Effects of Implements of Husbandry ‘Farm Equipment’ on Pavement Performance

Pooled Fund TPF-5(148)

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Iowa State University
Professional Nutrient Applicators Association of Wisconsin
Chula Vista, Wisconsin Dells

December 20, 2011
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  - Curt Smejkal, Jian Gao, Jianhua Yu, Rahman Shaidur, Ying Lai, Yu Kuang
Outline

- Objectives
- Field Testing Overview
  - MnROAD Farm Loop
  - Testing Vehicles and Program
  - Instrumentation Layout
- PCC Research and Findings (ISU)
- HMA Research and Findings (Univ. of Minn.)
- Strategies to Minimize Damage
- Million Gallon Question
Objectives

- Determine pavement responses generated by heavy agricultural equipment
- Compare measured responses to a typical 5-axle semi truck
- Develop models to evaluate pavement damage from heavy vehicles
MnROAD Research Facility

- A comprehensive pavement research facility
- Constructed in 1994 and located about 40 miles NW of the Twin Cities
- Mainline and Low Volume Road (LVR) sections
- Originally more than 4,500 sensors embedded within 40 sections
- Strain gauges, LVDTs, thermocouples, pressure cells, etc.
MnROAD Farm Loop

- **PCC Test Sections**
  - Cell 32
  - Cell 54

- **HMA Test Sections**
  - Cell 83
  - Cell 84
MnROAD Farm Loop: PCC

- **Cell 32**
  - 5.5” PCC
  - 6” aggregate base

- **Cell 54**
  - 7.5” PCC
  - 12” aggregate base
MnROAD Farm Loop: HMA

- **Cell 83**
  - 3.5” HMA with PG58-34
  - 8” gravel aggregate base
  - A-4 subgrade soil

- **Cell 84**
  - 5.5” HMA with PG58-34
  - 9” gravel aggregate base
  - A-4 subgrade soil
Test Vehicles

Notes: R4, R5, and G1 are not normally loaded running down the road
## Test Program

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Test Dates</th>
<th>Vehicle Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HMA</td>
</tr>
<tr>
<td>Spring 2008</td>
<td>March 17(^{th}) – 19(^{th}) &amp; 24(^{th}) – 26(^{th})</td>
<td>400</td>
</tr>
<tr>
<td>Fall 2008</td>
<td>August 26(^{th}) – 29(^{th})</td>
<td>282</td>
</tr>
<tr>
<td>Spring 2009</td>
<td>March 16(^{th}) – 20(^{th})</td>
<td>960</td>
</tr>
<tr>
<td>Fall 2009</td>
<td>August 24(^{th}) – 28(^{th})</td>
<td>782</td>
</tr>
<tr>
<td>Spring 2010</td>
<td>March 15(^{th}) – 18(^{th})</td>
<td>776</td>
</tr>
<tr>
<td>Fall 2010_First-round</td>
<td>August 18(^{th}) – 19(^{th})</td>
<td>426</td>
</tr>
<tr>
<td>Fall 2010_Second-round</td>
<td>November 2010</td>
<td>120</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>3,746</td>
</tr>
</tbody>
</table>
# PCC Test Sections

## MnROAD Low Volume Road

<table>
<thead>
<tr>
<th>Section</th>
<th>Cell 32 (Thin section)</th>
<th>Cell 54 (Thick section)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>5 in. thick PCC</td>
<td>7.5 in. thick PCC</td>
</tr>
<tr>
<td></td>
<td>10 ft × 12 ft undoweled</td>
<td>15 ft × 12 ft with 1 in. dowel</td>
</tr>
<tr>
<td>Base</td>
<td>1 in. Class-1f</td>
<td>12 in. Class-6</td>
</tr>
<tr>
<td></td>
<td>6 in. Class-1e</td>
<td></td>
</tr>
<tr>
<td>Subgrade</td>
<td>A-4 subgrade soil (existing subgrade soil)</td>
<td>A-4 subgrade soil (existing subgrade soil)</td>
</tr>
</tbody>
</table>

![PCC Test Sections Image 1](image1.png)

![PCC Test Sections Image 2](image2.png)
Cell 32 – Sensor Instrumentation

- Strain Gauge
  - Longitudinal
  - Transverse
  - Diagonal
Cell 32 – Sensor Instrumentation (Fall 2010)

