

**Developing Optimized Maintenance Work Programs for an Urban Roadway Network
using Pavement Management System**

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Abstract

Pavement management systems (PMS) are used by highway agencies to establish best possible network level maintenance and rehabilitation work programs for the road network. PMS also help in establishing the funding levels required to meet agency desired pavement performance or level of service goals. Pavement management involves the identification of optimum maintenance strategies at various management levels. It aims to determine the most efficient maintenance program that yields maximum benefit for the public funds expended. However, the PMS generated maintenance programs can vary significantly based on underlying variables, decision trees, models and overall rationale exercised by pavement management engineers. Producing a network level work program that applies the right treatment at the right time on each network section is central to the success of a pavement management program. Uncertainties and constraints imposed on the maintenance funding levels underscore the need for implementing optimal maintenance programs. Having more accurate knowledge about the funding levels for future years, reliable pavement condition models, and reliable engineering inputs, can help an agency adopt an aggressive and efficient pavement preservation program that will extend the useful life of the pavement network.

This paper evaluates a variety of pavement work program scenarios for an urban road network which typically have large number of routes, most of them short in length and consequently have large number of short management sections in the network. Moreover, engineers need to account for network aberrations like intersections, turning lanes, curbs & gutter and similar features. This paper discusses several network analyses options available for establishing optimized work programs for urban road networks and outlines their individual strengths over other analysis methodologies.

Introduction

The transportation infrastructure is crucial to the socio-economic development for countries around the world. For the better part of the last century, local governments, state and federal highway agencies have invested significant amount of resources to improve mobility within their respective jurisdiction. However, in more recent decades, there is a growing emphasis on the maintenance and rehabilitation (M&R) of the highway infrastructure. Furthermore, there is an increasing interest among highway agencies in implementing pavement management systems for efficient and proactive management of their road networks.

After the economic recession of 2008 in USA, several highway agencies are challenged with budget shortfalls which forced them to operate under extremely limited maintenance funds. This underscores the importance of optimal utilization of the available resources so that the utility earned for M&R expenditure is maximized.

Asset management aims to serve the above mentioned objective through optimal allocation of resources. The concepts of asset management span across different industries and asset categories, including infrastructure assets such as highways, bridges, buildings, among others. A successful asset management program thrives on the identification of the *right treatment for the right asset at the right time*. In the pavement management domain, this would include identifying the optimal M&R work plan based on the prevailing decision variables – the type of treatment, the candidate section, and the timing of treatment.

There is anecdotal evidence suggesting that a dollar spent in preventative maintenance may help saving as much as six dollars spent on reactive maintenance. Therefore, efficient pavement management programs will generally lean towards preventative rather than reactive treatments. Pavement management systems (PMS) have been in existence as early as the 1970s, but over the years they have evolved from a prioritization oriented approach to optimization based analysis programs. Other advantages include the ability to forecast network condition under a variety of what-if scenarios that can include fund constraints, acceptance criteria for the overall network among many others. The end result is more reliable streamlining of M&R decisions.

Pavement management systems have found widespread application among state highway agencies maintaining large networks, comprising of multiple functional classes catering to a range of traffic volumes. However, PMS use in managing urban networks is relatively new as they share characteristics that are different from typical state highway network. These may include intersections, curbs and gutters, turning lanes, bus bays, etc. Furthermore, management sections in case of urban networks are typically much shorter compared to rural networks as their extents are dominated by the length of a block that can vary anywhere between 0.1 km to 0.5 km. Additionally, urban networks typically include facilities that cater to high traffic volumes with relatively low truck traffic percentage. Therefore the challenges encountered in implementation of a PMS system are quite different for an urban versus rural network.

Objective

This study evaluates the implementation of a pavement management system for an urban road network. It evaluates several potential M&R strategies and network analyses approaches and underscore the importance of implementing pavement management systems for optimization of highway M&R funds. A case study of an urban road network is included in this study which supports the inferences drawn in this study.

Background

There are several commercially available PMS products today, of which the AgileAssets Pavement Analyst™ is among the notable ones. In the United States, highway agencies including Caltrans, VDOT, NCDOT, and many others like them have been using the AgileAssets Pavement Analyst™. The following section includes a brief description of the framework adopted in Pavement Analyst™ and highlights the key features for each of the individual analysis methodologies.

The initial step in PMS implementation involves establishing the highway network and the inventory of management sections. Next steps include establishing roadway sections attributes including functional, geometry, structural, traffic, and condition data. Following this, pavement deterioration models are established for pavement performance classes. Agencies can choose desired distress types and their combinations for deterioration models and appropriate models are assigned to the pavement management sections. It will involve specifying the governing deterioration mechanism such as alligator cracking, roughness, etc. and their respective constitutive models that can largely vary between different pavement performance classes. A hierarchical pavement performance class will include a tree structure showing possible combinations of variables chosen to establish pavement performance class, for example: pavement type (asphalt, PCC), functional class (Interstate, Arterial, collector, etc.), urban or rural, traffic volume (high, medium, low) and so on. In the following steps, the system user is required to specify available treatments and their exclusion principles and establish the decision trees which will define the optimal context where the particular treatment applies best. As an example, extensive rehabilitation with thick structural layers can be justified for high volume roads but thin asphalt layers or multi-course surface treatments may be the optimal choice for low volume rural roads. Once the information is entered in the system, the user can determine the maintenance budget necessary to maintain the highway network at a pre-defined condition or alternately, the best possible network condition for the available maintenance budget.

