CTIPS Center for Transformative Infrastructure Preservation and Sustainability
USDOT Region 8 University Transportation Center

Assessing Condition of Rehabilitated Concrete Pavement with Slab Fracturing and Asphalt Overlay Using Distributed Fiber Optic Sensors

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Research Needs

The increasing number of vehicles places significant stress on transportation and road infrastructure, resulting in heightened congestion, wear, and tear. This vehicular surge leads to the formation of cracks, and in severe cases, reconstruction may become necessary. The reconstruction incurs prolonged disruptions in transportation, necessitates more extensive financial and human efforts, and further strains the infrastructure, exacerbating stress on transportation systems. On the other hand, if the cracks in the existing pavements are not serve and the reconstruction is not necessary, repair and rehabilitation is a more economic and effective approach for pavement maintenance. Among various pavement rehabilitation methods, asphalt overlay is a common practice. The Federal Highway Administration (FHWA) reports that the U.S. has 108,603 lane miles of composite pavements (PCC overlaid with asphalt), which is nearly double the lane miles of PCC-surfaced pavements ("Highway Statistics 2015 - Policy | Federal Highway Administration," n.d.). That means that nearly two-thirds of the concrete pavements in the U.S. have been overlaid with asphalt (West et al., 2020).

However, asphalt overlays on PCC pavements have a persistent problem, which is reflective cracking of joints and cracks through the asphalt overlays over time, leading to a shortened performance life of the overlay. Rather than removing the concrete, which can be costly to the owner agency and increase delay times for the travelling public, slab-fracturing techniques can be used prior to placement of an asphalt overlay to significantly reduce stress concentrations at concrete joints and cracks. There are three slab fracturing techniques methods, including crack and seat (C&S) for PCC without steel reinforcement, break and seat (B&S) for PCC with steel reinforcement, and rubblization for any type of concrete pavement. C&S is intended to reduce the effective slab length of PCC pavements by producing tight surface cracks. B&S is similar but typically requires greater fracturing effort. The rubblization process typically fractures slabs into fragments with a nominal size of 4 to 8 inches (Buncher et al., 2008; National Asphalt Pavement Association, 1999). In 1994, the National Asphalt Pavement Association (NAPA) released Information Series (IS)-117 Guidelines for Use of Asphalt Overlays to Rehabilitate PCC Pavements, describing the slab-fracturing processes and equipment (National Asphalt Pavement Association, 1999). Since then, many states have begun to expand the concrete pavement rehabilitation using slab fracturing and asphalt overlay.

To assess the performance of different PCC rehabilitation treatments, the Long-Term Pavement Performance (LTPP) program Specific Pavement Studies (SPS)-6 experiment was initiated, including 14 construction projects distributed among three climatic regions (wet-freeze, 9 wet-no freezes, and dry-freeze) (Hall et al., 2003, 2002). Among those, two sites are still active. They suggested performing site-by-site analyses to determine the effects of design factors and treatment methods on the long-term performance of rehabilitated pavements. However, there are limited technologies which can be used to assess or monitor the real-time conditions of the rehabilitated concrete pavement using slab fracturing and asphalt overlay. Researchers are exploring various methods for onsite early crack detection using cameras and light detection and ranging (Hu et al., 2024; Jiang et al., 2024) being a frequently used approach due to their ease of installation and ability to cover larger areas compared to point sensors. However, cameras can only identify surface cracks, while many originate from the bottom of the road. By the time these bottom cracks surface, the road issues have already become severe.

