Measuring Concrete Sleeper Rail Seat Pressure Distribution with Matrix Based Tactile Surface Sensors

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Abstract

A sustained increase in gross rail loads and cumulative freight tonnages worldwide is placing an increasing demand on railway infrastructure and its components, especially on heavy haul and shared railway infrastructure. To meet to this demand, concrete sleepers will require increased strength and durability, and the industry must also developed a deeper understanding of failure modes. One of the typical failure modes for concrete sleepers in North America is Rail Seat Deterioration (RSD), which can initiate through multiple failure mechanisms. Researchers have hypothesized that localized crushing of the concrete in the rail seat is one of the potential mechanisms that contributes to RSD. To better understand this mechanism, the University of Illinois at Urbana-Champaign (UIUC) is utilizing a matrix based tactile surface sensor (MBTSS) to measure and quantify the forces and pressure distribution acting at the contact interface between the concrete rail seat and the bottom of the rail pad. Preliminary data collected during laboratory testing has shown that a direct relationship exists between rail pad modulus (stiffness) and maximum rail seat force. A direct relationship between the lateral/vertical (L/V) force ratio and the maximum field side rail seat force has also been observed. Given that all preliminary results indicate that various combinations of pad stiffness, track geometry, and L/V ratios create localized areas of high pressure, crushing remains a potential mechanism leading to RSD, as will be discussed in this paper. Through the analysis of rail seat pressure data, valuable insight will be gained that can be applied to the development of concrete sleeper and fastening system component designs that meet current and projected service demands.

1. Introduction

Concrete sleepers are most economical in locations that place high demands on the railroad track structure and/or necessitate stringent geometric tolerances. For North American use, they were adopted in response to the inability of timber sleepers to perform satisfactorily in certain severe service conditions, such as areas of high curvature, heavy axle load or high speed passenger train traffic, high annual gross tonnages, steep grades, and severe climatic conditions [1]. The cast-in shoulders and molded rail seat of concrete sleepers increase their ability to hold gage under these loading conditions [1].

Concrete sleepers are not without their design and performance challenges. As reported in surveys conducted by the University of Illinois at Urbana-Champaign (UIUC) in 2008 and 2012, North American Class I Railroads and other railway infrastructure experts ranked rail seat deterioration (RSD) as one of the most critical problems associated with concrete sleeper and fastening system performance [2, 3]. Problems that arise from the deterioration of the concrete rail seat surface include widening of gauge, reduction in toe load of fastening clips, and insufficient rail cant [2]. All of these problems have the potential to create unsafe operating conditions and an increased risk of rail rollover derailments [4].

A suspected cause of RSD is high forces acting on the concrete rail seat surface, often in concentrated areas. To address this, a study was performed by the John A. Volpe National Transportation Systems Center on the effect of wheel/rail loads on concrete tie stresses and rail rollover. This study confirmed the possibility of these concentrated loadings producing stresses higher than the minimum design compressive strength of concrete as specified by the American Railway Engineering and Maintenance-of-Way Association (AREMA) [4].

The combination of static wheel loads and the dynamic impact loads that can occur due to track support variations, wheel defects, or rail irregularities, impart loads into the rail seat that potentially damage the concrete surface [5]. In North America, concrete sleeper track is often much stiffer than timber track. According to the *AREMA Manual for Railway Engineering,* the typical track modulus value for mainline concrete sleeper track is 41,370 N/m^2 (6,000 lb/in^2), which is twice as stiff as the typical timber sleeper track modulus of 20,680 N/m^2 (3,000 lb/in^2) [6]. A track structure that is stiffer produces a less resilient response to impact loads, resulting in higher loads being applied to the concrete rail seat surface. The design of the fastening system components plays a crucial role in providing some of the resiliency necessary to attenuate loads without damaging the concrete [7].

To better understand the forces acting at this surface, researchers at UIUC are using matrix based tactile surface sensors (MBTSS) as a means to measure load magnitude and distribution. MBTSS have been previously used in experimentation under the tie plates on timber sleepers [8]; however, researchers at UIUC are using this technology to explore the pressure distribution on the rail seats of concrete sleepers.

