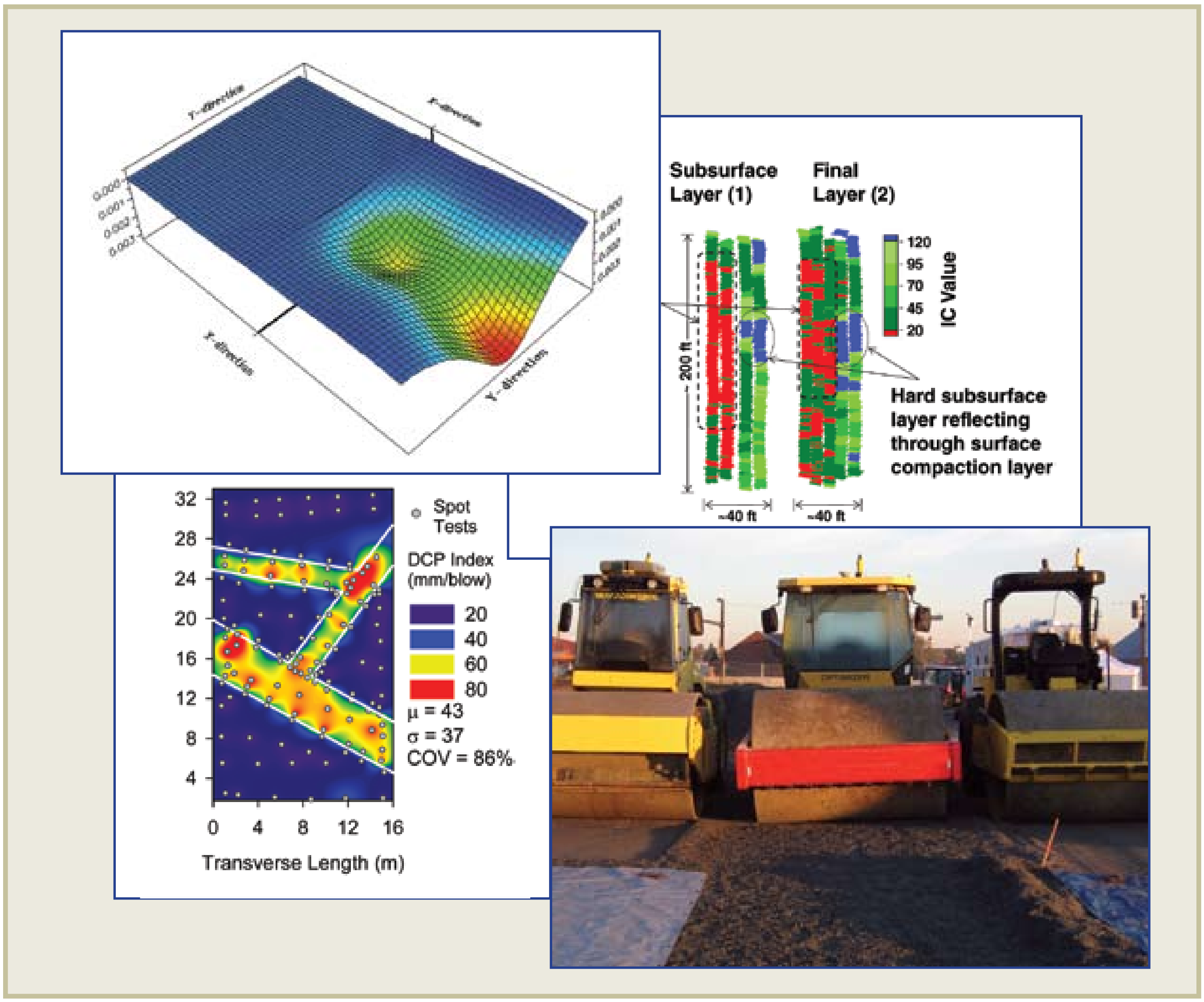
Report of the
Workshop on Intelligent Compaction for Soils and HMA

ER08-01 | **April 2–4, 2008**



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EARTHWORKS ENGINEERING RESEARCH CENTER

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IOWA STATE UNIVERSITY OF SCIENCE AND TECHNOLOGY

Iowa Department of Transportation

Report of the
Workshop on Intelligent Compaction for Soils and HMA

April 2–4, 2008

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**Sponsored by the Iowa Department of Transportation
and the Earthworks Engineering Research Center at Iowa State University**

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Preface

This document summarizes the discussion and findings of a workshop on intelligent compaction for soils and hot-mix asphalt held in West Des Moines, Iowa, on April 2–4, 2008. The objective of the meeting was to provide a collaborative exchange of ideas for developing research initiatives that accelerate implementation of intelligent compaction (IC) technologies for soil, aggregates, and hot mix asphalt. Technical presentations, working breakout sessions, a panel discussion, and a group implementation strategy session comprised the workshop activities. About 100 attendees representing state departments of transportation, Federal Highway Administration, contractors, equipment manufacturers, and researchers participated in the workshop.

Acknowledgments

The Earthworks Engineering Research Center (EERC) at Iowa State University of Science and Technology (ISU) gratefully acknowledges the Iowa Department of Transportation (Iowa DOT) for its sponsorship of this workshop. Travel support for most state DOT participants and support for the development of this report were made possible by the Iowa DOT.

The EERC also sincerely thanks the following individuals for their support of this workshop:

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Abbreviations

γ_d	=	dry unit weight
AMG	=	automated machine guidance
CBR	=	California bearing ratio
CCV	=	Sakai compaction control value; Caterpillar compaction value
CIV	=	Clegg impact value
CMV	=	compaction meter value
DCP	=	dynamic cone penetrometer
DOT	=	Department of Transportation
DTM	=	digital terrain model
EED	=	electronic engineering data
E_{LWD}	=	light weight deflectometer elastic modulus
E_{PLT}	=	plate load test elastic modulus
E_{SSG}	=	soil stiffness gauge elastic modulus
E_{vib}	=	BOMAG roller vibration modulus
FHWA	=	Federal Highway Administration
FWD	=	falling weight deflectometer
GPS	=	global positioning system
HMA	=	hot mix asphalt
IC	=	intelligent compaction
K	=	hydraulic conductivity
K_s	=	case/ammann roller stiffness
LWD	=	light weight deflectometer
MDP	=	Caterpillar machine drive power
RMV	=	resonant meter values
TDM	=	theoretical maximum density

Executive Summary

The objective of this workshop was to provide a collaborative exchange of ideas for developing research and educational initiatives that accelerate implementation of intelligent compaction (IC) technologies for soil, aggregates, and hot mix asphalt that will lead to conclusive and measureable improvements within five years. Several key strategies were identified and are documented in this report. Technical presentation slides, notes from the working breakout sessions, a summary of the panel discussion, and a summary of the group implementation strategy session are reported herein. A road map for implementation that identifies several key research and training focal areas is summarized at the end of this report.

Following several technical presentations, nine breakout sessions were conducted covering three topic areas: "IC for Soils and Aggregate," "IC for HMA," and "Implementation Strategies." Each group was asked to address their topic around the following questions:

- What are the existing knowledge gaps?
- What equipment advancements are needed?
- What educational/technology transfer needs exist?
- What standards/specifications and guidelines need to be developed?

Based on a detailed review of the results from this session, there were two levels of analysis of the results: (1) prioritized results for each topic area, and (2) a cross-cutting top 10 list of key research needs. The top 10 research needs are summarized in Table 2 from the report, replicated below.

Table 2. Summary of main IC technology research needs

Top 10 IC Technology Research Needs

1. **Correlation studies (cohesive, stabilized, granular, HMA, etc.) (136)**
2. **Education/training materials and programs (112)**
3. **Moisture content (influence + measurement) (61)**
4. **Integrated design + real-time data transfer (57)**
5. **Case histories + demos + benefit + successes (48)**
6. **Engineering parameter to measure (density, modulus, stiffness, core mat temperature) (47)**
7. **Addressing non-uniformity (34)**
8. **Establishing QC/QA framework - statistically significant (28)**
9. **Measurement influence depth (19)**
10. **Promoting good geotechnical practices (13)**

A panel discussion was carried out to reflect on the outcomes determined from the breakout sessions and what was learned from the workshop that may have changed perspectives on IC technology. The discussion points were divided into four categories:

- Reaction to breakout sessions
- New perspectives
- Specifications
- Technology developments

Each of these categories was summarized and condensed to four common themes. These themes are summarized in Table 3 of the report, which is replicated below.

Table 3. Summary of common themes from panel discussion

Common Themes from Panel Discussion Session

1. **High level of interest from the state DOTs in further studying opportunities to implement IC.**
2. **Implementation strategies need to build on existing information and past research.**
3. **Specifications for IC and in situ testing should not restrict manufacturer/equipment developer innovations.**
4. **Contractor and state DOT field personnel and engineers need educational materials for IC and in situ QC/QA testing.**

Following the panel discussion, the audience was given instructions to break up into groups to further brainstorm implementation strategies. A list of the three common strategies was derived from this exercise. The common strategies are summarized in Table 4 of the report, shown here.

Table 4. Summary of common themes from the group implementation strategy session

Common Themes from Group Implementation Strategy Session

1. **Develop IC training and certification program.**
2. **Demonstrate benefits of IC through demonstration projects.**
3. **Promote partnership as key strategy to implementation.**

At the conclusion of the workshop a discussion centered on understanding where we are and where we are going as a lead-in to developing a road map for implementation of IC technologies. Key points from the discussion are summarized in Table 5 of the report, shown on the following page.

To move from the current practice and knowledge base, several key strategies were considered and are listed in Table 6 of the report, shown on the following page.

Table 5. Summary of key points

Where we are:	Where we are going:
• Lack widely accepted IC specifications in U.S. • Need education/training materials • Innovative IC and in situ testing equipment • IC technologies provide documented benefits (smooth drum - granular) • Great potential and some limited successes for cohesive and HMA • Poor database development for IC projects and case histories • Human IC network initiated • Increasing acceptance/GPS infrastructure for stakeless grading/machine guidance • "Don't know what we don't know"	• Standardized and credible IC specifications inclusive of various IC measurement systems • Widespread implementation of IC technologies • High quality database of correlations • Several documented successes for cohesive/stabilized/granular/HMA • Better understanding of roadway performance - what are key parameters? • Innovative new sensor systems and intelligent solutions • Integrated and compatible 3D electronic plans with improved processes, efficiency and performance • Real-time wireless data sharing • Enhanced archival and visualization software • Improved analytical models of machine-ground interactions

Table 6. Strategies for moving forward

Strategies for Moving Forward
• Participate in partnerships for IC research and information exchange regionally and nationally • Be an advocate for IC implementation • Contribute to problem statement development for NCHRP, TRB, FHWA, AASHTO, ASCE Committees • Participate in IC conferences/studies and the annual EERC Workshop • Participate on EERC Scientific and Policy Advisory Council (35 members) – IC and other issues • Stay connected: Subscribe to EERC Technical Bulletins, Tech Transfer Summaries, Technical Reports, Educational Videos, etc. (www.intelligentcompaction.com). • Develop a comprehensive and strategic IC road map for research and educational/technology transfer

Results from the workshop provided significant information to outline the road map which can serve as a starting point for further discussions and assessment. Additional steps beyond peer reviewing the research/educational elements of the road map will be required to create an integrated research management plan, establish a schedule, and identify organizations, contractors, and equipment manufacturers that want to partner and leverage funding/equipment and human resources to move the program forward.

Introduction

The Challenge

When it comes to addressing the nation's infrastructure construction challenges, investment in new research and innovative technologies, changing policy and creating educational programs, and developing sustainable and environmentally-friendly practices are needed[1, 2, 3]. Although it lacks headline grabbing drama, improvements to earthwork operations and technologies potentially offer a significant return on investment. This is because whether it's highways, levees/dams, railways, airfields, underground tunnels, waterways, etc. all civil infrastructure projects are composed of, or supported by, soil and rock—the world's most abundant construction material. Unfortunately, many of the current problems with highway systems are attributed to unstable and non-uniform ground conditions. Intelligent compaction (IC) is one technology that could address compaction and non-uniformity problems for earth materials and hot mix asphalt (HMA). Roller-integrated global position system (GPS) documentation capabilities (i.e. mapping) provide new opportunities for providing 100 percent coverage information and documenting non-uniformity of compacted materials. To date, only a few research/demonstration projects have been completed, and no widely accepted specifications are available for the United States. To benefit from IC technologies, a comprehensive and strategic plan for research and educational/technology transfer activities is needed.

IC Workshop Vision

The objective of the IC workshop was to provide a collaborative exchange of ideas for developing research and educational initiatives that accelerate implementation of IC technologies for soil, aggregates, and hot mix asphalt that will lead to conclusive and measureable improvements within five years. Several key strategies were identified and are documented in this report. Technical presentation slides, notes from the working breakout sessions, a summary of the panel discussion, and a summary of the group implementation strategy session are reported herein. A road map for implementation that identifies several key research and training focal areas is summarized at the end of this report. As a lead-in, a brief review of intelligent compaction technologies, specifications, and in situ testing is described.

Background

Intelligent Compaction

Intelligent companion (IC) technologies consist of machine-integrated sensors and control systems that provide a record of machine-ground interaction. With feedback control and adjustment of vibration amplitude and/or frequency and/or speed during the compaction process, the technology is referred to as intelligent compaction. Without the vibration feedback control system the technology is commonly referred to as continuous compaction control (CCC).

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[1] *Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation* (2006). By National Research Council (U.S.), National Research Council.
[2] John O'Dohery (2007). *At The Crossroads: Preserving Our Highway Investment*, National Center for Pavement Preservation at Michigan State University.
[3] Report Card for America's Infrastructure (http://www.asce.org/reportcard/2005/index.cfm)

The machine-ground interaction measurements provide an indication of ground stiffness/strength and to some extent degree of compaction. Most of the IC/CCC technologies are vibratory-based systems applied to single drum self-propelled smooth drum rollers. IC/CCC technologies have also been applied to vibratory double drum asphalt compactors and self-propelled padfoot compactors. CCC vibratory roller systems have been used in Europe for more than 20 years. During this period the technologies have evolved to include a variety of different measurement techniques and GPS-based documentation systems. Most of the research documented in the literature deals with CCC applications for granular materials. More recently, non-vibratory (static) rollers have been outfitted with machine-integrated systems that provide measurement values based on machine drive power. This approach is being developed primarily for use in non-granular materials. Other IC measurements systems are also in development, and it is expected that these technologies will continue to improve and find applications to a wider range of earth materials and field conditions.

There are at least six IC/CCC systems/parameters: omega value, compaction meter value (CMV), stiffness (k_s), vibration modulus (E_{vib}), compaction control value (CCV), and machine drive power (MDP). The measurement parameters are well defined in the literature[4, 5, 6, 7, 8]. Figure 1 shows several of the manufacturer smooth drum vibratory compactors for soils and corresponding data visualization and management software displays.

Figure 1. Smooth drum compaction monitoring systems for soil and aggregate.

[4] Kröber, W., Floss, E., Wallrath, W. (2001). "Dynamic soil stiffness as quality criterion for soil compaction," Geotechnics for Roads, Rail Tracks and Earth Structures, A.A.Balkema Publishers, Lisse /Abingdon/ Exton (Pa) /Tokyo, 189-199.
[5] Thurner, H. and Sandström, Å. (1980). "A new device for instant compaction control." Proc., Intl. Conf. on Compaction, Vol. II, 611-614, Paris.
[6] Anderegg R., and Kaufmann, K. (2004). "Intelligent compaction with vibratory rollers - feedback control systems in automatic compaction and compaction control," Transportation Research Record No. 1868, *Journal of the Transportation Research Board*, National Academy Press, 124-134.
[7] Scherocman, J., Rakowski, S., and Uchiyama, K. (2007). "Intelligent compaction, does it exist?" 2007 Canadian Technical Asphalt Association (CTAA) Conference, Victoria, BC, July.
[8] White, D.J, Jaselskis, E., Schaefer, V., and Cackler, E. (2005). "Real-time compaction monitoring in cohesive soils from machine response." Transportation Research Record No. 1936, National Academy Press, 173-180.

Transportation agencies and contractors are beginning to investigate applications for the IC/CCC technologies as part of field demonstrations and a limited number of projects for which the technology has been specified[9]. Expectations are that the IC/CCC systems will (1) improve construction efficiency, (2) streamline quality management programs of earthwork and asphalt projects, (3) better link quality acceptance parameters and documentation with pavement design, and (4) improve the performance of compacted materials[10, 11, 12].

Mechanistic Based In Situ Testing for QC/QA

Traditional quality control and assurance (QC/QA) programs are typically fulfilled by performing in situ tests that provide information about the state or performance of the compacted materials. Soil dry density and moisture content are the most common measurements for acceptance for earth materials. Similarly, core samples and nuclear density testing are the predominant field quality assurance tests for hot mix asphalt. IC/CCC measurement values can be empirically related to density but generally requires an independent measure of moisture content and multiple regression analysis, particularly for cohesive soils[13]. In situ measurements of mechanistic parameters (e.g., elastic modulus, strength, etc.) are now being considered with growing interest as an alternative to traditional moisture/density control. One advantage of linking IC/CCC measurement values to mechanistic parameters is that it provides a link to performance-based specifications and input/verification for mechanistic pavement design.

Relationships between IC/CCC measurement values and in situ compaction measurements are influenced by operating conditions of the compactors[14] (e.g., roller size, vibration amplitude and frequency, and velocity) and material conditions (e.g., soil type, moisture content, lift thickness, underlying layer stiffness, asphalt temperature)[7, 15]. Recent studies have demonstrated empirical relationships, and limitations thereof, between the various IC/ CCC measurements values and conventional in situ spot test measurements for soil materials[16,17].

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9 White, D.J, Thompson, M., Vennapusa, P. (2007). "Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials," Mn/DOT Report No. MN/RC 2007-10, Iowa State University, Ames, IA.

10 Briaud , J. L., Seo, J. (2003). *Intelligent Compaction: Overview and Research Needs,* Texas A&M University.

11 Petersen, D., Siekmeier, J., Nelson, C., Peterson, R. (2006). "Intelligent soil compaction – technology, results and a roadmap toward widespread use." Transportation Research Record No. 1975, *Journal of the Transportation Research Board*, National Academy Press, 81–88.

12 Thompson, M., and White, D. (2007). "Field calibration and spatial analysis of compaction monitoring technology measurements." Transportation Research Record No. 2004, : *Journal of the Transportation Research Board*, National Academy Press, 69–79.

13 Thompson, M., and White, D. (2008). "Estimating compaction of cohesive soils from machine drive power." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, (in press)

14 Adam, D., and Kopf, F. (2004). "Operational devices for compaction optimization and quality control (Continuous Compaction Control & Light Falling Weight Device)." Proc., of the Intl. Seminar on Geotechnics in Pavement and Railway Design and Construction, December, Athens, Greece (Invited paper), 97–106.

15 White, D., and Thompson, M. (2008). "Relationships between in situ and roller-integrated compaction measurements for granular soils." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE (in press).

16 White, D.J, Thompson, M., Vennapusa, P. (2007). "Field study of compaction monitoring systems: self-propelled non-vibratory 825G and vibratory smooth drum CS-533 E rollers," Final Report, Center of Transportation Research and Education, Iowa State University, Ames, Iowa.

17 White, D., Vennapusa, P., Gieselman, H. (2008). "Roller-integrated compaction monitoring technology: Field evaluation, spatial visualization, and specifications." Proc., 12th Intl. Conf. of Intl. Assoc. for Computer Methods and Advances in Geomechanics (IACMAG), 1–6 October, Goa, India.

Because the relationships are influenced by roller operations, soil type, and stratigraphy underlying the soil being compacted, several factors should be considered during calibration. Figure 2 shows a simple example comparing IC measurement values to various in situ spot test measurements. Regression coefficient values (r) range from 0.5 to 0.9, indicating fair to good correlations. Improvements to these correlations are expected with improved understanding of the measurement influence depth of the rollers and various in situ testing devices. Figure 3 illustrates differences between measurement influence depths for rollers and various in situ spot test measurements[9]. One of the challenges with correlating in situ spot test measurements with IC measurement values is that the roller measurements values are an average or integrated value over the width of the drum up to depths equal to one meter and greater.

With the implementation of IC/CCC technologies, several new in situ compaction measurement devices have been developed and investigated. Figure 4 shows many of the in situ measurement devices that are being evaluated as an alternative to traditional density testing. Several recent research reports provide comparison measurements between the new devices and conventional measurements. However, very little has been done to link the IC measurement values analytically to in situ test measurements or to develop statistically reliable sampling and analysis plans.

Measuring soil density and moisture content, albeit relatively laborious and time-consuming using traditional techniques, provides information that can be easily understood and related to laboratory test results. But while density and moisture content are broadly accepted measures of compaction, the physical properties are not necessarily direct measures of performance. Some of the emerging testing technologies now focus on measurement of the in situ mechanistic properties of soil, namely strength and modulus, such as the dynamic cone penetrometer

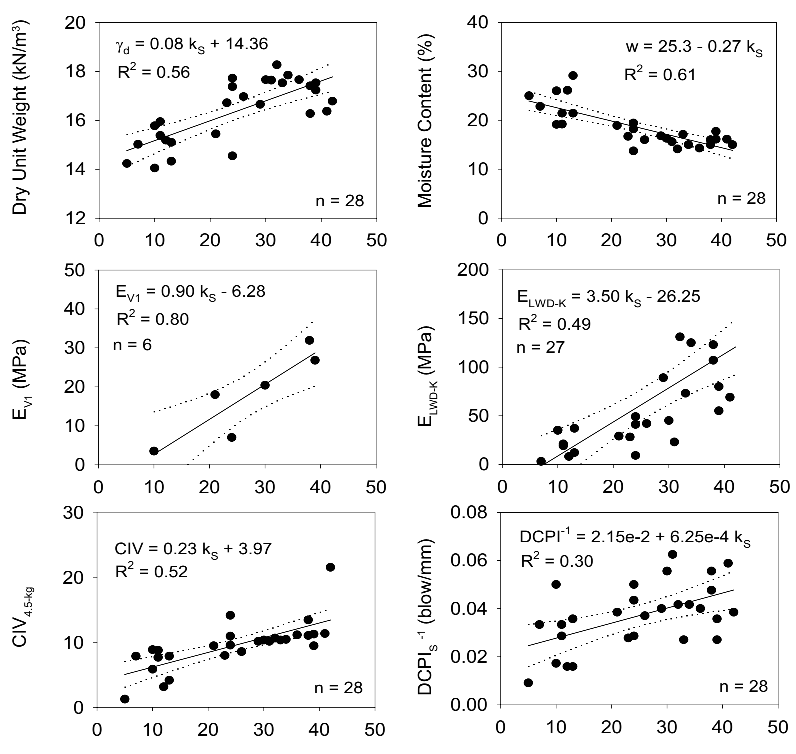

Figure 2. Relationships between ks and in situ compaction measurements—subgrade material.

(DCP), the Clegg impact tester, the soil stiffness gauge (SSG), the light weight deflectometer (LWD), dirt seismic pavement analyzer (D-SPA), etc. These tools are now being studied and in a few cases implemented into quality control and assurance programs with particular emphasis on characterizing pavement layers and subgrade for mechanistic-empirical (M-E) pavement design.

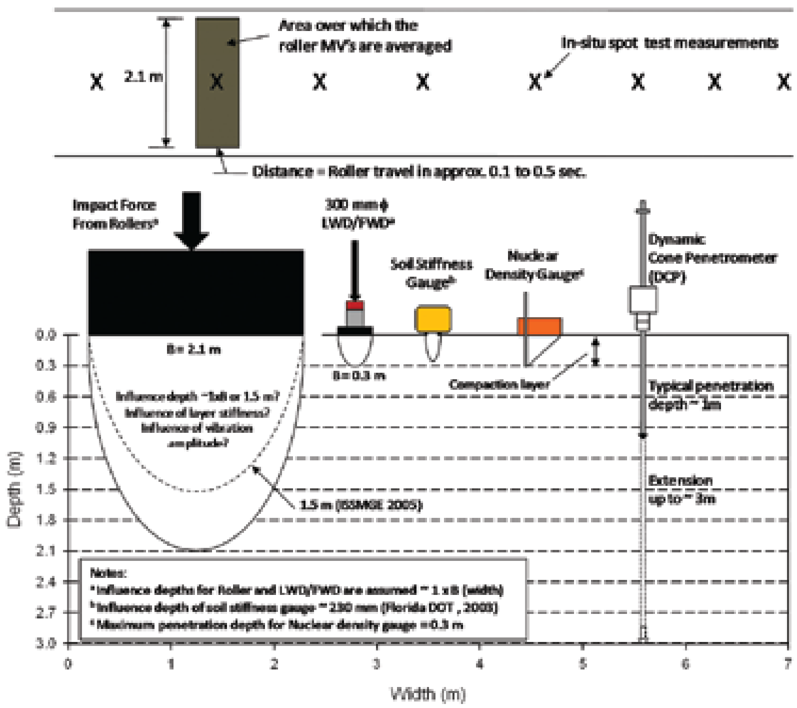

Figure 3. Measurement influence depth comparison for rollers and in situ test devices.

Figure 4. Various in situ compaction equipment for field QC/QA.

Data Visualization and Management

IC/CCC technology provides the opportunity to collect and evaluate information for 100 percent of the project area, but it can also produce large data files that create analysis, visualization, transfer, and archival challenges. Thus, approaches for managing the data need to be developed. IC measurement values referenced to GPS coordinates are spatially referenced, which can be useful for targeting QA testing and signaling to the contractor where additional rolling or rework is needed. Figure 5 shows an example data set for visualization and analysis for CMV data overlaid with in situ measurement values. This approach has the advantage of linking IC and in situ test measurements with electronic plans[18].

IC data output files have various formats that include *.xls, *.txt, *.csv, and *.dbf file types. Memory required for data storage will vary with the file type. For a section with plan dimensions of approximately 250 meters by 10 meters with compaction performed in five roller lanes, the memory required for single point data (assigned to one location across the drum) is approximately one to two megabytes for *.xls, *.txt, *.csv, and *.dbf file formats. The total memory required for creating a geodatabase for a project might be on the order of one to two gigabits.

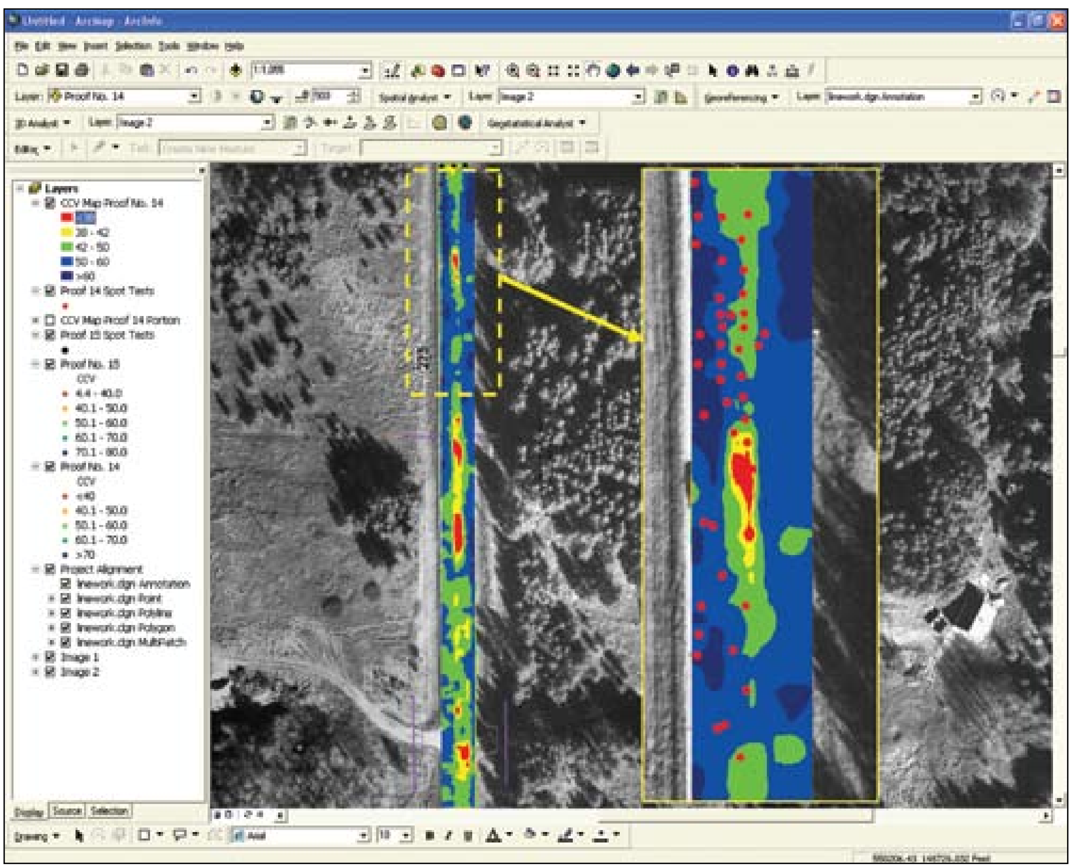

Figure 5. GIS data management approach.

[18] White, D., Thopmson, M., Vennapusa, P., and Siekmeier, J. (2008). "Implementing intelligent compaction specifications on Minnesota TH 64: Synopsis of measurement values, data management, and geostatistical analysis." Transportation Research Record: *Journal of the Transportation Research Board*, National Academy Press (in press).

Univariate statistics (e.g. mean and standard deviation) of IC measurement values alone do not characterize the spatial variability and specifically do not address the issue of uniformity from a spatial viewpoint[19] . Two data sets with identical distributions of the data (having similar mean, standard deviation, etc), can have significantly different spatial characteristics. This issue has not been addressed adequately in current specifications and will require new research to investigate the impact of non-uniformity on pavement performance.

Specifications

Specifications developed for use of CCC generally provide requirements on the equipment size, requirements for documentation of the machine sensor measurements and GPS mapping, machine operations (including speed and amplitude), and quality control compaction requirements. Table 1 lists some of the key attributes for specifications identified in the literature[9].

Current Intelligent Compaction Research Projects

Currently, there are two national studies underway to evaluate vibration-based IC and CCC systems—National Cooperative Highway Research Program (NCHRP) 21-09 and FHWA IC pooled fund study 954.

The NCHRP Study has the objectives of determining the reliability of intelligent compaction systems and to developing recommended construction specifications for the application of intelligent compaction systems in soils and aggregate base materials.

The FWHA study includes evaluation of asphalt rollers in addition to soil and aggregate. The emphasis of this study is centered on accelerating the development of IC QC/QA specifications, developing an experienced and knowledgeable IC expertise base within the participating DOTs, and identifying needed improvements and research for IC equipment and QC/QA field-testing equipment. A website has been established for this project (www.intelligentcompaction.com/).

In addition to these national level studies, a few states have conducted demonstration projects. Minnesota DOT (Mn/DOT) has implemented IC on several projects recently and has a detailed website dedicated to intelligent compaction (www.dot.state.mn.us/materials/researchic.html).

[19] Vennapusa, P., White, D.J. (2008). "Geostatistical analysis for spatially referenced roller-integrated compaction measurements," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE (in review, submitted July 2008).

Table 1. Summary of intelligent compaction specifications

	Equipment	Field size	Location Specs	Documentation	Compaction Specs	Speed	Freq.
Mn/DOT (2006 TH 64)*	Smooth drum or padfoot vibratory roller (25,000 lbs.)	300 ft x 32 ft (mini-mum at base). Max 4 ft. thick.	One calibration/ control strip per type or source of grading material	Compaction, stiffness, moisture, QC activities, and corrective actions (weekly report)	90% of the stiffness measurements must be at 90% of the compaction target value.	Same during calibration and production compaction	
ISSMGE	Roller chosen by experience	100 m by the width of the site	Homogenous, even surface. Track overlap ≤ 10% drum width.	Rolling pattern, sequence of compaction and measuring passes; amplitude, speed, dynamic measuring values, frequency, jump operation, and corresponding locations	Correlation coefficient ≥ 0.7. Minimum value ≥ 95% of Ev1, and mean should be ≥ 105% (or ≥ 100% during jump mode). Dynamic measuring values should be lower than the specified minimum for ≤ 10% of the track. Measured minimum should be ≥ 80% of the specified minimum. Standard deviation (of the mean) must be ≤ 20% in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
Earthworks (Austria)	Vibrating roller compactors with rubber wheels and smooth drums suggested	100 m long by the width of the site	No inhomogeneities close to surface (materials or water content). Track overlap ≤ 10% drum width.	Compaction run plan, sequence of compaction and measurement runs, velocity, amplitude, frequency, speed, dynamic measuring values, jump operation, and corresponding locations	Correlation coefficient ≥ 0.7. Minimum value ≥ 95% of Ev1, and median should be ≥ 105% (or ≥ 100% during jump mode). Dynamic measuring values should be lower than the specified minimum for ≤ 10% of the track. Measured minimum should be ≥ 80% of the set minimum. Measured maximum in a run cannot exceed the set maximum (150% of the determined minimum). Standard deviation (of the median) must be ≤ 20% in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
Research Society for Road and Traffic (Germany)	Self-propelled rollers with rubber tire drive are preferred; towed vibratory rollers with towing vehicle are suitable.	Each calibration area must cover at least 3 partial fields ~20 m. long	Level and free of puddles. Similar soil type, water content, layer thickness, and bearing capacity of support layers. Track overlap ≤ 10% machine width.	Dynamic measuring value; frequency; speed; jump operation; amplitude; distance; time of measurement; roller type; soil type; water content; layer thickness; date, time, file name, or registration number; weather conditions; position of test tracks and rolling direction; absolute height or application position; local conditions and embankments in marginal areas; machine parameters; and perceived deviations	The correlation coefficient resulting from a regression analysis must be ≥ 0.7. Individual area units (the width of the roller drum) must have a dynamic measuring value within 10% of adjacent area to be suitable for calibration.	Constant	
Vägverket (Sweden)	Vibratory or oscillating single-drum roller. Min. linear load 15–30 kN. Roller-mounted compaction meter optional.	Thickness of largest layer 0.2–0.6 m.	Layer shall be homogenous and non-frozen. Protective layers < 0.5 m may be compacted with subbase.	—	Bearing capacity or degree of compaction requirements may be met. Mean of compaction values for two inspection points ≥ 89% for sub-base under roadbase and for protective layers over 0.5 m thick; mean should be ≥ 90% for roadbases. Required mean for two bearing capacity ratios varies depending on layer type.	Constant 2.5–4.0 km/h	—

*** Note: The 2007 Mn/DOT intelligent compaction projects will implement new/revised specifications for granular and cohesive materials including a light weight deflectometer (LWD) quality compaction pilot specification.**

Presentations

The following is a list of the technical presentations delivered at the workshop. The slides follow.

1. Intelligent Compaction for Soils and Aggregate—David White
2. Intelligent Compaction (IC) for Hot Mix Asphalt (HMA)—Lee Gallivan
3. Automated Technologies in Construction—Dan Streett
4. Earthworks Engineering Research Center—David White
5. Intelligent Compaction at Mn/DOT—Glenn Engstrom, Craig Collison, and Art Bolland
6. European Experience with ICS—François Chaignon
7. Intelligent Compaction for Soil and Asphalt—Dean Potts
8. Asphalt Manager Intelligent Compaction—Chris Connolly
9. Intelligent Compaction for Soils & HMA—Stan Rakowski
10. Evaluation of Highway Subgrade Strength with Acceleration Wave of the Vibration Roller —Stan Rakowski
11. Intelligent Compaction: GPS-based Compaction Control—Kirby Carpenter
12. Intelligent Compaction—Khalil Maalouf
13. Intelligent Compaction: Where we are at and where we need to be—Brett Stanton
14. Facilitator Report / Discussion—Tom Cackler, Ed Engle, Heath Gieselman, Lisa Rold, Douglas Townes, David White

Intelligent Compaction for Soils and Aggregate

David White

IOWA STATE UNIVERSITY
Civil, Construction & Environmental Engineering

Intelligent Compaction For Soils and Aggregate

Intelligent Compaction for Soils and HMA Workshop
West Des Moines, Iowa
April 2-4, 2008

David J. White, Ph.D.
Associate Professor
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ctre

EERC

Dream it, Design it, Build it. www.ccee.engineering.iastate.edu

Outline

- Theory/Technology
- Specifications
- Why Important?
- Factors that Affect IC-MVs
- Correlation Studies
- Case histories

Technology

Caterpillar: CMV, RMV, MDP

Dynapac: CMV, Bouncing Value

Bomag: E_{VIB}

Sakai: CCV

Case/Ammann: k_s

IC Measurement Values

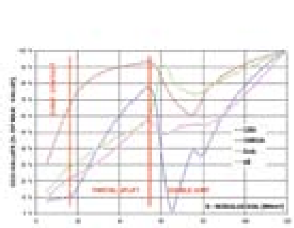
Manufacturer	Roller-Integrated Measurement Features	
	Compaction Measurement	Feedback Control
Ammann	$k_s = \Omega^2 r^2 \left(m_d + \frac{m_0 r_0 \cos(\phi)}{A}\right)$	Adjusts amplitude and frequency
Bomag	$z_a = \frac{(1-\nu^2)}{E_{vib}} \cdot \frac{F_s}{L} \cdot \frac{2}{\pi}\left(1.8864 + \ln\frac{L}{B}\right)$ where, $B = \sqrt{\frac{16}{\pi} \cdot \frac{R(1-\nu^2)}{E_{vib}} \cdot \frac{F_s}{L}}$	Adjusts amplitude direction on the drum
Caterpillar	Geodynamik $CMV = C\left(\frac{A_{2\Omega}}{A_\Omega}\right)$ Geodynamik $RMV = \frac{A_{0.5\Omega}}{A_\Omega}$ $MDP = P_g - WV\left(\sin\alpha + \frac{a}{g}\right) - (mV + b)$	Adjusts amplitude based on RMV
Dynapac	Geodynamik $CMV = C\left(\frac{A_{2\Omega}}{A_\Omega}\right)$ *Bouncing Value* $= \frac{A_{0.5\Omega}}{A_\Omega}$	Adjusts amplitude based on bouncing value
Sakai	$CCV = \left[\frac{A_{0.5\Omega}+A_{1.5\Omega}+A_{2\Omega}+A_{2.5\Omega}+A_{3\Omega}}{A_{0.5\Omega}+A_\Omega}\right] \cdot 100$	No

Influence of Drum Operating Mode

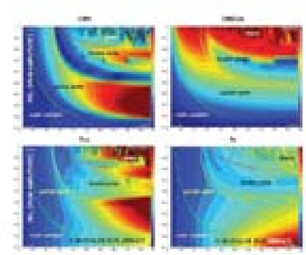
drum motion	interaction drum-soil	operating condition	soil contact force	application of CCC	soil stiffness	roller speed	drum amplitude
periodic	continuous contact	CONT. CONTACT		yes	low	fast	small
	periodic loss of contact	PARTIAL UPLIFT		yes			
		DOUBLE JUMP		yes			
		ROCKING MOTION		no			
chaotic	non-periodic loss of contact	CHAOTIC MOTION		no	high	slow	large

Summary of operating modes (from Adam and Kopf 2004)

Influence of Drum Operating Mode



Influence of drum operating condition on roller MVs relative to soil stiffness

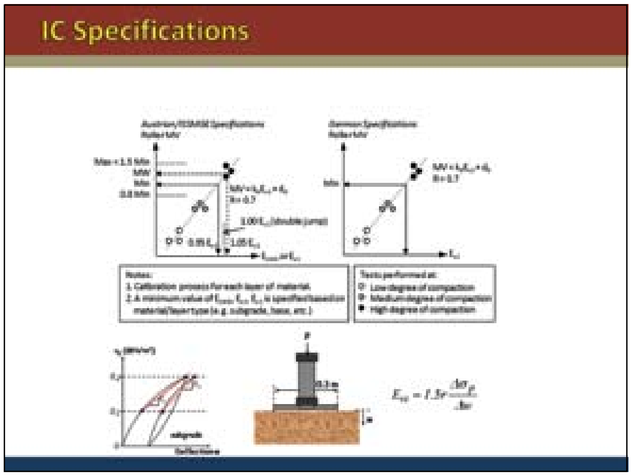


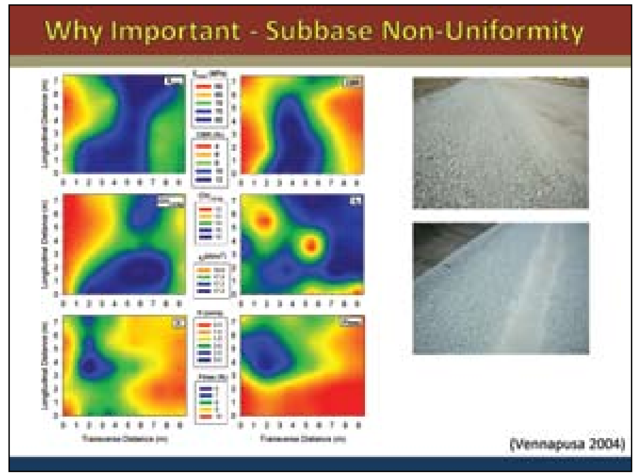
Roller MV variation with soil modulus and drum vibration amplitude

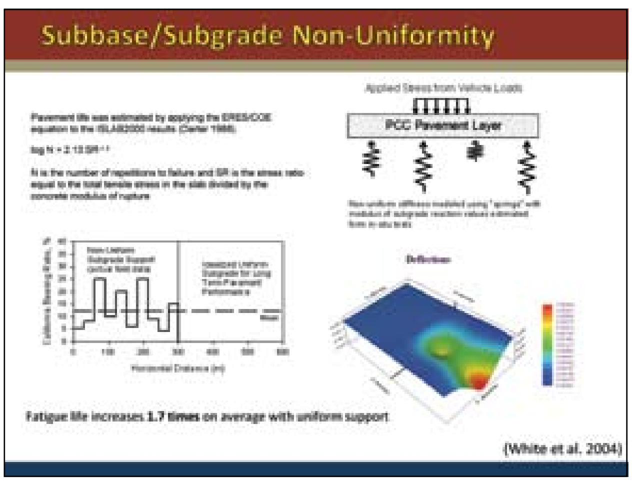
(results of numerical simulations, from Adam and Kopf 2004)

