A REVIEW OF ROLLER-INTEGRATED COMPACTION MONITORING TECHNOLOGIES FOR EARTHWORKS

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NOTATIONS

a	Theoretical vibration amplitude (eccentric moment divided by the drum mass)
a^*	Actual measured vibration amplitude (double integral of acceleration data)
A_{Ω}	Acceleration at fundamental frequency
$A_{X\Omega}$	Acceleration at X-order harmonic
A’	Machine acceleration
AFC	Automatic feedback control
b	machine internal loss coefficient used in MDP calculation
B	Contact width of the drum
BCD	Briaud compaction device
CBR	California bearing ratio
CCC	Continuous compaction control
CCV	Caterpillar compaction value
CMV	Compaction meter value
COV	Coefficient of variation (calculated as the ratio of mean and standard deviation)
E_{VIB}	Vibratory modulus determined from the roller
f	Vibration frequency
F	Shape factor
F_s	Drum force
FWD	Falling weight deflectometer
g	Acceleration of gravity
G_s	Specific gravity
GPS	Global positioning system
h	Separation distance
IC-MV	Intelligent compaction measurement value
k_s	Roller-integrated stiffness
LL	Liquid limit
LWD	Light weight deflectometer
m	Machine internal loss coefficient used in MDP calculation
m_d	drum mass
$m_e r_e$	Eccentric moment of the unbalanced mass
MDP	Caterpillar Machine drive power
MDP_{40}	See description in text
MDP_{80}	See description in text
P_g	Gross power needed to move the machine
PLT	Static Plate Load Test
Point-MV	In-situ point measurement value
R’	Radius of the roller drum
R^2	Coefficient of determination
RMV	Resonant meter value
W	Roller weight
z_d	Drum displacement
α	Slope angle (roller pitch from a sensor)
φ	Phase angle

INTRODUCTION

Development and evaluation of continuous compaction control (CCC) measurement technologies was initiated over three decades ago in Europe for use on vibratory rollers compacting granular soils (Forssblad 1980 and Thurner and Sandström 1980). Since its inception, the concept has been expanded to different measurement technologies and materials and is available commercially for different roller configurations. For vibratory roller configurations, CCC involves measurement and analysis of output from an accelerometer mounted to the roller drum and can provide a spatial record of compaction quality when linked to position measurements and a documentation system (Figure 1). When the measurement system provides automatic feedback control (AFC) for roller vibration amplitude and/or frequency, it is referred to as "intelligent" compaction (IC). Roller measurement values calculated based on accelerometer measurements use one of two different approaches: (1) calculate a ratio of selected frequency harmonics for a set time interval, or (2) calculate ground stiffness or elastic modulus based on a drum-ground interaction model and some assumptions. An alternative to accelerometer-based vibratory measurements is the measurement of rolling resistance/machine drive power and can be applied to both vibratory and non-vibratory roller operations. Regardless of the technology, the premise of CCC/IC is that the measurement values are related to traditional compaction measurements and will be useful as part of effective earthwork compaction operations and QC/QA practices. The purpose of this report is to provide an overview of the literature in areas of: (a) developmental history of CCC/IC; (b) CCC/IC technologies, manufacturers, and documentation systems; (c) factors influencing the CCC/IC measurements; (d) field correlation studies and factors influencing the correlations; and (e) specification attributes and concepts.