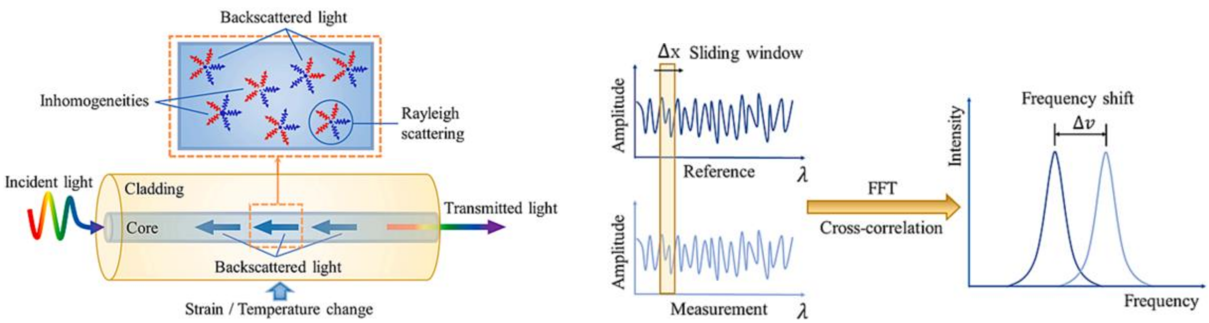
Therefore, it is essential to understand how the crack initialized and progressed in the rehabilitated concrete pavement using slab fracturing and asphalt overlay, however, is very challenging to assess. Previous lab experiments (Alshandah et al., 2020) revealed that the fiber optic sensors such as fiber Bragg grating (FBG) sensors embedded in pavement demonstrated an average accuracy of 82.4% in detecting bottom-up cracking propagation, especially when the cracks were in close proximity. However, due to the localized nature of FBG sensors as point sensors, crack detection is restricted to specific locations and faces challenges in accurately determining the distribution of cracks, requiring the installation of numerous sensors, incurring high costs and demanding substantial human effort. Predicting crack positions and distribution remaining challenging. In recent years, distributed fiber optic sensors (DFOS) have brought significant attention in detecting cracks of concrete and steel structures, which may provide a potential solution to understand the effectiveness of the rehabilitation using slab fracturing and asphalt overlay.

Research Objectives

The research aims to address the challenges and fill the existing research gap in understanding the cracking penetration pattern in the rehabilitated concrete pavement using slab fracturing and asphalt overlay. As vehicular traffic increases, so does the stress on transportation infrastructure, leading to cracks and wear on road surfaces. While asphalt overlays are a common method for pavement rehabilitation, they often suffer from reflective cracking over time, necessitating costly repairs. Slab-fracturing techniques offer a solution to reduce stress concentrations in concrete joints and cracks, but monitoring their effectiveness remains a challenge. To overcome this, the research proposes the use of distributed fiber optic sensing (DFOS) to detect bottom-up cracking, identify potential penetration paths, and assess the condition of rehabilitated pavements.

Research Methods

Distributed fiber optic sensing (as shown in Figure 1) network is proposed to detect bottom-up cracking, identify the potential penetration paths of cracking, and assess the condition of the rehabilitated pavements. The DFOS, operating on the principle of Optical Frequency Domain Reflectometry, utilizes coherent light interference to detect variations in the refractive index of an optical fiber caused by external factors such as strain or temperature changes. As a broadband optical source emits light guided through the fiber, it interacts with the fiber's refractive index variations along its length. These variations in scattering amplitude are unique, static, and highly repeatable properties of the fiber [Figure 1 (a)]. When temperature or strain is applied, inducing shifts in the Rayleigh scattering spectrum, they are identified through cross-correlation between the reference and perturbed signals [Figure 1 (b)]. Through signal processing techniques like Fast Fourier Transform, the amplitude of backscattered signals is converted to the frequency domain. The fiber is segmented into equally-length segments using a sliding window, allowing for the evaluation of frequency shifts and the accurate detection of changes in temperature and strain along the length of the fiber (Xu et al., 2024).



(a) (b)

Figure 1. Optical Frequency Domain Reflectometry sensing principle shows
(a) Rayleigh scattering in a single-mode optical fiber, and
(b) signal processing for measuring strain or temperature changes.

This study aims to bridge the above-mentioned research gaps by conducting numerical and laboratory experiments to examine the effectiveness of applying DFOS for such applications. Before directly employing the DFOS to assess cracking in rehabilitated concrete pavement, a numerical simulation utilizing finite element analysis such as ABAQUS or ANSYS will be conducted. This numerical simulation will entail diverse pavement materials and layer configurations, with a specific focus on the surface layer (asphalt). Both heterogeneous and homogeneous models will be meticulously tailored for the asphalt layer, with additional consideration given to subsequent pavement layers, including the concrete pavement base. By comprehensively simulating real pavement road conditions and analyzing crack tip parameters and their impacts on crack propagation, aggregate distribution, and crack length variations, this numerical simulation aims to understand the crack formation mechanisms.

