A GIS-based Multi-Objective Optimization Tool for the Development of the Migration Plan for Next-Generation Controllers

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ABSTRACT

Decisions about upgrade of traffic signal equipment are often made relying on the experience of the senior traffic engineers. Analysis often bases on conventional techniques such as before-after analysis, pilot studies, etc. Factors considered are the deployment time of the system, new technology available, and the performance of the system in the area under purview. Previous research has not defined guidelines or methods for developing a plan for the system replacement decision on a large scale. In addition, previous projects have not considered space and time for deployment of new signal control equipment. This paper presents methodology and a tool for large-scale signal-controllers migration plan. Methodology bases on the functional requirements of the next generation signal-control system. A tool is developed in Geographic Information System (GIS) environment. Upgrade plan is defined on a zone level and bases on optimizing budget constraints, control benefits and spatial distribution of equipment replacement. The entire evaluation methodology for the migration plan was demonstrated on signal control system of Northern Region of Virginia Department of Transportation.

INTRODUCTION

Traffic signals are considered as one of the vital control elements of the modern traffic management systems, directly affecting transportation networks parameters of mobility, safety, and environment. Today, there are more than 0.27 million traffic signals installed in the United States [1]. Some of the Departments of Transportation (DOTs) today are responsible for traffic signal control systems having over 1000 signalized intersections. Frequently, these vast signal control systems have obsolete and aging technology. Systems in this situation have an essential requirement for upgrade to the next generation of signal control system.

Previously, DOTs nationwide have developed plans for upgrade without defined set of guidelines for system replacement decision [2, 3]. System improvement plans were based on conventional techniques, and when the growth or change in traffic demand become evident indication for the improvement need [4]. Some agencies adopt the before and after studies using simulation to evaluate the benefits of system upgrade. In some cases, 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. Some of the previous projects [5, 6] dealing with developing plans for future signal systems had no clear recommendations or detailed upgrade plan developed. Frequently, transition to next generation signal system is per intersection – in the case of existing equipment failure or with the introduction of new traffic signal.

The upgrade of signal control system can rarely be instantaneous. The reasons for this are such as:

- Wide spatial area under purview,
- Direct impact of upgrade process on transportation users safety and mobility,
- Time required for installation and integration of the equipment
- Budget constraints and federal funding opportunities
- Agency’s work schedule and availability of resources
- Requirement for adjusted operations while in transition period

As empirically noted by some agencies, maintenance staff, even while working in full capacity, can rarely install more than 200 signalized intersections per year [3]. In addition, the upgrade to new signal controllers has potential for simultaneous upgrade of other infrastructure (such as communication, detection, lanterns, mast arms, etc.) and potential for signal retiming.

The research presented here is focusing on developing a methodology and a tool for large-scale upgrade to a next-generation signal-control system. The methodology and tool are developed for the needs of the Northern Region Operations (NRO) of the Virginia Department of Transportation (VDOT). NRO wanted to determine when/if the existing system should be replaced or retrofitted to a certain extent. In order to incorporate different economical, operational and installation constraints, there is a need to develop a strategic migration plan that would indicate the spatial location and time schedule for the upgrade. Since no previous research had dealt with such a migration plan, there is a need for developing a comprehensive but flexible methodology and a tool for finding an optimal migration plan for NRO next-generation signal-control system.

Geospatial information in signal control systems

Transportation agencies are facing with constant increase of the information scope to support effective decision making related to traffic signal infrastructure. Furthermore, wide economic and environmental development problems require sharing of data and agency cooperation at all levels [7]. Since traffic signal infrastructure can have a wide spatial range, information on temporal and spatial relationships is one of the critical steps in the decision-making process. In addition, there is an intuitive cognitive power of agency traffic engineers related to the spatial component of signal infrastructure. Geographic Information System (GIS) is recognized as a technique that can significantly enhance the development of the optimal migration plan. GIS can fulfill an essential requirement for manipulating spatial data in different forms and obtaining information related to spatial and temporal components of the system.

According to its definition, GIS integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information [8]. The early benefits of GIS were obtained from its ability to store, retrieve analyze and display spatial information. GIS is used for spatial analysis, spatial modeling and spatial statistics for visualization, data management and geographical modeling in different infrastructure management issues [9]. In the area of transportation, GIS has applications on planning, design, construction, operations and management level. Applications of GIS are in regional transportation planning [10], signal control [11], site impact analysis [12], real-time visualization [13], determination of infrastructure needs and utility management [14-18], crash analysis [19] and transit surveying [20]. These research cases have proven GIS as a powerful tool for data representation and analysis in transportation applications.