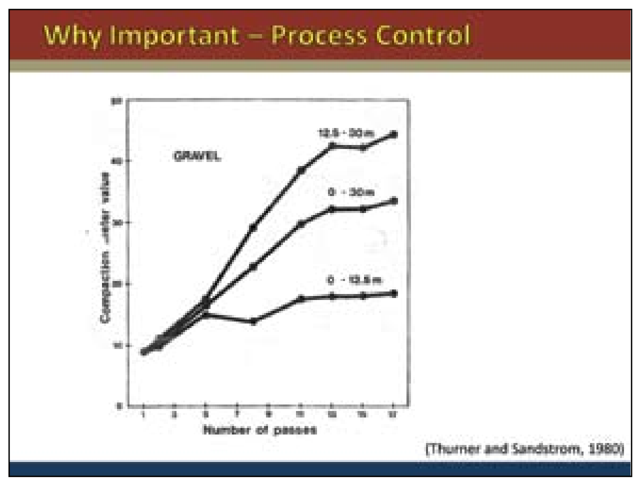
Intelligent Compaction for Soils and Aggregate

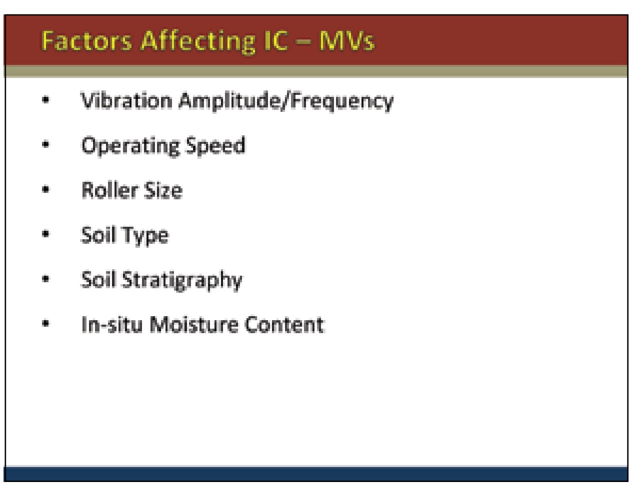
David White

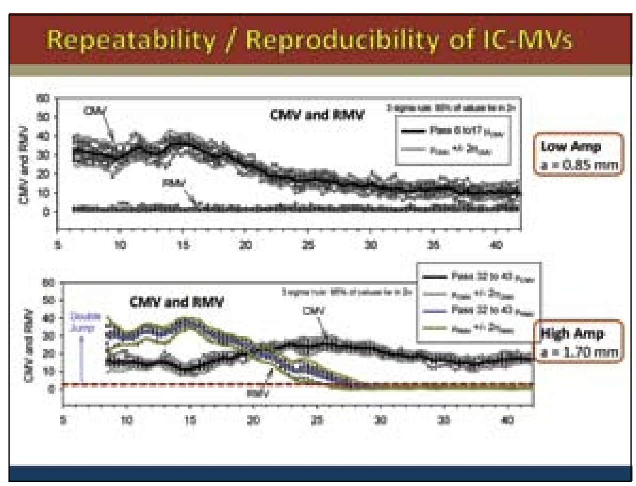




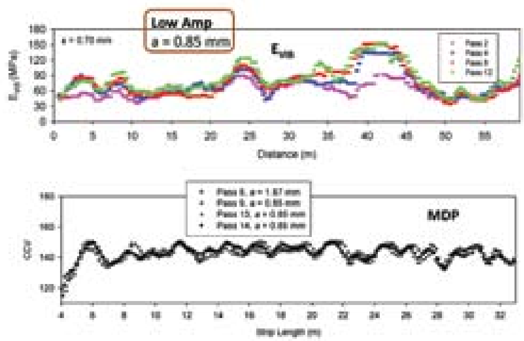








Repeatability / Reproducibility of IC-MVs



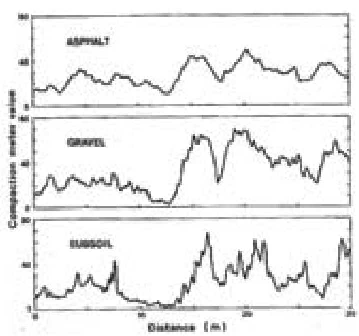
Preliminary Findings

- IC-MVs are *repeatable* under identical operating conditions
- *Reproducible* when:
  - Minor change in speed ~ 3 to 4.5 km/h and NO Double Jump

Work In Progress
Quantify Variation/Error associated with

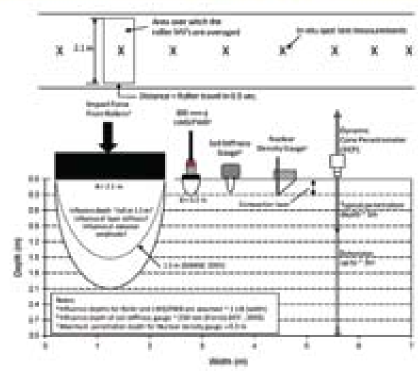
1. *Repeatability:* CMV, CCV, E_{VIB}, k_s under "identical" operating conditions
2. *Reproducibility:* CMV, CCV, EVIB, ks under changing operation conditions: *Speed, Amplitude, Direction of Travel*

Measurement Influence Depth



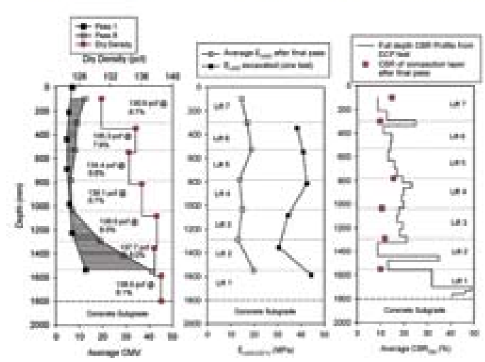
(Thurner and Sandstrom, 1980)

Measurement Influence Depth



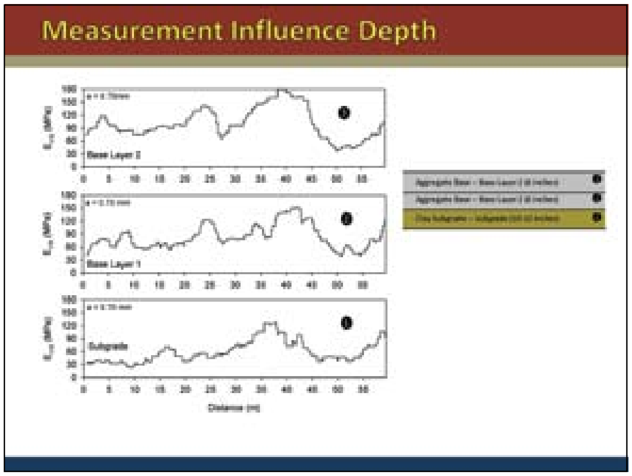
Measurement Influence Depth

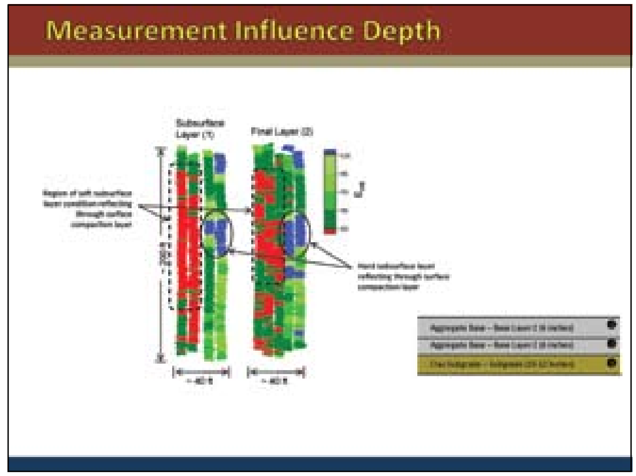
Measurement Influence Depth

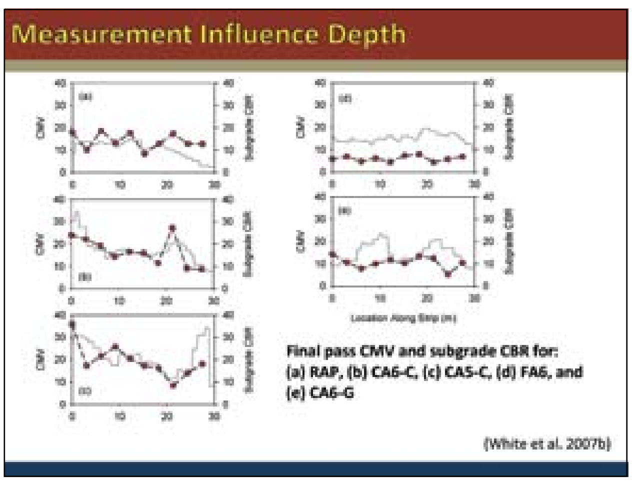


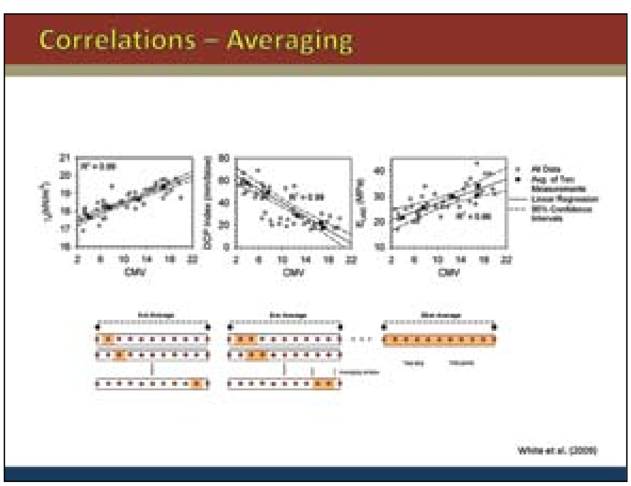
Intelligent Compaction for Soils and Aggregate

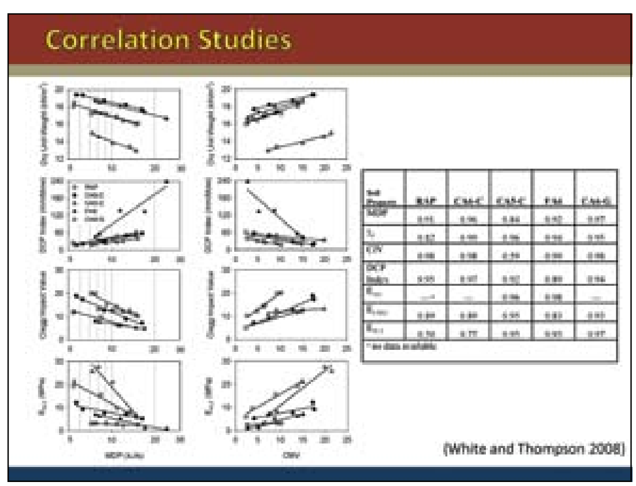
David White











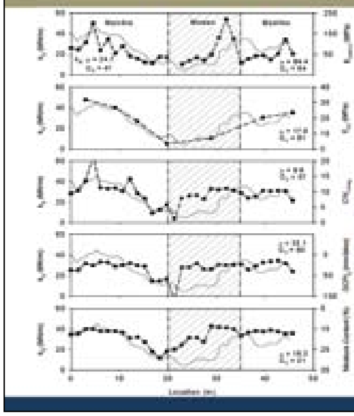
Intelligent Compaction for Soils and Aggregate

David White

Regression Relationships

(White et al. 2009)

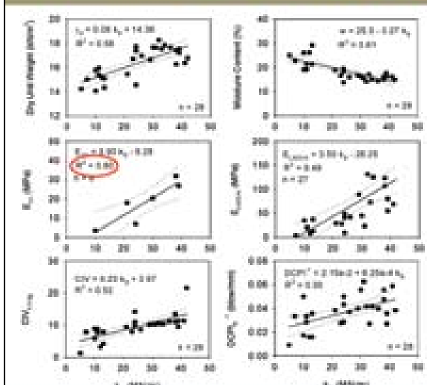
Correlations to PLT, LWD, DCP, Clegg



Comparison of k_s (solid line) and in-situ compaction measurements on a test strip comprised of subgrade material.

Thompson et al. (2008)

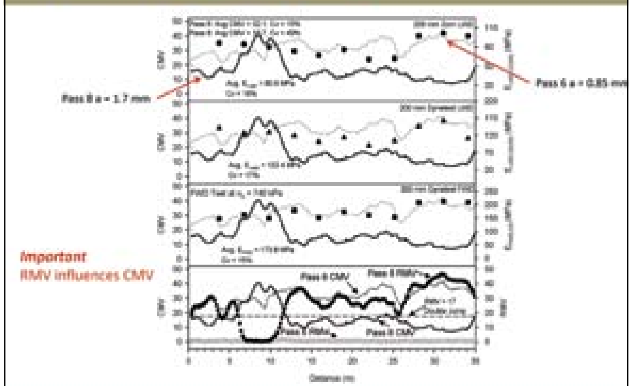
Correlations to DCP, LWD, PLT, Clegg, γ_d



Relationships between k_s and in-situ compaction measurements - subgrade material.

Thompson et al. (2008)

Correlations to LWD/FWD



Case History

TH 64 Reconstruction Project
Akeley, MN

Project Summary

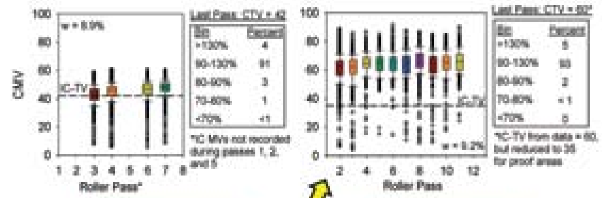
- TH 64 Widening and Reconstruction Project – 10 km
- First earthwork project in US with IC technology implementation
- Some Main Features of Specifications
  - *Control Strips:* 100 m x 10 m plan size – Compacted until no significant increase in CMV is noticed with additional pass and IC target values (IC-TVs) are established.
  - *Moisture Content:* 65% to 95% of standard Proctor optimum.
  - *Acceptance Specifications:*
    - ***90% of IC measurement values ≥ 90% of IC-TV***
    - ***If significant portion of grade > 130% of IC-TV, the IC-TV will be re-evaluated***

Intelligent Compaction for Soils and Aggregate

David White

Construction

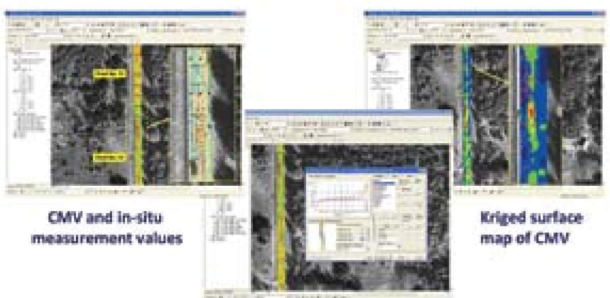
IC Results – Control Sections



1.1 m subcut Control Strip **0.25 m subcut Control Strip**

- Construction traffic contributing to compaction
- Evidence of the benefit of managing equipment fleet to aid in compaction process – mostly undocumented without IC !!
- Little compaction after first few passes – Importance of location and pass information from IC rollers

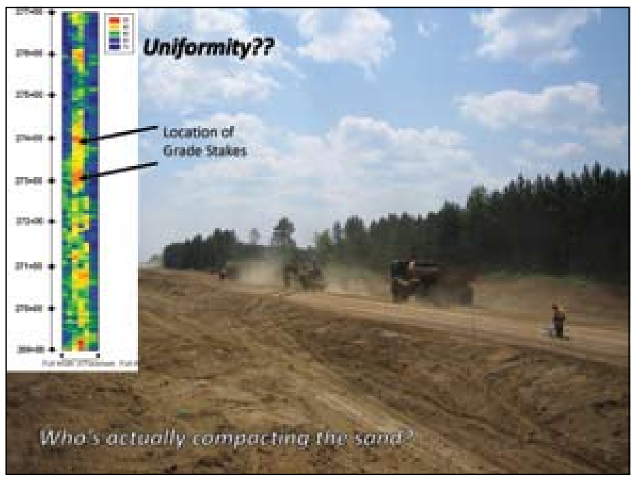
Data Management Using GIS



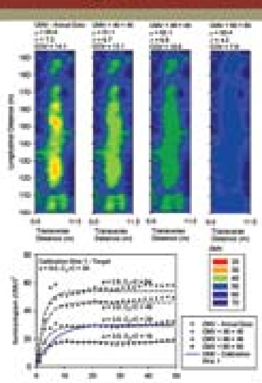
CMV and in-situ measurement values

Kriged surface map of CMV

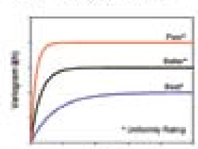
Semi-variogram analysis of CMV



Optimizing Construction Process



Characterizing Uniformity Using Geostatistics



Representative Samples and Number of Tests

$n = (3s/E)^2$ ASTM Designation E122

Spatial Area 1	Spatial Area 2
E_{LWD} = 10, 13, 16 MPa	E_{LWD} = 30, 33, 36 MPa

What is the required number of tests???

Scenario 1, soil data assigned according to soil type: The standard deviation in each case is 4, so the number of tests required to characterize each soil type is $n = (3 \times 4/4)^2 = 9$ *tests* for a total of 18 tests.

Scenario 2, soil data pooled: The standard deviation for all six tests is 12, so $n = (3 \times 12/4)^2$ = 75 tests total.

Important Lesson: To reduce random error, data should be assigned according to IC MV's. This requires that the IC maps be available during QA testing.

Intelligent Compaction for Soils and Aggregate

David White

Lessons Learned

- ✓ Construction traffic contributing to compaction – well observed with 100% coverage of IC data
- ✓ Little compaction after first few passes – Importance of compaction history from IC rollers
- ✓ CMV and in-situ test results are correlated at the project scale
- ✓ Scatter in relationships between IC and in-situ measurements – differences in measurement influence depth
- ✓ GIS can be used for effective data managing and archiving
- ✓ Geostatistics can help improve process control
- ✓ IC MV can be used to reduce # QA tests!

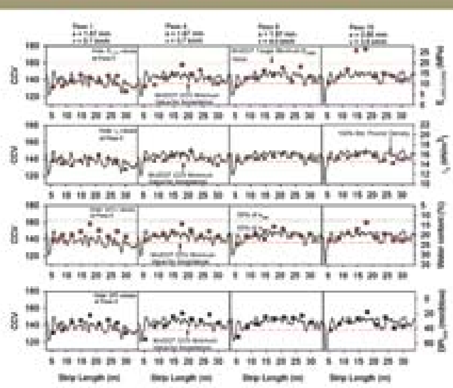
Case History

US 60 Project
Bigelow, MN

Construction

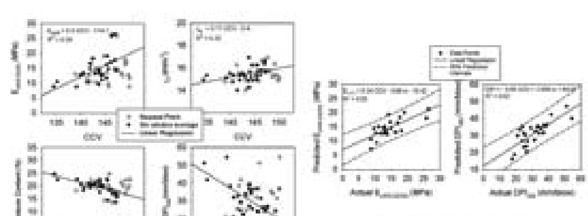
Test Strip Construction and Testing

Comparison Test Results



CCV = f(1/MDP)

Simple and Multiple Regression Analysis



Need to average data over a test strip for multiple passes to get narrow prediction limits

Intelligent Compaction for Soils and Aggregate

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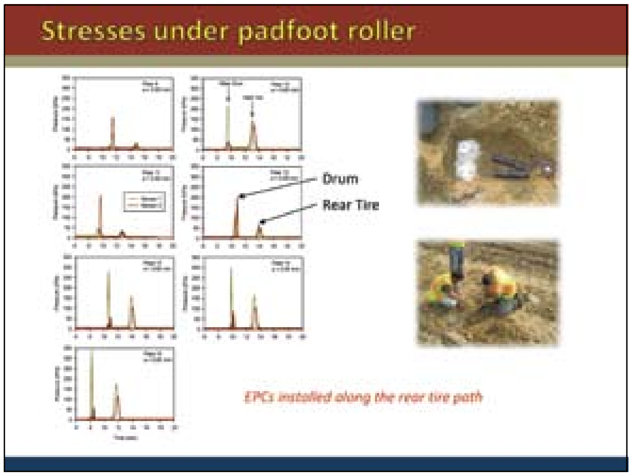

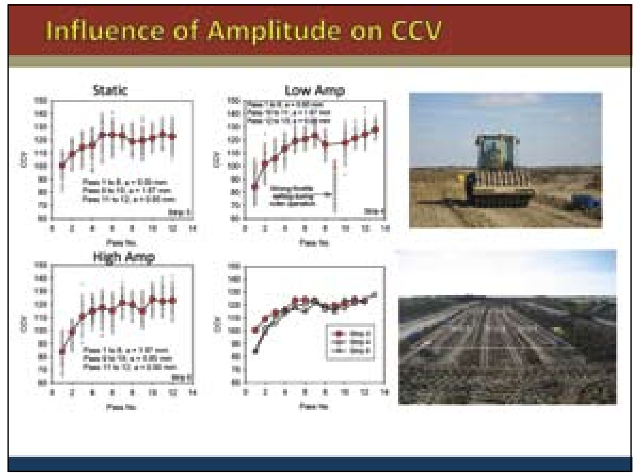

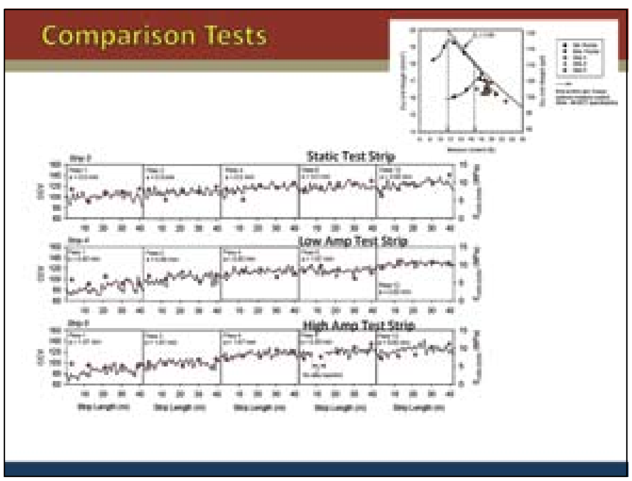

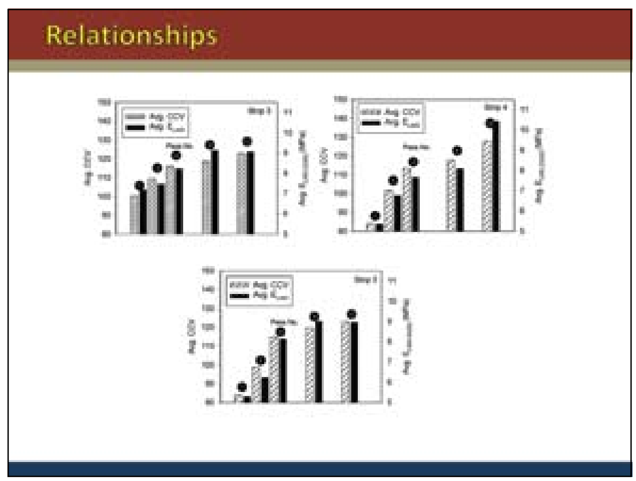

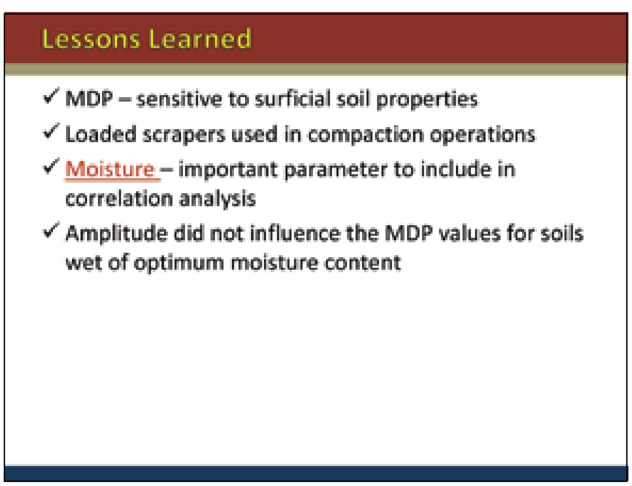

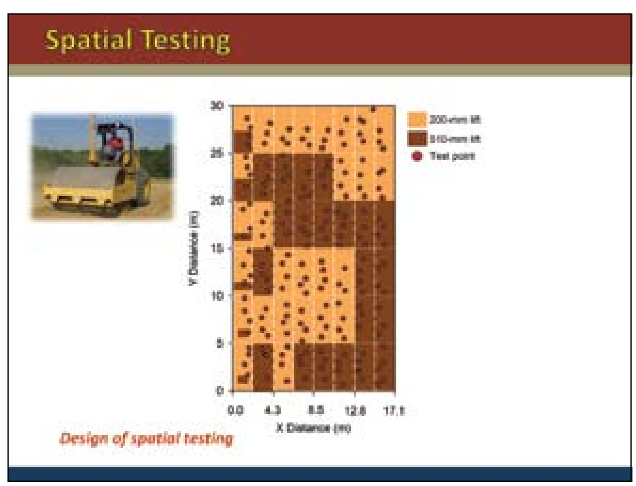

Intelligent Compaction for Soils and Aggregate

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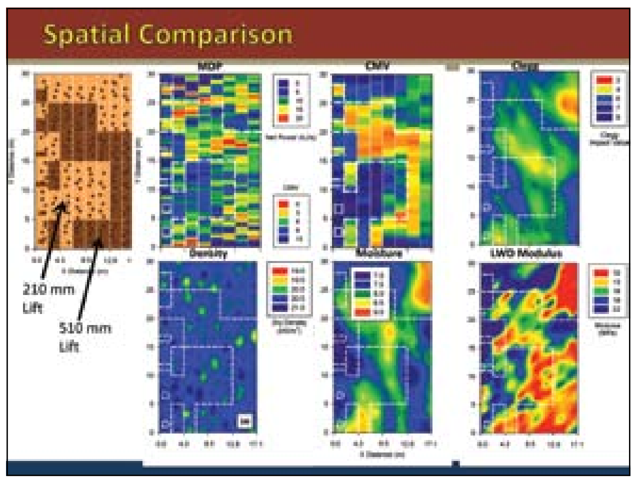
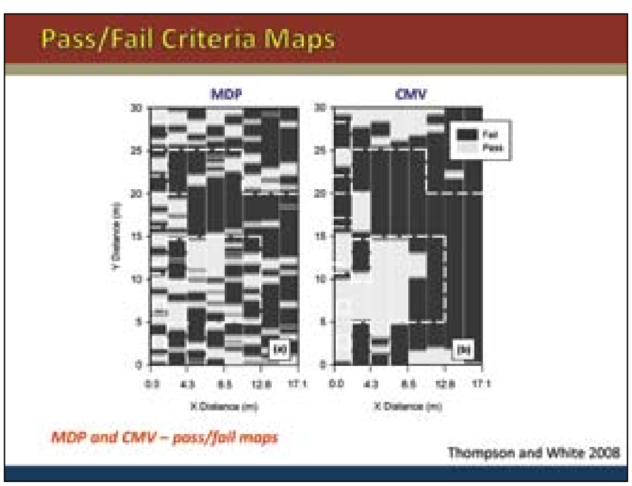
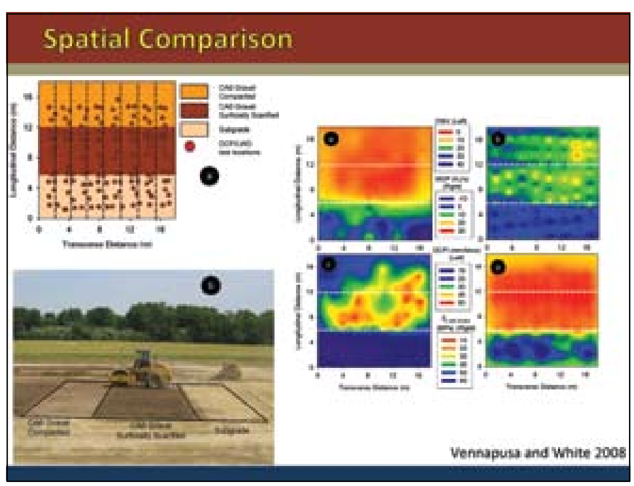


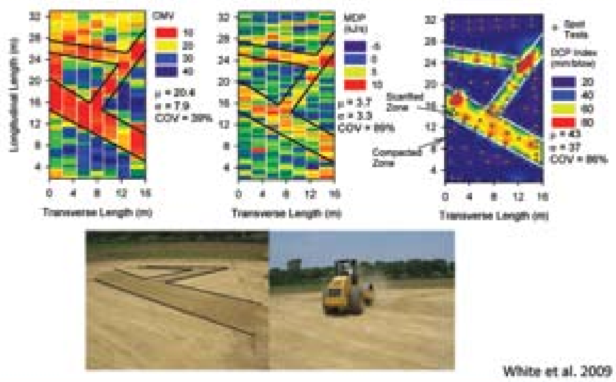




Intelligent Compaction for Soils and Aggregate

David White

Spatial Comparison



White et al. 2009

Lessons Learned

- ✓ Cannot run enough spot tests to create highly reliable spatial maps...IC is the best method
- ✓ IC data and LWD/DCP measurements show similar spatial variation

Case History

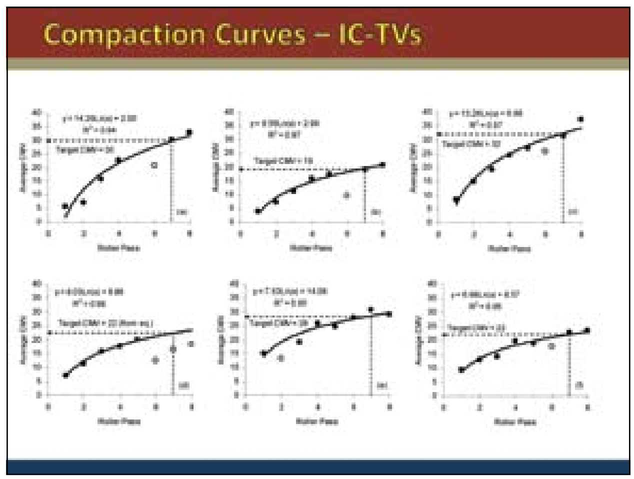
Bradshaw Field Training Area (BFTA) – Northern Territory, Australia

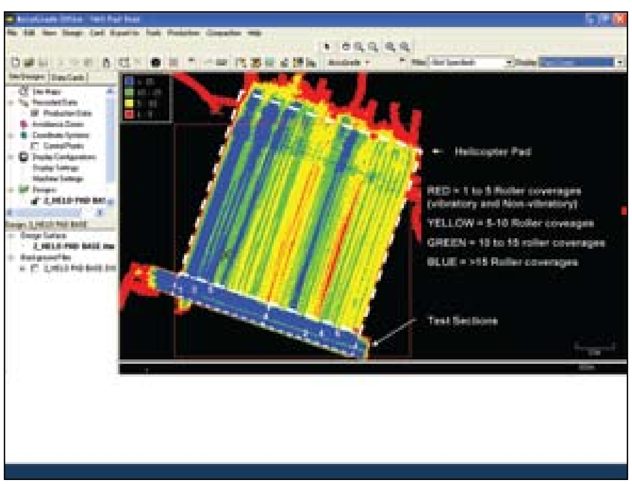
Joint Rapid Airfield Construction (JRAC) Program

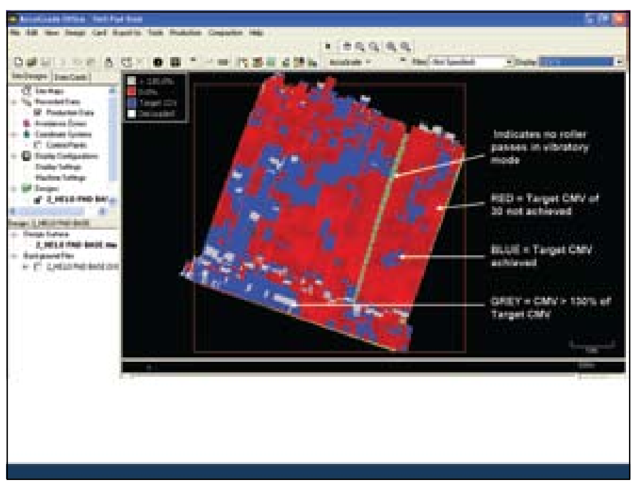
June 11 – 25, 2007

Intelligent Compaction for Soils and Aggregate

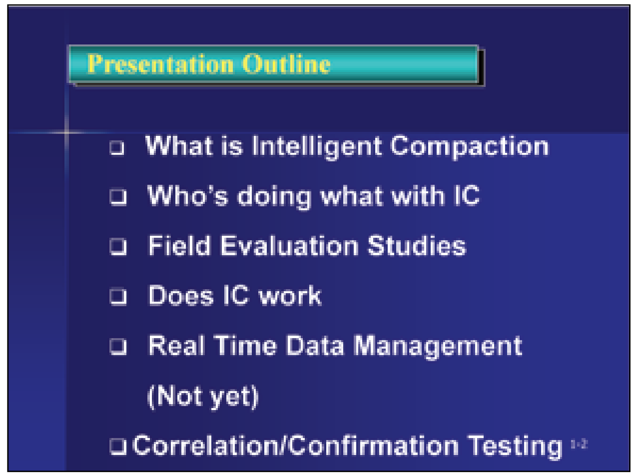
David White





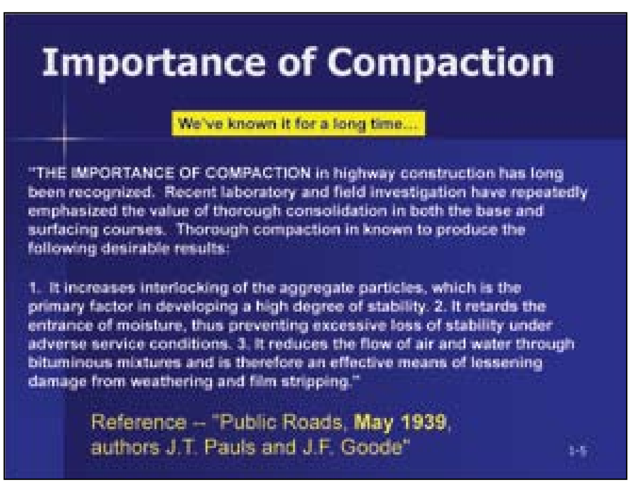



Intelligent Compaction (IC)
for Hot Mix Asphalt (HMA)
Iowa
Intelligent Compaction
Workshop
Lee Gallivan, HIPT
Federal Highway Administration
Federal Highway Administration
April 2, 2008


Presentation Outline
What is Intelligent Compaction
Who's doing what with IC
Field Evaluation Studies
Does IC work
Real Time Data Management
(Not yet)
Correlation/Confirmation Testing
1-2


What is Intelligent Compaction Technology
An Innovation in Compaction Control and Testing
Office of Pavement Technology
Federal Highway Administration
www.fhwa.dot.gov/pavement/

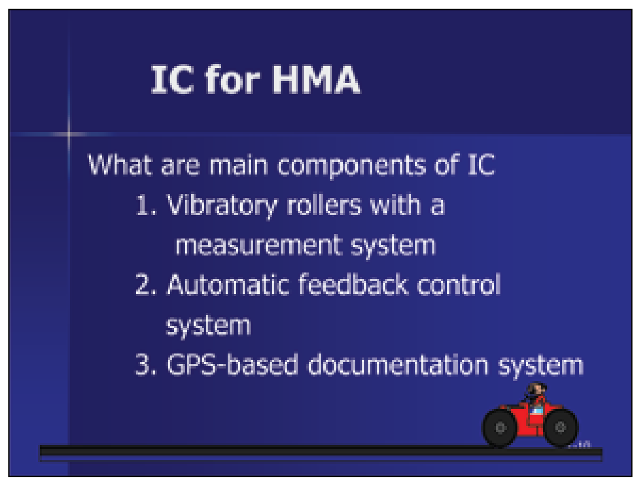

Intelligent Compaction
----Definition----
What is "Intelligence?"
– Oxford Dictionary: "...able to vary behavior in response to varying situations and requirements"
– Ability to:
Collect information
Analyze information
Make an appropriate decision
Execute the decision
Oxford
3000-4000 TIMES A MINUTE
1-4

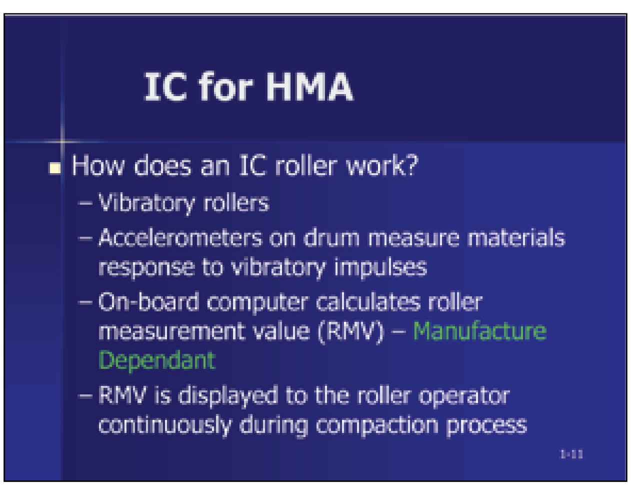

Importance of Compaction
We've known it for a long time...
"THE IMPORTANCE OF COMPACTION in highway construction has long been recognized. Recent laboratory and field investigation have repeatedly emphasized the value of thorough consolidation in both the base and surfacing courses. Thorough compaction in known to produce the following desirable results:
1. It increases interlocking of the aggregate particles, which is the primary factor in developing a high degree of stability. 2. It retards the entrance of moisture, thus preventing excessive loss of stability under adverse service conditions. 3. It reduces the flow of air and water through bituminous mixtures and is therefore an effective means of lessening damage from weathering and film stripping."
Reference -- "Public Roads, May 1939, authors J.T. Pauls and J.F. Goode"
1-5

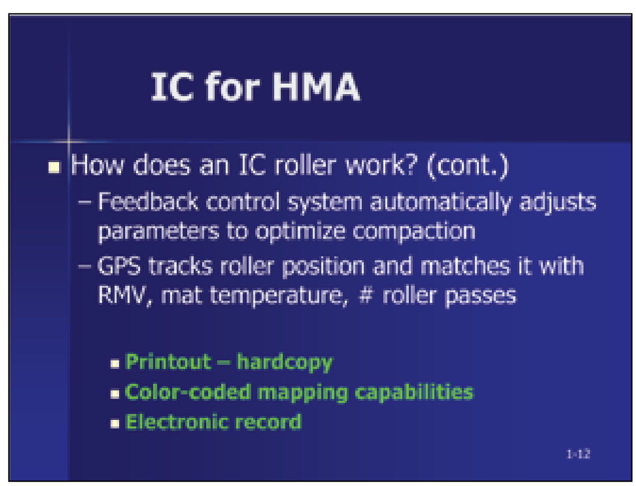

Conventional Density Testing Shortcomings
Density Acceptance...
Limited Number of Locations
After Compaction is Complete
1-6

Intelligent Compaction for Hot Mix Asphalt

Lee Gallivan

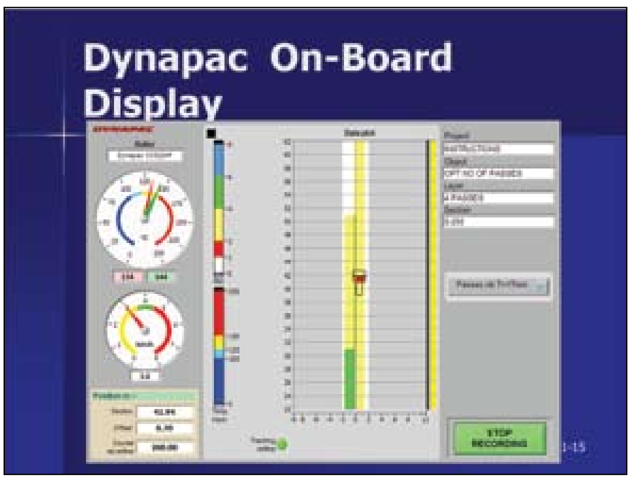




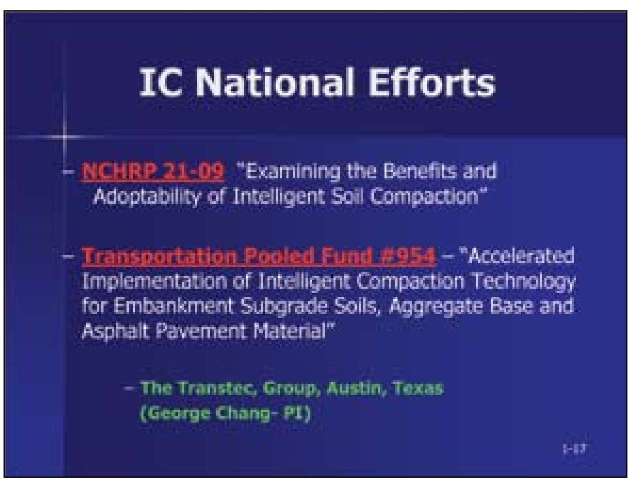



IC for HMA
1-13


Caterpillar On-Board Display
VariVibe
Passes
CMV
Find
Zoom
Actual
See All
Log Pt
Exit


