Mechanistic Load Restriction Decision Platform for Pavement Systems Prone to Moisture Variations

National Road Research Alliance

MnDOT Contract 1034192 Task 8: Final Memorandum on Research Benefits and Implementation Steps

Prepared by:

Majid Ghayoomi (PI)
Eshan Dave (Co-PI)
Francesco Preti (Graduate Research Assistant)

Department of Civil and Environmental Engineering
University of New Hampshire

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 RESEARCH PROJECT ABSTRACT AND OBJECTIVES

Excess moisture in aggregate base and subgrade soil layers has detrimental impacts on longevity and serviceability of pavements. Seasonal ground water level fluctuations, inundations due to storms and post-storm recess, frost penetrations and freeze-thaw effects lead to continuous moisture hysteresis and change of stress states in pavement foundation. Current analysis and design procedures often rely on approximate empirical approaches, which renders their ability to incorporate moisture-dependency and to conduct real-time and forecasted pavement capacity and load restriction analyses. A load restriction decision platform has been developed to provide a reliable and mechanistically-informed application (called PaveSafe) for pavement engineers to assess pavement performance and make traffic allowance decision during and after periods of excessive moisture. This app encompasses three core attributes: (1) A mechanics-based model that correctly captures soil and base response to saturated and unsaturated soil states. It was validated using actual pavement sections in Minnesota and North Dakota and can be further enhanced through the use of physically modelled scaled pavement sections as well as instrumented full scale test sections; (2) a system-based approach to integrate impacts of various stressors (soil moisture state, vehicular loads and volume, climatic conditions etc.), current pavement conditions, subgrade properties, hydro-geology, and short-term climate forecast. Due to large number of variables and their inter-dependencies, a system dynamics modelling approach can holistically capture all significant variables and provide a user-friendly system for pavement load restriction decision making; and (3) a mechanistically driven decision-platform that incorporates inputs from transportation agencies and users to facilitate its implementation and to realize the cost-effectiveness of such mechanistic approach.

1.2 SUMMARY OF RESEARCH METHODOLOGY (SCOPE)

This project developed a mechanistic pavement load restriction decision framework using system dynamics approach. The main outcome of this project is a toolkit for pavement engineers to make decisions regarding load restrictions due to storm-related and seasonal soil moisture variations, including those during post-flooding instances. The use of system-based approach was necessary to integrate impacts of various stressors (soil moisture state, vehicular loads and volume, climatic conditions etc.), current pavement conditions, subgrade properties, hydro-geology, and short-term climate forecast. Due to very large number of variables and their inter-dependencies, a system dynamics modelling approach can holistically capture all significant variables and provide a user-friendly tool for pavement load restriction (both in current time and for future forecasting) decision making. The current research was divided into 10 tasks. The study initiated with development of an initial memo to quantify research benefits and potential implementation steps (Task 1) and literature review (Task 2). This was followed with development of the system dynamics framework to mechanistically evaluate pavement load restrictions (Task 3). The next task pertained to conducting sensitivity analysis of the system dynamics model (Task 4). The next step was to develop a user-friendly toolkit that can be readily implemented for a pavement load restriction decision process (Task 5). The results in terms of deflection on the pavement surface from PaveSafe were compared to Layered Elastic Analysis (LEA) performed through the use of the commercial software for pavement evaluation GAMES (Task 6). In addition, PaveSafe was validated using data from Falling Weight Deflectometer (FWD) testing data on pavement sections before and after flooding events (Task 6). This memorandum (Task 8) finalizes the quantification of research benefits and provide guidance on implementation of the research products. Task 7 is out of state travel for researchers to present findings of this project at the annual meeting of the Transportation Research Board and Tasks 9 and 10 will develop and revise the final report for the study.

This memorandum serves as the primary deliverable for Task 8 (Research benefits and implementation steps) of the study.

1.3 ORGANIZATION OF THE MEMO

This memorandum is organized in three chapters. The subsequent two chapters provide a qualitative discussion of the estimated benefits as well as the key steps that agencies could take to implement the research including recommendations for the next phase that can enhance project outcomes through enhancements to the PaveSafe app as well as rigorous validation and refinement using physical modeling and instrumented pavement sections.