FRAMEWORK AND METHODOLOGY

Conventional approaches to upgrade of signal control equipment mainly base on expert knowledge of agency's traffic engineers. The main factor in these decisions was equipment's field deployment time. This has usually limited the information scope and level of details in analysis. However, developing a large-scale migration plan needs to include several framework constraints:

1. Budget, funding, and resources constraints
2. Numerical form of information regarding signal controllers
3. Spatial distribution of local information on traffic demand, patterns and users
4. Spatial distribution of upgrade process

The development of strategic migration plan bases on the goal of having exact points in time and spatial location for each intersection upgrade. Developed framework is intended to be flexible to compare performance of system in different conditions, incorporating local information and expert knowledge from the area under purview. In order to develop an effective migration plan, it is most important to know the existing system functional capability. The decision on the most suitable future system directly relates to the functional requirements (FR) for the next generation system. This framework assumes the availability of extensive database on controller performance. From the information on the controller's features and FR for future system, an evaluation criteria can be developed. Using that criteria and Multi-Criteria Decision Making techniques [21], analyst can obtain numerical score of controller functional capability. That score is defined by the term "Performance Index" (PI), and is used to calculate the difference between existing and alternate systems capabilities.

The migration plan framework allows several hierarchical levels. Level can be per intersection, per group of intersections (zone), or for the whole system. Having a specific hierarchical level has different advantages and disadvantages, related to analysis scale. Hierarchical level recommended by this research is a zone level. The reasoning for this is twofold, integrating reasons from installation and operations perspective (Figure 1). The grouping in zones allows a certain level of aggregation for easier process of upgrade. On the other side, this hierarchical level is still having significant level of flexibility for determining different functional requirements and levels of importance per zone. Intersections in a zone usually belong to the same corridor, have similar traffic characteristics and functional requirements for future system operation. For example, some intersections are already grouped in their operation and are simultaneously optimized using some commercial optimization software. In addition, some intersections belong to same maintenance plans and sectors. These intersections will be probably upgraded as a group, thus simplifying the workload during migration process. Empirical information from signal control experts should be included in the process of intersection grouping. A general recommendation is that groups of intersections should not exceed a number of 50 intersections.

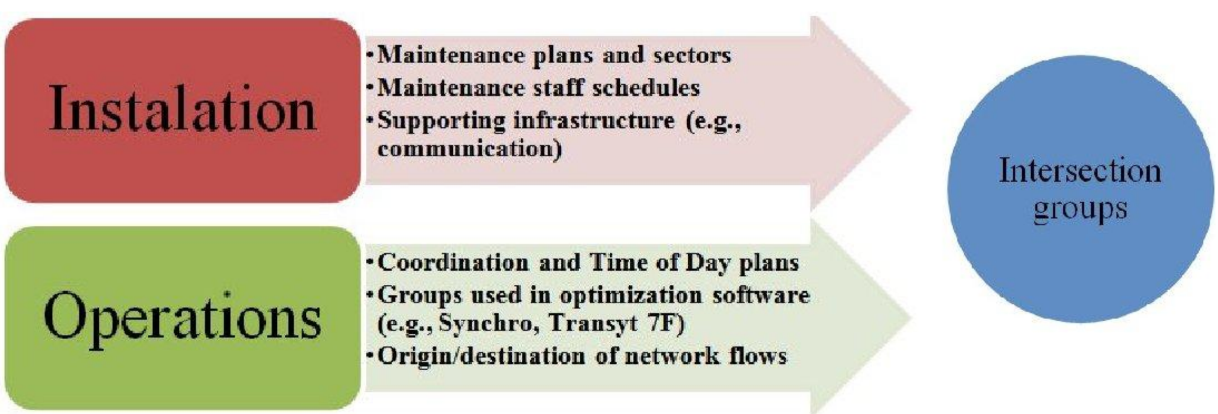

Figure 1: Criteria for grouping of intersections

Methodology

Considering the framework guidance and constraints, the initial step in the methodology is to determine zone for each intersection (Figure 2). The classification of intersections into zones for upgrade should later become the attribute information of GIS model, with every intersection having a zone ID assigned to it. All the controllers belonging to a particular zone would in this case have the same unique zone ID.

After the initial step, decision maker needs to determine functional requirements of each intersection. This would consequently lead to PI for all the alternative controllers potentially implemented on that location. A higher level of decision information is available in the case FRs are assigned to each intersection. This should consequently result in a closer system operation to the desired one. However, FR can be developed on an aggregated scale, for a corridor or even for the whole system. Developed geospatial methodology is flexible to incorporate different levels of FR aggregation. The distinction between different intersections, corridors or zones is obtainable using a separate weight factor that is determining relative importance of one FR category over the others. These weights should be assigned based on the knowledge and experience of DOT traffic engineers and considering the local factors.

Assuming that each intersection has its own FR, PI is calculated as a score for each intersection for each alternative controller. Each of the alternative controller scores is named as PI1, PI2, PI3, etc. After this, the benefit values are calculated for each intersection and for each alternative, represented as PI1_PI, PI2_PI, PI3_PI etc. The benefit values are the difference in performance of the existing system (PI0) and the new alternate system (PIk), represented as Benefit = (PIk-PI), where k is the alternate system considered.

After calculating the PI at each intersection, analyst needs to create the actual zones of intersections using GIS tools. By creating zones, the PI values of all the intersections in a zone are summed to get the total PI in that zone. In addition to that, the benefit of replacement of alternative systems is also calculated for the whole zone. At the final and the most important step, the analyst determines the zones to be upgraded first. This is done using an external multi-objective optimization tool. Finally, different migration plans obtained after optimization are displayed using GIS tools. All the solutions are presented to agency’s traffic engineers and decision makers that are responsible for final decision. This approach allows the consideration of specific knowledge of agency’s experts.

