# Quantifying the Impact of Pavement Diversity at the Network-Level: A Heuristic-Based Approach for Pavement Management

Omar Swei, Ph.D. Candidate[1], Jeremy Gregory, Ph.D. [1], Randolph Kirchain, Ph.D. [1]

## Abstract

Departments of transportation (DOTs) are increasingly utilizing pavement management systems for the efficient maintenance and preservation of the existing roadway system. Few studies to date, however, have considered sources of variation beyond pavement deterioration nor the implication of investing in multiple pavement materials. The goal of this study is to implement a heuristic-based model in a realistic case study so that one can understand the implication of (a) cost variation and (b) the consideration of multiple paving materials and designs on the performance of a roadway network.

The model is implemented in four different scenarios for a set of 3,000 pavement segments in the state of Virginia. The four scenarios include a deterministic case using asphalt and concrete and three probabilistic scenarios that utilizes either asphalt, concrete, or both materials. From the case studies, two interesting results emerge. First, incorporating not just more pavement designs, but also including alternative paving materials, in the pavement management model increases the overall performance of the system. Second, incorporating cost uncertainty increases the advantage of investing in alternative materials, something that the current paradigms do not consider.

## Introduction

Federal and state transportation agencies currently stand at a crossroad. Decreasing transportation funds, increasing maintenance and construction needs, and a growing understanding of the relationship between design and the environment has led to a push for major reform within agencies to take a long-term perspective to transportation investments (Zhang et al. 2013; Santero et al. 2011). Such concerns, which have haunted transportation agencies for decades, have pushed several departments of transportation (DOT) towards adopting asset management, the use of quantitatively based support tools in the planning and prioritization of infrastructure facilities (Markow 1995; Madanat et al. 2006). The overarching goal across the existing literature is to search for an (ideally) optimal or (at the minimum) near-optimal allocation solution while balancing between computational time and fidelity. Despite this commonality, the approaches of some of the influential work in the field diverges in many directions. In part, as will be discussed further, this can be attributed to the size (e.g., number of decision variables) of the problem.

The following section provides a brief synopsis of the pavement management literature, with a particular focus on the types of (a) maintenance and reconstruction options considered (b) optimization-based formulations and (c) sources of variation introduced. The findings of the literature review will motivate both the methods and case study utilized in the remainder of the paper.

[1] Massachusetts Institute of Technology, 77 Massachusetts Avenue Building E38-432, Cambridge, MA 02139. E-mail for corresponding author: oaswei@mit.edu

## Pavement Management Literature

Pavement management is broadly defined as the planning, management, and preservation of a pavement segment (often denoted as a *facility,* which will be used interchangeably in this paper) or network using quantitative information (Mbwana 2001). For a pavement network, the American Association of State Highway and Transportation Officials (AASHTO) asserts that a pavement management system should determine a set of network priorities by making use of budget requirements, pavement distress data, and structural adequacy information (AASHTO 1990).

Pavement management systems have historically followed a top-down approach, where funding levels are first established and then further sub-routines are implemented for the prioritization of roadway segments and determination of exact maintenance activities. Increasingly, however, researchers have recognized the limitations of such an approach in its ability to consider the heterogenic nature of pavement segments, and, as such, have moved towards bottom-up (referred to as facility-specific) models, where one develops a maintenance policy for each roadway/segment (Yeo et al. 2013; Sathaye and Madanat 2012). The remainder of this paper primarily focuses upon the latter which is gradually becoming the prevalent paradigm in the academic literature.

### *Methodologies of Research*

Although integer linear/non-linear programming has been used extensively for top-down approaches, such methods are incredibly costly (computationally) for the bottom-up methodology. Therefore, researchers have utilized genetic algorithms, dynamic programming, and heuristic-based offshoots. Heuristic-based approaches include Ouyang and Madanat (2004), who created a greedy algorithm to make locally best decisions throughout the analysis period, and Kuhn (2010), who used approximate dynamic programming. The general flow of these paradigms (particularly the latter two, the most common) is as follows. First, dynamic programming or a heuristic approach is first used to determine the best set of policies for each facility (using Bellman's principal of optimality). Afterwards, a network-level model selects the facilities to receive treatment in the current year based on the available budget (Yeo et al. 2012). The drawback of such an approach is that it ignores the fact that a facility will, potentially, be unable to follow the optimal path due to future budgetary constraints on the network.

