# Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials

tech transfer summary

**RESEARCH PROJECT TITLE**
Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials

**FINAL REPORT DATE**
April 2007

**SPONSORS**
Minnesota Department of Transportation
Federal Highway Administration

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**KEYWORDS**
Earthwork Quality, Intelligent Compaction, Geostatistics, In situ Testing, Laboratory Compaction Testing, Resilient Modulus

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The Partnership for Geotechnical Advancement (PGA) is part of the Center for Transportation Research and Education (CTRE) at Iowa State University. The mission of the PGA is to increase highway performance in a cost-effective manner by developing and implementing methods, materials, and technologies to solve highway construction problems in a continuing and sustainable manner.



## Objectives

The objective of this research project was to evaluate intelligent compaction (IC) monitoring technology for use in earthwork construction for purposes of quality control and assurance. The following research tasks were established for the study:

- Develop relationships between roller-integrated and in situ compaction measurements, including dry unit weight, dynamic cone penetration (DCP) index, Clegg impact value (CIV), and light weight deflectometer (LWD) modulus.
- Characterize measurement variation observed for the various measurement systems.
- Identify the influences of compaction energy and method on laboratory moisture-density relationships.
- Characterize laboratory resilient modulus in terms of soil type, stress state conditions, moisture content, and density.
- Develop QC/QA guidelines for incorporating roller-integrated compaction monitoring technology into soil compaction specifications.

## Problem Statement

The successful implementation of IC technology into earthwork construction practice requires knowledge of the roller-integrated compaction measurements and their relationships with the engineering and index properties of soil that may be used for pavement design (e.g., California bearing ratio, elastic modulus, resilient modulus). These relationships, which are influenced by the factors affecting roller response, were studied at three earthwork construction projects in Minnesota.

## Technology Description

To improve upon the traditional approaches of process control and spot tests, intelligent compaction may provide real-time compaction results with 100 percent test coverage. This study investigated compaction meter value (CMV), also known as Caterpillar compaction value (CCV), and machine drive power (MDP) from Caterpillar rollers, and kB stiffness from an Ammann roller.

## Field Evaluation of IC Technology

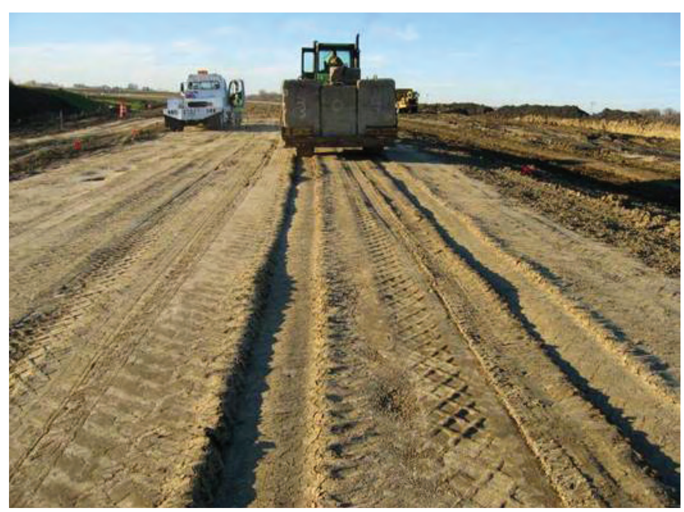
Three field studies were conducted to investigate relationships between roller compaction values (CMV, MDP, kB) and in situ test measurements including dry unit weight, DCP index, CIV, and LWD modulus. Key findings from each field study are as follows:

- ***Field Study 1:*** IC mapping trials were performed in conjunction with in situ testing at select locations. Results showed that IC technology has the potential to effectively identify the areas of weak or poorly-compacted soil with real-time readings and 100 percent coverage.
- ***Field Study 2:*** Test strips were established for collecting compaction data and performing regression analysis to better describe the relationships between in situ and IC measurement values. Statistically-significant correlations were observed between different measurement values for data collected over a relatively wide range of soil characteristics. Ammann kB was also related to rut depth measured after test rolling procedures.
- ***Field Study 3:*** This study was conducted on a grading project, in which IC technology was used as the principal method for quality control. The testing and analysis of this study, therefore, focused on evaluating the experience in terms of how the technology was used and how the technology performed. The calibration procedure and field results were documented, and the relationships between in situ and IC measurement values were investigated at the proof scale and at the project scale. The study findings show that IC technology is a feasible alternative for quality control and acceptance, but that some challenges in interpreting the measurement values still remain.