There are many factors that affect the rail seat pressure distribution, one of which is the transfer of forces at the wheel/rail interface through the rail web and base, which is then dstirubted through the rail pad assembly onto the rail seat of the sleeper. Additionally, the lateral to vertical (L/V) ratio of these resultant forces also vary greatly depending on track geometry conditions, as well as train operating speeds on curved track. Shared infrastructure presents diverging engineering requirements for track that can accommodate the heavy axle loads of slower speed freight trains with the possibility of high dynamic loads from higher speed passenger trains. The variables affecting the magnitude and distribution of pressure on the concrete rail seat are explored through laboratory experimentation. Preliminary results from these experimental tests are documented in this paper. It should be noted that material in this paper was also presented at the AREMA 2012 Conference in Chicago, Illinois, USA [9].

1.1 Sensor Technology and Protection

The sensor technology UIUC is currently using for quantifying forces and pressure distribution at the rail seat is the MBTSS manufactured by Tekscan® Inc. The MBTSS has an approximate thickness of 0.010 cm (0.004 in), and to protect from shear forces and puncture, is covered on both sides with thin layers of polytetrafluoroethylene (PTFE) and bi-axially oriented Polyethylene Terephthalate (BoPET). These two materials have thicknesses of 0.015 cm (0.006 in) and 0.018 cm (0.007 in), respectively. Calibration of MBTSS is conducted by applying known loads and correlating the loads with the respective raw sum units. This process emphasizes the importance of laboratory testing and familiarization with the technology prior to performing field testing.

1.2 Experimental Setup

UIUC's experimental testing was performed at the Advanced Transportation Research and Engineering Laboratory (ATREL). The Pulsating Load Testing Machine (PLTM), which is used to perform American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6 (Wear and Abrasion), as well as other experimental testing related to concrete sleepers and fastening systems, was used to execute the experiments within this paper. The PLTM consists of one horizontal and two vertical actuators, both attached to a steel loading head that encapsulates a short section of rail attached to one of the two rail seats on a concrete sleeper. Preliminary UIUC research included installing a MBTSS in the concrete sleeper fastening system, directly on the concrete rail seat area and beneath the rail pad, and loading the tie using the PLTM. The same MBTSS was used throughout each respective experiment to remove the possibility of inter-sensor variability.

2. Results of Experimentation

Several experiments have been conducted by UIUC researchers to collect data on the distribution of pressure on the concrete sleeper rail seat based on expected loading conditions at the rail seat. It should be noted that the experimental setup is not meant to replicate the common loading conditions seen in the field, but is designed to simulate extreme loading conditions that occur in the field. Therefore, this experimental setup simulates a single wheel load imparted onto a single sleeper.

This test was conducted to analyze and quantify the loading behavior at this interface using a variety of load inputs and todetermine a relationship between the rail pad modulus (a proxy for stiffness) and pressure distribution at the rail seat. Furthermore, various L/V ratios were explored in an attempt to simulate a variety of rail vehicle and track interaction conditions that could occur at the wheel/rail interface. Another objective of this testing was also to determine a relationship between L/V ratio and pressure distribution at the rail seat varying the rail pad component of the fastening system. There are many variables that can affect the L/V ratio, including the curve radius, wheel/rail interface profiles, suspension characteristics of railcar trucks, and train speed [10]. Researchers at UIUC theorize that a high concentration of field side loading could be seen on the high rail seat on a section of superelevated track with a train operating in an underbalanced condition, and that, inversely, a field side concentration on the low rail seat would be expected for a train operating in an overbalanced condition [9].

2.1 Rail Pad Modulus Test

Concrete sleeper fastening systems typically include a single or multi-layer rail pad assembly [11]. Part of this assembly includes an engineered polymer rail pad to attenuate the load and provide protection for the concrete rail seat [1]. Because concrete sleeper track in North American is often more rigid than the traditional timber sleeper track, concrete sleepers can impart higher stresses onto the ballast layer under train loading. An important purpose of the rail pad as an individual component is to provide increased resiliency for the concrete sleeper system. The increased resiliency provides the advantages of increased comfort for passengers and protection of the rolling stock [12]. Rail pads are manufactured from a variety of materials and molded into different geometries, which in turn govern the rail pad modulus. Rail pad modulus is a value that defines the stiffness of the material.

