top part of the table. The bottom of the table, marked in blue, is presenting summation of criteria values and a score that is a multiplication of sum with the weight for the criteria group.

TABLE 2: Scoring criteria, weights and scores for Controller hardware and software

Controller hardware and software		*Weight*	6.2	*Scoring procedure*
Controller	***1***	***2***	***3***	
User friendly interface	1	1	1	Score of 1 if option available, else 0.
LCD Display Screen - 8 Lines of 40 Characters	1	1	1	Score of 1 if option available, else 0.
Ability to upload/download from laptop	1	1	1	Score of 1 if option available, else 0.
Compatibility with central management software (download/upload) and all controller outputs (ph & O/L) and capable of being displayed properly on central management software graphics	1	1	0	Score of 1 if option available, else 0.
Compatibility with other Traffic Management Software (download/upload)	1	1	1	Score of 1 if option available, else 0.
Simulation/Testing program	1	0	1	Score of 1 if option available, else 0.
Interface with Signal Timing software for tuning (e.g.., Synchro)	0	0	0	Score of 1 if option available, else 0.
Controller code in C/C++	1	1	1	Score of 1 if option available, else 0.
Access restriction by district and Security issues in general (password for entering the controller menu)	1	1	1	Score of 1 if option available, else 0.
SUM	**8**	**7**	**7**	
SCORE	**49.8**	**43.6**	**43.6**	

TABLE 3: Scoring criteria, weights and scores for General Traffic Operation

General Traffic Operation		*Weight*	18.7	*Scoring procedure*
16 Phase operation	1	1	0	Score of 1 if option available, else 0.
Four (4) Timing Rings	1	1	0	Score of 1 if option available, else 0.
Conditional Service under Free or Coordinated Operation	1	0.5	0.5	Score of 2 if available in Free and Coordinated, 1 if available only in Free, 0 if option not present.
Phase re-servicing during Free or Coordinated operation	1	0.5	0.5	Score of 2 if available in Free and Coordinated, 1 if available only in Free, 0 if option not present.
Detector counting capability	1	1	1	Score of 1 if option available, else 0.
Detector switching capability	1	1	1	Score of 1 if option available, else 0.
Flexible detector mapping	1	1	1	Score of 1 if option available, else 0.
Queue Detection to override normal timing (preemption, alt coord plan, or different max setting)	1	0.67	1	Score of 3 if all options available, 2 if two available, 1 if one available, 0 if options not present.
Options for addressing yellow trap issues - (Flashing Yellow Arrow programming and Special Protected/Permitted LT programming)	1	1	1	Score of 2 if both options available, 1 if only one available, 0 if option not present.
Programming options for handling recurring situations and localized peaks (e.g., for schools)	0	0	1	Score of 1 if option available, else 0.
SUM	**9**	**7.67**	**7**	
SCORE	**168.2**	**143.4**	**130.8**	

TABLE 4: Scoring criteria, weights and scores for Traffic coordination and plan selection

Traffic coordination and plan selection		*Weight*	12.5	*Scoring procedure*
30+ time plans	1	1	1	Score of 1 if option available, else 0.
Cycle length exceeding 255 seconds	0	1	0	Score of 1 if option available, else 0.
Fixed versus floating force off per phase per plan	1	1	1	Score of 1 if option available, else 0.
Phase omit programming by plan	1	1	1	Score of 1 if option available, else 0.
Holiday Date structured to handle 40+ days	0	0	0	Score of 1 if option available, else 0.
Holiday Events capable of programming TOD type function in addition to events	1	1	1	Score of 1 if option available, else 0.
Offset per plan	1	1	1	Score of 1 per offset per plan available.
Transition algorithms	1	1	0.75	Score of 1 per transition algorithm available.
Ability to violate guaranteed ped programmed times when developing coord plans	1	1	1	Score of 1 if option available, else 0.
Traffic Responsive control	0	1	0	Score of 1 if option available, else 0.
Method to confirm the current TOD/DOW setting in the controller (Upload & Monitor controller clock)	0	1	0	Score of 1 if option available, else 0.
SUM	**7**	**10**	**6.75**	
SCORE	**87.2**	**124.6**	**84.1**	

TABLE 5: Scoring criteria, weights and scores for Signal Preemption and Transit Signal Priority

