DEVELOPMENT OF OPTIMAL MIGRATION PLAN FOR NEW TRAFFIC SIGNAL CONTROLLERS USING GIS AND MULTI-CRITERIA DECISION MAKING

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ABSTRACT
Signal Replacement decisions are often made based on the experience of the Traffic Engineers. These decisions are made while considering the deployment time of the system, the new technology available, and the performance of the system in the given location. However, there is no set of proper guidelines or methods which can quantify the system replacement decision in large scale projects. This thesis presents a methodology that can be applied to determine optimal migration plans for traffic signal controllers. A Multi-Criteria Decision Making technique has been adopted to evaluate various traffic signal controllers. Various controller manuals were studied and information was obtained from the vendors of the controllers. In addition to that, Geographic Information System (GIS) has been used as a tool to evaluate and identify the areas where the traffic signal controllers have to be replaced first. The study considers the budget constraints and the benefits that can be obtained by the replacement of the controllers. This thesis presents the Methodology adopted for the Migration Plan and a case study implementation on the Northern Virginia Region. Finally it presents the conclusions drawn from the research with insights into the scope for further research.
ACKNOWLEDGEMENTS

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DEDICATIONS

I would like to dedicate this thesis to my parents for the love and affection which they shared with me throughout my life. Without their encouragement and support I wouldn’t have completed my studies. I also like to thank my friends Vamsi, Deepti and Shyam who have always helped me and supported me both mentally and emotionally throughout my stay at Blacksburg. I also thank all my friends who always encouraged me and made me laugh in the hardest days of my work.
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1. INTRODUCTION

Traffic Signal Controllers play a vital role in the operation of a signalized intersection. Due to growing traffic needs, the functions of the existing systems often fail to reach the desired performance level. Hence, in order to increase the operational efficiency of the intersection, many new additional features are to be implemented. But the compatibility constraints between the existing and new systems lead to system replacement decisions. Usually, system replacement decisions are made by experienced engineers based on two factors: 1) their practical working knowledge, and 2) the period of time the system has been deployed in the field. But for large projects, engineering decisions based only on experience should be supplemented with more effective ways of decision making.

The research presented in this thesis is based on the need for a proper decision-making process of system replacement. To accomplish the above-mentioned task, a strategic migration plan has to be developed. The plan should consider the spatial location of the systems that have to be replaced and the benefit of candidate systems based on local conditions (e.g., traffic volume, type of road, pedestrian and vehicle flows, preemption requirements, transit requirements).

In order to develop an effective migration plan for the system replacement, it is most important to know the existing system capability and its functional capacity. This thesis presents a methodology for evaluation of signal controllers and for creation of a migration plan. In an effort to develop an evaluation technique for signal controllers, various traffic signal controllers were considered for the study in this research. Information about the features available in each of these controllers was obtained from their respective manuals and vendors. The migration plan was built on a Geographic Information System (GIS) framework that uses a Multi-Criteria Decision Making (MCDM) technique. An external Multi-Objective Optimization tool was introduced for obtaining the solutions. The thesis shows the integration of GIS, MCDM, and the optimization tool for creating a migration plan for the traffic signal controllers. This method not only justifies the system replacement judgments but also shows the improvement which can be obtained by replacing the system. The proposed methodology has the flexibility of evaluating systems that are based only on certain features that depend on the local conditions of the field. The whole methodology was applied on a demo file for the Northern Virginia Region (NOVA) and was successfully implemented and tested.

1.1 LITERATURE REVIEW

Multi-Criteria Decision Making Problems are mostly used to solve the non-spatial problems that integrate several criteria or attributes. The ranking or grading of the alternatives or attributes is mainly contingent upon the decision makers [1]. The number of decision makers may vary depending upon the project or case considered and its scope. The MCDM is classified into two different categories: Multi Attribute Decision Making (MADM) and Multi Objective Decision Making (MODM) [2]. Studies [3] suggest that in Multi Attribute Decision Making,
attributes are the elements which comprise a certain value that can be quantifiable based on a set of criteria. These attributes would help in selecting the alternatives based on the individual scoring or priority of the attributes for each of the alternatives. On the other hand in case of Multi Objective Decision Making \cite{4}, multiple objectives are evaluated to select the optimum objective.

The MCDM is being used in many fields and applications of engineering and science. Roy \cite{5} has established a general framework of MCDM that suggests a well-defined set of feasible alternatives. This is very important since the MCDM technique is not appropriate when the alternatives have no relation to each other. Well-defined set of attributes are also important so that each of the attributes can be evaluated easily and can be quantifiable. The applications of MCDM are vast and it has a flexibility to use any method to solve any of the problems that involve multiple criteria and alternatives.

The use of MCDM has largely been in the Natural Resource Management \cite{6} because of the diversity and disputative nature of the problems associated with it. With the use of MCDM, these problems can be narrowed down to single or appropriate solutions. Since the natural resource management issue deals with the involvement of public interest and also includes multiple attributes, this technique is mostly adopted. Gamini \cite{6} has classified the MCDM methods into two categories. He classified Multi-Attribute Value Theory (MAVT) method as a quantitative riskless category, and Multi Attribute Utility Theory (MAUT) and Elimination & Choice Expressing Reality (ELECTRE) methods as quantitative risk category.

The benefits of the MCDM are not only the selection of the appropriate decision, but also the evaluation of the results in a multi facet form. Studies \cite{7} suggest that MCDM has helped the decision makers in learning about the decisions of others and increased understanding about the decisions made. The MCDM was also known for its effective evaluation and faster decision making ability. It also showed that Multi-Criteria Group Decision Making (MCGDM) \cite{8} had greater over all benefits apart from the decision making alone.

There are many models of MCDM which are available and some of them are summarized by Jayanath and Gamini \cite{9}. They classified MCDM into MAVT, MAUT and Analytical Hierarchy Process (AHP). The MAVT was again classified into different methods. First one is the Simple multi-attribute rating technique (SMART), where the rating of the attributes is done on a scale basis. Second method is Weighted Summation technique where the weighted summation is used as a measure of evaluation. Again the selection of these methods is purely contingent on the problem and the decision makers. The MAUT is another technique which is used to solve the MCDM problems. The AHP \cite{10} uses either pair wise comparison so as to rate the alternatives. The rate or comparison is done based on certain set of criteria arranged in a network form. In this project the SMART was used to rate the attributes, where rating of the
attributes was given based on a scale of 1-10. Some of the studies suggest that Multi Attribute Utility Function (MAUF) [11] can be used in case of single utility function and weighting parameters being associated with the individual attributes. The Equation (1-1) [11] mentioned below shows the calculation of the Utility function.

$$Ut(x) = \Sigma_{i=1}^{n} w_i \times Uti(xi)$$ (1-1)

The $Ut(x)$ is the utility which is defined by various attributes. $Uti(xi)$ is the single utility function of the attribute $i$.

The MCDM has also been used in the Enterprise Resource Planning (ERP) [12] projects where the principles of MCDM are being applied to the ERP so as to increase its awareness in the industry. Unlike traditional method of considering attributes, the MCDM would be focusing more on values in the ERP projects. The research also provided new empirically founded evidence of implementation of MCDM to the field of EPR which was very first of its kind. This shows that the implementation of the MCDM technique is not restricted to certain fields only.

As mentioned above the flexibility of MCDM allows it to be used in various fields, but the non-availability/uncertainty of the information makes it difficult to evaluate the criteria. This leads to subjective judgments which are based on the experience of the decision makers [13]. Literature [14] suggest that the weights assigned are mostly based on by considering all the alternatives and not on the decision makers alone. Shipley [14] has suggested that the decision maker would compare the values of the alternatives with the ideal value. He further emphasizes that the more the alternatives considered are closer to the ideal value, the greater would be the uncertainty involved.

The use of MCDM in the field of transportation has not been so new. For example, the MCDM is used in many problems for planning purposes. Massam [15] attempted to classify the planning problem into three different components, which are plans, criteria and interest groups. While comparing his analysis with the traditional method, the plans can be compared to the alternatives considered. The criteria would be the scoring or ranking criteria and the interest groups would be the decision makers. So this can be accounted as Multi Group Decision making Problem in general. The measurement scales which were defined for the scoring are the ratio, interval, ordinal and nominal. Based on the attributes or decision groups, the appropriate scoring method is adopted.