- Strain Gauge
  - Longitudinal

Profile view

Plan view

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Distance from J1228 (ft.)</th>
<th>Distance from Surface (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>5.06</td>
<td>0.78</td>
</tr>
<tr>
<td>CS2</td>
<td>5.08</td>
<td>4.80</td>
</tr>
<tr>
<td>CS3</td>
<td>5.40</td>
<td>0.78</td>
</tr>
<tr>
<td>CS4</td>
<td>5.38</td>
<td>4.68</td>
</tr>
</tbody>
</table>
Cell 54 – Sensor Instrumentation

- Strain Gauge
  - Longitudinal
- LVDTs
HMA Test Sections

Cell 83

Cell 84

Legend:
- TC: ThermoCouple (Temperature)
- EC: Ech2O-TE (Moisture)
- TE: Asphalt Strain Gauge
- LE: Asphalt Strain Gauge
- AE: Asphalt Strain Gauge
- PG: Pressure Cell
- DT: LVDT
Cell 83 and Cell 84 – Sensor Instrumentation
Structural Response Measurement (stresses and strains)

Traffic Wander Measurement

Peak-Pick Analysis
<table>
<thead>
<tr>
<th>Tekscan</th>
<th>![Tractor Image]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>![Image] 10.00 in</td>
</tr>
<tr>
<td>50%</td>
<td>![Image] 1000 in</td>
</tr>
<tr>
<td>80%</td>
<td>![Image] 1000 in</td>
</tr>
</tbody>
</table>

**Legend:**
- **0%**: 7,980 lbs
- **50%**: 19,550 lbs
- **80%**: 24,680 lbs
Failure!!!

- PCC Cell 32 (Spring 09, Fall 10)
- HMA Cell 32 (Spring 09)
PCC RESEARCH AND FINDINGS (ISU)
Order of Field Measurement of Critical Tensile Strains on Cell 32

<table>
<thead>
<tr>
<th>Season</th>
<th>Vehicle</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 08</td>
<td>S3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td></td>
</tr>
<tr>
<td>Fall 2008</td>
<td>R4</td>
<td>32CE139</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Season</th>
<th>Vehicle</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2009</td>
<td>R5</td>
<td>32CE139</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mn80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mn102</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Season</th>
<th>Vehicle</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2010</td>
<td>G1</td>
<td>32CS102</td>
</tr>
</tbody>
</table>
Order of Field Measurement of Critical Tensile Strains on Cell 54

Notes: The reason why the maximum tensile strain produced by T1 and T6 are so great is because T1 was only tested in Spring 2008 while T6 has been tested four time during Spring 2009, Fall 2009, Spring 2010, and Fall 2010. The tensile strains plotted in Figures represent the maximum strain values for each test vehicle. Thus, the effect of seasonal variation was also introduced into the results.

Table:

<table>
<thead>
<tr>
<th>Season</th>
<th>Vehicle</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 2008</td>
<td>S3/T1/T2</td>
<td></td>
</tr>
<tr>
<td>Fall 2008</td>
<td>R4</td>
<td></td>
</tr>
<tr>
<td>Fall 2009</td>
<td>R5/T6/T7/T8/Mn80/Mn102</td>
<td></td>
</tr>
<tr>
<td>Spring 2010</td>
<td>R6/T6/Mn80/Mn102</td>
<td></td>
</tr>
<tr>
<td>Fall 2010</td>
<td>G1/T6/Mn80/Mn102</td>
<td></td>
</tr>
</tbody>
</table>
Order of Critical Pavement Strains Based on FE Analysis

- **Cell 32**: G1>T6>R6>R4>S4>T7>Mn102>R5>T5=T8>S5>Mn80>T2
- **Cell 54**: G1>R6>R4>T6>S4>Mn102>R5>T7>S5>T5=T8>Mn80>T2

$k = 200$ psi/in., $\Delta T = 0^\circ F$, $E = 4.5 \times 10^6$ psi, $\mu = 0.15$
Fatigue damage: Vehicle Comparisons (Cell 54)

- **Stress Ratio (SR) =** \( \sigma_{\text{max}} / \text{MOR} \)
  - **MOR:** Modulus of Rupture
- **According to PCA,** no fatigue damage is expected if stress ratio is less than 0.5

\[ k = 200 \text{ psi/in.}, \Delta T = 0 \text{ °F} \]

![Graph showing stress ratio vs. number of load repetitions to failure](image)
Summary of Findings