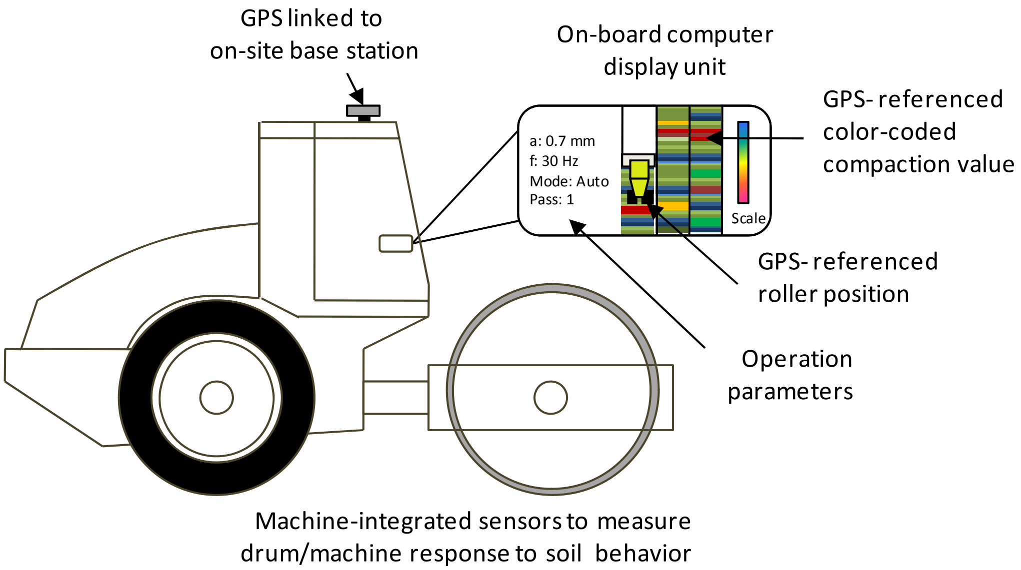


Figure 1. Overview of CCC/IC compaction monitoring systems

DEVELOPMENT OF CCC TECHNOLOGIES

The concept of CCC/IC was first investigated by Dr. Heinz Thurner of the Swedish Road Administration in 1974 by relating drum harmonics to soil compaction properties. Field trials were conducted by Dr. Thurner by instrumenting Dynapac vibratory smooth drum rollers using accelerometers on granular soils. Results from these field trials provided evidence that the ratio of the acceleration amplitude of the first harmonic and the acceleration amplitude of the fundamental frequency of the vibrating drum was an indicator of soil stiffness/modulus. In 1975, Dr. Thurner partnered with Åke Sandström and founded Geodynamik to continue research and development on CCC/IC. In 1976, Compactometer^{TM} Compaction Meter Value (CMV) measurement was developed by Geodynamik in cooperation with the Dynapac Research Department. In 1980, five technical articles were presented on the CMV measurement technology and its applications (Thurner 1980, Thurner and Sandström 1980, Forssblad 1980, Hansbo and Pramborg 1980, and Machet 1980) at the First International Conference on Compaction held in Paris.

In 1983, Geodynamik introduced the Oscillometer Value (OMV) for oscillatory rollers which is a dimensionless value obtained from the amplitude of the horizontal acceleration of the drum. HAMM AG adopted the OMV measurement technology (Thurner and Sandström 2000) for use on their smooth drum oscillatory rollers, but virtually no published information is available in the English literature on OMV relationships with soil properties.

In the early 1980s, BOMAG developed the Terrameter® system measuring the Omega value (BTM 1983). The Omega value provides a measure of the compaction energy transmitted to the soil using accelerometer data. Hoover (1985) published a research report from a field study evaluating the Omega value on three different types of granular soils which showed encouraging results. Later in 2000, BOMAG replaced the Omega value by introducing the Vibratory Modulus (E_{VIB}) value which uses acceleration data to determine drum displacement, an estimated applied force, and a dynamic roller-soil model (Kröber et al. 2001).

In the late 1990s, Ammann introduced the roller-integrated stiffness (k_s) measurement value, which provides a measure of quasi-static stiffness using the measured drum displacement, estimated applied force, and a spring-dashpot model representing roller-soil interaction (Anderegg and Kauffmann 2004).

Currently, Dynapac, Trimble, and Caterpillar use the CMV measurement technology as part of their CCC/IC systems by linking CMV data with GPS measurements for on-board real time display. Trimble offers a retrofit CCC system for smooth drum vibratory rollers (see White and Vennapusa 2009). In 2004, Sakai introduced Compaction Control Value (CCV) which is also a dimensionless parameter similar to CMV (Scherocman et al. 2007).