Although MCDM techniques are used in solving many spatial problems like vegetation, forest etc., major disadvantage is that the MCDM techniques do not consider the spatial aspects directly. Ferdinando et al [16] says that due to this drawback the principles of MCDM are unsuitable for Geographic Information System (GIS) applications. So in order to make the applications of GIS suitable for the MCDM they have considered a subset of MCDM and used that for the GIS as an extension. Another example of similar analysis is use of GIS for
conservation and landscape planning. The preferences on the criteria are usually expressed in the form of weights assigned by the decision makers. And these weights are coupled with GIS using programming techniques and tools which are directly in the maps. The methodology adopted in these kinds of problems is usually AHP. Since the landscape is a spatial entity and it is easier to identify the locations using GIS, the AHP acts as the ideal method for comparing and assigning the weights based on the relative importance of the alternatives. Mui-How [17] has used a similar technique for forest conservation planning. AHP technique was used in this case where the problem was represented graphically and weights were assigned based on the level of hierarchy. In this method pair wise comparison was done so as to know the relative importance of the alternatives and assign them the weights according to their importance.

Recent developments in GIS and its widespread usage have increased its potential application in solving Transportation Related Problems. The major problems solved in Transportation using GIS are concentrated in the areas of Transit services and Route choice behavior. There have been several applications in the Transit services which include selection of Bus Stops [18] or Transit Route planning [19, 20], which involves use of GIS tools in identifying the areas of improvement for effective transit service based on the location of the residents and other factors. In addition, GIS is also used for solving the Urban Traffic Data [21] related problems which integrate real time traffic data with the GIS system which is used in visually identifying the varying traffic patterns and helps in further decision making. The applications are further extended to make decisions for supporting other Transportation realm problems such as identifying the Pedestrian crash zones [22], which can be used for the planning purposes so as to take measures to ensure the pedestrian safety. GIS is also used as a data management tool, which helps in managing Dynamic data [23] that changes over time. In this project, GIS is used as a tool so as to identify the areas which need system upgrading.

This thesis presents a methodology which integrates the concepts of MCDM and GIS for evaluation of signal controllers and to develop a methodology for creation of migration plan for the traffic signal controllers. Based on the literature review [24] it has been identified that there are no proper guidelines for system replacement decision or migration plans. In addition to that there are no standard procedures for evaluation of various signal infrastructures. So this research focuses on the aspect of developing a comprehensive and flexible methodology for selection of effective candidate controllers and optimal migration plan.
1.2 RESEARCH OBJECTIVES

The major objectives of this research are:

- To develop a methodology to evaluate various traffic signal controllers based on the critical set of functional requirements.
- To introduce a methodology for developing an optimal migration plan for traffic signal controllers based on critical set of functional requirements.
- To make sure that the developed methodology is flexible and can be used to update existing migration plans in the future and at different places.

1.3 THESIS CONTRIBUTION

This thesis presents a research effort to develop a methodology and a framework to determine optimal migration plans. The framework produces optimal solutions that suggest which traffic signal controllers need to be replaced based on the functional requirements of the intersections and the associated costs. The developed framework also shows the relative benefit of replacing the existing system with new systems. This actually helps in assessing the benefit of replacement and can be used in the decision making process so as to select which zones would be most appropriate for upgrading. The Multi-Criteria Decision Making technique which was presented in the thesis would also help in deciding which signal controller would be more effective in solving the traffic problems for local conditions.

1.4 THESIS ORGANIZATION

The thesis is organized into five chapters. Chapter 1 gives a brief introduction of the project which includes the past work in MCDM and GIS. It also includes the main objective and contribution of this research to the field of Signal Systems. Chapter 2 presents a Multi-Criteria Decision Making (MCDM) method for selection of traffic signal controllers. It explains various Multi-Criteria Decision making techniques and its applications in many fields. It also describes about the various Functional Requirements and how each functional requirement is categorized into several controller feature requirements. It presents a method for evaluation of various traffic signal controllers using an equation. Criteria for scoring were also established based on the information from the manuals of the controllers and by directly contacting the vendors. The chapter also contains the actual scores for three different types of controllers which were used in the study. It also shows the calculation of the Performance of the three controllers for given requirements and the analysis of the results. Further conclusions and recommendations were also presented explaining how Multi-Criteria Decision Making technique would be used in evaluating the performance of various traffic signal systems infrastructure and how it can be applied in the field of transportation.
Chapter 3 presents the methodology for developing an optimal migration plan using Geographic Information Systems (GIS) and Optimization tools. The chapter also presents a methodology using GIS framework which is used in developing a migration plan for traffic signal controllers. The GIS framework includes the procedure for creation of the zones for system upgrade, then adopting the Multi-Criteria Decision Making technique for evaluating the new and existing systems. An external Multi-Objective optimization tool is used to obtain the solution based on the objective functions. Then the solution is integrated with the GIS framework and the zones to be upgraded are represented on the map. Chapter 4 explains the application process of the migration plan. It explains the application of various functional requirements under different traffic conditions. It also explains the Graphic User Interface (GUI) buttons which were developed for the execution of the process. Chapter 5 presents the summary and the conclusions of this research. It also suggests how the MCDM technique is useful for application in other fields of civil engineering. Finally the further recommendations are also presented on how the present method can be improved and how it would be useful for the researchers.
2. A MULTI-CRITERIA DECISION MAKING TECHNIQUE FOR SELECTION OF TRAFFIC SIGNAL CONTROLLERS BASED ON CRITICAL FUNCTIONAL REQUIREMENTS

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ABSTRACT

This paper presents a method based on Multi-Criteria Decision Making (MCDM) technique to evaluate various Traffic Signal Controllers. The method to evaluate the controllers depends on the critical set of functional requirements. These functional requirements constitute to the actual features in the controllers and were developed through discussion with professionals in the field of signal system operations. Criteria for scoring the controller features were developed from the information obtained from the vendors and the controller manuals. An illustration of the proposed framework for comparing three different controller types is also included. Finally, alternate methods were also suggested for evaluation purpose leaving scope for further research.
2.1 INTRODUCTION

Traffic Signal Controllers are one of the most important components of the Signal Infrastructure which play a crucial role in the operation of a signalized intersection. There are many types of traffic signal controllers which are commonly available in the market. Many of the modern controllers are equipped with advanced features which help in effective signal operation. Hence, it is important to know which controllers perform well under various traffic conditions. As such, there are no recommended set of guidelines or procedures to help us in evaluating signal controllers and to provide a numerical value of their performance. In this paper, a Multi-Criteria Decision Making Technique was used to evaluate different traffic signal controllers and rank them based on their performance under various traffic conditions.

2.2 MULTI-CRITERIA DECISION MAKING

Multi-Criteria Decision Making (MCDM) is a problem solving technique where alternatives are evaluated depending on the individual scoring of the attributes of the alternative. Although the MCDM techniques were never used for evaluating the signal controllers, literature [25] suggest that similar analysis has been done previously to evaluate other signal infrastructure using the functional requirements. But the alternatives used were evaluated on a broader scale and do not consider the features of the controllers.

A traffic signal improvement program [26] was developed by Denver Regional Council of Governments for the signal infrastructure improvement. They have taken into account the unreliable system communication effects and role of key signal corridors for improvement. Most of the improvement plan dealt with, replacement or up-grading of the communication aspects of signal infrastructure and extending the system control. Improvement measures were taken for specific operational features such as, transit signal priority and development of signal timing plans. But, the improvement plan does not take into account the comprehensive effect of traffic signal controllers and their features.

Another major drawback of past efforts is that, the objectives do not consider the features or attributes associated with each of them. This actually influences the decision making and wouldn’t be flexible enough for the user to evaluate alternatives based only on certain attributes. So MCDM has been adopted for this study for evaluating the alternatives which consists of individual attributes. This method for evaluation of the alternatives is based on the functional requirements.