- As relative offset increases, pavement tensile strains and deflections decrease.
- Compared to empty farm equipment, fully loaded MnROAD trucks produce higher pavement tensile stresses & strains.
- G1 (88 kips) and R6 (75 kips) produce higher pavement tensile stresses & strains than Mn80 (80 kips) and Mn102 (102 kips).
Summary of Findings (cont’d)

- Multi-axle vehicle configuration helps to reduce pavement tensile stresses, strains, & deflections produced by the farm equipment
- Pavement tensile stresses & strains measured in Spring 2009 are lower than those in other seasons
- When operated fully loaded, all the tested farm equipment generate more stresses & strains compared to standard semi-truck
We saw driving close to pavement edge is bad for pavement. If vehicle is allowed to drive in middle of roads (away from the edge), can it be loaded to 100% full?
No!!! They produce higher pavement stress than Mn80 even when they drive in the middle of the road.
No!!! They produce higher pavement stress than Mn80 even when they drive in the middle of the road.
Question 2

- How to theoretically explain the cracking of cell 32 (corner cracks)?
Answer 2

- Diagonal crack at the corner of the slab
- Caused by:
  - Load repetitions
  - Loss of subgrade/subbase support
  - Poor load transfer across the joint
  - Upward curling and warping behavior (construction curl) due to shrinkage

Vehicle: G1, $\Delta T = -6 \, ^\circ\text{F/in.}$
Question 3

- How to theoretically explain the cracking of cell 32 (longitudinal cracks)?
Answer 3

- Caused by excessive tensile stresses at the top of the slab
- Tensile stresses at the top of the slab are more critical than the ones at the bottom under negative temperature gradient

Vehicle: T7, $\Delta T = -4 \, ^\circ F/in.$
Answer 3 (cont’)

- Certain vehicle(s) could produce a tensile stress zone (see the stress contours in red) along the slab length
- Crack occurs when tensile stress exceeds the modulus of rupture (MOR) of the concrete pavement

Vehicle: T7, $\Delta T = -4 \, ^\circ F/in.$
Do tire pressures have a significant effect on pavement responses?
“Pavement engineers were concerned that increased tire pressures were resulting in greater pavement damage. Tests conducted over a wide range of tire pressure on instrumented pavements at the Pavement Testing Facility showed that tire pressure was a second order effect for relatively thick asphalt layers (greater than 125 mm) produced from properly designed mixes. The effect of tire pressure on flexible pavement response and performance was found to be less significant than the effects of load and pavement temperature.”

Answer 4 (cont’d)

- Less significant for relatively thick PCC layers

Vehicle: G1, L = 15ft, K=200 psi
HMA RESEARCH AND FINDINGS (UNIV. OF MINNESOTA)
Summary of Findings

- Cell 83 (3.5-in asphalt concrete [AC] section) failed in S09 (WB lane) and in F09 (EB lane); cell 84 (5.5-in AC section) has not shown significant distresses.

- Failure started at the location with a thinner AC thickness (about 2.5 in), but propagated several yards in both directions. Due to continued heavy trafficking of failed areas, a portion of cell 83 was damaged beyond repair.
Summary of Findings (cont’d)

- Thickness variability with current construction practices is common. In some cases in-place thickness can be less than as-designed thickness.
- In-service pavements can have distresses reducing bearing capacity.
Summary of Findings (cont’d)

- Although AC cracking could not be completely ruled out as the cause of failure, it is more likely that pavement first failed in the base/subgrade.
Summary of Findings (cont’d)

- All tested vehicles resulted in higher subgrade stresses than the standard truck.
- Pavement damage is governed by axle weight, not the gross vehicle weight. Therefore, it is important to ensure even load distribution among axles.
Measured Maximum Subgrade Stresses Normalized to Mn80 Subgrade Stress Cell 84, 80 percent loading
Summary of Findings (cont’d)

- A fully loaded 1,000 bushel grain cart caused the highest pavement stresses and strains. It was followed by fully loaded terragators 9203 and 3104.
Summary of Findings (cont’d)

• Presence of a paved shoulder reduces damage potential. In the absence of a paved shoulder, allowing to drive in the middle of roads (away from the edge) reduces a risk of pavement failure.

