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# AN ASSET MANAGEMENT FRAMEWORK FOR RAMP METERING SYSTEMS AND ADAPTIVE TRAFFIC CONTROL SYSTEMS

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Transportation systems management and operations (TSM&O) strategies such as adaptive traffic control systems (ATCSs) and ramp metering systems (RMSs) can be utilized to exploit existing transporting capacity instead of undertaking costly new construction projects. This paper presents an asset management framework for TSM&O components used in ATCSs and RMSs including signal heads, controllers, detectors, supporting structures, and communication lines to support the decision making processes of transportation agencies. ATCS and RMS overall condition ratings and importance indices are the two parameters that contribute to prioritization of these TSM&O applications. A fuzzy logic approach is used to combine these two major components. Inspection guidelines and published cost databases are primary data sources, while economic (agency), social (traveler), and environmental benefits that would be lost in case of failures are considered in developing procedures to determine the importance indices. This asset management framework allows transportation agencies to identify ATCS and RMS deployments with high risk considering both the condition levels and benefits provided by these deployments, and hence constitutes a highly important step towards development of risk management and mitigation plans featuring appropriate maintenance, repair and rehabilitation (MRR) strategies. Future research can integrate additional TSM&O components into the asset management framework, and the boundary of benefits considered in determining the importance indices can be expanded.

*Keywords*: Condition evaluation, Importance assessment, Fuzzy logic, Risk management, Maintenance, TSM&O.

## 1 INTRODUCTION

In recent years, congestion has become a severe problem due to aging transportation infrastructure systems and surging traffic demands. The 2013 Report Card for American Infrastructure has classified 42% of the main arterial roads in the United States as congested (ASCE 2013). The use of proper Transportation System Management and Operation (TSM&O) alternatives can achieve the goal of optimization by improving the performance of the overloaded transportation systems, which helps transportation agencies maximize the value of existing infrastructure without having to find solutions for congestion through new construction.

An adaptive traffic control system (ATCS) has the capability of adjusting and updating traffic signal timing in an automatic manner to smooth the traffic (Selinger and Schmidt 2010), while ramp metering systems (RMS) reduce freeway congestion by limiting the number of vehicles that enter the freeway from the ramp sections. Signal heads, signal controllers, inductive loop detectors, supporting structures and communication lines are among major physical facilities that constitute both systems. Inductive loop detectors, supporting structures and communication lines are essential components of ramp meters. Signal controllers assign the right-of-way based on a selected algorithm, and can work in isolation or in coordination with other controllers. Inductive loop detectors are used to collect various traffic parameters such as volume, occupancy, and speed. Communication lines establish the links between field controllers and master controllers or traffic management centers (Gordon and Tighe 2005).

The most recent National Intelligent Transportation System deployment survey (Gordon and Trombly 2014) showed that agencies nationwide have adopted different levels of inspection and maintenance, repair, and replacement (M, R&R) practices for TSM&O components. It was concluded that among all the motives to take remedial actions on TSM&O components, response to failure was the most dominant, followed by inspection and monitoring of conditions, hard-time maintenance, and obsolescence in the descending order of influence. It was also concluded that agencies deploying ITS technology generally report cost as the most important consideration (Gordon and Trombly 2014). These findings indicate that a higher level of emphasis should be placed on development of a comprehensive framework to support agencies' decision making procedures regarding TSM&O system components.

In 2013, the American Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) published Transportation Asset Management Guide: A Focus on Implementation as a high-level instructional guideline to assist agencies in establishing holistic asset management systems. Federal Highway Administration also developed Guidelines for the Installation, Inspection, Maintenance and Repair of Structural Supports for Highway Signs, Luminaires, and Traffic Signals, but it was intended for the mechanical fixtures of TSM&O components, and there were no other TSM&O system components (loop detectors, ramp meters, etc.) included in existing asset management guidelines. This research takes an initiative to bridge this gap through establishing a risk-based asset management framework taking into consideration the triple bottom line (TBL) of sustainability.

## 2 CONDITION EVALUATION

Condition data constitutes a critical component of an infrastructure management system for any type of infrastructure network. In addition, electronic and communication facilities, which account for a major portion of TSM&O components, usually require the inventorying of their identification and location data (e.g., owner, street address, longitude, and latitude, etc.), construction data (e.g. construction number, type and date, cable-material type, etc.), and cost and usage history data (e.g. total/annual construction cost, M, R&R cost, etc.) (Uddin *et al*. 2013). Due to the differences between TSM&O components and traditional transportation assets (e.g., pavements and bridges) that have relatively long service lives, state departments of transportation (DOTs) follow less detailed approaches while recording conditions for TSM&O components. Therefore, a condition rating system is proposed as in Table 1 based on inspection and maintenance guidelines (BMTS 2012, MnDOT 2015, Klein 2006). The overall condition of the ATCS at a given intersection or the RMS at a given ramp is determined by the lowest condition score recorded among all TSM&O components. This rule is established under the assumption that failure of any single TSM&O component will result in malfunction of the ATCS at an intersection or the RMS at an on-ramp.

