FHWA Research Project
DTFH61-07-C-00032

Intelligent Compaction:
Quality Assurance for In-Place Density Acceptance

Asphalt IC Demonstration
I-95, Island Falls, Maine
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FHWA-RD-12--</td>
<td>N/A</td>
<td>N/A</td>
<td>Intelligent Compaction: Quality Assurance for In-Place Density Acceptance  —  Asphalt IC Demonstration in Maine</td>
<td>November 2013</td>
<td>N/A</td>
<td>George Chang, PE, PhD, Qinwu Xu, and Jennifer Rutledge</td>
<td>N/A</td>
<td>The Transtec Group, Inc. 6111 Balcones Drive Austin TX 78731</td>
<td>N/A</td>
<td>DTFH61-07-C-00032</td>
<td>Federal Highway Administration Office of Pavement Technology, HIPT-10 1200 New Jersey Avenue, SE Washington, DC 20590</td>
<td>Final Draft</td>
<td>Contracting Officer's Technical Representative: Victor (Lee) Gallivan</td>
<td>The current IC technology output, roller measurement values (ICMV) relates to the stiffness of the underlying materials. On the other hand, density measurement is being used for Quality Control (QC) and Quality Assurance (QA) for most agencies and contractors. To accelerate the implementation of IC technology, this research takes the Federal Highway Administration (FHWA)/Transportation Pooled Funding (TPF) IC project to the next step and further investigates the relationship between ICMV and core densities in order to establish scientific-sound procedures to use IC as a Quality Assurance (QA) tool for in-place HMA densities. This study was initiated under the FHWA Contract No. DTFH61-07-C-00032, which includes nine (9) HMA demonstration projects between 2012 and 2014. This document is the final report for the Maine State Department of Transportation HMA IC field demonstration.</td>
<td>Intelligent compaction, IC roller, Hot mix asphalt, core, density, correlation</td>
<td>No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161</td>
<td>Unclassified</td>
<td>Unclassified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## SI* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>When You Know</th>
<th>Multiply By</th>
<th>To Find</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LENGTH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in</td>
<td>inches</td>
<td>25.4</td>
<td>millimeters</td>
<td>mm</td>
</tr>
<tr>
<td>ft</td>
<td>feet</td>
<td>0.305</td>
<td>meters</td>
<td>m</td>
</tr>
<tr>
<td>yd</td>
<td>yards</td>
<td>0.914</td>
<td>meters</td>
<td>m</td>
</tr>
<tr>
<td>mi</td>
<td>miles</td>
<td>1.61</td>
<td>kilometers</td>
<td>km</td>
</tr>
<tr>
<td><strong>AREA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in²</td>
<td>square inches</td>
<td>645.2</td>
<td>square millimeters</td>
<td>mm²</td>
</tr>
<tr>
<td>ft²</td>
<td>square feet</td>
<td>0.093</td>
<td>square meters</td>
<td>m²</td>
</tr>
<tr>
<td>yd²</td>
<td>square yard</td>
<td>0.836</td>
<td>square meters</td>
<td>m²</td>
</tr>
<tr>
<td>ac</td>
<td>acres</td>
<td>0.405</td>
<td>hectares</td>
<td>ha</td>
</tr>
<tr>
<td>mi²</td>
<td>square miles</td>
<td>2.59</td>
<td>square kilometers</td>
<td>km²</td>
</tr>
<tr>
<td><strong>VOLUME</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fl oz</td>
<td>fluid ounces</td>
<td>29.57</td>
<td>milliliters</td>
<td>mL</td>
</tr>
<tr>
<td>gal</td>
<td>gallons</td>
<td>3.785</td>
<td>liters</td>
<td>L</td>
</tr>
<tr>
<td>ft³</td>
<td>cubic feet</td>
<td>0.028</td>
<td>cubic meters</td>
<td>m³</td>
</tr>
<tr>
<td>yd³</td>
<td>cubic yards</td>
<td>0.765</td>
<td>cubic meters</td>
<td>m³</td>
</tr>
</tbody>
</table>

NOTE: volumes greater than 1000 L shall be shown in m³.

| **MASS** |               |             |           |        |
| oz      | ounces        | 28.35       | grams    | g      |
| lb      | pounds        | 0.454       | kilograms | kg     |
| T       | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| **TEMPERATURE (exact degrees)** |       |             |           |        |
| °F     | Fahrenheit    | 5 (F-32)/9  | Celsius  | °C     |
| or     |               | (F-32)/1.8  |           |        |
| **ILLUMINATION** |       |             |           |        |
| fc     | foot-candles  | 10.76       | lux      | lx     |
| fl     | foot-Lamberts | 3.426       | candela/m² | cd/m² |

| **FORCE and PRESSURE or STRESS** |       |             |           |        |
| lbf    | poundforce    | 4.45        | newtons  | N      |
| lbf/in²| poundforce per square inch | 6.89 | kilopascals | kPa    |

### APPROXIMATE CONVERSIONS FROM SI UNITS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>When You Know</th>
<th>Multiply By</th>
<th>To Find</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LENGTH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm</td>
<td>millimeters</td>
<td>0.039</td>
<td>inches</td>
<td>in</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
<td>3.28</td>
<td>feet</td>
<td>ft</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
<td>1.09</td>
<td>yards</td>
<td>yd</td>
</tr>
<tr>
<td>km</td>
<td>kilometers</td>
<td>0.621</td>
<td>miles</td>
<td>mi</td>
</tr>
<tr>
<td><strong>AREA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm²</td>
<td>square millimeters</td>
<td>0.0016</td>
<td>square inches</td>
<td>in²</td>
</tr>
<tr>
<td>m²</td>
<td>square meters</td>
<td>10.764</td>
<td>square feet</td>
<td>ft²</td>
</tr>
<tr>
<td>m²</td>
<td>square meters</td>
<td>1.195</td>
<td>square yards</td>
<td>yd²</td>
</tr>
<tr>
<td>ha</td>
<td>hectares</td>
<td>2.47</td>
<td>acres</td>
<td>ac</td>
</tr>
<tr>
<td>km²</td>
<td>square kilometers</td>
<td>0.386</td>
<td>square miles</td>
<td>mi²</td>
</tr>
<tr>
<td><strong>VOLUME</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mL</td>
<td>milliliters</td>
<td>0.034</td>
<td>fluid ounces</td>
<td>fl oz</td>
</tr>
<tr>
<td>L</td>
<td>liters</td>
<td>0.264</td>
<td>gallons</td>
<td>gal</td>
</tr>
<tr>
<td>m³</td>
<td>cubic meters</td>
<td>35.314</td>
<td>cubic feet</td>
<td>ft³</td>
</tr>
<tr>
<td>m³</td>
<td>cubic meters</td>
<td>1.307</td>
<td>cubic yards</td>
<td>yd³</td>
</tr>
<tr>
<td><strong>MASS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>grams</td>
<td>0.035</td>
<td>ounces</td>
<td>oz</td>
</tr>
<tr>
<td>kg</td>
<td>kilograms</td>
<td>2.202</td>
<td>pounds</td>
<td>lb</td>
</tr>
<tr>
<td>Mg (or &quot;t&quot;)</td>
<td>megagrams (or &quot;metric ton&quot;)</td>
<td>1.103</td>
<td>short tons (2000 lb)</td>
<td>T</td>
</tr>
<tr>
<td><strong>TEMPERATURE (exact degrees)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>°C</td>
<td>Celsius</td>
<td>1.8C+32</td>
<td>Fahrenheit</td>
<td>°F</td>
</tr>
<tr>
<td><strong>ILLUMINATION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lx</td>
<td>lux</td>
<td>0.0929</td>
<td>foot-candles</td>
<td>fc</td>
</tr>
<tr>
<td>cd/m²</td>
<td>candela/m²</td>
<td>0.2919</td>
<td>foot-Lamberts</td>
<td>fl</td>
</tr>
</tbody>
</table>

| **FORCE and PRESSURE or STRESS** |       |             |           |        |
| N      | newtons       | 0.225       | poundforce | lbf    |
| kPa    | kilopascals   | 0.145       | poundforce per square inch | lbf/in² |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)
Intelligent Compaction: Quality Assurance for In-Place Density Acceptance

Asphalt IC Demonstration in Maine

Prepared by:
George Chang, PE, PhD, Qinwu Xu, and Jennifer Rutledge
The Transtec Group, Inc.
6111 Balcones Dr. Austin, TX 78731

for

Federal Highway Administration
Office of Pavement Technology, HIPT-10
1200 New Jersey Avenue, SE
Washington, DC 20590

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the DOTs. This report does not contain a standard or specified technique.