• Pavement damage can be reduced if the most unfavorable conditions (fully saturated and/or thawed base and subgrade, high AC temperature) are avoided.
STRATEGIES TO MINIMIZE DAMAGE
Recommendations

- Vehicles should be driven 18-24 in. away from the slab edge
- When applicable, dowel bars are recommended to minimize the faulting damage and to improve the load transfer efficiency (LTE)
- To carry the same amount of load, tridem or quad axles are preferred for all farm equipment – having more axles is better for the roadway systems as the loads are distributed into a larger area
Recommendations (cont’d)

- The impact of farm equipment on transportation infrastructure system should be studied before the equipment design is finalized (gross weight, axle weight, tire pressure, axle spacing, wheel spacing, etc.)
- Pavement design engineers should take into account the existing farm equipment load levels, axle configuration, etc. for pavement design
What can be done to prevent damage on pavement systems?

- Avoid edge loading
- Avoid early Spring loading
- Distribute the loads evenly between the axles
- Avoid single axle loading when possible
- Use dowel bars in transverse joints for better load transfer mechanism
- A better drainage system (especially for the pavement foundation) would lead to better performing, long lasting pavements
MILLION GALLON QUESTION
Million Gallon Question

One million gallons of product (water) is to be moved. Which vehicle would cause the least damage on the concrete roads?

- Two concrete pavement sections considered: (1) 5-in thick and (2) 7-in thick JPCP
- Two asphalt pavement sections considered: (1) 7-TONN (3.5-in) thick and (2) 10-TONN (5.5-in) thick HMA pavements
## Estimated Product Weights in One Move (JPCP)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Max Volume Capacity*, gallons</th>
<th>Max Weight Weight**, lbs.</th>
<th>Number of Passes***</th>
</tr>
</thead>
<tbody>
<tr>
<td>R6</td>
<td>4,200</td>
<td>34,860</td>
<td>238</td>
</tr>
<tr>
<td>S4</td>
<td>4,650</td>
<td>38,575</td>
<td>215</td>
</tr>
<tr>
<td>S5</td>
<td>4,650</td>
<td>38,575</td>
<td>215</td>
</tr>
<tr>
<td>T2</td>
<td>4,000</td>
<td>33,200</td>
<td>250</td>
</tr>
<tr>
<td>T6</td>
<td>6,000</td>
<td>49,800</td>
<td>167</td>
</tr>
<tr>
<td>T7</td>
<td>7,300</td>
<td>60,570</td>
<td>137</td>
</tr>
<tr>
<td>T8</td>
<td>9,500</td>
<td>78,850</td>
<td>105</td>
</tr>
<tr>
<td>Mn102</td>
<td>7,650</td>
<td>63,495</td>
<td>131</td>
</tr>
<tr>
<td>Mn80</td>
<td>6,000</td>
<td>49,800</td>
<td>167</td>
</tr>
</tbody>
</table>

* Estimated

** 1 gallon = 8.3 lbs of water

*** Number of passes = 1,000,000 gallons (8,300,000 lbs.)/Max Capacity
5-in thick JPCP, PCC Fatigue Damage

![Chart showing damage comparison for different vehicles and 5-in thick JPCP.]
7-in thick JPCP, PCC Fatigue Damage
## Estimated Product Weights in One Move (HMA)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Weight, lbs</th>
<th>Number of Passes/Year**</th>
</tr>
</thead>
<tbody>
<tr>
<td>S4</td>
<td>32,549*</td>
<td>5,100</td>
</tr>
<tr>
<td>S5</td>
<td>39,410*</td>
<td>4,212</td>
</tr>
<tr>
<td>T6</td>
<td>49,790</td>
<td>3,334</td>
</tr>
<tr>
<td>T7</td>
<td>60,100</td>
<td>2,762</td>
</tr>
<tr>
<td>T8</td>
<td>76,000</td>
<td>2,184</td>
</tr>
<tr>
<td>T1</td>
<td>47,475*</td>
<td>3,497</td>
</tr>
<tr>
<td>T2</td>
<td>17,882*</td>
<td>9,283</td>
</tr>
</tbody>
</table>

* Estimated  
** The product is moved every year (20-year design life)
7-TONN (3.5-in thick HMA), Asphalt Damage
7-TONN (3.5-in thick HMA), Subgrade Damage
10-TONN (5.5-in thick HMA), Asphalt Damage
10-TONN (5.5-in thick HMA), Subgrade Damage
Optimizing Farm Equipment Axle Configuration for achieving Long-Life Pavements