Dynapac On-Board Display
STOP RECORDING
1-15


Sakai IC Roller Project
Roller Passes
Shoulder (Supported)
Paving Direction
Longitudinal Joint
Courtesy Sakai America
1-16


IC National Efforts
– NCHRP 21-09 "Examining the Benefits and Adoptability of Intelligent Soil Compaction"
– Transportation Pooled Fund #954 – "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material"
– The Transtec, Group, Austin, Texas (George Chang- PI)
1-17


NCHRP 21-09 Phase One Project
MnROAD Research Center
July 2006; MnROAD Research Center
1-18

Intelligent Compaction for Hot Mix Asphalt

Lee Gallivan

Ammann/Case Tandem Drum IC Roller

Capabilities

- Stiffness (kb) ?
- Auto Feedback
- GPS Mapping ?
- Status: Planned

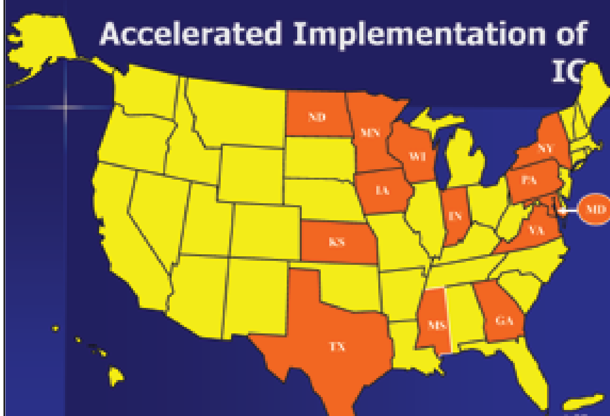
1-25

FHWA Pooled Funds Study (Soils / HMA)

- 3 year study of IC for Subgrade, aggregate bases, and HMA materials
- Work has started October 1st, 2007
- 13 participating states
- Estimate 1+ project / State / year ~ 15-20?
- Close coordination with NCHRP project – No repeats though
- To work closely with roller suppliers to increase the number of IC rollers and manufacturers

1-26

Accelerated Implementation of IC



1-27

Pooled Fund, Objectives

- **Objectives: Based on data obtained from field studies:**
  - Accelerated development of QC/QA specifications for granular and cohesive subgrade soils, aggregate base and Hot Mix Asphalt (HMA) pavement materials…

1-28

Pooled Fund, Objectives

- **Develop an experienced and knowledgeable IC expertise base within Pool Fund participating state DOT personnel**
- **Identify and prioritize needed improvements to and/or research of IC equipment and field QC/QA testing equipment (DCP, FWD, GeoGauge, etc)**
- **One Stop Shopping for IC (Web Page)**

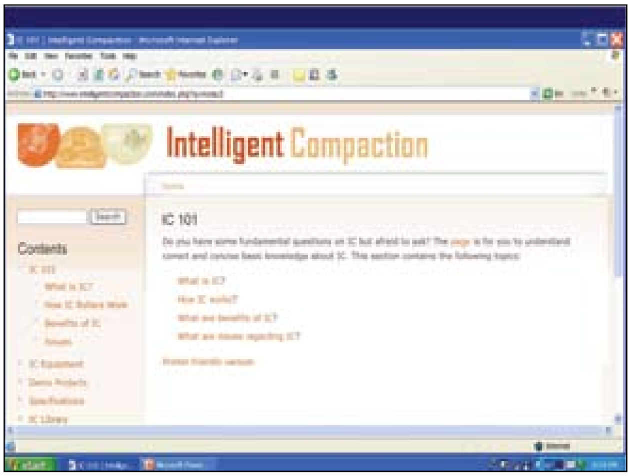
1-29

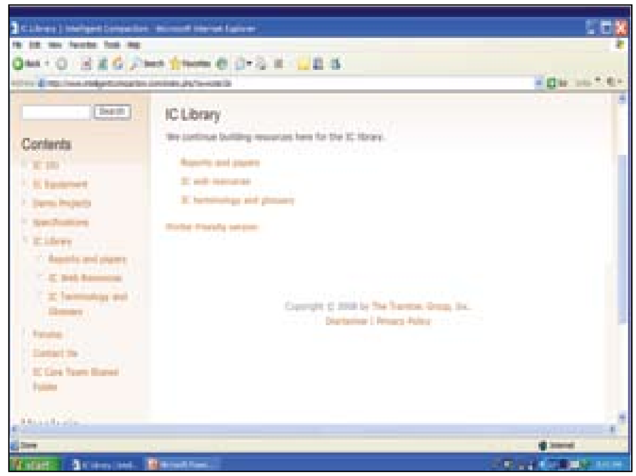
1-30

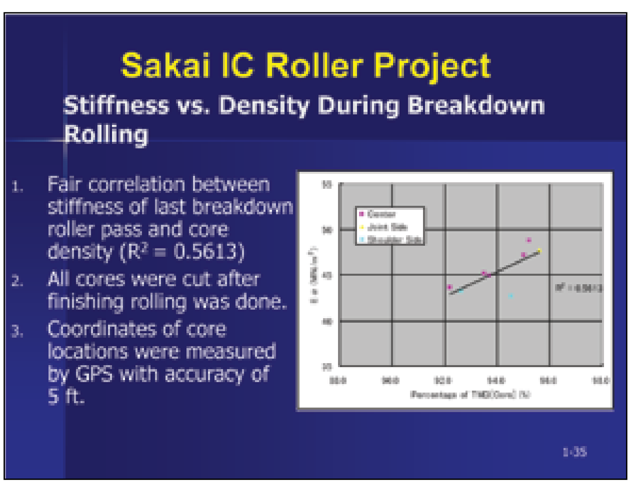
www.intelligentcompaction.com

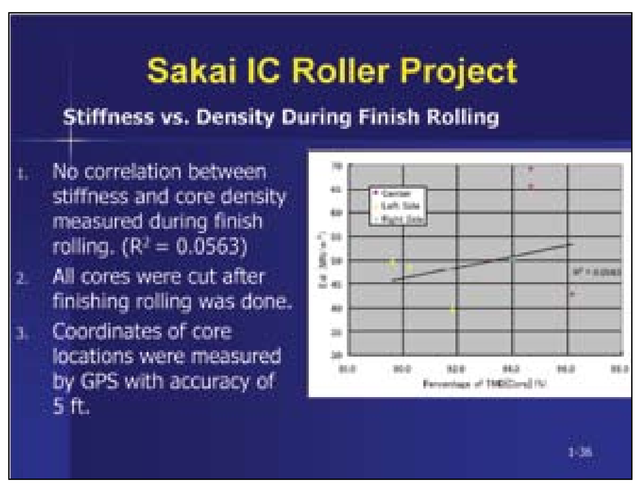
Intelligent Compaction for Hot Mix Asphalt

Lee Gallivan

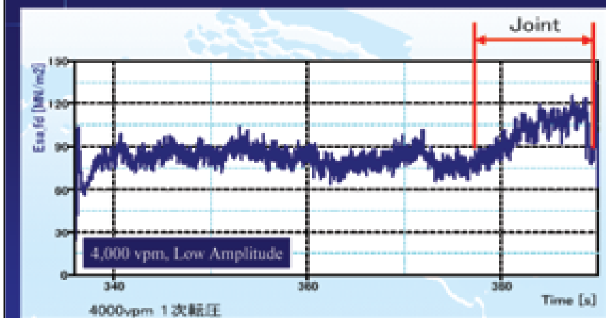








Sakai IC Roller Project



Distribution of roller-generated stiffness on final pass of breakdown rolling

Special Issues for HMA IC

- Thin lift construction
- Mixture type and size
- Allowable temperature ranges
- Surface vs. internal temperature measurement during placement
- Non-destructive, in-situ stiffness
- Response parameters

1-38

Question: Does IC work?

- Soils and Aggregate materials have had good experiences to date.
- HMA- the jury is still out, but stay tuned for future updates.

1-39

What have we learned so far?

- IC technology appears to have great potential to improve the compaction process
- Improved and more uniform density should increase pavement service life
- There is a great deal of interest among industry as well as federal and state DOTs to learn more about it

1-40

What have we learned so far?

- Roller manufacturers are responding to this interest by performing R&D, providing rollers and by coordinate efforts with state and national research efforts
- Preliminary findings for HMA from studies in US are not glowing but are encouraging

1-41

What is next?

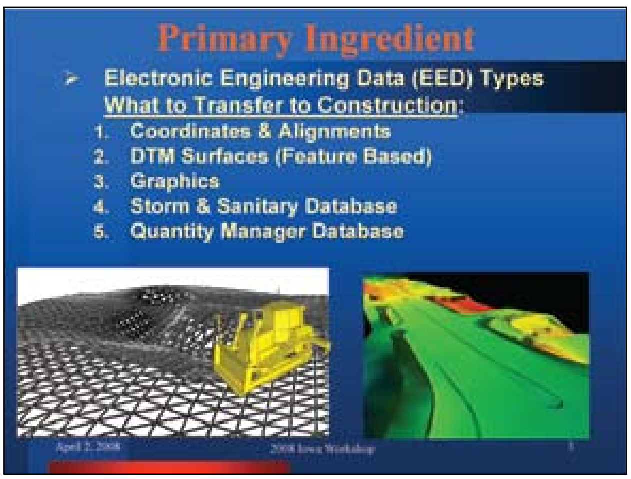
- FHWA is committed to working with others to accelerate the study and implementation of the technology
- Two major national studies of IC technology are being performed along with state projects
- A large number of projects are planned for the 2008-2010 construction seasons.
- Short term goals are to increase the number of IC rollers in the US, to learn how to use the technology effectively and to develop construction specifications for all material types

1-42


Thank you
143


Automated Technologies in Construction
2008 Iowa Workshop
Dan Streett, PE & LS
New York State DOT


Automated Technologies
1. Primary Ingredient – Electronic Engineering Data (EED)
2. Three Technology Components
3. Multiple Business Benefits
4. NY 2007 Project Experiences
5. Building Confidence
April 2, 2008
2008 Iowa Workshop
2


Primary Ingredient
Electronic Engineering Data (EED) Types
What to Transfer to Construction:
1. Coordinates & Alignments
2. DTM Surfaces (Feature Based)
3. Graphics
4. Storm & Sanitary Database
5. Quantity Manager Database
April 2, 2008
2008 Iowa Workshop
3

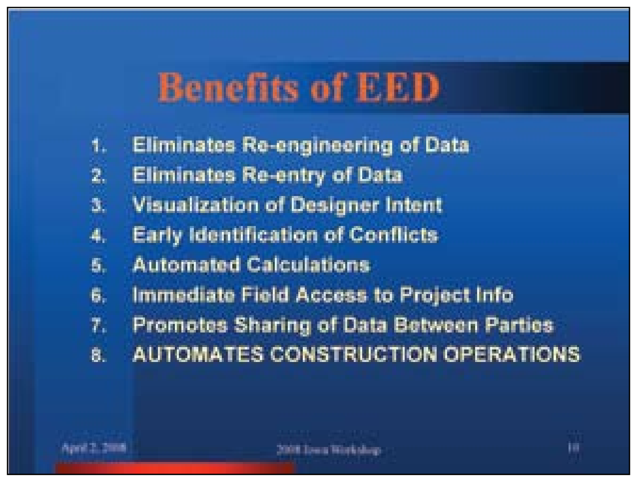

Primary Ingredient
Electronic Engineering Data (EED)
1. Requires Consistent, Reliable & Accurate Electronic Data
2. Created by Either Contractors or by DOT
3. Designer Should Provide EED to Contractor
4. Should be No Difference, Electronic vs Paper
April 2, 2008
2008 Iowa Workshop
4

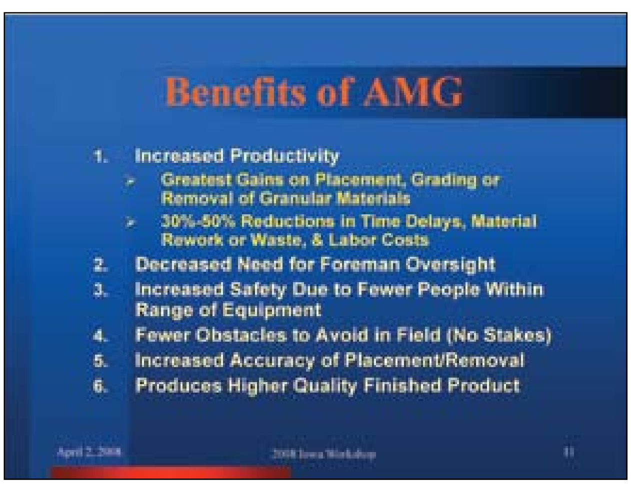

1st Technology Component
Automated Machine Guidance (AMG):
1. On-Board Computer, GPS and Machine Sensors Continuously Measure Direction, Elevation, & Slope
2. AMG Interpolates Engineering Data, Compares to the Spatial Position and Provides Directional Guidance
3. Operator has On Screen Graphics and Indicator Lights for Guidance on Direction and Depth
April 2, 2008
2008 Iowa Workshop
5

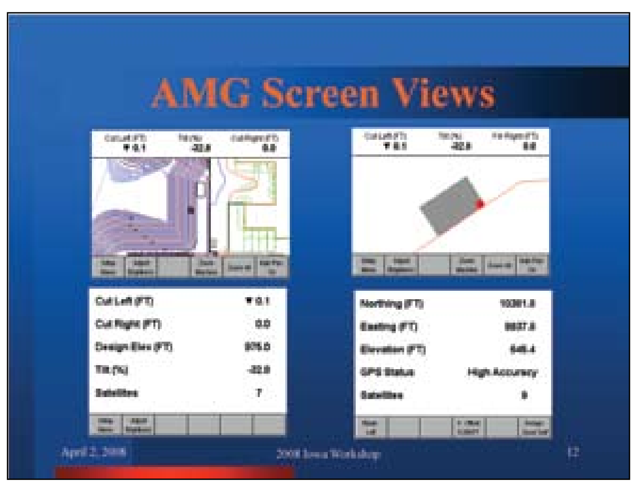

Trimble

Automated Technologies in Construction

Dan Streett







Benefits of Automated Stakeout & Inspection

1. 1 Person Can Accomplish Work Formerly of 2-3
   - No Need for Measuring Tapes, Levels or Level Rods
   - Measurements are Automated & Documented
   - More Information Accessible to the Operator
2. Operators Prefer Independent Check of Locations – No Reliance on Stakes or Markers
3. Reduced Recalculation Mistakes or Keying Errors
4. Allows for More QC/QA of Work

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Benefits of Automated Quantity Computations

1. More Accurate Interpretation of 3D Data
2. Reduced Calculation or Keying Errors
3. Takes 80% Less Effort
4. Small Changes are Instantly Adjusted
5. Documented Surfaces at Each Phase

April 2, 2008 2008 Iowa Workshop 14

NY 2007 AMG Experience

1. 8 Projects Evaluated in 2007
2. GPS Accuracy is Impressive
3. AMG Reduces Overuse/Undercut of Materials
4. Operators Learn Quick & Like Info Availability
5. AMG is Also Very Effective for Trenching
6. QC Against Known Locations & Elevations
7. AMG Uses Either 3D Surface Models, or Alignments, Profiles and Typical Sections

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2007 Automated Stakeout & Inspection Experience

1. AMG Necessitated Use of GPS for Inspection
2. Found Use of GPS Effective, Efficient & Accurate
3. Operators Have Taken to GPS & Don't Want to Work Without It
4. Allows for Real Time – On Demand Positioning Anywhere on Project
5. Provides Independent Checks for Contractor and Inspectors
6. Can be Connected to Bentley On-Site for Inspection Verification and Documentation
7. QC Against Known Control Points & Benchmarks

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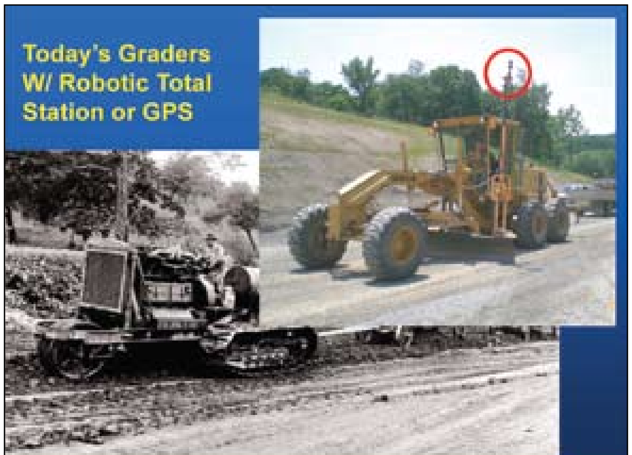
Today's Graders W/ Robotic Total Station or GPS



Building Confidence

1. NY Contractors Who Use AMG, Have High Confidence
2. Construction Needs EED Which Reflects Designer's Intent
3. Revised Survey Specs Now Require Sharing Electronic Data, and Verification of DTMs
4. Sharing Data Increases Level of Trust Between Parties
5. No Difference Between Paper or Electronic Responsibility
6. Need to Build QC/QA into Automated Procedures

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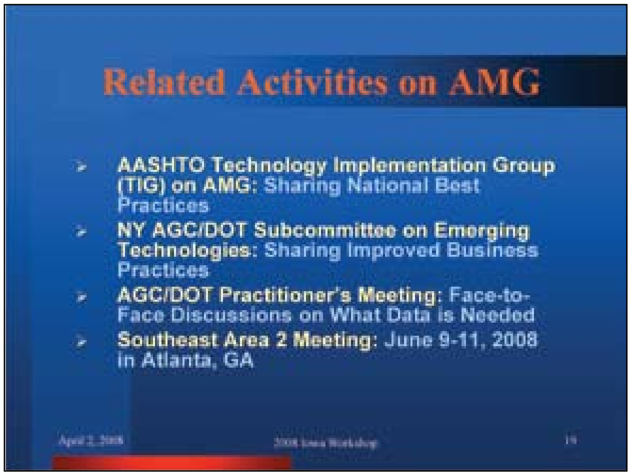
Related Activities on AMG
AASHTO Technology Implementation Group (TIG) on AMG: Sharing National Best Practices
NY AGC/DOT Subcommittee on Emerging Technologies: Sharing Improved Business Practices
AGC/DOT Practitioner's Meeting: Face-to-Face Discussions on What Data is Needed
Southeast Area 2 Meeting: June 9-11, 2008 in Atlanta, GA
April 2, 2008
2008 Iowa Workshop
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Summary
1. Contractors and DOT Find AMG:
More Productive, Saves
Safer and Greener
Higher Quality Products
2. DOT Inspectors Find GPS:
Faster Measurements
More Accurate Positions
Independent Results
3. Contractors & DOT Find EED:
Real World Data – ID's 3D Issues
Expedites Quantities & Payments
Reduces Errors, Increases Accuracy
Increases Trust & Confidence
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20


Questions or Comments?
Contact:
Daniel Streett, PE & LS
DSTREETT@DOT.STATE.NY.US
518-485-8227
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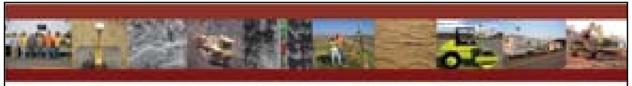
2008 Iowa Workshop
21



Earthworks Engineering Research Center

EERC

David J. White, Ph.D.
EERC Director
Wegner Professor of Civil Engineering
Geotechnical/Materials Division Leader
djwhite@iastate.edu

ctre

Iowa State University

Opportunity for Advancement…

- "The type and scope of geotechnical problems are changing, yet geotechnologists are for the most part not prepared for these changes." (NRC 2006)
- *"One of the greatest challenges that professionals in the geo-construction industry face is delivering dependable, reliable and cost efficiently designed and constructed "products"…" (ADSC 2005)*
- *"Addressing nation's 1.6 trillion infrastructure crisis … "(ASCE 2005).*

Thinking outside the box…GeoConE

- "The problems geo-engineers solve are important to society, and the current technological constraints are in many cases less likely to be solved by beating them with old approaches than they are to be cracked by new technologies and more interdisciplinary approaches…" (NRC 2006)
- *Geo-engineers and construction engineers should look to entirely new technologies and approaches to solve problems faster, better, cheaper.*

Geo-Construction Engineering
– 1st in the Nation

Earthworks Center – Business Model

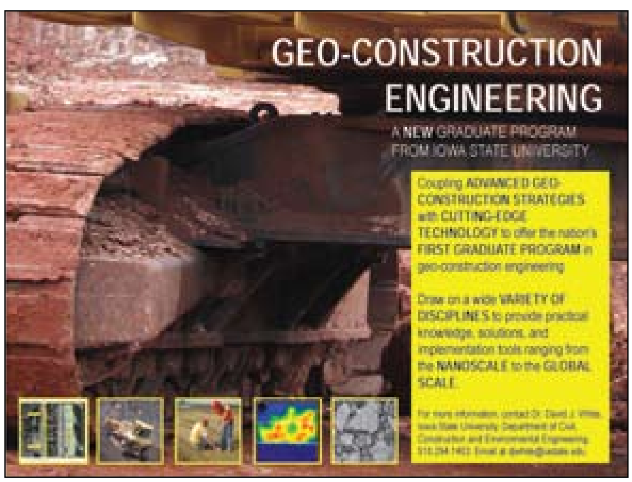
- Vision
- Mission
- Focus
- Objectives
- Executive Board of Directors
- **Scientific and Policy Advisory Council**
- Sustaining Research Partners

Contact me with questions!

Dr. David J. White, Iowa State University, Department of Civil, Construction and Environmental Engineering, 515.294.1463. Email at djwhite@iastate.edu

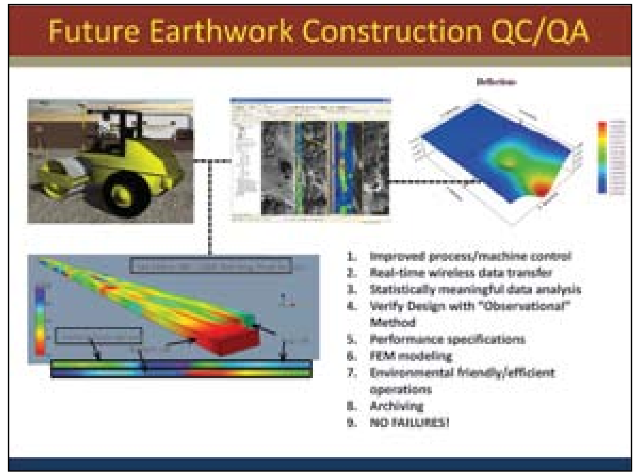
Strategies for Success

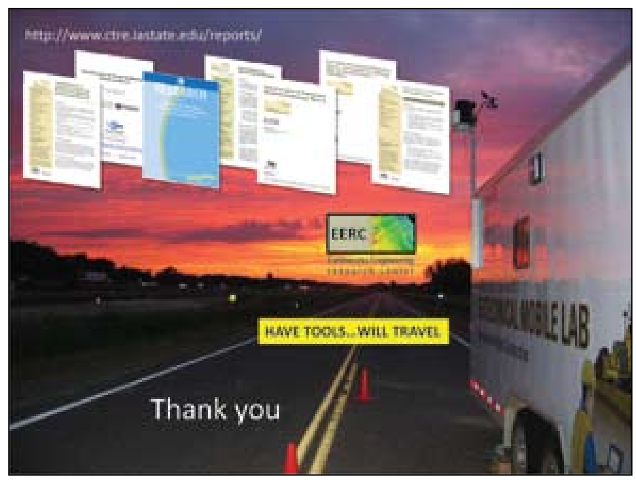
- Earthworks Engineering Research Center (EERC)
  - Innovative and Collaborative Research + Key Stakeholders+ Policy Changes + Education = Success
- Geo-Construction Engineering Academic Program
- Infrastructure Development
- Strategic Research Initiatives
  - Construction efficiency and innovation (e.g., TPF 1188)
  - National security (e.g. JRAC)
  - Mitigation of natural hazards
  - Frontier exploration and development



Earthworks Engineering Research Center

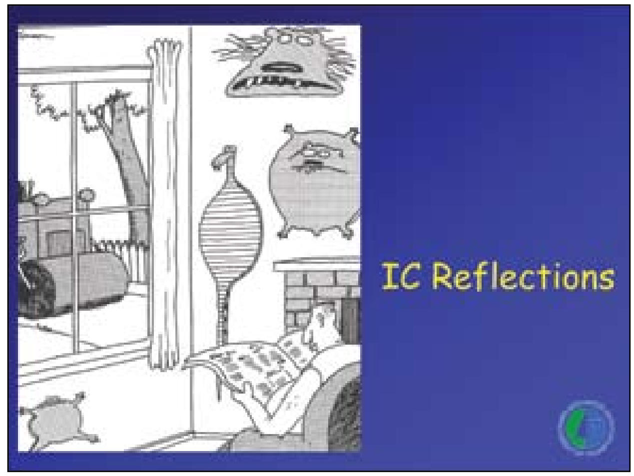
David White

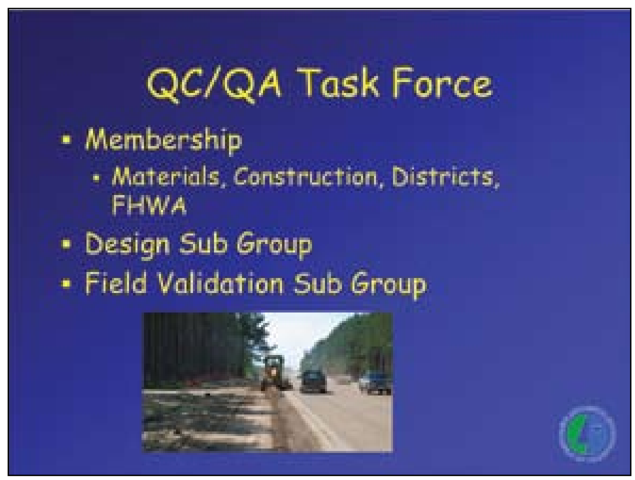




Intelligent Compaction at Mn/DOT

Glen Engstrom, Craig Collison, and Art Bolland





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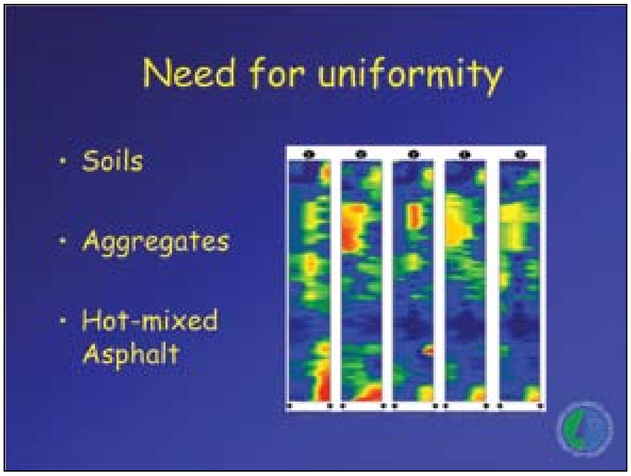
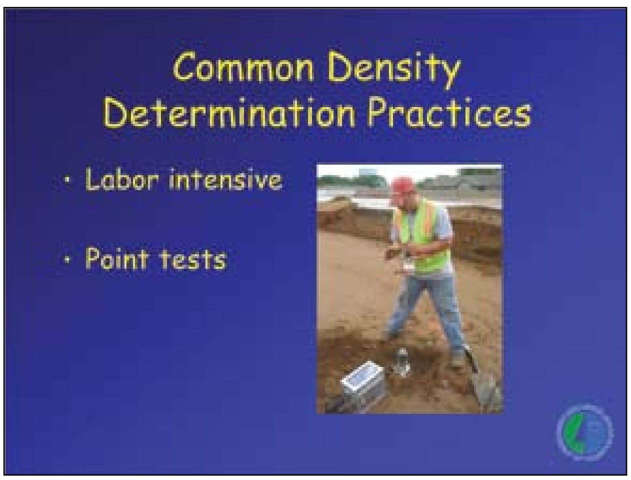
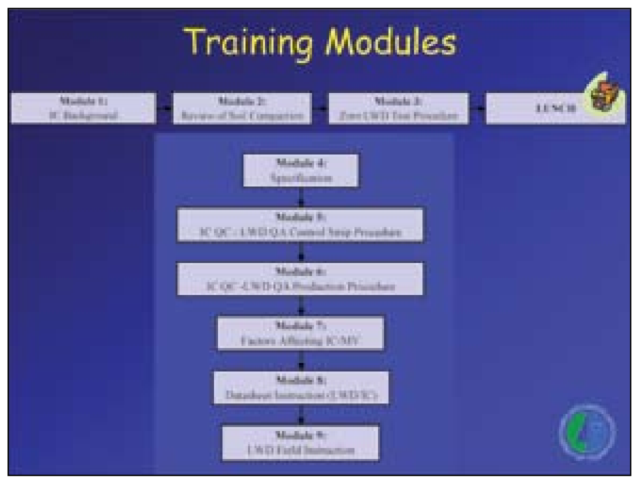


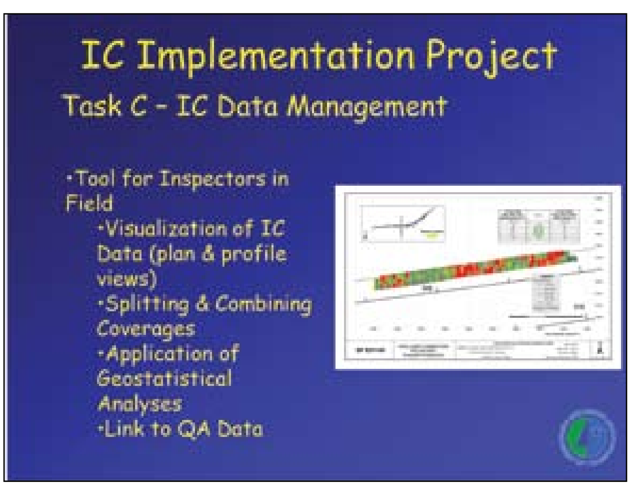



IC Implementation Project
• Task A – Monitor and Implement
- MnDOT Staff Time


IC Implementation Project
Task B – IC Validation Equipment
- LWD's, moisture, wireless, etc.


IC Implementation Project
Task C – Training
- Curriculum
- Field Training
08/01/2007


Training Modules


IC Implementation Project
Task C – IC Data Management
•Tool for Inspectors in Field
•Visualization of IC Data (plan & profile views)
•Splitting & Combining Coverages
•Application of Geostatistical Analyses
•Link to QA Data

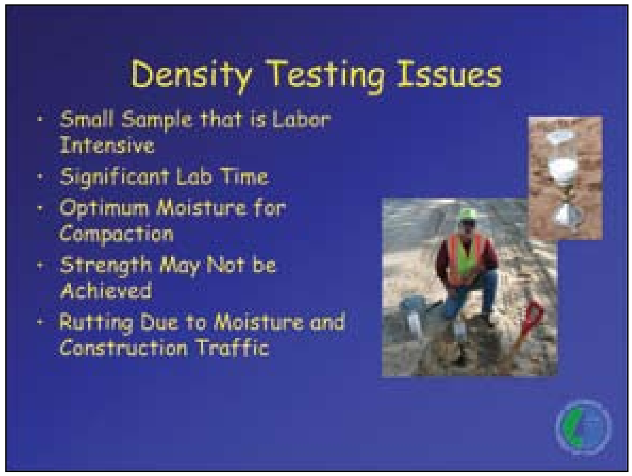

IC Implementation Project
• Task D – Refine and Develop Specs
- Eliminate control strips
- Develop target values for IC and LWD
- IC for non-granular
- Calibration procedures
- Future specifications (Statistically based)

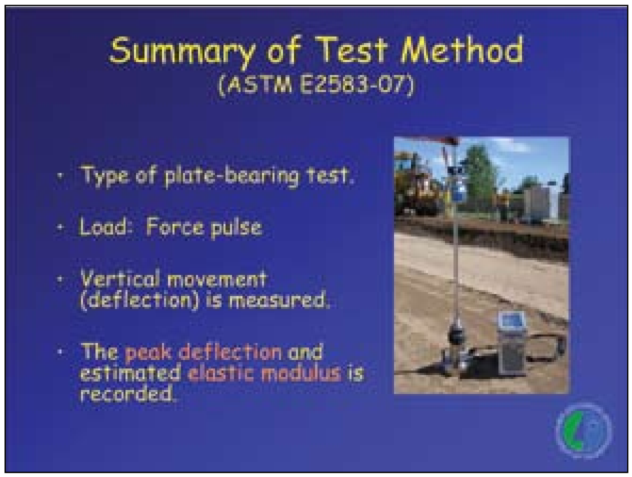
Intelligent Compaction at Mn/DOT

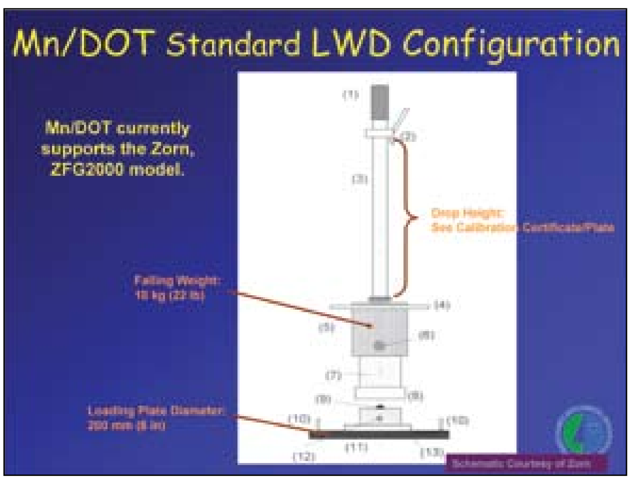
Glen Engstrom, Craig Collison, and Art Bolland

Intelligent Compaction at Mn/DOT

Glen Engstrom, Craig Collison, and Art Bolland







Intelligent Compaction at Mn/DOT

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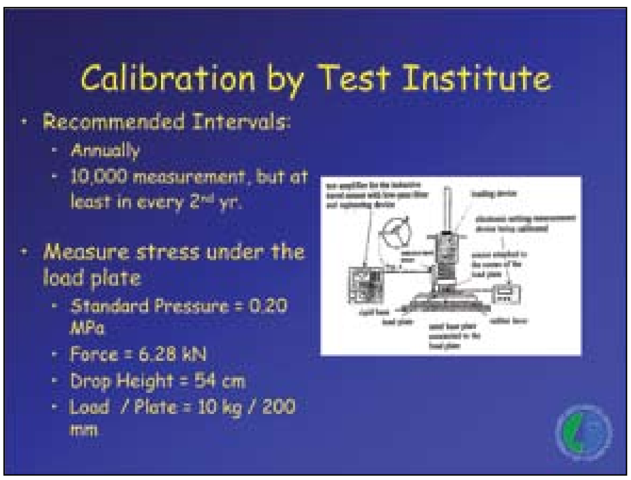
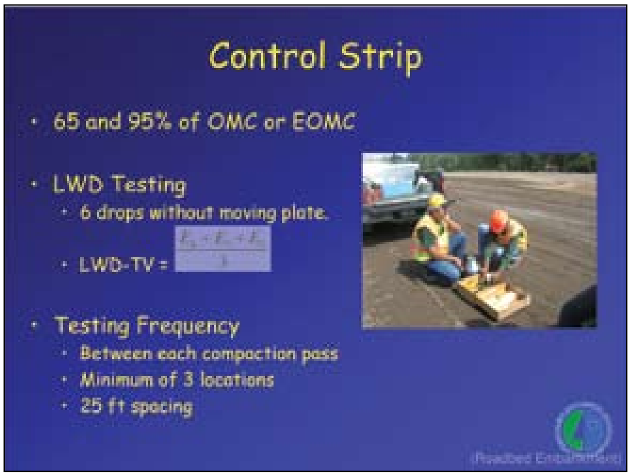


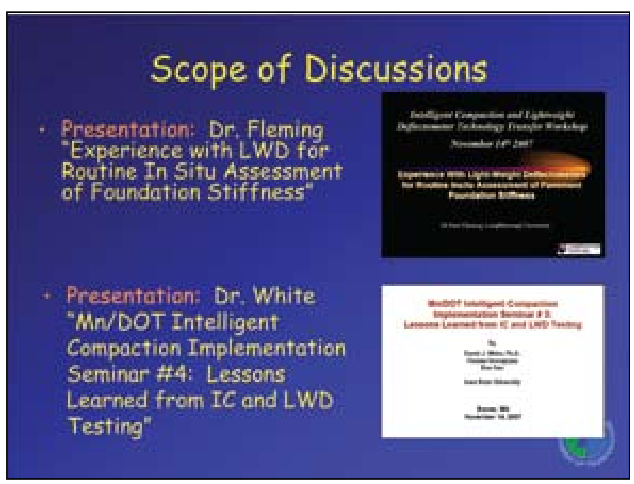

Control Strip
65 and 95% of OMC or EOMC
LWD Testing
6 drops without moving plate.
LWD-TV =
Testing Frequency
Between each compaction pass
Minimum of 3 locations
25 ft spacing
(Roadbed Embankment)


Acceptance Testing
Testing Lot
1000 ft length
Embankment Width
1 ft increments
Minimum 3 / nominal vertical increment / testing lot
Acceptance
E_i ≥ 0.90*LWD-TV
Corrections as needed
Re-test
E_i > 1.20*LWD-TV
Re-evaluate LWD-TV selection
Construct new control strip
(Roadbed Embankment)


Typical Zorn LWD Values
Soil Type | LWD Modulus (MPa)
Sand w/ Silt | 20-30
Silty gravel w/ sand | 30-35
Silty sand w/ gravel | 30-35
Poorly graded gravel | 40-45
Silty sand | 15-20
Clayey gravel | 30-40
Well graded sand w/ silt | 25-35


2008 LWD Quality Compaction Projects
17 Projects to Date - 2008
9 Projects - 2007
15 LWDs


Light Weight Deflectometer Technology Transfer Workshop
Baxter, Minnesota (November 14, 2007)
Attendees: Project & Resident Engineers, Inspectors, Materials Engineer


Scope of Discussions
Presentation: Dr. Fleming "Experience with LWD for Routine In Situ Assessment of Foundation Stiffness"
Presentation: Dr. White "Mn/DOT Intelligent Compaction Implementation Seminar #4: Lessons Learned from IC and LWD Testing"

Intelligent Compaction at Mn/DOT

Glen Engstrom, Craig Collison, and Art Bolland

Positive Characteristics

- Quick and Easy
- Inspector Remains on Grade
- Made Contractor more aware of what is needed for acceptance
- Better understanding of water content and processes.
- Improved Uniformity
- Improved over DCP
  - Quicker
  - Contractor better understands results
- Reliable Measurements
  - (e.g., 199 LWD tests out of ~ 200 matched those of the DCP).

Technology Transfer Continuum

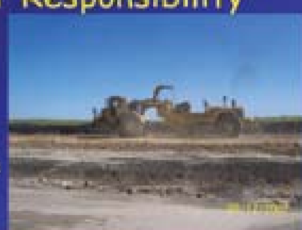
Troubles / Concerns

- Difficult portability in utility trenches.
- Can be a 2 person job.
- Not "light" weight.
- Water table can be drawn up and affect results.
- Set up of soil (soil curing) / bridging. Need to remove crust on clay prior to testing.
- LWD will move if sand is too wet and sloped.
- Need to level plate.
- Unable to obtain consistent LWD results with only 1 ft of sand above grade.

Technology Transfer Continuum

QC Contractor Responsibility

- Moisture testing and control was a continual battle.
- Contractor personnel are interested and asking for LWD values.



- Contractor is learning that scrapers should be run in different spots to achieve passing values compaction.

Technology Transfer Continuum

Changes Next Year

- Procedures need to be flexible, but balanced with the ability to enforce.
- Test on "surface" of aggregate base.
- Control strips need to be eliminated.
- Better if "over-built" and then dug down for testing with some confinement.

Technology Transfer Continuum

Some Keys to Success

- Know Your Organization
- Who makes the decision
- Beware of the pessimist and the optimist
- Find people that you know and will work with you
- Don't hold new technology to a higher standard
- Select Low Hanging Fruit
- You need to find your Rebecca
- Select "simple" projects
- Communication

Mn/DOT's Lessons Learned

- Operators learn how to make better decisions.
- IC roller must maintain contact across the drum to produce valid data (ie level surface)
- Soft areas can be identified and corrected earlier.

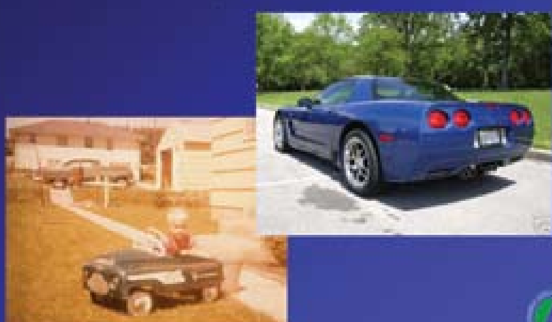
Mn/DOT's Lessons Learned

- Works well on grannular, 20% or less passing the #200.
- Produces a LOT of data – transfer and analysis methods need to be improved.
- Able to quantify grade stiffness variability

IC Future

- Continue to refine specifications
- Improve connection between field values and design criteria
- Create real-time data monitoring system
- Integrate data into construction quality system
- Monitor long-term pavement performance at IC projects

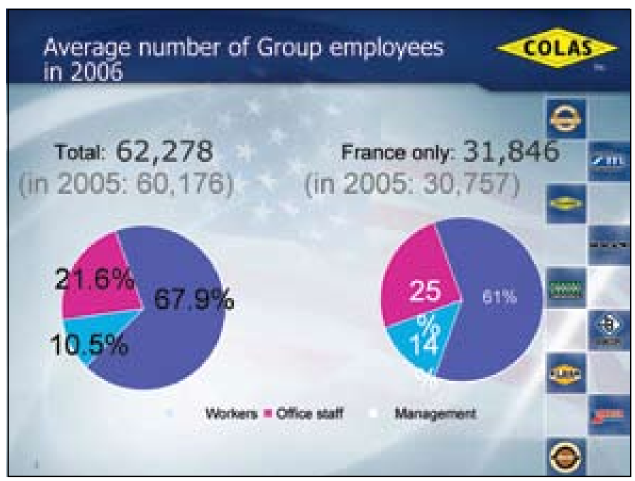
Questions?