The authors and the FHWA do not endorse products or manufacturers. Trade or manufacturers’ names appear herein solely because they are considered essential to this report.
# TABLE OF CONTENTS

Acknowledgement ........................................................................................................................................ 1

Introduction 2

Definition of Intelligent Compaction ................................................................................................. 2
Background of this Study .......................................................................................................................... 2
Project Goals ............................................................................................................................................. 3
Structure of this Document ....................................................................................................................... 3

Project Description ........................................................................................................................................ 4

Location .................................................................................................................................................... 4
Typical Cross Sections .............................................................................................................................. 5
Asphalt Mix Design .................................................................................................................................. 5

Intelligent Compaction Rollers ..................................................................................................................... 8

HAMM Double-Drum IC Roller .............................................................................................................. 8
  Overall System Description ..................................................................................................................... 8
  Measurement Value ................................................................................................................................. 11
  Documentation System .......................................................................................................................... 12
Caterpillar Double-Drum IC Roller ........................................................................................................ 15
  Overall System Description ..................................................................................................................... 15
  Measurement Value ................................................................................................................................. 17
  Documentation System .......................................................................................................................... 18

In-situ Test Devices .................................................................................................................................... 20

Nuclear Density Gauge (NG) .................................................................................................................. 20
Falling Weight Deflectometer (FWD) ...................................................................................................... 20
Light Weight Deflectometer for Asphalt (LWD-a) ................................................................................ 21

Field Demonstration Activities .................................................................................................................. 23

Summary of Activities ............................................................................................................................. 23
Test Bed Description ............................................................................................................................... 27
Roller settings and in situ tests ................................................................................................................ 28
GPS Settings ........................................................................................................................................... 29

Data Analysis 31

TB-1A and TB-1B Data Analysis (shoulder) .......................................................................................... 31
  Hamm IC Data ....................................................................................................................................... 32
  Caterpillar IC Data ................................................................................................................................. 35
TB-1C Data Analysis (main lane) ............................................................................................................. 40
LIST OF TABLES

Table 1. Features of the HAMM SD120 Double-drum IC Roller. .............................................................. 8
Table 2. Features of the Caterpillar CD54B split drum IC roller. .............................................................. 15
Table 3. Summary of Field Demonstration Activities ................................................................................ 23
Table 4. Test bed description. .................................................................................................................... 27
Table 5. Roller Settings and In-situ Tests. .................................................................................................. 28
Table 6. Fitted Parameter of the Draft Density Model. ................................................................................ 63

LIST OF FIGURES

Figure 1. Location Map of the IC Demo Project at I-95. .............................................................................. 4
Figure 2. HMA Mix Design (1 of 2) ............................................................................................................. 6
Figure 3. HMA Mix Design (2 of 2) ............................................................................................................. 7
Figure 4. HAMM HD+120 Double-drum IC Roller. ................................................................................... 8
Figure 5. Control panel on a HAMM roller. ................................................................................................. 9
Figure 6. The HAMM Compaction Quality (HCQ) system. ................................................................. 9
Figure 7. HAMM panel PC in the roller cabin. ......................................................................................... 10
Figure 8. OmniSTAR GPS receiver used on a HAMM roller. ................................................................. 10
Figure 9. The HAMM Compaction Quality (HCQ) measurement system. ......................................... 11
Figure 10. Illustration of changes in drum harmonics with increasing ground stiffness (modified from
Figure 43. TB-3 Hamm IC Data Maps ........................................................................................................ 50
Figure 44. TB-3 Statistics of Hamm IC Data ............................................................................................ 51
Figure 45. TB-3 Caterpillar IC Data Maps ............................................................................................... 53
Figure 46. TB-3 Statistics of Caterpillar IC Data .................................................................................... 54
Figure 47. TB-3 T5 data analysis ............................................................................................................. 55
Figure 48. TB-3 Core Data vs. NG Data .................................................................................................. 56
Figure 49. TB-1A, TB-1C, and TB-3 NG Data vs. PQI Data ................................................................. 57
Figure 50. TB-3 Core Density vs. Hamm IC Final Coverage Data ........................................................ 59
Figure 51. TB-3 Hamm Final Coverage Data vs. LWD Layer Moduli (MPa) ......................................... 60
Figure 52. TB-3 Hamm Final Coverage Data vs. FWD Layer Moduli (MPa) ......................................... 61
Figure 53. TB-3 FWD Layer Moduli vs. LWD Layer Moduli (MPa) ....................................................... 61
Figure 54. Predicted Densities vs. Core Density .................................................................................... 63
Figure 55. Open House – Indoor Presentation (1 of 2) ................................................................. 64
Figure 56. Open House – Indoor Presentation (2 of 2) ........................................................................ 65
Figure 57. TB-1B Test Point T2 Analysis ............................................................................................... 66
Figure 58. TB-3 Core Data vs. NG Data ................................................................................................. 67
Figure 59. Predicted Densities vs. Core Density (with final coverage data and pass-by-pass data) ........ 68
Acknowledgement

The authors would like to acknowledge the funding from FHWA to support this work.

The authors would also like to specifically acknowledge the following individuals for their contribution to this IC demonstration:

- FHWA: Victor (Lee) Gallivan
- FHWA – Maine Division: Mike Praul
- Asphalt Institute: Bob Horan
- Lane Construction: Joel Wardwell, Bruce Rideout, Cecil Dillon
- Maine DOT: Rick Bradbury, Jon Bither, Tom Stevens, Ryan Sullivan, Brian Luce, Wade McClay, Scott Bickford, Brad Foley, Derek Nener-Plante, Kevin Cummings, Dale Peabody
- Wirtgen/HAMM: Tim Kowalski, Josh Weston, Brandon, Christoph Korb
- Caterpillar: Todd Mansell
- Trimble: Pete Kaz, Bruce Hane
- SITECH NE: Tom Hogan
- Kessler: Garry Aicken
Introduction

Definition of Intelligent Compaction

Intelligent Compaction (IC) is an equipment-based technology that has been developed to improve the contractor’s quality control operations and improve the performance of the pavements. IC is defined as single or double-drum vibratory rollers with accelerometers mounted on the axel of drums, global positioning system and on-board computers that can display various roller operating settings on color-coded maps in real-time. Roller outputs include roller locations and passes, and stiffness of the compacted materials. For asphalt mixtures an infra-red temperature sensor is included for the real-time pavement temperature monitoring. Refer to Chang, et al. (2011) for the detailed history of development, background, and implementation of IC technologies.

The Federal Highway Administration (FHWA) has been leading a national effort to advance the IC technology through various projects such as the Transportation Pooled Funded (TPF) IC project with twelve (12) States department of transportation (DOT) from 2007 to 2011, and three National IC Workshops from 2011 to 2012. These efforts are in line with the FHWA initiative “Every Day Counts” or EDC to make the construction of national infrastructures “Faster, Safer, and Smarter”.

Background of this Study

Intelligent Compaction technology is an excellent technology to measure compaction quality with one hundred (100) percent coverage of compacted area in real-time. The current IC roller measurement values (ICMV) are accelerometer-based technology. The ICMVs, though varies from a vendor to another, relate to the stiffness of materials. On the other hand, density measurement is commonly being used for Quality Control (QC) and acceptance for agencies and contractors as in-place densities often relate to long-term performance of asphalt pavements. To accelerate the implementation of IC technology, it is essential to study the correlation between ICMV and HMA densities.

