FHWA Research Project
DTFH61-07-C-00032

Intelligent Compaction:
Quality Assurance for In-Place Density Acceptance

Asphalt IC Demonstration
I-80, Solano, CA
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### SI* (MODERN METRIC) CONVERSION FACTORS

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*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 California

Prepared by:
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for

Federal Highway Administration
Office of Pavement Technology, HIPT-10
1200 New Jersey Avenue, SE
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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.
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- Caterpillar: Todd Mansell
- Bomag: Chris Connolly, Tim Thuline, Tom Watson
- Sitech West: Steve Powers
- Kessler: Garry Aicken
- CalAPA: Russell Snyder and Rita Leahy
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-80, Solano, CA. The IC demonstration was conducted for the eastbound lanes with traffic closure in Solano, CA. Three main lane sections were paved. The total paving length is approximately 2,022 meter or 6,634 ft (1.26 miles).

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

Figure 1. Location Map of the IC Demo Project at I-80 (Bomag Evib is presented).
Typical Cross Sections

This project is a long-life asphalt pavement in the eastbound direction of I-80.

The pavement layer information is as follows (from bottom up):

- Existing cracked-and-seated PCC or HMA
- HMA leveling course (PG 64-10)
- 0.25’ intermediate HMA (25% RAP Long Life) (PG 64-10)
- 0.2’ HMA (15% Max. RAP Long Life) (PG 64-28PM)
- 0.1’ HMA- overlay

Geo synthetic pavement interlayer was placed on top of the HMA leveling course prior to the intermediate HMA course paving. The 0.25’ (3”) intermediate HMA course is the focus of this IC study.

Figure 2. Pavement structure and HMA mixture.
Intelligent Compaction Rollers

Bomag Tandem IC Roller System

Overall System Description

The Bomag tandem IC vibratory roller system is shown in Figure 3. This tandem IC roller is equipped with a global position system (GPS), a roller response measurement system, pavement surface temperature measurement, feedback control, and a documentation system. The roller response measurement value is called Evib, which is correlated to stiffness of compacted materials. The documentation system, BCM 05, can display color-coded maps for the recorded compaction data and the corresponding roller locations. The feedback control in the Bomag IC system is called VarioControl that enables the automatic adaptation of the amplitude during the compaction process. The features of this roller are described in Table 1.

Figure 3. Bomag Tandem Vibratory IC Roller
Table 1. Summarized Features of the Bomag Tandem Vibratory IC roller BW278AD-4

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</tbody>
</table>

The Bomag VarioControl IC system is illustrated in Figure 4. The Bomag single IC roller is equipped with two acceleration transducers, processor/control unit, distance measurement, GPS radio/antenna, Bomag Operation Panel, and onboard BCM 05 documentation system (BCM 05-Tablet-PC, BCM 05 mobile software). This system is capable of measuring compaction values that can be transferred to another computer using USB memory sticks for further analysis and reporting using the BCM05 office software.
Figure 4. Bomag VarioControl System

Figure 5. Bomag Operation Panel (BOP).
Measurement Value

The Bomag IC measurement value is called Evib [MN/m²] or vibration modulus (more strictly, stiffness). The Evib values are computed based on the compression paths of contact forces vs. drum displacement curves. Figure 6 shows that the Evib values increase with increasing pass number, and they are 86, 158, and 242 MN/m² for roller pass numbers 1, 3, and 6, respectively. Evib also responds to changes of material density and asphalt mixture temperature (with dropping compaction temperature, Evib of asphalt mixtures becomes greater).

Figure 6. Bomag IC measurement values, Evib.

The Bomag Evib values correlate well with load bearing capacities (Ev1/Ev2) from the plate loading tests. The analogue between the two is illustrated in Figure 7.

Figure 7. Plate Loading Test vs. Bomag Evib.
Feedback Control

The feedback control in the Bomag IC system is called VarioControl that enables the automatic adaption of the amplitude during the compaction process. VarioControl is based on a directed exciter (see Figure 8) which automatically adjusts the compaction energy generated by the vibration system of the roller (see Figure 9), according to a stiffness target and the compaction in the compacted layers.