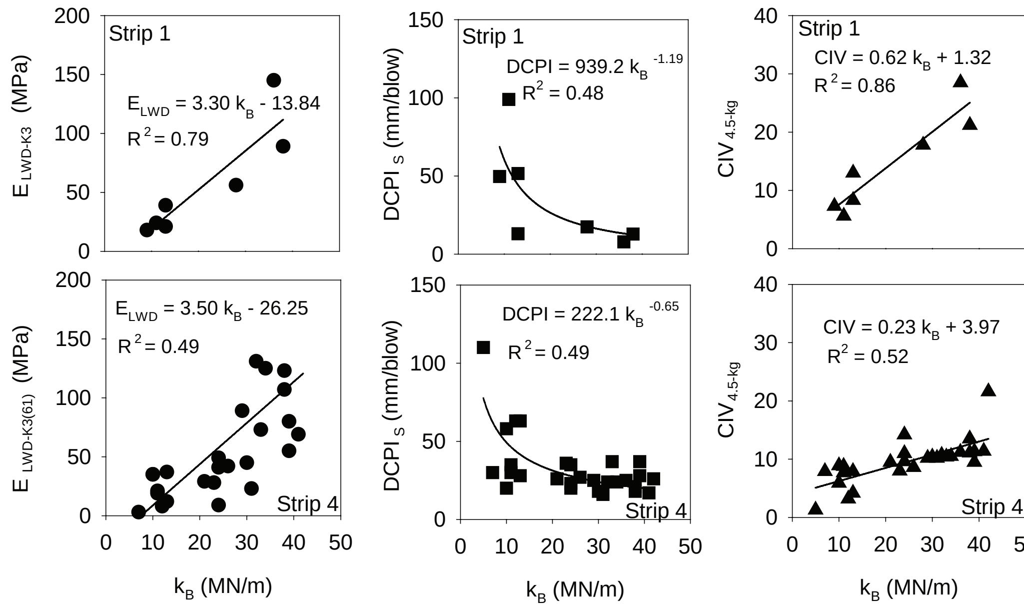

*Caterpillar vibratory smooth drum roller with integrated CMV and MDP technology: Field Study 1*

*Ammann vibratory smooth drum roller with ACE system to output kB stiffness values: Field Study 2*

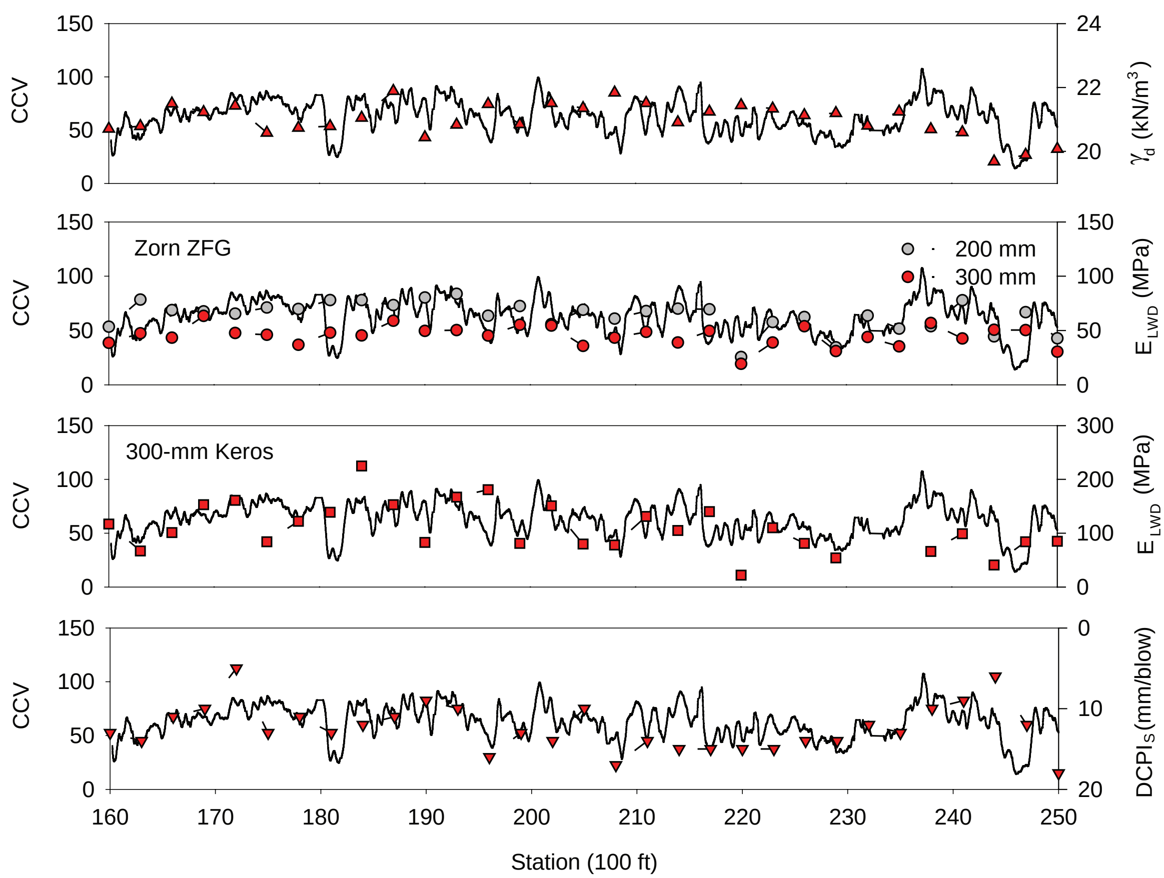
*Caterpillar vibratory smooth drum roller with integrated CMV technology: Field Study 3*



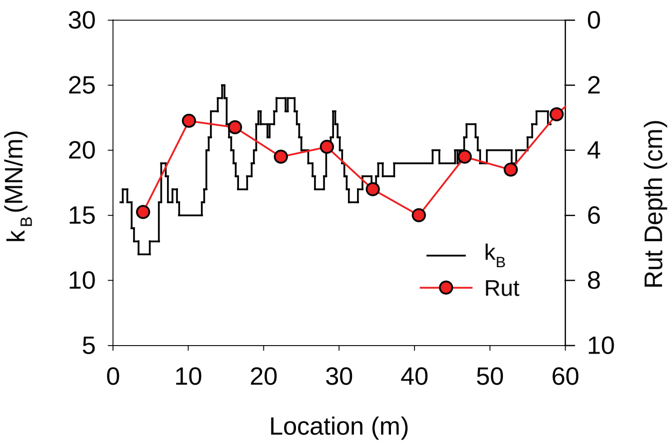
*Rutting of subgrade following test roller operation*