Table 1. Condition rating scores for TSM&O components (BMTS 2012, MnDOT 2015, Klein 2006).

| | Signal Heads | Controller | Loop Detector | Communication Line | Supporting Structure |
|---|---|---|---|---|---|
| Score | Descriptions | | | | |
| 10 | No deficiency | No deficiency | No deficiency | No deficiency | No deficiency |
| 9 | Backplates & visors slightly damaged, | Missing manuals or booklets | Minor cracks or deformation away from detector area | Mislabeling or disorderly arranged | Non-structural element minor deterioration |
| 8 | Backplates &visors moderately damaged | Timing slightly incompliant | Major cracks or deformation away from detector area | Insufficient slack cable in cabinet or bases | Structural element minor deterioration |
| 7 | Slight dimming | Minor damage to cabinet. Timing slightly incompliant | Minor cracks or deformation at detector area | Improper splice (out of cabinet or bases) | Structural element minor deterioration. Minor deformation |
| 6 | Slight dimming or slightly loose mounting | Minor damage to cabinet, Timing moderately incompliant | Major cracks or deformation at detector area | Slight Contamination | Structural element moderate deterioration. Loose connection or joints |
| 5 | Moderate dimming or partial failure | Minor damage to cabinet. Timing moderately incompliant | Exposed detector with slightly loose splice | Moderate contamination or slightly loose connection | Structural element moderate deterioration. Residual water Moderate deformation |
| 4 | Moderate dimming; partial failure; exposed wiring; slightly loose mounting | Moderate damage to cabinet. Timing moderately incompliant, | Exposed detector with slightly loose splice and damaged sealant | Severe contamination, loose connection | Structural element moderate deterioration. Missing non-structural elements |
| 3 | Severe dimming or partial failure or damaged lenses | Moderate damage to cabinet. Timing severely incompliant Some auxiliary devices not working | Exposed wires away from vehicle damage, loose splice | Damaged coating, loose connection | Structural element severe deterioration. Moderate deformation |
| 2 | Severe dimming or partial failure, Backplates, visors, & lenses damaged | Moderate damage to cabinet. Timing severely incompliant. Poorly bolted. | Exposed wires subject to direct vehicle damage, loose splice | Damaged or contaminated cable; resistance test failure | Structural element severe deterioration. Functional performance compromised |
| 1 | Dysfunctional | Severe damage to cabinet. Controllers dysfunctional | Broken wires or splice failure | Broken cable or connection failure | Structure close to collapse |

## 3 IMPORTANCE ASSESSMENT

In addition to the condition rating system, an evaluation system that indicates the consequences of failure is also essential in measuring the overall risk of system failure. Based on the observed economic, social, and environmental benefits of ATCSs and RMSs, ratings that capture the importance of both system deployments are shown in Tables 2 and 3, respectively.

For ATCS deployments, equal weights among all five indicators are assumed unless practitioners have preferences otherwise. For RMS deployments, the on-ramp delay is considered as a negative impact and a coefficient of 0.2 can be used to reflect the differing priorities between the freeway and on-ramp sections unless practitioners have preferences otherwise (Peng and Beimborn 2000).

Table 2. Rating Criteria to Assess the Importance of ATCS Deployments (Liu 2013, Chandra 2012, Smith *et al.* 2012, Utpal *et al.* 2010, Banerjee 2001, Skabardonis 2001, Sussman 2000, Greenough and Kelman 1999).

| **Performance Indicators** | **Importance Ratings**<br>1 | <br>2 | <br>3 | <br>4 |
|---|---|---|---|---|
| Intersection Speed Increase | Low<br>(< 6%) | Fair<br>(6~15%) | Moderate<br>(15~25%) | High<br>(>25%) |
| Peak hour Volume/Capacity Ratio | Low<br>(< 0.25) | Fair<br>(0.25 – 0.5) | Moderate<br>(0.5 – 0.75) | High<br>(> 0.75) |
| Reduction in Number of Stops | Low<br>(< 23%) | Fair<br>(23~29%) | Moderate<br>(29~36%) | High<br>(>36%) |
| Reduction in Number of Accidents | Low<br>(< 20%) | Fair<br>(20~27%) | Moderate<br>(27~30%) | High<br>(>30%) |
| Reduction in Delay and Waiting Time | Low<br>(< 19%) | Fair<br>(19~25%) | Moderate<br>(25~41%) | High<br>(>41%) |