In 2003, a research collaboration project between the Iowa Department of Transportation, Federal highway Administration ((FHWA), and Caterpillar was initiated to evaluate Caterpillar's Machine Drive Power (MDP) system for use on granular and cohesive soils. The MDP system is based on the principal of rolling resistance due to drum sinkage, and the approach works in both the vibratory and static modes. The measurement system has been investigated in field trials since 2003 (Tehrani and Meehan 2009, White et al. 2004, 2005, White and Thompson 2008, Thompson and White 2008) and has recently been recently used on a full-scale earthwork compaction project in Minnesota (White et al. 2009a, b).

Currently, BOMAG, Ammann, and Dynapac offer AFC/IC systems, wherein the vibration amplitude, and/or frequency are automatically adjusted when drum jumping is determined or when a preset threshold roller measurement value is reached. Some of the potential advantages cited in the literature (e.g., Adam and Kopf 2004) for using AFC for soil compaction are increased chance of more rapid compaction (i.e., less passes) and improved uniformity of soil properties. Based on this literature review, these benefits are not well quantified in the technical literature.

OVERVIEW OF CCC/IC TECHNOLGIES AND DOCUMENTATION SYSTEMS

Measurement Technologies

Compaction Meter Value (CMV)

Compaction meter value (CMV) is a dimensionless compaction parameter developed by Geodynamik that depends on roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed), and is determined using the dynamic roller response (Sandström 1994). The concept of development of different harmonic components of drum vibration with increasing ground stiffness is illustrated in (Figure 2). CMV is calculated using Eq. 1, where C is a constant (300), $A_{2\Omega}$ = the acceleration of the first harmonic component of the vibration, A_{Ω} = the acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004).

$$\mathrm{CMV} = \mathrm{C} \cdot \frac{\mathrm{A}_{2\Omega}}{\mathrm{A}_{\Omega}} \tag{1}$$

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

$$\mathrm{RMV\ or\ BV} = \mathrm{C} \cdot \frac{\mathrm{A}_{0.5\Omega}}{\mathrm{A}_{\Omega}} \tag{2}$$

Dynapac uses a preselected threshold BV as an indicator of roller jumping to adjust the amplitude in AFC mode compaction. Similarly, Caterpillar used RMV to adjust amplitude on a smooth drum vibratory roller used on a project (White et al. 2008b).

