Adaptive Traffic Control Systems: Guidelines for Development of Functional Requirements

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Abstract

Despite Adaptive Traffic Control Systems (ATCS) as highly sophisticated systems are frequently delivered in a manner of a “black box”, with little additional information available. This lack of transparency impairs effective decision-making for selecting and installing the future ATCS. Consequently, ATCS installation can sometimes lead to increased operation costs, lack of evident benefits, and even a shutdown of the system. This complex situation makes apparent the need for improved and analytically-based decision-making in selecting the optimal ATCS for procurement. In the case this was a single criterion problem, decision-making would be intuitive. Considering that there are several alternative ATCS, multiple criteria (e.g., multiple ATCS features), preference dependence, etc., there is a need for more sophisticated evaluation methods. However, ATCS selection is semi-structured decision problem, which cannot be solved by classic mathematical models. As a result, decision-making primarily relies on human intuition. In addition, one has to remember that engineers and technicians within transportation agency have extensive expert knowledge about features and operation of their existing traffic signal system. This dispersed knowledge base has a potential for effective integration and organization into a decision-support system (DSS). Such DSS could facilitate effective decision-making of transportation agencies during the procurement process for ATCS. This paper suggest the use of multi-attribute decision making (MADM) for developing a DSS for ATCS selection. MADM approach and techniques could enable a coherent ordering of alternative ATCS. A framework for DSS development bases on Analytic Hierarchy Process. In order to develop an effective DSS based on AHP, this paper first focuses on comparative lessons learned from potential advantages and issues accompanying ATCS procurement, installation, and operation worldwide. Furthermore, the paper presents a set of recommendations for development of functional requirements and establishment of a MADM-based DSS. Finally, the paper concludes with potential lessons, relevant to transportation agencies worldwide.

Introduction

Transportation agencies, especially those with a large number of urban signalized intersections under their purview, are constantly facing issues with changing traffic demand and patterns. This often leads to a growing number of signalized intersections installations. In addition to increase in the size of the traffic control systems, there is an evident need for advanced operational capabilities. However, the conventional fixed-time control systems are

not capable to respond to all the modern operational requirements. As a solution for the mature control technology, transportation agencies sometimes revert to installation of Adaptive Traffic Control Systems (ATCS). The ATCS are the last generation of traffic signal systems [1]. Basic premise behind ATCS operation are continuous and small adjustments of signal-timing parameters in response to changing traffic demand and patterns. Typical ATCS bases on the highly developed control algorithms, traffic model, different detector configuration, and centralized or decentralized architecture.
ATCS are usually implemented for network of signalized intersections. The ATCS are usually implemented to improve network control efficiency, reduce congestion, enhance incident responsiveness, and reduce signal-retiming costs. In general, ATCS are excellent in handling undersaturated and unpredictable traffic conditions by dealing with cycle length, split, offset, and phase sequence adjustment [2]. However, ATCS frequently have issues in dealing with some traffic control users (e.g., emergency vehicles, pedestrians, etc.) [3].
Although most of ATCS started as a research/academic projects, today, most of them are sold as final products, developed by different companies [2]. Currently, there is a multitude of ATCS available on the market, installed in various network environments and for various reasons, while having various operational effects. ATCS worldwide have many operational similarities but also many differences. ATCS, as integrated software and hardware systems, are usually vendor specific and delivered in the manner of “a black box”, due to the proprietary in-built modelling and optimization algorithms [4]. The lack of transparency impairs effective decision-making for selecting and installing the future ATCS. Consequently, ATCS installation can sometimes lead to increased operation costs, lack of evident benefits, and even a shutdown of the system.
All of the above are reasons why transportation agencies worldwide are facing the need for additional information about these systems before the procurement process. During the procurement stage, some of the main questions transportation agencies are facing are:
1. Is there the need for ATCS installation?
2. Where should ATCS installation be?
3. What ATCS should be installed?
4. How will the system be installed and operated?