![Figure 8. Bomag IC directed exciter system.](image8)

![Figure 9. Bomag VarioControl feedback system.](image9)
Documentation System

The Bomag IC onboard documentation system is called BCM 05 system (see Figure 10). The system is designed to accurately record and store continuous compaction data (Evib, type of roller, frequency, amplitude, and operating speed) and the corresponding roller locations from GPS signals. The tracking of the roller is achieved with a mobile GPS receiver on the roller and a stationary reference receiver or a GPS reference service (base station). Depending on the available onsite GPS, the accuracy of locations can be to be within 2 inches. The BCM system offers convenient measurement data management and extensive documentation and evaluation possibilities (see Figure 11). After data being transferred to a computer via USB memory sticks, BCM Office software can then be used to export IC data in Veda-compatible form for further analysis.

(Courtesy of Bomag)

Figure 10. Bomag IC onboard BCM 05 documentation system.
Figure 11. Bomag BCM Office displays.
Caterpillar Double-Drum IC Roller

Overall System Description

The Caterpillar CD54B split drum IC roller was used for this demonstration project (Figure 12). The features of this roller are summarized in Table 2.

![Figure 12 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&quot; (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      | VisionLink           |
| System             |                      |
| Contact            | Bryan Downing, 763-493-7533  
                       | Downing_Bryan_J@cat.com |

Table 2. Features of the Caterpillar CD54B split drum IC roller.
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.

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 21). 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).

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

(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).

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

Figure 13. 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, users 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 14. View data in VisionLink.
HAMM Double-Drum IC Roller

Overall System Description

The HAMM HD+120 double drum IC roller was used for this demonstration project (Figure 15). The features of this roller are described in Table 3.

![Figure 15. HAMM HD+120 Double-drum IC Roller.](image)

<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 16. Control panel on a HAMM roller.

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 17. The HAMM Compaction Quality (HCQ) system.

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 18). 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 18. 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 19). 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 19. OmniSTAR GPS receiver used on a HAMM roller.](image)
Measurement Value

The HAMM IC measurement value is called accelerometer-based on system, HMV (Figure 20). The algorithm of HMV is similar to compaction meter value (CMV).

![Figure 20. 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 21). 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).

$$CMV = C \cdot \frac{A_{2\Omega}}{A_{\Omega}}$$

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

(4)

Figure 21. 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 22 (roller passes and mat temperatures) and Figure 23 (HMV and mat temperatures).

Figure 22. Display of roller passes and asphalt mat temperature on the HCQ system.
Figure 23. Display of HMV and asphalt mat temperature on the HCQ system.
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 24. 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 24. 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 24).

Falling Weight Deflectometer (FWD)

The FWD test data were collected using a JILS-FWD (see Figure 25). 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 (10 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 26) 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 26. LWD-a equipment.
Field Demonstration Activities

Summary of Activities

A summary of day-to-day activities for this demonstration is described in Table 4. Trial runs and GPS verification as well as paving/compaction/testing operations are illustrated in Figure 27, Figure 28, and Figure 29. Test bed 1 was paved on Night 1 (TB-1A on EB Lane 1 and TB-1B on EB Lane 2). Test bed 2 (TB-2) was paved on Night 2 on EB Lane 3.

Table 4. Summary of Field Demonstration Activities

<table>
<thead>
<tr>
<th>Date</th>
<th>TB</th>
<th>Machine</th>
<th>Setting</th>
<th>Spot Tests</th>
<th>Notes/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night 1</td>
<td>1A/B</td>
<td>Hamm/</td>
<td>High amp, 3500vpm</td>
<td>NG, GPS, LWD-a</td>
<td>Breakdown compaction for asphalt base course. (2 rollers in echelon) 1. Compact with normal roller passes. 2. NG/GPS/LWD-a tests after each roller pass at selected locations within the test section.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1A/B</td>
<td>Bomag</td>
<td>Low amp, 3000 or 4000 vpm</td>
<td>NG, GPS, LWD-a</td>
<td>Intermediate compaction for asphalt base course. 1. Compact with normal roller passes. 2. NG/GPS/LWD-a tests after each roller pass at selected locations within the test section.</td>
</tr>
<tr>
<td></td>
<td>1A/B</td>
<td>Bomag Conv.</td>
<td>Static</td>
<td>NG</td>
<td>Finishing rolling 1. Compact with normal roller passes. 2. NG - a tests after finishing comp[action by contractor for QC.</td>
</tr>
<tr>
<td>Night 2</td>
<td>2</td>
<td>Hamm/</td>
<td>High amp, 3500vpm, 3mph</td>
<td>NG, GPS, LWD-a</td>
<td>Breakdown compaction for asphalt base course. . (2 rollers in echelon) 1. Compact with normal roller passes. 2. NG/GPS LWD-a tests after each roller pass at selected locations within the test section.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Bomag</td>
<td>Low amp, 3000/4000 vpm</td>
<td>NG, GPS, LWD-a</td>
<td>Intermediate compaction for asphalt base course. 1. Compact with normal roller passes. 2. NG/GPS LWD-a: tests after each roller pass at selected locations within the test section.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Bomag Conv.</td>
<td>Static</td>
<td>NG, GPS, LWD-a, FWD, GPR Coring</td>
<td>Finishing rolling 1. Compact with normal roller passes. 2. NG/GPS/LWD-a/FWD/GPR/Coring tests after the finishing rolling at the marked locations within the test section.</td>
</tr>
</tbody>
</table>