During the FHWA/TPF IC projects, unsatisfactory correlation between ICMV and in-place density was observed from the IC field demonstration projects. This may due to many factors such as the differences in nature and measurement depths between ICMV and in-place densities, uncertainties of in-situ density measurements with nuclear density gauges, and limited cores. Also, asphalt mixture temperatures during time of compaction would affect the correlation. Therefore, this project investigates the relationship between ICMV and core densities along with other factors (asphalt mixture design, ratios of nominal aggregate size and layer thickness, behind-the-pave densities, and compaction history, etc.) in order to establish procedures to use IC as a QA tool for in-place HMA densities. There are nine (9) IC field demonstration projects planned between 2012 and 2014.
Project Goals

The goals of this demonstration project are to:

- Investigate the relationship between ICMVs and in-place HMA densities;
- Develop a procedure to use IC as a QA tool for in-place HMA densities; and
- Identify and prioritize improvements and further research for IC technology.

Structure of this Document

The structure of this document is as follows:

- Introduction
- Project description
- IC rollers
- In-situ test devices
- Field demonstration activities
- Data analysis
- Open House activities
- Summary and Conclusions
**Project Description**

*Location*

This project is located at I-95, Island Falls-Oakfield, ME. The IC demonstration was conducted for the northbound lanes with traffic closure in Island Falls, ME. Two 25-ft wide main lane sections and a 10-ft wide outside shoulder were paved. The total paving length is approximately 12,000 ft or 2.3 miles.

The location map for this project is shown in Figure 1.

![Figure 1. Location Map of the IC Demo Project at I-95.](image)
**Typical Cross Sections**

This project is a new asphalt construction for two 25-ft wide sections and a 10-ft wide outside shoulder in the northbound direction.

The pavement layer information is as follows:

- 12" (+) Aggregate Base (hard, crushed stones)
- 2" 12.5mm Intermediate Course
- 12.5mm Surface Course.

The 2" 12.5mm intermediate course is the focus of this IC study.

**Asphalt Mix Design**

The intermediate course consists of HMA mix-12.5mm – course-graded with 20% RAP from a drum mix plant No. 32 in Smyrna. The binder grade is PG64-28. The asphalt mix design for the intermediate course is described as follows:
Figure 2. HMA Mix Design (1 of 2)
Figure 3. HMA Mix Design (2 of 2)
Intelligent Compaction Rollers

**HAMM Double-Drum IC Roller**

**Overall System Description**

The HAMM HD+120 double drum IC roller was used for this demonstration project (Figure 4). The features of this roller are described in Table 1.

![Image of HAMM HD+120 Double-drum IC Roller](image-link)

**Figure 4. HAMM HD+120 Double-drum IC Roller.**

**Table 1. Features of the HAMM SD120 Double-drum IC Roller.**

<table>
<thead>
<tr>
<th>Manufacturer/Vendor</th>
<th>HAMM/Wirtgen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Name</td>
<td>HCQ (Hamm Compaction Quality)</td>
</tr>
<tr>
<td>Model Number</td>
<td>HD+ 120 VVHF</td>
</tr>
<tr>
<td>Drum Width</td>
<td>78&quot; w/offset to 84.7&quot;</td>
</tr>
<tr>
<td>Machine Weight</td>
<td>Operating wt. 27,569 lbs. w/max of 32,187 lbs.</td>
</tr>
<tr>
<td>Amplitude Settings</td>
<td>High/Low -.028/.011 in. (0.71/0.27 mm)</td>
</tr>
<tr>
<td>Frequency Settings</td>
<td>Variable from 2700 - 4020 vpm</td>
</tr>
<tr>
<td>Auto-Feedback</td>
<td>NA</td>
</tr>
<tr>
<td>Measurement System</td>
<td>HAMM Compaction Quality (HCQ)</td>
</tr>
<tr>
<td>Measurement Value</td>
<td>HCQ indicator, density estimator, temperature, passes</td>
</tr>
<tr>
<td>Measurement Unit</td>
<td>[unitless, % compaction, °C, color coded]</td>
</tr>
<tr>
<td>GPS Capability</td>
<td>Yes</td>
</tr>
<tr>
<td>Documentation System</td>
<td>HCQ w/ability to download to Veda</td>
</tr>
</tbody>
</table>
The HAMM Compaction Quality (HCQ) modules are available for all state-of-the-art tandem rollers and rubber-wheeled rollers. If the roller is prefitted for HCQ, the HCQ components can be mounted and configured immediately.

![Figure 5. Control panel on a HAMM roller.](image)

The HCQ Indicator, HMV, enables monitoring of asphalt compaction. It also measures the asphalt temperature continuously in front of and behind the roller and shows the temperatures on the onboard display.

![Figure 6. The HAMM Compaction Quality (HCQ) system.](image)

Currently, new HAMM rollers can be delivered with the HCQ preliminary setup. This applies to soil compactors and asphalt rollers as well as machines with a cabin or ROPS roof. Retrofitting is also
possible for many existing machines. The system is extremely flexible: All of the other HCQ modules can be retrofitted individually and exchanged as required between different machines and construction sites.

At the core of the application is an extremely rugged panel PC with a touch screen and USB interface (Figure 7). This computer provides processing power as well as a monitor and data storage facilities. It is based on military standards, has a fully enclosed metal case, is protected against water and vibrations (IP 65) and has an operating range from -40 to +70°C.

![Figure 7. HAMM panel PC in the roller cabin.](image)

The DGPS receiver in a heavy-duty version with magnetic feet only takes seconds to mount on the roller (Figure 8). This device receives satellite signals along with a DGPS correction signal. Licenses for these signals are available in different accuracy classes. The HCQ Navigator retains the GPS signal for up to 16 hours even after the machine is shut down. This eliminates wait time for system initialization when starting work, after breaks, at the start of shifts, etc. When compacting under bridges or in locations with radio shadowing, sensors combine with the intelligent software to bridge over insufficient GPS signals for up to one minute.

![Figure 8. OmniSTAR GPS receiver used on a HAMM roller.](image)
**Measurement Value**

The HAMM IC measurement value is called accelerometer-based on system, HMV (Figure 9). The algorithm of HMV is similar to compaction meter value (CMV).

![Figure 9. The HAMM Compaction Quality (HCQ) measurement system.](image)

Compaction meter value (CMV) is a dimensionless compaction parameter developed by Geodynamik that depends on roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed), and is determined using the dynamic roller response (Sandström 1994). The concept of development of different harmonic components of drum vibration with increasing ground stiffness is illustrated in (Figure 10). CMV is calculated using 2, where C is a constant (i.e. 300), $A_{2\Omega}$ = the acceleration of the first harmonic component of the vibration, and $A_{\Omega}$ = the acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004).

\[
CMV = C \cdot \frac{A_{2\Omega}}{A_{\Omega}}
\]  

(1)

The Geodynamik system also measures the resonant meter value (RMV) which provides an indication of the drum behavior (e.g. continuous contact, partial uplift, double jump, rocking motion, and chaotic motion) and is calculated using Equation 2, where $A_{0.5\Omega}$ = subharmonic acceleration amplitude caused by jumping (the drum skips every other cycle. It is important to note that the drum behavior affects the CMV measurements (Brandl and Adam 1997) and therefore must be interpreted in conjunction with the RMV measurements (Vennapusa et al. 2010).
\[ \text{RMV} = C \cdot \frac{A_{0.5\Omega}}{A_{\Omega}} \]  \hfill (2)

**Figure 10. Illustration of changes in drum harmonics with increasing ground stiffness** (modified from Thurner and Sandström 1980).

It was found that CMV increases monotonously with the stiffness of soil. The HAMM IC measurement also consists of “compaction degree” values. The compaction degree indicates the percentage of asphalt compaction based on the asphalt density behind the paver (as “compaction rate by paver”), compactability of material (as “compaction resistance”), and a built-in empirical equation.

**Documentation System**

The HCQ-GPS Navigator software allows convenient data archival and evaluation:

- Logging of diverse data during the compaction process, e.g. DGPS position, compaction value, driving speed, frequency, amplitude, roller type.
- Geolines or graphics can be additionally provided in the project for orientation.
- Filtering of data based on dates/time, vibration status, temperature, and heights.
- Calibration against plate loading tests.
- Convenient data archival with data transfer via USB interface.
- Creation of result logs in digital format or as printouts.
• Export data for Veda analysis.

Examples of screenshots of the HCQ software are presented in Figure 11 (roller passes and mat temperatures) and Figure 12 (HMV and mat temperatures).