2.3 FUNCTIONAL REQUIREMENTS

Functional Requirements constitute the advanced features required in Traffic Signal Controllers and other aspects of the Signal System Operation and Maintenance. These were developed through discussions made by many professional traffic engineers dealing with signal system operation [27]. These functional requirements were classified into nine categories and various controller features were assigned to each of these categories depending on their function and operation.
The categories are specified below:
- General Traffic Operation
- Traffic Coordination and Plan selection
- Signal Preemption
- Pedestrians and Bikes
- Controller Hardware and Software
- Data Archiving Needs
- Maintenance Requirements
- Real-time Performance Measures
- System Communications

In this paper, an example evaluation of various controllers is conducted based on the requirements of General Traffic Operation, Traffic Coordination and Plan Selection, Signal Preemption and Priority, and, Pedestrians and Bikes. These four categories directly affect the performance of the intersection in terms of delay, stops etc., whereas the remaining categories do not have any direct influence on the performance of the intersection. These categories are mostly related to the Traffic Control Center and do not constitute to the functional requirements of the intersection. For example, the Controller Hardware and Software category has the requirement for better User Interface devices, but this has no direct impact on the operation of the intersection. Similarly, Data archiving needs has requirement for better database in the controllers. But they do not have any direct influence on the intersection performance. For that reason, only the first four categories are considered for evaluation in this paper.

2.4 EVALUATION PROCEDURE

The MCDM technique consists of functional requirements with the individual scoring criteria for all the specified controllers. An equation was developed to calculate the Performance Index (PI) of various controllers based on the individual scores and the weight assigned to each of the categories based on the functional requirements of a corridor.

2.4.1 Scoring Criteria

In Multi-Criteria Decision Making, each of the attributes is assigned a certain value or score. Depending on these scores, alternatives are evaluated and the best alternative is selected. The scoring of the attributes is usually done by a decision maker(s). After reviewing the manuals of various controllers, and having a thorough idea about various controller features and the functional requirements, the scoring criteria were developed for ranking each of these attributes for all the controllers. The rating was given on a scale of 0-5, which indicates the performance of the particular feature or an attribute considered. Each of the attributes or the features is compared with the minimum requirements and a comparison was done among the alternatives. The vendors of the controllers were also contacted, to evaluate the performance of the features which were not clearly stated in the manuals. After evaluating the attributes in all the methods mentioned the
final scores were given. These scores can be changed based on further modifications, improvements, or changes done to the controller features. Criteria for scoring are listed below in the Table 2-1, Table 2-2, Table 2-3, and Table 2-4 for the four functional requirement categories and for the three different type of controllers.

Table 2-1 Scoring Criteria and the Scores for Functional Requirements under General Traffic Operations

<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Scoring Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need for phase re-servicing, quad re-servicing, etc., during Free or Coordinated operation as standard features</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>Rated 2 points if feature is available in free and coordination. Rated 1 point if only in free mode, and rated 0 if option is not present.</td>
</tr>
<tr>
<td>Need to maintain existing counting capability utilizing the Detector Reset Line</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 if the detectors are able to count.</td>
</tr>
<tr>
<td>Conditional Service under Free or Coordinated Operation</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>Rated as 2 if conditional service is available in both free and coordination, else rated as 1 if only in free mode and 0 if option is not present.</td>
</tr>
<tr>
<td>Programmable feature: Max Recall shouldn’t cause max timer to immediately start counting down if we desire</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Rated 1 if Max recall can delay the max timer to start counting.</td>
</tr>
<tr>
<td>Detector Switching capabilities</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 if detector switching option is available, else rated as 0.</td>
</tr>
<tr>
<td>Flexible detector Mapping</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 if possible else 0.</td>
</tr>
<tr>
<td>Queue Detection to override normal timing by calling preemption, alternate coordination plan, or different max setting</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1. Only Queue detection: 1 point, 2. Initiate Preempt: 1 point, 3. Alternate Max Times: 1 point, 4. Alternate Pattern Mode: 1 point.</td>
</tr>
<tr>
<td>16 Phase operation</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Rated 1 if 16 phases, else 0.</td>
</tr>
<tr>
<td>Programming for LT Trap concern - FYA programming; Special Protected/Permitted LT programming</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>The controllers having Flashing Yellow Arrow are ranked as 2 points whereas controllers having feature to prevent left turn traps but do not provide FYA are rated 1 point.</td>
</tr>
<tr>
<td>Four (4) Timing Rings</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Ranked as 1 if 4 timing rings, else ranked as 0.</td>
</tr>
</tbody>
</table>
Handling recurring situations and localized peaks (e.g., for schools) | 0 | 1 | Given 1 point if functions are available for handling localized peaks. If no special functions are available then rated as 0.

| Average Score (FR) | 1.36 | 1.20 | 0.72 |

Table 2-2 Scoring Criteria and the Scores for Functional Requirements under Traffic Coordination and Plan Selection

<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Scoring Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset per plan and transition algorithms for achieving it.</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>Each offset is given 1 point</td>
</tr>
<tr>
<td>Look ahead ability to pick best time to change coordination plan to minimize transition</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Rated 1 if it has ability to look ahead to change coordination plan</td>
</tr>
<tr>
<td>More than 30 plans</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Rated 1 if it has more than 30 plans</td>
</tr>
<tr>
<td>Cycle Lengths exceeding 255 seconds</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1 if more than 255 sec</td>
</tr>
<tr>
<td>Fixed versus floating force off per phase per plan</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1. Rated as 2 if Force-offs available per phase and per plan 2. If only per phase than rated as 1 point.</td>
</tr>
<tr>
<td>Holiday Date structured to handle 40+ days</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>No Controller has 40+ holidays.</td>
</tr>
<tr>
<td>Holiday Events capable of programming Time of Day type function in addition to events</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>If Holidays capable of programming Time of day events then rated as 1 point, else 0.</td>
</tr>
<tr>
<td>Ability to violate guaranteed pedestrian programmed times when developing coordination plans</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>If the controller has the ability to violate guaranteed pedestrian programs then rated as 1 point.</td>
</tr>
<tr>
<td>Phase omit programming by plan</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>If controller is capable of Phase Omit per plan basis then rated as 1 point.</td>
</tr>
<tr>
<td>Method to confirm the current Time of day/Day of week setting in the controller (Upload &amp; Monitor controller clock)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Rated 1 if the controller has the capability to confirm the Time of Day/Day of Week settings.</td>
</tr>
<tr>
<td>Traffic Responsive capable</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Rated 1 point if the controller has internal Traffic Responsive capabilities.</td>
</tr>
<tr>
<td>Controller ability to execute system-wide transition plan directed from central control center</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Rated 1 point if capable of the operation.</td>
</tr>
<tr>
<td>Average Score (FR)</td>
<td>0.75</td>
<td>1</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-3 Scoring Criteria for Functional Requirements under Signal Preemption and Priority

<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Scoring Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximize emergency response and related features</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>Delay (1), Min Green (1), Min Walk (1), Change Next Phase decision (1).</td>
</tr>
<tr>
<td>Have bus priority (extended green only) with more efficient ways to recover from preemption</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1. Controllers having either TSP or soft preempts for bus priority are rated as 1 point. 2. If recovery from low priority is available then rated as 1 point.</td>
</tr>
<tr>
<td>Transit signal priority</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>(1) Controllers with Light Rail Vehicle &amp; Bus Priority are rated as 2. (2)Soft preempt or bus priority are rated as 1 point. (3) And with no priority options are rated as 0.</td>
</tr>
<tr>
<td>Communication capabilities for adjacent controllers (e.g., during preemption)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>If controllers are capable of Peer-to-Peer Communication then rated as 1 point.</td>
</tr>
<tr>
<td>Phase selection for exiting the Preemption</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>There are total 5 exit parameters 1. All un-service phases receive service (1 point). 2. Place call on any specific Exit Phase (1 Point). 3. Phases shortened will get priority (1 point). 4. Phases waited long will get priority (1 point). 5. Return to Coordination directly. (1 point). Entering into Normal Operation directly is given 0 points.</td>
</tr>
<tr>
<td>Transition algorithms</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>If transition is available from Preemption to Normal (not exit phases), then rated as 1 point. If no transition capabilities are mentioned then rated as 0 points.</td>
</tr>
<tr>
<td>Options for handling &quot;double&quot; preemption</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>All controllers which can handle double preemption are rated as 1 point.</td>
</tr>
</tbody>
</table>
Program and maintain progression through preemption | 0 | 1 | 0 | Rated 1 if progression through preemption is possible.