Pavement Analyst™ provides a wide range of optimization approaches for determining the optimized work plan for the network. It is important to note that the recommendation provided by the system can largely vary depending upon the choice of the optimization technique that is employed. At its simplest form, the user may choose to address the maintenance needs of the highway network that is most deficient (also known as “Worst-First” approach). As previously discussed, addressing the repair needs of the most deficient segments of the network will require extensive rehabilitation and hence offer lower utility for the repair funds spent. This drawback is overcome in “Ranking” approach, which uses benefit-cost ratio calculation for each management

section for determining the maintenance work program. In Pavement Analyst™, benefit is identified as the area between the performance curve for a rehabilitated section and that for a “do-nothing” scenario. As a result, the proposed work plan tends to offer higher utility for the maintenance budget compared to analysis procedures that select the candidate projects based solely on the condition scores (Worst-First). However, "Ranking" does not have the option to enter additional constraints which limits its application to real-world scenarios where highway agencies are tasked with catering to multiple network-level condition and costs constraints. The “Multi-Constraint” analysis methodology overcomes the aforementioned limitation by allowing more than one constraint which makes it more robust. It should be noted that each of the above mentioned analysis procedures determine the work plan for individual years in the planning horizon and the network condition is recalculated and carried forward to the subsequent year to determine the candidate projects for the following year. The process is iterated until the work program is developed for the entire planning horizon. The Pavement Analyst™ offers another analysis approach, “Multi-Year”, which relies on determination of the work program for the entire planning horizon by optimizing the most effective maintenance strategy for all the management sections that constitute the network. A maintenance strategy is defined as a work plan for a management section that encompasses all the individual years in the planning horizon. Therefore, in multi-year analysis, the candidate solutions include a list of candidate strategies for each management section and the system will obtain the optimal strategy for every individual section comprising the network.

The Pavement Analyst™ also offers the system user to include existing work plans as part of the network optimization. In the event when the user opts to include an existing work plan, the available budget is first allocated to fund the existing work plan and then it continues analyzing rest of the network. Other features like including or excluding certain portion of the network, incorporation of inflation and discount rates are some of the key functionalities provided in the AgileAssets Pavement Analyst™.

Literature Review

Several studies have been undertaken to highlight the benefits associated with implementation of PMS for optimization of M&R efforts for highway agencies. Sharaf (1993) evaluated three different analysis methodologies to identify what maintenance action to be taken and where and when to apply it so that the most cost-effective results are obtained (1). The first of these included a “Worst-First” approach. The next one included a “Ranking” approach where future benefits associated with a particular treatment was given consideration. And lastly, an “Optimization” technique was considered where both present and future benefits and the overall network condition were examined. Results indicated a considerable improvement in future network condition under each of the three techniques when compared with respect to the current state of practice adopted by the agency. The study highlighted that the “Optimization” technique produced the most cost-effective M&R work program.

In another case study undertaken for the Province of Alberta, Canada, the study team pointed out that the highway agency achieved a 7.9% improvement in road network condition (relative to the previous five years) despite the addition of 7.2% of road surface and an aging system through implementation of PMS. Furthermore, the authors noted that the implementation of PMS resulted in significant reduction of user operating costs and an improvement in the overall network condition (2).

Several studies have focused on the PMS implementation for the State of Arizona to quantify benefits associated with PMS implementations (3, 4). Results showed that the state DOT saved more than \$100 million as a result of PMS implementation for planning their maintenance activities for the Interstate and non-Interstate system over the five year period between 1982 and 1987 (5). The savings achieved were attributed to efficient selection of treatment strategies and objective planning of maintenance schedules.

It has been pointed out in the Pavement Management Guide published by the American Association of State Highway and Transportation Officials (6) that institutional barriers to PMS adoption and use presents significant challenges towards its successful implementation. The successful implementation of PMS helps overcome some of these issues by adding transparency and objectivity in the decision making process.

Therefore, the important conclusions that may be drawn from the foregoing discussion are as follows:

- The implementation of PMS has helped highway agencies in determining work plans that are optimized for the highway network under consideration. There is evidence suggesting that agencies have been successful in achieving significant cost savings through lower life-cycle costs.
- It removes bias due to personal judgment and helps achieve objective work plans that target addressing the department's maintenance needs efficiently.
- Implementation of PMS can help DOTs obtain a structured and rational approach towards M&R plans that abides by the agency's budget and desired parameters.

The implementations of PMS in urban networks pose certain additional challenges as they differ significantly from rural networks. Some of these differences are as follows:

- The most obvious difference is the presence of intersections which are handled separately from pavement management sections. Furthermore, the visual distresses on intersections are significantly different as they are often subjected to shoving and permanent deformation due to the dynamic shear stresses during acceleration and deceleration of vehicle when approaching intersections.
- The available curb height in urban areas dictates the rehabilitation alternatives that can be considered. As a result, extensive surface preparation might be necessary in situations where the curb height is inadequate.
- The lengths of urban sections are typically limited to one city block. Consequently, the number of management sections will be significantly higher compared to a rural network with the same overall length.