![Figure 11. Display of roller passes and asphalt mat temperature on the HCQ system.](image-url)
Figure 12. Display of HMV and asphalt mat temperature on the HCQ system.
Caterpillar Double-Drum IC Roller

Overall System Description

The Caterpillar CD54B split drum IC roller was used for this demonstration project (Figure 13). The features of this roller are summarized in Table 2.

![Figure 13 Caterpillar CD54B split drum IC roller.](image)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Caterpillar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Name</td>
<td>Tandem vibratory roller</td>
</tr>
<tr>
<td>Model Number</td>
<td>CD54B split drum</td>
</tr>
<tr>
<td>Drum Width</td>
<td>67” (1700 mm)</td>
</tr>
</tbody>
</table>
| Machine Weight        | Operating wt. 22,311 lbs.  
Static linear load 165 lb/in. |
| Amplitude Settings    | 0.024 – 0.013”       |
| Frequency Settings    | 2,520 and 3,200 vpm   |
| Auto-Feedback         | NA                   |
| Measurement System    | Compaction Meter Value (CMV) |
| Measurement Value     | CMV                  |
| Measurement Unit      | [unitless]           |
| Documentation System  | VisionLink           |
| Contact               | Bryan Downing, 763-493-7533  
Downing_Bryan_J@cat.com |
The Cat® CD54B is a 10 ton drum-steer roller with 1700 mm (67") vibratory drums. It offers excellent visibility, simple vibratory selection, wide mat coverage, and is available in solid or split drum models. Exceptional visibility and control with handwheel steering technology, touch-pad machine functions, ECO-mode operation, and automatic speed control. This machine can be equipped with a Cab or ROPS/FOPS.

Smooth operating powertrain with C3.4B engine that meets U.S. EPA Tier 4 Interim and E.U. Stage IIIB emissions standards. The split drum design delivers superior mat quality and smooth performance when turning. Four steering modes provide excellent maneuverability, while the large drum offset expands mat coverage. The traction control system automatically actuates and delivers a balanced torque to each drum.

Versatile vibratory performance delivered with dual amplitude, dual frequency vibratory system that automatically matches frequency and amplitude at the flip of a switch. Easily adjustable for thin and thick lift applications.

Cat® Compaction Control keeps the operator informed for higher performance and efficiency. Infrared temperature sensors combined with mapping keep the operator informed of when optimal temperatures exist and where compaction has taken place. Temperature Mapping records temperatures for data analysis, while Pass-Count Mapping keeps the operator informed of where mat coverage has taken place and the number of passes made.

Industry-Leading Water Spray System features dual water pumps, triple filtration, intermittent operation and high capacity for optimal performance. An optional freeze protection kit offers protection in cold temperatures.

Unmatched Uptime with ECO-mode operation conserves fuel, while oil-bath lubrication and 3 yr/3000 hr vibratory drum service interval extends operation and minimizes life-time operating costs.

Trimble retrofit IC systems use the Trimble CCS 900 as an onboard, in-cab, three dimensional (3D) display. The display is equipped with a keypad that allows the operator to interface with the system using push buttons and a color monitor. The operator can then view real-time information, such as machine location and speed, drum amplitude, vibration frequency, and number of passes, relative to the design plan. This system uses 3D design files that are stored on a CompactFlash data card and inserted into a slot next to the keypad.

Caterpillar IC systems use the Trimble CCS 900 as an onboard, in-cab, three dimensional (3D) display. The display is equipped with a keypad that allows the operator to interface with the system using push buttons and a color monitor. The operator can then view real-time information, such as machine location and speed, drum amplitude, vibration frequency, and number of passes, relative to the design plan. This
system uses 3D design files that are stored on a CompactFlash data card and inserted into a slot next to the keypad.

![Figure 32. Caterpillar IC onboard display.](image)

**Measurement Value**

The Caterpillar IC measurement value is accelerometer-based, Compaction Meter Value. The description is repeated below for ease of reading.

Compaction meter value (CMV) is a dimensionless compaction parameter developed by Geodynamik that depends on roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed), and is determined using the dynamic roller response (Sandström 1994). The concept of development of different harmonic components of drum vibration with increasing ground stiffness is illustrated in (Figure 10). CMV is calculated using equation (3), where C is a constant (i.e. 300), $A_{2\Omega}$ = the acceleration of the first harmonic component of the vibration, and $A_\Omega$ = the acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004).

$$CMV = C \cdot \frac{A_{2\Omega}}{A_\Omega}$$  \hspace{1cm} (3)

The Geodynamik system also measures the resonant meter value (RMV) which provides an indication of the drum behavior (e.g. continuous contact, partial uplift, double jump, rocking motion, and chaotic motion) and is calculated using Equation 2, where $A_{0.5\Omega}$ = subharmonic acceleration amplitude caused by jumping (the drum skips every other cycle. It is important to note that the drum behavior affects the CMV measurements (Brandl and Adam 1997) and therefore must be interpreted in conjunction with the RMV.
measurements (Vennapusa et al. 2010).

\[ RMV = C \cdot \frac{A_{0.5\Omega}}{A_{\Omega}} \]  

(4)

**Figure 14. Illustration of changes in drum harmonics with increasing ground stiffness (modified from Thurner and Sandström 1980).**

**Documentation System**

The Caterpillar IC AccuGrade CCS900 Compaction Control System makes use of Trimble SNM940 Connected Site Gateway and VisionLink (VL) for automatic data submission, archival and evaluation. VisionLink is a cloud-based solution that can be accessed by various devices such as tablets or smartphones. IC data can be wirelessly transmitting IC data to the VL at a 5-10 min. interval when cellular coverage is available. Manual upload to VL will be needed if cellular coverage is unavailable. In this case, uses need to transfer the *.tag files from the CS900 unit, use the Trimble Business Center to generate a DC file, then logon to VL to create an appropriate project and upload the files.

The VisionLink™ solution from Trimble integrates site productivity, material quantities, and materials movement with asset and fleet management to give you a holistic view of your site so you can make the right decision at the right time. Centralizing and simplifying the management of on-site operations maximizes efficiency, raises productivity and lowers costs for your entire fleet.
Know when and where your equipment is working
Monitor asset utilization and minimize idle times to reduce equipment depreciation and eliminate unnecessary and costly fuel burn.
Manage and make informed decisions about production efficiency.
See continuously updated surface models based on machine activity.
Scheduled reporting of business-critical information like volume and quality assurance data for easier and more accurate billing, inspections and project progress.

Compaction Monitoring

- Continuously monitor pass counts and compaction meter values over the entire area of compaction and on all material layers to improve testing success, reduce rework and lower ongoing maintenance costs
- Reduce over-compaction to optimize fuel use and machine time, and increase the finished surface quality
- Ensure uniform lift thicknesses and consistent compaction pass counts and meter values to increase the surface quality and operational life
- Monitor temperature maps for asphalt compactors fitted with temperature sensors to ensure compaction per the temperature range specified on the project

Figure 15. View data in VisionLink.
In-situ Test Devices

Nuclear Density Gauge (NG)

The nuclear density gauge (NG) was used to measure the densities of HMA materials, as shown in Figure 16. The nuclear density gauge measures the in-place material density based on the gamma radiation. NG usually contain a small gamma source (about 10 mCi) such as Cesium-137 on the end of a retractable rod (University of Washington website, see reference).

The device consists of a hander, a retractable rod, the frame, a shielding, a source, and a Geiger-Mueller detector as shown in Figure 16. The source emits gamma rays that interact with electrons in the HMA pavement through absorption, Compton scattering, and the photoelectric effect. The detector (situated in the gauge opposite from the handle) counts gamma rays that reach it from the source. Then, the received number of gamma rays by the detector is correlated to the density of HMA materials (see Figure 16).

Figure 16. Nuclear density gauge mechanism.