Dr. Halil Ceylan
Dr. Rangan Gopalakrishnan
Dr. Sunghwan Kim

Iowa State University

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- Prof. Marshall R. Thompson
- Dr. Franco Gomez-Ramirez
- Dr. Dulce Rufino Feldman
Outline

- Boeing Aircraft Wheel Configuration Studies
  - Flexible Pavements
  - Rigid Pavements

- Relevance to Farm Equipment Study
Background

New Generation Aircraft (NGA)
### Background - NGA

- **Increased wheel loads**
- **Higher tire pressures**
- **Complex gear configurations**

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Gear Configuration</th>
<th>Dimensions (inches)</th>
<th>Maximum Wheel Load (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B777</td>
<td><img src="image1.png" alt="B777 Gear Configuration" /></td>
<td>X: 55  Y: 57</td>
<td>57,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A380</td>
<td><img src="image2.png" alt="A380 Gear Configuration" /></td>
<td>X: 60  Y: 67</td>
<td>62,000</td>
</tr>
<tr>
<td>A340-600</td>
<td><img src="image3.png" alt="A340-600 Gear Configuration" /></td>
<td>X: 55  Y: 78</td>
<td>65,000</td>
</tr>
</tbody>
</table>
FAA’s NAPTF
FAA’s NAPTF
National Airport Pavement Test

Wheel Loads: 24, 30 and 36 kips

Similar Boeing/Airbus NGA Tridem Gear
BOEING AIRCRAFT WHEEL CONFIGURATION STUDIES:
Flexible Pavements (FP)

Gomez-Ramirez (2001)
Gopalakrishnan (2004)
Three Wheel Load Levels per Gear Configuration

- 24,000 lbs
- 30,000 lbs
- 36,000 lbs

Gomez-Ramirez (2001)
NAPTF CCI FP Traffic Testing

B777 Gear
- 55 in.
- 57 in.
- 57 in.

B747 Gear
- 44 in.
- 58 in.
- 57 in.

Speed
- 5-mph

Wheel Load
- 45-kip
RESPONSE SUPERPOSITION
Experimental Studies (NAPTF)

Response Zones

Dual Gear Response Curve *

Dual-Tandem Gear Response Curve

Dual-Tridem Gear Response Curve

Peaks/Troughs for specific zone if concavity/convexity is present.

Midpoint value within zone if concavity/convexity is not present.

* (or distribution of Dual-tandem and Dual-Tridem for deep locations)
Important Conclusions: FP

- Subgrade Stress Distribution depends on level of stress overlapping
  - Axle spacing
  - Dual wheel spacing
  - Pavement thickness/subgrade condition

- Number of Load Applications associated with
  - Distribution of transverse stresses
  - Aircraft Wander
BOEING AIRCRAFT WHEEL CONFIGURATION STUDIES:
Rigid Pavements (RP)

Ceylan (2002)
A Typical Runway Layout

90 m

150 ft (6 @ 25 ft)

15 m

(50 ft)

Transverse Joints

B-777 Gear Loading

Longitudinal Joints

Traffic Area
Graphical Representation of the ANN Program

**INPUTS**
1. x
2. y
3. t
4. k
5. LTE_x
6. LTE_y
7. Loading Configuration

**OUTPUTS**
1. Maximum Bending Stresses in the x- and y-Directions; (σ_x-max., σ_y-max.),
2. Maximum Deflections (δ-max.),
3. Rigid Pavement Fatigue Algorithms

ANN ISLAB
I-PAVE Pavement Design Tool

Pavement Response Calculation
B-777 Gear To The Slab Edge Locations

Defined Locations:

OR MANUALLY:
X coordinate: 40
Y coordinate: 50

Boeing B-777 Main Gear Configuration Information

Slab Properties

Modulus of Subgrade Reaction:
(k: 50 to 500 psi/in)

Slab Thickness:
(h: 12 to 24 in)

Load Transfer Efficiency In
(LTE-x: 25% - 90%)

Load Transfer Efficiency In Vertical
(LTE-y: 25% - 90%)

Results

Maximum Stress in Horizontal Direction:
σ_x

Maximum Stress in Vertical Direction:
σ_y

Maximum Deflection:
δ

US Customary          Metric System
σ_x 144 Psi           993 kPa
σ_y 298 Psi           2055 kPa
δ    .133 ln          3.378 mm