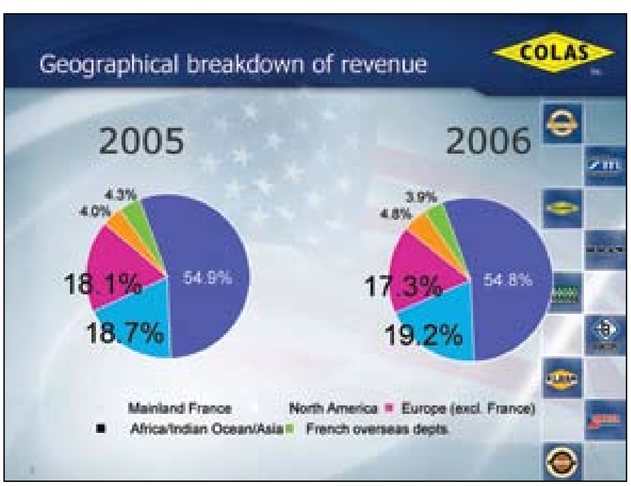


Thank You!

European Experiance with ICS

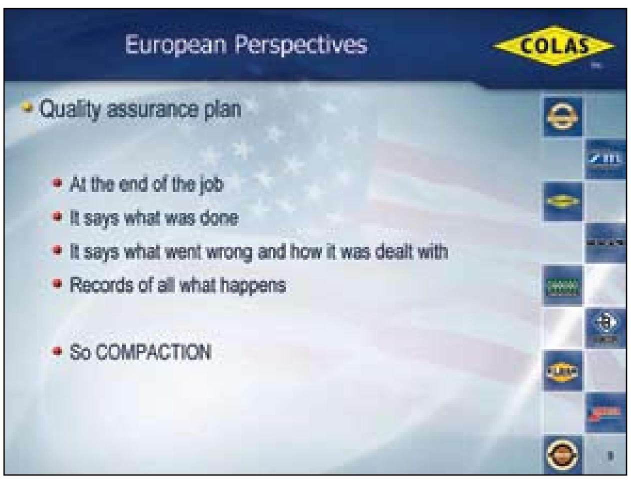
François Chaignon

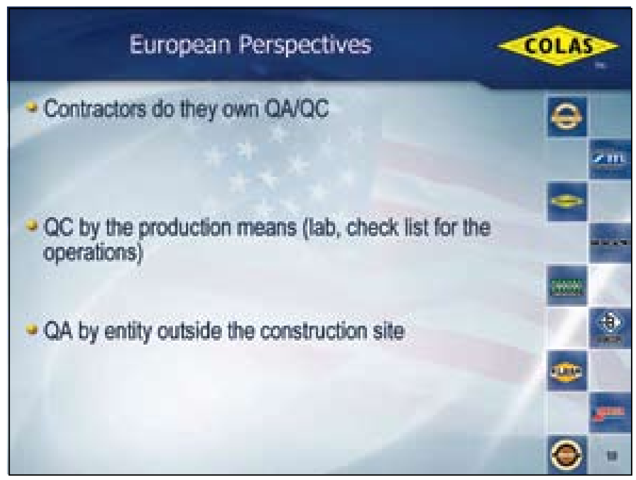


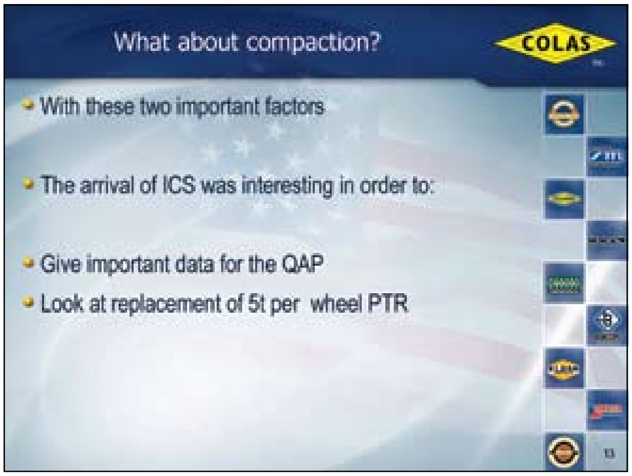


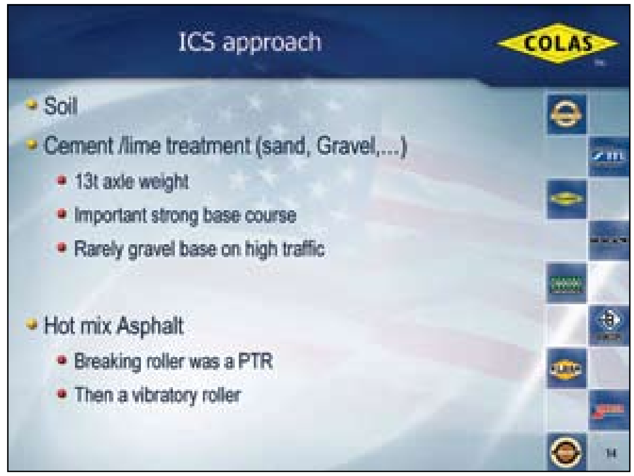
European Experiance with ICS

François Chaignon





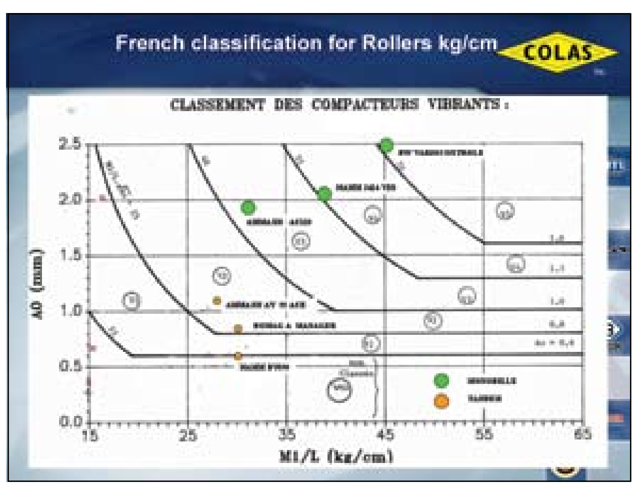

What about compaction?
COLAS
With these two important factors
The arrival of ICS was interesting in order to:
Give important data for the QAP
Look at replacement of 5t per wheel PTR
13


ICS approach
COLAS
Soil
Cement /lime treatment (sand, Gravel,...)
13t axle weight
Important strong base course
Rarely gravel base on high traffic
Hot mix Asphalt
Breaking roller was a PTR
Then a vibratory roller
14


AMMAN
COLAS

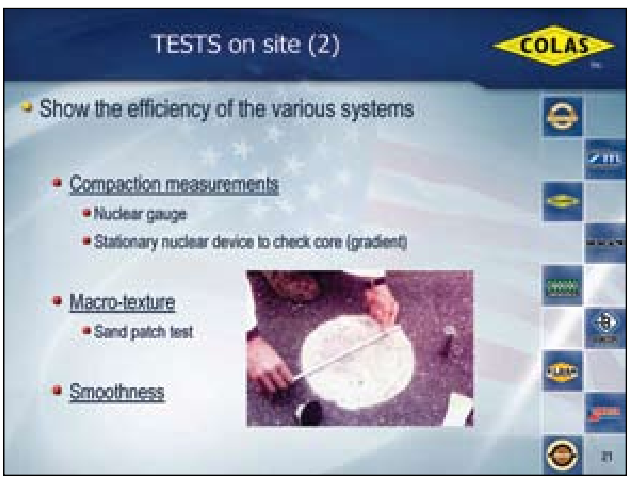

BOMAG
COLAS

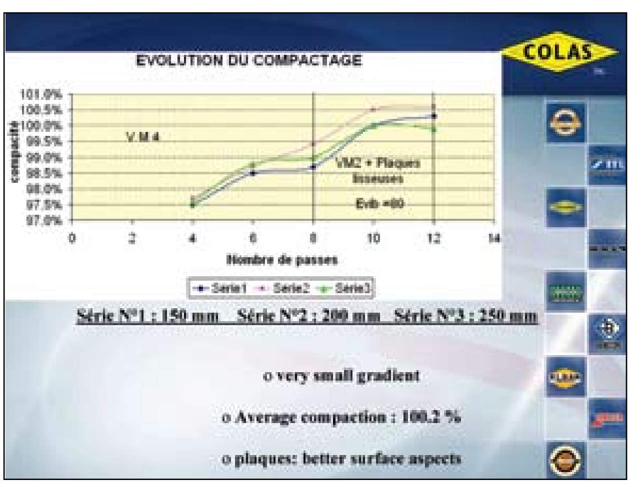

HAMM
COLAS


French classification for Rollers kg/cm
COLAS
CLASSEMENT DES COMPACTEURS VIBRANTS :
A0 (mm)
2.5
2.0
1.5
1.0
0.5
0.0
15
25
35
45
55
65
M1/L (kg/cm)

European Experiance with ICS

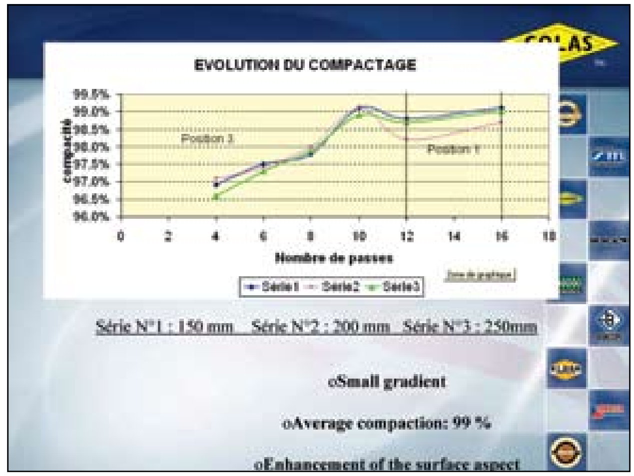
François Chaignon

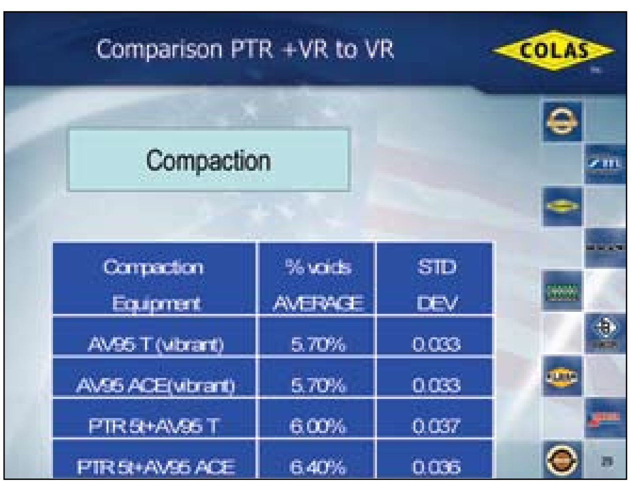


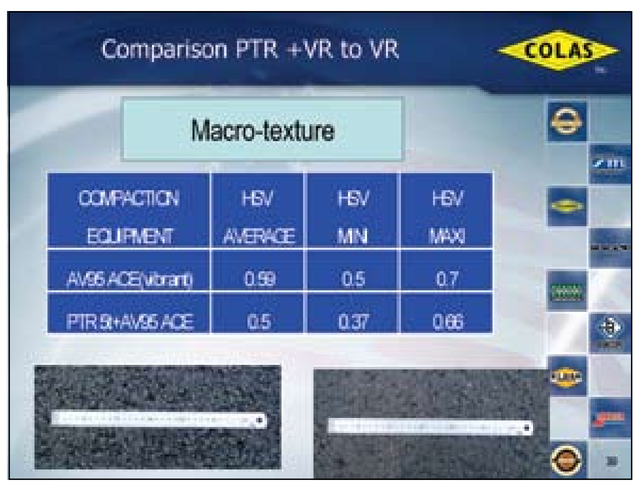


European Experiance with ICS

François Chaignon

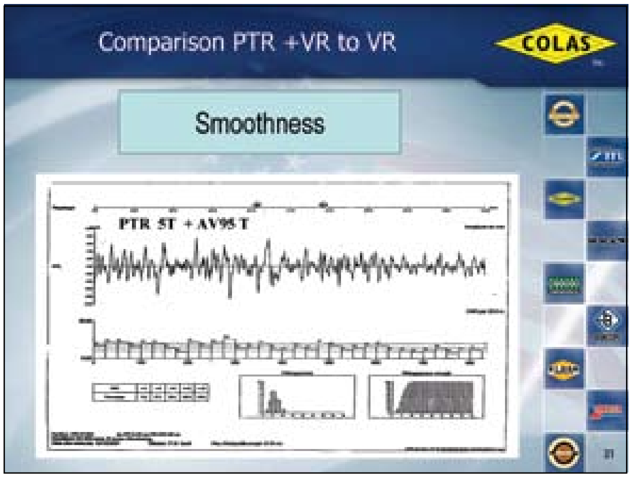


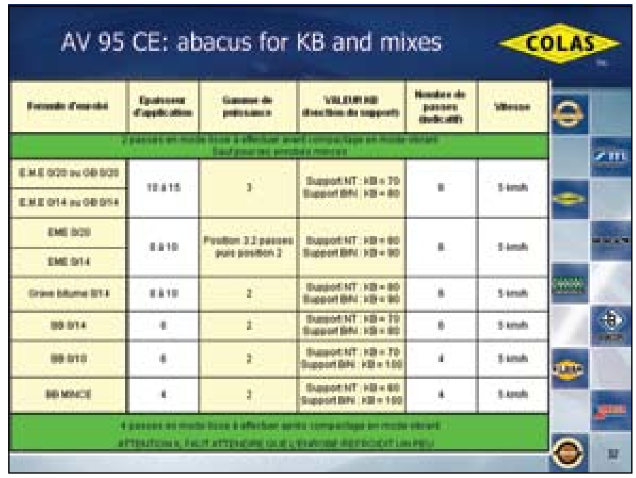


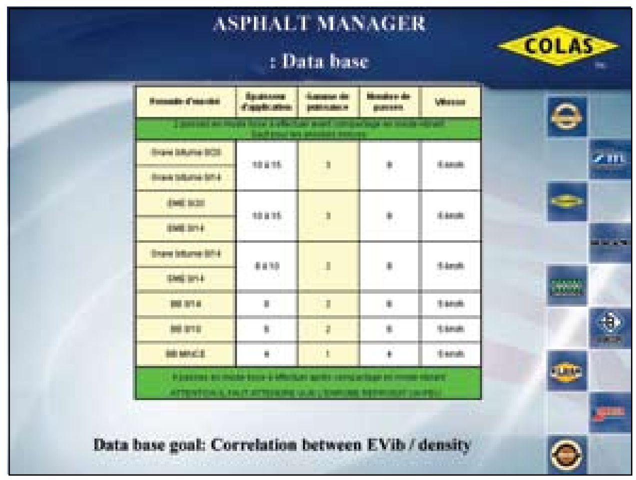


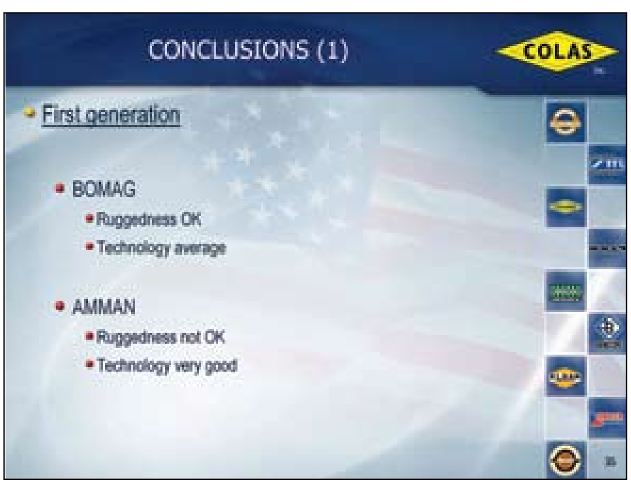
European Experiance with ICS

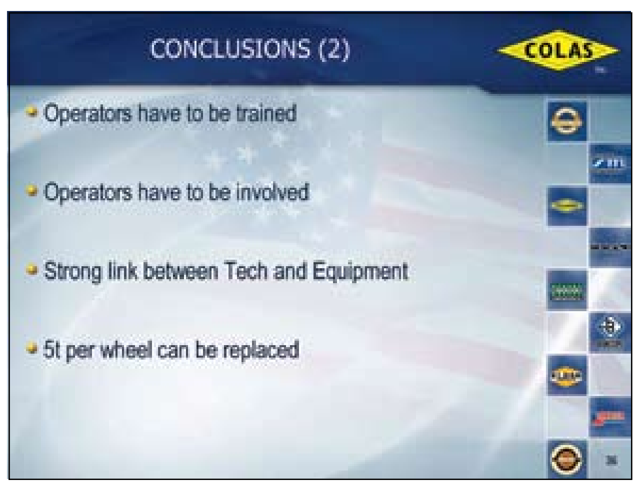
François Chaignon

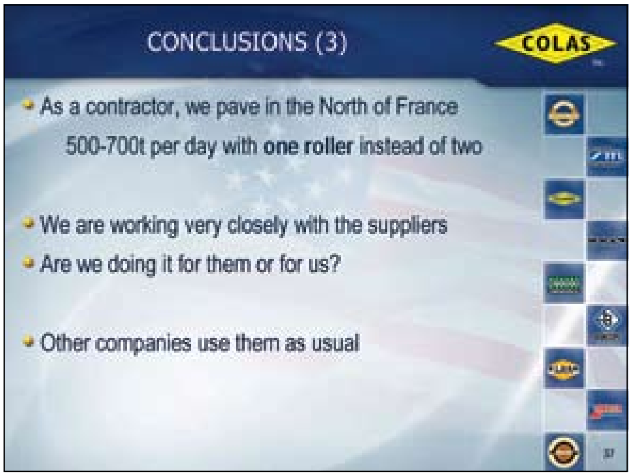


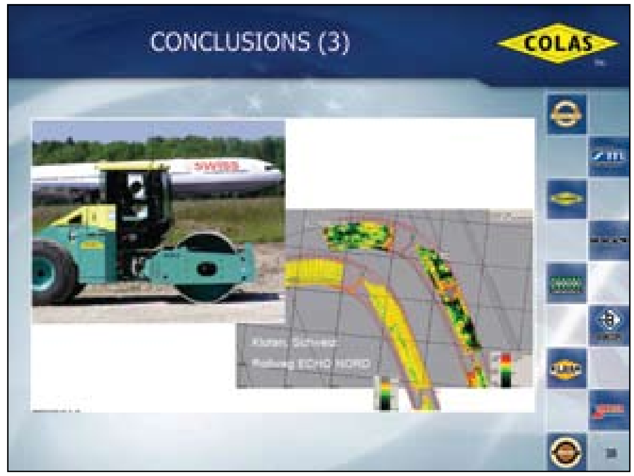









CONCLUSIONS (3)
COLAS
As a contractor, we pave in the North of France
500-700t per day with **one roller** instead of two
We are working very closely with the suppliers
Are we doing it for them or for us?
Other companies use them as usual
37


CONCLUSIONS (3)
COLAS
SWISS
Kloten, Schweiz
Rollweg ECHO NORD
38


Thank you for your attention
COLAS
Any Questions?
39

Intelligent Compaction for Soil and Asphalt

Dean Potts

Intelligent Compaction for Soil and Asphalt

Dean Potts - Engineering Manager

Advanced Design Group

The AccuGrade ® Connected Work Site

AccuGrade® Technologies

AccuGrade® Cross Slope
Controls the slope of the blade to maintain desired surface cross slope.

AccuGrade® Sonic
Maintains the blade at a vertical distance to an external reference.

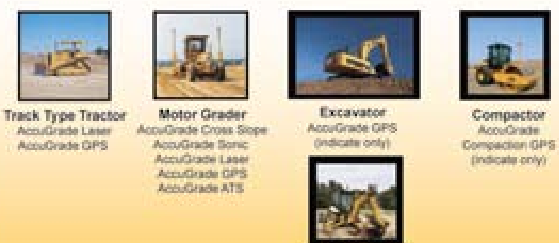
AccuGrade® Laser
Provides constant elevation information for accurate blade positioning.

AccuGrade® ATS (Advanced Tracking System)
Instrument tracks a on-board target for precise 3D positioning.

AccuGrade® GPS
Compares the blade position to a 3D computerized site plan.

AccuGrade® Site Reference System
Allows the operator to set target grades relative to points on the work-site.

AccuGrade ® Product Line



AccuGrade® Office

- •Converts engineering design files to AccuGrade compatible format
- •Supports wireless communication between the machine and office
- •Allows "drill-down" of compaction data
- •Compatible with all AccuGrade machines
- •Supports text messaging in real time with operator
- •Productivity module for cycle times, as-built data, and production related information
- •Compaction module for detailed compaction analysis

AccuGrade® Office

Compaction Module

•Allows inspectors to analyze compaction date by providing a detailed view of the various layers, passes, and CCV's of the designated compaction area.

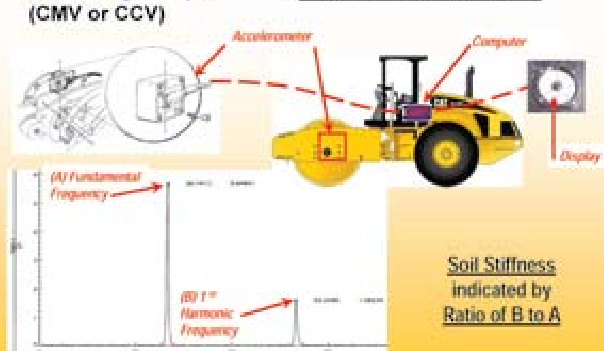
•The module saves and enables the inspector to view the time, date and location of compaction information such as…

- CCV/layer	- RMV
- CCV/pass	- Amplitude
- Thickness/pass	- Direction of travel
- Thickness/layer	- Vibration state

Four Types of Compactor based Compaction Measurement.

1. **The Compaction Meter Value method (CMV & CCV)**
   - Drum mounted accelerometer measures G-force at vibratory frequency and harmonics. (typically vertical accelerations only)
   - Signals can be used to control amplitude of drum.
2. **The Force vs Displacement method. (E-vib, Kb)**
   - Drum mounted accelerometers/position sensors.
   - Signals can be used to control drum amplitude and frequency.
3. **The Energy or Machine Drive Power (MDP) method.**
   - Measures driveline power used to roll over soil or asphalt with corrections made for grade and machine acceleration.
   - Works on both vibratory and non-vibratory compactors.
4. **Pass Count and Temperature Measurement (asphalt)**

Measuring Compaction via Compaction Meter Value (CMV or CCV)



Soil Stiffness indicated by Ratio of B to A

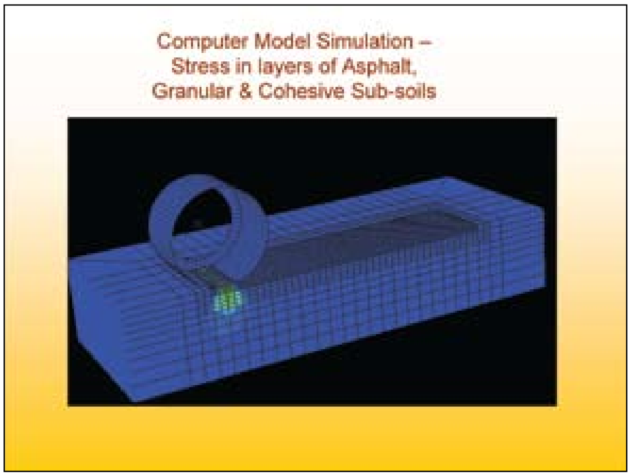
CAT AccuGrade ® Compaction – CMV (CCV)

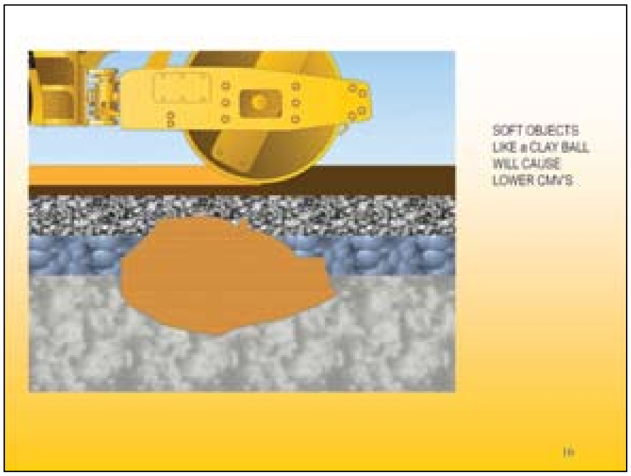
Operator Display

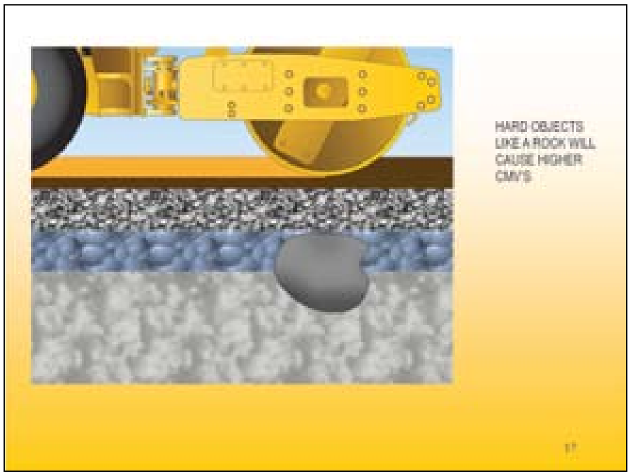
Operator Display


Operator Display
CAT


Operator Display
CAT


Computer Model Simulation –
Stress in layers of Asphalt,
Granular & Cohesive Sub-soils

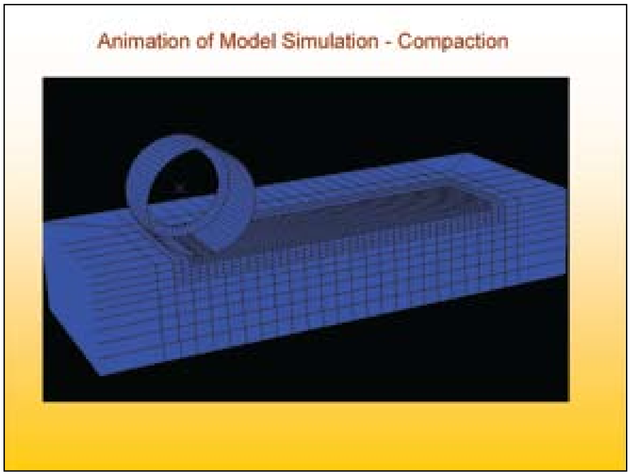

SOFT OBJECTS
LIKE a CLAY BALL
WILL CAUSE
LOWER CMV'S

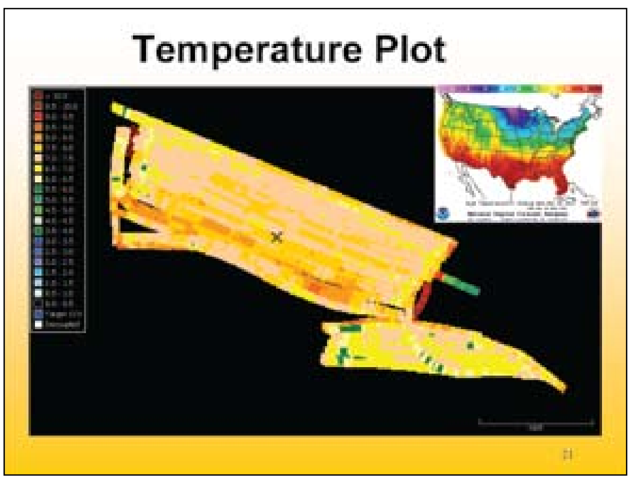

HARD OBJECTS
LIKE A ROCK WILL
CAUSE HIGHER
CMV'S

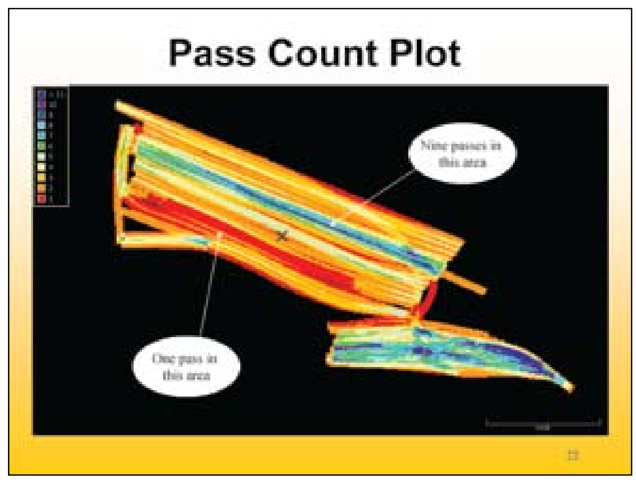

CP-563E with Machine Drive Power

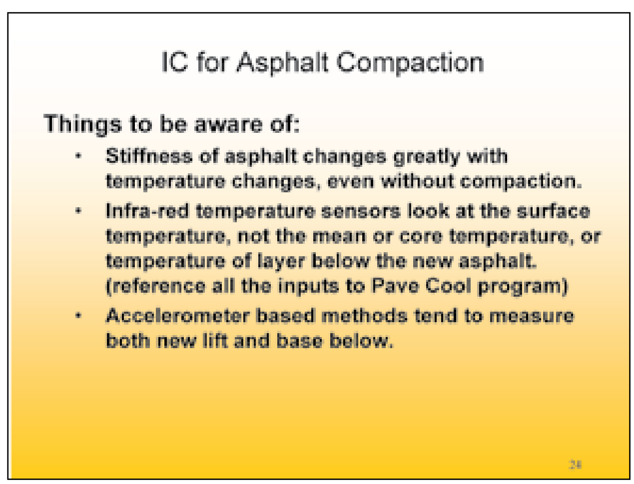
Intelligent Compaction for Soil and Asphalt

Dean Potts









Asphalt Manager, Intelligent Compaction

Chris Connolly

BOMAG

Asphalt Manager
Intelligent Compaction

ASPHALT-MANAGER E_{VIB}

Best for COMPACTION

BOMAG

WHAT IS INTELLIGENCE

1) Collect Information

2) Use the Collected Information to Make a Decision

3) Execute the Decision

BOMAG — History

Surface Covering Compaction Measurement

- 1983 Terrameter BTM 01 (OMEGA)
- 1993 Guidelines for Surface Covering Measurements National Research Association
- 1994 ZTVE / TP BF-StB 94, proof methods FDVK/ SCCC
- 1996 Compaction Management System BCM 03
- 1998 VARIOCONTROL
- 2001 Measuring device for evaluation of stiffness (Evib)
- 2004 Modular Measuring System with GPS support

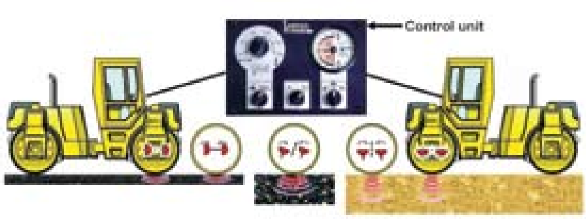
BOMAG — History

BOMAG Compaction Technology

1996	Variomatic for asphalt rollers
1998	Variocontrol for soil rollers
2000	Evib (MN/m^2)
2001	Asphalt Manager
2004	Research project of German DOT (BAST), Oct / Nov. 2004;

BOMAG

VARIOMATIC roller with directed vibration



low dynamic energy

Compaction principle
static pressure and dynamic energy which is automatically adjusted to type of material, compactibility, layer thickness and base layer conditions.

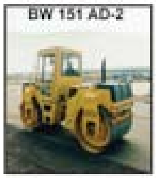
high dynamic energy

Applications: asphalt layers, granular bases and subbases.

BOMAG — Asphalt Manager

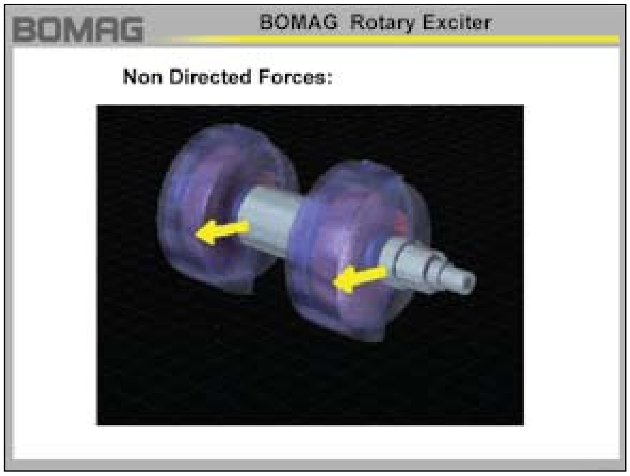
Worldwide proven design:

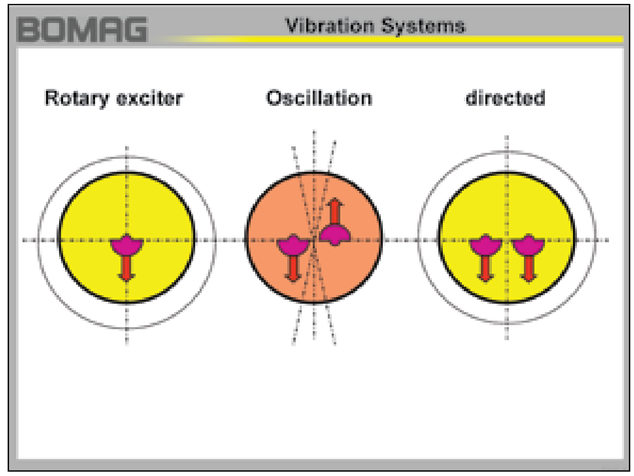
Several hundreds Tandem rollers

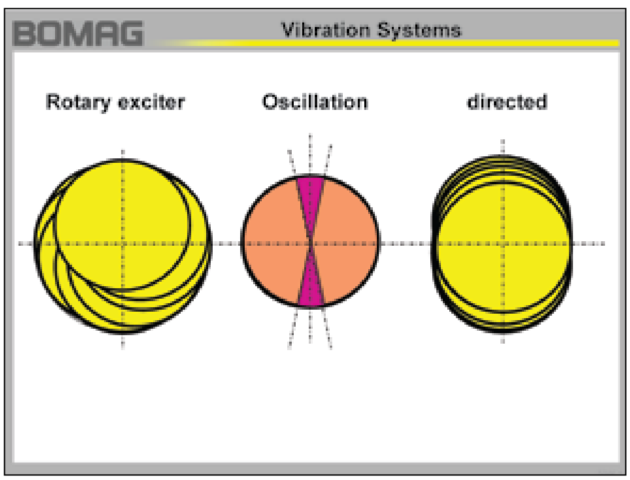


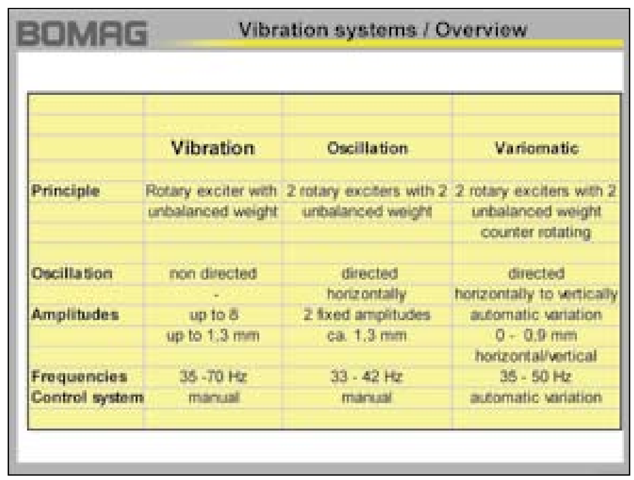
Asphalt Manager, Intelligent Compaction

Chris Connolly

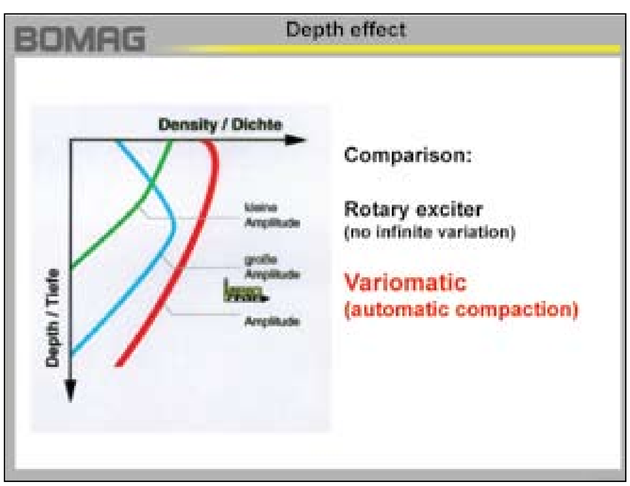


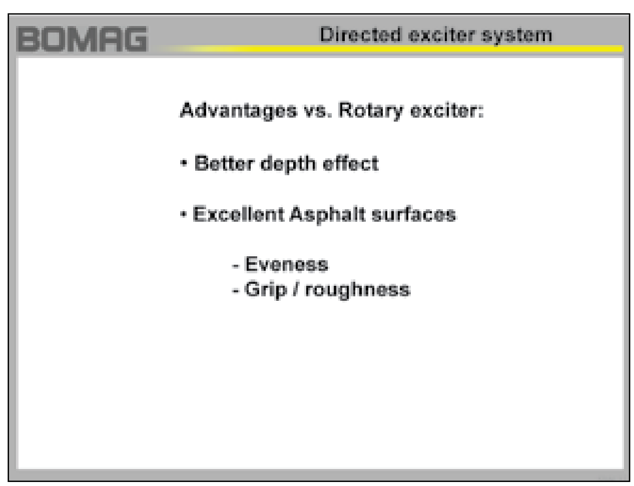






	Vibration	Oscillation	Variomatic
Principle	Rotary exciter with unbalanced weight	2 rotary exciters with 2 unbalanced weight	2 rotary exciters with 2 unbalanced weight counter rotating
Oscillation	non directed	directed	directed
	-	horizontally	horizontally to vertically
Amplitudes	up to 8	2 fixed amplitudes	automatic variation
	up to 1,3 mm	ca. 1,3 mm	0 - 0,9 mm
			horizontal/vertical
Frequencies	35 -70 Hz	33 - 42 Hz	35 - 50 Hz
Control system	manual	manual	automatic variation





Asphalt Manager, Intelligent Compaction

Chris Connolly

BOMAG

Asphalt Manager

Benefits for contractors:

- Universal use on
  - Road base
  - Wearing course layers
  - Thin layers
- Higher compaction performance
- Uniform compaction, even on sub-bases with inhomogeneous stiffness
- Better eveness and more uniform surface structure
- Low tendency to scuffing

BOMAG

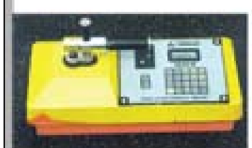
Compaction of 6 cm asphalt binder course 0/10, RN13 France
Operating weight and compaction technique affect smoothness and eveness

15 t tandem vibratory roller
8 passes

8 t BOMAG VARIOMATIC BW 151 AD
8 passes

BOMAG

Density and roughness measurement on asphalt binder layer



Punctual compaction measurement with portable isotope probe

Continuous compaction measurement with mobile isotope probe [1 measurement / 10 m]

BOMAG

Comparison between conventional compaction concept and VARIOMATIC

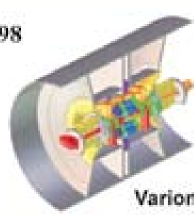
	Compaction						Roughness		
	Portable isotope probe			Mobile isotope probe [1 measurem./10 m]			Sand spot method		
	n	X1	σ	n	X1	σ	n	X2	σ
4 passes with 25 t rubber tire roller and 4 passes with 15 t tandem vibratory roller	14	92,5 %	1,22	59	94,6 %	1,29	12	0,46 mm	0,07
8 passes with BW 151 AD-2 VARIOMATIC	14	92,5 %	0,54	59	93,8 %	1,06	12	0,60 mm	0,05

n = number of measurements, X1 = mean value of achieved Gyrator test compaction value (93% Gyrator value ~ 98% Marshall value), X2 =mean value of characteristic roughness value

BOMAG

1996

1998



Variomatic 2

advanced, more powerful

also for split drums !