Following the numerical simulation, laboratory testing will be performed to test the DFOS for monitoring of crack propagation in the laboratory specimens subjected to controlled loading conditions. Continuous surveillance of changes in strain and temperature along the length of the specimens will be facilitated by the DFOS, providing real-time data insights into crack initiation and propagation dynamics. This information will be used to calibrate the sensors, conduct sensitivity analysis, understand the cracking penetration patterns, and assess the effectiveness of the sensing network.

The significance and potential impact of this study lie in its capacity to revolutionize pavement condition monitoring through the innovative application of DFOS. By introducing a novel approach to crack detection from a bottom-up perspective, this research aims to significantly enhance early identification capabilities. The proposed methodology, underpinned by comprehensive lab experiments, promises to yield invaluable insights into the effectiveness of DFOS for pavement assessment. Ultimately, the outcomes of this study hold the potential to drive significant advancements in infrastructure maintenance practices, furnishing stakeholders with more accurate and timely information for informed decision-making. Specifically, this project focuses on three major tasks as below.

<u>Task 1: Investigation of Traffic Loading Influence on Crack Tip Parameters in the Rehabilitated Concrete Pavement using Slab Fracturing and Asphalt Overlay Using Finite Element Analysis</u>

<u>*Task 1.1 Pavement Structure Setup for Bottom-up Crack Propagation Simulation (1-2 months):*</u>
This study aims to comprehensively analyze crack formation and propagation within pavement layers, with a particular focus on the asphalt layer. Initially, the study considers the geometric complexities inherent in typical road structures, encompassing multiple layers such as the asphalt overlay, PPC layer, base layer, subbase layer, and subgrade layer. Using ABAQUS or ANSYS software, a Finite Element Model is crafted to simulate potential cracks in the pavement, thereby elucidating the influence of traffic loading on crack formation dynamics. After setting up the basic road information, special attention is given to the most crucial layer for crack monitoring, which is the asphalt layer. Design specifications for the asphalt layer are necessary for this study. Typically, two modeling approaches are used for simulating asphalt: homogeneous and heterogeneous models. Homogeneous models are valued for their simplicity and ease of use in simulation studies, assuming uniform material properties across pavement layers. They offer computational efficiency and quick insights into pavement behavior. Conversely, heterogeneous

models provide a more realistic representation by considering material variability, reflecting the actual pavement composition and yielding more accurate results.

Comparing both modeling approaches allows for a comprehensive assessment of material variability's impact on crack propagation and pavement performance. While previous research predominantly relies on homogeneous models to analyze asphalt, it's crucial to acknowledge asphalt's inherent heterogeneity due to its composite nature. Incorporating both modeling approaches enables a comparative analysis, evaluating their accuracy in representing real-world pavement behavior. Furthermore, considering sieve size for the heterogeneous model enhances simulation comprehensiveness by accurately representing asphalt mixture composition. This improvement leads to more precise predictions of crack propagation and pavement distress.

Task 1.2 Sensitivity Analysis and Parameter Optimization for Crack Propagation Simulation (3-5 months): This task involves conducting a sensitivity analysis and establishing critical parameters necessary for simulating crack propagation using the Finite Element Model in ABAQUS. The analysis will focus on crack tip parameters, including Stress Intensity Factors (KI, KII), and T-stress, under various traffic loading conditions. Stress Intensity Factors (KI, KII) quantify stress concentration at the crack tip, with KI representing tensile stress and KII representing in-plane shear stress. Understanding these factors aids in designing resilient pavement structures. T-stress reflects the out-of-plane stress component at the crack tip, aiding in predicting crack behavior under different loading conditions. Analyzing the interplay between KI, KII, and T-stress facilitates more accurate crack propagation prediction and pavement design. Additionally, this study will conduct sensitivity tests on parameters such as vehicle weight, wheel distance relative to the crack plane, and coarse aggregate distribution. The pressure exerted by vehicles, computed based on their weight and tire contact surface, will be transferred to the pavement through pressure distribution and applied to the simulation. Understanding the influence of these factors on crack behavior enhances pavement design accuracy and resilience against real-world traffic conditions.