Boeing 777 -300

Click Run-ANN command to see the
Processing Time Requirements

For 20,000 Analyses

<table>
<thead>
<tr>
<th>Critical Pavement Responses</th>
<th>Required Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE Models</td>
<td>11-28 days</td>
</tr>
<tr>
<td>Neural Network</td>
<td>Less than 1 sec!</td>
</tr>
</tbody>
</table>
Design Example: Optimization of NCTC - Gear Configuration

- NCTC Gear Configuration
Design Example: Optimization of NCTC - Gear Configuration

- Gear Loading Positions in 9-Slab (3 by 3) Concrete Pavement Assembly

<table>
<thead>
<tr>
<th>Loading Position 1 (Top Edge)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>s lab (20' x 20')</td>
<td>s lab (20' x 20')</td>
<td>s lab (20' x 20')</td>
<td></td>
</tr>
<tr>
<td>s lab (20' x 20')</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>s lab (20' x 20')</td>
<td>s lab (20' x 20')</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loading Position 2 (Right Edge)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>s lab (20' x 20')</td>
<td>s lab (20' x 20')</td>
<td>s lab (20' x 20')</td>
<td></td>
</tr>
<tr>
<td>s lab (20' x 20')</td>
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</tr>
<tr>
<td>s lab (20' x 20')</td>
<td>s lab (20' x 20')</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PCC Slab Thickness (in)</th>
<th>PCC Slab Modulus (psi)</th>
<th>PCC Slab Poisson's Ratio</th>
<th>Coefficient of Thermal Expansion, $10^{-6}$ in/in/°F</th>
<th>Unit Weight (lb/in³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.00</td>
<td>4,000,000</td>
<td>0.15</td>
<td>5.50</td>
<td>0.087</td>
</tr>
</tbody>
</table>
# Design Example: Optimization of NCTC - Gear Configuration

- Gear Loading Positions in 9-Slab (3 by 3) Concrete Pavement Assembly

<table>
<thead>
<tr>
<th>Axle Conf. Number</th>
<th>Axle Name</th>
<th>Load Level per Gear (lb)</th>
<th>No of Wheels</th>
<th>Aspect Ratio (b/a or X/Y)</th>
<th>Tire Length a (in)</th>
<th>Tire Width b (in)</th>
<th>Tire Pressure (psi)</th>
<th>Wheel Spacing (in)</th>
<th>Axle Spacing (in)</th>
<th>Max of $\sigma_{x\text{-max}}$ (psi)</th>
<th>Max of $\sigma_{y\text{-max}}$ (psi)</th>
<th>Principal Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1a</td>
<td>NCTC-51x58</td>
<td>237,500</td>
<td>4</td>
<td>1</td>
<td>18.16</td>
<td>18.16</td>
<td>180</td>
<td>51.00</td>
<td>58.00</td>
<td>929.7</td>
<td>892.4</td>
<td>941.0</td>
</tr>
<tr>
<td>G-2a</td>
<td>NCTC-51x64</td>
<td>237,500</td>
<td>4</td>
<td>1</td>
<td>17.23</td>
<td>17.23</td>
<td>200</td>
<td>51.00</td>
<td>64.00</td>
<td>927.2</td>
<td>885.4</td>
<td>938.5</td>
</tr>
<tr>
<td>G-3a</td>
<td>NCTC-57x58</td>
<td>237,500</td>
<td>4</td>
<td>1</td>
<td>16.43</td>
<td>16.43</td>
<td>220</td>
<td>57.00</td>
<td>58.00</td>
<td>905.7</td>
<td>895.8</td>
<td>913.3</td>
</tr>
<tr>
<td>G-1b</td>
<td>NCTC-51x58</td>
<td>213,750</td>
<td>4</td>
<td>1</td>
<td>17.23</td>
<td>17.23</td>
<td>180</td>
<td>51.00</td>
<td>58.00</td>
<td>853.2</td>
<td>815.5</td>
<td>863.6</td>
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<tr>
<td>G-2b</td>
<td>NCTC-51x64</td>
<td>213,750</td>
<td>4</td>
<td>1</td>
<td>16.35</td>
<td>16.35</td>
<td>200</td>
<td>51.00</td>
<td>64.00</td>
<td>850.9</td>
<td>813.9</td>
<td>861.2</td>
</tr>
<tr>
<td>G-3b</td>
<td>NCTC-57x58</td>
<td>213,750</td>
<td>4</td>
<td>1</td>
<td>15.59</td>
<td>15.59</td>
<td>220</td>
<td>57.00</td>
<td>58.00</td>
<td>827.4</td>
<td>817.5</td>
<td>834.3</td>
</tr>
<tr>
<td>G-1c</td>
<td>NCTC-51x58</td>
<td>178,125</td>
<td>4</td>
<td>1</td>
<td>15.73</td>
<td>15.73</td>
<td>180</td>
<td>51.00</td>
<td>58.00</td>
<td>734.9</td>
<td>696.3</td>
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</tr>
<tr>
<td>G-2c</td>
<td>NCTC-51x64</td>
<td>178,125</td>
<td>4</td>
<td>1</td>
<td>14.92</td>
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<td>200</td>
<td>51.00</td>
<td>64.00</td>
<td>732.9</td>
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<tr>
<td>G-3c</td>
<td>NCTC-57x58</td>
<td>178,125</td>
<td>4</td>
<td>1</td>
<td>14.23</td>
<td>14.23</td>
<td>220</td>
<td>57.00</td>
<td>58.00</td>
<td>706.2</td>
<td>696.7</td>
<td>712.5</td>
</tr>
</tbody>
</table>