Table 3. Rating Criteria to Assess the Importance of RMS Deployments (Diakaki *et al.* 2000, Peng and Beimborn 2000, Cambridge Systematics 2001, Hourdakis and Michalopoulos 2002, Kansas City Scout Program 2011, Shah *et al.* 2013).

| **Ramp Metering System Indicators** | **Importance Ratings**<br>1 | <br>2 | <br>3 | <br>4 |
|---|---|---|---|---|
| Level of Deployment | Simple | Optimized | Extended | Corridor |
| Freeway Traffic Throughput Increase | Low<br>(< 6%) | Fair<br>(6~10%) | Moderate<br>(10~18%) | High<br>(> 18%) |
| Freeway Speed Increase | Low<br>(<10%) | Fair<br>(10~15%) | Moderate<br>(15~25%) | High<br>(>25%) |
| Reduction of Accidents on Freeway | Low<br>(<20%) | Fair<br>(20~26%) | Moderate<br>(26~38%) | High<br>(>38%) |
| Average On-ramp Delay (minutes) | Low<br>(<0.5) | Fair<br>(0.5~2) | Moderate<br>(2~3.5) | High<br>(>3.5) |

## 4 RISK-BASED PRIORITIZATION TOOL

With the system condition and importance ratings identified, a risk-based prioritization tool covering both likelihood and consequence of system failure is developed to qualitatively describe the level of risk for certain ATCS and RMS deployments. Because the evaluation of condition status and the importance index involves subjectivity and ambiguity, utilization of fuzzy logic is proposed in this research. Fuzzy logic was developed by Zadeh (1965) and has been used widely in processes that involve ambiguity, subjectivity, or uncertainty. Fuzzy subsets for the overall condition status and their boundaries are: Critical [1, 1, 2, 4], Poor [2, 4, 6], Fair [4, 6, 8], and Good [6, 8, 8, 10], which apply to both ATCS and RMS deployments. Fuzzy subsets for the importance rating of ATCS deployments and their boundaries are: Low [5, 5, 7, 9], Fair [7, 9, 11, 13], Moderate [11, 13, 16, 18], High [16, 18, 20, 20]. Fuzzy subsets for the importance rating of RMS deployments and their boundaries are: Low [3.2, 3.2, 4.4, 6.6], Fair [4.4, 6.6, 8.4, 10.4], Moderate [8.4, 10.4, 12.4, 14.4], High [12.4, 14.4, 15.8, 15.8]. Fuzzy subsets for the risk of failure and their boundaries are: Low [0, 0, 1, 3], Moderate [1, 3, 4, 6], High [4, 6, 7, 9], Very High [7, 9, 10, 10]. A total of 16 fuzzy rules were generated shown in Table 4, following the typical form of a risk matrix. It is also assumed that the decision makers place a higher level of importance on the overall condition rating, as it is more relevant to system failures.

Table 4. Risk matrix for ATCS and RMS deployments.

| **Fuzzy Rules** | | **Importance Rating** | | | |
|---|---|---|---|---|---|
| | | Low | Fair | Moderate | High |
| **Condition Rating** | Good | Low | Low | Low | Moderate |
| | Fair | Low | Moderate | Moderate | Moderate |
| | Poor | Moderate | Moderate | High | High |
| | Critical | Moderate | High | Very High | Very High |

## 5 CONCLUSIONS

The proposed risk-based prioritization tool can assist transportation agencies in determining the type of maintenance, repair, and replacement practices that need to be undertaken under different scenarios:

- For overall risk ratings of 0 ~ 2, existing inspections, either annually or semi-annually, should continue with an emphasis on collecting performance data for documentation and condition monitoring purposes.
- For overall risk ratings of 2 ~ 5, inspection intervals may be re-adjusted and causes of deterioration may be identified and closely monitored.
- For overall risk ratings of 5 ~ 8, inspection intervals should be shortened and repair or replacement work should be planned no later than the next routine maintenance.
- For overall risk rating of 8 ~ 10, immediate actions are needed within 48 hours or as specified in manuals, guidelines, or contracts to prevent deployment failure.

Future research efforts may focus on expanding or customizing the condition and importance rating systems, and integrating cost information into the prioritization tool for a comprehensive asset management framework.

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