- Pavement deterioration is determined by loading rate and many other factors. In case of urban road networks, traffic is typically slower compared to rural freeways and therefore requires extensive rehabilitation in the event of load-related structural deficiency.

Methodology

The study area chosen for his study includes an urban road network that comprises of approximately 4900 kilometers of lane distance. The network comprises of six different functional classes, namely, arterials, collectors, expressways, freeways, industrial roads, and city streets (for more details, please refer to Figure 1).

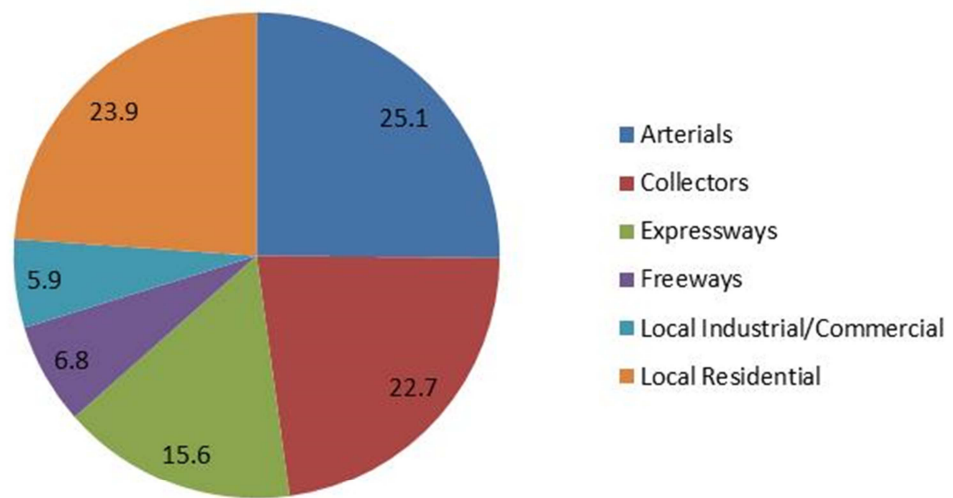


Figure 1: Distribution of the lane distance by functional class

The focus of this study as highlighted in the introductory discussion, is determining the suitability of different analysis approaches and their respective pros and cons in the context of analyzing an urban network M&R work program.

Prior to undertaking network analysis, the study team looked at the existing condition of the network in an effort to determine the maintenance funding necessary to maintain the network at its current level. It was found that the average overall network index is approximately 89.1% which is classified as “Excellent” according to the condition states defined by the highway agency. It was interesting to note that the structurally deficient segment of the road network is limited to less than 5% of the overall network. For more details on the condition states for the respective functional classes, please refer to Figure 2.

In the following step, the study team analyzed a wide range of scenarios with an aim to establish the necessary budget to maintain the network at prescribed levels. To that effect, the authors used the “Ranking” analysis option to determine the budget levels. Results indicated the following:

- An estimated annual budget of \$2 million would be necessary to achieve a terminal condition score equal to the current network condition.
- In addition, an annual budget of \$2.5 million, \$5 million, and \$10 million would suffice to achieve a terminal network condition of 89.5%, 90.8%, and 92.8%, respectively.