Average Score (FR) | 1.625 | 1.125 | 1.125

<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Scoring Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian Overlap capabilities - operational under all programming conditions such as Free, Coordination, etc</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1) Rated 2 if Overlap’s are available in both free and Coordination mode. 2) Rated 1 if only under free operation.</td>
</tr>
<tr>
<td>Ability to assign more vehicle phases with pedestrian phases</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 point if capable of the operation.</td>
</tr>
<tr>
<td>Allow pedestrians to get 4 seconds advance green before the phase</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 point if capable of the operation.</td>
</tr>
<tr>
<td>Optional right arrow with pedestrian phase</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>If right turn overlaps exist then rated as 1 point.</td>
</tr>
<tr>
<td>Pedestrian phase re-service and walk extension</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Rated 1 if controller can take extra pedestrian time from other phases.</td>
</tr>
<tr>
<td>Different minimum pedestrian time (push for normal, hold for extend)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Rated 1 if controller has different pedestrian times based on if the button is pushed and if the button is pushed and hold.</td>
</tr>
<tr>
<td>Vehicle clearance and pedestrian clearance for countdown purposes</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 point if pedestrian and vehicle clearances are available.</td>
</tr>
<tr>
<td>Pedestrian clearance during preemption</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Rated 1 point if capable of operation.</td>
</tr>
<tr>
<td>Average Score (FR)</td>
<td>1</td>
<td>0.875</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

2.4.2 Assignment of Weights

The Critical set of functional requirements associated with an intersection should not necessarily be given equal importance. In other words, a corridor might require both Transit and Pedestrian facilities but the Transit features might be more important than the pedestrian requirements. So the methodology has been framed in such a way, that it considers the importance of each critical functional requirement at each intersection. To define the importance and to quantify it a weight factor has been used, which requires assignment of a weight to each of the critical functional requirement based on the intersection. This weight factor defines the importance of each critical functional requirement for that intersection alone. The local
conditions must also be taken into account while assigning the weights. An example of a rational approach to determine these weights for a given corridor would be, to determine the percentage of intersections in a corridor (or a zone) where a given requirement (e.g., TSP) applies as will be described below.

### 2.5 CALCULATION OF PERFORMANCE INDEX

The actual methodology involves evaluating the performance of various controllers at an intersection according to its critical functional requirements and to suggest the most effective controller for that intersection. So to evaluate the individual controllers a term called Performance Index (PI) has been introduced. The PI of each of the controllers is calculated using Equation (2-1) shown below.

\[
PI = \frac{\left( W_{pre} \cdot FR_{pre} + W_{ped} \cdot FR_{ped} + W_{coord} \cdot FR_{coord} + W_{GT} \cdot FR_{GT} \right)}{\left( W_{pre} + W_{ped} + W_{coord} + W_{GT} \right)}
\]

Where:
- \( PI \) = Performance Index of the controller
- \( W_c \) = Weight assigned to the critical functional requirement category ‘c’ on a scale of 1-10
- \( FR = \sum (Y_i \cdot X_i)/n \)
- \( Y_i \) = 1 if the attribute (Functional Requirement) ‘i’ is considered, else 0
- \( X_i \) = The score of the attribute ‘i’ for the given controller.
- \( n \) = Number of attributes considered in the given functional requirement category

The performance of a controller is evaluated using the above equation. From the tables showing the scoring criteria and the scores, the FR values are calculated. Based on the FR values obtained the performance of the controller is evaluated by assigning appropriate weights to various Critical Functional Requirement Categories.

As an example consider a zone with certain number of traffic signal controllers. Each of the intersection has to be evaluated to know the performance of the new system with the given functional requirements. Considering the fact that General Traffic Operations and Signal Coordination are most commonly needed at all intersections the weight of 10 is given to their Functional Requirement categories. Now considering that the transit vehicle passes through 80% of the intersections in this zone, weights of 8 is given to the preemption category. Assuming that the pedestrian movements are present at 50% of the intersections, a weight of 5 is given to that category. The FR values can be obtained from the previous tables for each of the controller type.

So the total performance can be calculated as shown below

PI for Controller Type 1:

\[
PI = \frac{(8 \cdot 1.625 + 5 \cdot 1 + 10 \cdot 0.75 + 10 \cdot 1.363)}{(8 + 5 + 10 + 10)}
\]

So the PI for Controller Type 1 is PI = 1.185

PI for Controller Type 2:

\[
PI = \frac{(8 \cdot 1.125 + 5 \cdot 0.875 + 10 \cdot 1 + 10 \cdot 1.2)}{(8 + 5 + 10 + 10)}
\]
So the PI for Controller Type 2 is $PI = 1.071$

PI for Controller Type 3:

$$PI = \frac{(8 \times 1.125 + 5 \times 1 + 10 \times 0.33 + 10 \times 0.727)}{(8 + 5 + 10 + 10)}$$

So the PI for Controller Type 3 is $PI = 0.744$

The calculations above show that the Performance Index values for the three controllers vary with same functional requirements and same weights. The results show that Controller Type 1 got a score of 1.185, Type 2 has obtained a score of 1.071 and Controller Type 3 which is the existing type controller has got a score of 0.744. If the existing controller type 3 is replaced by the new controller type 1 then the improvement with regard to FR satisfaction would be 59%. Whereas if the existing system is replaced by the controller type 2 than the performance would be increased by 43%. From these calculations, it is evident that for the given functional requirements and weights, controller type 1 is more effective than controller type 2 based on this method. If Functional requirements for traffic coordination alone are considered then controller type 2 should be more efficient since it has higher score than controller type 1. It can be observed that the scores differ by the functional requirements considered and the weights assigned to each of the categories of the functional requirements. So these weights can be assigned by the user depending on the requirements and considering the field conditions.

By using the above mentioned formula, the PI values can be calculated for each of the controller type. The PI values act as a scale in evaluating the controllers based on the features. It acts as measure of the controller performance and represents the benefit of alternate systems in terms of the score. Based on the requirements of the intersection each of the alternatives can be evaluated using this procedure. The controller which gets higher score or benefit value can be considered as more efficient based on this method.

2.6 CONCLUSIONS AND FUTURE WORK

This paper presents a method for evaluation of traffic signal controllers based on the functional requirements using MCDM technique. An equation was developed which uses functional requirements, scores and weights to calculate the performance of the controller. Criteria were developed for scoring of the controller features depending on the information from the manuals and from the vendors. Finally, this method was applied on three different controllers and the benefit of replacing the controllers was also explained. This method serves as an effective way for evaluating the signal controllers and to numerically represent its performance.

This method would further help the researchers by providing techniques for evaluation of alternatives in case of large scale projects. This work can further be enhanced by developing a method or an algorithm, that tests the system dynamics and assigns scores based on Measure of Effectiveness expected from each controller features. The method developed can also be applied for evaluation of other signal system infrastructure. The functional requirements specified in this paper were developed based on the requirements of general signal system operations. These functional requirements can be enhanced, or changed depending on the project.
3. A GIS-BASED MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK FOR DETERMINATION OF NEW TRAFFIC SIGNAL CONTROLLERS MIGRATION PLAN

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ABSTRACT

Signal Replacement decisions are often made relying on the experience of the Traffic Engineers. These decisions are made by considering the deployment time of the system, the new technology available, and the performance of the system in the given location. But there are no set of proper guidelines, or methods, which can quantify the system replacement decision for large scale projects. In this paper we propose a methodology, for developing a migration plan for signal controllers based on the functional requirements of the corridor. Geographic Information System (GIS) is proposed as a tool to evaluate and identify the order of upgrade for different corridors within the budget constraints. This paper addresses various aspects of optimizing the migration plan, so that the users can evaluate the benefits associated with the system replacement. A Multi-Criteria Decision Making technique was also used for estimating the benefits of replacing the existing systems with various alternatives. Finally, the entire evaluation process and the methodology for the migration plan were demonstrated on a GIS framework.
3.1 INTRODUCTION

The objective of the project was to develop a Strategic Migration plan which indicates the time frame and spatial location of the systems which has to be replaced, and what system is most suitable depending on the functional requirements of the zone/corridor considered. In order to develop the migration plan it is most important to know the existing system capability and its functional capacity, and what type of systems are currently deployed in the field. The process starts with classification of the region into various zones/corridors using Geographic Information System (GIS). The second step is to evaluate the performance of the existing system and evaluating the benefits of using alternate systems, with a Multi Criteria Decision Making (MCDM) technique. And finally, to determine the zones to be upgraded using the optimization technique.