### *Treatment of Uncertainty*

The models described have historically been implemented treating parameters as deterministic, with the exception of pavement deterioration parameters. When uncertainty is typically considered, it is done so using Markov Chains, where the probabilistic deterioration in the next period is only a function of the current state. Uncertainty in pavement deterioration is, therefore, purely aleatory, as deterioration is random and not due to any heterogeneous/external factors that are accounted for in project-level tools (Prozzi et al. 2004).

It is worth mentioning that there are a few instances where uncertainty beyond pavement deterioration is considered. For example, Smilowitz and Madanat (2000) extended the latent Markov decision process (LMDP) methodology developed by Madanat and Ben-Akiva (1994) for the integration of uncertainty in the measurement of pavement condition. Kuhn (2010) considered uncertainty in the benefit of a given treatment. Wu and Flintsch (2009) transformed the stochastic uncertainty in future budget levels into a deterministic constraint, finding that ignoring future budget uncertainty and not accounting for the aversion of decision-makers to go over budget leads to overly-optimistic maintenance plans. Lastly, Chootinan et al. (2006) utilized the same approach, but transformed uncertainty in future traffic volumes into a deterministic constraint.

### *Types of Rehabilitations Considered*

As for rehabilitation alternatives, generally studies only consider a small subset ($\leq 6$) of the possible actions at the disposal of a state agency. Furthermore, rehabilitation alternative types are fairly generic, except for Chan et al. (1994) and Zhang et al. (2013), the latter considering very specific actions for both asphalt and concrete pavements. Alternatively, some studies only consider the predominant type of rehabilitation action, overlays, allowing thickness to be a continuous function (Sathaye and Madanat 2011; Sathaye et al. 2012). As researchers continue to move towards larger networks while preserving segment-specific information, being able to consider a large number of realistic rehabilitation types presents an opportunity to continue to progress the existing pavement management tools.

### *Summary of Gaps*

A few gaps are particularly noteworthy. First, uncertainty is primarily limited to pavement deterioration even though uncertainty for future economic and environmental conditions has been established as important at the project-level. Second, the drawback of modeling pavement deterioration using Markov chains with homogenous transitional probabilities for a pavement condition index is three-fold. Differently designed pavement segments subject to diverse conditions are assumed similar, uncertainty is overestimated by treating explainable variation as unexplainable noise, and multi-attribute information, which provides insight on the appropriate rehabilitation action to apply, is removed. Lastly, the majority of research utilizes generic pavement designs, whereas, in reality, a more realistic and larger set of design options could possible lead to increased performance.

There are clearly several opportunities to augment pavement management systems as a whole. Of the gaps described, one particularly interesting area is the implication of cost uncertainty on network-level performance and the implication of considering multiple pavement materials and designs. In short, would the consideration of cost variation and alternative pavement materials lead to a different maintenance policy across a network?

## Methodology: Greedy Approach to Pavement Management

In order to explore the importance of cost variation, a greedy algorithm is implemented for the maintenance of a pavement network under four scenarios: a deterministic case using both materials and three probabilistic scenarios where either asphalt, concrete, or both materials are utilized. The goal of the model is to minimize pavement vehicle fuel consumption due to roughness (PVI-xFC), a metric that has not been implemented prior in existing pavement management tools (Akbarian et al. 2012). In order to estimate PVI-xFC, this study makes use of the calibrated HDM-IV model that correlates pavement roughness and traffic to vehicle fuel consumption (Zaabar and Chatti, 2010). Although other performance attributes fall outside the scope of the presented objective function, the authors realize the importance of integrating multi-attribute pavement condition data for allocation decisions, something lacking in the current frameworks (Chan et al. 1994).