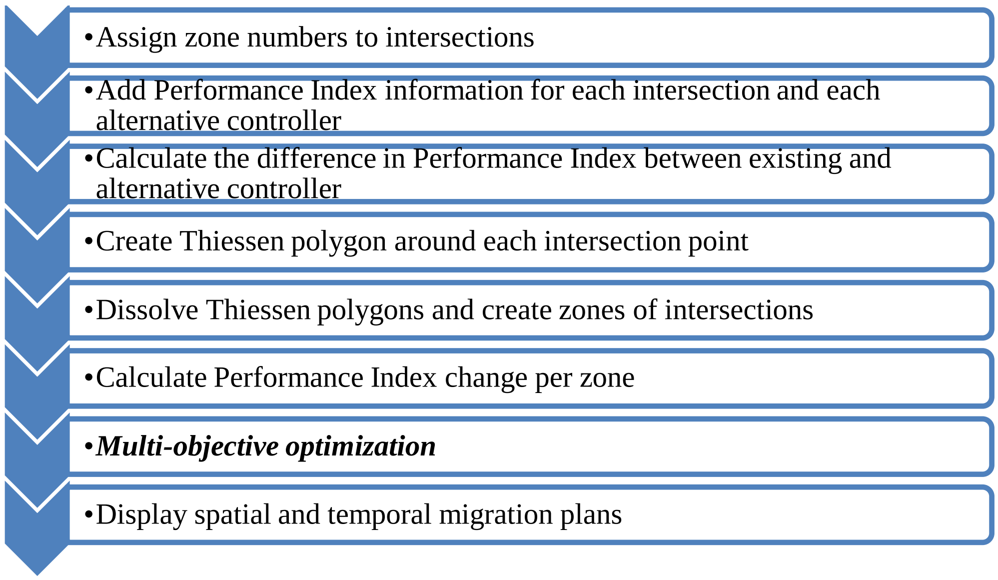

Figure 2: Initial methodology steps of geospatial analysis

Multi-objective optimization

Optimization formulations can be Linear programming, Integer programming, Multi-objective programming, etc. [22]. The problems can be linear or non-linear, having single or multiple objectives [23]. There are many optimization techniques available, generally classified into conventional and nonconventional optimization techniques. The conventional technique includes the Iterative Mathematical search while the Non-Conventional techniques include Heuristic search method, Genetic algorithm (GA), Tabu search (TS), Simulated annealing (SA), etc. Presented optimization tool used for developing migration plan uses GA for finding the optimal solution. This optimization uses Multi-objective, obtaining many solutions and representing them as Pareto-optimal solutions. Initial optimization objective for the problem is assumed as maximizing the benefit values and minimizing the budget. However, the optimization objective has been expanded considering the spatial distribution of zones for upgrade. Mathematical formulation of the optimization problem is presented bellow.

Objectives:

Maximize the Benefit value

$$\mathbf{Max} \sum_{\mathbf{i=0}}^{\mathbf{n}} (\mathbf{B_0} * \mathbf{Z_0} + \mathbf{B_1} * \mathbf{Z_1} + \dots\dots\dots\dots + \mathbf{B_n} * \mathbf{Z_n})$$

Minimize the Total budget

$$\mathbf{Min}\sum_{\mathbf{i=0}}^{\mathbf{n}}(\mathbf{N_0} * \mathbf{C_0} * \mathbf{Z_0} + \mathbf{N_1} * \mathbf{C_1} * \mathbf{Z_1} + \ \dots\dots\dots\dots + \ \mathbf{N_n} * \mathbf{C_n} * \mathbf{Z_n})$$

Where

B_i = Benefit of Zone *i* which is calculated as PI*i* – PI

Z_i = Design Variables with the binary value

N_i = Number of controllers in Zone *i*

C_i = Cost of upgrading controller *i*

In the above equations, the first objective function is aiming to maximize the summation of benefit values. The second objective function is aiming to minimize the total cost related with installation of the equipment. The decision variable Z_i is the output variable, indicating which zones are to be upgraded based on the objective functions.

In addition to two objective functions, the optimization formulation is expanded using the Degree of Detachment. The Degree of Detachment (DOD) was initially developed for optimization of traffic-responsive signal control [24]. In this research, DOD is used as a performance measure of upgrade continuity in the migration plan. DOD is a measure of adjacency of each zone with respect to other zones determined for upgrade. It determines how relatively close the zones for upgrade are. The importance of DOD is the desire to improve the upgrade process in relation to space, by upgrading adjacent zones rather than picking the random zones that might be far apart. The assumption is that reducing random upgrade of zones can lower the overall migration plan costs. For each given solution, optimization obtains a DOD value. The lower DOD value indicates that greater numbers of zones are adjacent to each other, while the higher value indicates that the zones are more scattered in space.

Optimization output consists of various zone combinations at a specific point in time. Each corresponding solution consists of a set of zones that are determined for upgrade in one migration step. The total cost, total benefit and the DOD of zones for upgrade are obtained. From this information we can obtain a Pareto-front, indicating 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. After the upgrade of specified zones in the first migration step, the optimization can be iteratively run, determining the zones selected for next migration step. Finally, an analyst obtains the migration plan for the next generation of signal control system at different temporal points.