The agencies frequently do not consider all of these questions in-depth. The objective of this paper is to aid the decision-making process for selecting and installing ATCS worldwide. Considering that previous research focused primarily on describing control algorithms, or individual evaluation of ATCS, the intention of this research was improving agency’s decision-making for ATCS selection.

Summary lessons from ATCS installations worldwide

In order to improve the decision-making process, and have a successful ATCS implementation, transportation agency needs first information about ATCS features. The most well-known ATCS worldwide are:

- Split Cycle Offset Optimization Technique (SCOOT) [5-10]
- The Sydney Coordinated Adaptive Traffic System (SCATS) [10-17]
- The Urban Traffic Optimization by Integrated Automation (UTOPIA)/System for Priority and Optimization of Traffic (SPOT) [11, 18]
- Balancing Adaptive Network Control Method (BALANCE) [19, 20]
- Method for the Optimization of Traffic Signals in Online-Controlled Networks (MOTION) [21, 22]
- Real Time Hierarchical Optimized Distributed Effective System (RHODES) [23-25]
- Optimized Policies for Adaptive Control (OPAC) [10, 26-31]
- Los Angeles Adaptive Traffic Control System (LA-ATCS) [4, 13]

In addition, a common traffic control systems is ACS Lite, which was initiated by the Federal Highway Administration (FHWA) with an idea to create a system for automatic monitoring and adjusting of traffic signal operational parameters but with smaller investment costs than traditional adaptive systems in the United States [32, 33]. In addition to literature review, previous research by the authors [34] has used surveys and interviews to investigate associated costs, hardware compatibility, experiences in operation, installation and operations costs per intersection and compatible controllers. Important point to understand is that ATCS can result in benefits but also in disadvantages. Some of the positive aspects of ATCS are:

- Effective dealing with changes in traffic conditions
- Short system response time to fluctuating demand
- Large traffic data stored
- Efficient dealing with special effects
- Spillback on Interstate reduced

Some of the negative aspects are:

- Black box – difficult to understand operation
- Lot of maintenance and operational effort to maintain system in the optimal performance
- Steep learning curve
- Lack of support
- Initial set-up time and costs

Lessons learned from all the previous and current implementations can be categorized as:

- The need for better support from local vendor,
- The need for better planning for in-house support,
- Good assessment of existing infrastructure (detection and communication), and

Detailed pre-installation functional requirements and evaluation is necessary for estimation of costs and benefits.

The following Table 2 shows compiled information related to the ATCS under analysis. Presented information is on system architecture, traffic signal controller compatibility, detector location, Public Transport Priority features, communication requirements, congestion management features, additional features, installation costs per intersection and installation locations.
Most of the modern ATCS are decentralized, and even originally centralized systems (e.g., SCOOT, LA-ATCS) are nowadays having higher degree of control logic on the intersection level. In addition, there are always certain levels of network decomposition and intersection grouping in each ATCS. It is notable that different ATCS have different levels of optimization, using reactive and/or predicting algorithms. These algorithms directly relate to ATCS adaptability to site-specific problems. Controller comparability of different ATCS ranges from only one controller type up to the open controller interface. Most of the ATCS use upstream and stop bar detectors. Most of ATCS have features for Public Transport vehicles priority. Usually, ATCS have significant communication requirements with local intersections, especially in the case of centralized systems. Very rarely, ATCS have established congestion management or advanced features that go beyond coordinated network signal control. Except SCOOT and SCATS, other ATCS are very rarely present on several continents.
Information on ATCS is usually dependent on the vendor itself and partially available in existing research. The usual comparison of ATCS in previous literature is on case-by-case basis, having a small comparison scale and before-after analysis [4, 12, 18, 19, 26, 35-44]. Previous research is mainly comparing up to three ATCS, with the focus of comparison on ATCS control algorithms. The usual evaluation is through comparison with fix-time or actuated control. Evaluation is done using pilot field studies, hardware-in-the-loop, or software-in-the-loop simulation, comparing usually smaller networks with different

characteristics and different levels of traffic demand. Frequently, comparison is limited to only experience from one country and even one urban area.