BOMAG

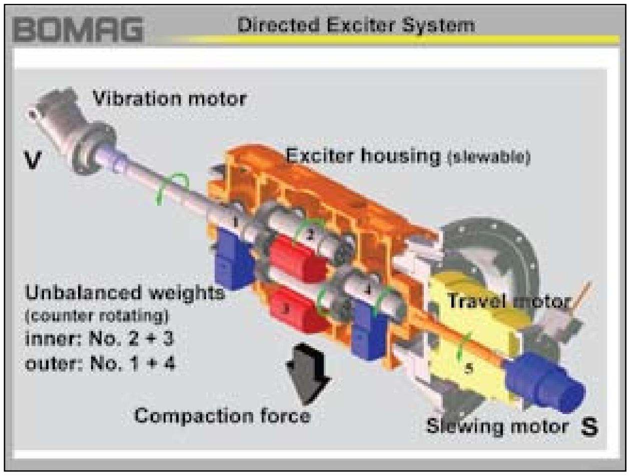
Latest developments of compaction technology

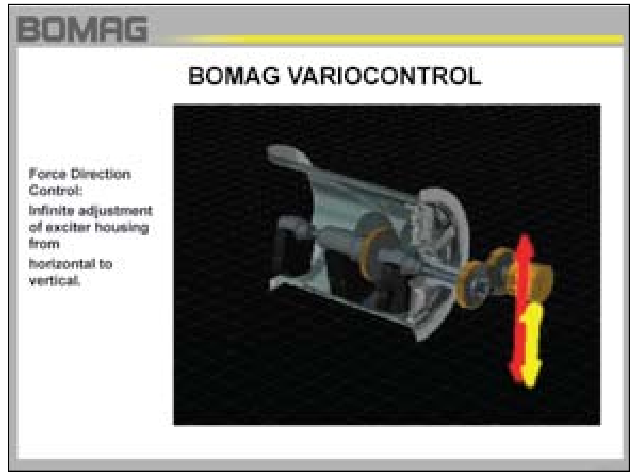
1996 Variomatic for asphalt rollers

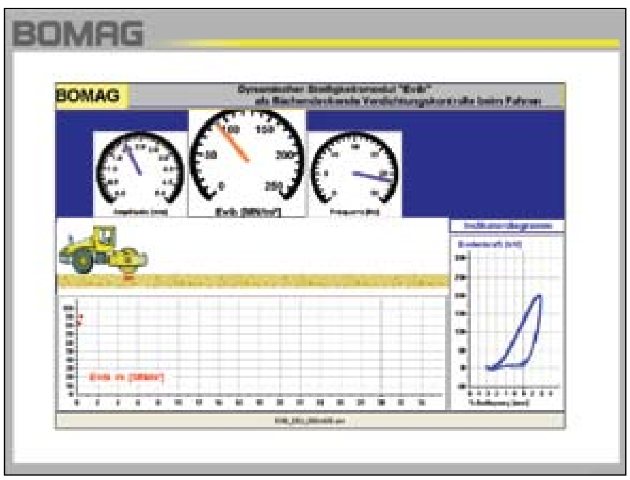
1998 Variocontrol for soil rollers

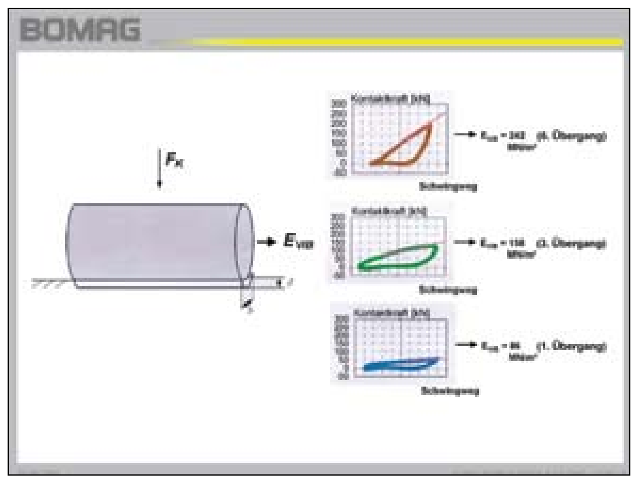
2000 Evib (MN/m²)

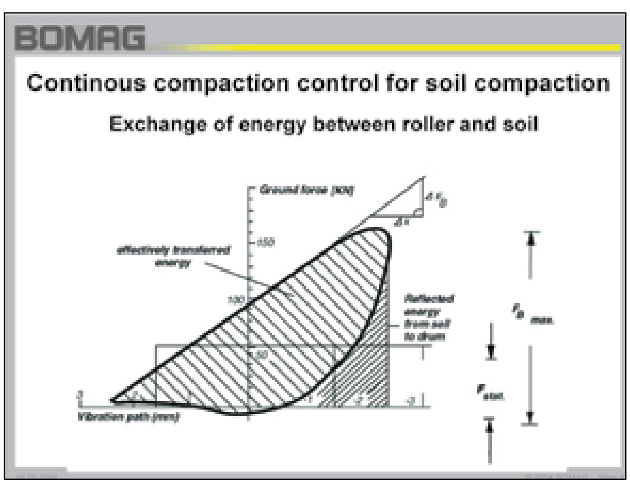
2001 Asphalt Manager

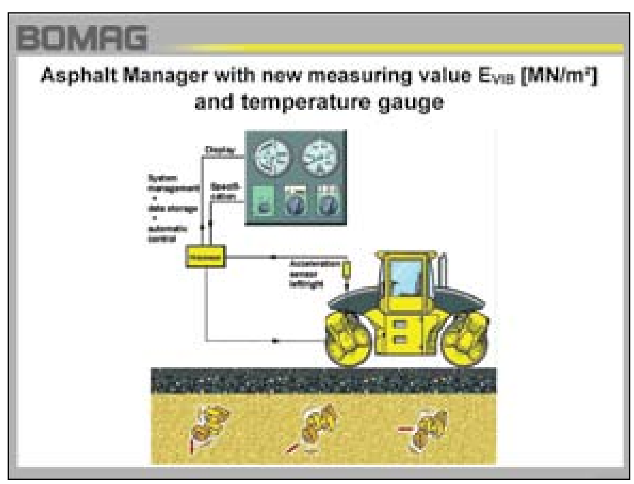

BOMAG
Directed Exciter System
Vibration motor
V
Exciter housing (slewable)
Unbalanced weights
(counter rotating)
inner: No. 2 + 3
outer: No. 1 + 4
Travel motor
Compaction force
Slewing motor S


BOMAG
BOMAG VARIOCONTROL
Force Direction Control:
Infinite adjustment of exciter housing from horizontal to vertical.


BOMAG
BOMAG

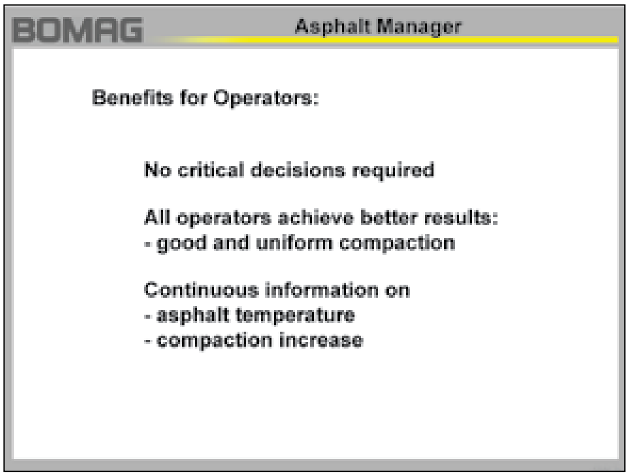

BOMAG

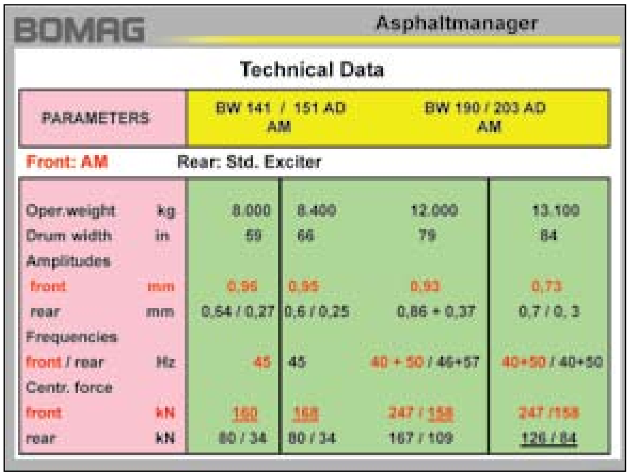

BOMAG
Continous compaction control for soil compaction
Exchange of energy between roller and soil
Ground force [kN]
effectively transferred energy
Reflected energy from soil to drum
Vibration path (mm)


BOMAG
Asphalt Manager with new measuring value E_{VIB} [MN/m²]
and temperature gauge

Asphalt Manager, Intelligent Compaction

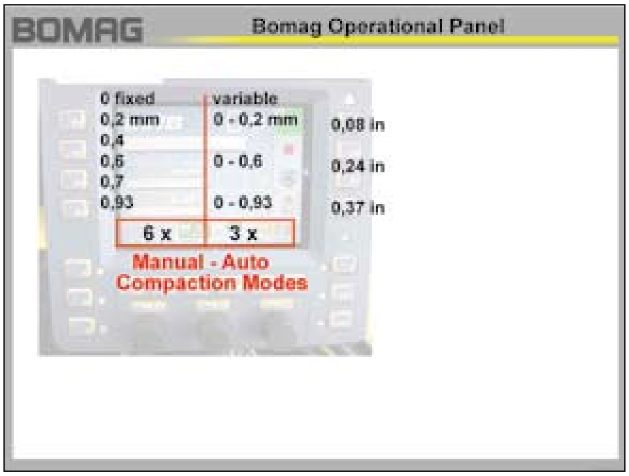
Chris Connolly





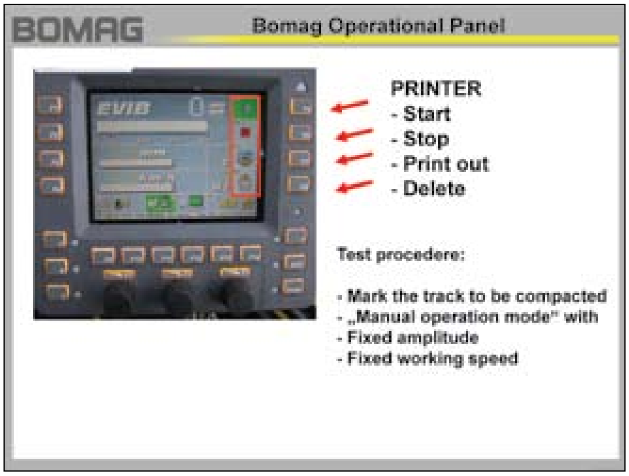
Technical Data

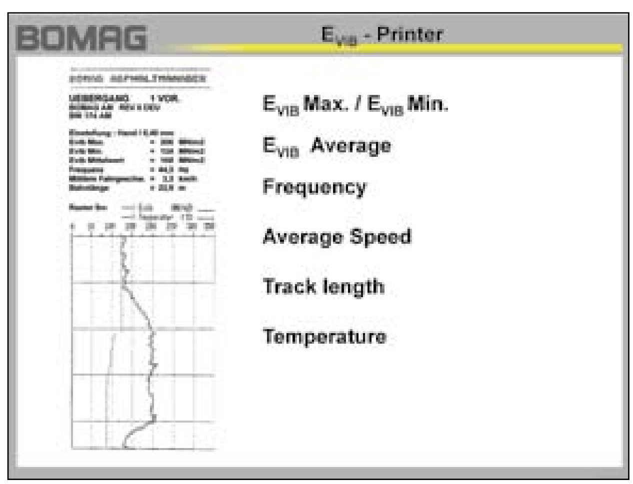
PARAMETERS		BW 141 / 151 AD AM		BW 190 / 203 AD AM	
Front: AM	Rear: Std. Exciter				
Oper.weight	kg	8.000	8.400	12.000	13.100
Drum width	in	59	66	79	84
Amplitudes					
front	mm	0,95	0,95	0,93	0,73
rear	mm	0,64 / 0,27	0,6 / 0,25	0,86 + 0,37	0,7 / 0, 3
Frequencies					
front / rear	Hz	45	45	40 + 50 / 46+57	40+50 / 40+50
Centr. force					
front	kN	160	168	247 / 158	247 /158
rear	kN	80 / 34	80 / 34	167 / 109	126 / 84



Asphalt Manager, Intelligent Compaction

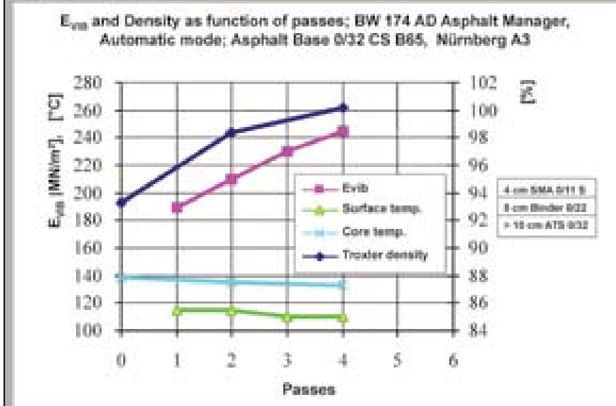
Chris Connolly

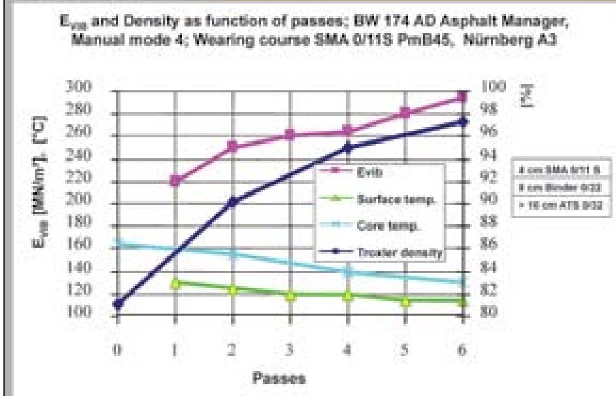




Asphalt Manager, Intelligent Compaction

Chris Connolly





BOMAG — Asphalt Manager

Advantages:

- Immediate determination of dynamic stiffness in MN/m² (E_{VIB})
- E_{VIB} can be correlated with the increase of compaction
- E_{VIB} is widely independent from roller parameters
- E_{VIB} printouts for area covering compaction control

In Development:

- Target E_{VIB} values to be pre-selectable
- „Ready“ indication if target value is achieved (red light)
- „Ready“ indication if no further compaction is possible (red light)

BOMAG — Number of passes with vibratory rollers

Recommended figures:

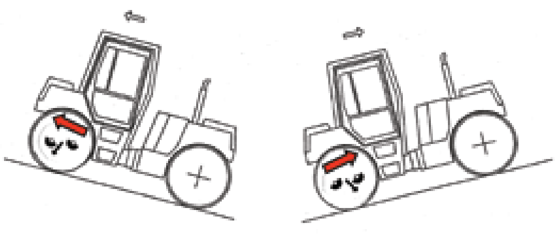
Layer thickness d [cm]	No. of passes with vibration of different tandem rollers		
	3 t	6 t	9 t
2	2 - 4	1 - 2 (L)	1 - 2 (L)
4	4 - 6	2 - 4 (L)	2 - 4 (L)
6	4 - 8	4 - 6 (L)	2 - 4 (L)
10	6 - 8	4 - 8 (L, H)	4 - 6 (L, H)
14	–	6 - 8 (H)	4 - 6 (H)
18	–	6 - 8 (H)	4 - 8 (H)
SMA d = 2	–	1 - 2 (L) + stat. passes	1 - 2 (L) + stat. passes
(Stone mastix) d = 4	–	4 - 6 (L) + stat. passes	4 - 6 (L) + stat. passes
Porous asphalt d = 4	–	1 - 2 (L) + stat. passes	1 - 2 (L) + stat. passes

L = low amplitude, H = high amplitude
3 t = Machine with only the amplitude

Assumption: Compaction temperature > 100°C

BOMAG — VARIOMATIC 2

Further advantages:
better gradability- less shoving effect



Automatic force adaption with travel direction

BOMAG — Asphalt-Manager

Evib (MN/m²) Vibration modulus

Equivalent for dynamic Stiffness;

Directly picked up by the roller;

Physical value for compaction increase on asphalt.

Asphalt Manager, Intelligent Compaction

Chris Connolly

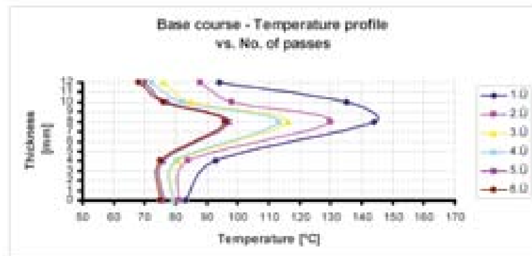
BOMAG **Asphalt Manager**

Benefits for Contractors: Investment for Profit

Compaction
- Uniform and predictable results while rolling
- Avoids under / overcompaction
- Better eveness and roughness
- Eliminates drum bouncing

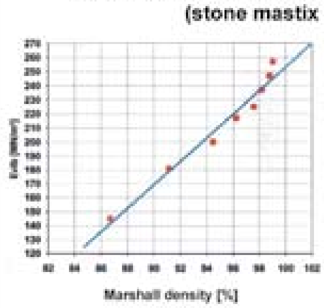
Economical and quality aspects
- More efficient roller utilization with fewer passes
- Reduced shock loads in sensitive environment e.g. buildings, bridges
- Area coverage method

BOMAG **Temperature development**



BOMAG **E_{VIB} [MN/m²] vs. Marshall density [%]**

Compaction test on asphalt wearing course (stone mastix asphalt)

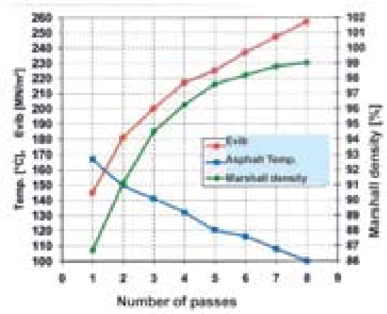


Perfect correlation:
Evib + Marshall density

Adequate conditions:
- Temperature between (170-120 °C)
- Asphalt layer on solid ground

BOMAG

Compaction test on asphalt wearing course (stone mastix asphalt)



Increase of Evib = Increase of compaction

BOMAG **Application**

Comfort + Quality:

Compaction of joints hot against cold
- avoids shock loads
- no bouncing
- better eveness

BOMAG Application

Leipzig:

"Augustusplatz"

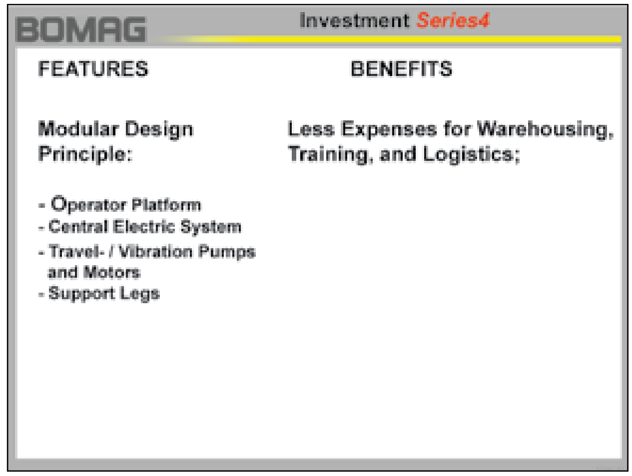
Compaction on a parking roof top;

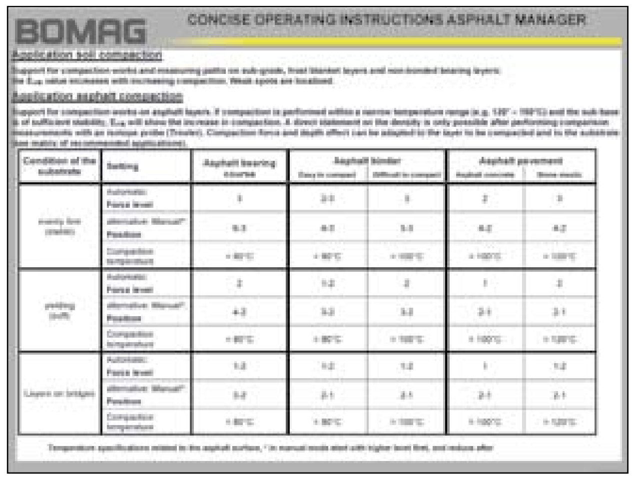
Alternatives:

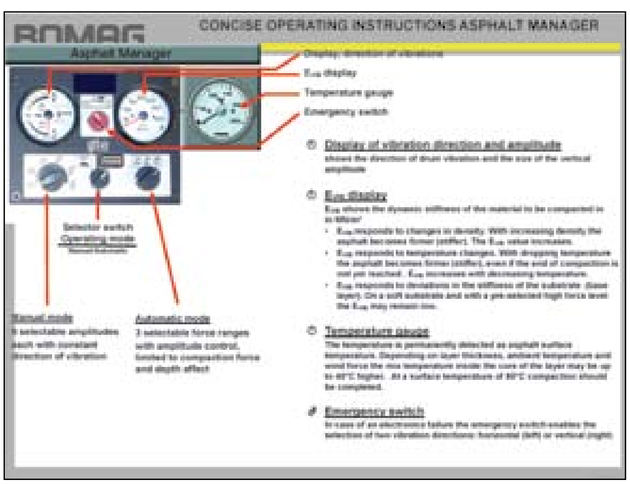
15 t static roller With BVM	- 15 cm layers - 40 cm layers

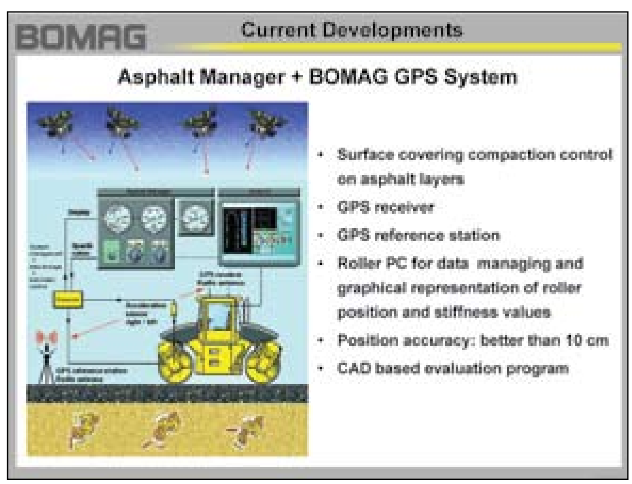
Asphalt Manager, Intelligent Compaction

Chris Connolly



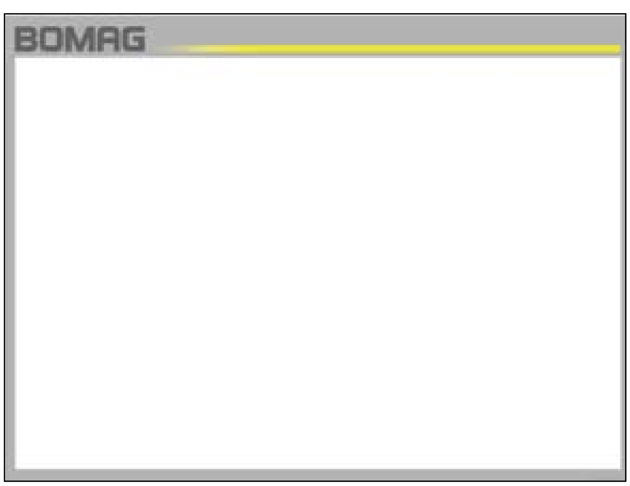






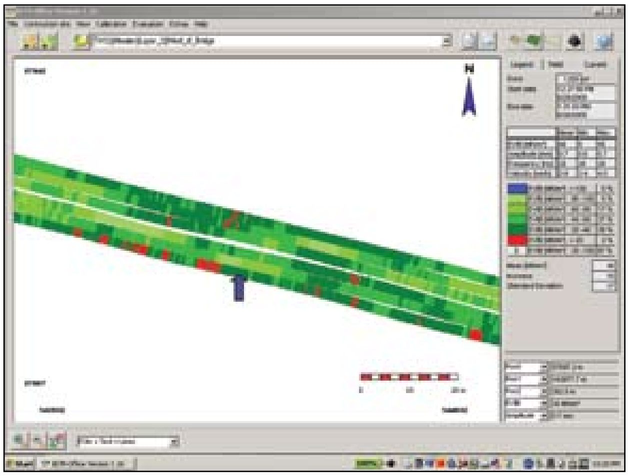
Asphalt Manager, Intelligent Compaction

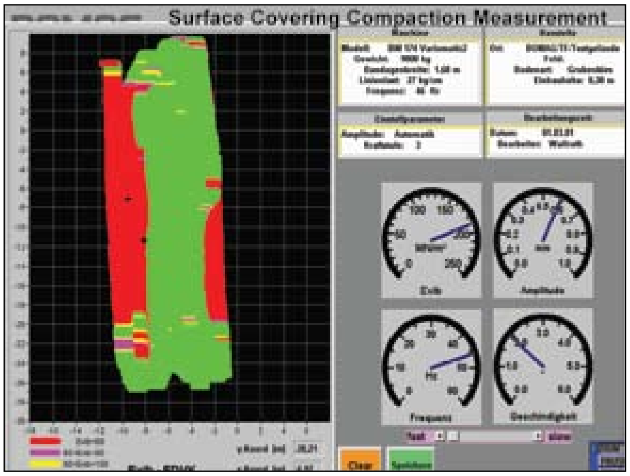
Chris Connolly

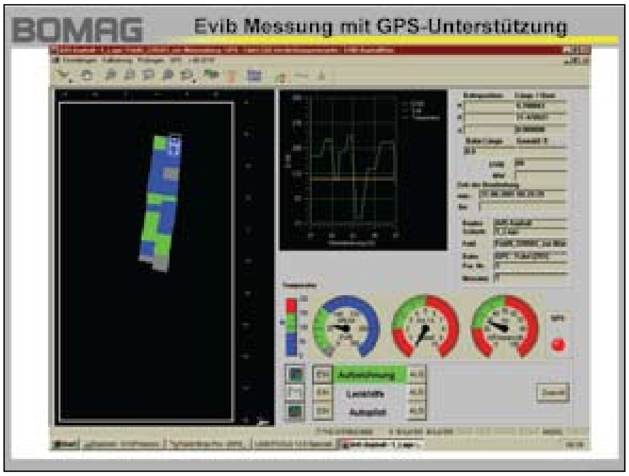


Asphalt Manager, Intelligent Compaction

Chris Connolly

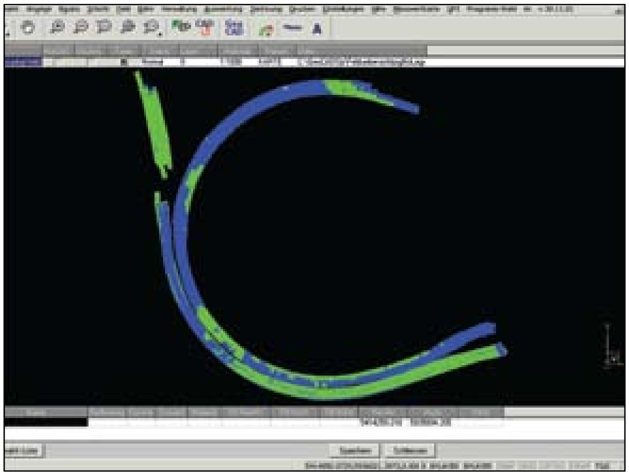


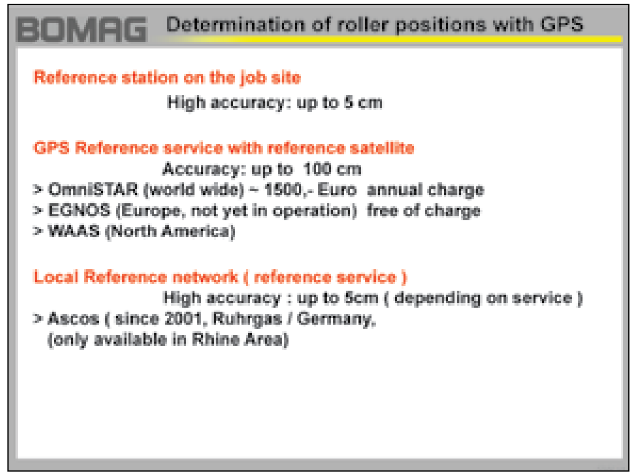


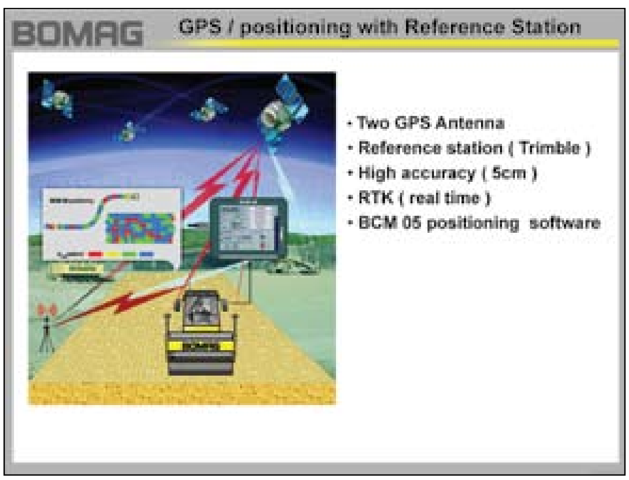


Asphalt Manager, Intelligent Compaction

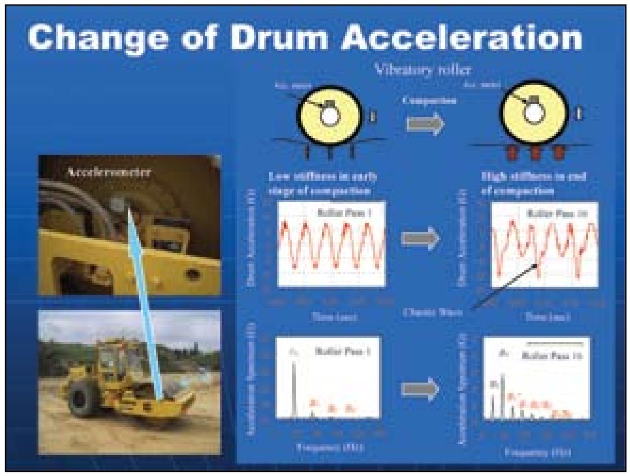
Chris Connolly

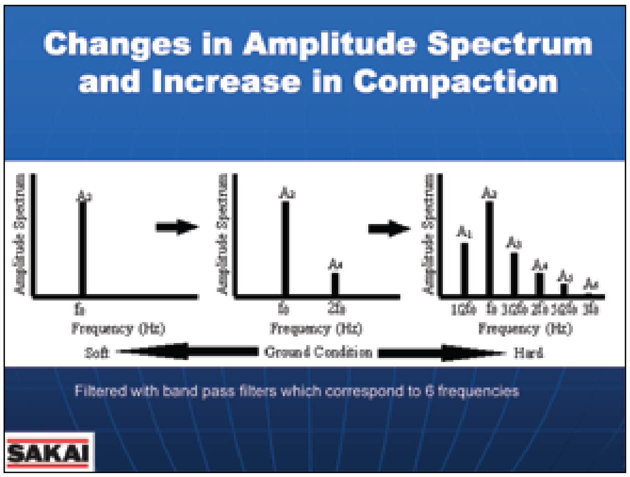


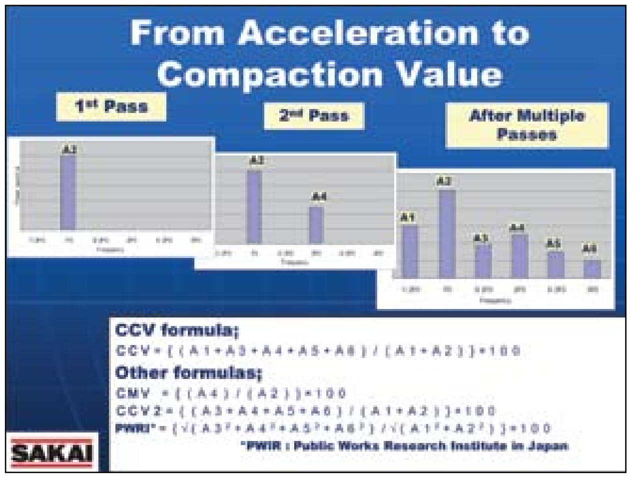


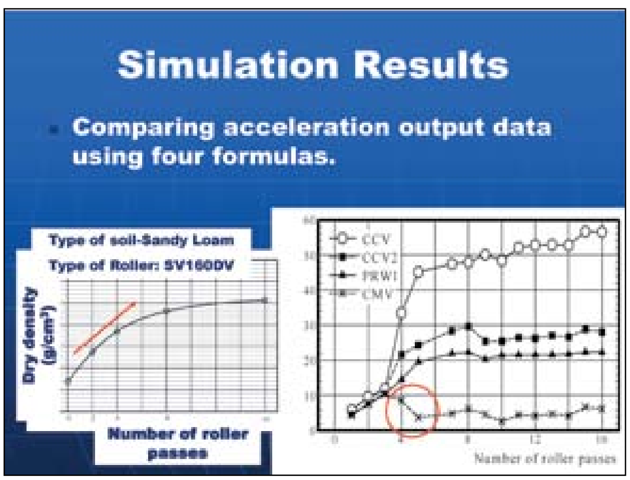



Intelligent Compaction for Soils & HMA
SAKAI
Stan Rakowski
Iowa IC Workshop


Change of Drum Acceleration
Vibratory roller
Accelerometer
Low stiffness in early stage of compaction
High stiffness in end of compaction


Changes in Amplitude Spectrum and Increase in Compaction
Amplitude Spectrum
Frequency (Hz)
Soft
Ground Condition
Hard
Filtered with band pass filters which correspond to 6 frequencies
SAKAI

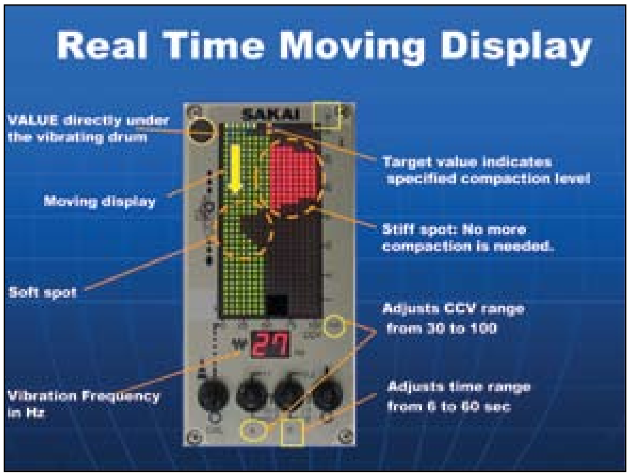

From Acceleration to Compaction Value
1st Pass
2nd Pass
After Multiple Passes
CCV formula;
CCV = [(A1 + A3 + A4 + A5 + A6) / (A1 + A2)] × 100
Other formulas;
CMV = [(A4) / (A2)] × 100
CCV2 = [(A3 + A4 + A5 + A6) / (A1 + A2)] × 100
PWRI* = [√(A3² + A4² + A5² + A6²) / √(A1² + A2²)] × 100
*PWRI : Public Works Research Institute in Japan
SAKAI

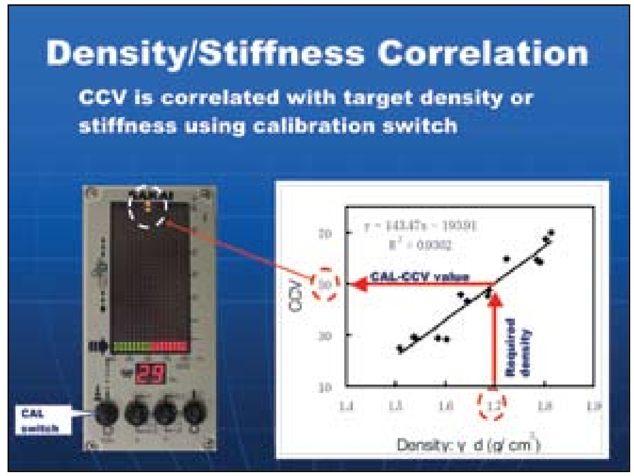

Simulation Results
Comparing acceleration output data using four formulas.
Type of soil-Sandy Loam
Type of Roller: SV160DV
Dry density (g/cm³)
Number of roller passes
CCV
CCV2
PRWI
CMV
Number of roller passes

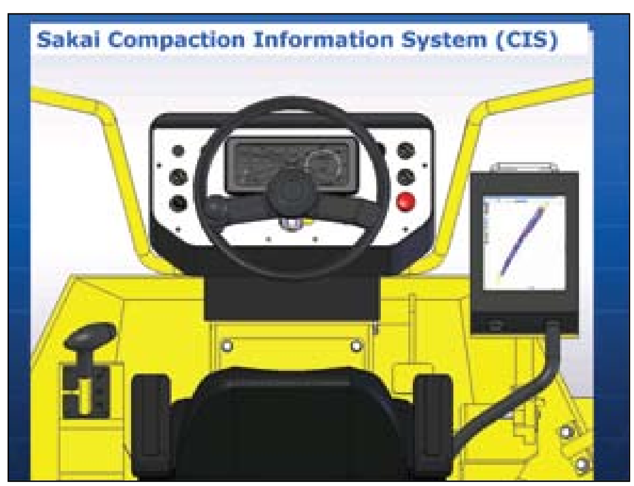

CCV System
SAKAI

Intelligent Compaction for Soils and HMA

Stan Rakowski







Intelligent Compaction for Soils and HMA

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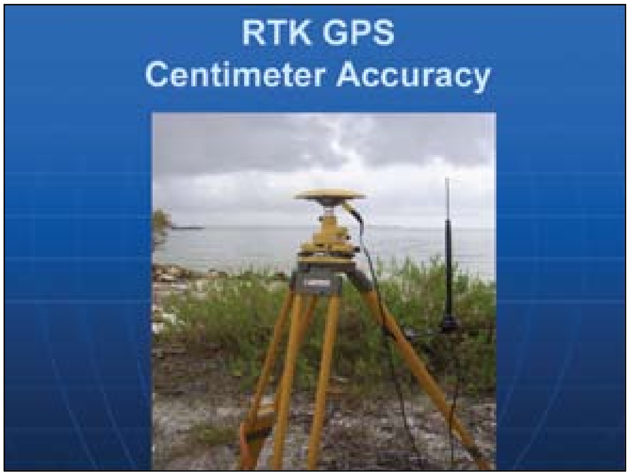

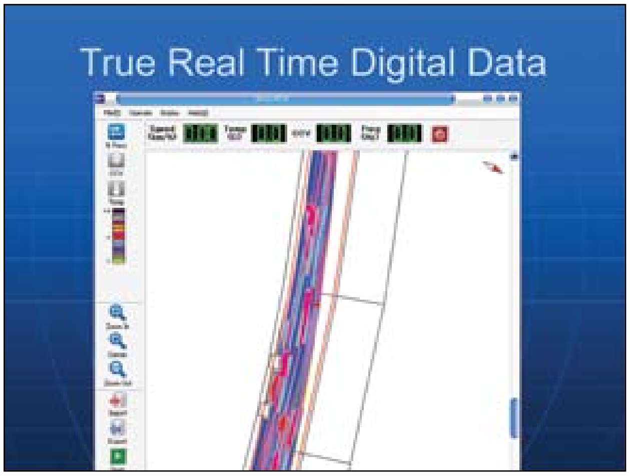

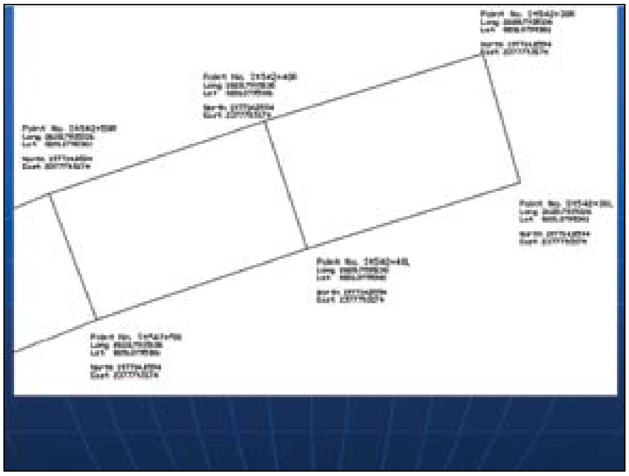

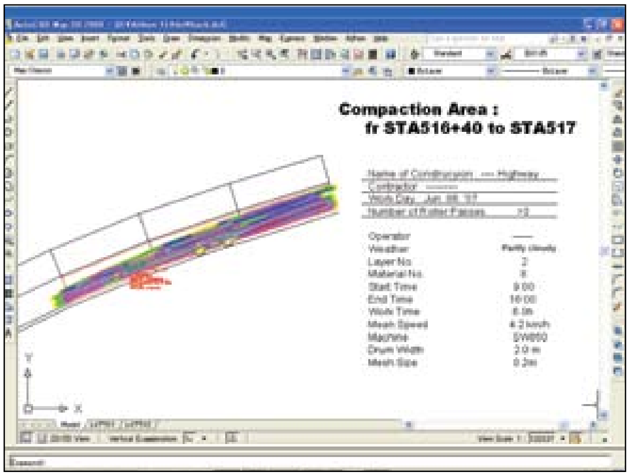

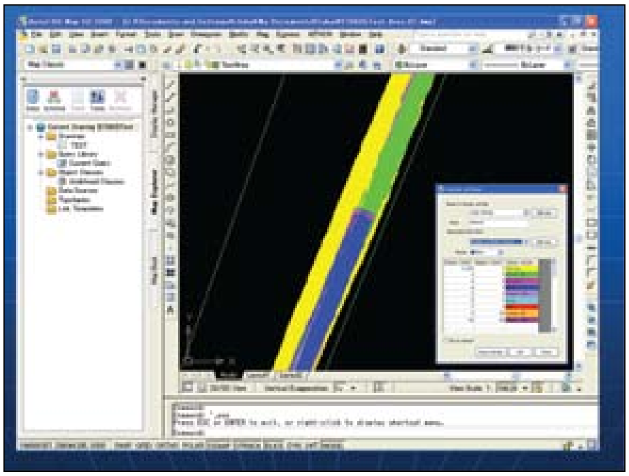

Intelligent Compaction for Soils and HMA

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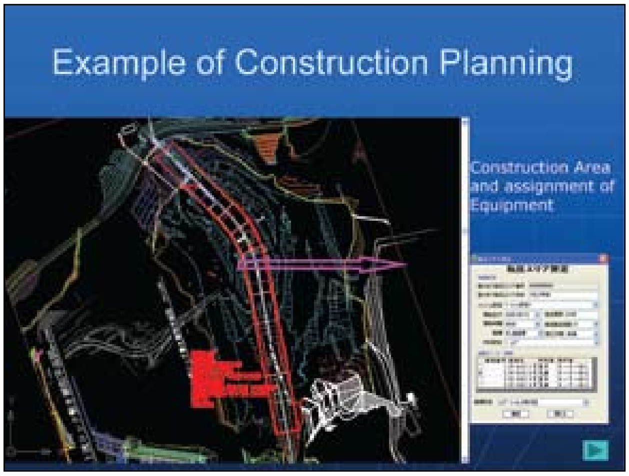
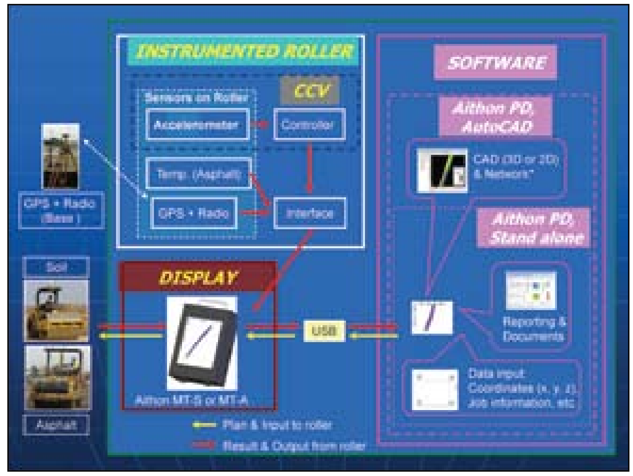
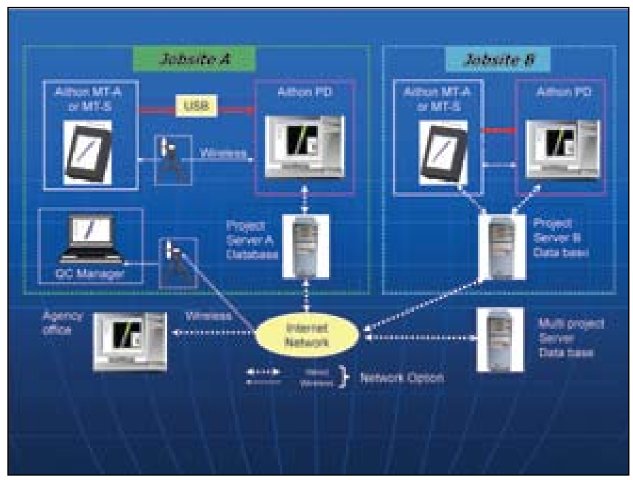