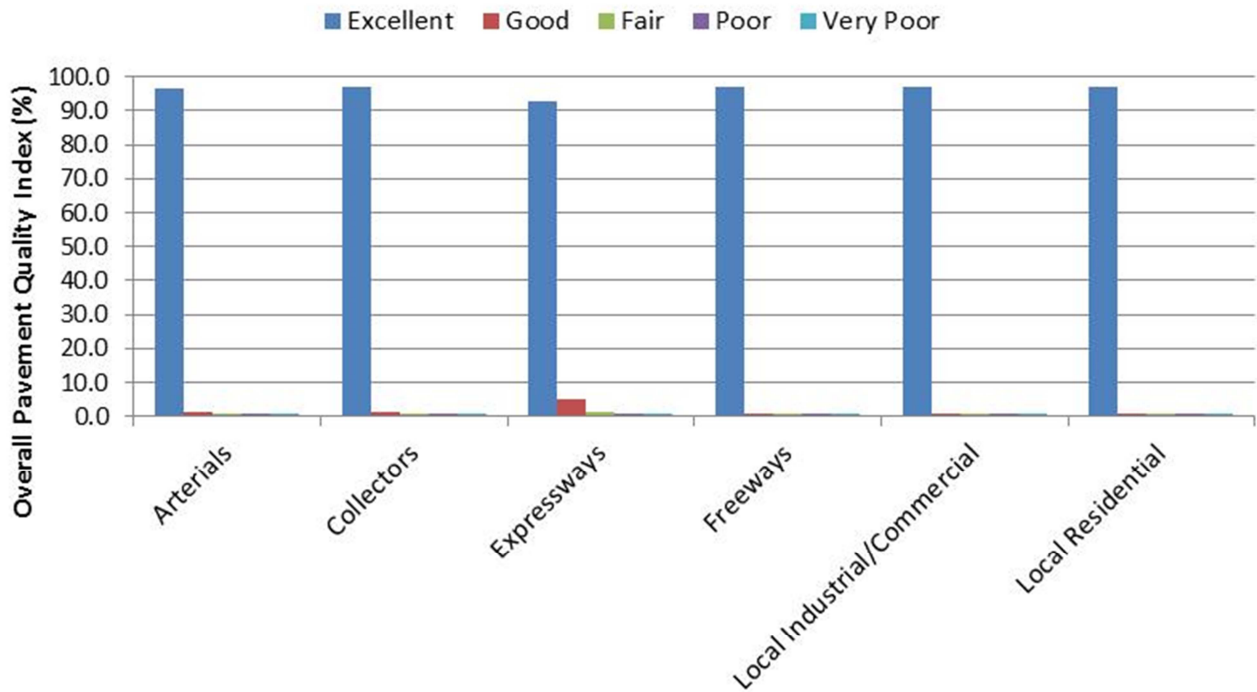


Figure 2: Current network condition by functional class

It should be noted that the authors will refer to the aforementioned budget scenarios in the discussion that follows. The adoption of this approach will help the authors use a common frame of reference to compare the results obtained in each of the individual scenarios.

Results

The "Worst-First" analysis approach offers the simplest solution towards determination of the maintenance work plan. The study team simulated the budget scenarios identified (annual maintenance budget of \$2 million, \$2.5 million, \$5 million, and \$10 million) in the previous section. While the weighted average overall pavement quality index (OPQI) is 89.1%, the results presented in Figure 3 indicate that the network continues to deteriorate irrespective of the funding level. This indicates that neither of the funding scenarios are enough to sustain the maintenance needs of the network. As discussed in the previous sections, the "worst-first" analysis approach uses a simplified procedure in which the maintenance needs of the most deficient sections are addressed until the maintenance funds are completely exhausted. As a result, the worst-first approach in most scenarios will select candidate sections that require significant rehabilitation which are relatively expensive compared to preventive treatments.

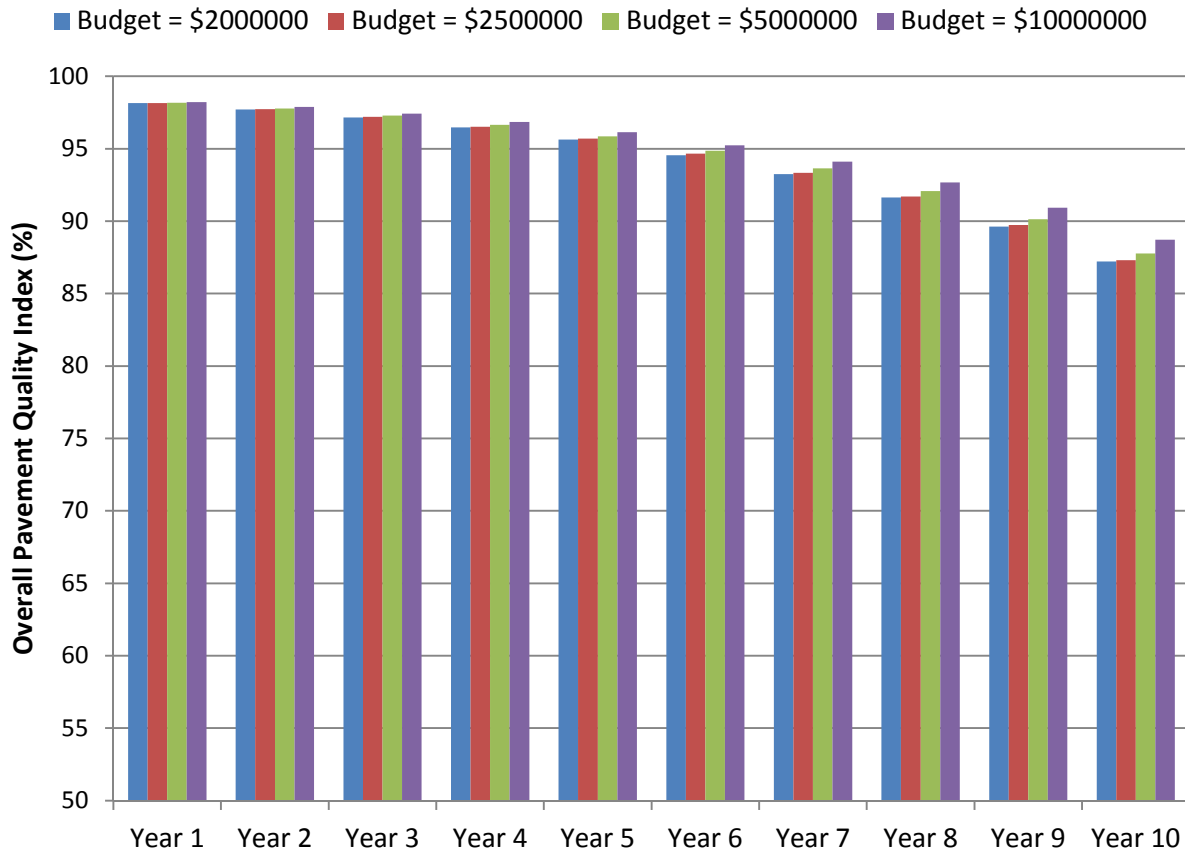


Figure 3: Overall network condition with “Worst-First” analysis approach

As discussed in the previous sections, the “Ranking” approach is a significant improvement over “Worst-First” for the reason that it accounts for the cost and benefit associated with individual treatments. In most scenarios, preventive maintenance is more cost-effective than reactive treatments as they involve lighter surface treatments that extend pavement life and prevent major failures. As a result, “Ranking” tends to favor the preventive treatments and hence offers a more effective maintenance plan with respect to “Worst-First”. The results presented in Figure 4 underscore the above mentioned rationale.