Part of the research being conducted at UIUC is investigating the effect of the rail pad's modulus (stiffness) on mitigating high loads imparted on the rail seat while continuing to protect the concrete rail seat. Researchers at UIUC are exploring the possibility that a rail pad of a lower modulus (i.e. softer) will distribute the applied load over a wider area of the concrete rail seat. Although a softer rail pad may better mitigate high impact loads, its high resiliency allows for greater rail deflection, which can increase wear and fatigue of other components of the fastening system [1]. The softer pad in combination with the elastic clips commonly used in concrete sleeper fastening systems can perform well in moderate traffic loading conditions, but under heavier loads, as are becoming increasingly common in North America, excessive lateral movement and wear can occur [11].

In performing the AREMA Test 6 (Wear and Abrasion) using the PLTM, researchers at UIUC have seen this excessive lateral movement of the rail cause wear on the field side cast-in steel shoulder, which could potentially lead to gauge-widening. In both the 2008 and 2012 surveys of North American Class I Railroads, shoulder/fastener wear or fatigue ranked second behind RSD as the second most critical concrete tie problem [2, 3]. Also, UIUC researchers are exploring the possibility that a rail pad with higher modulus (i.e. stiffer) will help reduce the stress on the fastening system as a whole, but will place a higher concentration of load on the concrete rail seat surface, and in turn result in increased ballast pressures on the bottom of the sleeper [11].

An experiment was performed to compare the pressure distribution of a higher modulus, medium density polyethylene (MDPE) rail pad to a low modulus Thermoplastic Vulcanizate (TPV) rail pad. The rail pads used were cast with a flat surface specifically for this experiment to remove variation in pad geometry. **Table 1** shows both the TPV and MDPE pads used for this experiment. It should be noted that although the numerical value for the TPV rail pad Shore Hardness is higher than that of the MDPE, the type A scale is used for softer plastic materials, whereas the type D is used for harder plastic materials. In this instance, the value of 60 for the type D scale indicates a harder material than does the value of 86 for the type A scale.

Table 1 : Material Properties for Rail Pad Test

	TPV	MDPE
Shore Hardness	86 (A)	60 (D)
Flexural Modulus, mPa (psi)	103.42* (15,000)	827.37 (120,000)

**Approximate flexural modulus based on a TPV with a similar Shore Hardness of 87A*

Loading conditions were consistent for both series of tests, having a constant vertical load of 144.56 kN (32,500 lb) and corresponding lateral loads based on the L/V ratios being simulated. To compare the relative performances of the two rail pads, the maximum loaded frame per L/V ratio was identified and obtained for each pad (**Figure 1**). **Table 2** is a compilation of the results from this series of tests. The data collected for each rail pad is presented side-by-side by L/V ratio to show the difference in pressure distribution for the two materials under identical loading conditions.