*Relationships between kB and in situ measurements for subgrade soil from Strips 1 and 4 (Field Study 2)*

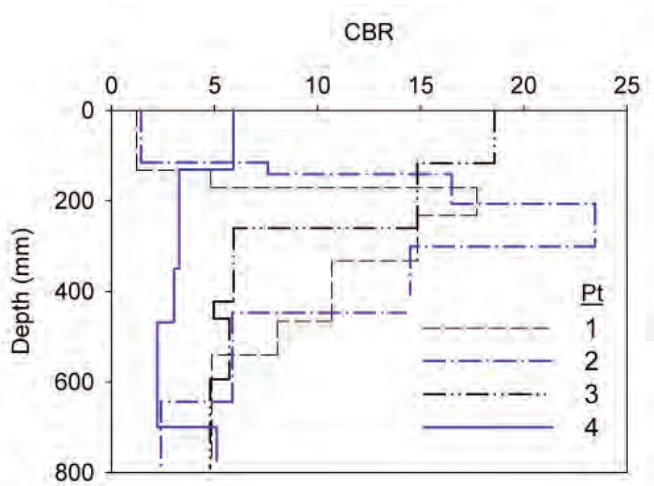



*Comparison of CCV and in situ compaction measurements on a 2-inch granular capping material underlain by native sand subgrade over 1.7 miles (Field Study 3)*




*Comparison of Ammann $k_B$ and rut depth along a subgrade test section (Field Study 2)*

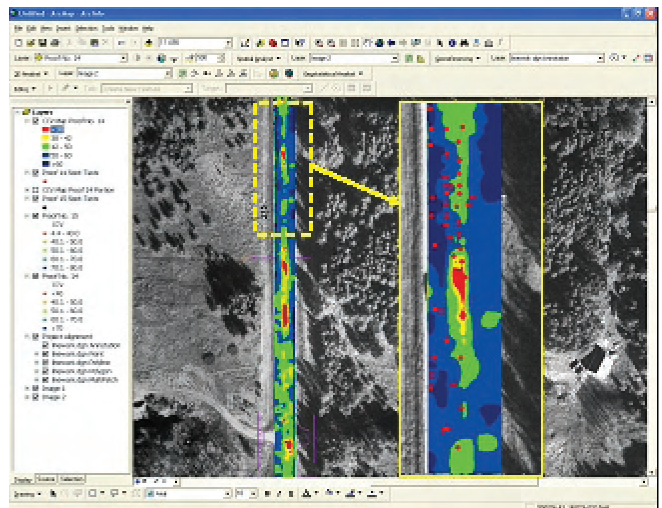

*Field Study 1: Compaction monitor view at County 55 (viewing area 137 x 110 m) identified by DCP test locations*




*Field Study 1: DCP profiles at test shown in the above figure*

## GIS Database

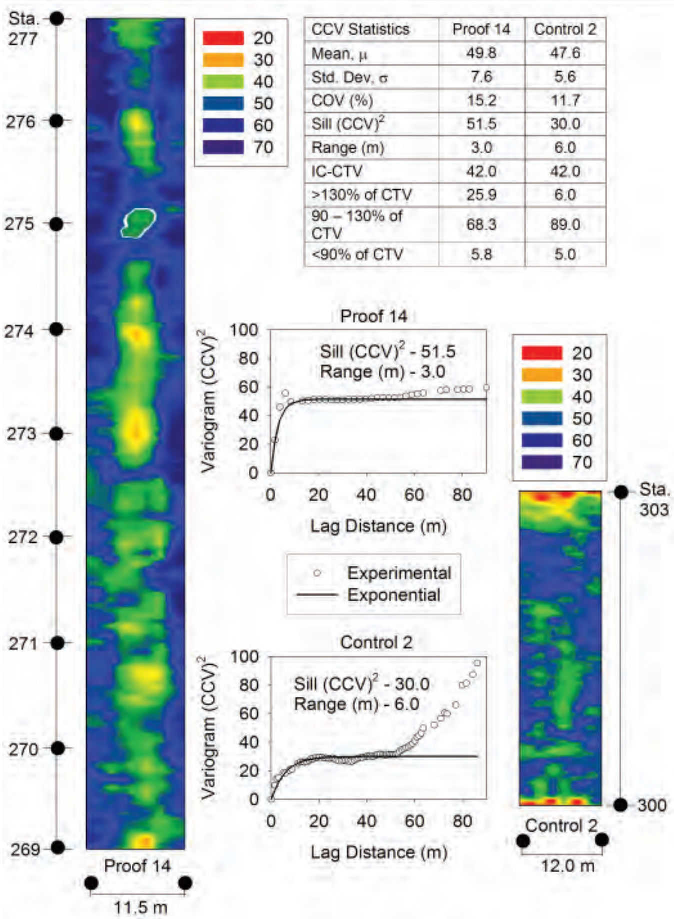
IC technology provides opportunity to collect and evaluate information for 100 percent of the project area, but it also produces large data files that create analysis, visualization, transfer, and archival challenges. An approach for managing the data by creating a "geodatabase" using ArcGIS/ArcInfo modules is presented in the report. The geodatabase consists of TH 64 project IC data from proof and control sections, spot test measurements, and aerial images. Data visualization and analysis such as creating histogram plots, semivariogram models, and geostatistical analysis can be performed using ArcGIS.