Signal Preemption/Transit Priority		*Weight*	23.4	*Scoring procedure*
Consistency issues (numbers assigned to each preemption)	1	1	1	Score of 1 if option available, else 0.
Phase selection for exiting the Preemption	1	1	1	Score of 1 if option available, else 0.
Option for recovery from Preemption	0.8	0.4	1	Score of 1 per option available.
Soft (Low) preemption available	1	1	0	Score of 1 if option available, else 0.
Programming options and Communication capabilities for adjacent controllers during preemption	1	0	1	Score of 1 if option available, else 0.
Special options for handling "double" preemption	0	0	0	Score of 1 if option available, else 0.
Options to program and maintain progression trough preemption	1	1	1	Score of 1 if option available, else 0.
Bus priority (primarily green only)	1	1	1	Score of 1 if option available, else 0.
LRV Transit signal priority	1	1	1	Score of 1 if option available, else 0.
Option for recovery from Priority	1	1	1	Score of 1 if option available, else 0.
SUM	**8.8**	**7.4**	**8**	
SCORE	**205.6**	**172.9**	**186.9**	

TABLE 6: Scoring criteria, weights and scores for pedestrian and bike operation

Pedestrians and bikes		*Weight*	23.4	*Scoring procedure*
Pedestrian overlap capabilities under Free and Coordinated operation	1	0.5	1	Score of 2 if available in Free and Coordinated, 1 if available only in Free, 0 if option not present.
Pedestrian phase re-service and walk extension (Ability to distribute extra pedestrian green from other phases)	1	0	0.5	Score of 2 if both options available, 1 if only one available, 0 if option not present.
Ability to provide 4 seconds advanced pedestrian green before the vehicle phase	1	1	1	Score of 1 if option available, else 0.
Different minimum pedestrian walk time (push for normal, hold for extend)	0	0	1	Score of 1 if option available, else 0.
Pedestrian clearance priority over preemption	1	1	1	Score of 1 if option available, else 0.
SUM	**4**	**2.5**	**4.5**	
SCORE	**93.5**	**58.4**	**105.1**	

TABLE 7: Scoring criteria, weights and scores for reports, data archiving, and communications

Reports, Data Archiving Needs, Communications		*Weight*	4.7	*Scoring procedure*
MOE able for upload to Traffic Management Center	0	1	1	Score of 1 if option available, else 0.
30 days of data storage	0	1	1	Score of 1 if option available, else 0.
Logging data on actuated greens	0	1	1	Score of 1 if option available, else 0.
Logging data on cycle length	0	1	1	Score of 1 if option available, else 0.
Logging data on number of vehicles in queue	0	0	0	Score of 1 if option available, else 0.
Logging pedestrian count and frequency	1	1	1	Score of 1 if option available, else 0.
Alarms	1	1	1	Score of 1 if option available, else 0.
Multiple Polling rates / comm. rates	1	1	1	Score of 1 if option available, else 0.
SUM	**3**	**7**	**7**	
SCORE	**14.0**	**32.7**	**32.7**	

TABLE 8: Scoring criteria, weights and scores for Advanced controller features and user survey ranking

Advanced Controller Features		*Weight*	9.3	*Scoring procedure*
Free programmable options	1	0,5	1	Score of 1 per level of options available.
SIL availability	1	0	0	Score of 1 if option available, else 0.
SUM	**2**	**0.5**	**1**	
SCORE	**18.7**	**4.7**	**93**	
User Survey ranking		*Weight*	1.8	*Scoring procedure*
General controller capabilities grade	1	0,8	0,8	Overall score obtained through survey.
SCORE	**1.9**	**1.5**	**1.5**	

ASSIGNMENT OF WEIGHTS

The weights used in the evaluation can develop on several levels, depending on the perspective and goals of the decision-maker. The weight level can be per intersection, per group of intersections, or for the whole system. The disaggregation or aggregation of weights for attribute groups might have advantages or disadvantages based on the level of details for decision, uniformity of functional requirements over the region under DOT purview, and the calculation efforts.

As previously stated, each CFR group should not necessarily have equal importance. For example, a certain example, a certain corridor might require both transit and pedestrian facilities but the transit features may features may be more important than the pedestrian requirements. The methodology has been designed to designed to consider the importance of each CFR group at each intersection. The alternative scores can scores can change based on further modifications and improvements to the controller features. The scores The scores can be also change depending on the weights of particular group of attributes. By changing the changing the weights of CFR groups according to their priority to future control system, analyst can affect can affect the final scores of mutual assessment of controllers. For example, by assigning the score of 100 to score of 100 to the CFR group Traffic Coordination and Plan Change and score of 5 for Data Archiving Archiving Needs, the analyst implies that first group of features is 20 times more important than the second the second one. However, these weights values should maintain the relative relationship including all the including all the listed CFR groups. On the other hand, scores for each feature are fixed according to the level according to the level of controller capability to address the requirement for future operation capability. capability. TABLE 9: Relative weights matrix presents ratios for all the group weights that are used in determining normalized weights implemented in MADM. Finally, it also presents the scaled weight values, on the far right of the table, that were used in TABLE 2 to

TABLE 8.