CHAPTER 2: RESEARCH BENEFITS

2.1 HOW DOES THIS RESEARCH BENEFIT TAXPAYERS OF THE NRRA MEMBER STATES?

At present, a majority of roadway load restriction (LR) protocols in NRRA state DOTs depend on either use of subsurface soil information, historic seasonal moisture data, or observational post-flooding evaluation. In addition, neither of these methodologies provide robust estimate of actual pavement structural load carrying capacity and these approaches do not account for climate variations within the assessment of roadways in post-storm scenarios. Further, none of these approaches allow for forecasting of load restrictions by using future climate predictions. Due to empirically driven nature of the LR protocols there is potential for imposing either over- or under- restriction on roadways. When over-restriction is used it results in losses to businesses due to limits imposed on trucking and other mean of freight transport. When there is under-restriction scenario, it substantially limits the life span of roadway infrastructure that can result in excessive pavement repair, rehabilitation and reconstruction costs. Thus, both of these scenarios would result in substantial economic loss to National Road Research Alliance (NRRA) member state entities as well as general population of those states.

This research developed a mechanistic framework to improve the robustness of load restriction decision process. Through use of mechanistic relationships within a system dynamics framework, the research study enhanced assessment procedures for pavement load capacity determination. The system dynamics framework allowed for a flexible platform that can incorporate multivariate effects and provide a tool with ability for forecasting. This tool can allow transportation officials to plan for storm-related and seasonal load restrictions into future. Finally, due to incorporation of hydrological, geotechnical and climatic inputs, the tool also has ability to aid in making decisions regarding post-flooding road traffic allowance as well as to plan for future road closing decisions. This ability will have tremendous effects on NRRA state DOTs' taxpayers as it directly impacts post-flooding access to affected areas, especially by emergency responders.

2.2 BENEFITS

The following benefits will be realized by adopting the outcomes of this research:

- **Decrease Engineering/Administrative Costs:** The developed decision toolkit will facilitate and accelerate decision-making process by state DOTs with regards to when the road should be reopened after flooding. This will result in less personnel time for both field assessments and analytical evaluations. In fact, it was demonstrated how with the use of PaveSafe software it is possible to make relatively accurate prediction of pavement structure response under traffic loading application in different conditions. This would eliminate or lower the need for in situ testing (e.g. FWD testing) and subsequent analysis of the collected data.

- **Lifecycle:** This research provides more reliable evaluation of pavement capacity to different vehicular classes both under current condition and short-term future forecasted climate. Such mechanistic assessment would increase the lifespan of roadways by minimizing the frequency of very high traffic-induced roadway damage potentials which in-turn will improve pavement longevity. This is an important advantage with respect to the current approach, which does not provide any forecasting ability. Furthermore, by imposing load restrictions during vulnerable states, pavement longevity will be extended.
- **Operation and Maintenance Savings**: The results of this project including the sensitivity analysis, pavement performance assessment, and the development of the toolkit will reduce the maintenance costs of roadways by providing a decision platform for load and traffic restrictions when the roads are in their vulnerable state. All of these research outcomes generated new knowledge with respect to pavement and climate conditions that could increase pavement vulnerability to damage. This information as well as the use of PaveSafe will result in lowering of maintenance needs and costs.
- **Reduce Risk:** The results from system dynamics sensitivity analysis through a holistic, multivariate and mechanistic pavement response assessment increased the reliability of the load restriction decisions app, which reduces the risk of substantial damage to roadways as well as to road-users.
- **Selective reopening:** The ability of the software to simulate the pavement response under different vehicle classes loading application and identify which vehicles are safe to transit on the roadway section and which ones are not, allows to perform more selective decisions for traffic restrictions. For example, instead of completely closing the roadway to traffic, only the vehicle classes that resulted in pavement deflections that would exceed the assigned threshold in the software simulation, can be restricted from having access to the roadway section.

2.3 CURRENT TECHNICAL OUTCOME

The following list summarizes all the technical outcome from the research up to date:

- A mechanistic framework to improve robustness of the load restriction decision process was developed using system dynamics approach.
- A flexible platform that incorporates multivariate effects with forecasting capability was implemented. This was achieved through system dynamics modeling and analysis.
- A toolkit was developed for load restriction decision, especially for post-flooding road restrictions. This toolkit was verified by comparing its results in terms of surface deflection with a commercial software for pavement evaluation (GAMES) and further validated using field data (FWD testing results),.
- The use of the toolkit will improve post-flooding and seasonal pavement performance assessment.