*Kriged surface map of CCV from proof no. 14 with overlaid spot test measurements (in red circles) – created using ArcMap*

## Geostatistical Analysis

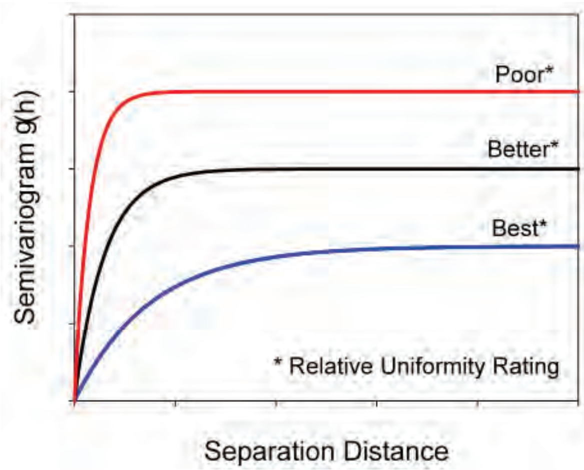
Applying geostatistical methods in the analysis of IC data has the advantage of quantifying spatial variability, which is not possible with classical statistical analysis. A "semivariogram" model can be used to characterize uniformity of the IC data. To demonstrate the application, IC data collected for two *control* and two *proof* sections of the TH 64 project were analyzed and compared with the Mn/DOT specified quality control criteria. Critical differences in spatial statistics relating to uniformity were observed between the two control sections, which were not observed with the univariate statistics. The two proof sections which "pass" the Mn/DOT acceptance criteria failed to meet an alternatively proposed "sill" criterion that establishes a uniformity criterion at a 30 m spatial scale. The implication of such incremental spatial analysis is that it will aid the contractor in identifying localized poorly compacted areas or highly non-uniform conditions, which are often the cause of pavement problems. Using "range" distance determined from a semivariogram model as the minimum window size for an area of evaluation, a 60 m long section was analyzed. The results showed that several isolated locations failed to meet the Mn/DOT acceptance criteria. The scale at which the acceptance criterion is based is still a question that needs further research.



| CCV Statistics | Proof 14 | Control 2 |
|---|---|---|
| Mean, μ | 49.8 | 47.6 |
| Std. Dev, σ | 7.6 | 5.6 |
| COV (%) | 15.2 | 11.7 |
| Sill $(CCV)^2$ | 51.5 | 30.0 |
| Range (m) | 3.0 | 6.0 |
| IC-CTV | 42.0 | 42.0 |
| >130% of CTV | 25.9 | 6.0 |
| 90 – 130% of CTV | 68.3 | 89.0 |
| <90% of CTV | 5.8 | 5.0 |



*Comparison of a proof section with a control strip using CCV surface maps and variograms*



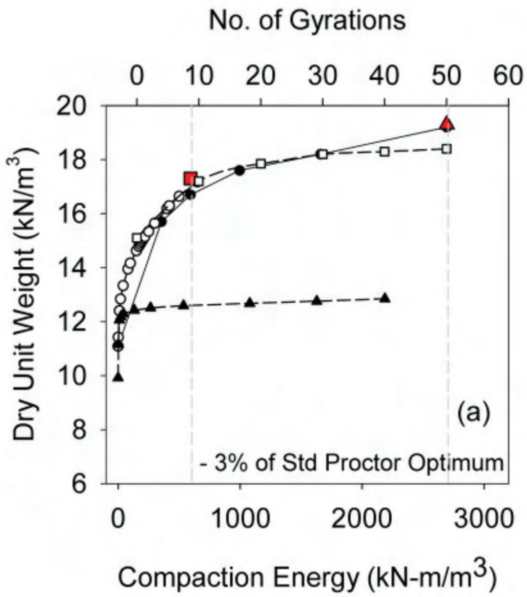


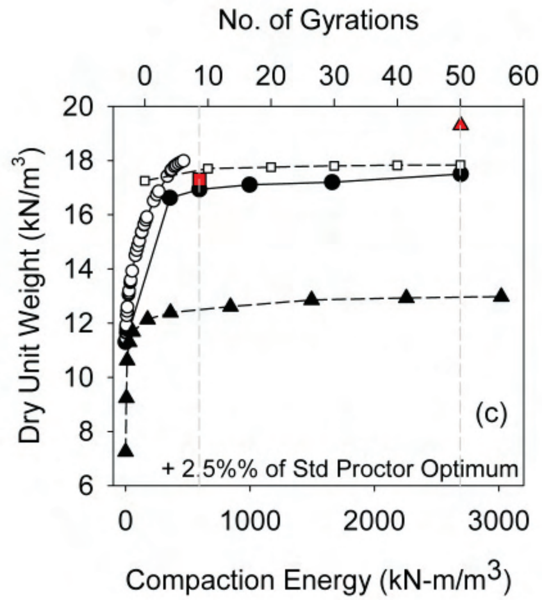
*Hypothetical illustration of semivariograms characterizing uniformity*