Tool description

All the data used in the analysis are represented as layers in ArcGIS [25]. Layers needed for the analysis should be previously organized with ArcCatalog, a module of ArcGIS. The actual migration plan is developed in ArcMap, another module of ArcGIS. Performance Index values are the part of GIS layer of signalized intersections. Macro command actions and Graphic User Interface (GUI) command buttons are developed for the implementation of the optimization process. The tool was developed using Visual Basic for Applications (VBA) inbuilt in ArcMap. GUI is presented on the Figure 3 bellow. GUI buttons are ordered from up to down in the order they are used in the process as:

1. **“Database to CSV**” – used to convert the GIS database file to comma-separated value (.csv) file
2. **“Batch File” –** used to run the optimization batch file
3. **“DOD”** – used to create an additional column in the attributes of the zone polygon calculating the adjacent zone ID for each corresponding zone
4. **“Join Output”** – used to join the output from the optimization tool back to GIS database

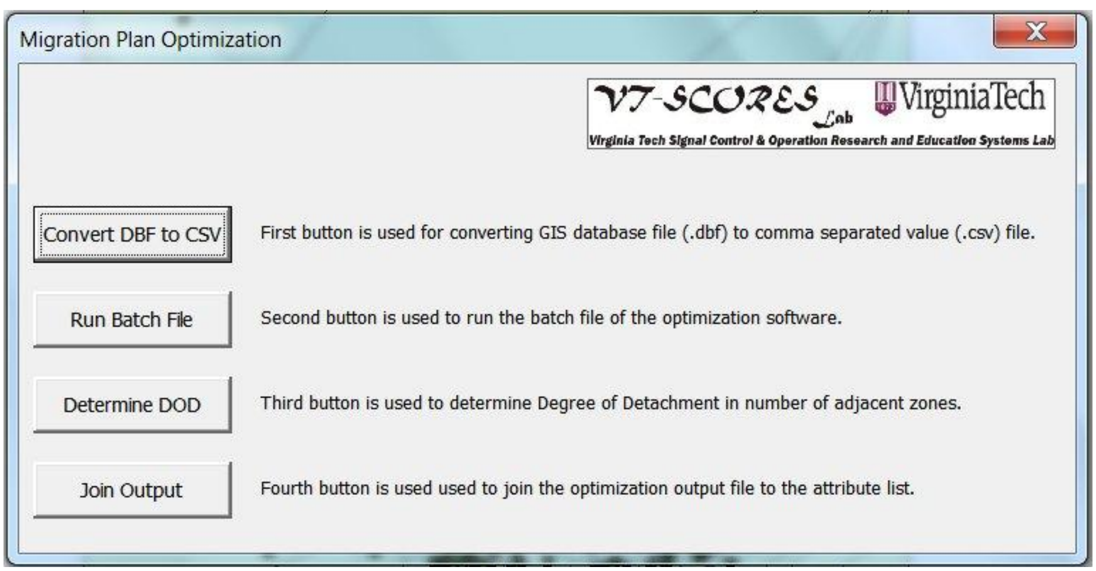

Figure 3: VBA form used for migration plan optimization

DEVELOPMENT OF MIGRATION PLAN FOR VDOT

Existing signal system of Northern Region Operations

The NRO of VDOT operates and maintains more than half the traffic signals under VDOT's purview. Northern Region includes the counties of Fairfax, Loudoun, Prince William, King George, Spotsylvania, and Stafford (Figure 4). Northern Region VDOT currently owns and maintains around 1560 traffic signals, 136 flashers, 14 intersection control beacons, 24 lane control signals, 5 emergency/fire signals, and 27 auxiliary control devices.