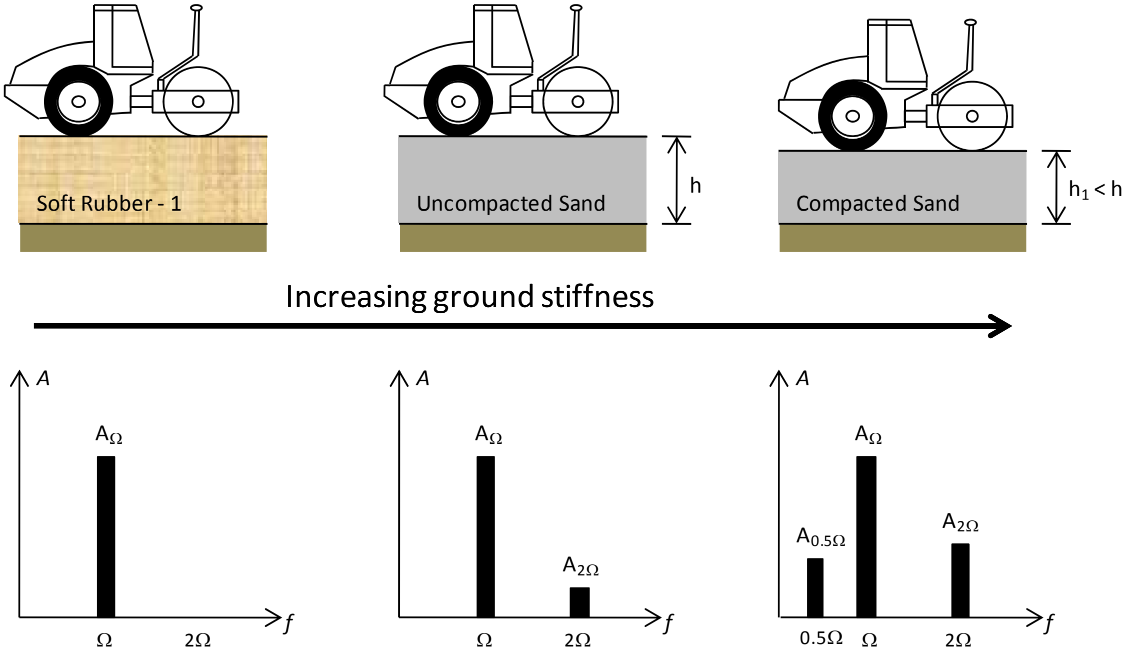


Figure 2. Illustration of changes in drum harmonics with increasing ground stiffness (modified from Thurner and Sandström 1980)

Oscillometer Value (OMV)

Oscillometer Value (OMV) is an index dimensionless parameter developed specifically for oscillatory rollers, and is obtained from the amplitude of the horizontal acceleration of the drum center (when there is no slip) from an accelerometer mounted on the bearing plate in horizontal direction (Thurner and Sandström 2000). The OMV reflects the horizontal force transferred from the drum to the soil and hence the horizontal stiffness of the soil surface under dynamic loading. Thurner (1993) noted that the OMV is quite insensitive to moderate variations (from about 28 to 32 Hz) in the excitation frequency.

Compaction Control Value (CCV)

The CCV determination takes the acceleration data from the first (0.5**Ω**), fundamental (**Ω**), and higher-order harmonics (1.5**Ω**, 2**Ω**, 2.5**Ω**, 3**Ω**) into account by using Eq. 3. Research conducted by Sakai (Scherocman et al. 2007) found that as the ground stiffness increases and the roller drum starts to enter into a "jumping" motion, vibration accelerations at various frequency components are developed as illustrated in Figure 3.

$$\mathrm{CCV} = \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right] \times 100 \qquad (3)$$

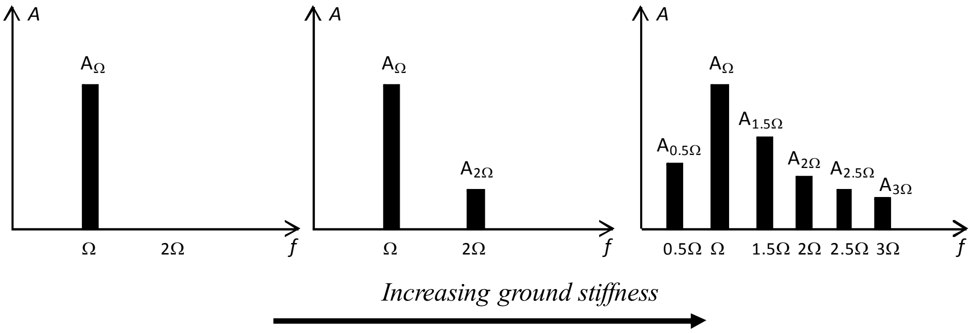


Figure 3. Changes in amplitude spectrum with increasing ground stiffness (modified from Scherocman et al. 2007)

Roller-Integrated Stiffness (k_s)

The roller-integrated stiffness (k_s) measurement system was introduced by Ammann based on a lumped parameter two-degree-of-freedom spring dashpot system illustrated in Figure 4 (Anderegg and Kauffmann 2004). The spring dashpot model has been found effective in representing the drum-ground interaction behavior (Yoo and Selig 1980). The drum inertia force and eccentric force time histories are determined from drum acceleration data and eccentric position (neglecting frame inertia). The drum displacement (z_d) is determined by double integrating the measured peak drum accelerations.