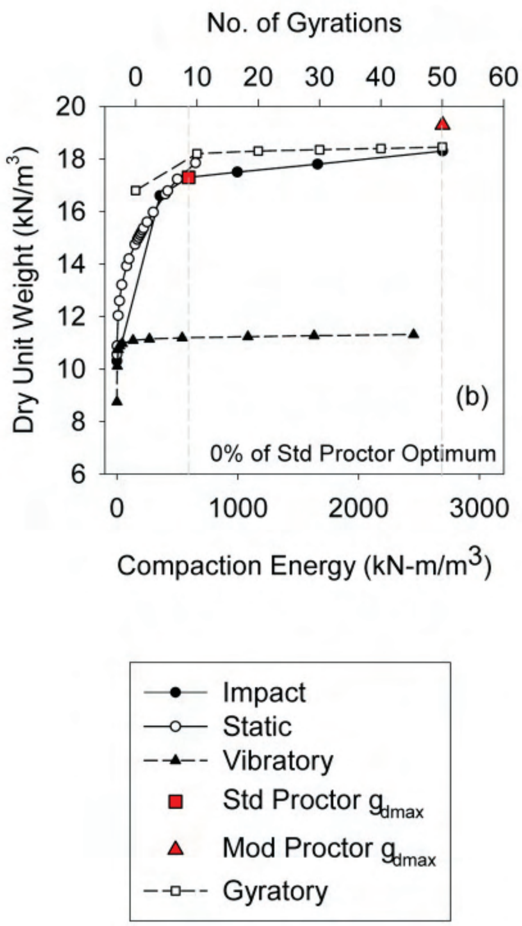
## Laboratory Compaction Study

Laboratory compaction of soils should simulate the mechanics and energy delivery system that occurs in the field. This is particularly important as it relates to soil fabric/structure and measuring engineering properties (e.g., strength and stiffness) of materials compacted in the lab. Laboratory compaction tests performed using impact, static, gyratory, and vibratory compaction methods for one cohesive soil and one granular soil resulted in distinctly different moisture-density relationships. On an energy per unit volume basis, the static compaction method can be more efficient than impact compaction for the cohesive soil, but is found inadequate for the granular soil as it requires high contact stresses. The vibratory compaction method is inadequate to characterize moisture-density relationships for the cohesive soil, while it works effectively for the granular soil.

From limited laboratory resilient modulus ($M_r$) and unconsolidated-undrained (UU) strength tests on samples prepared using different compaction methods, it is found that the vibratory and impact compaction samples produce higher $M_r$ and shear strength ($\tau_{max}$) than static compaction samples for both soils. The vibratory method generally resulted in lower $\tau_{max}$ than the impact method, while it produced similar or slightly higher $\tau_{max}$ than the impact method for granular soil. A profound influence of moisture content is realized for the cohesive soil with $M_r$ and $\tau_{max}$ values decreasing with increasing moisture content. Moisture content did not have significant influence on the $M_r$ and $\tau_{max}$ values for the granular soil.




*Comparison of relationship between dry unit weight and impact, static, and vibratory compaction energy, and number of gyrations for mixed glacial till at (a) dry of optimum, (b) optimum, and (c) wet of optimum moisture content from standard Proctor test.*

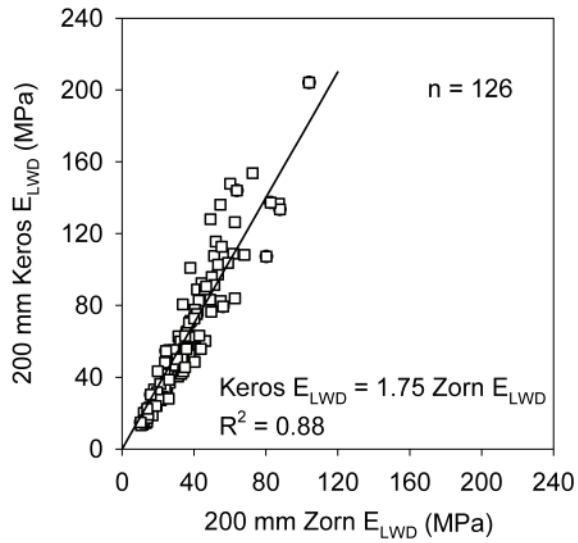
## Field Comparison Study of LWD Devices

To successfully implement the use of different LWD devices in QC/QA, it is important to understand the conditions for which they provide reliable measurements and also if differences exist between the calculated elastic modulus values between the various devices. Some key factors that influence the estimation of $E_{LWD}$ include plate size, plate contact stress, type and location of deflection transducer, usage of load transducer, loading rate, and buffer stiffness.

Two LWD devices (ZFG 2000 manufactured by Zorn Stendal from Germany, and the Keros manufactured by Dynatest in Denmark) with different plate diameters were evaluated to observe the differences in $E_{LWD}$ between the devices and the influence of plate diameter on the $E_{LWD}$ values. It is found that the Keros $E_{LWD}$ is on average 1.8 to 2.2 times greater than Zorn $E_{LWD}$. The primary contributor for differences in $E_{LWD}$ between these devices is the difference in measured deflections. The Zorn device measures about 1.5 times greater deflection than Keros for the same plate diameter, drop height, and drop weight. A Zorn device with 200 mm plate results in $E_{LWD}$ about 1.4 times greater than with 300 mm plate.