Furthermore, the study will explore variations in material properties, including the modulus of elasticity, Poisson's ratio, and layer thickness. Analyzing these variations enables the selection of materials better suited to prevent cracks and ensure longer pavement lifespan, resulting in substantial cost savings over the pavement's lifecycle. Moreover, investigating aggregate distribution and crack length dynamics enhances understanding of crack behavior and propagation mechanisms. This understanding informs the development of targeted maintenance strategies, enabling timely interventions to mitigate crack propagation and extend pavement service life. By addressing cracks promptly and effectively, road agencies can minimize road hazards, ensure smoother driving experiences, and maximize pavement durability, benefiting both road users and communities.

Task 2: Experimental Investigation of Crack Propagation in the Rehabilitated Concrete Pavement Using Slab Fracturing and Asphalt Overlay

Task 2.1 Preparation of Two-Layer Pavement Specimens with DFOS Installation for Crack Propagation Analysis (5-7 months): To mimic bottom-up cracks in the rehabilitated concrete pavement using slab fracturing and asphalt overlay, this task will design testing specimens with two layers composed of asphalt and concrete materials. The goal is to simulate conditions where the lower layer (asphalt) develops cracks and examine how these bottom-up cracks propagate to the upper layer (concrete). The concrete layer will be artificially cracked to simulate real-world conditions and observe how cracks propagate to the upper layer under various loading conditions as shown in Figure 2. DFOS sensors will be installed in the asphalt layer to measure strain when bottom-up cracks emerge. Various parameters identified from the simulations in Task 1 will be applied to test the samples.

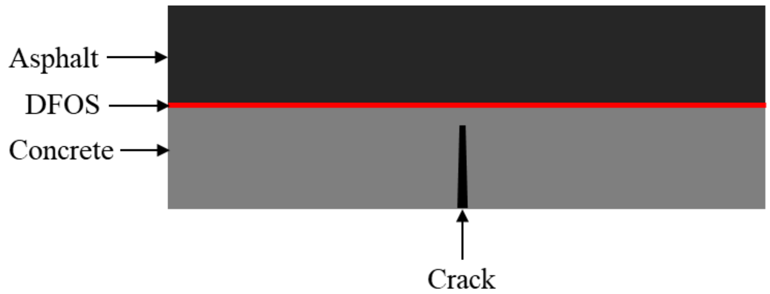


Figure 2. Two-layer specimen with DFOS installation.

The DFOS will be installed in two distinct layouts to facilitate comprehensive monitoring. The initial layout involves positioning sensors on both sides of the wheel path, running parallel to it, as depicted in Figure 3 (a). The second layout adopts a zig-zag configuration around the wheel path, as illustrated in Figure 3 (b). These layouts are strategically designed to capture strain distribution and crack propagation dynamics across the pavement surface under different loading conditions. By enabling real-time monitoring of strain and temperature changes induced by loading and environmental factors, the DFOS will provide valuable insights. Continuous data acquisition systems will be utilized to collect and process sensor data seamlessly.

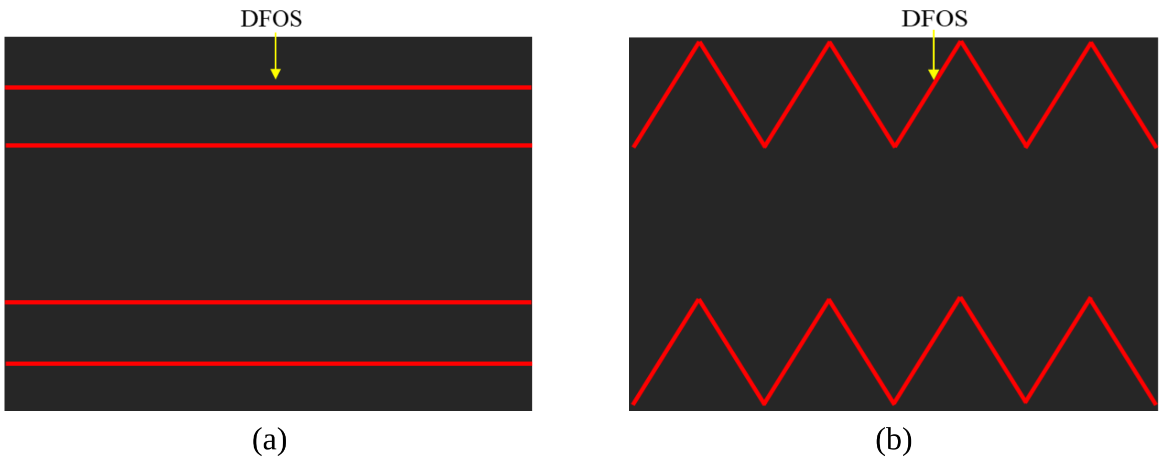


Figure 3. DFOS installation layout (a) parallel to wheel path; (b) zig-zag around wheel path.

