（Form6）

論　文　要　旨
Thesis Abstract

（yyyy/mm/dd）　　2024 年　01 月 11 日

※報告番号	甲第３４０号	氏　名 (Name)	Azam Amir

主論文題名　（Title）Rational maintenance management system for road infrastructure applying machine learning at the network and project levels

内容の要旨　（Abstract）

Road infrastructure serves as the primary mode of transport in many countries, playing a pivotal role in development and economic progression. Globally, reliance on road transport is evident in the transportation of industrial goods, construction materials, daily necessities for communities, fruits and vegetables from farm to market, and in providing enhanced facilities. Moreover, in the competitive global race for continual development and economic advancement, both developing and developed countries are increasingly investing in the construction and expansion of their road networks. However, this focus on expansion often leads to the neglect of existing road network maintenance management. This oversight can render it challenging for road departments to maintain these networks efficiently and in a timely manner, risking their transformation from valuable assets to significant economic burdens. Therefore, an effective Pavement Maintenance Management System (PMMS) is the need of the time. Such a system can guide and assist road agencies in more efficiently and proactively addressing maintenance requirements, aligning with the current demands of road infrastructure management.

Over the past few decades, as road infrastructure increasingly shows signs of aging, a noticeable shift, especially in developing countries, has occurred towards the advancement in PMMS to enhance decision-making efficiency in maintaining road networks. An effective PMMS involves the rational allocation of a maintenance budget across road sections, guided by their current conditions and specified maintenance and rehabilitation needs. The American Association of State Highway and Transportation Officials (AASHTO) defines a PMMS as a collection of tools or methods that aid decision-makers in identifying cost-effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition, both at the network and project levels. Moreover, this concept also aligns with the Plan-Do-Check-Act (PDCA) cycle, which is a management methodology employed to control and constantly improve processes. However, given the PMMS's critical role in optimally distributing a substantial budget, a PMMS should be devised to align seamlessly with the objectives of AASHTO and the stages of the PDCA cycle. This means that a PMMS should not only facilitate planning, evaluation, and maintenance activities but also guide the continuous improvement of future systems. Therefore, this research aimed to develop an effective data-driven PMMS to improve decision-making processes by integrating the PDCA cycle with machine learning algorithms.

The objectives of the research were to develop a framework for analyzing network-level data to enable a refined data-driven approach for network-level planning, to investigate decision-makers perspectives regarding PMMS and utilize this knowledge for improved PMMS, and then to establish a robust framework for evaluating PMMS, specifically focusing on the data-driven aspect by integrating the PDCA (Plan-Do-Check-Act) cycle with machine learning algorithms and finally to enhance network-level decision-making by effectively integrating network and project-level data, thus steering towards a more sustainable and condition-specific data-driven PMMS.

In pursuit of developing a data-driven PMMS, this research utilized the data from the provincial highway network of Khyber Pakhtunkhwa province in Pakistan. The data at the network level typically comprises road sections of considerable lengths within the network, characterized by heterogeneous factors influencing pavement conditions. Utilizing this data for predicting pavement conditions can be challenging. In the case of pavement deterioration prediction with the stochastic model, such as with the count-based Markov chain analysis, where the approach does not incorporate the effects of factors affecting the rate of deterioration during prediction modelling, the application of Markov chain on heterogeneous road sections becomes difficult. To address this, the research presents a framework that integrates machine learning with the Markov chain. Initially, a clustering approach was applied to categorize the heterogeneous road sections into families with homogeneous influencing factors. Subsequently, the Markov chain was applied to each family. This method proved effective in predicting the rate of deterioration and identifying factors that influence it.

Moreover, the lengthy road sections within the network result in a relatively low volume of data. Consequently, for machine learning-based pavement condition prediction models, achieving the desired accuracy in pavement condition prediction models can be challenging. To address this, the effectiveness of two common machine learning approaches — Artificial Neural Networks (ANN) and K-Nearest Neighbors (KNN) — was evaluated for low-volume network-level data. The application of sensitivity analysis using Garson's algorithm on the ANN model was assessed. It was found that the ANN model, when enhanced with this analysis, demonstrated improved accuracy and was effective for the given low-volume network-level data.

The success of PMMS in maintaining and improving pavement conditions is significantly influenced by the perceptions and decisions of those in management, especially those directly involved in the implementation process. Therefore, a questionnaire survey was conducted and analyzed the perspectives of experts involved in road management in Khyber Pakhtunkhwa province, aiming to understand their roles, knowledge levels, and the challenges and opportunities they perceive in the implementation of pavement maintenance management. A part of the survey was also utilized for evaluating the PMMS. This approach specifically focused on decision-makers viewpoints regarding factors influencing pavement conditions, which was then compared with data-driven factors affecting pavement conditions obtained from provincial road network data. This comparative analysis serves to assess the current PMMS, highlighting the necessity for potential improvements in the existing system.

The research further aimed to formulate a framework for evaluating or assessing the data-driven PMMS. This conceptual approach involved reverse-engineering the decision-making process behind road maintenance budget allocation by performing decision tree analysis, a machine learning technique. The developed conceptual framework helped in identifying the factors influencing budget allocation. Hence, based on these revelations, future maintenance plans can be improved, leading to a more efficient and effective PMMS as aligned with the PDCA cycle.

The final objective of the research was to develop a maintenance plan that enhances the budget allocation process, tailored to specific road conditions. This includes a unique framework involving integrated network-level analysis, such as pavement condition modeling, with detailed project-level distress data. In PMMS, key questions include which sections require maintenance, as well as when and what type of treatment is needed. The predictive models, based on pavement condition categorizations like PCI (Pavement Condition Index), IRI (International Roughness Index), or other pavement metrics, predict pavement conditions and treatment time but addressing the type of treatment required has been challenging. For instance, a model based on PCI might predict the pavement condition at a certain time, where two or more pavement sections could have similar PCI but different types of deterioration due to the presence of various distress types. To develop a strategy that predicts area of distress types, leading to more specific maintenance treatments, the integration of Markov-based prediction results with project-level distress details was undertaken. The approach involved the calculation of distress density, formulated as the ratio of the area of a given distress to the total area of the road section for each level of road condition. The change in area of each distress was then predicted over time using the results of the Markov chain analysis for each cluster. This integration approach enables the prediction of specific distress types in road sections, which is crucial in determining the necessary treatment for each type of distress. This novel approach significantly enhances the model's predictive capabilities, especially in identifying specific treatments needed for maintaining the highway network. The framework developed aimed to integrate distress data into Markov results, thereby establishing a more condition-specific, data-driven PMMS.

The methodologies and frameworks proposed in this research are valuable for establishing effective and sustainable data-driven maintenance planning for road infrastructures within pavement engineering. Firstly, they provide a means to establish an improved and condition-specific PMMS aligned with the Plan-Do-Check-Act (PDCA) cycle's goal of continuous improvement in management processes. This approach facilitates decision-making by employing machine learning algorithms at various levels, including network and project levels. And finally, by adopting an integrated approach that combines these levels, a more sustainable, condition-based, and data-driven PMMS can be developed, thereby enhancing the effectiveness of maintenance planning.