An effort was made in this research to build a database of $E_{LWD}$ to $M_r$ relationship by obtaining shelby tube samples from a compacted subgrade, at the locations of LWD tests. Based on limited data, a linear relationship between $E_{LWD}$ and $M_r$ is observed at a selected stress condition, with $R^2$ values ranging from 0.85 to 0.97.

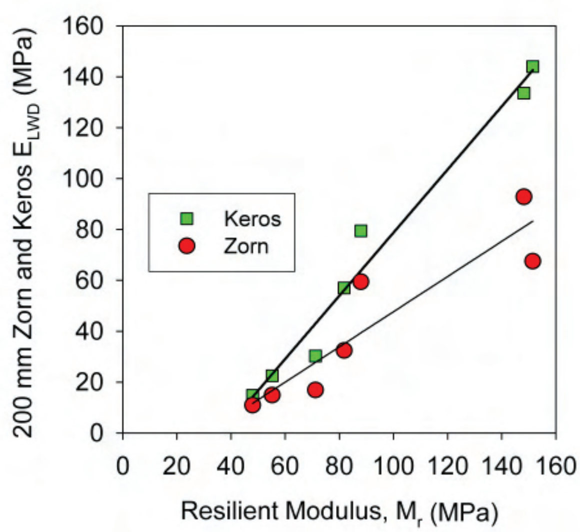
*200 mm Zorn ZFG 2000 LWD (left), 200 mm Keros LWD (Right)*




*Comparison of 200 mm Zorn and Keros $E_{LWD}$*

## Key Attributes for Quality Management using IC: Equipment Requirements

- Real-time corrections in the compaction process by the roller operator and inspection personnel.
- On-demand visual review of in-cab monitor by inspector.
- Data provided to inspector in a timely manner in the form of printed, plan-view color maps, and electronically in the form of delimited ASCII data files.
- Summary of quality control parameters that include roller compaction value (e.g., IC-CTV), resonance meter value (RMV), operation parameters (amplitude, frequency, speed), and roller pass number.
- Roller position for each data record accurate to the frequency of the drum (x, y, z) coordinates for each end of the drum in UTM NAD 1983.
- Timestamp for each data record to the frequency of the drum.




*Comparison of 200 mm Zorn, Keros $E_{LWD}$, and Resilient Modulus ($M_r$)*

## Options and Approach to Quality Acceptance (and Database Population) Using IC

### Method Overview

The results from field studies in this project and data analyses provided the basis for a conceptual process of quality acceptance and database development using IC technology (see figure below). As with any instrumented system, some level of calibration is required and is comprised of five primary steps that include (1) roller data collection on a calibration area, (2) semivariogram modeling to determine sampling requirements, (3) in situ testing using other approved testing devices on calibration area parallel with compaction process, (4) regression analysis to determine target values, and (5) evaluation of production soil compaction using target machine values and semivariogram parameters as indicators of quality.

### Level 1: Statistically-Rigorous Roller Calibration

A statistically-rigorous roller calibration can be achieved with sufficient IC of roller and in situ measurement values. The need for many measurement values results from several sources of variability and measurement error that influence the precision and bias and also several factors affecting IC measurement values. These issues complicate generating relationships between IC data and in situ test measurements. Large datasets allow for statistical averaging that increases the reliability of a measurement at a particular location and also for improved correlation between measurement systems. Guidelines for establishing calibration data requirements apply principally to in situ testing, as IC measurement values are monitored and stored nearly continuously. For statistically rigorous correlation studies, in situ testing using approved devices should occur at three locations across the drum width to (1) account for soil variability, (2) account for the influence of rear tire compaction, and (3) increase the measurement reliability. These data may be collected at three to five test locations within the calculated (geostatistical) range interval (9 to 15 tests performed per range interval). Then, in building a regression from data collected throughout the entire compaction process (e.g., 1, 2, 4, 8 passes), the data within each range interval (three to five points) may be averaged—in which case IC measurement values are also averaged over the range interval—or treated as individual test points.

### Level 2: Reduced Roller Calibration Requirements

Level 1 roller calibration admittedly requires significant initial investment in collecting in situ compaction measurements. Provided the contractor and/or owner are willing to accept some risk, the sampling requirements may be reduced. Level 2 roller calibration may also be used at later stages of earthwork projects after the initial calibration relationships have been developed. An inspector may overlay the regressions from calibration with reduced sampling over those generated from more frequent sampling to evaluate whether significant changes (if any) are attributed to changes in material type, construction operations, etc. Calibration that does not appear to reflect the new conditions may indicate the need to re-calibrate the intelligent compaction measurements (Level 1) for the new conditions. The in situ testing requirements may be reduced to only one test at each location (i.e., not three across the drum width) and only one test location per range interval. These data may still allow for regression model development or verification, but may disallow geostatistical analysis.

### Level 3: Options for Eliminating Roller Calibration

The current Mn/DOT IC specification requires the construction of control strips in order to determine target values. The following options may serve as potential alternatives to constructing control/calibration strips:

- Mn/DOT may initially incorporate calibration on projects, but with time and experience, the agency may populate a large database that includes different IC technology compaction measurements and roller configurations, soil types, and representative lift sections. Field inspectors may use target values from the database that correspond to conditions of a specific project. Some supplemental in situ verification testing for quality assurance may be required during production soil compaction to verify that the target value is providing reasonable estimates of in situ performance parameters.
- Develop new laboratory testing protocols for estimating target values for the roller and other in situ devices that allow for some empirical relationships to in situ compaction/stiffness measurements (by roller and in situ devices).