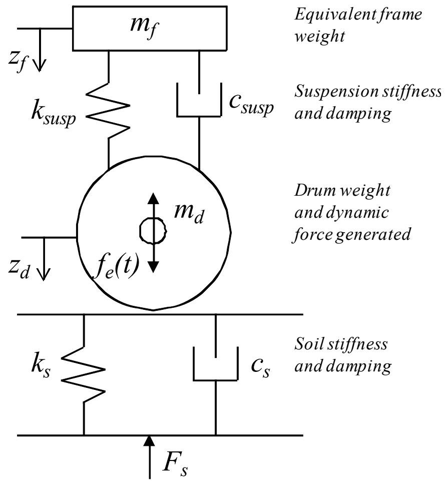


Figure 4. Lumped parameter two-degree-of-freedom spring dashpot model representing vibratory compactor and soil behavior (reproduced from Yoo and Selig 1980)

The k_s value is determined using Eq. 4, where f is the excitation frequency, m_d is the drum mass, $m_e r_e$ is the eccentric moment of the unbalanced mass, φ is the phase angle, a is vibration amplitude. The k_s value represents a quasi-static stiffness value and is reportedly independent of the excitation frequency between 25 to 40 Hz (Anderegg and Kaufmann 2004).

$$k_s = 4\pi^2 f^2 \left[\frac{m_d + m_e r_e \cos\phi}{a} \right] \tag{4}$$

The k_s measurement system has the capability to perform compaction in a manual mode and in an automatic feedback control (AFC) mode. The AFC operations in the Case roller are controlled by the Ammann Compaction Expert (ACE) plus system. Three AFC operation settings are possible using the ACE plus system (Anderegg et al. 2006):

1. Low performance setting: Maximum applied force = 14 kN with vibration amplitude (a^*) varying from 0.4 to 1.5 mm.
2. Medium performance setting: Maximum applied force = 20 kN with vibration amplitude (a^*) varying from 1.0 to 2.0 mm.
3. High performance setting: Maximum applied force > 25 kN with vibration amplitude (a^*) varying from 2.0 to 3.0 mm.

When operated in AFC mode, as sub-harmonic vibrations occur, the roller automatically adjusts the eccentric mass moment to adjust the vibration amplitude and excitation frequency (Anderegg et al. 2006). Correlation studies relating k_s to soil dry unit weight, strength, and stiffness are documented in the literature (Anderegg and Kaufmann 2004).

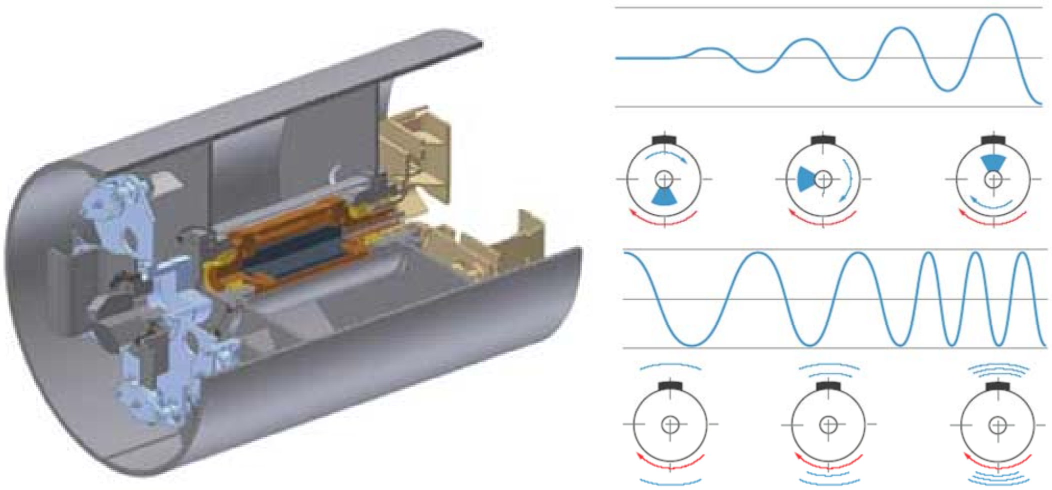


Figure 5. Ammann two-piece eccentric mass assembly and AFC of vibration amplitude and frequency (picture courtesy of Ammann)

Omega Value

Omega value provides a measure of the energy transmitted to the soil. The concept is illustrated by the schematic of the forces acting on the drum as a one-degree-of-freedom lumped parameter model in Figure 6, where: F_s is the force transmitted to the soil, z_d is the drum displacement, $\dot{z}_d$ is the drum acceleration, m_d is the static mass of the drum, m_f is the mass of the drum frame, Ω is the excitation frequency, $m_o e_o$ is the eccentric mass moment, and g is the acceleration due to gravity.