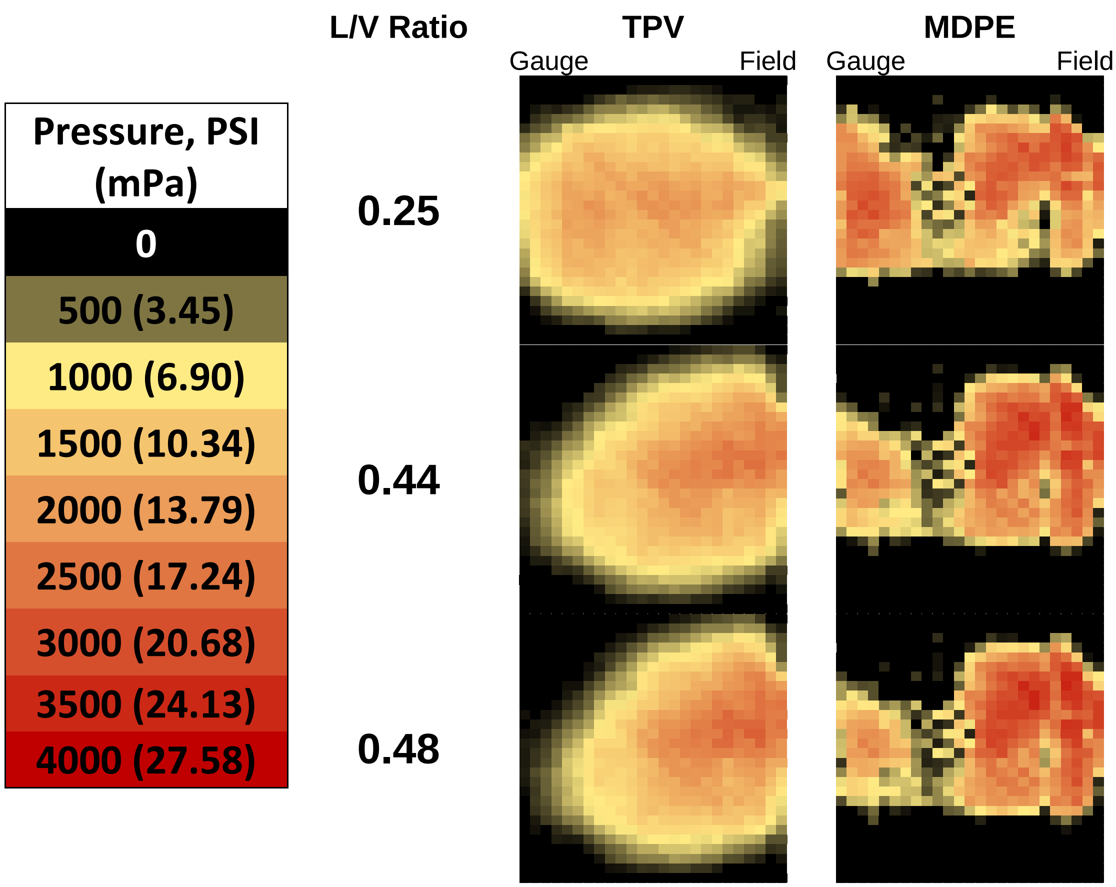

Figure 1 : Comparison of Rail Seat Pressure Distributions for Different Pad Moduli and Varying L/V Ratios