Falling Weight Deflectometer (FWD)

The FWD test data were collected using a JILS-FWD (see Figure 17). The test was performed on the intermediate asphalt course. The test strip has 30 test spots on one test line with 50 ft intervals. The test settings were as follows:

- Platen Size: 5.9” radius (rigid plate)
- Geophone positions: 0, 8, 12, 18, 24, 36, 60 inches (7 sensors)
- Drops/Loads: 2 drops targeting 9,000 lbs
- File format: *.DAT, and *.THY (time history)
Light Weight Deflectometer for Asphalt (LWD-a)

The LWD data were collected using a modified Zorn ZFG 2000A device (see Figure 18) to measure the stiffness of hot mix asphalt following the compaction. This LWD is designed for testing freshly paved HMA layers. The test settings were as follows:

- Drop weight: 10 kg;
- Drop height: 70 cm;
- Pulse time: 17 ms;

The collected data for each drop includes the deflections with time series, the drop speed, etc. By using the deflection data collected from these sensors, the modulus of pavement layers were back-calculated by Zorn’s software program.
Figure 18. LWDa equipment.
Field Demonstration Activities

Summary of Activities

A summary of day-to-day activities for this demonstration is described in Table 3. Trial runs and GPS verification as well as paving/compaction operations are illustrated in Figure 19 and Figure 20. In-situ spot tests and coring operations are illustrated in Figure 21.

Table 3. Summary of Field Demonstration Activities

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 0 Sunday</td>
<td>• Conduct IC rollers/GPS setup and trial runs (equipment vendors and FHWA IC team only) at the staging area. (2PM-4PM)</td>
</tr>
<tr>
<td>(Aug 18)</td>
<td></td>
</tr>
<tr>
<td>Day 1 Monday</td>
<td>• Set up the GPS base station and IC roller/GPS system (by 7AM).</td>
</tr>
<tr>
<td>(Aug 19)</td>
<td>• Conduct project briefing at the staging area and IC training for roller operators (7AM-8AM).</td>
</tr>
<tr>
<td></td>
<td>• Start paving with one IC roller at breakdown and another IC roller at intermediate position.</td>
</tr>
<tr>
<td></td>
<td>• Select a 500-ft section as a test strip to establish the rolling pattern.</td>
</tr>
<tr>
<td></td>
<td>• Conduct NG/GPS/LWD-a testing immediately behind the paver and at selected locations after each breakdown and intermediate roller pass within the test strip.</td>
</tr>
<tr>
<td></td>
<td>• Perform production compaction using the rolling pattern.</td>
</tr>
<tr>
<td></td>
<td>• Conduct NG/GPS/LWD-a at selected locations after the finishing rolling.</td>
</tr>
<tr>
<td>Day 2 Tuesday</td>
<td>• Cancelled due to rain</td>
</tr>
<tr>
<td>(Aug 20)</td>
<td></td>
</tr>
<tr>
<td>Day 3 Wednesday</td>
<td>• Set up the GPS base station and IC roller/GPS system (by 7AM).</td>
</tr>
<tr>
<td>(Aug 21)</td>
<td>• Start paving with one IC roller at breakdown and another IC roller at intermediate position.</td>
</tr>
<tr>
<td></td>
<td>• Select a 500-ft section. Conduct NG/GPS/LWD-a testing immediately behind the paver and at selected locations after each breakdown and intermediate roller pass within the test strip.</td>
</tr>
<tr>
<td></td>
<td>• Perform production compaction using the rolling pattern.</td>
</tr>
<tr>
<td></td>
<td>• Conduct NG/GPS/LWD-a at selected locations after the finishing rolling.</td>
</tr>
<tr>
<td>Days 4 Thursday</td>
<td>• Conduct the Open House event including presentation and equipment demonstration.</td>
</tr>
<tr>
<td>(Aug 22)</td>
<td></td>
</tr>
</tbody>
</table>

- GPS: Hand-held Global Positioning System rover will be provided by SITEH-NE.
• NG: Nuclear density gauge and an operator will be provided by Lane Construction.
• LWD-a: Lightweight deflectometer for asphalt tests will be provided by Kessler.
• FWD: Falling weight deflectometer and an operator will be provided by Maine DOT.
• GPR: Ground penetrating radar will be provided by Maine DOT.
• Coring: 60 X 4” cores will be taken with two core rigs by Maine DOT.

Figure 19. Trial runs and GPS setups.
Figure 20. Asphalt paving and IC Compaction.
Figure 21. In-Situ Point Measurements and Coring.
**Test Bed Description**

Table 4 summarizes the test bed information, with test locations shown in Figure 22.

**Table 4. Test bed description.**

<table>
<thead>
<tr>
<th>Test Bed (TB)</th>
<th>Material/Layer</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>2”, 12.5mm intermediate course</td>
<td>NB outside 10-ft shoulder</td>
</tr>
<tr>
<td>1B</td>
<td>2”, 12.5mm intermediate course</td>
<td>NB outside 10-ft shoulder</td>
</tr>
<tr>
<td>1C</td>
<td>2”, 12.5mm intermediate course</td>
<td>NB 25-ft main line</td>
</tr>
<tr>
<td>3</td>
<td>2”, 12.5mm intermediate course</td>
<td>NB 25-ft main line</td>
</tr>
</tbody>
</table>

**Figure 22. Test Bed Locations.**
Roller settings and in situ tests

Summarizes the roller settings and in-situ tests are presented in Table 5.

<table>
<thead>
<tr>
<th>TB</th>
<th>Date</th>
<th>Machine</th>
<th>Position</th>
<th>Settings</th>
<th>Passes</th>
<th>In-Situ Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB-1A</td>
<td>8/19</td>
<td>Hamm</td>
<td>breakdown</td>
<td>3500vpm, low amp</td>
<td>4</td>
<td>T1 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pneumatic</td>
<td>intermediate</td>
<td>static</td>
<td>3</td>
<td>No tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td>finishing</td>
<td>3500vpm, low amp</td>
<td>1</td>
<td>T1 NG after each pass</td>
</tr>
<tr>
<td>TB-1B</td>
<td>8/19</td>
<td>Hamm</td>
<td>breakdown</td>
<td>3500vpm, low amp</td>
<td>10</td>
<td>T2 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td>intermediate</td>
<td>3000vpm, low amp</td>
<td>5</td>
<td>T2 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pneumatic</td>
<td>finishing</td>
<td>static</td>
<td>1</td>
<td>No tests</td>
</tr>
<tr>
<td>TB-1C</td>
<td></td>
<td>Hamm</td>
<td>breakdown</td>
<td>3500vpm, low amp</td>
<td>9</td>
<td>T4 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td>interm/finishing</td>
<td>3000vpm, low amp</td>
<td>5</td>
<td>T4 NG after each pass</td>
</tr>
<tr>
<td>TB-3</td>
<td>8/21</td>
<td>Hamm</td>
<td>breakdown</td>
<td>3500vpm, low amp</td>
<td>10</td>
<td>T5 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td>interm/finishing</td>
<td>3000vpm, low amp</td>
<td>4</td>
<td>T5 NG after each pass GPS,FWD, LWD, GPR at core locations</td>
</tr>
</tbody>
</table>
GPS Settings

GPS is the core of the IC technology to tie all data source together. The UTM-19N (Figure 23) is selected as the grid reference for all GPS devices used during this demonstration.

The Caterpillar IC system was equipped with a Trimble receiver and a radio (Figure 24). A Trimble GPS base station was setup on-site to provide correction signals to the Sakai IC system in order to achieve Real Time Kinematic (RTK) precision (Figure 25). A hand-held Trimble GPS rover was tied to the same GPS base station. GPS checks were conducted at a daily basis. The GPS check results are very satisfactory.
The HAMM IC system was equipped with a GPS receiver which makes use of OmniStar HP subscription signals, a network type RTK, instead of an on-ground GPS base station (Figure 26). The precision that can be achieved with the OmniSTAR HP subscription is said to be 5 to 10 cm. Another GPS receiver with OmniStar HP subscription was used with a HAMM data logger for relating to the HAMM IC measurements as both devices use the same network type RTK.

Figure 26. HAMM IC system with an OmniStar GPS Receiver.
Data Analysis

TB-1A and TB-1B Data Analysis (shoulder)

TB-1A and TB-1B was compacted during the Day 1 paving operation of the intermediate course. The location was at the outside 10-ft shoulder in the NB direction of I-95. The Hamm IC roller was used as the breakdown roller with the front drum vibrating at the high frequency and low amplitude settings. For TB-1A, the Caterpillar IC roller was used as the intermediate roller with the front drum vibrating at the high frequency and low amplitude settings. A conventional pneumatic roller was used as the finishing roller in static mode. For TB-1B, a conventional pneumatic roller was used as the intermediate roller in static mode while the Caterpillar IC roller was used as the finishing roller with the front drum vibrating at the high frequency and low amplitude settings. The schematic of the test plan for TB-1A and TB-1B is shown in Figure 27 and Figure 28, respectively.