The following describes in detail the algorithm implemented in this research which is similar to that of Ouyang and Madanat (2004). Equation 1 states the objective: at the start of each year, $t^*$, the goal is to maximize the expected fuel consumption savings related to the roughness of a pavement, *FC*, from applying rehabilitation action, *a*, to pavements *n*, in the current year, denoted as $X_{ant*}$ (hence it is binary). The fuel consumption savings from a rehabilitation is proportional to the traffic level, $E_{nt*}$, the immediate change in pavement condition after a rehabilitation, $B_{ant}$ (e.g., change in pavement service rating), and the difference between the deterioration rate until the end of the analysis period, *T*, without a rehabilitation action, $DR^{-}_{a=0,nt*}$, and after a maintenance event, $DR^{+}_{ant*}$. It is assumed that the second component only applies to reconstructions; that is, a maintenance or rehabilitation event does not alter the existing pavement structure significantly, and so the rate of deterioration will be the same. Equation 2 asserts that the change in pavement condition of any rehabilitation action cannot exceed the maximum possible pavement service rating (PSR) for a facility. Equation 3 and 4 condition that no more than one rehabilitation action is used for any segment in a given year and that the decision is binary. Lastly, Equation 5 stipulates that the cost of applying rehabilitations, $C_{ant*}$, across the network does not exceed the available budget, *B*.

$$\max \Delta FC = \sum_{n=1}^{N} FC(X_{ant^*}B_{ant^*}, E_{nt^*}) + FC(\int_{t^*}^{T} (DR^{-}_{a=0,nt^*} - DR^{+}_{ant^*}dt\,, E_{nt}) \tag{1}$$

$$\text{s.t.}$$

$$0 \leq B_{ant^*} \leq PSR_{max} - PSR_{n,t^*} \tag{2}$$

$$\sum_{a=1}^{A} X_{ant^*} \leq 1 \qquad \forall\, n = 1,2 \dots N \tag{3}$$

$$X_{ant^*} \in \{0,1\} \tag{4}$$

$$\sum_{n=1}^{N} X_{ant^*}C_{ant^*} \leq B \tag{5}$$

| | |
|---|---|
| $N$ | Number of pavement segments in network |
| $T$ | Analysis period |
| $t*$ | Current year |
| $FC$ | Fuel consumption as measured in gallons |
| $X_{ant*}$ | The decision to apply rehabilitation action *a* to segment n in year *t** |
| $B_{ant*}$ | The change in pavement condition by applying rehabilitation action *a* to segment *n* in year *t** |
| $E_{nt*}$ | Traffic-level of pavement segment *n* in year *t** |
| $DR^{-}_{a=0,nt*}$ | Deterioration rate until the end of the analysis period for segment n in year *t** when subject to no rehabilitation |
| $DR^{+}_{ant*}$ | Deterioration rate until the end of the analysis period for segment *n* in year *t** after rehabilitation action *a* |
| $PSR_{max}$ | Maximum PSR for a pavement segment |
| $PSR_{n,t*}$ | PSR for segment *n* in year *t** |

| | |
|---|---|
| $C_{ant^*}$ | The cost to apply rehabilitation action *a* to segment n in year *t** |
| $B$ | Available annual budget for network |

With respect to Equation 5, it is important to note that cost variation can manifest in two forms: future costs within the analysis period (which this model addresses) and variation across pavement facilities at a given point in time. Although the latter tends to be quite important at the project-level, one would expect its implications to be mitigated for a network. Assume one applies the same action to a number of homogenous facilities at year *t* with an associated cost, $C_{a=1,nt}$. If $C_{a=1,nt}$ is Gaussian distributed and uncorrelated across facilities, then the expected cost of applying that action across the network rather than a single pavement scales by *n* while the standard deviation only increases by $n^{1/2}$. Therefore, if *n* is sufficiently large, then its reasonable to assume that the implications of this source of variation would be minimal, and so only uncertainty in how average construction costs will evolve over time is considered.

Since the problem is very tractable, a Monte Carlo simulation is integrated into the analysis. For each simulation, costs are randomly generated over the time-horizon and locally optimal decisions are made each year. The analysis is conducted for 200 simulations in order to estimate the uncertainty in how the model performs for the three probabilistic cases.