TABLE 9: Relative weights matrix

		w1	w2	w3	w4	w5	w6	w7	w8	
		General	Hardware	Coord	PE/TSP	Ped	Data	Advanced	Survey	**Scaled Weight**
w1	**General**	1.00	3.00	1.50	0.80	0.8	4.00	2.00	10.00	**6.2**
w2	**Hardware**	0.33	1.00	0.50	0.27	0.267	1.33	0.67	3.33	**18.7**
w3	**Coord**	0.67	2.00	1.00	0.53	0.533	2.67	1.33	6.67	**12.5**
w4	**PE/TSP**	1.25	3.75	1.88	1.00	1.00	5.00	2.50	12.50	**23.4**
w5	**Ped**	1.25	3.75	1.87	1.00	1.00	5.00	2.50	12.50	**23.4**
w6	**Data**	0.25	0.75	0.375	0.20	0.20	1.00	0.50	2.50	**4.7**
w7	**Advanced**	0.50	1.50	0.75	0.40	0.40	2.00	1.00	5.00	**9.3**
w8	**Survey**	0.10	0.30	0.15	0.08	0.08	0.40	0.20	1.00	**1.9**

FINAL EVALUATION

In the MADM Decision Matrix used for the evaluation of controllers, each of the attributes is assigned a certain score depending on the level that the controller satisfies technical requirements. The comparison was performed among the alternative controllers. An equation was developed to calculate the Performance Index (PI) of the individual controllers [36]. The PI of each controller is calculated using the equation shown below:

$$\boldsymbol{PI} = \frac{(\boldsymbol{FR_{hard}} * \boldsymbol{W_{hard}} + \boldsymbol{FR_{gen}} * \boldsymbol{W_{gen}} + \boldsymbol{FR_{coord}} * \boldsymbol{W_{coord}} + \boldsymbol{FR_{pre}} * \boldsymbol{W_{pre}} + \boldsymbol{FR_{ped}} * \boldsymbol{W_{ped}} + \boldsymbol{FR_{rep}} * \boldsymbol{W_{rep}} + \boldsymbol{FR_{adv}} * \boldsymbol{W_{adv}} + \boldsymbol{FR_{surv}} * \boldsymbol{W_{surv}})}{(\boldsymbol{W_{gen}} + \boldsymbol{W_{hard}} + \boldsymbol{W_{coord}} + \boldsymbol{W_{pre}} + \boldsymbol{W_{ped}} + \boldsymbol{W_{rep}} + \boldsymbol{W_{adv}} + \boldsymbol{W_{surv}})}$$

Where:

PI - Performance Index of the controller

W_c - Weight assigned to the CFR category **"c"**

FR= ∑ *(Yi*Xi)* – summation of decision matrix scores

Y_i - Binary relation, 1 if the attribute (FR) **'i'** is considered, else 0

X_i - Score of the attribute **'i'** for the given controller

By using the formula above, the PI values can be calculated for each controller, thus creating a comparison scale. That PI scale is a measurement of the controller performance and represents the score/benefit of alternate systems. Based on the requirements of the intersection or zone, each of the alternatives is evaluated using this procedure.

Evaluation results

The MADM evaluation leads to the Weighted Performance Index for each controller, resulting in pure ordinal scale with relative ranking as shown on FIGURE 5. We can observe that controller 1 has the highest score (6.4), followed by controller 3 (5.9) and controller 2 (5.8).