- Use existing relationships between machine parameters and material properties that have been documented in this report and in other literature (White et al. 2006, 2007). These relationships might be extrapolated for use on earthwork construction projects, but must consider the influence of moisture content, lift thickness, variable stiffness of underlying layers, and roller operational conditions (e.g., amplitude, frequency, speed) on soil compaction and machine response.

## Recommendations for Implementation

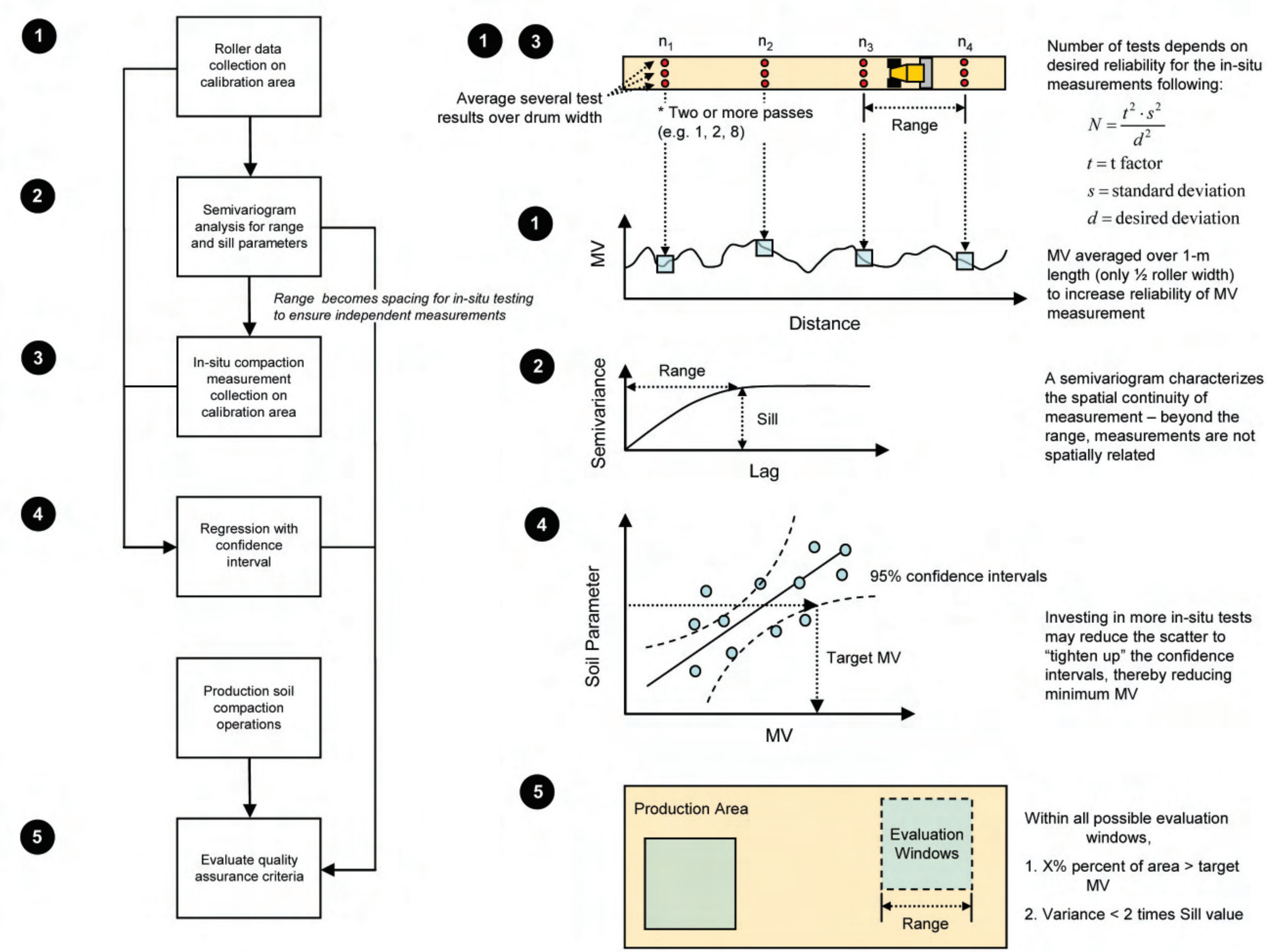
The following recommendations are based on the present research study findings and communication with representatives from Mn/DOT personnel, industry, and contractors.

**Education**

- Prepare a condensed field inspector's guide to intelligent compaction technologies, testing, documentation, and operations.
- Develop training curriculum for using intelligent compaction rollers, as well as other in situ testing methods used for calibration and verification testing.
- Begin implementing IC specifications on a limited basis with on-site training/seminars for inspectors and contractors. A research team may further facilitate technology transfer and training and speed up the implementation process. Such demand will additionally increase the availability of IC rollers in Minnesota.
- Educate designers on how to use intelligent compaction technology to refine/validate pavement design and, ultimately, participate in establishing quality criteria for IC rollers.
- Facilitate discussion between roller manufacturers for the purpose of establishing some level of consistency between roller usage—a measure that will help eliminate bias towards a specific technology and enabling the users to select from a wide range of manufacturers.