## Data for Case Study

The model is applied to pavement condition data collected for the state of Virginia. The entire network constitutes 3,000 pavement segments, representative of the size of a pavement network a DOT could potentially be in charge of maintaining. Pavement deterioration models, cost of alternative rehabilitation types and their associated benefits are taken from the previously cited Chootinan et al. (2006) except for reconstruction costs (as can be seen in Table 1). The fundamental assumption of the deterioration model is that the annual change in PSR is deterministic and a function of climactic, traffic, structural, and age factors. The cost of a typical asphalt and concrete reconstruction is estimated based upon bid data collected for previous research. PSR is transformed into IRI based upon a relationship established by the Minnesota DOT.

**Table 1 Cost and maximum change in PSR for the four possible actions per Chootinan et al. (2006) as well as estimates of reconstruction costs via bid data collected by the authors. Linear interpolation is used to estimate benefits for non-listed ages in Chootinan et al. (2006).**

| Treatment | Real Cost ($/SQY) | Increase in PSR for each action as a function of age | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 20 | 19 | 16 | 13 | 10 | 7 | 4 | 1 |
| Routine Maintenance | 0.2 | 0 | 0 | 0 | 0.23 | 0.23 | 0.45 | 0.45 | 0.45 |
| Surface Treatment | 0.74 | 0 | 0.45 | 0.68 | 1.13 | 1.58 | 1.58 | 1.58 | 1.58 |
| Overlay | 4.67 | 0 | 0.9 | 1.58 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| Rehabilitation | 7.74 | 4.5 for all ages | | | | | | | |
| Thin Asphalt Reconstruction | 14.28 | | | | | | | | |
| Medium Asphalt Reconstruction | 22.86 | | | | | | | | |
| Thick Asphalt Reconstruction | 31.43 | | | | | | | | |
| Thin Concrete Reconstruction | 16.67 | | | | | | | | |
| Medium Concrete Reconstruction | 26.67 | | | | | | | | |
| Thick Concrete Reconstruction | 36.67 | | | | | | | | |

In order to account for future cost uncertainty, it is assumed that maintenances and rehabilitations, which are not necessarily material intensive, move together via a construction cost index (CCI). Asphalt and concrete reconstructions, however, each have their own individual cost index. It is presumed that these three indexes are independent of one another and are Gaussian distributed around current day construction costs with a coefficient of variation (COV) equal to 0.15.

## Results from Case Study

Figure 1 (and Figure 2) presents the annual (total) fuel consumption usage due to pavement condition over the 15-year analysis period for the four scenarios discussed previously. Both instances where only one material is considered underperforms significantly compared to the case where both materials are utilized. The asphalt reconstructions tend to perform lower (in terms of pavement deterioration rate) relative to the concrete designs yet at a lower construction cost. Hence, the asphalt-only scenario outperforms the concrete-only scenario early on (poorer designs but more can be repaired) while towards the later part of the analysis period the opposite phenomena occurs.

Perhaps the more interesting finding is the performance of the deterministic and probabilistic scenarios where both materials are used. If cost variation is ignored, the deterministic results track the performance of the asphalt-only case; in other words, the asphalt design always has a lower cost, and given the construct of the decision-rule currently, the extra benefit in performance is not worth the additional cost. In the probabilistic case, however, in some instances concrete prices are lower than asphalt, making the benefit of going with a concrete design attractive in those instances.