<u>Task 2.2 Experimental Investigation of Crack Propagation in Asphalt-Concrete Specimens Using Wheel Tracker Machine and DFOS (7-9 months):</u> After preparing the specimens, experiments using the wheel tracker machine (Figure 4) can commence. The various parameters determined in Task 1.3 will be utilized to apply the loading wheel load and position to the specimens. Cracks in the asphalt layer will manifest after the wheel applies rotations. Approximately 40 cycles per

minute will be applied to the specimens. The specimens will undergo continuous monitoring to track crack propagation, assessing parameters such as crack length and width across various loading conditions. Data collected from the DFOS will be analyzed to evaluate crack propagation, utilizing signal processing methodologies and data visualization techniques to interpret sensor outputs and identify critical areas susceptible to cracking. Correlation between the DFOS data and crack propagation patterns observed through visual inspections and other monitoring methods will be established, enhancing understanding of the relationship between sensor measurements and actual pavement distress. A camera positioned next to the specimen will monitor crack formation on the asphalt layer. The camera results will be compared with those from the DFOS to calibrate and validate the findings.

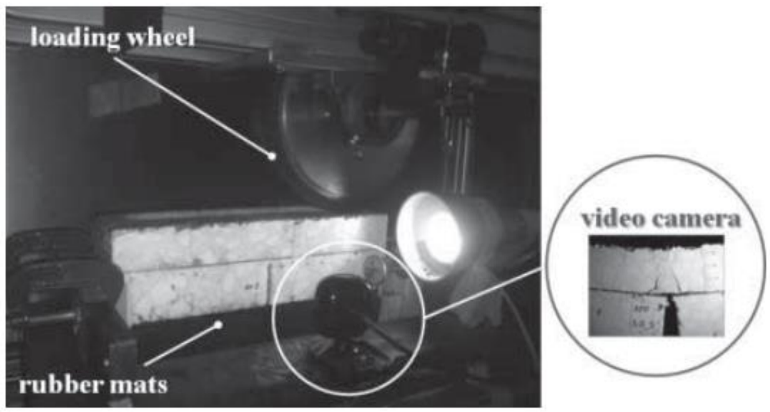


Figure 4. Wheel Tracker Machine Setup and Crack Monitoring Camera Placement (Pasquini et al., 2015).

<u>Task 3: Comparative Analysis of Finite Element and Experimental Results and Final Report Preparation</u>

<u>*Task 3.1 Comparative Analysis (10-11 months):*</u> The results obtained from Task 1 (finite element analyses) and Task 2 (experimental analyses) will undergo comparison and analysis. Discrepancies or similarities in crack propagation behavior and crack tip parameters between the finite element analyses and experimental analyses will be identified and interpreted. A correlation study will be conducted to assess the degree of agreement between the finite element predictions and experimental observations, utilizing statistical methods and correlation coefficients to quantify the correlation between the two sets of results.

<u>*Task 3.2 Final Report (11-12 months):*</u> A final technical report will be completed and submitted for review two weeks prior to the project's end date, ensuring compliance with all necessary submission requirements.

Relevance to Strategic Goals

The proposed project aligns closely with the USDOT strategic goal of Safety, which serves as the primary focus of the initiative. By implementing DFOS to monitor crack propagation and assess the condition of rehabilitated concrete pavement, the project directly contributes to enhancing road safety. Through early detection of cracks and identification of potential penetration paths, the project aims to mitigate the risks associated with deteriorating road infrastructure, thereby reducing the likelihood of accidents and injuries for motorists. Furthermore, the project's secondary alignment with the strategic goal of Climate and Sustainability underscores its broader impact on transportation systems. By promoting proactive maintenance strategies and minimizing the need for costly repairs and reconstruction, the project contributes to the sustainability of transportation infrastructure, reducing resource consumption and environmental impact associated with extensive pavement rehabilitation efforts. Overall, the project's focus on safety and sustainability underscores its significant relevance to the strategic goals outlined by USDOT, positioning it as a vital initiative in ensuring the resilience and efficiency of transportation networks.