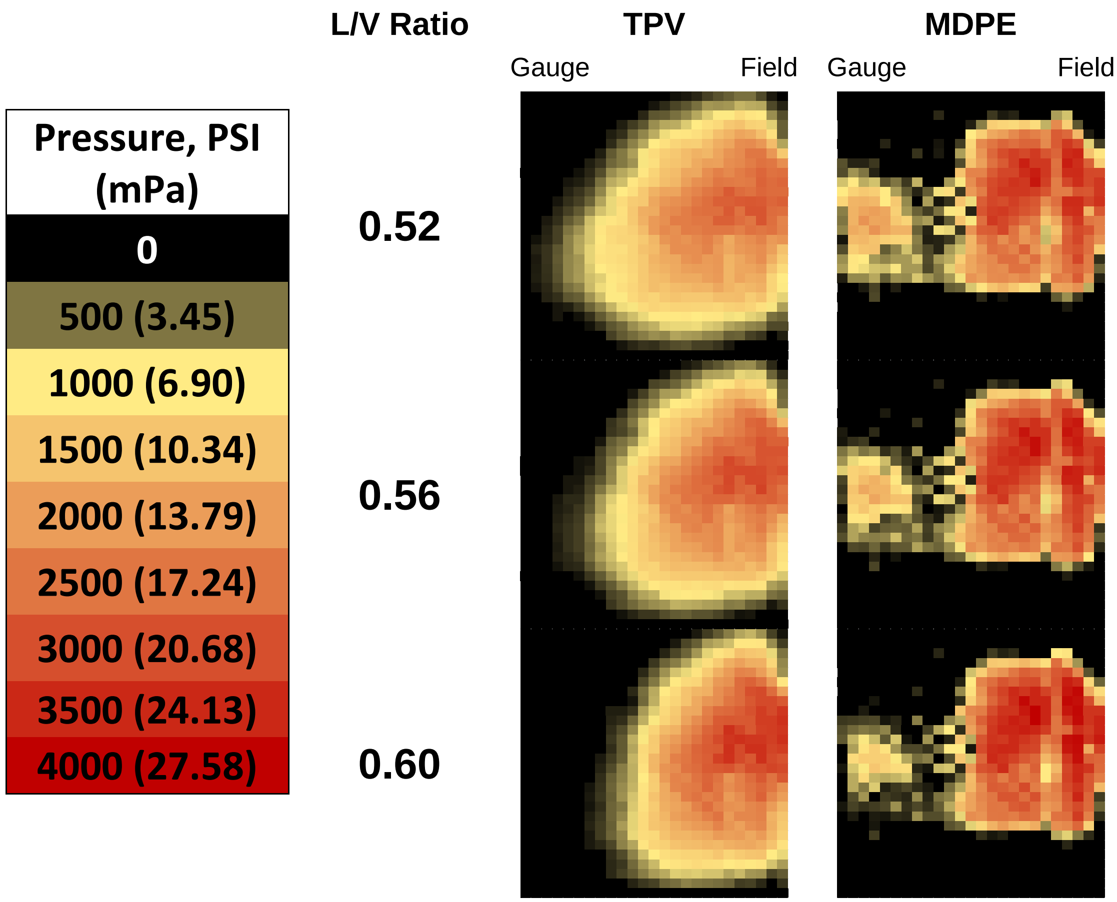

Figure 1 Cont. : Comparison of Rail Seat Pressure Distributions for Different Pad Moduli and Varying L/V Ratios

Table 2 : Results of Rail Pad Modulus Test

L/V Ratio	**0.25**		**0.44**		**0.48**	
Pad Material	**MDPE**	**TPV**	**MDPE**	**TPV**	**MDPE**	**TPV**
Vertical, kN (kips)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)
Lateral, kN (kips)	36.14 (8.13)	36.14 (8.13)	63.61 (14.30)	63.61 (14.30)	69.39 (15.60)	69.39 (15.60)
Contact Area, cm^2 (in^2)	129.61 (20.09)	185.48 (28.75)	124.58 (19.31)	180.19 (27.93)	123.35 (19.12)	175.81 (27.25)
% of Rail Seat	59	85	57	82	56	80
Peak Pressure, mPa (psi)	22.15 (3,213)	14.75 (2,139)	23.92 (3,469)	17.74 (2,573)	24.45 (3,546)	19.31 (2,800)
Contact Area over 20.68 mPa (3000 psi), cm^2 (in^2)	2.19 (0.34)	0	10.00 (1.55)	0	14.97 (2.32)	0

Table 2 Cont. : Results of Rail Pad Modulus Test

L/V Ratio	0.52		0.56		0.60	
Pad Material	**MDPE**	**TPV**	**MDPE**	**TPV**	**MDPE**	**TPV**
Vertical, kN (kips)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)	144.56 (32.50)
Lateral, kN (kips)	75.17 (16.90)	75.17 (16.90)	80.96 (18.20)	80.96 (18.20)	86.74 (19.50)	86.74 (19.50)
Contact Area, cm^2 (in^2)	122.71 (19.02)	166.13 (25.75)	120.19 (18.63)	154.58 (23.96)	114.58 (17.76)	137.42 (21.30)
% of Rail Seat	56	76	55	71	52	63
Peak Pressure, mPa (psi)	25.66 (3,721)	20.17 (2,925)	26.46 (3,838)	21.80 (3,162)	28.24 (4,096)	23.44 (3,400)
Contact Area over 20.68 mPa (3000 psi), cm^2 (in^2)	18.45 (2.86)	0	22.19 (3.44)	3.42 (0.53)	26.52 (4.11)	11.23 (1.74)

This experiment shows that the MDPE rail pad distributed the same applied load over a noticeably smaller area of the rail seat than the low modulus TPV rail pad. For an L/V ratio of 0.25, the contact area of the load for the high modulus MDPE rail pad was 129.61 cm^2 (20.09 in^2), which is only 70% of the 185.48 cm^2 (28.75 in^2) of contact area recorded for the low modulus TPV rail pad under the same load. This reduced the total percentage of rail seat area being loaded from approximately 85% to 59%. Peak pressures for each pad occurred during the L/V ratio of 0.60, as it was the same vertical load being applied to smaller areas. For the MDPE rail pad, this value was 28.24 mPa (4,096 psi); approximately 20% higher than the 23.44 mPa (3,400 psi) recorded for the TPV rail pad, and it distributed the load over 11% less of the rail seat surface. It should also be noted that although the MDPE rail pad had a smaller total contact area, it had a larger amount of area loaded at higher pressures, as is evident in the rows showing contact area over 20.68 mPa (3,000 psi) (**Table 2**).