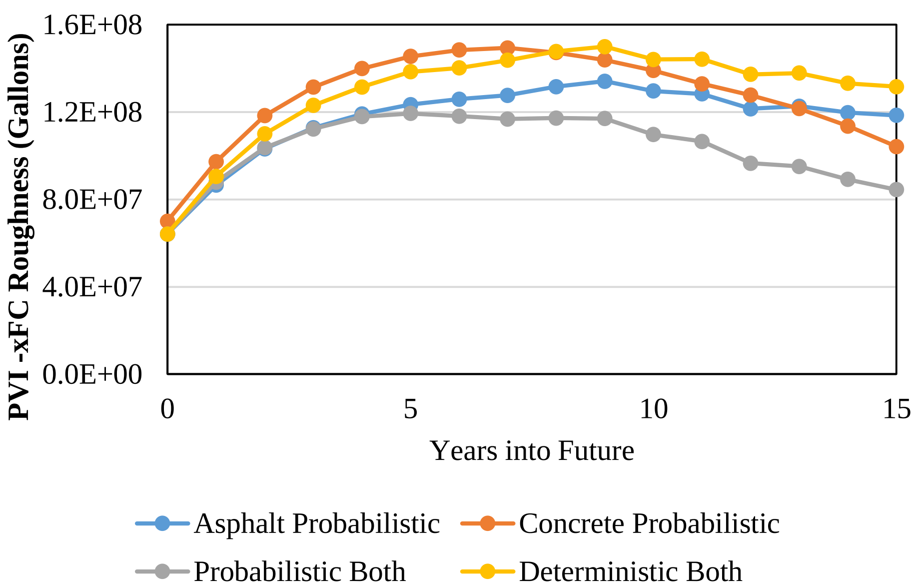


**Figure 1 Average fuel consumption per year over simulations when (a) only considering asphalt reconstructions (b) only considering concrete reconstructions (c) considering both probabilistically and (d) considering both deterministically**

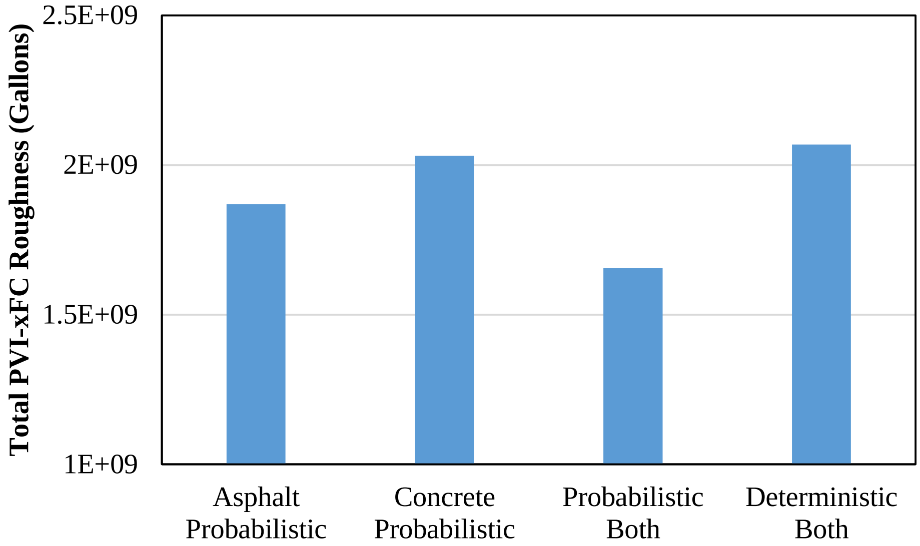


**Figure 2 Total fuel consumption over simulations when (a) only considering asphalt reconstructions (b) only considering concrete reconstructions (c) considering both probabilistically and (d) considering both deterministically**

## Conclusions and Future Work

There are two significant conclusions from this work. First, cost variation is one example of the type of uncertainty currently being ignored by the literature as a whole and can have implications on the optimal pavement management strategy. This can be noted by the difference in expected performance per Figure 2 between the probabilistic and deterministic instances. Second, in the presence of cost uncertainty, incorporating multiple pavement materials is an effective way to increase performance across a network. Despite the promising results of this analysis, there is certainly room to augment the current research.

One major drawback of the methodology discussed is that it makes locally optimal decisions without looking ahead to the path dependence of those choices. A computationally efficient framework is needed that can do just that that (i.e., dynamic programming/optimal control) while simultaneously balancing between network-level and project-level constraints. Additionally, the present research only considers material and design choices at the network-level. Future research should consider these decisions not only for reconstructions, but also for different types of rehabilitation and maintenance actions. Lastly, it would be particularly useful to validate the performance of the paradigm proposed by collecting historical data for a pavement network and measuring its actual performance over time as compared to the hypothesized performance of the presented model.

## References

1. Akbarian, M., S.S. Moeini-Ardakani, F.J. Ulm, and M. Nazzal. Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact on Life-Cycle Assessment. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2306,* Transportation Research Board of the National Academies, Washington, D.C, 2012, pp. 171-179.
2. *Guidelines for Pavement Management Systems*, American Association of State Highway and Transportation Officials, 1990.