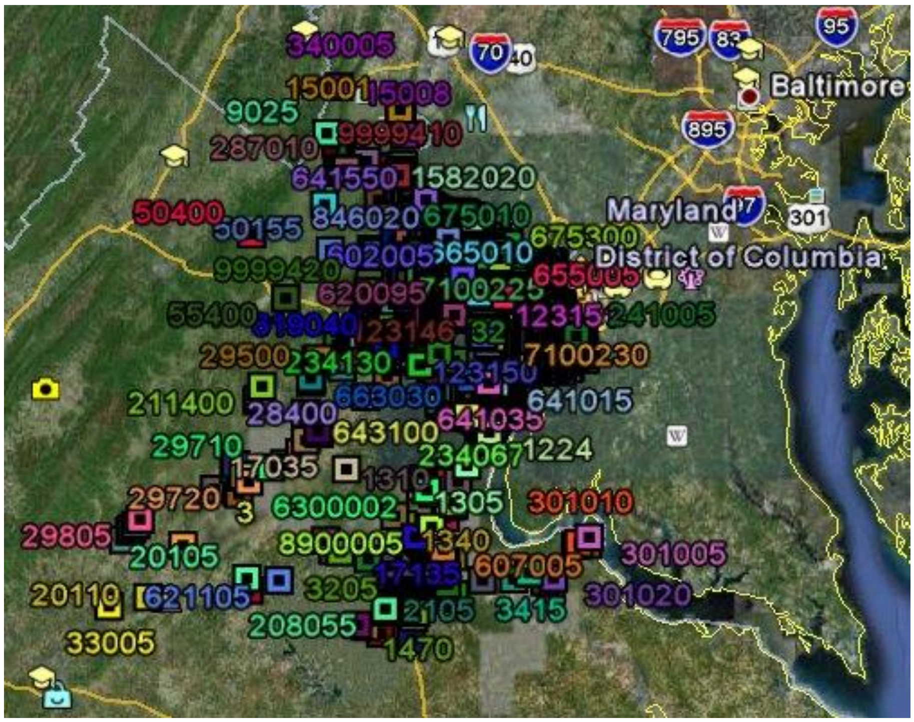

Figure 4: Spatial distribution of NRO signalized intersections

In the majority of Northern Region, signal system consists of McCain Signal Supply 170E controllers having 233 signal control software and OS9 operating system. Fredericksburg district operates with Eagle NEMA TS-1 controllers. Existing system of traffic controllers represents a significant maintenance investment and is certainly a critical component of the region's operations infrastructure. This system was deployed 12 years ago, with most of that infrastructure reaching the limit of its operational effectiveness and capabilities based on changing traffic patterns and volumes in the region.

The issues that NRO has with existing controller equipment are:

- Small number of phases
- Pedestrian overlaps operation
- Transit Signal Priority operation
- Signal Preemption operation

- Transition methods in Coordinated mode

In order to meet the future demand and implement advanced features of signal systems (such as the transit priority, special pedestrian options, etc.) NRO needed to decide on the phased upgrade approach regarding field equipment and controller software. NRO based this decision on the long-term decision on their next-generation system and its calculated PI values.

Geospatial database and initial analysis

Starting geospatial layer used in migration plan development is point Controller_Layer. The attributes of this point layer are OBJETID, SIGNL_NBR, PRIM_NM, SCND_NM, TYPE, and OPR (Figure 5):

- OBJECTID is an identification number assigned by VDOT, numbering a point in the layer.
- SGNL_NBR is identification number for a signal, assigned by VDOT.
- PRIM_NM and SCND_NM are names of intersection streets.
- TYPE determines the type of signal – if it is a signal, flasher or ramp metering point.
- OPR contains if signal is (Y) or is not operational (N). Some of the initial attributes (e.g., PRIM_NM and SCND_NM) are not used.

Attributes of trafficsignalsFeb2010

FID	Shape	OBJECTID	SGNL_NBR	PRIM_NM	SCND_NM	TYPE	OPR
0	Point	1	613076	BEULAH ST	SERVICE RD/WILS RD	SIGNAL	Y
5	Point	6	703015	SHREVE RD E/B	BIKE TRAIL W&OD S	SIGN FLASHER	Y
6	Point	7	703010	SHREVE RD W/B	BIKE TRAIL W&OD N	SIGN FLASHER	Y
11	Point	12	688005	LAKE JACKSON	LIBERIA AVE	SIGNAL	Y
44	Point	51	7100180	FAIRFAX CO PKWY	RUGBY RD	SIGNAL	Y
50	Point	71	7700050	FAIR LAKES PKWY	FAIRLAKES BLVD.	SIGNAL	Y
104	Point	598	7100100	FAIRFAX CO PKWY	DULLES TOLL RD NORTH/ WEST RAMP	SIGNAL	Y
108	Point	1093	15052	JAMES MADISON HWY	DOMINION VALLEY DR/GRADUATION DR	SIGNAL	Y
109	Point	1254	677010	OLD COURTHOUSE RD	HOWARDS AVE	SIGNAL	N
111	Point	530	4701010	COLTS NECK DR	SOUTH LAKES	SIGNAL	Y
118	Point	354	7100120	FAIRFAX CO PKWY	FOX MILL RD	SIGNAL	Y
136	Point	1282	1231	JEFFERSON DAVIS HWY	POSSUM POINT FLASHER	SIGN FLASHER	Y
142	Point	1035	29118	LEE HWY	HEATHCOTE BLVD	SIGNAL	Y
145	Point	79	674015	HUNTERMILL RD	SUNRISE VALLEY DR	SIGNAL	Y
149	Point	227	602045	RESTON PKWY	SUNSET HILLS RD	SIGNAL	Y

Figure 5: Attributes of NRO traffic signal database

Decision to include a point in the layer depends on the TYPE and OPR attribute of the traffic signal database. The point is included if the TYPE attribute field value is SIGNAL and if OPR attribute field value is Y. Zone ID attribute is added to controller layer, defining the zone to which controller belongs. This zoning has been based on the input from traffic engineers in NRO, grouping the intersections based on the maintenance and operations plans. Zones having intersections in the coordinated system have assigned ID number starting from 1. In addition, zones having signalized intersections operating in Free operation mode have assigned ID numbers starting from 1001. NRO intersection points grouped by assigned ID are presented the following Figure 6.