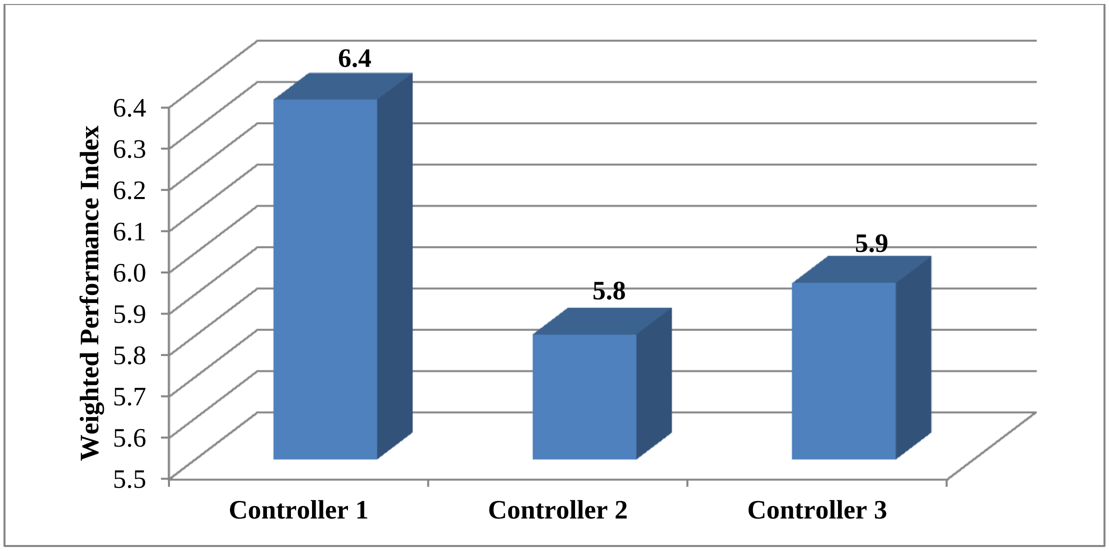

FIGURE 5: Performance Index for each alternative

From the figure above we can conclude that controller 1 is the controller that provides the highest satisfaction to established CFR for the next generation control system. However, from the decision matrix above, it is notable that none of the controllers evaluated satisfied all the established CFR requirements, since they all had scores bellow 10. In addition, every controller has advanced capabilities in some CFR groups, but has missing capabilities in some other group of required features (FIGURE 6). In this case, weights of CFR groups are becoming very important since they can directly decide on the controller PI. For further analysis, we can observe capabilities of each controller in detail.

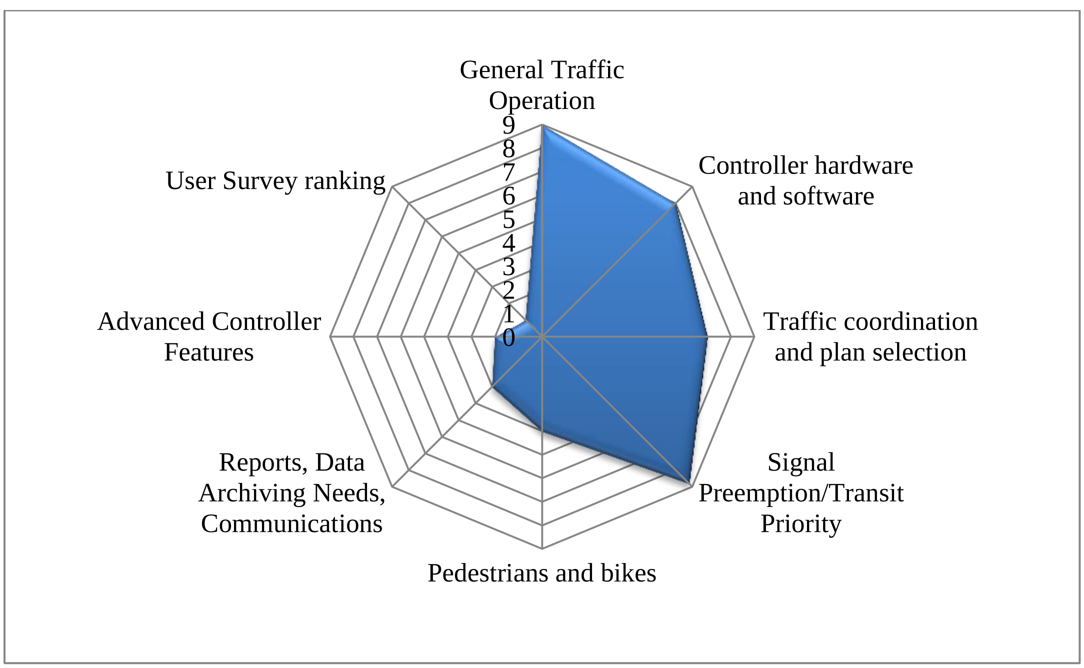

FIGURE 6: Controller 1 capability for each group of FR

Comparisons of capabilities per CFR group for all three controllers are presented on the following FIGURE 7. It is obvious that some controllers have better mapping to some CFR groups and lack capability in some other groups. Once again, the weights of each CFR group are demonstrated to be very important, since they can change the value shape on the spider web diagram by changing the PI value for all the alternative controllers. However, the design of the decision-support system is flexible to accommodate any changes in either the weights or the criteria values for any number of controllers.