Figure 27. TB-1A Schematic of Test Plan
Hamm IC Data

The Hamm IC mapping data are presented in Figure 29 while the statistics for those IC data are in Figure 30. The observations are as follows:

- ICMV: The mean HMV value is 31 with standard deviation of 18. The zero HMV values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 105°C with standard deviation of 28°C. It appears to consist of 2 distributions with one erroneous population in the lower temperatures range less than 80°C.
- Pass Counts: The roller patterns set by the contractor is 4 vibratory passes in TB-1A and increased to 10 in TB-1B. The mean passes for the combined group is 4.
• Speed: The mean roller speed is 3 kph.
• Frequency: The mean frequency is 53Hz.
• Compaction curve: The curve grows monotonically without an apparent optimal value.

Figure 29. TB-1A and TB-1B Hamm IC Data Maps.
Figure 30. TB-1A and TB-1B Statistics of Hamm IC Data.
Caterpillar IC Data

The Caterpillar IC data maps are presented in Figure 31 and the statistics of the IC data are presented in Figure 32. Only the front drum data are analyzed. The observations are as follows:

- **ICMV**: The mean CMV value is 46 with standard deviation of 17.
- **Temperature**: The mean surface temperature is 56°C with standard deviation of 14°C. There are two sub-distributions that reflect the intermediate at higher temperatures and finishing compactions in lower temperatures.
- **Pass Counts**: The roller patterns set by the contractor is 1 vibratory pass in TB-1A and increase to 5 passes in TB-1B. The mean passes for the combined group is 3.
- **Speed**: The mean roller speed is 6 kph.
- **Frequency**: The mean frequency is 45 Hz. There are two distributions with one centering at 43 Hz and another one, 53 Hz.
- **Compaction curve**: The curve grows monotonically without an apparent optimal value.
Figure 31. TB-1A and TB-1B Caterpillar IC Data Maps.
Figure 32. TB-1A and TB-1B Statistics of Caterpillar IC Data.
**NG Data and Pass-by-Pass IC Data**

NG measurements were made at 3 locations (T1 at TB1A; T2 at TB1B) after the paver and each roller pass. The plots of NG densities and surface temperatures vs. passes are presented in Error! Reference source not found..

- The trend of NG densities varies slightly among test locations partly due to changes of rolling patterns. After the breakdown phase, the NG density growth curve normally reaches the plateau around 90% Gmm. No de-compaction is observed.
- At T1, the NG density growth curve’s plateau is below 90% Gmm after 4 Hamm roller passes at vibratory mode. No further analysis was performed due to a GPS record issue.

![Figure 33. TB-1A Test Point T1 Analysis](image-url)
At T2, the density grew higher than 90% Gmm due to increased number of passes. After 5 Hamm rollers at vibratory mode, the density reaches at 90% Gmm. After additional Caterpillar and Hamm roller passes, the density increases to 94% Gmm. The trends for both density growth and HMV are similar. The linear correlation between the two indicates an $R^2$ value of 0.7. Therefore, the ICMV from the Hamm IC roller at the break down position correlate well with the nuclear density gauge measurements at TB-1B. Not further analysis with the Caterpillar IC data due to a GPS offset issue.

Figure 34. TB-1B Test Point T2 Analysis
**TB-1C Data Analysis (main lane)**

TB-1C was compacted during the Day 1 paving operation of the intermediate course. The location was at the main lane in the NB direction of I-95. The Hamm IC roller was used as the breakdown roller with the front drum vibrating at the high frequency and low amplitude settings. The Caterpillar IC roller was used as the intermediate/finishing roller with the front drum vibrating at the high frequency and low amplitude settings. No additional roller was used. The schematic of the test plan for TB-1C is shown in Figure 35.

![Figure 35. TB-1C Schematic of Test Plan](image-url)
Hamm IC Data

The Hamm IC mapping data are presented in Figure 29 while the statistics for those IC data are in Figure 30. The observations are as follows:

- ICMV: The mean HMV value is 37 with standard deviation of 14. The zero HMV values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 85°C with standard deviation of 13°C.
- Pass Counts: The roller patterns set by the contractor is 9 vibratory passes.
- Speed: The mean roller speed is 3 kph.
- Frequency: The mean frequency is 63Hz.
- Compaction curve: The curve grows monotonically without an apparent optimal value. Note that some Caterpillar passes were inserted between Hamm roller passes.
Figure 36. TB-1C Hamm IC Data Maps.
Figure 37. TB-1C Statistics of Hamm IC Data.
Caterpillar IC Data

The Caterpillar IC data maps are presented in Figure 38 and the statistics of the IC data are presented in Figure 39. The observations are as follows:

- **ICMV**: The mean CMV value is 38 with standard deviation of 7.6.
- **Temperature**: The mean surface temperature is 66°C with standard deviation of 9°C.
- **Pass Counts**: The roller patterns set by the contractor is 5 vibratory passes.
- **Speed**: The mean roller speed is 5 kph.
- **Frequency**: The mean frequency is 54Hz.
- **Compaction curve**: The curve grows monotonically without an apparent optimal value. Note that some Hamm passes were inserted between Caterpillar roller passes.
Figure 38. TB-1C Caterpillar IC Data Maps.
Figure 39. TB-1C Statistics of Caterpillar IC Data.
**NG Data vs. IC Roller Data**

NG measurements were made at 1 location, T4 after the paver and each roller pass. The plots of NG densities and surface temperatures vs. passes are presented in Figure 40.

- After the breakdown phase using Hamm roller compaction, the NG density growth curve reaches the plateau around 93% Gmm. No further density gains were observed within the intermediate and finishing phases using the Caterpillar roller.
- The density growth and HMV values do not indicate a good correlation at TB-1C.

![Figure 40. TB-1C T4 data analysis.](image)
TB-3 Data Analysis (main lane)

TB-3 was compacted during the Day 3 paving operation of the intermediate course. The location was at the main lane in the NB direction of I-95. The Hamm IC roller was used as the breakdown roller with the front drum vibrating at the high frequency and low amplitude settings. The Caterpillar IC roller was used as the intermediate roller with the front drum vibrating at the high frequency and low amplitude settings. A pneumatic roller was used as the finishing roller in static mode. Extensive tests were conducted after each roller pass and after the finishing rolling. The schematic of the test plan for TB-3 is shown in Figure 41. A portion of the core locations are shown in Figure 42.

![Figure 41. TB-3 Schematic of Test Plan](image-url)
Hamm IC Data

The Hamm IC mapping data are presented in Figure 43 while the statistics for those IC data are in Figure 44. The observations are as follows:

- ICMV: The mean HMV value is 34 with standard deviation of 16. The zero HMV values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 88°C with standard deviation of 20°C.
- Pass Counts: The roller patterns set by the contractor is 10 vibratory passes. The recorded mean roller passes is 8.
- Speed: The mean roller speed is 3 kph.
- Frequency: The mean frequency is 61Hz.
- Compaction curve: The curve grows monotonically with a very narrow range (6 HMV) without an apparent optimal value.
Figure 43. TB-3 Hamm IC Data Maps.
Figure 44. TB-3 Statistics of Hamm IC Data.
Caterpillar IC Data

The Caterpillar IC data maps are presented in Figure 45 and the statistics of the IC data are presented in Figure 46. The observations are as follows:

- ICMV: The mean CMV value is 42 with standard deviation of 9.
- Temperature: The mean surface temperature is 63°C with standard deviation of 12°C.
- Pass Counts: The roller patterns set by the contractor is 4 vibratory passes. The recorded mean roller passes is also 4.
- Speed: The mean roller speed is 5.4 kph.
- Frequency: The mean frequency is 53Hz.
- Compaction curve: The curve is with a very narrow range (around 42 CMV) without an apparent optimal value.
Figure 46. TB-3 Statistics of Caterpillar IC Data.
**NG Data vs. Roller Passes**

NG measurements were made at 1 location, T5 after the paver and each roller pass. The plots of NG densities and surface temperatures vs. passes are presented in Figure 40.