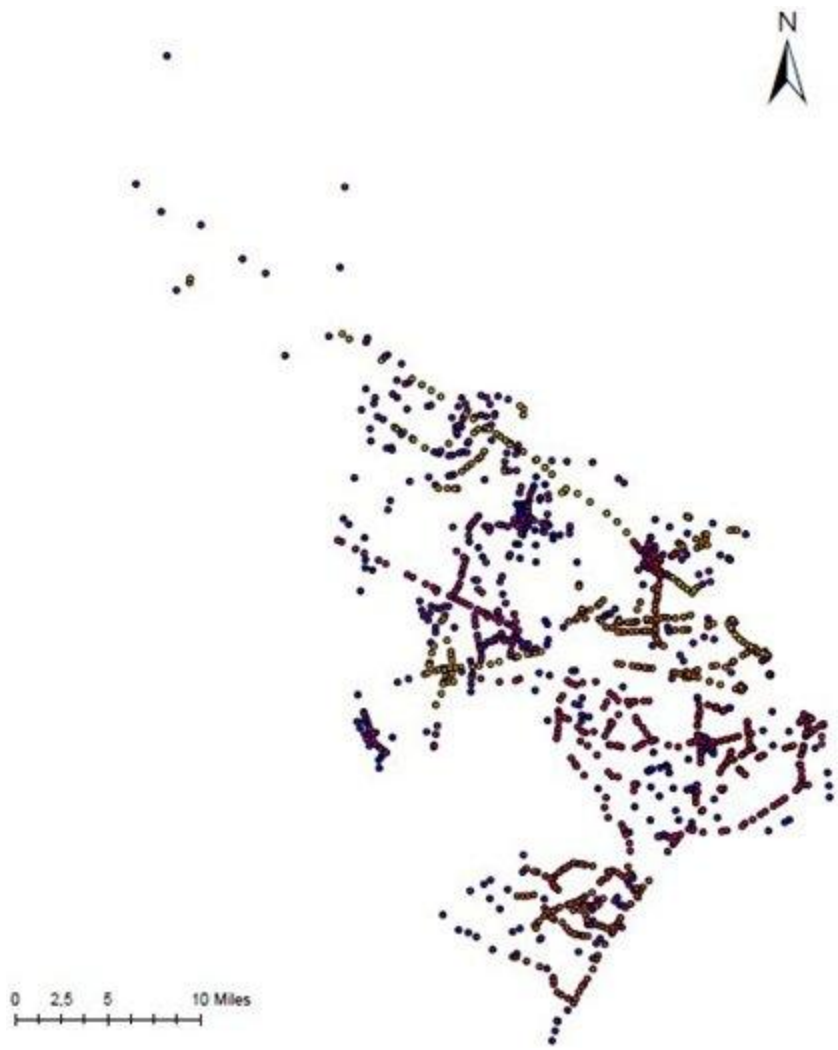

Figure 6: Intersections under NRO purview grouped for spatial analysis

Performance Index is an input for each intersection and for each alternative. The PI values are added as attribute to GIS database. The difference (PI_Diff) between PI value for the existing controller (PI_In) and for alternative controllers (PI_Alt) is calculated for each intersection, and added as another attribute of the GIS database. Intersection point layer is converted into polygon zone layer, thus enabling the analysis on the level of zone. This is done using Thiessen polygon tool, that created a polygon around each point, and Dissolve tool, that merged all the polygons having the same zone ID. In this process, each PI value of each intersection is added to the PI value for each alternative for a respective zone. Obtained controller zones are presented on the following Figure 7. The next step is external multi-objective optimization.