**Future Research**

- Continue research in identifying and quantifying all the factors affecting IC measurements. Continue evaluating the relationships between in situ test results and IC data for different pavement foundation conditions.
- Continue development of database of relationships between design parameters (e.g., $M_r$) to in situ LWD measurements.
- Develop new or refine existing roller calibration procedures.
- Continue research on the appropriate scale at which the acceptance criteria are based.
- Continue research in the areas of modulus-based QC/QA protocols implicit to performance-based specifications.
- Monitor construction expediency and cost of projects using IC technology. Favorable comparison with conventional construction methods would warrant more rapid implementation. In the long term, pavement performance may further support the effectiveness of IC technology.
- Document/verify that use of IC technology produces a higher quality product than does the conventional approach. This task may involve comparing IC output with test rolling results or may involve, in the longer term, comparison of performance of road sections constructed using different technologies/methods.
- Investigate how intelligent compaction technologies and specifications can be used to improve conventional earthwork operations (e.g., improved compaction efficiency, improved material uniformity).
- Develop standard methods for managing, analyzing, and archiving the large quantities of IC data produced throughout a project.




*Conceptual process for quality assurance using IC technology*

*Values for CMV, dry unit weight, $E_{LWD}$, and DCP index for different soils (mean, coefficient of variation)*

| Soil Type | Roller Configuration | CMV | w (%) | Dry Unit Weight (kN/m³) | $E_{LWD}$ (MPa) | DCP Index (mm/blow) | Dataset Reference |
|---|---|---|---|---|---|---|---|
| **GM** [a] | Vibratory Smooth | 10.3 | 8, 10 | 17.2, 4 | 38, 38 | 17, 21 | White et al. (2007) |
| **SM** [b] | Vibratory Smooth | 17.3 | 4, 15 | 19.4, 3 | 34, 18 | 17, 10 | |
| **GP** [c] | Vibratory Smooth | 21.5 | 3, 15 | 15.0, 6 | – | – | |
| **SM** [d] | Vibratory Smooth | 15.1 | 6, 14 | 18.7, 3 | 23, 25 | 45, 20 | |
| **GC** [e] | Vibratory Smooth | 14.9 | 8, 11 | 18.5, 2 | 40, 49 | 19, 31 | |
| **SW-SM** | Vibratory Smooth | 0-50 | 5-15 | 16-19 | – | – | Field Study 1 |
| **SP** [f] | Vibratory Smooth | 40-65 | 7-12 | 17-21 | 35-90 [h] | 10-25 [i] | Field Study 3 |

[a] $w_{opt}$ = 8%, $\gamma_{d,max}$ = 19.5 kN/m³; [b] $\gamma_{d,max}$ = 20.1 kN/m³; [c] Standard Proctor not applicable; [d] $w^{opt}$ = 8%, $\gamma_{d,max}$ = 19.8 kN/m³; [e] $w_{opt}$ = 10%, $\gamma_{d,max}$ = 20.0 kN/m³; [f] $w_{opt}$ = 10%, $\gamma_{d,max}$ = 20.0 kN/m³; [g] $E_{LWD-K3(61)}$; [h] $E_{LWD-Z2(63)}$; [i] Mn/DOT DPI calculation

*Values for $k_B$, dry unit weight, $E_{LWD}$, and DCP index for different soils (range)*

| Soil Type | Roller Configuration | $k_B$ (MN/m) | w (%) | Dry Unit Weight (kN/m³) | $E_{LWD-K3(61)}$ (MPa) | $DCPI_S$ (mm/blow) | Dataset Reference |
|---|---|---|---|---|---|---|---|
| **CL** [a, b] | Vibratory Smooth | 30-40 | – | – | 10-50 | 5-10 | Field Study 2 |
| **SP-SM** [c] | Vibratory Smooth | 20-35 | 10-14 | 16-17 | 20-40 | 40-110 | |
| **CL** [a, b] | Vibratory Smooth | 20-45 | 15-20 | 16-18 | 60-110 | 10-40 | |
| **SP-SM** [c] | Vibratory Smooth | 25-40 | 7-10 | 18-19 | 10-70 | 25-50 | |
| **CL** [a] | Vibratory Smooth | 10-35 | 15-20 | 16-17 | 10-80 | 10-60 | |

[a] $w_{opt}$ = 18%, $\gamma_{d,max}$ = 16.2 kN/m³; [b] Excludes median testing; [c] $w_{opt}$ = 8%, $\gamma_{d,max}$ = 19.6 kN/m³

*Values for $E_{VIB}$, dry unit weigh, and DCP index for different soils (mean and coefficient of variation)*

| Soil Type | Roller Configuration | $E_{VIB}$ (MPa) [a] | w (%) | Dry Unit Weight (kN/m³) | $DCPI^S$ (mm/blow) | Dataset Reference |
|---|---|---|---|---|---|---|
| **SM** [b] | Vibratory Smooth | 46.6, 91 | 10, 28 | 19.6, 4 | 40, 77 | Petersen (2005) |
| **GW-GM** [c] | Vibratory Smooth | 46.6, 91 | 4, 25 | 20.6, 4 | 23, 18 | |

[a] Values for combined soils; [b] $w_{opt}$ = 10%, $\gamma_{d,max}$ = 19.3 kN/m³; [c] $w_{opt}$ = 11%, $\gamma_{d,max}$ = 20.7 kN/m³

*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 ft 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 $Ev_1$, 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 sub-base. | — | 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.