- After the breakdown phase using Hamm roller compaction, the NG density growth curve reaches the plateau around 91.5% Gmm. Then, the density gains 1% Gmm after 4 more Caterpillar roller passes and 1% Gmm after two more pneumatic roller passes.
- The correlation between the NG density and HMV is moderate with a $R^2$ of 0.38 at TB-3.

![Figure 47. TB-3 T5 data analysis.](image-url)
Correlation Analysis

The correlation analysis is to investigate the relationships among various measurements including Hamm IC data, Caterpillar IC data, nuclear density gauge measurements, core densities, FWD, and LWD measurements.

Univariate Regression

Univariate regression is used to investigate relationship between one dependent variable and one independent variable. The regression uses a linear function. Only the proofing data (i.e., last pass data) from the IC measurements are evaluated.

Core Data vs. Nuclear Density Gauge (NG) Data

- The correlation between core data and nuclear density gauge data shows a R² value of 0.78. The core densities are systematically higher than the nuclear density gauge data. Therefore, calibration of the NG device is required. (Figure 48)
- The mean core density is 94.8% with minimum of 92.4 and maximum of 96.7 (i.e., the range is 4.3%).

![Figure 48. TB-3 Core Data vs. NG Data.](image)
**Nuclear Density Gauge (NG) Data and PQI data**

- Both NG and non-nuclear density gauge (PQI) data were collected during the pass-by-pass data collection at test locations, T1, T4, and T5.
- The correlation between nuclear density gauge and non-nuclear density gauge (PQI) data shows a $R^2$ value of 0.75. The PQI data are systematically higher than the nuclear density gauge data. (Figure 48)

![Graph showing correlation between NG and PQI data](image)

**Figure 49. TB-1A, TB-1C, and TB-3 NG Data vs. PQI Data.**
Core Density Data vs. Final Coverage IC Data

The Hamm data within 1 m radius of coring locations were evaluated. Results of Hamm HMV data analyses with core density as dependent variables indicate very low correlation of $R^2 = 0.01$. The correlation with pass count shows a low $R^2 = 0.25$ (Figure 50)

No further analysis was performed for Caterpillar IC data due to a GPS offset issue.
Figure 50. TB-3 Core Density vs. Hamm IC Final Coverage Data.
**LWD Data vs. Final Coverage ICMV Data**

The Hamm data within 1 m radius of LWD test locations were evaluated. Result of Hamm HMV data analyses with backcalculated LWD moduli as dependent variables indicates low correlation of $R^2 = 0.01$ (Figure 51).

![Figure 51. TB-3 Hamm Final Coverage Data vs. LWD Layer Moduli (MPa).](image-url)
FWD Data vs. Final Coverage ICMV Data

The Hamm data within 1 m radius of FWD test locations were evaluated. Result of Hamm HMV data analyses with backcalculated FWD moduli as dependent variables indicates low correlation of $R^2 = 0.03$ (Figure 52). The correlation between FWD and LWD backcalculated moduli is also low (Figure 53).

Figure 52. TB-3 Hamm Final Coverage Data vs. FWD Layer Moduli (MPa).

Figure 53. TB-3 FWD Layer Moduli vs. LWD Layer Moduli (MPa).
Multivariate Regression

Multivariate regression is used to investigate relationship between one dependent variable and more than one independent variable. The purpose of this analysis is to investigate the effects of all other measurements on specific measurements assuming “the other measurements” are independent with each other.

A draft multivariate, nonlinear stochastic density model is developed to predict field in-place density with a general form as:

\[
\rho(i,j) = \rho_0(i) + (Gmm - \rho_0(i))e^{-\left(\frac{a_1 Kac + a_2 T + a_3 f + a_4 V_R}{j}\right)^{\beta}} + \Delta\hat{\rho}(i,j)
\]

Where

\(\rho(i,j) = \text{density at location } i \text{ after pass no. } j\)

\(\rho(i) = \text{initial or zeropass density at location } i\)

\(Gmm = \text{maximum density}\)

\(Kac = \text{asphalt moduli}\)

\(T = \text{asphalt surface temperature}\)

\(f = \text{roller vibration frequency}\)

\(V_R = \text{roller speed}\)

\(\Delta\hat{\rho}(i,j) = \text{density changes during finishing rolling at location } i \text{ after pass no. } j\)

\(a_1, a_2, a_3, a_4, \beta = \text{fitted parameters}\)

The usage of the model starts with the calibration data from a test strip to obtain the fitted parameter. Then, the fitted model is used to predict densities for the production compaction. As indicated in the pass-by-pass analysis, caution should be taken when using a single fitted model for density prediction as the density growth curves change from a location to another.
While the above model is still under revision, the following example is used to demonstrate its current usage. The pass-by-pass data at T5 and a sub-set of the Hamm final coverage data are used to obtain the fitted parameter by using the goal seek tool of MS Excel (Table 6).

Table 6. Fitted Parameter of the Draft Density Model

<table>
<thead>
<tr>
<th>$\rho_0$</th>
<th>Gmm</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$\alpha_4$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.1</td>
<td>98.52063</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.012753</td>
<td>6.26E-01</td>
</tr>
</tbody>
</table>

The results of predicted density vs. core density indicate $R^2 = 0.20$ and 0.71 for using final coverage data and the combined final coverage data and pass-by-pass data, respectively. (Figure 54)

![Figure 54. Predicted Densities vs. Core Density.](image-url)

Please note that the above results are simply a demonstration of an interim density model. It is anticipated that the above draft density model will be modified as more IC field data and core density data are available. Alternative density models in simplified forms may also be developed for practical implementation in real world projects instead of research projects.
Open House

Maine DOT coordinated an Open House event for this demonstration. The Open House was conducted at the Waterville Elks Banquet and Conference Center in Waterville, ME, including an approximately 3-hour indoor presentation (Figure 55 and Figure 56). No equipment demonstration was included. The presenters included the FHWA IC team, IC vendors, and GPS vendor(s). It was well attended by agencies and industry personnel.

Figure 55. Open House – Indoor Presentation (1 of 2).
Figure 56. Open House – Indoor Presentation (2 of 2).
Summary

From the above data analysis, the followings are the interim observations:

Operations of IC Systems

- Both the Caterpillar and HAMM IC roller systems functioned well during the demonstration. Both IC data were successfully exported from the IC systems (HCQ from Hamm and VisionLink from Cat pillar/Trimble) and imported to a standardized tool, Veda, for further analysis.
- The correlation analysis was not performed for the Caterpillar IC data due to a GPS offset issue.
- These IC systems can be used for quality control by improving the consistency and uniformity of compaction. However, the IC systems were not used to their potential at this project as the roller patterns were dictated by the QC personnel instead of taking advantage of the IC passes tracking systems.

NG Density Growth Curves vs. IC Roller data

- The trend of NG densities and Hamm HMV (at break down position) show a good correlation at TB-1B.

Figure 57. TB-1B Test Point T2 Analysis
Linear correlation analysis

- The correlation between core data and nuclear density gauge data shows a $R^2$ value of 0.55 at TB-3. The core densities are systematically higher than the nuclear density gauge data. Therefore, calibration of the NG device is required.

![Figure 58. TB-3 Core Data vs. NG Data.](image)

- At TB-3, the correlation between backcalculated moduli from the LWD data and Hamm HMV (breakdown) is poor. Same does the FWD data.
- At TB-3, the correlation between core data and the Hamm final coverage data is poor although the correlation was satisfactory for the pass-by-pass data at TB-1B.

Multivariate nonlinear stochastic density model

- A preliminary multivariate nonlinear stochastic density model was developed. The pass-by-pass data at T5 and a sub-set of the Hamm final coverage data are used to obtain the fitted parameter by using the goal seek tool of MS Excel. The results of predicted density vs. core density indicate $R^2 = 0.71$ for using the combined Hamm final coverage data and pass-by-pass data. Therefore, this initial validation test was found satisfactory. The model will continue to be revised as more field data are available during this study.
Figure 59. Predicted Densities vs. Core Density (with final coverage data and pass-by-pass data).