- The rolling pattern was designated by Teichert Construction.
- A Bomag conventional roller (Bomag Conv.) was used as the finishing roller.
- GPS: Hand-held Global Positioning System rover was provided by SITEH-West.
- NG: Nuclear density gauge and an operator was provided by Teichert Construction.
- LWD-a: Lightweight deflectometer for asphalt tests was provided by Kessler.
- FWD: Falling weight deflectometer and an operator was provided by Caltrans.
- GPR: Ground penetrating radar was provided by Caltrans.
• Coring: 35 X 4” cores was taken with one coring rig by Caltrans’ contractor, though 60 cores were originally planned.

Figure 27. Trial runs and GPS setups.
Figure 28. Night one operations
Figure 29. Night 2 operations

- GPS base station
- Fabric laying
- LWD test
- NG and Temp measurements
- Coring
- Core
Table 5. Test Bed Description.

<table>
<thead>
<tr>
<th>Test Bed</th>
<th>Material/Layer</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB-1A</td>
<td>3” intermediate course</td>
<td>EB Lane 1 (Station 375+00 to 425+00)</td>
</tr>
<tr>
<td>TB-1B</td>
<td>3” intermediate course</td>
<td>EB Lane 2 (Station 375+00 to 425+00)</td>
</tr>
<tr>
<td>TB-2</td>
<td>3” intermediate course</td>
<td>EB Lane 3 (Station 325+00 to 425+00)</td>
</tr>
</tbody>
</table>

Figure 30. TB-1A and TB-1B Location.
Figure 31. TB-1A and TB-1B Location.
Roller Settings and In Situ Tests

Summarizes the roller settings and in-situ tests are presented in Table 6. The schematics of test plans are illustrated in Figure 32 and Figure 33 for TB-1A/B and TB-2, respectively.

### Table 6. Roller Settings and In-situ Tests.

<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>9/4-5</td>
<td>Hamm/CAT</td>
<td>breakdown</td>
<td>3500vpm, high amp</td>
<td>3/2-3</td>
<td>T1,T2 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bomag</td>
<td>intermediate</td>
<td>3000vpm, low amp</td>
<td>2-5</td>
<td>T1,T2 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bomag</td>
<td>finishing</td>
<td>Static</td>
<td>1-3</td>
<td>T1,T2 NG after each pass</td>
</tr>
<tr>
<td>TB-1B</td>
<td>9/4-5</td>
<td>Hamm/CAT</td>
<td>breakdown</td>
<td>3500vpm, high amp</td>
<td>3/2-3</td>
<td>T3 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bomag</td>
<td>intermediate</td>
<td>3000vpm, low amp</td>
<td>2-5</td>
<td>T3 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bomag</td>
<td>finishing</td>
<td>Static</td>
<td>1-3</td>
<td>After finishing, GPS, FWD, LWD, GPR at core locations</td>
</tr>
<tr>
<td>TB-2</td>
<td>9/5-6</td>
<td>Hamm/CAT</td>
<td>breakdown</td>
<td>3500vpm, high amp</td>
<td>3/3</td>
<td>T3 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bomag</td>
<td>intermediate</td>
<td>3000vpm, low amp</td>
<td>3</td>
<td>T3 NG after each pass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bomag</td>
<td>finishing</td>
<td>Static</td>
<td>1-3</td>
<td>FWD, LWD, GPR at core locations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conv.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 32. Schematic of Test Plan for TB-1A and TB-1B.
Figure 33. Schematic of Test Plan for TB-2.
GPS Settings and Validation

GPS is the core of the IC technology to tie all data source together. The UTM-10N (Figure 34) is selected as the grid reference for all GPS devices used during this demonstration.