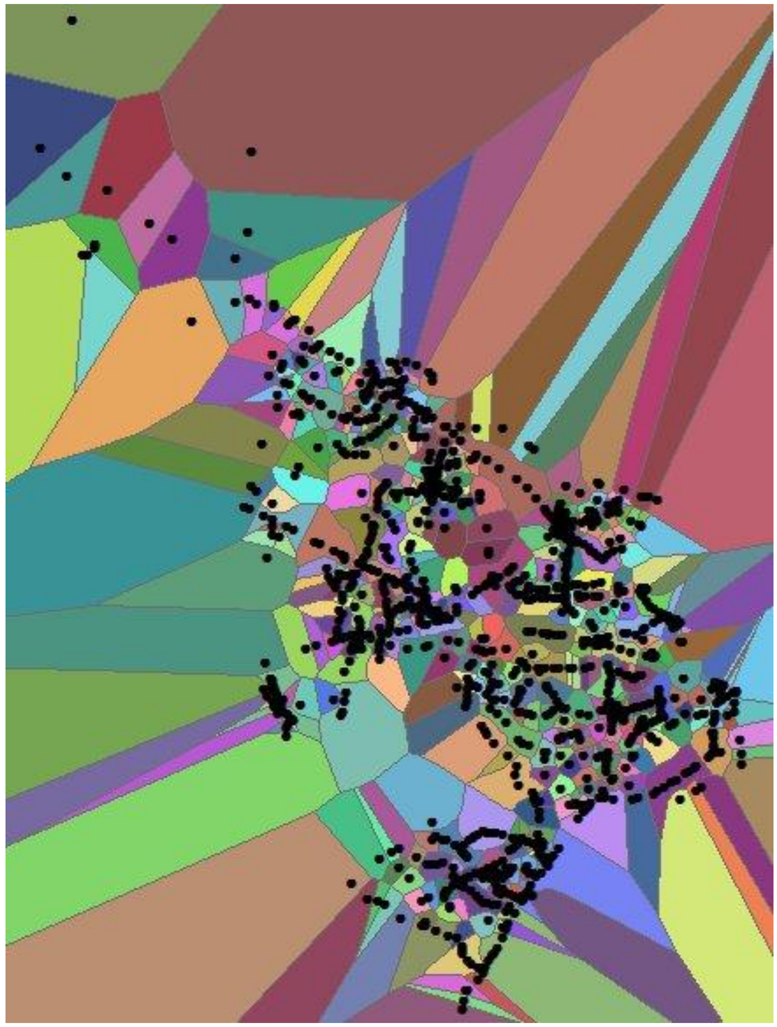

Figure 7: Controller zones in NRO

Migration plan optimization

The multi-level optimization uses the VBA macro based on GIS objects. Initially, the tool coverts the zones database into .csv file, in order to batch run the calculations for benefits and costs. After that, the optimization tool obtains DOD for all the zones and creates a final optimization output. All the GIS analysis and optimization is done on the zone layer. The attributes of zone layer are presented on the Figure 8, where we can see summation of PI values for initial and alternative system, which indicate the the benefit obtained by replacing the alternate systems. In addition to that, the value of DOD, expressed as number of adjacent zones, is the last attribute of this layer. The PI values are aggregated on the zone level, representing the total benefit value in each zone.

Attributes of Zones

Shape	ZONE_ID	SUM_PI_In	SUM_PI_Alt	SUM_Count	adj_zones
Polygon	142	150	264	3	ZONE_ID: 3,6,146,175,177,178,206,463,464,487,488, Total: 11
Polygon	143	550	968	11	ZONE_ID: 126,127,131,132,137,138,145,146,152,448,473,484, Total: 12
Polygon	144	200	352	4	ZONE_ID: 135,136,146,151,153,484,486, Total: 7
Polygon	145	150	264	3	ZONE_ID: 146,151, Total: 2
Polygon	146	200	352	4	ZONE_ID: 15,127,133,134,142,438,473, Total: 7
Polygon	147	1200	2112	24	ZONE_ID: 141,142,143,144,147,148,149,151,152,153,463,464,466,469,470,472,475,476,478,479,4
Polygon	148	150	264	3	ZONE_ID: 146,149,466,481,485, Total: 5
Polygon	149	150	264	3	ZONE_ID: 4,146,149,474,475,488, Total: 6
Polygon	150	450	792	9	ZONE_ID: 4,146,147,148,150,465,466,467,468,475,481,483, Total: 12
Polygon	151	150	264	3	ZONE_ID: 3,4,149,480,482,483, Total: 6
Polygon	152	50	88	1	ZONE_ID: 143,144,146,153, Total: 4
Polygon	153	100	176	2	ZONE_ID: 142,146,448,471,472, Total: 5
Polygon	154	50	88	1	ZONE_ID: 135,143,146,151,464, Total: 5
Polygon	1001	50	88	1	ZONE_ID: 0,38,155, Total: 3
Polygon	1002	50	88	1	ZONE_ID: 0,38,154,156,159,304,308, Total: 7
Polygon	1003	50	88	1	ZONE_ID: 0,155,157,159, Total: 4
Polygon	1004	50	88	1	ZONE_ID: 0,156,159, Total: 3
Polygon	1005	50	88	1	ZONE_ID: 0,38,287,292,307, Total: 5
Polygon	1006	200	352	4	ZONE_ID: 0,122,155,156,157,308,381, Total: 7

Figure 8: Attributes table of Zones layer

The optimization provides a total benefit, total cost and DOD values that create Pareto front, as on the Figure 9. Pareto front provides all the possible optimal solutions. Each solution is a combination of different zones determined for upgrade. Pareto front shows better migration plans as having lower DOD, lower Total Cost, and higher Total Benefit. The optimal solution selected should give the maximum benefit based on the DOD and the total budget available. Here the cost of upgrading, relates only to the controller replacement cost and do not consider external cost such as user costs, installation labor cost, etc.