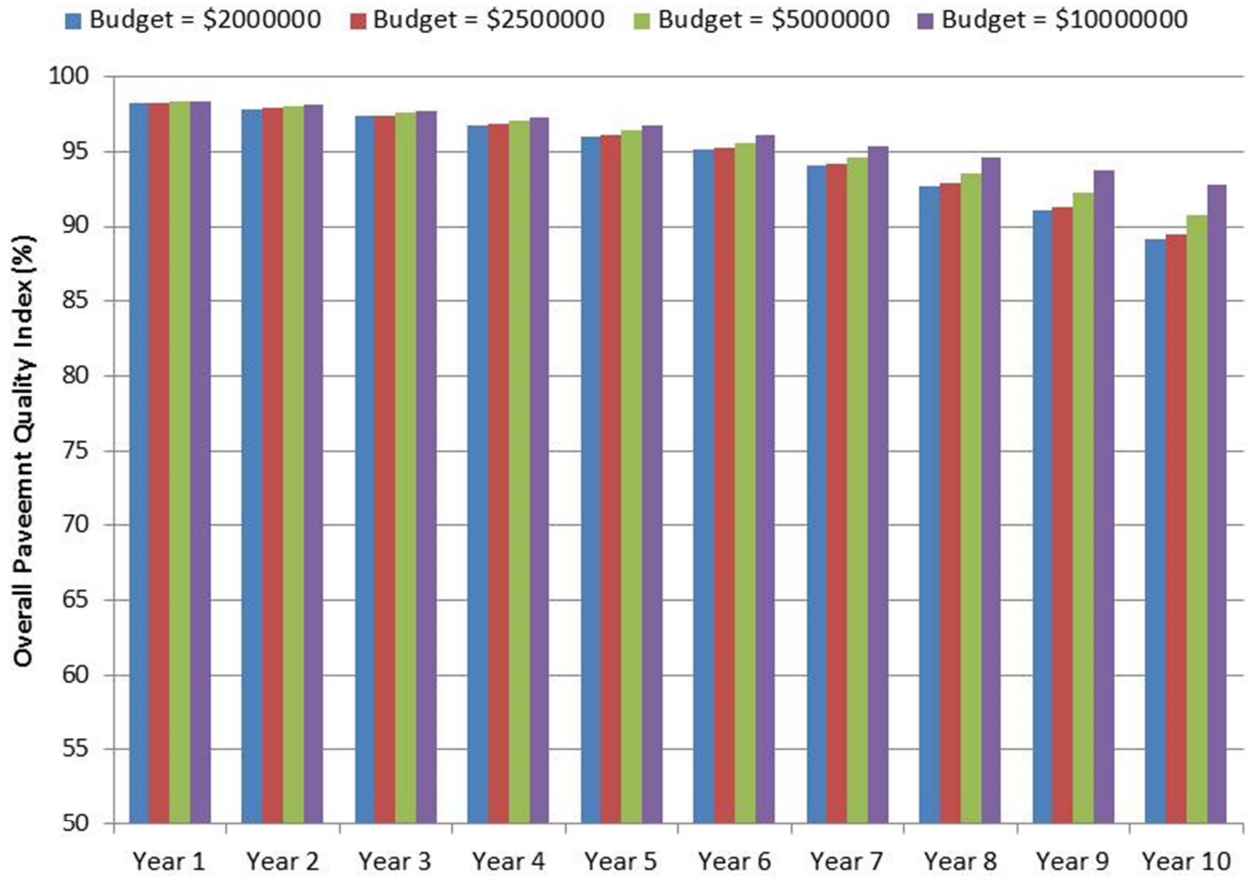


Figure 4: Overall network condition with “Ranking” analysis approach

Although the “Ranking” analysis approach includes major benefits with respect to the “Worst-First”, it has limitations. Mainly the number of constraints cannot be more than one. As a result, situations that requires addressing multiple network-level maintenance needs, the “Ranking” approach falls short (please refer to the scenario explained in next paragraph).

The “Multi-Constraint” approach helps overcome the single constraint limitation and hence allows handling of multi-constraint analysis problems. For example, highway agencies are often tasked with attaining the maximum network condition possible for the maintenance fund available while restricting the number of deficient lane-miles to a certain threshold. The use of “Multi-Constraint” approach is beneficial in these scenarios. It should be noted that the “Multi-Constraint” analysis is synonymous with “Ranking” for scenarios that include a single constraint. In an effort to compare the results between the “Multi-Constraint” and “Ranking” analysis approaches, the authors evaluated a scenario where the agency is tasked with maximizing the overall network condition while limiting the proportion of deficient lane miles to no more than 10% of the overall network for a given maintenance budget. In the context of this paper, an OPQI of 70 or below is considered deficient. The results from this analysis are summarized in Figure 5.