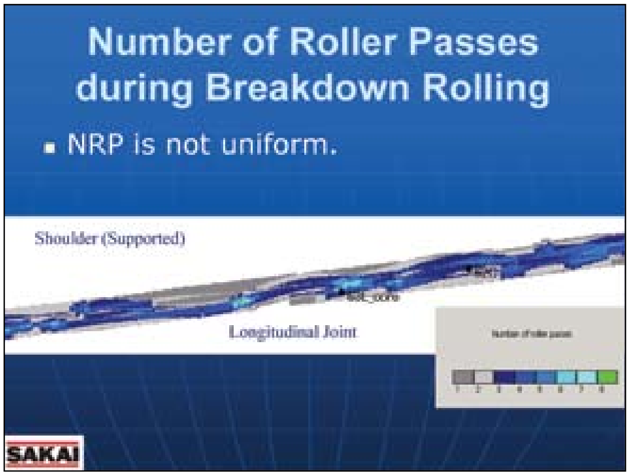
Future Developments

- Real time wireless network (2009)
- Server network system (2009)

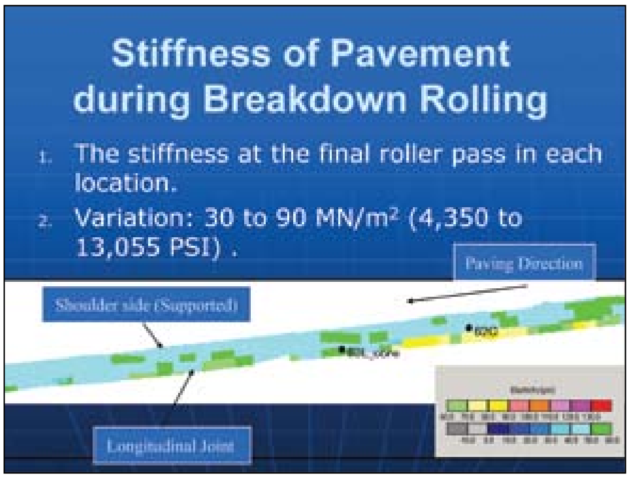


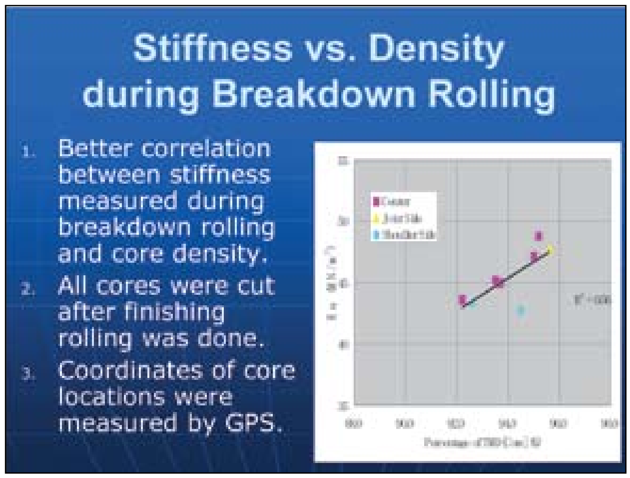
Software Solutions

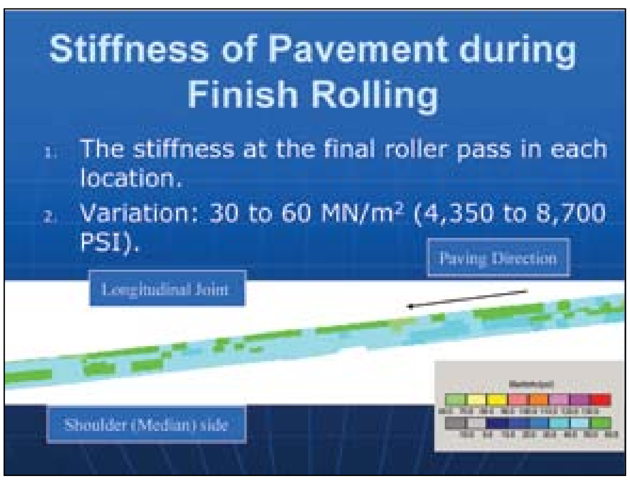
- Machine control grading/design programs
- Multifaceted Data Analysis and maximum use of data 2D, 3D analysis
- Data transparency
- Effective use of Data Obtained
- Monitoring of pavement layer life
- Real time data management and archiving

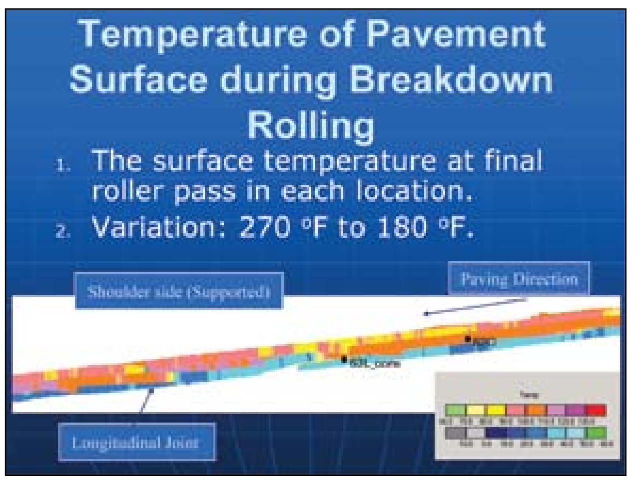

Number of Roller Passes during Breakdown Rolling
▪ NRP is not uniform.
Shoulder (Supported)
Longitudinal Joint
SAKAI


Number of Roller Passes during Finish Rolling
▪ NRP is not uniform.
Longitudinal Joint
Shoulder (Median) side
SAKAI


Stiffness of Pavement during Breakdown Rolling
1. The stiffness at the final roller pass in each location.
2. Variation: 30 to 90 MN/m² (4,350 to 13,055 PSI) .
Paving Direction
Shoulder side (Supported)
Longitudinal Joint

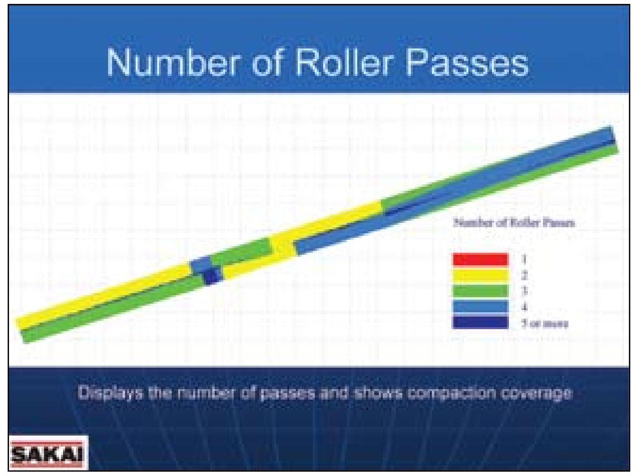

Stiffness vs. Density during Breakdown Rolling
1. Better correlation between stiffness measured during breakdown rolling and core density.
2. All cores were cut after finishing rolling was done.
3. Coordinates of core locations were measured by GPS.

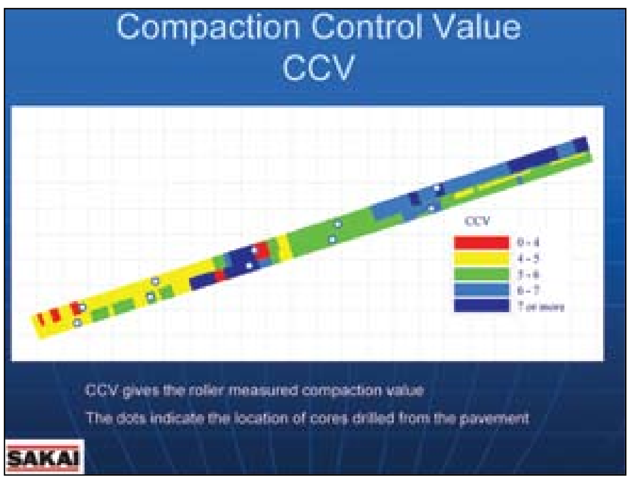

Stiffness of Pavement during Finish Rolling
1. The stiffness at the final roller pass in each location.
2. Variation: 30 to 60 MN/m² (4,350 to 8,700 PSI).
Paving Direction
Longitudinal Joint
Shoulder (Median) side

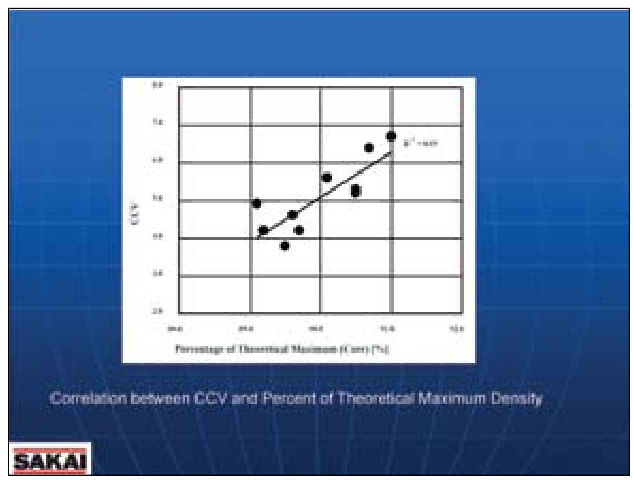

Temperature of Pavement Surface during Breakdown Rolling
1. The surface temperature at final roller pass in each location.
2. Variation: 270 °F to 180 °F.
Paving Direction
Shoulder side (Supported)
Longitudinal Joint

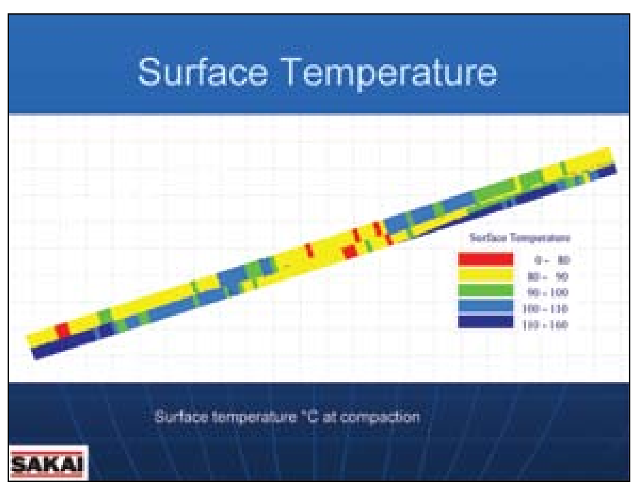
Intelligent Compaction for Soils and HMA

Stan Rakowski



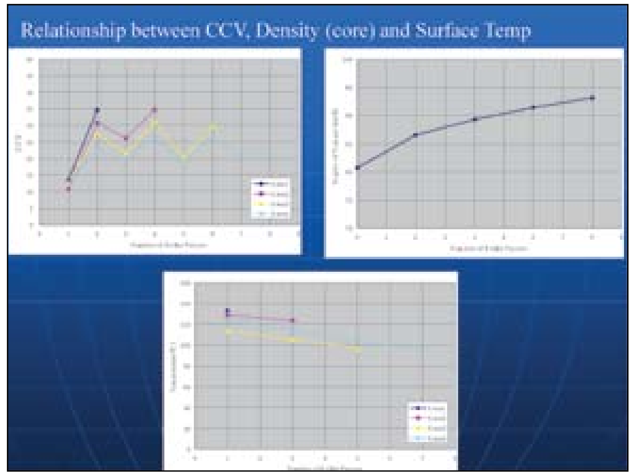


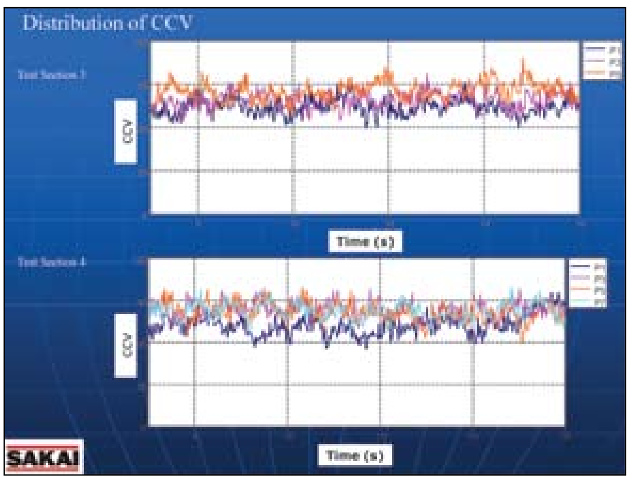


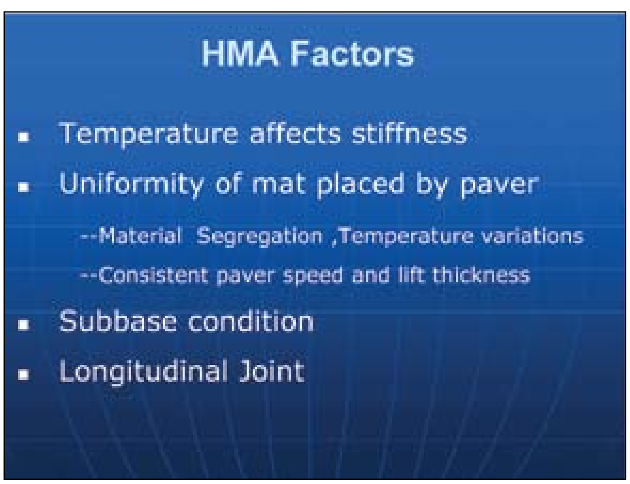


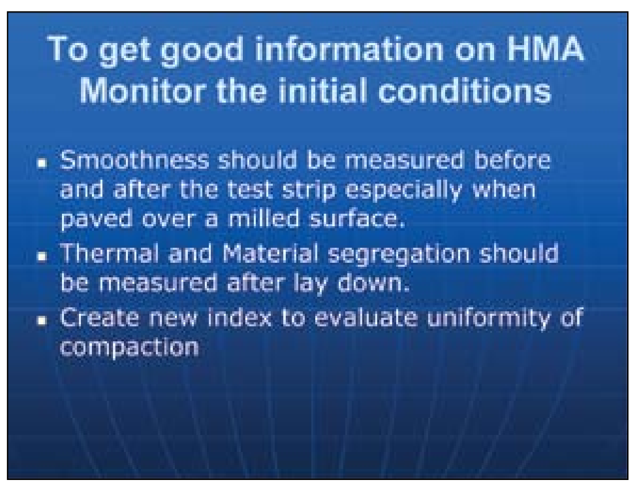
Intelligent Compaction for Soils and HMA

Stan Rakowski










Thank you
SAKAI

Evaluation of the Highway Subgrade Strength with the Acceleration Wave of the Vibration Roller

Stan Rakowski

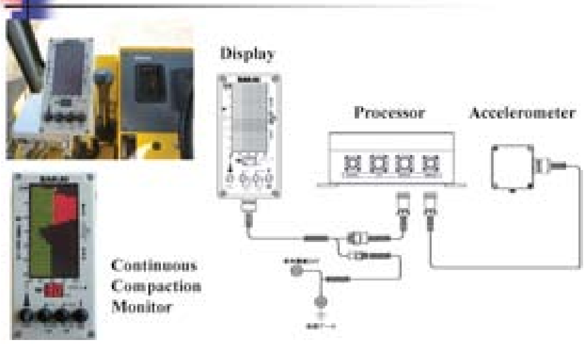
Evaluation of the highway subgrade strength with the acceleration wave of the vibration roller

Japan Highway Public Corp., Y. Kitamura & K. Fujioka
Sakai Heavy Industries, Ltd., K. Uchiyama
Fudo Construction Co., T. Nishio
Hazama Co., S. Nakajima

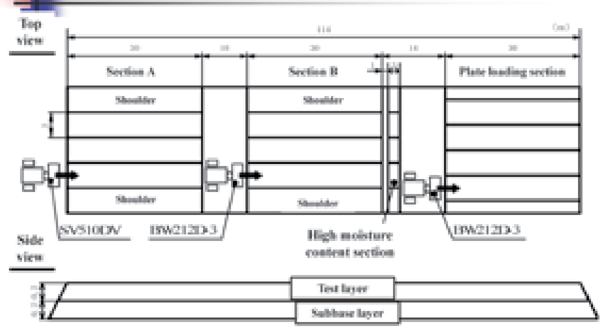
Objectives of Test Project

- Establish new compaction QC method for embankment and subgrade using acceleration of vibratory roller such as CCV
- Comparison of the conventional testing method with the new one such as CCV.
- Investigate the influence of various levels of stiffness of underlying layer on the drum acceleration measured on the upper layer

SAKAI CCV
Compaction Control Value



Test Section View



Roller in Test Section

Mechanical Quantities Measured

- CCV
- Density by nuclear gauge
- Stiffness by plate loading test
- Deflection by Benkelman beam and FWD
- Surface sinkage

Evaluation of the Highway Subgrade Strength with the Acceleration Wave of the Vibration Roller

Stan Rakowski

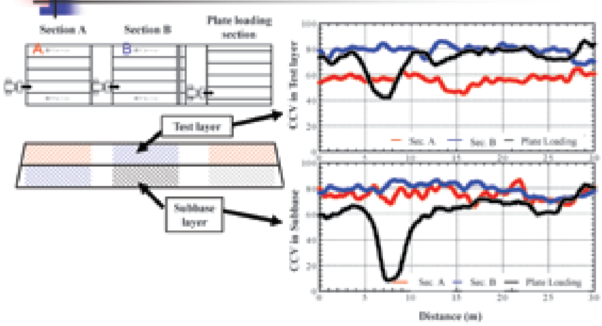
Material Information

Unified Classification System	Gravel Sand (GS)		Remarks
Density of soil particles	t/m^3	2.644	
Maximum aggregate size	mm	75.0	
Uniformity Coefficient Uc		16.7	
Max dry density	t/m^3	1.902	(E-b)
Optimum moisture content	%	12.0	
Average moisture content during test	%	8.3	

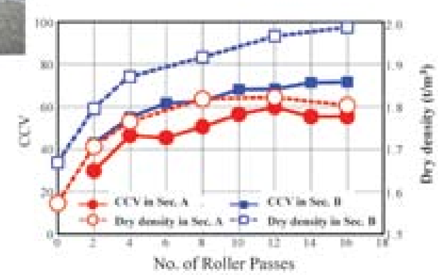
Test Rollers

Model		SV510DV	BW212D-3
Make		SAKAI	BOMAG
Mass	kg	11,400	11,750
Centrifugal force	kN	226	275
Frequency	Hz	30	30

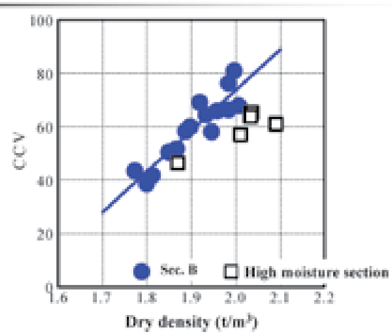
Influence of Stiffness of Underlying Layer on CCV



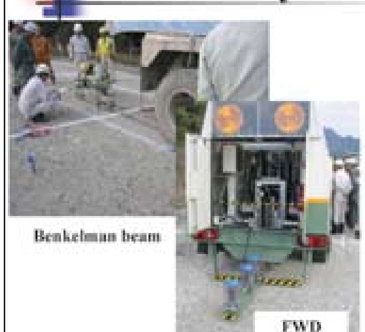
Density by nuclear Gauge & CCV

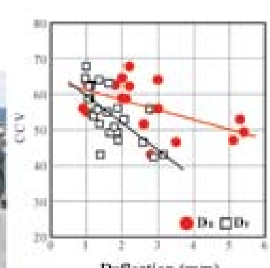


Density vs. CCV



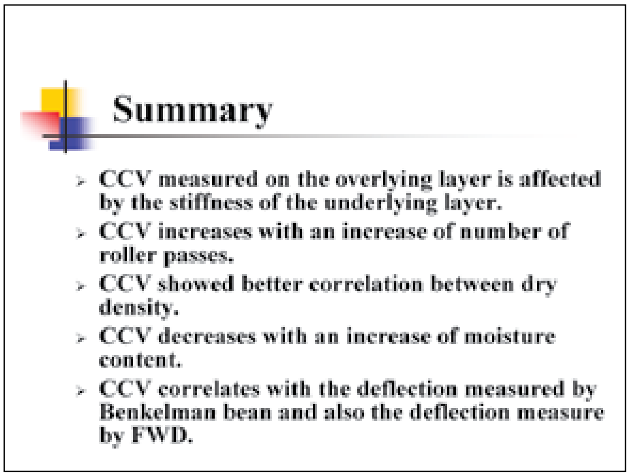
Deflection by FWD and CCV





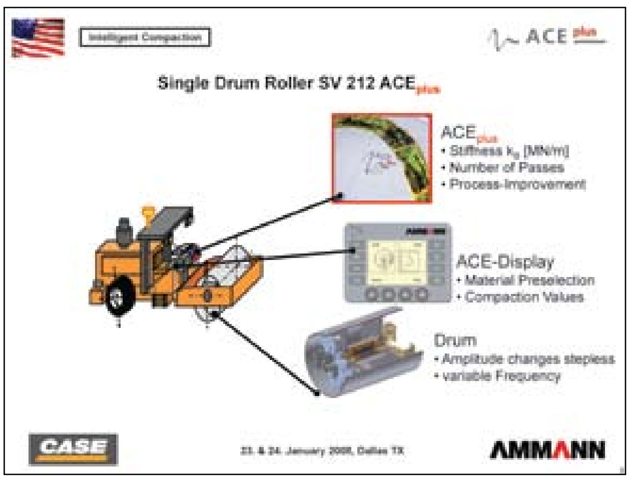
Evaluation of the Highway Subgrade Strength with the Acceleration Wave of the Vibration Roller

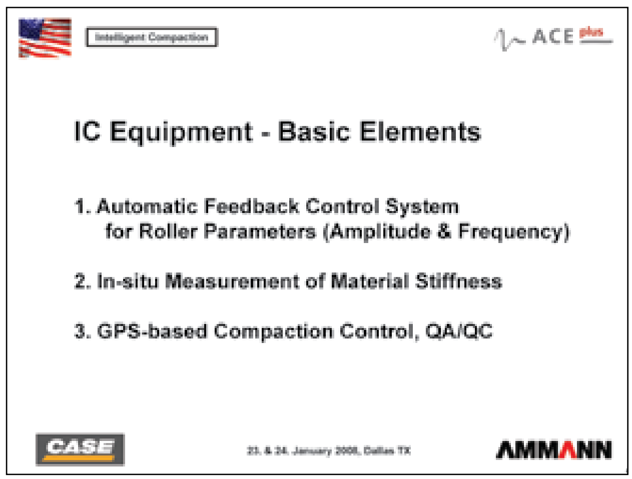
Stan Rakowski

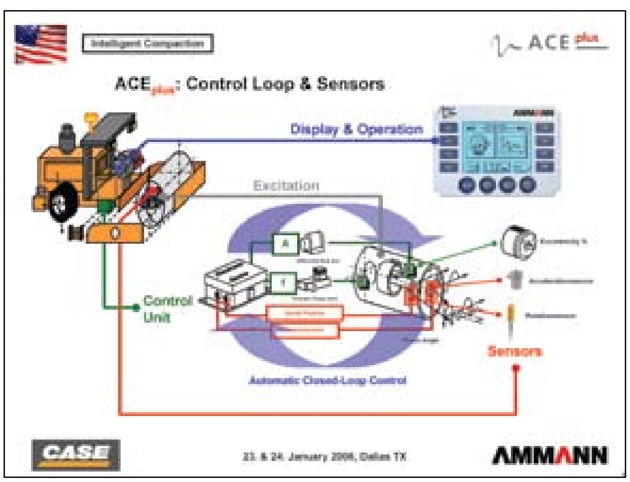


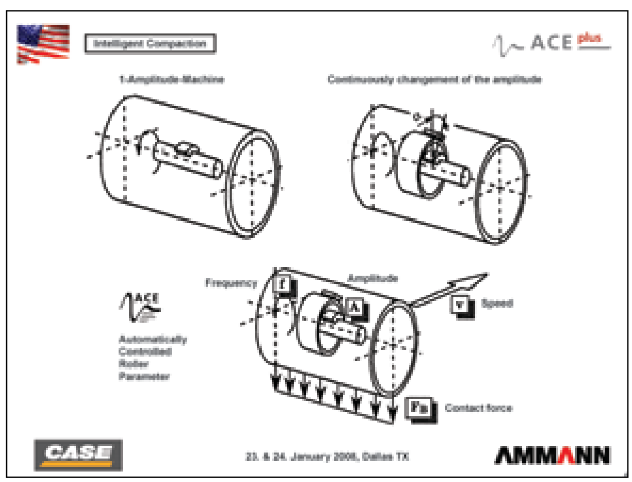
Intelligent Compaction: GPS- based Compaction Control

Kirby Carpenter



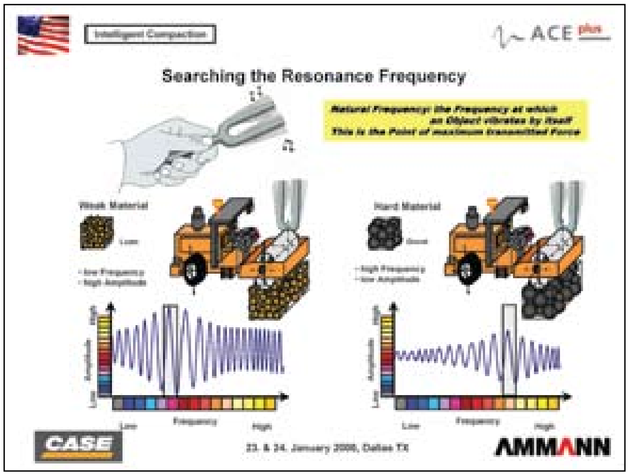


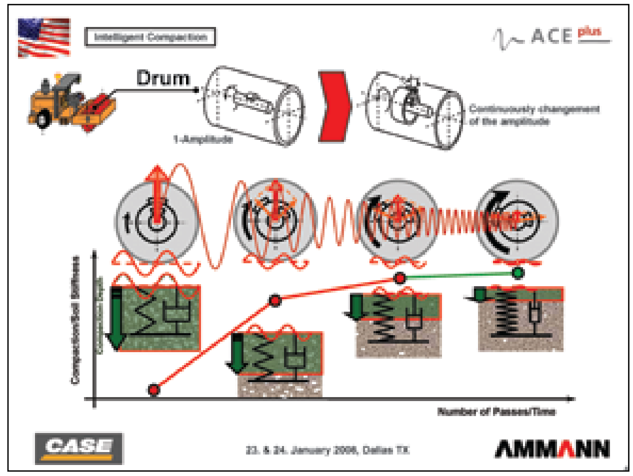


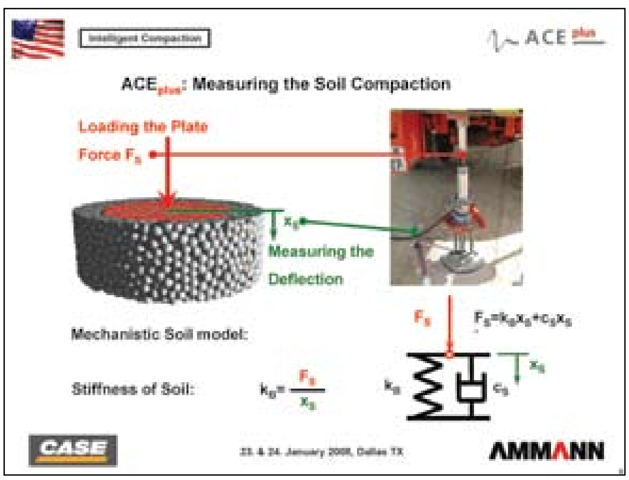


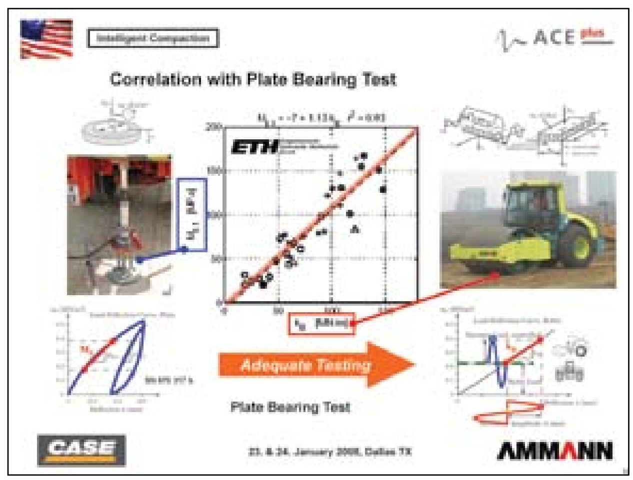
Intelligent Compaction: GPS- based Compaction Control

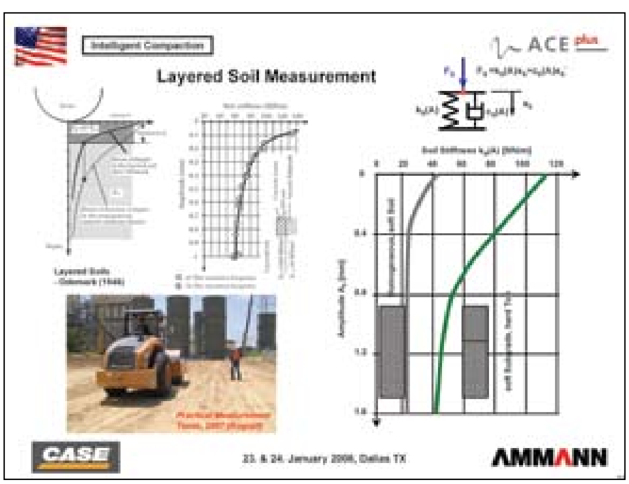
Kirby Carpenter

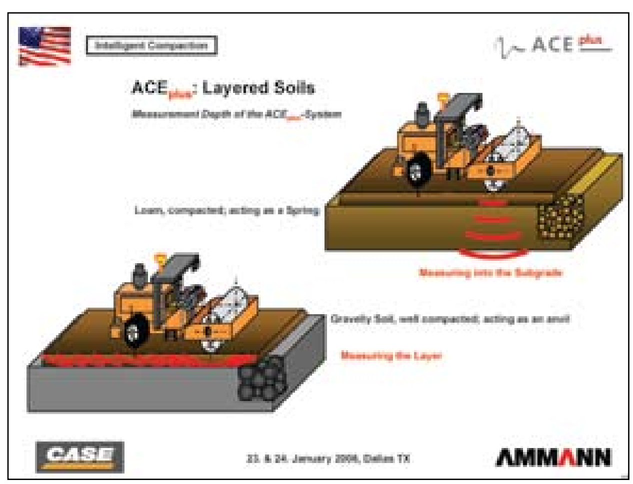






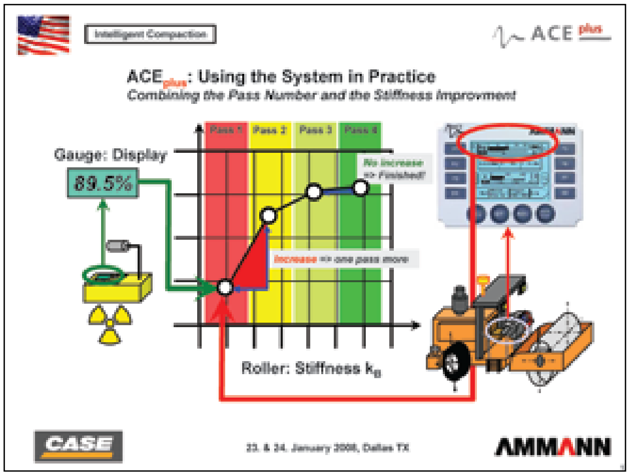


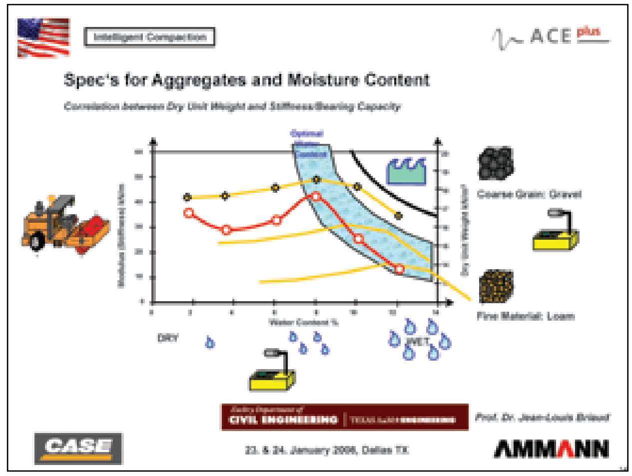


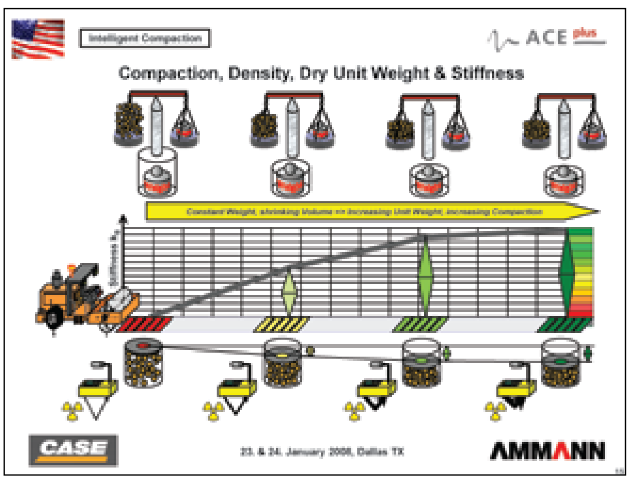


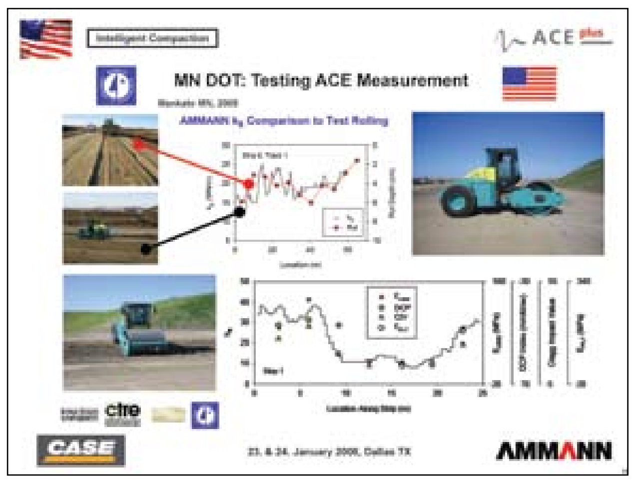
Intelligent Compaction: GPS- based Compaction Control

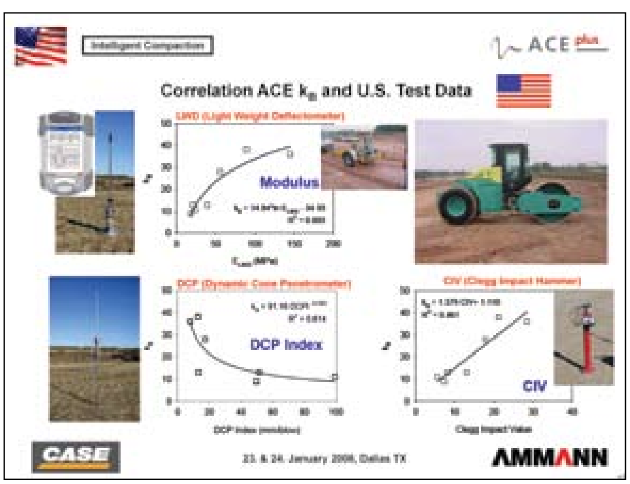
Kirby Carpenter

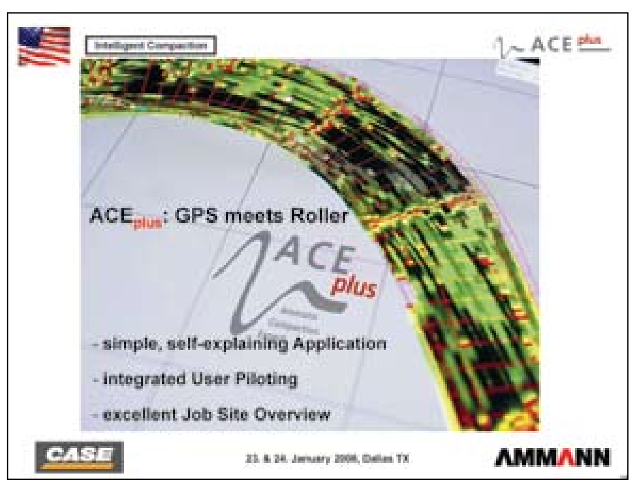












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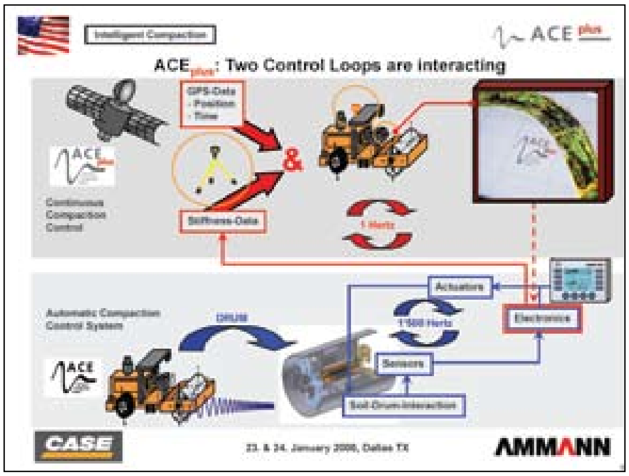