ATCS	System Architecture	Compatible controllers	Detector location	PTP	Comm. requirements	Congestion management	Additional features	Average Cost ($)/inter-section	Location of installation
SCOOT	Centralized	Siemens, Peek, Craig Gardner	50 - 300 m upstream	YES	High	YES	Traffic Information Database, Integrated Incident Detection	50k	Worldwide
SCATS	Two level decentralized	Siemens, Econolite, Naztec, McCain, Aldridge, Tyco, Quick Turn Circuits	Stop bar with sporadic upstream	YES	Low	YES	Special control for pedestrians and bikes	60k	Worldwide
RHODES	Three level decentralized	Siemens, Econolite	30 - 50 m upstream	YES	Medium	NO	None	45k	USA
OPAC	Three level decentralized	Siemens, McCain, Peek, Econolite	130 - 200 m upstream, stop bar	YES	Medium	NO	None	68k	USA, Canada
LA-ATCS	Centralized	LA DOT	65 to 100 m upstream	NO	High	YES	Critical Intersection Control, Critical Link Control	N/A	Los Angeles only
ACS Lite	Decentralized	Siemens, Econolite, McCain and Peek	Stop bar, 80 - 170 m upstream	NO	Medium	NO	None	40k	USA
UTOPIA/ SPOT	Two level decentralized	SignalbauHuber, Swarco, Siemens, La Semaforica	Exit lane detectors	YES	Medium	NO	Special Public Transport module	N/A	Europe, USA
BALANCE	Three level decentralized	Open interface	Stop bar	YES	Medium	NO	Event Manager	N/A	Europe
MOTION	Three level decentralized	Siemens	10 - 50 and 50 - 200 m upstream	YES	Medium	YES	Incident management	N/A	Europe, Asia

Table 2: ATCS technical information matrix.

Potential advantages

The reasons for introducing ATCS can vary significantly, with different potential benefits. The advantages that transportation agency might have after installation of ATCS are:

- Utilization of advanced optimization and modelling algorithms for improved network control.
- Effectiveness in dealing with changes in traffic conditions, responding to fluctuating demand in a short time.
- Effectiveness in dealing with special events.
- Effectiveness in reducing spillback on the freeway.
- Availability of large amounts of real time performance measurements, along with capabilities to create numerous reports.
- Capability of storing large amounts of traffic data.
- Visualization of network condition.
- Integration with Traffic Management Centre software.
- Capability of handling short-term communication or detector failure.

- Capability to delay the start or shorten the period of congestion.
- Capability to provide priority for Public Transport vehicles.

Potential issues

Alongside with potential benefits, all of the agencies having ATCS installation had some issues. The potential issues that transportation agencies might have with their ATCS installation are:

- Benefits dependent on the type and quality of operation of the system before ATCS.
- Lack of benefits for networks with predictable or oversaturated conditions.
- No special consideration for pedestrian or bike operation.
- Long initial setup time (calibration of optimization and modelling parameters) can go even beyond 18 months.
- Vendor specifications not completely open and documented, with accompanying controller equipment and communication interfaces frequently being tied to one vendor.
- Steep learning curve because of difficulties to explain the operation.
- Lack of support after installation.
- High installation requirements for detector and communication equipment.
- Higher maintenance and operational costs for maintaining system in the optimal performance.
- Lack of agency's resources to handle the system properly.
- System installation cost of over €45,000 per junction in average.