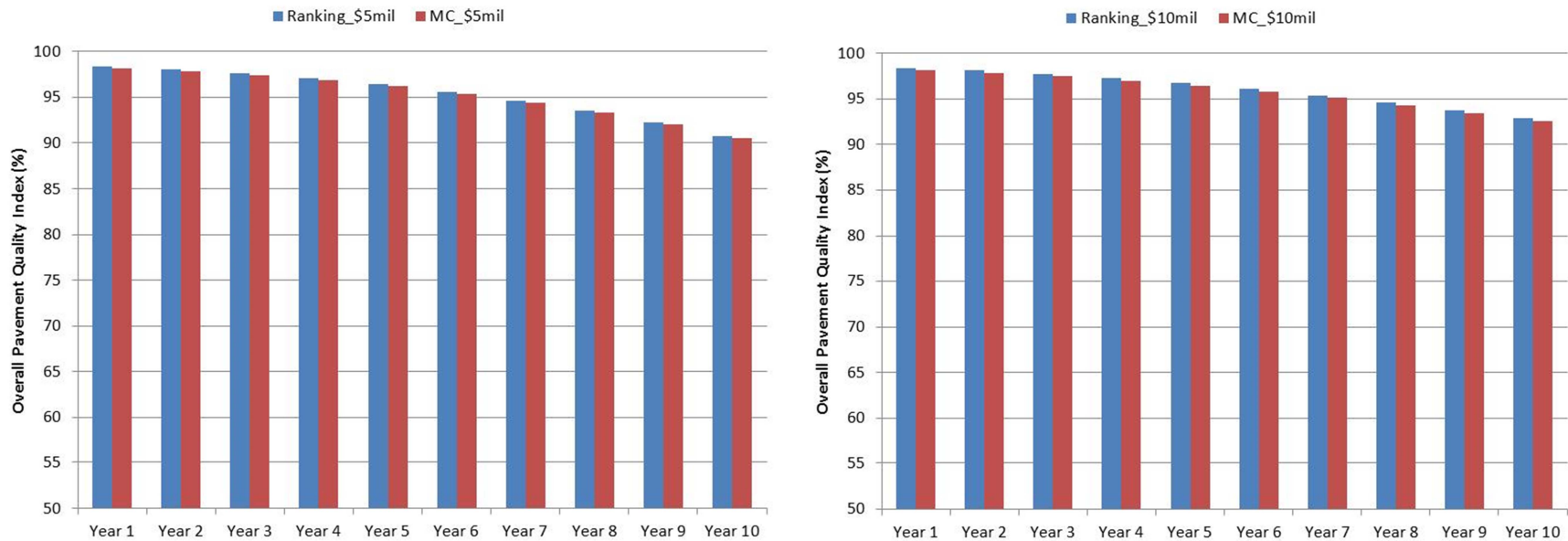


Figure 5: Comparison of overall network condition b/w “Ranking” and “Multi-Constraint” approaches

The results in Figure 5 show that the overall network conditions for “multi-constraint” option are consistently lower than the “Ranking” option with the maintenance budget held constant. This is because of the additional constraints that are imposed in the multi-constraint analysis, as opposed to “Ranking”, which leads to a solution that is suboptimal when compared against the unconstrained problem (“Ranking” includes the budget constraint only and no additional constraint). More details on this subject can be found elsewhere as this topic deviates from the focus of this study (7, 8). However, the inclusion of additional constraints when defining the problem makes the scenario a more realistic depiction of the actual operating conditions and makes it useful to highway agencies that are challenged with the task of satisfying multiple concurrent maintenance needs.

The background section of this paper introduced yet another analysis method, namely “Multi-Year” analysis and it is particularly beneficial in circumstances where the agency is interested in determining a long-term pavement preservation program for the network. The “Multi-Year” analysis starts off by calculating all possible candidate solutions which implies evaluating “what-if” scenarios. The solution space includes each candidate section receiving the prescribed treatment and also the scenarios where they don’t receive the treatment. The process is repeated iteratively for all the years included in the analysis. Once the solution space is constructed, the system evaluates potential scenarios for the stated objective function subject to the constraints that define the problem boundaries (in this case, objective function is maximizing the overall network condition subject to the budget constraint of \$5 million and \$10 million with no more than 10% deficient lane distance). Results from this analysis are summarized in Figure 6. While the results presented below do not indicate a significant improvement in the overall network condition, it still indicates that there is a systematic improvement in case of the “Multi-Year” analysis when compared against the “Multi-Constraint” results. This is primarily due to the fact that the system knows the future maintenance funding options and therefore has the liberty to choose the most efficient treatment strategy that offers the maximum benefit for the maintenance funds expended (9). However, it should be noted that the methodology used in “Multi-Year” analysis involving creation of the solution space and subsequent determination of the optimized work plan based on maintenance strategies for candidate sections is computationally expensive. Therefore, adequate engineering judgment must be exercised in determining the problem definition. Furthermore, as discussed earlier, the “Multi-Year” analysis requires forecasted for the entire planning horizon, which at times might be difficult to provide. Hence, the recommended work plan is subject to change significantly should there be need for adjustments to the anticipated maintenance funding as the work program for prior years is contingent upon the funding level for future years.