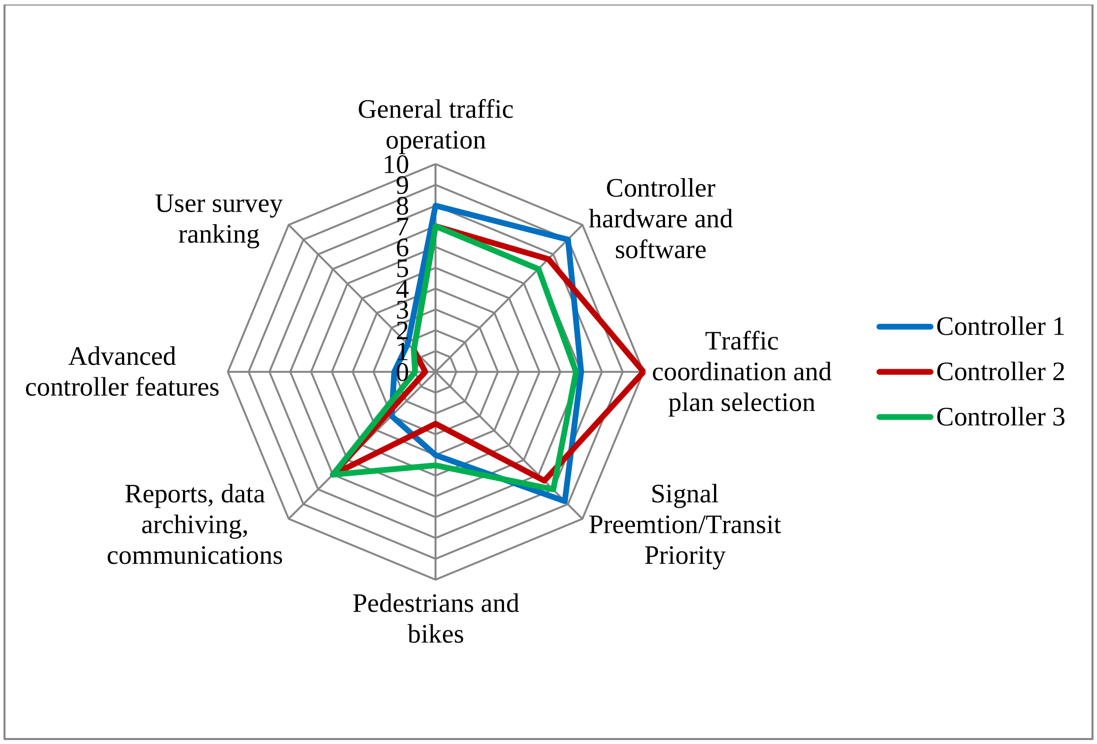

FIGURE 7: Comparison of capabilities per CFR group for all three alternatives

CONCLUSION AND FUTURE WORK

This paper presents a procedure for evaluating traffic signal controllers based on the critical functional requirements using MADM technique. In addition to the procedure for the developing the CFR, this research provides a structured list of evaluation criteria that has not been developed before. This input has been created with a significant input from signal control engineers across North America. The equation for the calculation of a Weighted Performance Index of each controller was also developed. The equation respects listed critical functional requirements, and includes scores and weights for each controller. Attributes in MADM process are based on critical functional requirements and are clustered in a weights assignment process. The values in the respective decision matrix are obtained from controller manuals, vendor information, testing and modeling of controller features. The developed evaluation method is presented for three different market controllers and proves as an effective way for evaluating the signal controller, by numerically representing their features. This evaluation method should be used as a decision-support system for DOTs, in the selection process for the next generation control equipment. The presented evaluation method can be enhanced even further by developing a method that tests the system's dynamics and assigns scores based on the Measure of Effectiveness expected from each controller features. The developed method can also be applied to the evaluation of other signal system infrastructure or to further MADM evaluation of controllers including all of their advanced features.

Being an initial research in the area of traffic signal controller evaluation, this paper concludes that the optimal solution has to be analytically determined, since no alternative is the best in all the criteria. In addition, a large number of customized features available in modern Advanced Transportation Controllers can prove to be beneficial to system operation. Stricter standardization might simplify the evaluation process itself. However, introducing too strict standardization in area of the controller software that could restrict competitive development might only harm the further advancements in controller software features.

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