CHAPTER 3: POTENTIAL IMPLEMENTATION STEPS

3.1 INTRODUCTION

To further enhance the developed decision framework and toolkit, more detailed mechanistic pavement performance data are needed. In addition, to reduce the material model uncertainties and improve the pavement structure response calculation, results from systematically controlled and monitored pavement response should be incorporated. Thus, a subsequent project phase is proposed that could include improvement of software graphical interface and computational efficiency, series of physical modeling and testing of scaled and full-scale pavement sections, and instrumented field segments monitored pre- and post-flooding.

3.2 RESEARCH IMPLEMENTATION STEPS

The implementation strategy and project flow chart is schematically shown in Figure 3-1.

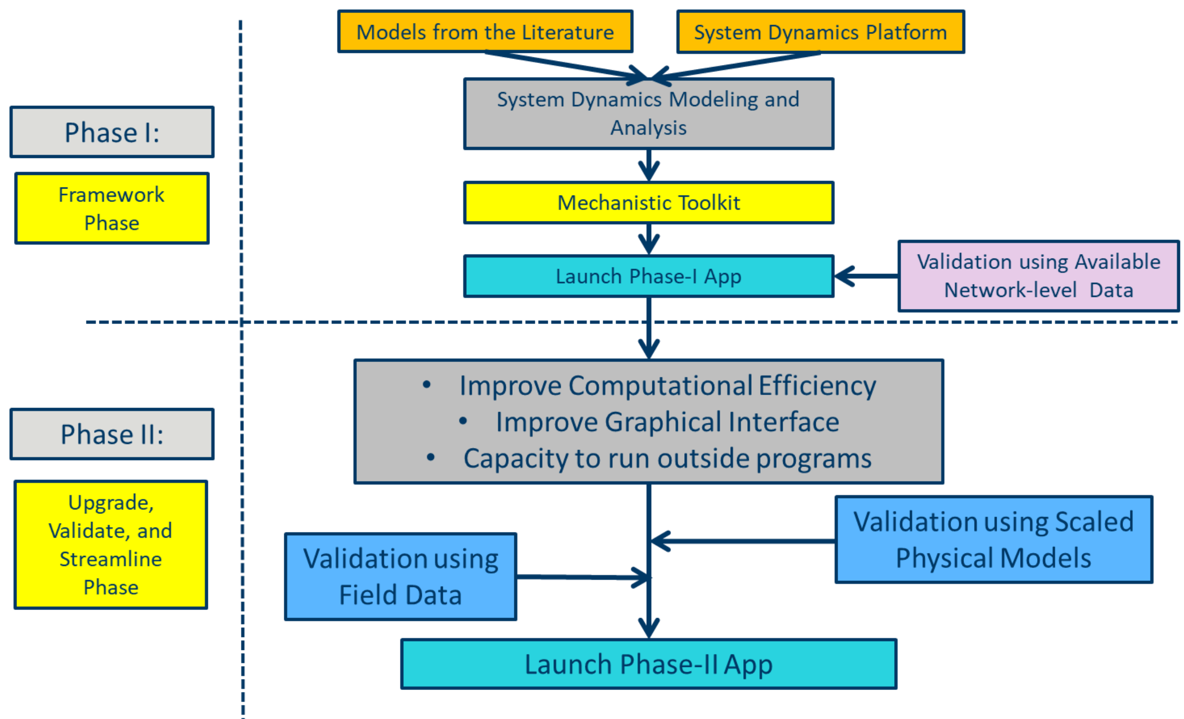

Figure 3-1 Implementation Flow Chart

The proposed comprehensive pavement assessment platform incorporates various components with major effects on pavement systems including:

- Pavement structural properties such as pavement layer types, modulus, Poisson's ratio, and thickness.

- Climatic conditions such as rainfall induced water infiltration in unsaturated soil zone.
- Soil properties such as type, density, plasticity, resilient modulus, and soil-water retention characteristics.
- Loading conditions such as vehicle type and load repetition.

Systems dynamics was implemented using a computer software, i.e. Vensim. Vensim is a simulation software for improving the performance of real systems. It is capable of conducting sensitivity analysis, reality checks, statistical modeling, and instant outputting. Different models/equations presented in previous Tasks are included in this model.