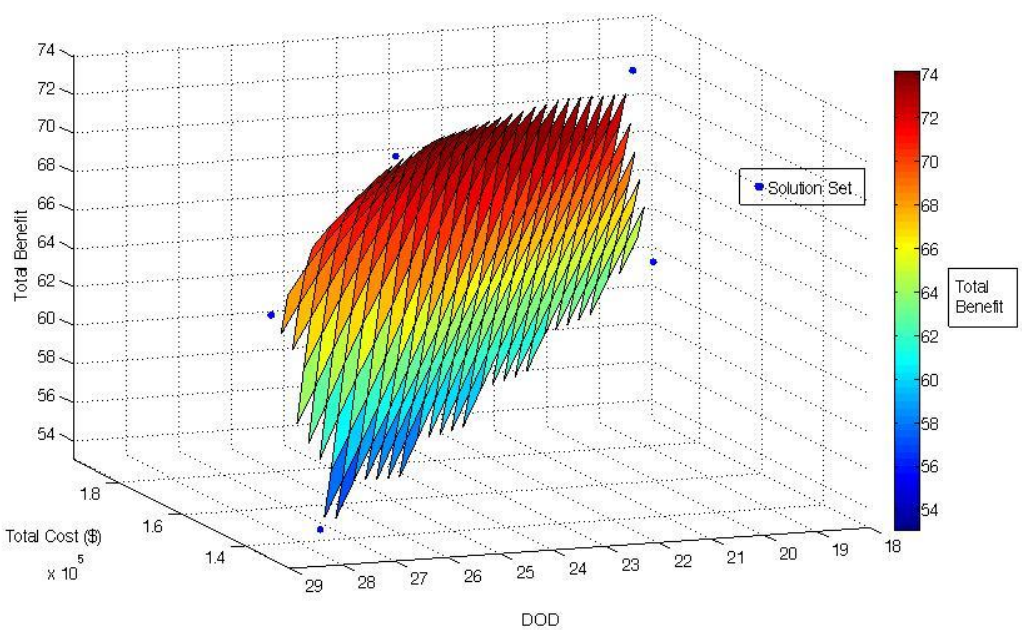

Figure 9: Representation of Pareto front for migration plan

Figure 10 bellow shows the representation of one of the solutions. In the zone layer properties, value of zero indicates that the zone is not to be upgraded at that point in time, and zones having value one will be upgraded at that point in time. The spatial representation can be shown for every solution in numerous time points. Consequently, zones selected for upgrade at one point in time are excluded from the next iteration. At this point, the expert opinion of agency's traffic engineers is consulted for final decision. Traffic engineers are those that have to consider the variability of spatial migration plan based on the benefits, costs and spatial distribution of upgraded zones. In addition, they could redefine the functional requirements. The framework, methodology and developed tool are framed in such a way to provide flexibility for obtaining migration plans in different temporal points.

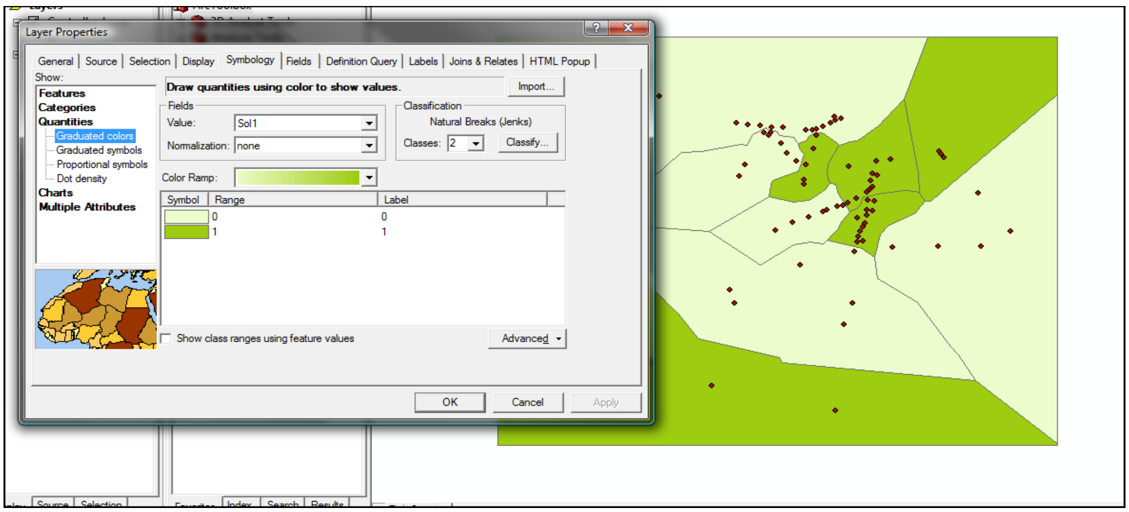

Figure 10: Representation of solution

CONCLUSION

This paper presents a groundwork methodology and a tool for developing the optimal migration plan for upgrade of traffic signal controllers. Previous upgrade projects were without defined set of guidelines for system replacement decision. The decision-making was mainly based on conventional techniques such as before-after analysis, pilot studies, etc. Factors considered in previous projects were the deployment time of the system, new technology available, and the performance of the system in the area under purview. Previous research has not focused on developing a long-term migration plan for large-scale signal-control systems.

The developed decision-making framework considers several spatial, temporal, organizational, and financial constraints. The methodology is including functional requirements for future signal control system and information on existing and alternate traffic signal controller capabilities. GIS is used as the environment for implementing the analysis and developing the tool for migration plan. GIS is introducing a major difference by significantly enhancing decision-making process through analyzing spatial data. The decision level for migration plan is zone of intersections, defined by installation and operational constraints. GIS was integrated with external multi-objective optimization tool, aiming to obtain benefit, cost, and spatial distribution of zones for upgrade. Total benefit, total cost and DOD create a Pareto front of optimal migration plans. GIS mapping capabilities are used for displaying the optimal migration plan. The important feature of developed methodology and tool is its flexibility to provide migration plan in different temporal points and potentially for any signal control area under analysis.

Presented methodology can be further enhanced by improving the optimization technique. The present method is limited by the cost function, which considers only the cost of system replacement costs. No external costs were considered, so further enhancements could be introducing user and additional installation costs. In addition, asset management features during and after the process of upgrade can potentially be incorporated into the developed GIS tool.

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