3.2 MIGRATION PLAN

This paper describes a method for creating a migration plan for traffic signal controllers. But before making the system replacement decision, it is important to know under what conditions or situations does the signal system has to be improved or upgraded. Literature [28] suggests that the growth or change in traffic demand is one of the signs for signal improvements. With increase in volume, the congestion becomes evident and this would be a clear indication for the signal system improvement. Another measure indicating the need for signal improvement is, frequent failures in the signal infrastructure equipment that results in inefficient operation of the intersection. The need of advanced technology which is available in modern signal infrastructure and not available in the existing infrastructure, can also serve as a measure for the need of system upgrade. The study for the National Corporative Highway Research Program (NCHRP) [24] indicates that, many of the system improvement plans are done using conventional techniques. The process includes, reviewing the volume of the intersections or arterials, prioritization based on volumes, identifying the needs and requirements, setting up goals and objectives, and proceeding with the system upgrade. The alternative evaluation method is also done to evaluate the benefits of the alternate system if the upgrade plan has to be carried. The study also suggests that, some of the agencies also adopt the before and after technique’s, where simulation is done to evaluate the benefits of system upgrade. Perhaps, this kind of procedure is very difficult in case of macro level analysis.

The Traffic signal Policy and guidelines adopted by the Oregon Department of Transportation [29] has provided some guidance for signal system installation and approval. These guidelines mostly focus on the physical aspects of the road or intersection, the intersection volume, existing level of service and existing and future traffic signal systems. But there are no recommendations made as such for signal improvements/upgrade. Studies conducted by the Columbus traffic signal system [25], provides a clear idea of the various aspects which are to be considered while developing a migration plan. The study includes survey of various member agencies, to know the existing traffic signal system infrastructure and the standards which are adopted for the signal operation by those member agencies. It also suggests the evaluation of
various alternative traffic control systems and then developing a system implementation plan for the communication and signal infrastructure.

All the above studies do not consider the functional requirements while developing the system improvement plan. The base objective of this paper is, to develop a method to identify the corridors or intersections which have to be upgraded based on the functional requirements. And then, to develop a method to evaluate the benefits of implementation of alternate systems against the existing signal infrastructure. The signal infrastructure term in this paper refers to the Traffic Signal Controllers.

The system improvement plan can be broadly classified into two different tasks. First task is to identify the existing system performance and relate it to the controller features. The second task is to quantify and develop a method which suggests which systems are to be replaced first. MCDM technique is adopted to evaluate the performance of signal controllers at each intersection. Based on the functional requirements of the intersection, the performance of the existing and new system is calculated. Then, the benefit of replacing the existing system with the new system is estimated by calculating the difference between their performance values. Here GIS is used to classify the whole area into zones based on the existing network. The benefit values calculated from the MCDM technique is assigned to the respective zones in the GIS. Following which an optimization technique is used, to find the zones to be upgraded first based on the objective of maximizing the benefit values and minimizing the budget.

3.3 METHODOLOGY
This section describes the actual methodology for the whole migration plan process. It includes the integration of the GIS framework with the MCDM technique and optimization process.

3.3.1 Zonal Classification
The zonal classification of the controllers is done based on the existing signal networks. Each zone consists of a certain number of controllers which are operating together in a network. Initially, each controller is assigned a unique value representing the zone in which it falls. So all the controllers belonging to a particular zone has the same unique id. After that zones are created using various tools available in Arc GIS [30]. The output would be the final zones showing the controllers which fall in each zone. After creating the zone, now each controller has to be evaluated to estimate its performance.

3.3.1.1 Calculation of Performance Index

All the controllers or intersections in each zone are evaluated against the functional requirements. Each intersection has its own functional requirements, for which the performance is calculated in terms of a score. These scores are obtained from the Multi-Criteria Decision Making technique which is used for the evaluation of controllers. The performance of the controllers is estimated from the scores assigned to the individual attributes of the alternatives. These scores were assigned based on certain criteria.
3.3.1.2 Scoring Criteria

The criteria for scoring were developed keeping in view of the various features available in different type of controllers. The features of the controllers were obtained from the manuals and by contacting the vendors of various controllers studied. The scores were assigned on a scale for each functional requirement for all the controllers.

3.3.1.3 Assignment of Weights

It is not necessary that each corridor has the same set of functional requirements. Some corridors might have greater requirement for some categories of functional requirements than others. So a weight factor was used to take into account the relative importance of one functional requirement category over other. These weights are to be assigned carefully based on the knowledge, experience and considering the local factors.

3.3.1.4 Calculation of Benefit Values

Each intersection is analyzed and weights are assigned depending on the importance of the selected functional requirements at that intersection. Based on the functional requirements considered at the intersection we get the corresponding score value of the intersection. This score value is defined by the term called ‘Performance Index’ (PI), which is calculated for the existing system as well as the alternative systems. Each of the alternatives is named as PI1, PI2, PI3, etc. The scores for calculating the PI values are obtained from the MCDM Technique. The benefit values are calculated at each intersection, which are represented as PI1_PI, PI2_PI, PI3_PI etc. These benefit values are the difference in performance of the existing system and the new alternate system. It can be represented as Benefit = (PIk-PI), where k is the alternate system considered.

3.3.2 System Replacement Decision

Conventionally, the system replacement decisions are generally made by the Traffic Engineers based on their experience and considering the time since the system has been deployed in the field. Evaluation of certain factors by conducting before and after studies is another method of making the system replacement decision. But, there are no proper set of guidelines that suggest the system replacement, considering field conditions and multiple factors for a larger scale migration plan. This papers deal’s with the identification of these factors and attempts to assess the performance of the existing system in those conditions. And check if the candidate system can perform better in those conditions. If the new systems can improve the performance, then the most effective alternative is selected based on the score of the systems. Usually the system replacement is done for whole corridor or zone. Since the replacement of the system is related to many other factors such as communication issues, operating in a network and compatibility of the systems, the whole zone has to be replaced at once. Considering that, the methodology has been framed in such a way that the whole zone is considered for replacement if has to be upgraded to a new system.

After calculating the PI at each intersection, the PI values of all the intersections in a zone are added together to get the total PI in that zone alone. Likewise for each zone the PI values are
obtained by the summation of the individual PI at each intersection. In addition to that, thebenefit of replacement of alternative systems is also calculated for the whole zone by summationof benefit values at individual intersections. Now it has to be determined which zones are to beupgraded first to get the maximum benefit value. This is done using an external optimization

technique.

### 3.3.3 Optimization Process

The optimization process takes place outside the GIS program where the zones areselected based on the objective function. There are many optimization techniques which areadopted in general. But, the optimization problem itself has to be formulated mathematicallybefore solving it. There are many Mathematical programming formulations such as LinearProgramming, Multi-objective programming, Integer Programming, Multilevel Programming,etc. The current problem can be formulated as a Linear Programming problem. The equationscan be modeled as shown below:

**Objectives:**

Maximize the Benefit value

\[
\text{Max} \sum_{i=0}^{n} (B_0 \times Z_0 + B_1 \times Z_1 + \ldots \ldots \ldots + B_n \times Z_n)
\]  \hspace{1cm} (3-1)

Minimize the Total budget

\[
\text{Min} \sum_{i=0}^{n} (N_0 \times C_0 \times Z_0 + N_1 \times C_1 \times Z_1 + \ldots \ldots \ldots + N_n \times C_n \times Z_n)
\]  \hspace{1cm} (3-2)

Where

- \(B_i\) = Benefit of Zone \(i\) which is calculated as \(\Pi_i \times PI\)
- \(Z_i\) = Design Variables which takes in the Binary value i.e., either 0 or 1
- \(N_i\) = Number of controllers in Zone \(i\)
- \(C_i\) = Cost of upgrading controller \(i\)

The above mentioned Equations represent’s the formulation for the given problem, whichcan be solved using any optimization technique. The first objective function is, to select thezones to maximize the total benefit values. The second objective function is, to minimize thetotal cost which is incurred by upgrading the zones. The decision variable \(Z_n\) is the outputindicating which zones are to be upgraded based on the objective function.