Decision-Support System

Considering that ATCS are highly sophisticated systems, which can result in both benefits and disadvantages, as well as complex to install and operate, agency's decision-making is significantly impaired. This is the reason there is a need for improved and analytically-based decision-making in selecting the optimal ATCS for procurement. In the case this was a single criterion problem, decision-making would be intuitive [45]. Considering that there are several alternative ATCS, multiple criteria (e.g., multiple ATCS features), preference dependence, etc., there is a need for more sophisticated evaluation methods. However, ATCS selection is semi-structured decision problem, which cannot be solved by classic mathematical models. As a result, decision-making primarily relies on human intuition. In addition, one has to remember that engineers and technicians within transportation agency have extensive expert knowledge about features and operation of their existing traffic signal system. This dispersed knowledge base has a potential for effective integration and organization into a decision-support system (DSS). Such DSS could facilitate effective decision-making of transportation agencies during the procurement process for ATCS. DSS have been used previously for equipment selection [46-48].
Considering that expert knowledge of DOT's traffic engineers is very valuable in this decision-making process, DSS should incorporate expert knowledge acquisition component [49]. In addition, DSS is developed for flexible collecting and analyzing the expert knowledge. DSS should allow agency's decision-makers to perform a "what-if" alternative analysis, include any preferences not initially expressed into the decision process, and have supporting graphical representation for improved decision-making. DSS-ATCS consists of knowledge, model, data, and dialog management. In addition, DSS-ATCS has relations with external data, and system user. A conceptual model for DSS-ATCS is presented in the following Figure 1.

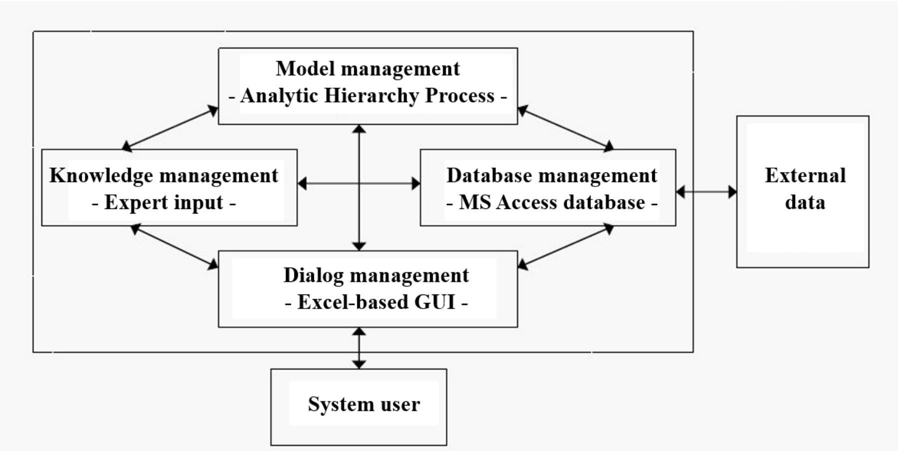

Figure 1: Conceptual DSS model

This paper suggest the use of multi-attribute decision making (MADM) for developing a DSS for ATCS selection. MADM approach and techniques could enable a coherent ordering of alternative ATCS. There are many MADM techniques implemented in practice (e.g., Simple Additive Weighting, ELECTRE, TOPSIS, PROMETHEE). Considering the evaluation procedure and the emphasis for using each technique, this research propose a use of Analytical Hierarchy Process (AHP) technique [50]. AHP was developed to model subjective decision-making processes based on multiple attributes in a hierarchical system, and structures process as a hierarchical decomposition, reducing complex problems into sub-problems [51]. AHP procedure has five steps, which will be described in the context of DSS-ATCS:

1) Establish decision context, and decompose a problem into an interrelated hierarchy of goal, criteria, sub-criteria, and alternatives.
2) Collect data from the experts or decision-makers, as a pairwise qualitative comparison of criteria to create reciprocal matrix.
3) Organize pairwise criteria comparison into a square quantitative matrix.
4) Evaluate matrix consistency.
5) Multiply the weights of the criteria with the score for each attribute and then aggregate to obtain local ratings with respect to each criterion, that are finally aggregated to obtain global ratings.

Considering that AHP is the core element of the DSS, first step described above requires special attention due to the direct connection to expert knowledge acquisition process. Considering that the goal is selecting an optimal ATCS, and alternatives are different ATCS, decision-making criteria are the main component missing for establishing the decision context. In order for the agency to obtain highest benefits for lowest investments possible from ATCS installation, it is of essential importance to establish the right criteria.