3. Chan, W.T., T.F. Fwa, and C.Y. Tan. Road-Maintenance Planning Using Genetic Algorithms I: Formulation. *Journal of Transportation Engineering*, Vol. 120, No. 5, 1994, pp. 693-709.
4. Chootinan, P., A. Chen, M.R. Horrocks, and D. Bolling. A multi-year pavement maintenance program using a stochastic simulation-based genetic algorithm approac. *Transportation Research Part A*, Vol. 40, No. 9, 2006, pp. 725-743.
5. Fwa, T.F., W.T. Chan, and K.Z. Hoque. Analysis of Pavement Management Activities Programming by Genetic Algorithms. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1653*, Transportation Research Board of the National Academies, Washington, D.C, 1998, pp. 1-6.
6. Kuhn, K.D. Network-Level Infrastructure Management Using Approximate Dynamic Programming. *Journal of Infrastructure Systems*, Vol. 16, No. 2, 2010, pp. 103-111.
7. Madanat, S. and M. Ben-Akiva. Optimal Inspection and Repair Policies for Infrastructure Facilities. *Transportation Science*, Vol. 28, No. 1, 1994, pp. 55-62.
8. Madanat, S., S. Park, and K. Kuhn. Adaptive Optimization and Systematic Probing of Infrastructure System Maintenance Policies under Model Uncertainty. *Journal of Infrastructure Systems*, Vol. 12, No. 3, 2006, pp. 192-198.
9. Markow, M.J. Highway Management Systems: State of the Art. *Journal of Infrastructure Systems*, Vol. 1, No. 3, 1995, pp. 186-191.
10. Mbwana, J. A Framework for Developing Stochastic Multi-Objective Pavement Management. *Technology Transfer in Road Transportation in Africa Conference Proceedings*, 2001, pp. 350-363.
11. Ouyang, Y. and S. Madanat. Optimal scheduling of rehabilitation activities for multiple pavement facilities: exact and approximate solutions. *Transportation Research Part A*, Vol. 38, No. 5, 2004, pp. 347-365.
12. Prozzi, J.A. and S.M. Madanat. Development of Pavement Performance Models by Combining Experimental and Field Data. *Journal of Infrastructure Systems*, Vol. 10, No. 1, 2004, pp. 9-22.
13. Santero, N.J., E. Masanet, and A. Horvath. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation, and Recycling*, Vol. 55, No. 9-10, 2011, pp. 801-809.
14. Sathaye, N. and S. Madanat. A bottom-up solution for the multi-facility optimal pavement resurfacing problem. *Transportation Research Part B*, Vol. 45, No. 7, 2011, pp. 1004-1017.
15. Sathaye, N. and S. Madanat. A bottom-up optimal pavement resurfacing solution approach for large-scale networks. *Transportation Research Part B*, Vol. 46, No. 2012, pp. 520-528.
16. Smilowitz, K. and S. Madanat. Optimal Inspection and Maintenance Policies for Infrastructure Networks. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, No. 1, 2000, pp. 5-13.
17. Wu, Z. and G.W. Flintsch. Pavement Preservation Optimization Considering Multiple Objectives and Budget Variability. *Journal of Transportation Engineering*, Vol. 135, No. 5, 2009, pp. 305-315.
18. Yeo, H., Y. Yoon, and S. Madanat. Maintenance Optimization for Heterogeneous Infrastructure Systems: Evolutionary Algorithms for Bottom-Up Methods. *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering*, 2013, pp. 185-200.
19. Zaabar, I., and K. Chatti. Calibration of HDM-4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S. Conditions. In *Transportation Research*

*Record: Journal of the Transportation Research Board*, No. 2155, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 105–116.

20. Zhang, H., G.A. Keoleian, M.D. Lepech, and A. Kendall. Life-Cycle Optimization of Pavement Overlay Systems. *Journal of Infrastructure Systems,* Vol. 16, No. 4, 2010, pp. 320-332.
21. Zhang, H., G.A. Keoleian, and M.D. Lepech. Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization. *Journal of Infrastructure Systemss*, Vol. 19, No. 1, 2013, pp. 99-107.