There are many optimization techniques used in general. Mukherjee [31] has classifiedthese optimization techniques into, Conventional optimization techniques and Non-Conventionaloptimization technique. The Conventional technique includes the Iterative Mathematical searchtechnique to find the optimal solution. The problems were formulated as linear or non-linearproblems. On the other hand he classified the Non-Conventional techniques into varioustechniques which included Heuristic search method, Genetic Algorithm (GA), Tabu Search (TS)and Simulated Annealing (SA) technique.

From the above mentioned techniques, the GA optimization technique is the mostcommonly adopted for many of the optimization problems. The GA [32] problems can again bedefined as Single Objective and Multi-Objective Problems. In the single objective problem only
one optimal solution set is obtained. Whereas, in Multi-Objective method many solutions are obtained which are known as Pareto-optimal solutions. In the current problem, Multi-Objective Optimization technique is used to get the multiple solutions.

3.3.3.1 Calculation of Degree of Detachment

Degree of Detachment (DOD) was introduced by Abbas et al [33] which is used as a performance measure of scheduling continuity. It has been defined as, the degree by which a zone is detached from its adjacent zones. In other words, the number of unselected adjacent zones around a selected zone is the degree of detachment for that zone. So for each given solution we get a DOD value. The lower DOD value indicates that the zones are more adjacent to each other. The higher value indicates that the zones are more scattered in space. This DOD value is important for the migration plan, since some of the organizations prefer upgrading the zones based on the adjacency. In other words, randomly upgrading the zones is avoided to lower the overall cost of upgrading. Hence it can be suggested that lower the DOD value, closer are the zone’s that are to be upgraded.

3.3.4 Output

The output of the optimization tool consists of various zone combinations for the given objective functions. Each corresponding solution consists of a set of zones which are to be upgraded. So the total cost, total benefit and the DOD of upgrading those zones can be obtained. A Pareto-front is drawn which indicates the total cost, total benefit and the DOD values for each corresponding solution. The solutions above the surface of the Pareto-front are the sub optimal solutions and the solutions below the surface are the infeasible solutions.

3.4 CASE STUDY

The above methodology of the migration plan and MCDM was applied on a GIS framework for the Northern Region of Virginia (NOVA). The Northern Regional Operations (NRO) under Virginia Department of Transportation (VDOT) currently uses a 170 and NEMA model traffic signal controllers. The number of traffic signal controllers which are currently under operation in NOVA region is more than 1500. In this case, since the functional requirements vary indefinitely, microscopic analysis of the signal controllers is a very tedious task and not suitable for large scale migration plan. So a large scale analysis process has to be adopted where controllers which come under same zone are replaced together.

The zonal classification of the controllers is done, based on the suggestions obtained from VDOT. Each zone consists of a certain number of controllers, which are operating together in a network. These zones are developed keeping in view the existing traffic signal controller networks which operate together. The

<table>
<thead>
<tr>
<th>Unique Zone ID</th>
<th>PI values</th>
<th>Performance Index values and benefit obtained by replacing the alternate systems</th>
</tr>
</thead>
</table>

Table 3- 1 below, show the attributes which are entered in GIS at each intersection. The Unique Zone ID indicates the zone in which the intersection is operated, and the PI values indicate the Performance Index values and benefit obtained by replacing the alternate systems.
Table 3-1 Attributes used in GIS for calculation of Benefit value at each intersection

<table>
<thead>
<tr>
<th>Signal Number</th>
<th>Unique Zone ID</th>
<th>PI</th>
<th>PI1</th>
<th>PI2</th>
<th>PI1_PI</th>
<th>PI2_PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>639130</td>
<td>8</td>
<td>4.3</td>
<td>7.9</td>
<td>7.9</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>627008</td>
<td>6</td>
<td>4</td>
<td>6.3</td>
<td>5.8</td>
<td>2.3</td>
<td>1.8</td>
</tr>
<tr>
<td>3215</td>
<td>7</td>
<td>4.1</td>
<td>6.2</td>
<td>5.3</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>3225</td>
<td>7</td>
<td>4.1</td>
<td>6.2</td>
<td>5.3</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>208035</td>
<td>4</td>
<td>3.6</td>
<td>6.2</td>
<td>5.1</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>3260</td>
<td>7</td>
<td>4.1</td>
<td>6.2</td>
<td>5.3</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>1440</td>
<td>2</td>
<td>3.5</td>
<td>6</td>
<td>5.4</td>
<td>2.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

After calculating the Performance Index values at each intersection, zones are created in GIS using various tools. The $\sum PI$ values and the benefit values are aggregated and assigned to the whole zone. The Table 3-2 below represents the attributes showing the total benefit value in each zone.

Table 3-2 Attributes showing the total benefit value for each alternate system

<table>
<thead>
<tr>
<th>Unique Zone ID</th>
<th>$\sum PI$</th>
<th>$\sum PI1$</th>
<th>$\sum PI2$</th>
<th>$\sum (PI1_PI)$</th>
<th>$\sum (PI2_PI)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.2</td>
<td>26.6</td>
<td>25.1</td>
<td>13.4</td>
<td>11.8</td>
</tr>
<tr>
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<td>71.6</td>
<td>83.8</td>
<td>13.0</td>
<td>25.2</td>
</tr>
</tbody>
</table>

The DOD value for each solution is estimated by the DOD file. This file consists of information about the adjacency of the zones. It gives the unique ID values of all the zones which are adjacent to a given zone. Table 3-3 below shows the zones which are adjacent to a given zone. The first column indicates the zone which is considered and each row shows the zones adjacent to that corresponding zone.

Table 3-3 Adjacent zone id’s for each corresponding zone

<table>
<thead>
<tr>
<th>Unique Zone ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</tr>
<tr>
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<td>1</td>
<td>2</td>
<td>8</td>
<td>-</td>
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<td>6</td>
</tr>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>
The table below shows the various solutions of the optimization process. Each solution set represents the zones to be upgraded based on the objective function. The number represents the corresponding controller type which is used in that zone. The value zero indicates that the zone is not to be upgraded.

Table 3- 4 Attributes consisting of Zones to be upgraded for each corresponding solution

<table>
<thead>
<tr>
<th>Unique Zone ID</th>
<th>Solution1</th>
<th>Solution2</th>
<th>Solution3</th>
<th>Solution4</th>
<th>Solution5</th>
<th>Solution6</th>
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</thead>
<tbody>
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<td>1</td>
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</tr>
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<td>2</td>
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<td>4</td>
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<td>6</td>
</tr>
<tr>
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<td>4</td>
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<td>6</td>
</tr>
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<td>5</td>
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<tr>
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<td>0</td>
<td>3</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

After finding the zones to be upgraded for each corresponding solution, the total benefit value, degree of detachment value and the total cost of upgrading those zones are estimated. Here the cost of upgrading relates only to the controller replacement cost and do not consider external cost such as transportation cost, installation cost etc. The table below shows the total benefit value, DOD and the total cost for each solution which is used to develop a Pareto-front.