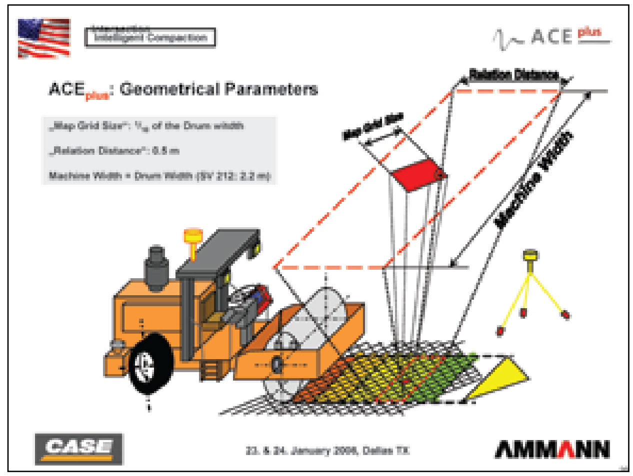

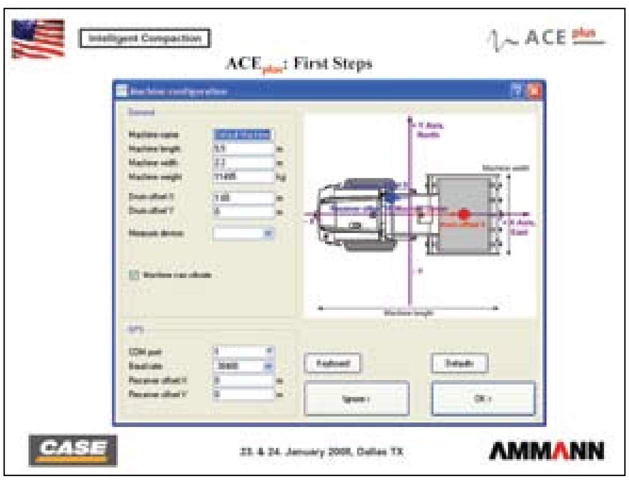

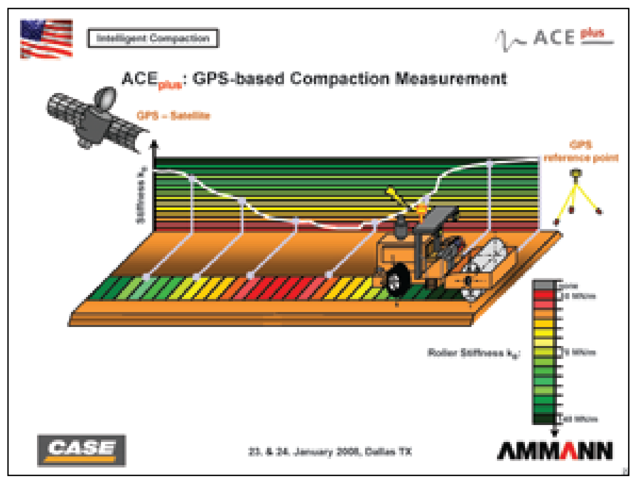

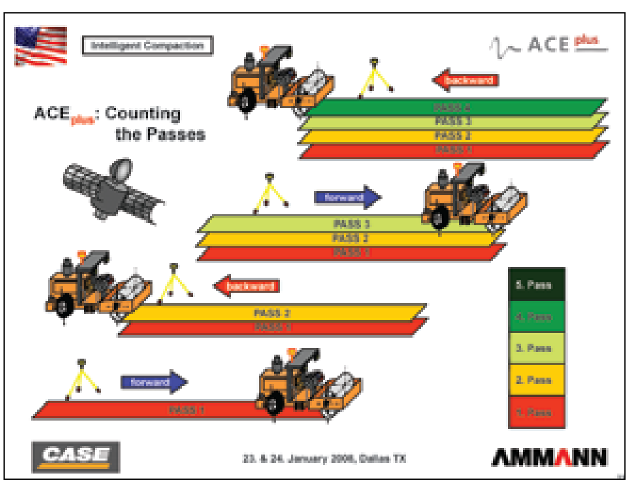

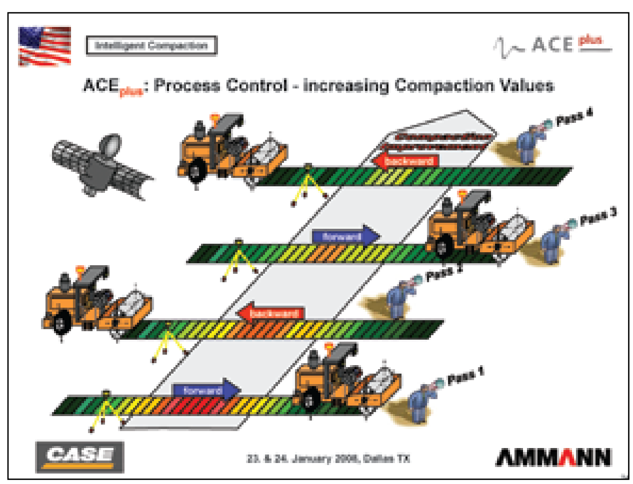

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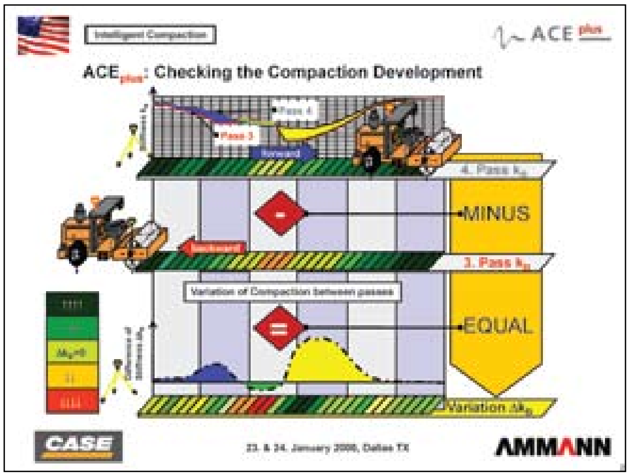

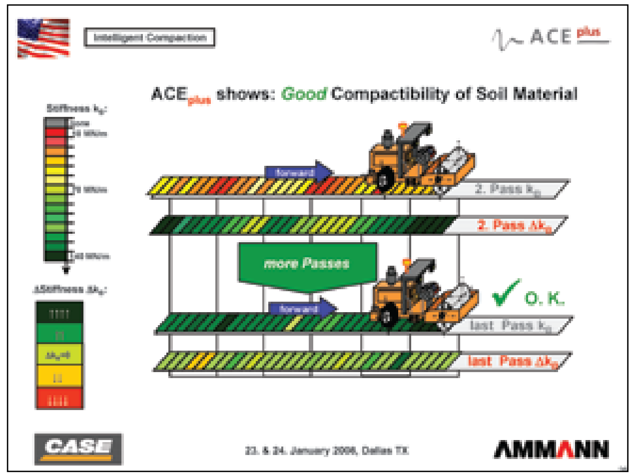

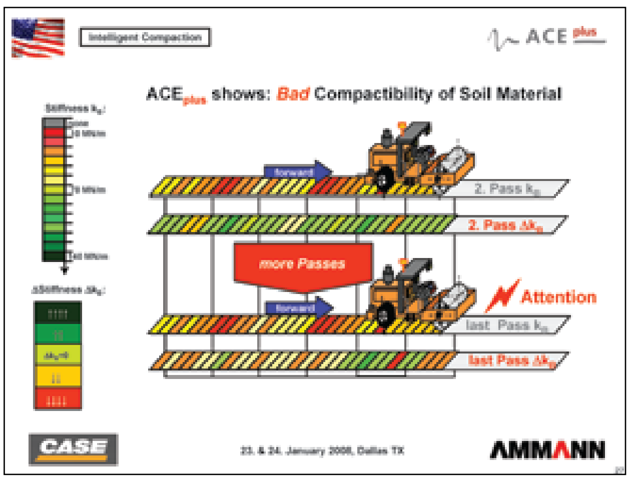

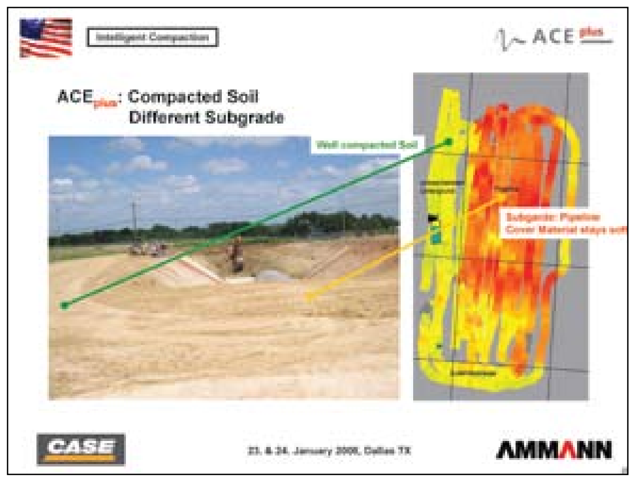

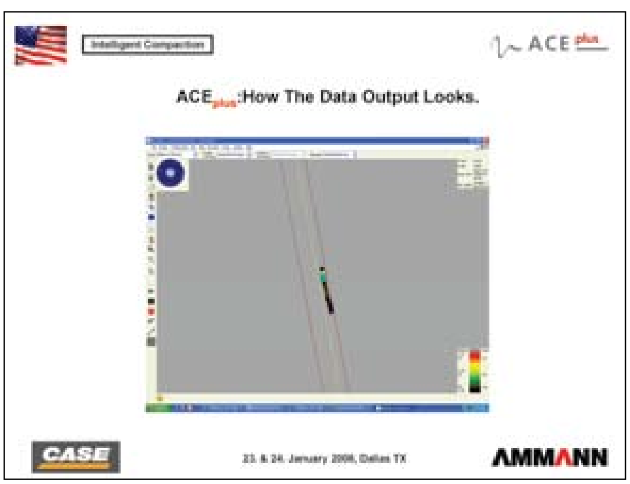

Intelligent Compaction: GPS- based Compaction Control

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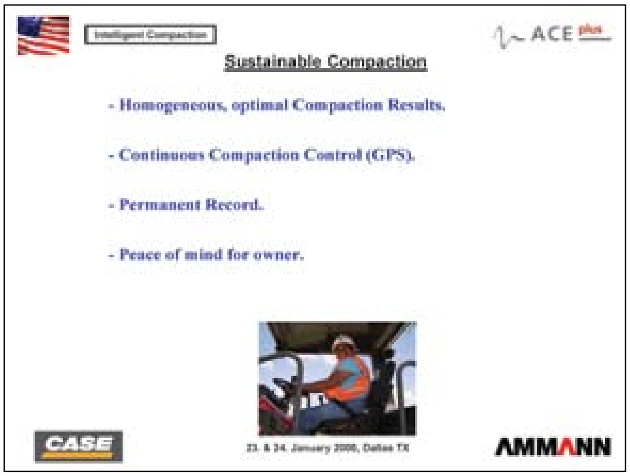
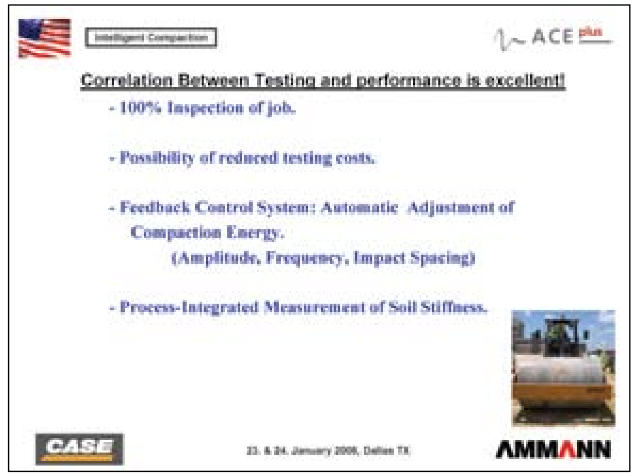
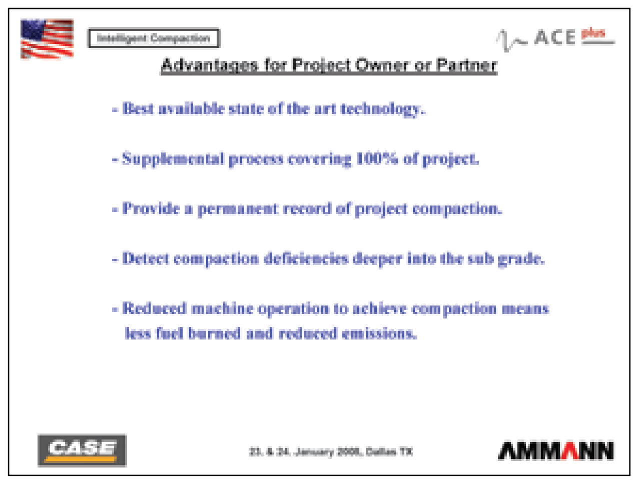
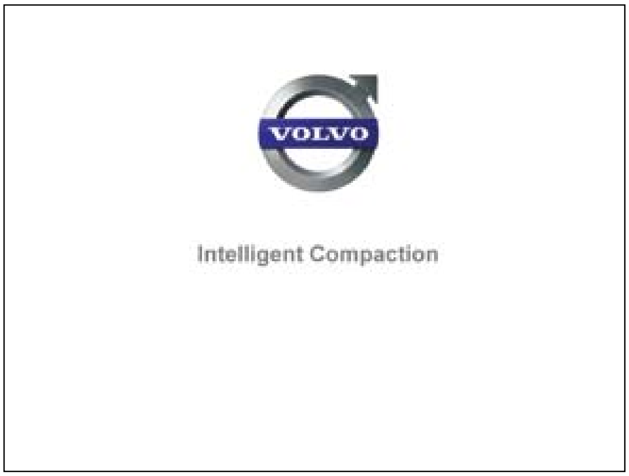


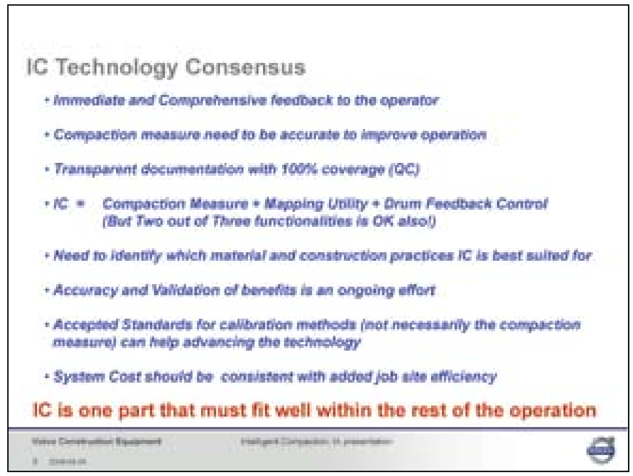


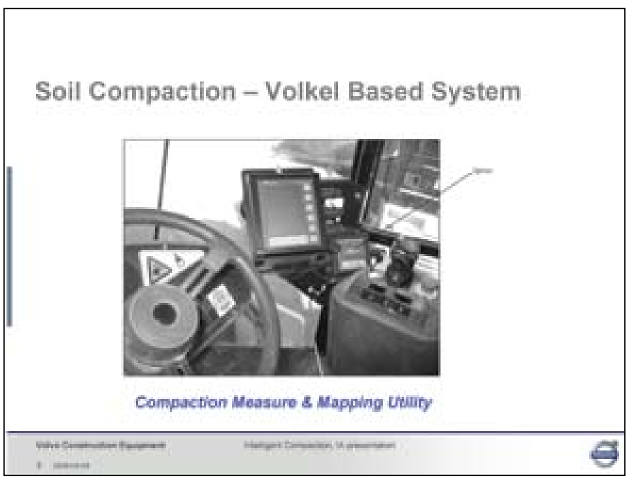


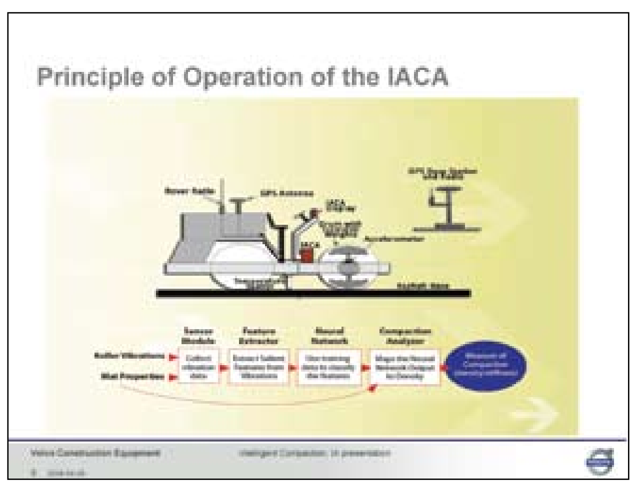
Intelligent Compaction

Khalil Maalouf









Intelligent Compaction

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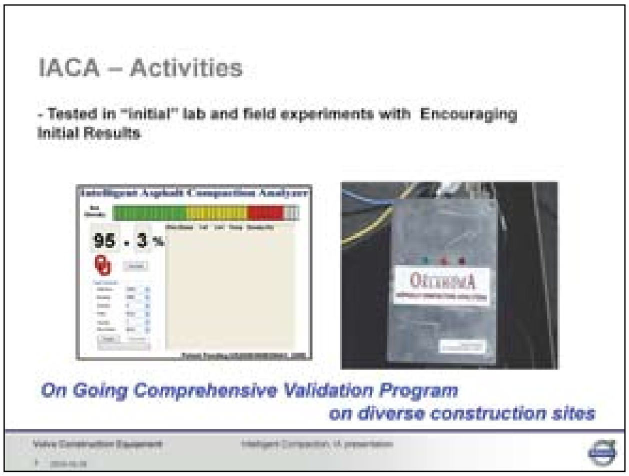


Intelligent Compaction: Where we are at and where we need to be

Brett Stanton

INTELLIGENT COMPACTION

Where we are at and where we need to be.

PAYNE & DOLAN
INCORPORATED

INTRODUCTION

CONTRACTOR'S DEFINITION:

Intelligent compaction is a compaction system that allows increasing productivity while decreasing risk.

REGULATORY AGENCY'S DEFINITION:

Intelligent compaction is another means of measuring and recording the quality of compaction during the construction process.

2

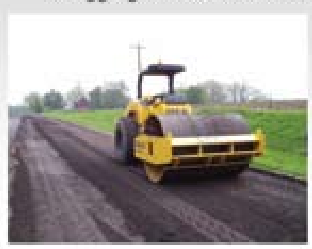
INTRODUCTION

- Experience with Intelligent Compaction
  - Unbound Crushed Aggregate Base
  - Rubbilized Concrete
  - Asphalt Pavement
- Future Expectations

3

EXPERIENCE

- Intelligent Compaction on CABC
  - Good correlation between nuclear density gauges and CCV for aggregate base courses using established test strips

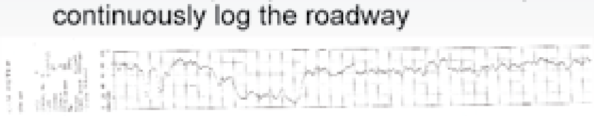


- Greatly improves efficiency by reducing over rolling
- Base courses were not left open to weather and traffic as long prior to paving
- Improved communication with inspectors and a reduction in QC testing intervals

4

EXPERIENCE

- Used to identify soft areas to be undercut
- Reduces cost to the DOT and time to traveling public
- Reduces risk to the contractor. Identifies areas prone to failure
- Continuous quality control due to ability to continuously log the roadway



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EXPERIENCE

Intelligent Compaction on Rubbilzed Concrete

- 426,000 tons of HMA over rubbilized concrete - MDOT Warranty project
- Rubbilized to stop reflective cracking
- Typical modulus values of the layer: 50ksi
- Correlated results from Falling Weight Deflectometer (FWD) to readings from CCV device

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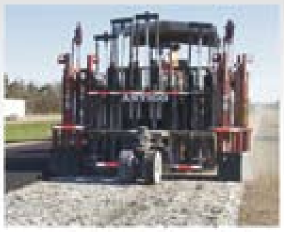
Intelligent Compaction: Where we are at and where we need to be

Brett Stanton

EXPERIENCE

- CCV ensured aggregate interlock of PCC layer by not over rubbilizing
- Intelligent compaction is much quicker than translating FWD numbers and could be used to VALUE ENGINEER HMA overlays on rubbilized PCC
- Could increase modulus numbers easily to 150ksi from 50ksi, a three fold increase



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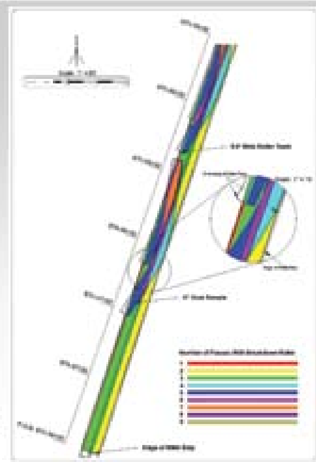
Experience

Intelligent Compaction on Asphalt Pavement

- Uniform asphalt pavement densities are related to:
  - Temperature
  - Mix Uniformity
  - Uniform rolling patterns
- Current technology allows the monitoring of
  - Temperature
  - Rolling Patterns
  - Density?

8

Roller coverage as determined by GPS Data



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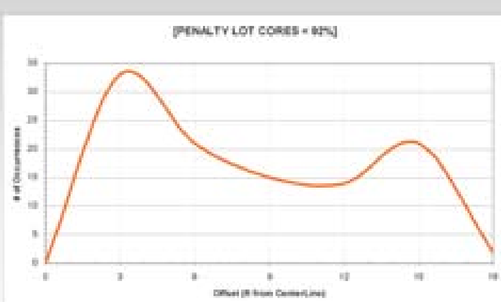
Experience



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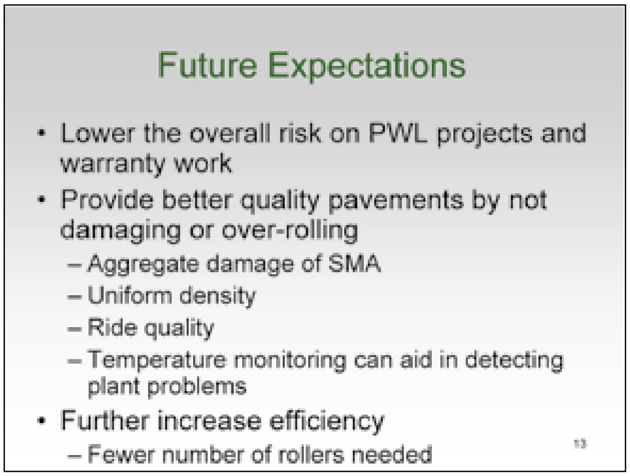
CONCLUSION

- Intelligent compactors correlated well with density results on CABC
- Can be used to determine amount of rubbilization needed for rubbilized PCC pavements
- Intelligent compaction has increased project efficiency
- Lowered contractors exposure to risk
- Allows for crucial future design data to be gathered for performance
- Can aid in value engineering pavement
- Can supply continuous QC information
- Benefits the traveling public by reducing user delays

12

Intelligent Compaction: Where we are at and where we need to be

Brett Stanton



Facilitator Report / Discussion

Tom Cackler, Ed Engle, Heath Gieselman,
Lisa Rold, Douglas Townes, David White

IOWA STATE UNIVERSITY
Civil, Construction & Environmental Engineering

Facilitator Report - Discussion

Intelligent Compaction for Soils and HMA Workshop
West Des Moines, Iowa
April 2-4, 2008

Facilitators: E. Tom Cackler, Ed Engle, Heath Gieselman, Lisa Rold, Douglas Townes
Recorders: Jerod Gross, John Puls, Pavana Vennapusa, David White, Paul Wiegand

ctre
EERC

Dream it, Design it, Build it. www.ccee.engineering.iastate.edu

Sessions

- IC for Soils and Aggregate (3)
- IC for HMA (4)
- Implementation Strategies (2)

Knowledge Gaps | Equipment Advancements | Education and T² | Specifications and Standards

Outcome: Develop a framework to move intelligent compaction/machine control forward into the mainstream of highway construction.

Identify Constraints ☑ → Strategies to Overcome ☑ → Action Plan/Tasks → Successful Outcome

IC for Soils and Aggregate

Knowledge Gaps

- Correlation Studies (73)
  - Different Soil Types (Granular, Cohesive, Recycled, Stabilized)
  - Different Roller Configuration (Smooth, Padfoot)
- Rapid In-situ w% determination (14)
- Modulus Based QC/QA (12)
- Understanding what IC-MVs are? Experience (10)
- Measurement Influence Depth? (7)
- Acceptable Non-Uniformity? (4)
- Trouble Shooting – Unusual Conditions, Machine Capabilities, and Limitations (3)
- Data Visualization (1)
- Benefits? (1)

Equipment Advancements

- w% measurement on roller (29)
- Integrated solutions between multiple technologies (3D Design - 4D Construction) (18)
- Real-time data transfer/wireless (14)
- Retrofit systems (3)
- Repeatability/sensitivity of IC-MVs (2)
- Compaction diagnostics - red flag indicator (2)
- On-site geotechnical lab (2)
- Available machine configurations to match soil and site conditions (0)
- Machine/Technology maintenance differences (0)

Education/Technology Transfer

- Contractor/Field Engineer/Owner Training (52)
- Opportunity to promote good geotechnical practices (13)
- Cost/ROI (11):
  - Equipment Investment
  - Field Implementation
- Proven case histories to "sell" the technology (effectiveness to quality/efficiency) (9)
- Definitions of "IC" terminology (3)
- Operator/Inspector guide & Troubleshooting Manuals (3)
- Certification for contractor (1)
- Data amount and analysis (0)

Facilitator Report / Discussion

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Specifications and Standards

- Uniformity criteria (20)
- Selecting engineering parameters to measure (e.g. density, modulus, stiffness) (19)
- Consolidate IC-MVs to one unified parameter or report raw accelerometer data (11)
- How will w% be specified? (5)
- Contractor/owner/researcher/manufacturer input for specification development (4)
- Establishing IC target values/test strip guidelines (1)
- Establish IC documentation standards (GPS and output parameters) (1)

IC for HMA

Knowledge Gap

- Correlation of IC-MVs to engineering properties (39)
- Understanding IC-MV non-uniformity (mixture) (10)
- Measurement Influence Depth/Adjustment (9)
- Key in-situ engineering parameters to measure (7)
- Mix design, binder grade, and aggregate on IC-MVs (5)
- Benefits of IC and reliability of current methods (5)
- Data Integration (3)
- Link between IC-MVs and performance (4)
- Best applications for IC (e.g., overlays, HMA, etc.) (2)
- Applications for IC for QA (1)
- Modeling of compaction and cooling mat (1)

Equipment Advancements

- Involvement of roller train or just the breakdown roller (14)
- Influence of temperature (surface /internal), compaction time/speed, frequency/amplitude, and roller passes (6)
- Retrofit (5)
- Real-time data transfer (5)
- Mapping of underlying layers and existing pavements (3)
- Similarities between IC output (2)
- Corrective action after map (1)
- Compare mapping of IC and pneumatic roller (1)
- Integrated systems approach (1)
- What are public agency needs (0)
- In-situ compaction test equipment (0)

Education and Technology Transfer

- Demonstration projects, open houses, and hands-on opportunities (10)
- Documented successes (4)
- Establish framework for training contractor/owner (3)
- Economic/contractor benefits (2)
- Software compatibility (design, machine, analysis) (1)
- Harmonization/standardization of technology (1)
- Communicate opportunities for IC projects with interested parties (0)
- Pooled fund website, NCAT research (?), NCHRP, International conference (0)

Specifications and Standards

- Establishing QC and QA criteria and framework (9)
- End-result specifications (7)
- Keep it simple (5)
- Standard calibration method to establish IC and in-situ target values (3)
- Mapping as QC tool (2)
- Structure to minimize risk to contractor and agency – total risk management (2)
- Allow for contractor QC plans to accommodate variations in equipment (2)
- Goal is better performance and optimized cost (1)
- Better define IC (0) & Eliminate IC definitions (1)
- Begin w/ contractor to use – transition (0)
- Model similar w/Superpave end-result (0)

Facilitator Report / Discussion

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Implementation Strategies

Implementation Strategies

- Correlation between roller MVs and soil properties (12)
- Research
  - Demonstration projects (11)
  - NCHRP synthesis of existing practices (7)
  - FHWA IC pooled fund (4)
- Improved design tools
  - What stiffness value? (9)
  - Relation to MEPDG parameters (8)
  - Design life/quality (7)
  - 3/4D design (5)

Implementation Strategies

- Education and Training
  - Data interpretation (29)
  - Common standards (17)
  - NHI training courses (5)
  - IC 101 (4)
  - Knowledge sharing by contractor (2)
- Equipment Advancements
  - Moisture sensors in real-time (13)
  - Padfoot compaction in cohesive soils (12)
  - Real-time data transfer/wireless (9)
  - Method of marking problem areas (6)

Implementation Strategies

- Specifications
  - Incentive or directive needed (3)
  - QC easier to implement (2)
  - QA development (1)
- Partnerships/Communication (4)

Top 10 Overriding Issues – All Sessions!

1. Need correlation studies (cohesive, stabilized, granular, HMA, etc.) (136)
2. Education/training materials and programs (112)
3. Moisture content (influence + measurement) (61)
4. Integrated design + real-time data transfer (57)
5. Case histories + demos + benefit + successes (48)
6. Engineering parameter to measure (density, modulus, stiffness)? (47)
7. Addressing non-uniformity (34)
8. Establishing QC/QA framework - statistically significant (28)
9. Measurement influence depth? (19)
10. Promoting good geotechnical practices (13)

What Next?

A → B

<u>Where we are at</u>:
- Lack widely accepted IC specifications in U.S.
- Need education/training materials
- IC technologies provide documented benefits (smooth drum - granular)
- Great potential and some successes for cohesive and HMA
- Human IC network
- Increasing acceptance/GPS infrastructure for stakeless grading/ machine guidance
- "Don't know what we don't know"

<u>Where we are going</u>:
- Standardized and credible IC specifications inclusive of various IC measurement systems
- Widespread implementation of IC technologies
- High quality database of correlations
- Better understanding of roadway performance - what are key parameters?
- Innovative new sensor systems and intelligent solutions
- Several documented successes for cohesive/stabilized/granular/HMA
- Compatible 3D electronic plans with improved integrated processes, efficiency and performance

Facilitator Report / Discussion

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Breakout Sessions

On day two, there were nine breakout sessions covering three topic areas: "IC for Soils and Aggregate," "IC for HMA", and "Implementation Strategies." "IC for Soils and Aggregate" was discussed by three groups. "IC for HMA" was discussed by four different groups. "Implementation Strategies" was discussed by two groups. A sign-up sheet was provided on day one to target 20 participants per group. Each group had a facilitator and recorder.

The outcomes from the breakout sessions were centered on developing a framework to move intelligent compaction forward into the mainstream of highway construction. Each group was asked to address their topic around the following questions:

- What are the existing knowledge gaps?
- What equipment advancements are needed?
- What educational/technology transfer needs exist?
- What standards/specifications and guidelines need to be developed?

After the groups generated a list of topics for each question, the list was prioritized through discussion and, in some cases, voting. The following is a summary of the findings of each group. For some sessions, (#) indicates number of votes given to a topic for prioritization.

IC for Soils and Aggregate 1—Heath Gieselman (Facilitator), Pavana Vennapusa (Recorder)

Knowledge Gaps:

- Roller MVs in cohesive soils for both pad foot and smooth. (11)
- Intelligent compaction feedback control efficiency and effectiveness. (1)
- Increased moisture content information using simple techniques in field. (14)
- Relationships between roller outputs and soil properties. (10)
- Roller data overlaid on 3D project data. (1)

Equipment Advancements:

- Moisture measurement by rollers. (11)
- Retrofitting costs vs. new costs. (3)
- Knowledge of best machine model/size depending on soil conditions. (0)
- Pre-design tool?
- Machine maintenance issues (higher costs?)

Educational/Technology Transfer:

- Data amount and analysis.
- Contractor/operator and field engineer/owner training for IC. (12)

- Certification for contractor. (1)
- Proven case histories to "sell" the technology to the organization/contractor—quantitative information on efficiency of the technology. (9)
- Initial cost for contractor with using the technology.
- Implementation of technology without increasing the resources
  - total $$ savings ROI. (11)

Standards/Specifications and Guidelines:

- What in situ measurement is needed for correlations? (5)
- Tolerance in specifications (as it relates to cost)—uniformity? (2)
- Control strip specifications—how to deal with highly variable material conditions, time to preparation. (1)

General:

- Continue with current technology.
- IC draft specifications.
- Demonstration projects by state.
- Look for a simple project and show success.
- Proper project selection.
- Partnership with contractors by state.
- FHWA support on projects and support from university researchers.

IC for Soils and Aggregate 2—Ed Engle (Facilitator), John Puls (Recorder)

Knowledge Gaps:

- Experience with technology (owner & contractor).
- Different technology by manufacturers, requirements for output, standard output by all manufacturers.
- Capabilities and limitations of operations: Response from sub-grade rather than base (but we pay for upper layers). May be an education issue. Can we identify expected stiffness values for given soils? Being able to adapt to real-world situations (expected vs. actual project soils). Site-specific achievements.
- Adopting stiffness level vs. moisture-density relationships—specifications changes?
- Ability to understand damping and mechanics for different materials—aggregates manufactured and soils natural. Lack of experience with cohesive soils in general. Need for "pre-investigation" prior to compaction. Timeframe for knowledge about soils—contractor. Variability in modulus/stiffness method.
- Defining important properties are required for a successful project: Relationship between

field measured and lab measured data. Quality control built into use of machine. Machine calibration—DOT or contractor operation? Machines to be calibrated on regular basis to ensure quality. Build reliability and confidence into the technology. Calibration standards for machines. Machine-specific parameters are proprietary. Correlation to parameters with which we are familiar.

- Indentifying problem areas. How to determine corrective action? How do we measure this against the uniformity of the rest of the material consistently?
- Will stiffness actually replace density, or will it simply be used to correlate to expected density? Can we rely on it? What is more important: density or stiffness?
- How do you build reliability and repeatability into the technology to increase confidence level of the user?

Equipment Advancements:

- Integrated solution for all technologies. Data to designers. Geotechnical mobile offices—electronic solution (virtual on-site professionals). Limitations of staffing. On-site engineers a plus (soil identification and lab testing).
- Where does civil engineer come in to identify soils? Variability in soils and how they affect stiffness values. Understanding of what roller is doing, how soil is responding. Expected stiffness values?
- Standardize stiffness values for all entities. Need education and technology transfer.
- Moisture control measurements. Continuous measurements of moisture content to ensure quality.
- How do we approach the uniformity issue? Good or bad.
- Integrated solutions with regard to quantities: as-constructed quantities, provide data to designers and contractors, advantage to know what has been rolled vs. what hasn't, take time to run lab tests on this soil, cannot eliminate testing, but streamline it instead, make field/lab testing more efficient, mapping is a huge tool to be used for quality control, test spot selection (elimination and addition).
- Mapping prior to construction could be used for pre-construction risk analysis.
- Using MEPDG version for soils: sampling of soil, environmental conditions, and future traffic levels. Plug these into MEPDG and determine what stiffness you should have in the soil.

Educational/Technology Transfer:

- Joint education between industry and owners. Agreement on specifications.
- Agreement between terminology (CMV, CCV, etc) and units.
- Education program to be shared across all DOTs—national program.
- Listen to operators and learn from their experience.
- Opportunity to promote good geotechnical practices.

Standards/Specifications and Guidelines:

- Other acceptance criteria in addition to stiffness?
- Document procedures for specifications.
- Development of a standard to characterize the technology: standard deviation values, comparing equipment. Need awhile to continuously monitor calibration of a given machine.
- How to set levels of quality (90%, etc.)?
- Speed consistency of machines—is it an issue for soils and aggregates?
- Two major broad geotechnical issues: (1) what the machines can tell us and (2) how do we connect the two?

General:

- Stiffness replacing moisture density: Indices for moisture-density and stiffness? What methods do we have to measure moisture? How do we overcome these? Need fastest test possible. Replacing m-d relationship with stiffness, or adopting stiffness? Which stiffness are we monitoring—manufacturer (spring) or academic (modulus). What are we going to measure? How do we measure it? How do we develop acceptable criteria? Stiffness/Density. Machine value suitable for quality assurance?
- Soil characteristics identification for technology. Soils database for states. Boring logs/soil classification database for states.
- Don't have stiffness testing/data for these soils. Machine settings, soils, equipment used for various projects. Challenges associated with stiffness—layer (lift) thickness vs. stiffness. Quantity of historical data? No idea of quality of historical data. Variability during course of a project and evaluating site conditions. Finite element analysis could give insight.
- Mapping and stiffness used to minimize testing. Challenge is accurate, quick moisture content measurements. How to get equipment to job site if not a bid item? How is data submitted? Printout. Software. Programs different for manufacturers? How does contractor bid this? Need to develop correlations between machine data and standard testing.
- How do we intend to use QC values in the QA system? How is acceptance determined? What should be the proper form of verification? If/Then statements. How do contractors know what to bid for QC items? Lump sum?

IC for Soils and Aggregate 3—Ed Engle (Facilitator), Pavana Vennapusa (Recorder)

Knowledge Gaps:

- Correlations for roller MVs to soil properties (moisture, density, and stiffness). Laboratory testing—different soil types, moisture contents, LTPP database—correlations between modulus and soil classification properties for about 4000 soils (1500 subgrade soils). Regression equations are not all that good. Lab vs. field issues. Repeatability of testing, effective of sample size, stiffness might not correlate well with density. Many groups should be involved in research projects. Focus on field testing methods. Sensitivity analysis.

Difficult to get agreement on what soil property should be correlated between different groups.

- Measurement influence depth.
- What do you consider as the depth you want to be measuring?
- Proper soil characteristics and behavior and how it relates to roller MVs.
- Bridging effects?
- Application of IC to different types of materials (natural and recycled materials).
- Cohesive soils.
- Influence of moisture changes with depth?
- How do we get target stiffness? What is a target value?
- Use of Vibratory IC system for unstable boundary conditions (e.g. shallow water table)?
- What is the benefit to contractors?

Equipment Advancements:

- What does the roller give us? Need of real stiffness value.
- Specify the device type to check the roller data.
- Standardizing information from rollers.
- Real-time moisture sensing requirement (GPR, electrical resistivity).
- Repeatability of roller measurements—sensitivity analysis. What is the acceptable amount of variation?
- Goal-oriented compaction system (alarming the operator to stop compaction).
- Real-time data transfer.

Educational/Technology Transfer:

- NCHRP Synthesis project on existing practices.
- NHI courses.
- Different levels of education: operator/contractor, field engineers/owner, specification writers.
- Demonstration projects and shadow projects. Variable soil conditions? Pick some projects that are simple. Money. Not enough variables available at existing project sites. All levels of training and education included. Willing partners and communication. Documentation of demonstration projects. Develop plans. Reasonable expectations (both short-term and long-term).
- Troubleshooting manuals.

Standards/Specifications and Guidelines:

- Specify the device type to check the roller data.
- Specify speed limit and other requirements to be efficient during construction process. Other requirements of record: speed, frequency, amplitude, GPS location, lift thickness, stiffness measurement.
- Specifications on stiffness for acceptance, how do we measure it, and how do we relate those to roller MVs? Depends on the correlations. Need target ranges for stiffness and moisture. What type of stiffness? Who? Owner for acceptance and contractor for process control? NCHRP 21-09 study. Side by side projects. IC and non-IC project demo. Review Europe specifications. Bigger machines and thicker lifts in Europe. Fuel costs.
- Uniformity of response.
- Troubleshooting manuals. Who will pay for trouble shooting?
- Moisture content requirements depending on soil type.
- One number and have roller manufacturer figure out how to get that number.

IC for HMA 1—Tom Cackler (Facilitator), David White (Recorder)

Knowledge Gaps:

- Meaningful data tied to performance. (1)
- Correlation of machine data to engineering properties (methodology). (7)
- What engineering properties should be measured? (4)
- How to deal with depth of IC data? (2)
- Effects of binder grade and aggregate on stiffness data. (2)
- Mixture non-uniformity impact. (1)
- Links system performance to IC data. (1)
- How to integrate data IC and existing measures?
- How does technology affect design?
- Identifying variability of IC results and where to draw line. (3)
- Can IC data be used for acceptance? (1)
- Understanding depth of influence and how to adjust.
- Method for establishing target values?
- Statistical analysis of reliability of current methods. (2)
- Modeling of compaction and cooling mat. (1)
- System for complete data integration. (3)

- Is IC better than current baseline?
- How much IC data, and what kinds are needed?

Equipment Advancements:

- Mapping.
- Mapping underlying layers prior to compaction. (2)
- Corrective action after mapping. (1)
- Real-time data transfer.
- What do public agencies want?
- Uniform accepted and understand IC data. (2)
- In situ compaction test equipment?
- Verification of machine output.

Educational/Technology Transfer:

- Inexperience gap.
- Framework for training. (2)
- QC framework/requirements.
- Software compatibility. (1)
- Hands-on opportunities. (2)

Standards/Specifications and Guidelines:

- Goal is better performance and optimized cost. (1)
- Mapping as QC tool. (2)
- Moving to end-result specifications. (7)
- Structure to minimize risk to contractor and agency—total risk management. (2)
- Model similar w/ Superpave end-result.
- What are we going to put in specification?
- Don't over complicate. (5)
- Define positional accuracy.
- Structure to get broad support.
- Define IC.
- Allow for mix advancement.
- Eliminate definitions. (1)

General:

- FHWA IC project team to help implement IC in 13 states. Focus on four different materials. Experimental plan in place to move project forward.
- Mapping of the existing layers before asphalt construction. Opportunity to evaluate pavement layer system.
- Modeling of asphalt compaction to optimize compaction operations. Cooling.
- Mapping for QC—how to do this in uniform manner. How to specify such that all manufacturers are on level planning field.
- How can we use EED? Are there other tools that we need (nuclear data)? Electronic data integration. Real-time information.
- Hands-on opportunities.
- Huge inexperience gaps.
- Appropriateness of design. How is technology going to affect design?
- Why use density control if measuring modulus?
- How write specifications at high enough level such that contractors-industry-contractor…. performance/end result/warranty specification?
- 80% overlays. When doing overlays map first. Correct bad spots before paving. How do you fix existing before? Corrective action after mapping?
- 50000 ft view. Risk management. Complex. Focus on total risk management. Changes completion of approach. Life of project issues.
- Definitions may become a barrier to advancing practice.
- Need data to convince contractor to use the technology. Show contractor that data is meaningful.
- Years ago used IC HMA in Michigan. Documented everything…temperature, roller… hit it hot…hit it again. Use to optimize process…speed, amplitude, passes. How does stiffness relate to density vs. stiffness? Requirement for initial QC.
- Better performing pavement? Goal is better performance and optimized performance.
- Do we know what we don't know? For HMA—correlation of machine value to engineering properties. Are we measuring the correct engineering properties?
- Knowledge gap—mixture non-uniformity. Just because we can measure it, we need to understand the variability and figure out what is OK. It is a variable product. Even if reduce variability…different temperature during the day. How interpret results? What range of variability is acceptable? Leads to specification development.
- Contractor wants to reduce risk. Owners want better performance. Need IC data that is meaningful and we understand? Understand how much data we need. Just because we can collect, what do we really need? What kind of data?
- How IC applied to overlays versus new construction?