Figure 34. UTM Zones in the US.

Both the Bomag and Caterpillar IC systems were equipped with a Trimble receiver and a radio (Figure 35). A Trimble GPS base station was setup on-site to provide correction signals to the above IC systems in order to achieve Real Time Kinematic (RTK) precision (Figure 35 and Figure 36 for Caterpillar IC and Bomag IC, respectively).

Figure 35. Trimble GPS Receiver and Radio on Caterpillar IC system.
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 37). The precision that can be achieved with the OmniSTAR HP subscription is said to be 5 to 10 cm.
A hand-held Trimble GPS rover was tied to the same ground-based GPS base station. GPS checks were conducted at a daily basis. The GPS check results are satisfactory for the Caterpillar IC system; moderate for the Hamm IC system; unsatisfactory for the Bomag IC system (Table 7).

![Trimble GPS rover](image)

Figure 38. Trimble GPS rover for validation tests.

### Table 7. GPS Validation Test Results.

<table>
<thead>
<tr>
<th>Hamm UTM-10N (WGS 84)</th>
<th>OmniSTAR HD</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>Northing (m)</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>H1</td>
<td>4255848.770798</td>
</tr>
<tr>
<td>H2</td>
<td>4255852.504517</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deg. Min. Seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
</tr>
<tr>
<td>H2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bomag UTM-10N (WGS 84) RTK</th>
</tr>
</thead>
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Data Analysis

All IC data maps and analyses were performed using Veda 2.1 and complemented with Excel. The data goal seek function in Excel was used for the nonlinear correlation analysis. The LWD backcalculation and normalized to moduli values referenced at 20°C was performed using a Zorn utilities software by Kessler. The FWD backcalculation was performed using Transtec in-house software based on linear-elastic theory.

TB-1A Data Analysis (Lane 1)

TB-1A was compacted during the Night 1 paving operation on Lane 1 of EB I-80. The Hamm/CAT IC rollers were used as the breakdown rollers in echelon with the front drum vibrating at the low frequency and high amplitude settings. The Bomag IC roller was used as the intermediate roller with the front drum vibrating at the high frequency and low amplitude settings. A conventional Bomag roller was used as the finishing roller in static mode.

Hamm IC Data

The Hamm IC maps are presented in Figure 39 and the statistics are shown in Figure 40 and Figure 41. The observations are as follows:

- ICMV: The mean HMV value is 63 with standard deviation of 24. The zero values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 239.5°F with standard deviation of 16°F.
- Pass Counts: The roller patterns set by the contractor is 3 vibratory passes also as the mean passes.
- Speed: The mean roller speed is 1.5 mph.
- Frequency: The mean frequency is 2,652 vpm.
- Compaction curve: The curve grows monotonically though drops slightly at pass number 4.
- Fixed interval report: The frequency in the first 500-ft segment is 3,200 vpm while the rest of the segments are 2,500 vpm. Since the HMV is influenced by roller amplitudes and frequencies, the HMV values cannot be compared for the above two groups. The mean mat temperatures are fairly uniform for all segments except for the first 2 segments. The roller passes are very consistent for all segments.
Figure 39. TB-1A: Hamm IC Data Maps.
Figure 40. TB-1A Statistics of Hamm IC Data (1 of 2).
Figure 41. TB-1A Statistics of Hamm IC Data (1 of 2).
Caterpillar IC Data

The Caterpillar IC data maps are presented in Figure 42 and the statistics are presented in Figure 43 and Figure 44. Only the front drum data are analyzed. The observations are as follows:

- **ICMV**: The mean CMV value is 37 with standard deviation of 13.
- **Temperature**: The mean surface temperature is 161°F with standard deviation of 73°F. There are two sub-distributions that include the lower temperatures during mobilization between Lane 1 and Lane 2 compaction.
- **Pass Counts**: The mean passes for the combined group is 2.
- **Speed**: The mean roller speed is 4.4 mph. It consists of erroneous high speed values due to unknown reasons.
- **Frequency**: The mean frequency is 3,148 vpm. There are two distributions with one centering at 2,550 vpm and another one, 3,250 vpm.
- **Compaction curve**: The curve grows then level off with the peak value at the pass number of 4.
- **Fixed interval report**: The frequency in the first 500-ft segment is 2,600 vpm while the rest of the segments are 3,200 vpm. Since the CMV is influenced by roller amplitudes and frequencies, the CMV values cannot be compared for the above two groups. The mean mat temperatures are fluctuated over the segments with one stands out at 190°F. It is suspected that those temperatures may be unreliable considering the Caterpillar roller was at the breakdown position. The roller passes are also not very consistent over the segments.
Figure 42. TB-1A Caterpillar IC Data Maps.
Figure 43. TB-1A: Statistics of Caterpillar IC Data (1 of 2).
Figure 44. TB-1A: Statistics of Caterpillar IC Data (2 of 2).
Bomag IC Data

The Bomag IC maps are presented in Figure 45 while the statistics are shown in Figure 46 and Figure 47. The data are lost after 1,500 ft due to system issues. The observations are as follows:

- ICMV: The mean Evib value is 33 ksi (228 MPa) with standard deviation of 24. The zero Evib values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 152°F with standard deviation of 54°F. There are two sub-distributions that include the lower temperatures during mobilization between Lane 1 and Lane 2 compaction.
- Pass Counts: the mean pass number is 2.
- Speed: The mean roller speed is 3.1 mph.
- Compaction curve: The curve stays flat then decreases after 4 passes. The range is narrow.
- Fixed interval report: Due to the data loss, only the first four 500-ft segments are analyzed. The mean mat temperatures are fairly uniform between 180°F and 190°F. The roller passes are not consistent for all segments.
Figure 45. TB-1A: Bomag IC Data Maps.
Figure 46. TB-1A: Statistics of Bomag IC Data (1 of 2).
Figure 47. TB-1A: Statistics of Bomag IC Data (2 of 2).
NG Data and Pass-by-Pass IC Data

NG measurements were made at 2 locations (T1 and T2) after the paver and each roller pass. The plots of NG densities and surface temperatures vs. passes are presented in Figure 48 and Figure 49.

- 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% or above Gmm. No de-compaction is observed.
- At T1, the NG density grows to 88% Gmm after three Hamm roller passes and gains 3 points after two more Bomag roller passes. Temperatures during the compactions are between 233°F and 180°F.

![Figure 48. TB-1A Test Point T1 Analysis](image)
At T2, after 5 combined Hamm/CAT roller passes, the density increases to 90% Gmm. After one additional Bomag roller pass, the density increases 2 points but stays flat for additional 4 more Bomag roller passes. Temperatures during the compactions are between 233°F and 187°F.

Figure 49. TB-1A Test Point T2 Analysis
TB-1B Data Analysis (Lane 2)

TB-1B was compacted during the Night 1 paving operation on EB Lane 2 of I-80. The Hamm and Caterpillar IC rollers were used as the breakdown rollers in echelon with the front drum vibrating at the low frequency and high amplitude settings. The Bomag IC roller was used as the intermediate roller with the front drum vibrating at the high frequency and low amplitude settings. A conventional Bomag roller was used as the finishing roller in static mode. Note that portion of Evib of Bomag was not recorded due to a system issue.

Hamm IC Data

The Hamm IC data are presented in Figure 52 while the statistics for those IC data of Lane 1 are in Figure 51. The observations are as follows:

- IC MV: The mean HMV value is 66 with standard deviation of 23. The zero values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 236.5°F with standard deviation of 14°F.
- Pass Counts: The roller patterns set by the contractor is 3 vibratory passes also as the mean passes.
- Speed: The mean roller speed is 1.5 mph.
- Frequency: The mean frequency is 2,606 vpm.
- Compaction curve: The curve grows and starts decreasing after three passes.
- Fixed interval report: The mean HMV fluctuates among segments. The mean mat temperatures are all above 220°F. The roller passes are very consistent for all segments except for the first three segments.
Figure 50. TB-1B Hamm IC Data Maps.
Figure 51. TB-1B Statistics of Hamm IC Data (1 of 2).
Figure 52. TB-1B Statistics of Hamm IC Data (2 of 2).
Caterpillar IC Data

The Caterpillar IC data maps are presented in Figure 53 and the statistics are presented in Figure 54 and Figure 55. Only the front drum data are analyzed. The observations are as follows:

- **ICMV**: The mean CMV value is 39 with standard deviation of 13.
- **Temperature**: The mean surface temperature is 213°F with standard deviation of 34°F. There are two sub-distributions that may include the lower temperatures during mobilization between Lane 1 and Lane 2 compactions.
- **Pass Counts**: The mean passes for the combined group is 2.
- **Speed**: The mean roller speed is 3.1 mph. There are some erratic speed data at higher values due to unknown reasons.
- **Frequency**: The mean frequency is 3,216 vpm.
- **Compaction curve**: The curve grows and then levels off after 3 passes.
- **Fixed interval report**: The mean HMV fluctuates among segments. The mean mat temperatures are all above 200°F. The mean roller passes fluctuates among segments. Note that fractional roller passes are computed from individual drum passes.
Figure 53. TB-1B Caterpillar IC Data Maps.
Figure 54. TB-1B Statistics of Caterpillar IC Data (1 of 2).
Figure 55. TB-1B Statistics of Caterpillar IC Data (2 of 2).
Bomag IC Data

The Bomag IC mapping data are presented in Figure 56 and the statistics are in Figure 57 and Figure 58. Since there is data loss due to system issues, the following statistics have limited meanings. Nonetheless, the observations are as follows:

- **ICMV:** The mean Evib value is 28 ksi (193 MPa) with standard deviation of 13. The zero Evib values may be due to sudden acceleration or stops of the roller.
- **Temperature:** The mean surface temperature is 173°F with standard deviation of 44°F. The data include lower temperatures during the mobilization between Lane 1 and Lane 2 compaction.
- **Pass Counts:** the mean pass number is 1.
- **Speed:** The mean roller speed is 3.2 mph.
- **Frequency:** The mean frequency is 3,270 vpm.
- **Compaction curve:** The interpretation of the compaction curve is limited here due to data loss.
- **Fixed interval report:** The interpretation of the fixed interval report is limited here due to data loss.
Figure 56. TB-1B Bomag IC Data Maps.
Figure 57. TB-1B Statistics of Bomag IC Data (1 of 2).
Figure 58. TB-1B Statistics of Bomag IC Data (2 of 2).

Spotted data - Data loss for most of area
TB-2 Data Analysis (Lane 3)

TB-2 was compacted during the Night 2 paving operation on EB Lane 3 of I-80. The Hamm and Caterpillar IC rollers were used as the breakdown rollers in echelon with the front drum vibrating at the low frequency and high amplitude settings. The Bomag IC roller was used as both the intermediate roller with the front drum vibrating at the high frequency and low amplitude settings and the finishing roller with a static mode. A Bomag convention roller as used as the finishing roller in static mode. Due to the data loss of Hamm resulted from GPS connections issues, only Bomag and Caterpillar IC data analyses are presented in the following sections.

Caterpillar IC Data

The Caterpillar IC data maps are presented in Figure 59 and the statistics are presented in Figure 60 and Figure 61. The observations are as follows:

- ICMV: The mean CMV value is 63 with standard deviation of 17.
- Temperature: The mean surface temperature is 170°C with standard deviation of 94°C.
- Pass Counts: The roller patterns set by the contractor is 2 vibratory passes. The recorded mean roller passes is also 2.
- Speed: The mean roller speed is 3.7 mph. However, there are erratic speed records due to unknown reasons.
- Frequency: The mean frequency is 2,560 vpm.
- Compaction curve: The curve grows monotonically without an apparent optimal value.
- Fixed interval report: The mean HMV values are relatively lower in the first 5 segments (i.e., the first 2500 ft). The mean temperatures are also lower within this area due to a faulty wire connection. The mean pass counts fluctuate over the segments.
Figure 59. TB-2 Caterpillar IC Data Maps.
Figure 60. TB-2 Statistics of Caterpillar IC Data (1 of 2).
Figure 61. TB-2 Statistics of Caterpillar IC Data (2 of 2).
Bomag IC Data

The Bomag IC data maps are presented in Figure 62 and the statistics are presented in Figure 63 and Figure 64. The observations are as follows:

- **ICMV**: The mean Evib value is 51 with standard deviation of 8.
- **Temperature**: The mean surface temperature is 176°F with standard deviation of 42°F. The distribution includes lower temperatures likely due to mobilization.
- **Pass Counts**: The roller patterns set by the contractor is 3 vibratory passes. The recorded mean roller passes is also 3.
- **Speed**: The mean roller speed is 7 mph.
- **Frequency**: The mean frequency is 2,873 vpm.
- **Compaction curve**: The curve is within a very narrow range (Evib values between 26 and 30) without an apparent optimal value.
- **Fixed interval report**: The mean Evib values fluctuate over segments. With exceptions of 3 segments, the mean temperatures are fairly uniform around 190°F. The mean pass counts values fluctuate over segments.
Figure 62. TB-2 Bomag IC Data Maps.
Figure 63. TB-2 Statistics of Caterpillar IC Data (1 of 2).
Figure 64. TB-2 Statistics of Caterpillar IC Data (2 of 2)
NG Data vs. Roller Passes

NG measurements were made at 1 location, T3 after the paver and each roller pass. The plots of NG densities and surface temperatures vs. passes are presented in Figure 65.

- The density curve reaches at the 92.6% Gmm. Then, the density stays flat for 6 additional Bomag roller passes.
- The temperatures are between 220°F and 160°F during the compaction.

![Figure 65. TB-2 T3 data analysis.](image)

Correlation Analysis

The correlation analysis is to investigate the relationships among various measurements including Bomag IC data, nuclear density gauge measurements, core densities, FWD, and LWD measurements. Due to the data loss of Hamm IC roller and the GPS offset issues of Caterpillar IC roller, only Bomag IC data (as the intermediate roller) were used for the subsequent correlation analysis.

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 low $R^2$ value of 0.08. The bias is toward the core density values. The causes for the low correlation and bias are unknown. Therefore, the interpretation for the subsequent correlation between either core density or NG density with IC data is limited.

- The mean core density is 94.9% with minimum of 93.1% and maximum of 96.2% (i.e., the range is 3.1%, only half of the range of the NG density values).

![Figure 66. TB-3 Core Data vs. NG Data.](attachment:image.png)
Core Density Data vs. Final Coverage IC Data

The Bomag IC data within 1 m radius of coring locations were evaluated. Results of Bomag Evib data analyses with core density as dependent variables indicate very low linear correlation of $R^2 = 0.06$. The correlation between core density and pass count indicates a low $R^2 = 0.11$ (Figure 68).

Figure 67. TB-3 Core locations.
Figure 68. TB-2 Core Density vs. Bomag IC Final Coverage Data.
NG Density Data vs. Final Coverage IC Data

Results of Bomag IC data analyses with NG density as dependent variables also indicate very low linear correlation (Figure 69).

Figure 69. TB-2 NG Density vs. Bomag IC Final Coverage Data.
**LWD Data vs. Final Coverage ICMV Data**

The Bomag IC data within 1 m radius of LWD test locations were evaluated. Result of Bomag Evib data analyses with backcalculated LWD moduli as dependent variables indicates low correlation of $R^2 = 0.01$ (Figure 70).

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**Figure 70. TB-2 Bomag Final Coverage Data vs. LWD Layer Moduli (MPa).**
FWD Data vs. Final Coverage ICMV Data

The Bomag IC data within 1 m radius of FWD test locations were evaluated. Result of Bomag Evib data analyses with backcalculated FWD moduli as dependent variables indicates low correlation with the $R^2 = 0.16$ (Figure 71).

Figure 71. TB-2 Bomag Final Coverage Data vs. FWD Layer Deflections (mils).
NG Data vs. All-pass ICMV Data

At T1 of TB-1A, the growth trend of NG density is in line with that of Hamm HMV as the breakdown roller. The correlation between the two is with an excellent R² of 0.96.

![Figure 72. TB-1A T1 BG density vs. Hamm pass-by-pass HMV data.](image)

At T3 of TB-2, the growth trend of NG density is in line with that of Bomag Evib as the intermediate roller. The correlation between the two is with an excellent R² of 0.97.

![Figure 73. TB-2 T3 NG density vs. Bomag pass-by-pass Evib data.](image)

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:

\[ \rho_n = \rho_0 + (G_{mm} - \rho_0) \times e^{\left[\frac{a_1k_ac+a_2f+a_3V+a_4(T-T_r)}{n}\right]^{\beta}} + \Delta \rho_n \]  

(5)

Where

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

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

\[ G_{mm} = \text{maximum density} \]

\[ Kac = \text{asphalt moduli} \]

\[ T = \text{asphalt surface temperature} \]

\[ f = \text{roller vibration frequency} \]

\[ V_R = \text{roller speed} \]

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

\[ a_1, a_2, a_3, a_4, \beta = \text{fitted parameters} \]

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. Only Bomag data is available for the density measuring locations, and thus it is used for the model demonstration. The pass-by-pass data at T3 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 8).