Table 3- 5 Total benefit values for each solution along with the degree of detachment for an Example Problem

<table>
<thead>
<tr>
<th>Solution Number</th>
<th>Total Benefit</th>
<th>DOD</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.5</td>
<td>26</td>
<td>140000</td>
</tr>
<tr>
<td>2</td>
<td>65.7</td>
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<td>52.7</td>
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<td>126000</td>
</tr>
<tr>
<td>5</td>
<td>61.1</td>
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<td>195000</td>
</tr>
<tr>
<td>6</td>
<td>73.7</td>
<td>20</td>
<td>168000</td>
</tr>
</tbody>
</table>

The Figure 3- 1 below shows the various solutions with their total benefit values and the corresponding DOD. Each solution is a combination of different zones which are to be upgraded. It can be observed that lower the DOD value better is the migration plan, but at the same time the total cost is on the higher side. Similarly when the cost is decreased the benefit value is also on the lower side. So the optimal solution is selected to give the maximum benefit based on the DOD and the total budget available.
3.5 CONCLUSIONS AND FUTURE WORK

In this paper we presented a method for developing, optimal migration plan for traffic signal controllers using GIS and Optimization techniques. We then show the utility of using GIS, to classify the controllers into zones and to calculate the benefit associated with implementation of the new system. The MCDM technique was suggested for evaluation of the controllers and to calculate the system benefit values. The optimization technique was used, to specify which zones are most appropriate for upgrade based on the objective function. Finally the zones are displayed on the Map using GIS. This method is first of its kind where, GIS and optimization technique both are used to develop a migration plan for traffic signal controllers. The method presented is flexible enough so that it can be applied for any area for the signal system improvement. The whole process was tested on a demo file which had the working GIS framework.

The methodology presented in this paper integrates GIS, MCDM and Optimization technique to create a migration plan. This method can further be enhanced by improving the optimization technique. The present method is limited by the cost function, which considers only the cost of system replacement and do not consider external cost associated with it. The GIS framework can further be improved, by providing better Graphic User Interface for easy implementation of the whole process. This method can further be applied for developing improvement plans for other signal system infrastructure as well, but not restricted to this alone.
4. APPLICATION OF THE MIGRATION PLAN

This chapter presents the application part of the migration plan which was explained earlier. The migration plan developed is flexible enough to be applied elsewhere. But in order to create a migration plan it is important to know about the functional requirements of a region and functionality of the GIS framework. The first part of this chapter presents a set of guidelines which helps in selecting the functional requirements under various traffic conditions. These guidelines were developed after a thorough review of literature. These guidelines can be used when this method is applied to a new region or area where the migration has to be implemented.

After selecting the functional requirements and calculating the performance index values these are entered into the GIS database. Now the GIS database has to be integrated with the optimization process for further analysis. The second part of this chapter describes the functionality of the GIS framework and how it is integrated with the optimization tool. It also explains about the Graphic User Interface (GUI) command buttons developed for the implementation of the process.

4.1 CRITERIA FOR SELECTING THE FUNCTIONAL REQUIREMENTS

The functional requirements were established based on the general requirements of the signal system operation. Since the functional requirements at each intersection is not same, it is important to know what functional requirements are to be selected under various traffic conditions. The following is the certain set of guidelines that were developed after a thorough review of literature. The guidelines suggest what type of functional requirements are to be selected based on certain factors such as, location of the intersection, geometry of the intersections, intersection type such as isolated or free etc. These guidelines can be used when this migration plan has to be implemented in another location. These guidelines were classified into various groups based on the functional requirements.

4.1.1 Transit Priority

Urban areas with larger population have a greater need for Transit Priority features to reduce the overall delay and increase the serviceability. Research [34] shows that Transit Signal Priority (TSP) provides benefits for the transit vehicles and has low system-wide impacts for low traffic demands. So it can be recommended from the above studies, that implementation of TSP on lightly congested approaches is not suggested when the conflicting approaches are heavily congested. Further studies on arterials [35] show that signal preemption may not result in oversaturated conditions, when sufficient green time is available in the system cycle length. It also suggests that, the decision to grant transit priority at an intersection would actually result in excess delay, if the arrival time of the transit vehicle is not taken into consideration.

From the above research the problems in Transit Priority can be accounted as follows: Arterials with larger intersection spacing might require advance transit priority option or peer-to-peer communication capabilities to avoid excess delays. Arterials with closer intersection
spacing require systems to recover quickly from coordination immediately after preemption to avoid saturated conditions. The frequency of transit vehicle and the number of approaches the transit vehicle travel’s, specifies the need to handle dual preemption or number of preempt sequences. For nearly saturated flows having greater transit priority requirements, the controllers should be able to provide greater transition immediately after preemption.

Based on the problems associated with TSP, the following controller features can be recommended: Traffic Signal Controllers having the peer-to-peer detection capabilities can be used in case of arterials, to avoid excessive delays at the intersections. Controllers which allow coordination in the background during preemption, helps in returning to direct coordination after preemption. This feature is helpful in case of intersections with shorter spacing, to avoid the queues created by disrupted system and avoid backing of vehicles to the upstream intersections.

4.1.2 Coordination

Coordination of traffic signals is one of the major factors in arterials, to increase the serviceability of the signal system and enhance smooth flow of traffic. Studies [36] show that there are several factors which influence the selection of a control strategy which depend on traffic, design and system characteristics. Literature review suggested that Fixed Time Signal control in coordination is better suitable for intersections operating near to capacity, whereas semi-actuated signal control is more effective for intersections with low volumes on actuated phases. Fully actuated signal control as uncoordinated is more applicable for intersections which are operating close to saturation on all approaches.

In order to deal with the problems of coordinate traffic signal systems, many modern controllers are equipped with additional features. Some of them have the ability, to violate the guaranteed pedestrian phases while developing the coordination plans. Some controllers offer techniques which more likely act like a traffic responsive system in arterials. In addition to that the techniques for platoon progression can be used for better coordination of the signals.

4.1.3 Pedestrian & Bike

Most of the modern controllers offer many new features which can be implemented to effectively manage the intersection vehicular and pedestrian flow. Literature [37] suggest that, timing based on pedestrian minimum is more appropriate for longer cycle lengths and for medium to high pedestrian crossing activities. In addition to that, pedestrian crossing with protected left turn arrow [38] is also implemented to improve the efficiency of the signalized intersection.

Some of the controllers have the ability to provide early green for pedestrians, which can be incorporated based on the location and the pedestrian flow. Issues dealing with preemption and pedestrian flows can be dealt with controllers providing minimum pedestrian clearance time before preemption. In addition to that some of the 2070 controllers have special features for bike signals which can be used in large cities with greater bike population.
4.1.4 Transition Plans

Selection of appropriate transition plan determines the operational efficiency of any signalized intersection. Research [39] shows that one transition plan may not be appropriate for all traffic conditions. Studies showed that, short transition is most effective in general but in congested conditions add transition has performed better. There are many factors [40] which are involved in the selection of transition schemes for exit preemption control. Such as vehicular and pedestrian volume, signal timing plan, number of phases etc.

The modern traffic signal controllers have a greater ability in providing transition schemes under various operations. Few 2070 controllers have the capability to make a smooth transition from free to coordinated operation, which is required for nearly saturated intersections. In addition to that some controllers have an ability to decide the transition method (Long-way, Short-way/Long-way) to synchronize the offsets during coordination.

4.1.5 General Traffic Operation

General traffic information is needed so as to categorize various operations available in the controllers. Based on the data some of the features which might be required are:

4.1.5.1 Traffic Responsive: This feature is needed when there are unexpected traffic flows and the timing plans are supposed to adjust to the traffic conditions. For saturated or nearly saturated intersections this feature may not be an appropriate measure for selection. Traffic Responsive Plan [41] selection would be more appropriate for abnormal traffic conditions and incidents or events such as holidays. Many of the 2070 controllers are Traffic Responsive capable and can be considered for replacing the 170 controllers.

4.1.5.2 Left Turners: Selection of left turn phasing schemes at signalized intersections depends on the left turn and through traffic flows. Studies [42] showed that greater delays occurred in case of protected phasing rather than protected permitted phasing. In addition to that National Corporative Research Program (NCHRP) [43] has conducted evaluation of various traffic signal displays for left turners. From the details provided by this report and from the safety point of view of left turners it can be suggested that Flashing Yellow Arrow (FYA) signal head would be more appropriate for heavy left turn lanes. The 2070 controllers are equipped with this feature can be used in the field.