From this experiment, it can be seen that a direct relationship exists between a high rail pad modulus and concentrated loading of the rail seat. It is also important to note that a highly concentrated loading of the rail seat could lead to crushing of the concrete surface; although the peak pressure values recorded in this laboratory experimentation did not approach the AREMA recommended minimum 28-day-design compressive strength of concrete used for concrete ties of 48.26 mPa (7,000 psi) [6]. This is the value that researchers from the John A. Volpe National Transportation Systems Center have been using to compare rail seat pressures calculated from eccentric lateral and vertical wheel/rail loads. These researchers have found that 48.26 mPa (7,000 psi) contact pressures can be exceeded in extreme loading scenarios [4]. It is also possible that highly concentrated loads could be seen in the field because although the maximum vertical load explored in this laboratory experimentation was only 144.56 kN (32.5 kips), wheel impact load detector (WILD) sites in revenue service can record loads of greater than 444.82 kN (100 kips) [13]. It is likely that a load of this magnitude would produce pressures on the rail seat well in excess of 48.26 mPa (7,000 psi).

3. Conclusions and Future Work

The following conclusions can be drawn from the analysis of data collected in these preliminary experiments using MBTSS:

- Lower modulus rail pads distribute rail seat loads over a larger contact area, reducing peak pressure values and mitigating highly concentrated loads at this interface
- Higher modulus rail pads distribute rail seat loads in more highly concentrated areas, possibly leading to localized crushing of the concrete surface under extreme loading events
- A lower L/V ratio of the resultant wheel load distributes the pressure over a larger contact area
- A higher L/V ratio of the resultant wheel load causes a concentration of pressure on the field side of the rail seat, resulting in higher peak pressures

Given the projected increase in the use of concrete sleepers in the North American railroad industry, research will continue at UIUC to develop a comprehensive laboratory and field instrumentation plan to better understand interactions at this interface. The experiments described in this paper were theoretical in nature, with the loading conditions chosen by researchers based on expert opinion and working knowledge rail seat loads.

Future laboratory testing planned by researchers at UIUC includes installing MBTSS on rail seats of concrete sleepers with various models of fastening systems to further view the effect that variations in clip design have on rail seat pressure distribution. Future testing using more intermediate L/V ratio values will aid the understanding of the transition of pressure from the gauge to field side under an increasing lateral component of the resultant wheel load.

Having run several preliminary tests in the laboratory, as well as developing a means to modify and protect the sensor for more accurate data collection, researchers at UIUC plan to instrument MBTSS on concrete sleepers in the field. Field testing will allow analysis of actual loading conditions on the concrete rail seat surface with varying configurations of train loads, speeds, and track geometry. Field testing will also play a crucial role in guiding the future of laboratory experimentation. A good working relationship between field data and experimental data is expected as the pressure distribution data collection process is refined, and field conditions are better simulated in the laboratory.

In summary, the use of MBTSS appears to be a feasible, non-intrusive means to instrument concrete sleepers to measure rail seat pressure distributions. Furthermore, results from this work will be leveraged, as the data collected from MBTSS in the laboratory and field will be used as an input for rail seat loads into finite element model (FEM) analysis of the concrete sleeper and fastening system currently being performed at UIUC.

4. Acknowledgements

This research was funded by Amsted RPS / Amsted Rail and the United States Department of Transportation (US DOT) Federal Railway Administration (FRA). The published material in this report represents the position of the authors and not necessarily that of DOT. J. Riley Edwards has been supported in part by grants to the UIUC Rail Transportation and Engineering Center (RailTEC) from CN, CSX, Hanson Professional Services, Norfolk Southern, and the George Krambles Transportation Scholarship Fund. For providing direction, advice, and resources the authors would like to thank Jose Mediavilla, Director of Engineering at Amsted RPS, Brent Wilson, Director of Research and Development at Amsted Rail, Mauricio Gutierrez from GIC Ingeniería y Construcción, Professor Jerry Rose and Graduate Research Assistant Jason Stith from the University of Kentucky, and Vince Carrara from Tekscan®, Inc. The authors would also like to thank Marc Killian, Tim Prunkard, and Don Marrow from UIUC for their assistance in laboratory experimentation, and graduate students Ryan Kernes, Brandon Van Dyk, Brennan Caughron, Sam Sogin, and Amogh Shurpali for their peer editing and valuable input.

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