**NOTE:** Turquoise color indicates the LOW bending stress values  
Orange color indicates the HIGH bending stress values

- Use **NCTC-57x58** to limit the damage on the airfield slabs.
Advantages of An ANN-Based Pavement Analysis & Design Toolbox

- Pavement Engineers & Designers Provided with the State-of-the-Art FEM (ISLAB) Solutions
  - what-if scenarios in design
- No Complex Input Requirements
- No Large Computer Resources Needed
- Computation Performed Practically in the Blink of an Eye (Real Time)
- Provide Solutions for any Geometry of Gear Configuration using the Principle of Superposition
  - predict $\sigma$ and $\delta$ throughout the slab
Advantages of An ANN-Based Pavement Analysis & Design Toolbox

- Can be very useful in optimizing axle/gear configuration (relevance to farm equipment study)
RELEVANCE TO FARM EQUIPMENT STUDY
Test Vehicles

Notes: R4, R5, and G1 are not normally loaded running down the road
Impact of Axle Addition for G1

Single Axle (Mid-span edge loading)

Single Axle (Edge-joint loading)

Two-axle loading

Three-axle loading

G1 /L=15ft /W=12ft/k=200psi/in
Impact of Axle Addition for G1 (cont’d)

![Graph showing the impact of axle addition on maximum stress in PCC slab thickness.](image)

- Axle = 1/Mid-slab Edge Load
- Axle = 1/Edge-joint Load
- Axle = 2
- Axle = 3
Impact of Axle Addition for G1 (cont’d)

![Chart showing the impact of axle addition on maximum deflection for different PCC slab thicknesses. The chart compares the deflection for Axle = 1/Mid-slab Edge Load, Axle = 1/Edge-joint Load, Axle = 2, and Axle = 3. The y-axis represents Maximum Deflection in inches, and the x-axis represents PCC Slab Thickness in inches. The data points for slab thicknesses 5, 7, and 10 are illustrated with bars of different colors representing each axle configuration.]
Impact of Axle Addition for GI (cont’d)
Impact of Axle Addition for T7

Three-axle (Mid-span edge loading)

Four-axle (Mid-span edge loading)

T7 /L=15ft /W=12ft/k=200psi/in

Axle = 3/Mid-slab Edge Load
Axle = 4/Mid-slab Edge Load
Impact of Axle Addition for T7 (cont’d)

Three-axle (Edge-joint loading)

Four-axle (Edge-joint loading)

T7 /L=15ft /W=12ft/k=200psi/in
Impact of Axle Addition for T7 (cont’d)

![Graph showing the impact of axle addition for T7.]
Impact of Axle Addition for T8

Four-axle (Mid-span edge loading) vs. Five-axle (Mid-span edge loading)

T8 /L=15ft /W=12ft/k=200psi/in
Impact of Axle Addition for T8 (cont’d)

Four-axle (Edge-joint loading)

Five-axle (Edge-joint loading)

T8 /L=15ft /W=12ft/k=200psi/in

Axle = 4/Edge-joint Load
Axle = 5/Edge-joint Load

Maximum Deflection, inch

PCC Slab Thickness, inch

5 7 10
Benefit of Axle Increases: T8 (cont’d)
THANK YOU !!!

Questions?
Comments?