Recommendations for future study:

- Calibration of the NG device against core density is required.
- More extensive pass-by-pass data need to be collected and compaction history needs to be captured in order to consider all factors that affect the eventual asphalt in-place density.
- Density measurements after all roller passes (including breakdown and intermediate compaction) are recommended to provide complete time-history data for density prediction model developments;
- A stochastic multivariate nonlinear model based on compaction history data needs to be revised to predict density from all IC measurements.
- Alternative density models in simplified forms may also be developed for practical implementation in real world projects instead of research projects.
- All IC measurements using accelerometer-based technology need to be conducted at elevated temperatures in order to reflect the internal structure of compacted mat, such as the aggregate contacts and interlocks.

Notes

The above observations from this specific IC field project under this study are interim results. The final conclusions of the HMA in-place density vs. IC will be provided when all nine (9) field studies are completed by October 2014.
References


Bibliography


## Appendix A - On-site Personnel

The contact information of all parties involved in the field demonstration is listed below:

<table>
<thead>
<tr>
<th>First name</th>
<th>Last name</th>
<th>Affiliation</th>
<th>Telephone</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHWA IC Project Team</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>George</td>
<td>Chang</td>
<td>Transtec Group</td>
<td>512-659-1231</td>
<td><a href="mailto:gkchang@thetranstecgroup.com">gkchang@thetranstecgroup.com</a></td>
</tr>
<tr>
<td>Qinwu</td>
<td>Xu</td>
<td>Transtec Group</td>
<td>512-709-4155</td>
<td><a href="mailto:qinwu@thetranstecgroup.com">qinwu@thetranstecgroup.com</a></td>
</tr>
<tr>
<td>Lee</td>
<td>Gallivan</td>
<td>FHWA</td>
<td>317-605-4704</td>
<td><a href="mailto:Victor.Gallivan@dot.gov">Victor.Gallivan@dot.gov</a></td>
</tr>
<tr>
<td>Bob</td>
<td>Horan</td>
<td>Asphalt Institute</td>
<td>804-539-3036</td>
<td><a href="mailto:bhoran@AsphaltInstitute.org">bhoran@AsphaltInstitute.org</a></td>
</tr>
<tr>
<td>Mike</td>
<td>Praul</td>
<td>FHWA - Maine</td>
<td>207-462-0317</td>
<td><a href="mailto:Michael.Praul@dot.gov">Michael.Praul@dot.gov</a></td>
</tr>
<tr>
<td>State DOT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rick</td>
<td>Bradbury</td>
<td>Maine DOT</td>
<td>207-441-2474</td>
<td><a href="mailto:Richard.bradbury@maine.gov">Richard.bradbury@maine.gov</a></td>
</tr>
<tr>
<td>Jon</td>
<td>Bither</td>
<td>Maine DOT</td>
<td>207-557-1050</td>
<td><a href="mailto:Jon.bither@maine.gov">Jon.bither@maine.gov</a></td>
</tr>
<tr>
<td>Tom</td>
<td>Stevens</td>
<td>Maine DOT</td>
<td>207-592-4508</td>
<td><a href="mailto:Thomas.Stevens@maine.gov">Thomas.Stevens@maine.gov</a></td>
</tr>
<tr>
<td>Ryan</td>
<td>Sullivan</td>
<td>Maine DOT</td>
<td>207-446-0118</td>
<td><a href="mailto:Ryan.Sullivan@maine.dot">Ryan.Sullivan@maine.dot</a></td>
</tr>
<tr>
<td>Brian</td>
<td>Luce</td>
<td>Maine DOT</td>
<td>207-446-0360</td>
<td><a href="mailto:Brian.Luce@maine.gov">Brian.Luce@maine.gov</a></td>
</tr>
<tr>
<td>Wade</td>
<td>McClay</td>
<td>Maine DOT</td>
<td>207-462-1443</td>
<td><a href="mailto:Wade.McClay@maine.gov">Wade.McClay@maine.gov</a></td>
</tr>
<tr>
<td>Scott</td>
<td>Bickford</td>
<td>Maine DOT</td>
<td>207-215-3857</td>
<td><a href="mailto:Scott.Bickford@maine.dot">Scott.Bickford@maine.dot</a></td>
</tr>
<tr>
<td>Brad</td>
<td>Foley</td>
<td>Maine DOT</td>
<td>207-624-3539</td>
<td><a href="mailto:Brad.Foley@maine.gov">Brad.Foley@maine.gov</a></td>
</tr>
<tr>
<td>Derek</td>
<td>Nener-Plante</td>
<td>Maine DOT</td>
<td>207-215-0849</td>
<td><a href="mailto:Derek.Nener-Plante@maine.gov">Derek.Nener-Plante@maine.gov</a></td>
</tr>
<tr>
<td>Kevin</td>
<td>Cummings</td>
<td>Maine DOT</td>
<td>207-592-0907</td>
<td><a href="mailto:Kevin.Cummings@maine.gov">Kevin.Cummings@maine.gov</a></td>
</tr>
<tr>
<td>Dale</td>
<td>Peabody</td>
<td>Maine DOT</td>
<td>207-624-3305</td>
<td><a href="mailto:Dale.Peabody@maine.gov">Dale.Peabody@maine.gov</a></td>
</tr>
<tr>
<td>Vendors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tim</td>
<td>Kowalski</td>
<td>Wirtgen/Hamm</td>
<td>615-594-4604</td>
<td><a href="mailto:tkowalski@Wirtgenamerica.com">tkowalski@Wirtgenamerica.com</a></td>
</tr>
<tr>
<td>Josh</td>
<td>Weston</td>
<td>Wirtgen/Hamm</td>
<td>615-693-9839</td>
<td><a href="mailto:jweston@Wirtgenamerica.com">jweston@Wirtgenamerica.com</a></td>
</tr>
<tr>
<td>Todd</td>
<td>Mansell</td>
<td>Caterpillar</td>
<td>763-447-5695</td>
<td><a href="mailto:Mansell_Todd_W@cat.com">Mansell_Todd_W@cat.com</a></td>
</tr>
<tr>
<td>Garry</td>
<td>Aicken</td>
<td>Kessler (LWD-a)</td>
<td>703-989-6612</td>
<td><a href="mailto:garry@kesslerdep.com">garry@kesslerdep.com</a></td>
</tr>
<tr>
<td>Pete</td>
<td>Kaz</td>
<td>Trimble</td>
<td>937-609-1946</td>
<td><a href="mailto:Pete_kaz@trimble.com">Pete_kaz@trimble.com</a></td>
</tr>
<tr>
<td>Bruce</td>
<td>Hane</td>
<td>Trimble</td>
<td>937-609-1946</td>
<td><a href="mailto:Bruce_Hanes@Trimble.com">Bruce_Hanes@Trimble.com</a></td>
</tr>
<tr>
<td>Tom</td>
<td>Hogan</td>
<td>SITEH-NE</td>
<td>508-717-9502</td>
<td><a href="mailto:Tom_Hogan@sitechnortheast.com">Tom_Hogan@sitechnortheast.com</a></td>
</tr>
<tr>
<td>Paving Contractors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joel</td>
<td>Wardwell</td>
<td>Lane Construction</td>
<td>207-852-5602</td>
<td><a href="mailto:jwardwell@laneconstruct.com">jwardwell@laneconstruct.com</a></td>
</tr>
<tr>
<td>Bruce</td>
<td>Rideout</td>
<td>Lane Construction</td>
<td>207-944-1917</td>
<td><a href="mailto:BMRideout@laneconstruct.com">BMRideout@laneconstruct.com</a></td>
</tr>
<tr>
<td>Cecil</td>
<td>Dillon</td>
<td>Lane Construction</td>
<td>919-327-0445</td>
<td><a href="mailto:CLDillon@laneconstruct.com">CLDillon@laneconstruct.com</a></td>
</tr>
</tbody>
</table>

71
Contact Information
Victor (Lee) Gallivan, P.E.
FHWA Indiana Division
575 N. Pennsylvania St.,
Indianapolis, IN 46204
(317) 226-7493,
victor.gallivan@dot.gov

George Chang, P.E., PhD
The Transtec Group, Inc
6111 Balcones Dr. Austin, TX 78731
(512) 451-6233 Fax (512) 451-6234
gkchang@thetranstecgroup.com

Report Prepared by
George Chang, P.E., PhD
Qinwu Xu
Jennifer Rutledge
The Transtec Group, Inc.