After completing the system dynamics modeling and analysis, the information was used for developing a user-friendly toolkit for load restriction decision. This toolkit will facilitate user interface with different expertise level and different output formats. Then, the toolkit was verified with comparison to commercial pavement design software and validated based on available FWD testing results from pavement sections in Minnesota and North Dakota, both before and after flooding events. This was completed in the current project and a Phase-I version of the toolkit was launched for TAP input and assessment. As shown in Figure 3-1, Phase 2 of the project is expected to involve an improvement of the computational efficiency of the software, improve the graphical interface and it could be potentially implemented with the ability to run outside programs and perform Linear Elastic Analysis (LEA) of the pavement structure. In addition, physical modeling of inundated pavements would be implemented, which would include both scaled and full-scale models. These will be very helpful for a better evaluation of the toolkit, improve the system, and refine some of the underlying constitutive and material models. For example, a variability for the SWRC parameters for the different subsurface materials could be introduced based on the physical modeling results. Subsequently, the software could be implemented with the ability of running Monte Carlo simulation to calculate the uncertainty related to the predicted outcomes and the probability associated with the results. At this point, a second round of validation for the software could be performed comparing its results to available field data (e.g. FWD testing results). All of those steps would contribute to Phase 2 toolkit launch.

3.3 BENEFIT IMPLEMENTATION AND QUANTIFICATION

The benefits listed in Section 2.2 were implemented and quantified through the following approaches:

- Task 2 provided a comprehensive assessment of current state-of-the knowledge and practice. This was important in order to identify the need for better models to reduce risk, which was discussed in the Task 2 Deliverable.

- Task 4 identified key factors in post-inundation pavement response (with a focus on post-flooded conditions) through a system dynamics sensitivity analysis. The results provided a quantifiable measure of how a mechanistic model will improve the current approaches by state DOTs. Thus, the outcome clarified how the lifecycle can be impacted by such model, maintenance costs will be saved, and the risk of damage to roadways will be reduced.

- Task 5 generated a toolkit to be used by state DOTs to decrease the engineering/administrative costs. The verification/validation step included in Task 6, in comparison with currently available field data (FWD testing results), showed the ability of the toolkit to achieve the listed benefits.
- Task 9 will provide a comprehensive report including literature review and all of the findings from the research up to the launch of Phase-I App and all the verification and validation results.
- Task 10 will involve editorial review and publication of final report. This task will also include a recorded webinar highlighting key project outcomes as well as necessary steps involved with adoption of research products by transportation agencies.

CHAPTER 4: PROJECT PHASE II AND CONCLUSIONS

4.1 PHASE II: UPGRADE, VALIDATE AND STREAMLINE PAVESAFE APP

The Phase II of the project could enhance and amplify the recently developed post-flooding roadway assessment app (“PaveSafe”). Although the current toolkit encompasses all fundamental aspects of pavement response, it incorporates several material models and constitutive relations from the literature. Some of these relations are empirical and some were developed for limited material options or boundary conditions. Thus, it is expected that the toolkit requires additional validation and modification. These modifications are needed to ensure the most accurate and reliable pavement response assessment. Further, this calibration and validation campaign should be done at different scales to provide a balanced approach between the practicality and technical soundness. The envisioned calibration and validation campaign could be developed based on a phased approach: (1) using the currently available network-level data; (2) using the results of small-scale physical models; (3) using the results of large scale physical models; (4) using advance numerical models; and (5) using field data from instrumented road sections. Lastly, the ability to import agency specific inputs (such as each agencies traffic characterization system as well as load spectra and typical material inputs) is presently limited. For wide-spread implementation this functionality needs to be added.

4.2 CONCLUSIONS

In conclusion, Phase II of the project could involve: (1) development of a scaled pavement physical model for conducting experiments with variable moisture profiles within pavement to amplify, calibrate and validate the toolkit; (2) update and refinement of Phase-I app, on the basis of results and findings from scale physical model testing; (3) enhancement of the toolkit user-interface through inclusion of more graphical features and capacity to interact with other common pavement analysis software. The proposed research effort would focus on dissemination of research by providing training and implementation support to transportation agencies (local and state) to adopt the toolkit. This includes asking state members to test the toolkit and provide feedback during various phases of the project. The final product would provide immediate access to a decision toolkit that can be easily implemented by state DOTs for post-flooding roadway assessment.