- Lot of data out there. Subbase affects testing. Exactly how do you know what you are getting from base? Depth influence issues. At what point to you stop to define what is really needed? How deal with depth of influence?
- Software…AutoCAD. Make work with something else? Education between designers and contractors and industry. Compatibility.
- Relationship to quality pavement. If does not improve quality what is point? Meaningful data tied to performance.
- Education standards. How will training and guidelines be handled? Framework for training.
- Data transfer. How get info rapidly? Cell phone issues (GPS). Real-time data transfer?
- Need to change vocabulary. Is density the right parameter to measure? Working with huge variables—crushing, weather, etc. Hope to have an averaging product. Risk involved. Eliminate risk to contractors. Structure to minimize risk to contractor and agency.
- Specs! How we get paid and how owner is comfortable. Need to get past nuclear density gauge. If IC machine works better process control. Owner gets past phobia of changing what they are measuring. Use IC measurement values for QA?
- Correlate between IC measurement values and specifications that are being asked for. How do we capture the methodology for correlation?
- Need specification and standardization of equipment. Can't do this unless we know what we need to measure. Equipment dollars. Don't want to invest $ if not going to be used in acceptance. End result specifications. Superpave…done on federal end otherwise each state going to do something different.
- Some DOTs don't want warranty projects. Relation to IC.
- What about warm mix asphalt? Need specs to reflect mixture technologies.
- Affects of binder grade on stiffness results.
- Can't have standardized framework. Somewhat standardized.
- Superpave is a QC/QA process. Concerned about geotech group. NCHRP superpave process to establish specification. End-result. How to use outside the box? Eliminate density? How measure stiffness? How on asphalt? LWD? Stiffen binder changes target.
- Depth affects and area of influence under machine. As vector of drum changes measurement influence dept changes. Mn/DOT 1.5 inch layer. Need to know what you are on top of. Try not to over complicate this thing. Don't really have a lot of data for HMA. Need to have practical amount of data. OK for research, but need to get to final result.
- Risk management. That's where this comes from. Proof. How much data do we need? Enough to provide it to manage risk. Maybe we don't need all passes and all data. Lower bonding costs. It has to last 10 years. You have proof along the way. Everyone has to agree on map as it covers the data.

- Identifying the affects of mixture non-uniformity on IC values?
- Accuracy? How accuracy is accurate enough. GPS? Millimeter precision with base station critical? Define tolerances and position accuracy.
- Define IC for HMA. Different between different machines.
- Using the field IC results to system behavior. Linking system performance to IC data.
- Methods for establishing target values.
- Verify machine IC results?
- Don't get too complicated. If trying to sell new idea, easier if simple. Get more people on board.
- Format and output of data.
- System approach to data management. Info from batch plate, etc.
- Is IC better than conventional? Early evidence says yes, but need more baseline projects with success.
- Companion tests for asphalt. What about other tests for asphalt? How measure modulus? In situ companion test equipment.
- NCHRP 10-65. Out in the next month.
- What is important to public agencies in terms of output?
- Over confidence. Need solid statistical analysis as part of specification.
- Moving to end-result specifications: Complicated because of system issues. Contracting may not be suited to this approach for IC HMA? We know the performance design parameters such as strain at base of pavement layer…Roller operator needs to know if he is on it at right temperature. NPA has a program. How do we relate this information to agency? All of the above are tied together. What are the first generation IC specifications going to look like? Use a shadowing concept. Superpave projects decide that there would be projects…couple interstate, county, etc. with bid item for reimbursing contractor. How do we build confidence? Rapidly. No state ready to write specification. What does shadow concept measure? Make relationship between what IC can provide and what current known performance parameters are and current QC/QA protocols. What info is important to get from roller? Temperature, mapping, and modulus.
- First generation end-results shadow with temperature, mapping, stiffness, speed, frequency, amplitude (data set to capture). Keep the current acceptance criteria. Need to map underlying stiffness. Keep current acceptance criteria, shadow concept, current IC methods, temperature, mapping, stiffness data (map underlying support layer), speed, frequency, amplitude
- Correlation of machine data to engineering properties (methodology): Engineering properties (Density, temperature), Statistically valid plans, Different mix designs—overlay, warm mix, hot mix, different underlying ground stiffness conditions, Map all data? Current projects with Ham don't necessarily include mapping. Need to move beyond volunteer effort to build these requirements into specifications.

- Don't over complicate.
- What engr. properties should be measured?

IC for HMA 2—Lisa Rold (Facilitator), Paul Weigand (Recorder)

Educational/Technology Transfer:

- Up to now, industry has driven. Contractors and equipment folks are key.
- If we go to QA, agencies will need to be more involved.
- Comparative data to ensure that the contractors can make incentives.
- How do the mix characteristics impact the results?
- Does a brand of roller impact the results?
- Develop coordination with equipment manufacturers.
- Identify whether all equipment needs the IC or just isolated pieces.
- Is wireless communication in real-time transmitted over the internet an important item to include?
- Determine method of determining mat uniformity and measurable criteria.
- Hands on demonstrations for contractors, not workshop format.
- Use pool fund website to get info out.
- Emphasize the value to both contractors and agencies in price adjustments and quality of pavement.
- Share the knowledge.

General:

- Concern over costs—what are they? Costs vary. GPS: $20,000; Base station: $15,000. IC product costs: $25,000
- Can IC systems be adapted to older equipment? May be difficult because of the complexity of the drum equipment.
- Consideration must be given to vandalism and weatherproofing.
- Differences in process and quality of measurements make it difficult to write a spec. Could this be handled by using test strips? Stiffness connection to density and permeability is a question.
- Some states are writing permeability specs.
- Need to develop that connection from machine information to good pavement.
- If only used for QC, no specifications are needed. Contractor use only, but they must see value
- Each project must be run as an isolated system related to density and permeability. Do test strip evaluation prior to the project so cores and other verification methods can be used.

- Stiffness and roller speed measurements are important, in addition to temp and number of passes. Speed especially important to DOT folks.
- Should all rollers have the equipment? DOT reps said yes in order to verify the quality.
- Can the ultimate density be predicted based on the breakdown roller activity? That is the assumption since the finish roller does not vibrate.
- Temperature is critical as it relates to final roller—that is a gap now. Monitoring of core temperature on all rollers will tell when to start and stop rolling.
- Will IC rollers be able to identify mix segregation since that will impact density? Equipment people say no.
- What information is of greatest value to operator? Stiffness corrected to core temperature.
- What is the program needed to make it a QA for DOTs? What is the correlation from stiffness to density? Research has developed one.
- Can there be an algorithm developing density output—yes say equipment people but only on vibratory equipment.
- Common/standard language related to machine language could be valuable in writing spec. Also universal file format for machine output.
- Current acceptance is based on density of cores (primarily) or nuclear density gauge.
- Are the agencies ready to pay for the use of IC equipment as a bid item to jump start use? Some DOT, will others not.
- Concern over frequency of calibration for the equipment? Equipment people say that the accelerometer annually. Also that is taken into account as the job setup with the project mix calibration.
- Will agencies start to require IC? The FHWA pooled fund project will establish baseline information. Minnesota has required it for earthwork, not HMA.
- Where to go—focus on QC initially to get data then for potentially QA. Must identify benefits to contractors initially.
- Where is the best place in the construction process for IC? Breakdown roller gets about 90% of the density.
- Internet transfer of information is a possibility.
- QC elements: speed, modulus, passes, temperature, density, accuracy of mapping (GPS) – lateral is more critical than longitudinal
- Questions: Take IC from QC to QA? Correlation between field info and performance values. Uniform reporting system across equipment. For instance, currently accept contractor's smoothness traces.
- How do we add the incentive to use IC? Have IC as a pay item? Recognize better pavement value from mat uniformity and lack of coring.

- Research priorities (in order of voting). Identify whether all equipment needs the IC or just isolated pieces of the roller train. Is it possible to incorporate rolling weight deflectometer? How do the mix variables and characteristics impact the results? Databases developed by agencies showing what works and what doesn't. Develop a measure of mat uniformity. Develop system to transmit IC data in real time over the internet to servers or laptops. Develop retro fit equipment for existing rollers. Develop coordination between equipment manufacturers related to uniform language. Correlate IC with long-term pavement performance. Not just material testing, but modifying the complete construction process/ operation.

IC for HMA 3—Tom Cackler (Facilitator), David White (Recorder)

Knowledge Gaps:

- What is ultimate goal in field, and how does it relate to current acceptance. (3)
- Validate applicability as QA tool. (1)
- Non-correlations of IC data to density. (7)
- Correlation of field IC data to design parameters (combine above).
- Is measuring stiffness important. (1)
- What do we measure that relates to quality and life of road? (2)
- How do we use IC data considering depth of influence? (7)
- Where is IC best used. (1)
- Where is IC best used—size, base conditions, overlays, etc. (1)

Equipment Advancements:

- Correlate surface temp to internal temperature including time, internal temp, roller passes. (6)
- How to incorporate to existing equipment. (1)
- Can agencies use IC to evaluate existing pavements? (1)

Educational/Technology Transfer:

- Agency and contractor IC 101. (1)
- Communicate opportunities with IC.
- Harmonization of definitions and technology. (1)
- Economic benefits. (2)
- Benefits from contractor's perspective (combine above).

Standards/Specifications and Guidelines:

- Standard calibration method. (3)
- Begin w/ contractor to use—transition.

- Allow for contractor QC plans to accommodate variations in equipment. (2)
- What project size to use.

General:

- Mat temperature—get at internal temperature from surface temperature. Gives the roller operator more flexibility. Time + temperature + number of passes.
- Training for contractors/operators/state DOT people—broad-based education. “IC 101”.
- Roll immediately after construction at cooler temperature. Useful for future rehabilitation?
- What do we ultimately want to measure in the field? What is our ultimately goal in the field. How do we use the information in conjunction with what we are doing now?
- What are we trying to do? Under education—show me some projects with respect to correlations? More correlations studies. Communicate opportunities w/ IC.
- Depth of influence issues. 1 -3m? How do I restrict to thin lifts.
- Lots of milling and resurfacing. What do you hold contractor responsible to.
- Any info available now…large paving contractors using…mat temperature? Want benefit-cost analysis.
- Can IC be used as a QA tool?
- Standard calibration method.
- Where is IC best used?
- Appears that there is not a good correlation between stiffness and density? Go way you trust IC alone. Maybe mapping is the best tool.
- Allow either or. May take 20 years to implement. What about existing equipment? Begin with contractor option to use—transition.
- Contractor submits QC plan for review. 30 days to review. Allows it to be flexible. If they don’t follow their plan then not pass.
- How does this relate back to the things we designed for? Are we looking at the right parameters? Relation to design parameters.
- How does subgrade affect HMA design?
- Is there a point where this is not appropriate (e.g., 2 inches of HMA of concrete overlay?) Need to select appropriate technology.
- How will we get measurements that go over state lines? Will specifications be recognized state to state so contractor’s equipment is widely useful?
- Custom specifications for each manufacturer? Some flexibility to contractor.
- Use IC to identify areas for strengthening.
- Size a project an issue? Minimum size to require?

- It would be interesting to get inspector input. Compare the inspector's observations with IC mapping capability.
- How do adjust HMA for pre-existing base conditions?
- Do the readings relate to how long the road last? Need to know what to measure to relate to the quality and life/performance of road.
- Economic of IC? If show that it has a financial advantage, then going to be a lot more popular.
- How to judge the quality the HMA layer, especially considering variability of underlying layers. Is measuring stiffness for HMA important?
- Need to harmonize—dictionary of terms. This is how the parameters relate.
- Doing it before the fact. Roll in low-vibe and combine with GPR to get existing info.
- New technology with great opportunity. Can add IC to existing equipment? What is the key—temperature or roller operations. Can you upgrade existing rollers?

IC for HMA 4—Lisa Rold (Facilitator), Paul Weigand (Recorder)

Knowledge Gaps:

- Research/Gaps (in order of voting): Develop correlation of IC technology with stiffness, density, modulus. For acceptance criteria use mapping of existing pavement and % improvement rather than smoothness. Use method spec vs. results spec. Determine the flexibility of IC relating to construction variability related to mix design and type of roller use.

Educational/Technology Transfer:

- Industry based for contractors is best because it is targeted to the equipment and what is important.
- Demonstration projects/open house information posted on the pooled fund website (www.intelligentcompaction.com).

General:

- Need incentive for contractors to get involved.
- How do you write a spec when knowledge isn't there?
- Add $$ to bids to get contractors to make the investment in equipment.
- Compare real field data and IC data.
- Measure what is important, not necessarily what has been measured in the past.
- Agencies need to define the parameters to develop uniformity across equipment.
- Standard method of implementing change must not be used. Work together between agencies and contractors.

- Break down implementation into steps of mapping (number of passes); temperature; and then stiffness.
- Shadow existing density verification work with IC to show the correlation and use a proof testing.
- Iowa contractors like to use pneumatic rollers to improve density, and it is important to determine the impact of pneumatic rollers on stiffness.
- Roller patterns and types of rollers will vary according to states and mix designs. For instance, roller sizes vary, use of pneumatic rollers, use of vibratory or static, etc.
- Roller speeds will impact stiffness results, although generally stiffness is mix dependent.
- Does stiffness from design and lab correlate with field measured stiffness across machines?
- What methods are best to relate machine information to stiffness? Different equipment developers use different methods.
- IC identifies weak spots that can be worked before the final paving operation. Also could be used to determine weak spots before paving.
- Use finish roller at low vibration to verify final results.
- Concern over differences in information provided by different pieces of equipment starting with the quality of the accelerometer and the algorithms used to convert the data into stiffness.
- Manufacturers would like to be told of the design characteristics (stiffness, modulus of elasticity, etc.) to target.
- Mapping, temperature, stiffness (density) are major issues to be included in IC.
- Manufacturing groups are the ones that are currently pushing the technology of IC. If it gets to QA, the agencies must get involved.
- Activities with IC must be flexible enough to accept changing technologies, such as mix (warm mix asphalt) and others.
- Is there a mechanism to get IC output from a pneumatic roller?

Implementation Strategies 1— Douglas Townes (Facilitator), John Puls (Recorder)

Knowledge Gaps:

- Collaborative design between contractor and designer. (2)
- Need a better tool for measuring existing conditions; pre-design. (6)
- Which standard to use? MEPDG. What are IC measurements going to be?(8)
- Equating measurement tool to design life/quality. (7)
- Is there a better way to measure compaction than what we already know? (2)

- 3/4D design lacking. (5)
- What stiffness values are we shooting for? How consistent is consistent? What are the target values? Stiffness/uniformity. Clay soils have more unknowns than granular soils. (9)
- IC machine data acceptance.
- IC machine data trust. (4)

Equipment Advancements:

- Moisture sensors in real-time. (13)
- GPS communication between manufacturers. (2)
- Sharing data wirelessly. Wireless real-time communication between operator and inspector/contractor management (office). Sharing operator data via wireless to other operators/foremen (portable) (9)
- Method of marking problem areas. (6)
- Padfoot compaction in cohesive soils. Measurement tool for cohesive soils is needed. (12)

Educational/Technology Transfer:

- Construction inspector training, design staff training, DOT materials group (training on acceptance), upper management (DOT), operator through owner education (contractor), venders understanding of DOT role in the process.
- Knowledge of different available equipments.
- Learning to interpret data and work with contractor. (14)
- Acceptance standards. (15)
- Data processing/storage training. (1)
- Meaningful pre-design data to contractor (geotechnical data). (2)
- Soil identification (physical). (6)
- Interpretation raw data to meet state specifications: How to correct a failure? Critical thinking for corrective actions tying experience-based knowledge to IC technology. (9)
- Sharing of general knowledge/information. (1)
- Cross-communication between manufacturers. (1)
- Common official universal standard and terminology. (11)

Standards/Specifications and Guidelines:

- Standardizing data formats. Data to the contractor and data coming back from contractor.
- Deciding what to measure: How often? How accurately?
- Placing more risk onto contractor: Low control over on-site soils, performance-based specs.
- Specifications must evolve slowly.

- Uniformity is more important than absolute measurements.
- Would you (contractor) buy IC based on end-result specification?
- Variability in IC values determined by site conditions: Before and after rain: Will contractor be paid to re-do work? Contract end date does not change.
- Incentives for contractor. Incentives for increase quality.
- DOT: Writing incentives so that it's profitable for contractor to increase quality. Minimum level for compaction value and a bandwidth for uniformity. Higher incentives for better uniformity.

General:

- Challenges: Getting contractors on board to use IC on HMA.
- What's in it for the taxpayer? Road lasts longer, safety, smoother, higher quality, decrease in lane-closure time, savings $.
- What's in it for the agency? Inspection costs, complete coverage, risk management, 100% coverage on inspection, less reliance on nuclear density measurements, public safety, facilitate change in technology, decreased maintenance costs, longer lasting pavements, better designs, construction costs,
- What's in it for the contractor? Compliance documentation, potential to increase productivity, employees have a career instead of a job, training, specialization, pride, increased communication, increased cross-training opportunities, increases responsibility of roller operator, potential for increased incentives, and data gives worker feedback for a good job.
- New industry: major financial companies can get into insurance of roads. Differing premiums. Insurance rather than warranty: potential for increased sales.
- Design tools, education, training and specifications.

Implementation Strategies 2—Heath Gieselman (Facilitator), Jerod Gross (Recorder)

Knowledge Gaps:

- Contractor motivation/incentive. (1)
- Communication from design through construction (plans and specs).
- Little experience with technology. (7)
- Standardization of industry for QA (long term). (5)
- Correlation between machine values and actual properties. (12)
- Proven technology.
- Upgrades in machinery and software. (2)
- Need to identify knowledge gaps in asphalt and soils separately. (6)

- Definition of equipment terminology and defining accuracy.
- What is our goal? QA or QC?
- Communication with industry of implementation plan.
- Cost of training.
- Integration of technology.
- Contractors should share knowledge.
- Translation of data to determine acceptance.
- Proper site selection for demo projects.
- Define acceptance limits.

Equipment Advancements:

- Need for rollers to measure all properties including internal temperatures. (1)
- Needs to be user friendly & ergonomics. (4)
- Initial cost.

Educational/Technology Transfer:

- Phased implementation of IC. (3)
- Document design/build projects.
- Contractors should share knowledge.
- Advertise IC through select projects. (2)

Standards/Specifications and Guidelines:

- Incentive or directive needed. (3)
- QC easier to implement. (2)
- QA requires development of specs. (1)
- IC not specified but is an advantage to contractors. (2)
- Dissimilarity of roller outputs for soil and asphalt. (6)
- Standardize data output.

Facilitator Report–Summary

The results of the breakout sessions were analyzed to identify the priorities for advancement in the outcome areas of "Knowledge Gaps," "Equipment Advancements," "Educational/ Technology Transfer," and "Standards/Specifications and Guidelines" for each of the topics areas: "IC for Soil and HMA," "IC for HMA," and "Implementation Strategies." Prioritization was determined based on a detailed review of the recorder notes, finding common topics among sessions, and summarizing the participant votes. There were two levels of analysis of the results: (1) prioritize the results for each topic area, and (2) develop a broader top 10 list of key issues for needs and accelerating implementation of IC technologies.

The top priorities for each breakout session topic are summarized in the following:

IC for Soils and Aggregate

Knowledge Gaps

1. Correlation Studies: Different Soil Types (Granular, Cohesive, Recycled, Stabilized) and different Roller Configuration (Smooth, Padfoot) (73)
2. Rapid in situ w% determination (14)
3. Modulus-based QC/QA (12)
4. Understanding what IC-MVs are? Experience (10)
5. Measurement influence depth? (7)
6. Acceptable non-uniformity? (4)
7. Trouble shooting—unusual conditions, machine capabilities, and limitations. (3)
8. Data visualization. (1)
9. Benefits? (1)

Equipment Advancements

1. w% measurement on roller. (29)
2. Integrated solutions between multiple technologies (3D Design - 4D Construction). (18)
3. Real-time data transfer/wireless. (14)
4. Retrofit systems. (3)
5. Repeatability/sensitivity of IC-MVs. (2)
6. Compaction diagnosticsred—flag indicator. (2)
7. On-site geotechnical lab. (2)

Education/Technology Transfer

1. Contractor/field engineer/owner training. (52)
2. Opportunity to promote good geotechnical practices. (13)
3. Cost/ROI. (11):
4. Equipment investment.

5. Field implementation.
6. Proven case histories to "sell" the technology (effectiveness to quality/efficiency). (9)
7. Definitions of IC terminology. (3)
8. Operator/inspector guide & troubleshooting manuals. (3)
9. Certification for contractor. (1)

Standards/Specifications and Guidelines:

1. Uniformity criteria. (20)
2. Selecting engineering parameters to measure (e.g. density, modulus, stiffness). (19)
3. Consolidate IC-MVs to one unified parameter or report raw accelerometer data. (11)
4. How will w% be specified? (5)
5. Contractor/owner/researcher/manufacturer input for specification development. (4)
6. Establishing IC target values/test strip guidelines. (1)
7. Establish IC documentation standards (GPS and output parameters). (1)

IC for HMA

Knowledge Gaps

1. Correlation of IC-MVs to engineering properties. (39)
2. Understanding IC-MV non-uniformity (mixture). (10)
3. Measurement influence depth/adjustment. (9)
4. Key in situ engineering parameters to measure. (7)
5. Mix design, binder grade, and aggregate on IC-MVs. (5)
6. Benefits of IC and reliability of current methods. (5)
7. Data integration. (3)
8. Link between IC-MVs and performance. (4)
9. Best applications for IC (e.g., overlays, HMA). (2)
10. Applications for IC for QA. (1)
11. Modeling of compaction and cooling mat. (1)

Equipment Advancements

1. Involvement of roller train or just the breakdown roller. (14)
2. Influence of temperature (surface /internal), compaction time/speed, frequency/amplitude, and roller passes. (6)
3. Retrofit. (5)
4. Real-time data transfer. (5)
5. Mapping of underlying layers and existing pavements. (3)
6. Similarities between IC output. (2)
7. Corrective action after map. (1)

8. Compare mapping of IC and pneumatic roller. (1)
9. Integrated systems approach. (1)

Education/Technology Transfer

1. Demonstration projects, open houses, and hands-on opportunities. (10)
2. Documented successes. (4)
3. Establish framework for training contractor/owner. (3)
4. Economic/contractor benefits. (2)
5. Software compatibility (design, machine, analysis). (1)
6. Harmonization/standardization of technology. (1)

Standards/Specifications and Guidelines:

1. Establishing QC and QA criteria and framework. (9)
2. End-result specifications. (7)
3. Keep it simple. (5)
4. Standard calibration method to establish IC and in situ target values. (3)
5. Mapping as QC tool. (2)
6. Structure to minimize risk to contractor and agency—total risk management. (2)
7. Allow for contractor QC plans to accommodate variations in equipment. (2)
8. Goal is better performance and optimized cost. (1)
9. Better define IC (0) & Eliminate IC definitions. (1)

Implementation Strategies

Knowledge Gaps

1. Correlation between roller MVs and soil properties. (12)
2. Demonstration projects. (11)
3. What stiffness value? (9)
4. Relation to MEPDG parameters. (8)
5. NCHRP synthesis of existing practices. (7)
6. Design life/quality. (7)
7. 3/4D design. (5)
8. FHWA IC pooled fund. (4)

Equipment Advancements

1. Moisture sensors in real-time. (13)
2. Padfoot compaction in cohesive soils. (12)
3. Real-time data transfer/wireless. (9)
4. Method of marking problem areas. (6)

Education/Technology Transfer

1. Data interpretation. (29)
2. Common standards. (17)
3. NHI training courses. (5)
4. IC 101. (4)
5. Knowledge sharing by contractor. (2)

Standards/Specifications and Guidelines:

1. Partnerships/Communication. (4)
2. Incentive or directive needed. (3)
3. QC easier to implement. (2)
4. QA development. (1)

After analyzing the topic-specific results, an effort was made to find common needs across the topics areas and prioritize a top 10 list of overriding needs. The cross-cutting top 10 list of priority issues are summarized in Table 2.

Table 2. Summary of main IC technology research needs

Top 10 IC Technology Research Needs

1. **Need correlation studies (cohesive, stabilized, granular, HMA, etc.) (136)**
2. **Education/training materials and programs (112)**
3. **Moisture content (influence + measurement) (61)**
4. **Integrated design + real-time data transfer (57)**
5. **Case histories + demos + benefit + successes (48)**
6. **Engineering parameter to measure (density, modulus, stiffness, core mat temperature)? (47)**
7. **Addressing non-uniformity (34)**
8. **Establishing QC/QA framework - statistically significant (28)**
9. **Measurement influence depth? (19)**
10. **Promoting good geotechnical practices (13)**

Panel Discussion

A panel discussion was held on day three for one and a half hours and moderated by Max Grogg. Panel members included Chris Connolly, Lee Gallivan, Khalil Maalouf, Dean Potts, John Smythe, Stan Rakowski, and David White. The aim of discussion was to reflect on the outcomes determined from the breakout sessions and what was learned for the workshop that may have changed perspectives on intelligent compaction technology. Questions from the audience followed on specification needs and new technology developments. The discussion points are divided into four categories: reaction to breakout sessions, new perspectives, specifications, and technology developments. Each of these categories is summarized below.

Reaction to Breakout Sessions

- Facilitators boiled information down to a few keys items that should be the focus of research.
- Exciting from manufacturer perspective to see high level of interest.
- Established a good baseline for technology and current state of implementation.
- Lots of opportunities ahead for implementation of IC and 3D/4D GPS technologies.

New Perspectives

- Significant level of interest from state DOTs.
- IC technology is further along than previous thought.
- Implementation should build on existing knowledge.
- IC is not going to change fundamental properties of soil (moisture content) or HMA (temperature, gradation). Therefore, can't replace good geotechnical and materials engineering.
- Tremendous potential for IC in QC applications and may become QA tool in the future, but will require courage and effort to change.

Specifications

- A question that still needs to be answered - what are the important properties to measures?
- Some specifications are being written as part of ongoing research projects, and Mn/DOT has implemented a specification(s) on actual projects for soils and aggregates.
- Several European specifications exist for continuous compaction control (CCC).
- IC specifications may eliminate unneeded testing by the QA agency.
- Machine specifications are needed.
- During early implementation, having some flexibility to revise the specification during the course of the project to make improvements may be an effective strategy to faster implementation.
- Contractors and state DOTs need to be educated on how IC can be used as a QC/QA tool.
- Calibration of the machine IC values to spot test measurements needs to be defined.

- With respect to IC standardization, need to allow the manufacturers to be innovative and not close the box too quickly with standardization.
- Focus the specification around rapid detection of road problems.
- Premature failure like HMA segregation is not a condition that IC measurement will necessarily detect, and thus inspectors and independent spot measurements will always be needed.
- The contractors need to be engaged in this process to determine what level of risk is being shifted with IC.

Technology Development

- What are next steps to develop onboard moisture and temperature sensors?
- Resolution of GPS-based maps need to be relatively accurate and precise to correlate with in situ spot test measurements.
- New sensors are needed to measure soil moisture content and are an area of ongoing research.
- Asphalt surface temperature is relatively easy to measure; the critical mat temperature is much more difficult to determine but good goal and challenge.
- Surface temperature can vary widely; therefore, internal mat temperature is needed.
- There are many factors that affect mat temperature, including several environmental factors, and it is not a trivial problem to solve.
- Core temperature could be measured with probe system. Heat loss occurs through the top and bottom of the mat is an issue
- Surface temperature combined with analytical model and onboard computer calculations may be useful. Some experimental research is underway with this effort to measure core mat temperature
- Manufacturers cannot solve all the issues.
- Collaborations and partnership are needed to identify critical needs and move technology implementation forward.

Summarizing the panel discussion comments, there are four central discussion points that were condensed as shown in Table 3.

Table 3. Summary of common themes from panel discussion

Common Themes from Panel Discussion Session

1. **High level of interest from the state DOTs in further studying opportunities to implement IC.**
2. **Implementation strategies need to build on existing information and past research.**
3. **Specifications for IC and in situ testing should not restrict manufacturer/equipment developer innovations.**
4. **Contractor and state DOT field personnel and engineers need educational materials for IC and in situ QC/QA testing.**

Group Exercise to Identify Implementation Strategies

Following the panel discussion, the audience was given instructions to break up into seven- to ten-person groups representing the contractor, manufacturer, or state DOT perspective. There were two groups for each category. Each group had representatives from the three positions. The groups were charged with looking five years into the future and brainstorming reasons why implementation of IC was successful. The question posed to each group was:

What specifically did you do to implement intelligent compaction technologies on projects, and why were you successful?

Each group designated a leader to present the results to the audience after a 20-minute brainstorming session. The groups' comments are summarized below by category.

Contractor Perspective

- Became more aware of IC technologies.
- Completed IC projects.
- Contributed to standardizing IC and it becomes part of normal operations.
- 30% of state DOTs now use IC.
- IC roller operators become certified.
- IC became common practice with the benefits being realized by documenting savings (no rework or overwork and fuel savings).
- Reduced risk and increased confidence in results and better process control.
- Developed a common language with state DOTs such that IC is accepted and understood.
- Further developed electronic plans implementation.
- Feel comfortable with IC measurements and eliminated barriers with a research program.

Manufacturer Perspective

- Soil moisture content measurement system was developed.
- HMA core map temperature measurement/analysis was solved.
- Common software was developed that meets the needs of the IC roller operator and state DOT inspectors.
- The roller IC computer interface was improved.
- Successful marketing.
- Collected feedback from owners and agencies to discuss issues and what is possible.
- Helped promote research and partnerships.
- Selected high profile demonstration projects.
- Listened to needs of state DOTs and contractors.

- IC certification over the winter months was developed as a joint venture between academia/state DOT/AGC.

State Agency Perspective

- IC was implemented early on projects with the right people, right project conditions, and reasonable cost.
- IC projects demonstrate that the final products are more consistent, there are less maintenance problems, reduced construction costs, and less routine inspection testing.
- More QC/QA information exchanging during the construction process.
- IC education was significantly improved.
- The top 10 list of research needs identified from this workshop were implemented.
- Reduced number of claims.
- DOT became better organized with more open communication.
- Encouraged participation from contractors/AGC/industry during the process of implementation of IC.
- Let several IC demonstration projects and partnered with successful contractors, university researchers to collect and analyze data.
- Clearly showed the benefits of IC measurements for QC.

Some common themes between the groups were identified as key implementation strategies as shown in Table 4.

Table 4. Summary of common themes from the group implementation strategy session

Common Themes from Group Implementation Strategy Session
1. Develop IC training and certification program.
2. Demonstrate benefits of IC through demonstration projects.
3. Promote partnership as key strategy to implementation.

Outcomes

The key outcomes from this workshop were as follows:

1. Technical information exchange.
2. Prioritized lists of knowledge gaps, education/technology transfer needs, specification and standards, and implementation strategies for IC for soil and aggregate and HMA.
3. A list of the top 10 overriding issues was developed that cut across the various IC technologies and materials.
4. Establishment of a network of people interested in partnership and implementation of IC technologies, specifications, and new developments with in situ testing.
5. Plans for a follow-up workshop to explore further IC technologies, in situ testing alternatives, educational/training program, and other earthwork technological advancements.

Next Steps

The IC workshop provided a baseline for stakeholders to provide input on current state of the practice/technology and next steps in terms of research and educational priorities and implementation strategies. At the conclusion of the workshop, a discussion centered on understanding where we are and where we are going. Table 5 summarizes some of the key points.

Table 5. Summary of key points

Where we are:	Where we are going:
• Lack widely accepted IC specifications in U.S. • Need education/training materials • Innovative IC and in situ testing equipment • IC technologies provide documented benefits (smooth drum - granular) • Great potential and some limited successes for cohesive and HMA • Poor database development for IC projects and case histories • Initiated human IC network • Increasing acceptance/GPS infrastructure for stakeless grading/machine guidance • "Don't know what we don't know"	• Standardized and credible IC specifications inclusive of various IC measurement systems • Widespread implementation of IC technologies • High quality database of correlations • Several documented successes for cohesive/stabilized/granular/HMA • Better understanding of roadway performance - what are key parameters? • Innovative new sensor systems and intelligent solutions • Integrated and compatible 3D electronic plans with improved processes, efficiency and performance • Real-time wireless data sharing • Enhanced archival and visualization software • Improved analytical models of machine-ground interactions

To move from the current practice and knowledge base several key strategies were considered and are listed in Table 6.

Table 6. Strategies for moving forward

Strategies for Moving Forward
• Participate in partnerships for IC research and information exchange regionally and nationally
• Be an advocate for IC implementation
• Contribute to problem statement development for NCHRP, TRB, FHWA, AASHTO, ASCE Committees
• Participate in IC conferences/studies and the annual EERC Workshop
• Participate on EERC Scientific and Policy Advisory Council (35 members) – IC and other issues
• Stay connected: Subscribe to EERC Technical Bulletins, Tech Transfer Summaries, Technical Reports, Educational Videos, etc. (www.intelligentcompaction.com).
• Develop a comprehensive and strategic IC road map for research and educational/technology transfer

Although with many of these strategies it is clear how to move forward, developing a comprehensive road map for implementation of IC technology is a strategy that will require further input from many stakeholders, brainstorming events, problem statement identification, and research action plan development. Results from this workshop, however, provided significant information to outline a preliminary road map that can serve as a starting point for further discussions and assessment.

The vision for the road map is to identify and prioritize action items that accelerate and effectively implement IC technologies into earthwork and HMA construction practices. Coupled with the IC technologies are advancements with in situ testing technologies, data analysis and analytical models to better understand performance of geotechnical systems supported by compacted fill, software and wireless data transfer, GPS and 3D digital plan integration, new specification development, and risk assessment. What follows in Table 7 is a preliminary road map for implementation of IC technology based on information derived from the workshop sessions and the author's viewpoint.

Table 7. IC road map research and educational elements

IC Road Map Research and Educational Elements

1. **Intelligent Compaction Research Database.** This research element would define IC project database input parameters and generate web-based input protocols with common format and data mining capabilities. This element creates the vehicle for state DOTs to input and share data and an archival element. In addition to data management/sharing, results should provide an option for assessment of effectiveness of project results. Over the long term the database should be supplemented with pavement performance information. It is important for the contractor and state agencies to have standard guidelines and a single source for the most recent information. Information generated from this research element will contribute to research elements 2 through 5.
2. **Intelligent Compaction and In situ Correlation Studies.** This research element will develop field investigation protocols for conducting detailed correlation studies between various IC measurement values and various in situ testing techniques for earth materials and HMA. Standard protocols will ensure complete and reliable data collection and analysis. Machine operations (speed, frequency, vibration amplitude) and detailed measurements of ground conditions will be required for a wide range of conditions. A database and methods for establishing IC target values will be the outcome of this study. Information generated from this research element will contribute to research element 1, 4, and 5.
3. **Project Scale Demonstration Case Histories.** The product from this research element will be documented experiences and results from selected project level case histories for a range of materials, site conditions, and locations across the United States. Input from contractor and state agencies should further address implementation strategies and needed educational/ technology transfer needs. Conclusive results with respect to benefits of IC technology should be reported and analyzed. Information from this research element will be integrated into research element 1, 4, and 5.
4. **Intelligent Compaction Specifications.** This research element will result in several specifications encompassing method, end-result, and performance-related options. This work should build on the work conducted by various state DOTs and from ongoing research as part of NCHRP 21-09 and the ongoing FHWA IC Pooled Fund Study 954.
5. **Educational Program/Certification Program.** This educational element will be the driver behind IC technology and specification implementation. Materials generated for this element should include a broadly accepted and integrated certification program than can be

delivered through short courses and via the web for rapid training needs. Operator/inspector guidebook and troubleshooting manuals should be developed. The educational programs need to provide clear and concise information to contractors and state DOT field personnel and engineers. A potential outcome of this element would be materials for NHI training courses.

6. **Understanding Roller Measurement Influence Depth.** **Potential products of this research element include improved understanding of roller operations, roller selection, interpretation of roller measurement values, better field compaction problem diagnostics, selection of in situ QA testing methods, and development of analytical models that relate to mechanistic performance parameter values. This element represents a major hurdle for linking IC measurement values to traditional in situ test measurements.**
7. **IC Technology Advancements and Innovations.** **Potential outcomes of this research element include development of improved IC measurement systems, addition of new sensor systems such as moisture content and mat core temperature, new onboard data analysis and visualization tools, and integrated wireless data transfer and archival analysis. It is envisioned that much of this research will be incremental and several sub-elements will need to be developed.**
8. **In situ Testing Advancements and Mechanistic Based QC/QA.** **This research element will result in new in situ testing equipment and testing plans that target measurement of performance related parameter values including strength and modulus. This approach lays the groundwork for better understanding the relationships between the characteristics of the geo-materials used in construction and the long-term performance of the system.**
9. **Data Management and Analysis.** **The data generated from IC compaction operations is 100+ times more than tradition compaction QC/QA operations and presents new challenges. The research element should focus on data analysis, visualization, management, and be based on a statistically reliable framework that provides useful information to assist with the construction process control. This research element is cross cutting with research elements 1, 2, 3, 5, 7, and 8.**
10. **Understanding Impact of Non-uniformity of Performance.** **This track will investigate relationships between compaction non-uniformity and performance/service life of infrastructure systems—specifically pavement systems. Design of pavements is primarily based on average values, whereas failure conditions are affected by extreme values and spatial variations. The results of the research element should be linked to MEPDG input parameters. Much needs to be learned about spatial variability for earth materials and HMA and the impact on system performance. This element is cross cutting with research elements 4, 5, and 9.**

The research elements above represent a first step in developing a formal research road map for implementation of IC technologies. Additional steps beyond fine-tuning the research elements will be developing an integrated research management plan, seeking peer review, establishing a schedule, and identifying organizations, contractors, and equipment manufacturers that want to partner and leverage funding and human resources to move the program forward. The Earthworks Engineering Research Center (EERC) Scientific and Policy Advisory Council (35 members representing government agencies, industry, and researchers) is one entity that can contribute to provide peer review and management of this effort. The council membership was discussed at the workshop, and the membership is being identified. Follow-up correspondence to the workshop attendees will transpire with respect to this report, the council, and the 2009 annual EERC workshop meeting.

Appendices

Appendix A: Workshop Agenda

Intelligent Compaction for Soils and HMA
April 2–4, 2008
Sheraton Hotel, West Des Moines, Iowa

Sponsors: Iowa Department of Transportation and Iowa State University Earthworks Engineering Research Center (EERC)

Mission: Building upon current knowledge and experience, this workshop will provide and record a collaborative exchange of ideas for using design tools and intelligent compaction technology for measuring and documenting performance and quality characteristics of soils, aggregates, and hot mix asphalt that are verifiable and appropriate for use for contractor quality control and owner acceptance decisions.

Day 1—Wednesday, April 2, 2008

6:30 a.m. **Breakfast and Registration**

AM Moderator: Sandra Larson

8:00 **Welcome**—Sandra Larson, Iowa DOT

Why are we here?—Kevin Mahoney, Iowa DOT

Workshop mission—John Smythe, Iowa DOT

8:30 **Intelligent Compaction for Soils and Aggregate**—Dr. David White, ISU

9:45 **Break**

10:15 **Intelligent Compaction for Hot Mix Asphalt and Update on the Intelligent Compaction Pooled Fund Project**—Lee Gallivan, FHWA

11:15 **NYS DOT Experience with Machine Control/Intelligent Construction** —Dan Streett, NYS DOT

12:15 p.m. Lunch

PM Moderator: Max Grogg

1:00 **New Earthworks Engineering Research Center at Iowa State University** —Dr. David White

1:15 **Minnesota Experience with Intelligent Compaction and In situ Testing Projects**—Glenn Engstrom, Mn/DOT

2:30 **Break**

3:00 **European Experience with Intelligent Compaction**—François Chaignon, COLAS

4:15 **Wrap-up, Review of the Workshop Mission, Tomorrow's Session—Sandra Larson and John Smythe, Iowa DOT**

Workshop attendees: dinner on your own

Day 2—Thursday, April 3, 2008

6:30 a.m. Breakfast

Moderator: Mike Kvach

7:30 **Industry Equipment Manufacturer Presentations on Research and Development Efforts**

9:15 **Break**

9:45 **Charge to the Group**—John Bartoszek, Payne & Dolan

10:15 **Session 1— Breakout discussion groups (2 groups of each topic)**

- IC for Soils and Aggregate
- IC for HMA
- Design tools, Education/training, Specifications

12:00 p.m. **Lunch**

1:00 **Session 1 continues**

1:45 **Break**

2:15 **Session 2—Breakout discussion groups (2 groups of each topic)**

- IC for Soils and Aggregate
- IC for HMA
- Design tools, Education/training, Specifications

4:45 **Adjourn**

Workshop attendees: dinner on your own

Day 3—Friday, April 4, 2008

6:30 a.m. Breakfast

Moderator: Max Grogg

7:30 **Facilitators report on Day 2 discussions**

- IC for Soils and Aggregate
- IC for HMA
- Design tools, Education/training, Specifications

9:00 **Break**

9:30 **Panel Discussion and Questions**—David White, Lee Gallivan, Dan Streett, Mn/DOT, John Bartoszek, Industry representatives

11:00 **Wrapup and discussion of next steps—Sandra Larson, Iowa DOT**

11:30 **Adjourn**

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