4.1.5.3 Timing Plans: For intersections with no greater change in flows throughout the day the number of timing plans required might be less. Areas like CBD, recreational centers, schools and shopping malls have varying traffic flow patterns and localized peaks. So in order to handle the variations in the traffic flows the number of timing plans required is more. Many of the 2070 controllers offer many number of timing plans for various timings of the day.

4.1.5.4 Queue Detection: For corridors or arterials with smaller intersection spacing and higher flows might require queue detectors so as to avoid blocking of the upstream intersections. 2070 controllers offer queue detectors and many additional features. These controllers have the ability to alter the coordination plans or to initiate preemption when is detected. Many of the 170 Controllers do not offer such advanced features. So when implemented on an arterial or urban corridor 2070 controllers would be a better option.
4.2 GRAPHIC USER INTERFACE FOR THE GIS FRAMEWORK

The methodology presented in the thesis requires integration between GIS and the optimization tool. The input for the optimization tool is obtained from the GIS database. This database has to be converted into a different file format for the optimization tool to use it. So a Graphic User Interface (GUI) was developed in Arc GIS using Arc Objects which acts as an Application Programming Interface (API) for GIS.

Figure 4- 1 GUI buttons developed in the GIS framework

The Figure 4-1 shows the Graphic User Interface buttons which were developed in the ArcGIS. The ‘Database to CSV’ button converts the GIS database into .csv file format. This file acts an input to the Optimization technique. Another user interface button runs a batch file which is used to execute the optimization tool. The output from the optimization tool is obtained in the form of .csv file. This output is integrated to the GIS by using the ‘Join Output’ command button. The ‘DOD’ [44] button is used to create the DOD file. These four GUI command buttons help to easily create the migration plan.
5. SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

The thesis presents a method to develop a migration plan for traffic signal controllers, using Multi-Criteria Decision Making (MCDM) and Geographic Information System (GIS). Increasing traffic demand has raised the need, for increased safety and efficiency of the signalized intersections. But, the controllers which are already deployed in the field from long time fail to achieve the desired performance in the intersection operation. This calls in the need for system replacement decisions. Usually these decisions are made based on the knowledge and experience of the traffic engineering professionals. But there are no proper guidelines, which can evaluate the system replacement benefit, and suggest which systems are to be replaced first and what systems are most effective under different conditions.

The project aims at developing a large scale migration plan considering the above requirements. Due to the budget constrain and large number of controllers has to be replaced, the migration plan has to be gradual rather than all at once. In addition, there are many traffic signal controllers available in the market that performs equally well. Hence it is difficult to assess the performance of these controllers based just on engineering judgment. So a procedure for an optimal migration plan has been developed, which suggests which systems are to be replaced first and what system suits best depending on the local traffic conditions. This procedure is based on the MCDM and GIS.

This research provides an insight into various MCDM techniques which are commonly adopted in many fields of engineering. It also gives a review of various decision making process for signal system replacement. But these methods of decision making process are conventional in nature and often lack the ability to demonstrate the reasons for system replacement. This thesis provides a method for evaluating various signal controllers and to estimate their performance and indicate them in the numerical forms. This often helps in providing proper substantial evidence for system replacement judgments.

In order to evaluate various traffic signal controllers it is important to study the various features available in each of the controllers. These controller features are often related to the intersection requirements which can also be called as functional requirements. These functional requirements constitute many advance features in the controllers, which were developed based on the discussion with the professionals in the field of signal system operation. Each functional requirement category consists of, the corresponding features or the requirements in the controller for that category. For example, the Preemption and Priority category consists of, all the functional requirements which are related to the Emergency Vehicle Preemption and Transit Signal Priority features in the controller. Likewise for Pedestrians, Coordination, General Traffic Operations, etc. These functional requirements were used for the evaluation of the signal controllers based on decision making techniques.

A Multi-Criteria Decision Making (MCDM) technique was adopted in this project for evaluation of the signal controllers. This technique has been considered in the project since it has
an advantage of considering multiple attributes for the evaluation process. The functional requirements are considered as attributes in this study. The scoring of the attributes was done depending on the criteria which were developed. This criterion was based on the information obtained from the manuals of the various controllers. In the process of creating the scoring criteria, various vendors were also contacted to obtain the information about the controllers which was not clearly defined in the manuals. An equation was developed to calculate the Performance Index of the controllers for the given Functional Requirements. Using the equation which was presented the performance of the controllers can be estimated for a given set of functional requirements. This performance index acts as a measure of the controller effectiveness for those requirements. After calculating the performance of the controllers, it is important to estimate the benefit of the replacement of the existing system with the new system. This is used for creation of the migration plan and to know the potential system replacement zones.

The migration plan was developed using a Geographic Information System (GIS) framework which integrates the MCDM technique which was described earlier. The GIS tool is used to classify the controllers into various zones. Each of these zones consists of the controllers which operate together in the form of a network. If a system replacement decision is taken then all the controllers in a given zone are replaced at once. Here the MCDM technique is used to evaluate various systems and to find the most effective system for a given functional requirements. After which, the benefit of replacement of the system is calculated by the difference in the Performance index values of the new and existing system. Then the total benefit of replacement of the zone is estimated by summation of all the benefit values of the controllers in that zone. Now each zone has a benefit value which indicates which type of the system is more effective. But, it is important to know which zones are to be upgraded first to obtain the maximum benefit.

To find the order of the zones for system replacement an external Multi Objective Optimization technique was adopted. This optimization technique suggests which zones are to be upgraded, and what system would be suitable for the zone based on the relative benefit values. The Multi-Objective Optimization considers the relative benefit of the system replacement and the total budget constraints. After knowing the zones to be replaced from the optimization technique, the Degree of Detachment was calculated for various solutions. This Degree of Detachment is a measure of adjacency for each zone with respect to other zones. It determines how relatively close the zones to be upgraded are. This is important since the system upgrades are usually done in the zones which are more adjacent rather than picking the random zones which are far apart.

After finding the zones to be upgraded the total cost, benefit and Degree of detachment values are estimated for each corresponding solution. And the output of optimization solution is integrated back to GIS, to graphically represent which zones are selected under each solution. A Pareto front was plotted representing the degree of detachment, the total cost and the total benefit value. The solution which is most optimal is selected from this graph and represented in the GIS.
The migration plan presented in this thesis is flexible enough to be applied elsewhere. In order to enhance the flexibility of the migration plan certain guidelines were established which help in selection of the functional requirements under various traffic conditions. These guidelines were developed considering the intersection type, geometry and the physical location of the intersection. A thorough literature review of various signal system operations was conducted for developing these guidelines. These guidelines are expected to help the users in carefully evaluating the functional requirements during the selection process. In order to further extend the flexibility of the method a Graphic User Interface (GUI) was developed in GIS using Arc Objects. This GUI helps the users to easily perform the above motioned tasks without significant knowledge of GIS.

5.2 CONCLUSIONS AND RECOMMENDATIONS

This thesis has presented a methodology for developing an optimal migration plan, for traffic signal controllers using the GIS and MCDM frame work. The use of MCDM has been extensive in various fields, but its usage in the field of signal system infrastructure is very rare. A method for evaluating various alternative systems based on some critical factors was presented. This opens the door for further research by applying the techniques of this method for other problems in the field of Signal System Operation. The scoring criteria presented in this thesis were developed considered only the feature of the controllers. But, in reality these features in each of the controllers might perform differently. So a method can be developed where the scores are assigned not just based on the manuals, but by actually testing each of the features of the controllers through simulation, or field testing, and assigning the scores based on the obtained results. In addition to that, the functional requirements presented were developed based on the general signal system operations. These functional requirements can further be enhanced, or new requirements can be introduced based on the technical advancements.

The GIS framework presented in this thesis, has an advantage of being flexible enough to be applied in any migration plan of existing signal controllers. The limitation of the framework is that it does not consider the external cost of system replacement such as installation cost, management cost or transportation cost of the old systems. So the methodology can further be enhanced, by considering ways to incorporate the implicit cost of the system replacement. Apart from that that, the GIS framework alone can further be improved so that it contains a better Graphic User Interface. In addition, new methods can be found, so that the optimization process takes place inside the GIS frame work itself.
REFERENCES


30. ESRI, ArcGIS 9.3, Editor.