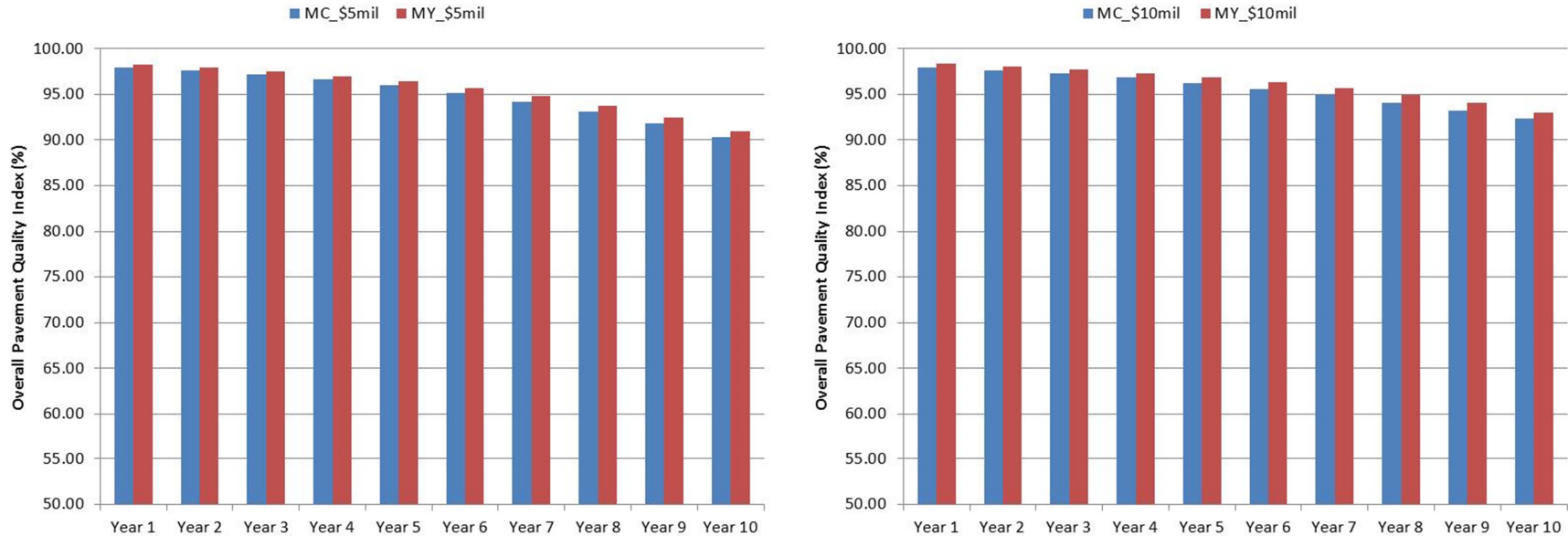


Figure 6: Comparison of overall network condition b/w “Multi-Constraint” and “Multi-Year” approaches

While the results presented in Figure 6 shows that the net improvement between the “Multi-Constraint” and “Multi-Year” analysis appears insignificant, the same is not true when comparing the budget necessary to maintain the network at prescribed levels. In an effort to highlight the budget implications when switching from one method to the other, the study team used the network condition obtained using “Multi-Constraint” as baseline for conducting this comparative analysis. In other words, the study team attempted to determine the maintenance budget that would otherwise be needed to attain the same overall network condition using “Multi-Year” analysis as already found in case of “Multi-Constraint” analysis. The results summarized in Figure 7 indicate that the highway agency could potentially save 6 to 10% in the maintenance budget if using “Multi-Year” over “Multi-Constraint” analysis methodology. It should be noted that the aforementioned estimates strictly apply to the pavement network analyzed in this study which has been in an overall excellent category and hence should not be purported to highway networks that do not share similar characteristics.