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The results of predicted density vs. NG density indicate \( R^2 = 0.15 \) and 0.11 for using final coverage data
and the combined final coverage data and pass-by-pass data, respectively (Figure 74). The correlation is lower, but the interpretation of the results is limited due to low correlation between the core density and NG density data.

Figure 74. Predicted Densities vs. Core/NG Density.

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

Caltrans coordinated an Open House event for this demonstration. The Open House was conducted at the Translab Auditorium in Sacramento, CA, including an approximately 3-hour indoor presentation (Figure 75 and Figure 76). No equipment demonstration was included. The presenters included the FHWA IC team, IC vendors, LWD vendor, and GPS vendor. It was well attended by agencies and industry personnel.

Figure 75. Open House – Indoor Presentation (1 of 2).
Figure 76. Open House – Indoor Presentation (2 of 2).
Summary

From the above data analysis, the following observations are summarized.

IC Systems

- The Bomag, Caterpillar and HAMM IC roller systems functioned well during the demonstration except for some isolated instances. IC data were successfully exported from the IC systems (HCQ from Hamm and VisionLink from Caterpillar/Trimble, and BCM 05 from Bomag) and imported to a standardized tool, Veda, for further analysis.
- However, there were challenges due to data loss and GPS offsets on some occasions. A portion of Bomag IC data were not collected during Night 1 due to GPS connections and other unknown issues. There were also data loss of the HAMM IC data during Night 2 due to its expiration of OmniSTAR subscription. The Caterpillar IC data has a GPS offset issue. All the above issues are isolated instance and they are fixable.
- Even with the isolated instances stated above, these IC systems can still be used for tracking roll passes and surface temperatures as a quality control tool by improving the consistency and uniformity of compaction.

NG Density Growth Curves vs. IC Roller data

- The trends of density growth curves based on nuclear density gauge values are slightly different due to changes of rolling patterns.

![Figure 77. Density growth curves at Test Points T1, T2, and T3 (left to right)](image)

Linear correlation analysis

- The correlation between core data and nuclear density gauge data shows a low $R^2$ value of 0.08. The bias is toward the core density values. The causes for the low correlation and bias are
unknown. Therefore, the interpretation for the correlation between either core density or NG density with IC data is limited.

- During the test section at TB-2, 60 locations were marked for NG measurements and coring. However, only 35 cores were taken due to limitation of time and using one coring rig.
- Based on the final coverage data at TB-2, the correlation between backcalculated moduli from the LWD data and Bomag Evib is poor. Similar results are observed for the correlation between Bomag Evib and FWD data.
- Based on the final coverage data at TB-2, the correlation between core data and the Bomag IC data is poor.
- Based on the pass-by-pass IC data, the correlation between NG density and ICMV are excellent for both Hamm (breakdown) roller, and Bomag (intermediate) roller at Test Points T1 and T3, respectively.

![Figure 78. Correlation of Pass-by-pass ICMV data and NG density at T1 (left) and T3 (right).](image)

- Based on the above observation, all-passes IC data can be used to predict in-place density while the final coverage data do not. The causes for the latter may be due to the uncertainty of IC data process to produce final coverage data and also due to the hardening states of asphalt at lower temperature ranges. Further investigation is recommended.

Multivariate nonlinear stochastic density model

- A preliminary multivariate nonlinear stochastic density model was developed. The pass-by-pass data at T3 and a sub-set of the Bomag final coverage data are used to obtain the fitted parameter by using the Solver tool of MS Excel. The results of predicted density vs. core/NG density values indicate $R^2 = 0.15$. As indicated above, the interpretation for the correlation between either core
density or NG density with IC data is limited. The model will continue to be revised as more field data are available during this study. It is expected the model may be revised to take advantage of the all-passes IC data that show excellent correlation with the NG density data.

Recommendations for future study:

- Daily GPS validation is required.
- 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;
- The density models (linear and non-linear) should be may be revised to take advantage of the all-pass IC data that show excellent correlation with the NG density data.
- 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>
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<th>First name</th>
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