Functional Requirements

Taking into consideration that each transport agency will have its specific context for its traffic control system, decision-making criteria will have to be developed on a case-by-case basis. The set of decision-making criteria should be based upon technical requirements developed for future ATCS. Those technical requirements originate from the functional requirements for operation of a signal control system in general [52]. Following this line of action, as in Figure 2, transportation agency needs to develop functional requirements, then technical requirements, followed by decision-making criteria for ATCS evaluation.

Figure 2: The process of decision-making information development.

In order to develop functional requirements, transportation agency needs to consider all the information on ATCS operation, their disadvantages and potential benefits. ATCS advantages, such as, utilization of advanced optimization and modelling algorithms, effectiveness in dealing with changes in traffic conditions, capability to provide real-time reports and visualization of network conditions, should be considered. On the other hand, issues such as predictable or frequent oversaturation network conditions, no special consideration of pedestrian or bicycle flows, or step learning and calibration curve, are also influencing development of functional requirements. In addition to this, information on agency current and future ITS components are influencing functional requirements development. In addition, functional requirements have to incorporate high-level and long-term plans for signal control system, along with other Intelligent Transportation System subsystems.
The recommendations for groups of functional requirements, considering all the potential factors, are:

- The size of signal control system

The number of signalized junctions is one of the main information to consider for ATCS functional requirement. Relatively small signal control systems, with fewer than 50 signalized junctions, rarely need the investment in ATCS installation. Similar operational effects, instead of ATCS installation, can be achieved with conventional and well-coordinated actuated control, with retiming of signals every two to three years.

- Network configuration

In addition to the number of signalized junctions, network configuration itself plays a significant role in deciding for or against ATCS installation. Short and equally spaced junctions on a grid network or large number of isolated junctions would probably not be the best case for installation of ATCS. The ideal network configuration would be a combination of grid and arterial networks, especially outside of highly congested central-business-district area.

- Variability of traffic demand

Installing ATCS on a network that has predictable traffic demand could not prove as beneficial, since all the advantages of adaptive modelling and optimization algorithms might not be used at all. In the case of predictable traffic demand, fixed time systems could operate perfectly well, without additional costs involved with ATCS.

- General phase features

General traffic operation features should be available in all the ATCS operation modes. Functional requirements of general traffic operations should include the number of phases, phase overlap, phase conditional service, left turn and queue detection options available under ATCS operation. These features frequently depend on the relation of controllers and ATCS itself.

- Coordination features

Cycle length and offset settings and optimization, along with available transitioning algorithms are usually the main requirements for operational features related to coordinated operation. These are the key functional requirements to be defined for large networks, usually over 100 junctions. Grouping of intersections in corridor or network zones is also one of the potential issues for coordinated operation, and distances between potential border intersections have to be considered.

- Signal pre-emption and priority for public transport vehicles

Options for recovery from priority, such as exit phase selection, priority and pre-emption along arterials, and Light Rail Vehicle priority are the usual requirements to consider in the future ATCS. Most of the modern ATCS have these options, but the level of development is different. This is the reason transportation agency needs to firmly define the requirements for special vehicle operation.

- Pedestrians and Bikes

Most of the systems do not have special options for control of these user's flows. However, functional requirements regarding these special user types should be related to pedestrian phase re-service, walk time extension, and possibility for special bike timing options. These requirements are very important in parts of network with highly urbanized business-residential areas.

- Operation modes

Some agencies need expanded capability of ATCS, in a manner of several operation modes, for planned or unplanned special events. These modes can range from Coordinated, Isolated, Manual, Emergency, to Special control. Agency needs to define this need based on the list of special events and their operational requirements.

- Controllers compatibility

One of the very important functional requirements is compatibility of ATCS with existing signal controller infrastructure. In addition to this is the general compatibility with controller on the market. ATCS are usually tied to operate only on restricted number of controllers, and this can be a limiting factor for ATCS installation.