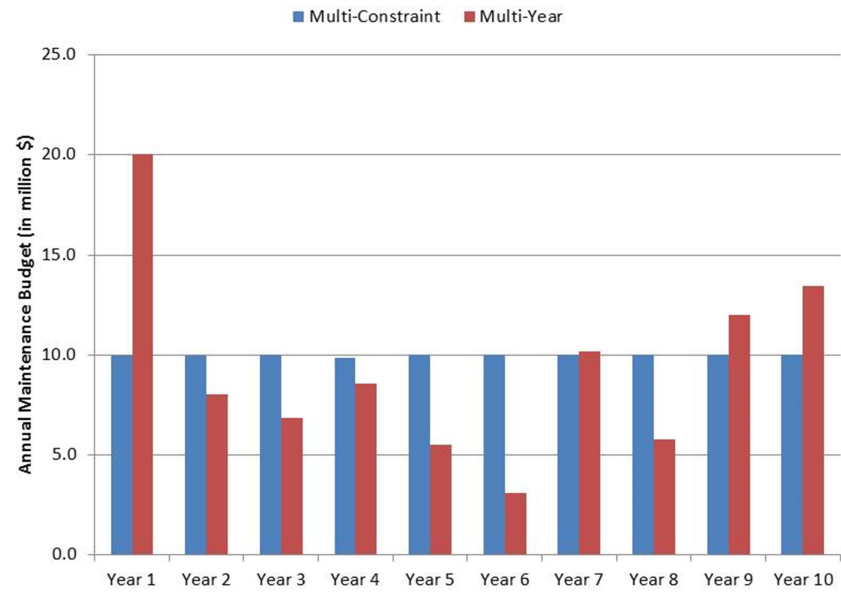
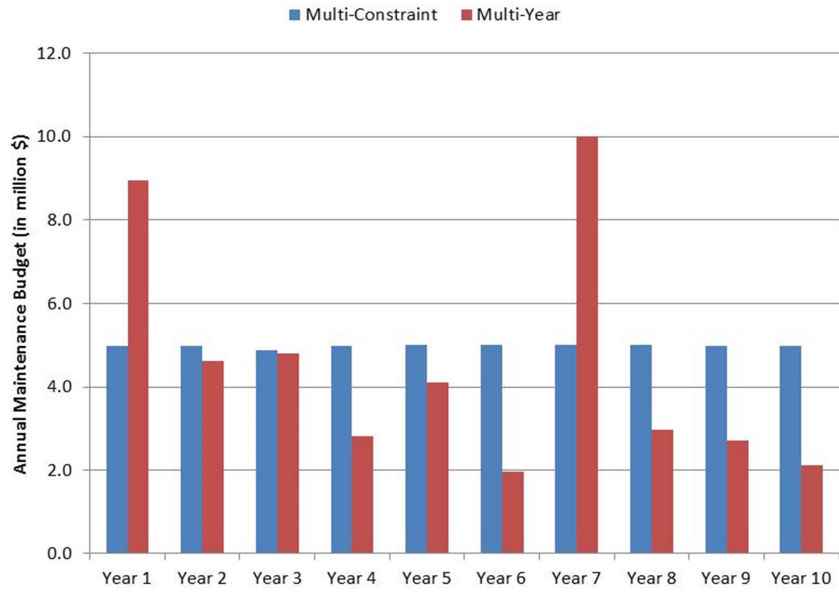


Figure 7: Budget comparison b/w “Multi-Constraint” and “Multi-Year” analyses at prescribed network condition

Conclusion

This paper presents a case-study involving the suitability and benefits of implementing a pavement management system for an urban road network. The study team evaluated four different analysis methods, namely “Worst-First”, “Ranking”, “Multi-Constraint”, and “Multi-Year” with different maintenance budget levels.

The analysis results highlighted in Figure 3 indicated that the “Worst-First” approach, though analytically simple, generates work plans that are significantly expensive when compared against other analysis procedures. The observation can be at best attributed to the fact that the “Worst-First” analysis is not an optimization procedure by definition as the candidate projects are selected based on the condition metric prescribed by the analyst. Hence, the benefit associated with the alternative lower initial maintenance expenditure is overlooked.

The “Ranking” analysis (single constraint benefit-cost) methodology though relatively sound, has an inherent limitation that it allows only one constraint which can be a significant limitation where the Analyst may be required to define a multi-constraint problem due to agency policy and other technical or administrative stipulations. A few classic examples were highlighted in the paper.

The “Multi-Constraint” analysis approach overcomes the single constraint restriction and lets the user specify multiple constraints. However, results presented in this paper (Figure 5) indicate that the overall network condition was systematically lower in case of “Multi-Constraint” when compared against “Ranking”, keeping the maintenance budgets constant. This can be attributed to the additional constraints that are imposed in a “Multi-Constraint” analysis that result in a sub-optimal solution when compared against the unconstrained problem (Ranking).

The last analysis type discussed includes the “Multi-Year” methodology which represents a paradigm shift in PMS network optimization methods. Each of the previous analysis procedures are solved discrete in time, which implies that the analysis domain is constrained to a single year in the planning horizon and the solution is progressively carried forward to the successive year. Contrary to that, the “Multi-Year” procedure determines potential candidates for M&R treatment across the entire planning horizon and chooses the optimal treatment strategy for the individual sections. The results presented in Figure 6 indicate that the overall network condition is merely 0.5-1.0% higher with the “Multi-Year” analysis when compared against “Ranking” or “Multi-Constraint”.

Furthermore, the authors demonstrated through Figure 7 that should the highway agency choose to determine the budget necessary at prescribed levels, the adoption of the “Multi-Year” analysis can result in M&R cost savings between 6 and 10%.

In summary, the results presented in this paper provide evidence that the implementation of PMS in an urban road network can yield significant benefits for the concerned highway agency. Not only it has the potential to streamline maintenance processes and programs but also make informed decisions on the optimal use of maintenance funds such that the agency may obtain the maximum utility for the funds expended. Furthermore, it was highlighted that an efficient maintenance program, if adopted, can lead to significant savings and higher level of service.

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