Educational Benefits

This project will involve train graduate students and one undergraduate student. The students will participate the numerical simulation, design the experiments, and conduct the experimental studies discussed in the Tasks. In addition, this project will also be used as a demonstration course project for CE303L Materials Lab with an enrollment of 50~60 undergraduate students and CME303 Construction Materials with an enrollment of around 50 undergraduate students to show the students how to construct real-world concrete pavement and the asphalt overlays.

Outputs through Technology Transfer

This project will transfer technology through peer-reviewed research report, one to two peer-reviewed journal articles, one to two peer-reviewed conference papers, in addition to newsletters, workshops, webinars, seminars, the CTIPS website, etc. This project will also participate the CTIPS T2 programs to engage clients and disseminating research results through (1) virtual delivery via live webinars, recorded online modules, videoconferences; (2) in-person seminars or presentations; (3) conferences or workshops that organize related T2 topics into day-long or multi-day events.

Expected Outcomes and Impacts

The expected outcomes of this research include:

1) Advancements in pavement condition monitoring through the innovative application of distributed fiber optic sensing (DFOS) technology and assessing the effectiveness of DFOS in real-world scenarios;
2) Comprehensively understanding crack formation mechanisms by integrating numerical simulations and laboratory experiments;
3) Providing insights into crack propagation dynamics, crack initiation and propagation, and pavement behavior prediction, and enabling early identification of pavement issues.

The outcomes of this project promise to revolutionize infrastructure maintenance practices by providing stakeholders with accurate and timely information for informed decision-making, ultimately enhancing the longevity and sustainability of transportation networks.

Work Plan

The main tasks are as follows:

TASK 1: Investigation of Traffic Loading Influence on Crack Tip Parameters in the Rehabilitated Concrete Pavement using Slab Fracturing and Asphalt Overlay Using Finite Element Analysis

TASK 1.1 Pavement Structure Setup for Bottom-up Crack Propagation Simulation (1-2 months)

1) Establish geometric complexities within pavement layers.
2) Create Finite Element Model in simulation software.
3) Model asphalt layer using homogeneous and heterogeneous approaches.
4) Conduct sieve size analysis for heterogeneous model.
5) Compare modeling approaches for crack propagation analysis.

TASK 1.2 Sensitivity Analysis and Parameter Optimization for Crack Propagation Simulation (3-5 months)

1) Conduct sensitivity analysis on crack tip parameters.
2) Analyze Stress Intensity Factors (KI, KII) and T-stress.
3) Perform sensitivity tests on parameters like vehicle weight and wheel distance.
4) Investigate variations in material properties and aggregate distribution.
5) Optimize parameters for more accurate crack propagation prediction.

TASK 2: Experimental Investigation of Crack Propagation in the Rehabilitated Concrete Pavement Using Slab Fracturing and Asphalt Overlay

TASK 2.1 Preparation of Two-Layer Pavement Specimens with DFOS Installation for Crack Propagation Analysis (5-7 months)

1) Design two-layer pavement specimens with asphalt and concrete materials.
2) Install DFOS sensors in the asphalt layer.
3) Implement two distinct layouts for DFOS installation.
4) Enable continuous monitoring of strain and temperature changes.

TASK 2.2 Experimental Investigation of Crack Propagation in Asphalt-Concrete Specimens Using Wheel Tracker Machine and DFOS (7-9 months)

1) Apply wheel load and rotations using the wheel tracker machine.
2) Monitor crack propagation and assess parameters like crack length and width.
3) Analyze DFOS data to evaluate crack propagation dynamics.
4) Compare camera results with DFOS data for calibration and validation.

TASK 3: Comparative Analysis of Finite Element and Experimental Results and Final Report Preparation

TASK 3.1 Comparative Analysis (10-11 months)

1) Compare results from finite element analyses and experimental analyses.
2) Identify discrepancies or similarities in crack propagation behavior.
3) Conduct correlation study between finite element predictions and experimental observations.

TASK 3.2 Final Report (11-12 months)

1) Compile and prepare a comprehensive technical report.
2) Ensure compliance with all necessary submission requirements.

Project Cost

Total Project Costs:	$230,158
CTIPS Funds Requested:	$115,079
Matching Funds:	$115,079
Source of Matching Funds:	North Dakota State University

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