- Transportation Management Software compatibility

In the case ATCS is installed simultaneously or as an addendum to a Transportation Management Software in a control centre, the compatibility of these two ITS components needs to be considered as a functional requirement. Frequently, interface between these two can be a limiting factor for full-scale ATCS operation.

- Reports and Data Archiving

ATCS usually have higher number of reports available, partially due to the large data archiving capabilities. However, functional requirements should include a detailed real-time reports and potential for improved utilization of archived data for optimization/modelling purposes. Visualization capabilities of ATCS should be considered in the functional requirements.

- Communication infrastructure requirements

Scope of the communication infrastructure requirements depends on the requirements for data exchange that a particular ATCS has and the existing infrastructure that already exists as a support to a signal control system. Installation of communication infrastructure for support of ATCS control can be a significant investment so transportation agency needs to be aware of all the network capabilities, in relation to space.

- Interface with simulation software

Some of the ATCS have it readily established with simulation software such as VISSIM, AIMSUN, and PARAMICS. Interface with simulation software should be considered as one of the requirements, since this can provide easy way for pre-installation and post-installation evaluation. Simulation software can be used to test the ATCS before the actual implementation, or calibrate some of the control parameters.

- Accessibility and security capabilities

Frequently different organizational units inside of transportation agency can have different levels of access to ATCS. Majority of signal control engineers can have access to visualization or reports levels, but very few can actually change the optimization parameters or modes of operation. Functional requirements should include additional accessibility and security capabilities, such as different password-protected levels for different user input control.

- Advanced Features

Finally, some ATCS can have advanced features, in addition to essential adaptive signal control. Those features could relate to oversaturation or incidence situations, or involve special interface with public transportation fleet management. Transportation agency needs to determine which from these features are important for current or future installations.

Conclusion

Market ATCS are currently delivered by multiple vendors, with a multitude of features. In addition, ATCS frequently have uncertain benefits, due to the uncertain adaptability to site-specific problems and quality of operation of the system before ATCS [4]. This research has aimed to improve the knowledgebase on features and experiences in operation of ATCS, and consequently aiding decision-making for ATCS selection.

Considering their features and potential pros and cons, we can conclude that ATCS are not almighty systems that can be blindly purchased to solve traffic congestion. ATCS are not systems that are implementable always and everywhere. No matter how advanced and adaptive their capabilities are, ATCS still need human supervision. ATCSs as complex systems, heavily rely upon human factor, thus requiring adequate additional training, and a deeper understating of operation concepts and features, to achieve desired results. ATCS can be a great solution if implemented at the right place in the right way, especially when integrated with other ITS subsystems, such as parking management, traveller information, Public Transport fleet management, tunnel management, etc. This is the reason transportation agencies need a thorough evaluation of potential benefits and costs for their local network conditions.

It is important to emphasize that ATCS, as highly complex systems, need careful planning and evaluation before the actual process of selection and installation. This process is actually important since ATCS installation might result in additional and frequently hard to estimate costs. In order to successfully complete the evaluation process, transportation agency’s personnel needs better understanding of ATCS features operation along with the understanding of the traffic control system under their purview. Potential advantages and issues with ATCS features, along with features of the existing ITS components, should be used to create Functional requirements for ATCS selection. Focused on this issue, here are presented potential functional requirements for improved decision-making in selection of future ATCS. Presented functional requirements are aiming to help agencies question their decisions on installation. In addition, these functional requirements are recommendations for development of customized functional requirements for evaluating different ATCS at specific urban areas.

An important recommendation is that transportation agency needs to approach conservatively the decision for procurement of ATCS, considering their pros and cons. For improved evaluation and development of functional requirements, agency itself needs a wide scale involvement of staff operating in different ITS areas. Better planning for in-house support is an essential component for decision-making on future ATCS. This is especially important for adequate preparations of detection and communication infrastructure supporting ATCS installation. Finally, decision-making can be further improved by continuing development of a robust DSS model for ATCS selection and installation.

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