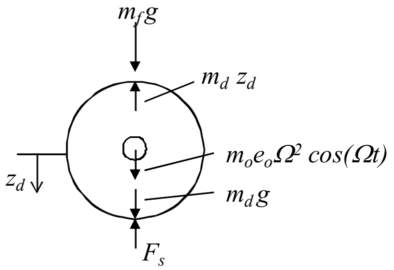


Figure 6. One-degree-of-freedom lumped parameter model representation of vibratory compactor (reproduced from Kröber et al. 2001)

F_s is determined by summing the static force (roller mass), drum inertia and the eccentric force ignoring the frame inertia. Accelerometer mounted on the drum provides the drum acceleration time history. The Omega value is then determined by integrating the transmitted force F_s and drum displacement z_d time history over two consecutive cycles of vibration using Eq. 5 (Kröber 1988).

$$Omega = \oint_{2T} \left(-(m_d)\dot{z}_d + (m_d + m_f)g + m_o\,e_o\Omega^2\right)\dot{z}_d\,dt \tag{5}$$

Vibratory Modulus (E_{VIB}) Value

The vibratory modulus (E_{VIB}) value is calculated using the one-degree-of-freedom lumped parameter model (Figure 6) and Lundeberg's theoretical solution (Lundberg 1939) for a rigid cylinder on an elastic half-space. A detailed description of the E_{VIB} measurement technology is provided by Kröber et al. (2001). Previous studies (Krober 1998 and Krober et al. 2001) reported that the E_{VIB} value is related to the modulus determined from a static plate load test. The drum force (F_s) and displacement (z_d) behaviour is related to E_{VIB} (see Eq. 6) using Lundberg's analytical solution. According to Hertz (1895), the contact width of a cylindrical drum (B) can be calculated using the geometry of the drum, applied force, and the material properties (see Eq. 6). The two equations (Eqs. 6 and 7) are numerically solved to determine the E_{VIB} value.

$$z_d = \frac{\left(1-\eta^2\right)}{E_{VIB}} \cdot \frac{F_s}{L} \cdot \frac{2}{\pi} \cdot \left(1.8864 + \ln\frac{L}{B}\right) \tag{6}$$

$$\text{where } B = \sqrt{\frac{16}{\pi} \cdot \frac{R'(1-\eta^2)}{E_{VIB}} \cdot \frac{F_s}{L}} \tag{7}$$

Where, η = Poisson's ratio of the material, L = length of the drum, B = contact width of the drum, and R' = radius of the drum.

The automatic feedback control (AFC) system developed by BOMAG uses a concept of counter-rotating eccentric mass assembly that is directionally vectored to vary the vertical excitation force on the soil (see Figure 7). If the counter-rotating masses are opposite each other in their rotation cycles, the eccentric force is zero. On the other hand, when the counter-rotating masses pass each other, the eccentric force is at maximum. The AFC system automatically adjusts the amplitude (by adjusting the vectors) depending on the pre-selected settings or the drum behavior (see Figure 7). Two different AFC settings are available as described below.

1. Pre-selected target E_{VIB} and a maximum amplitude a_{max} value: In this setting, the vibration amplitude is reduced below the a_{max} value when $E_{VIB} \geq$ target E_{VIB}, and the amplitude is at the a_{max} value when $E_{VIB} <$ target E_{VIB}.
2. Pre-selected a_{max} value: In this setting, the vibration amplitude is controlled based on the drum double jump behavior (described more in detail below) as measured by the jump value. When the jump value increases above 0, the amplitude is lowered to 0.6 mm.

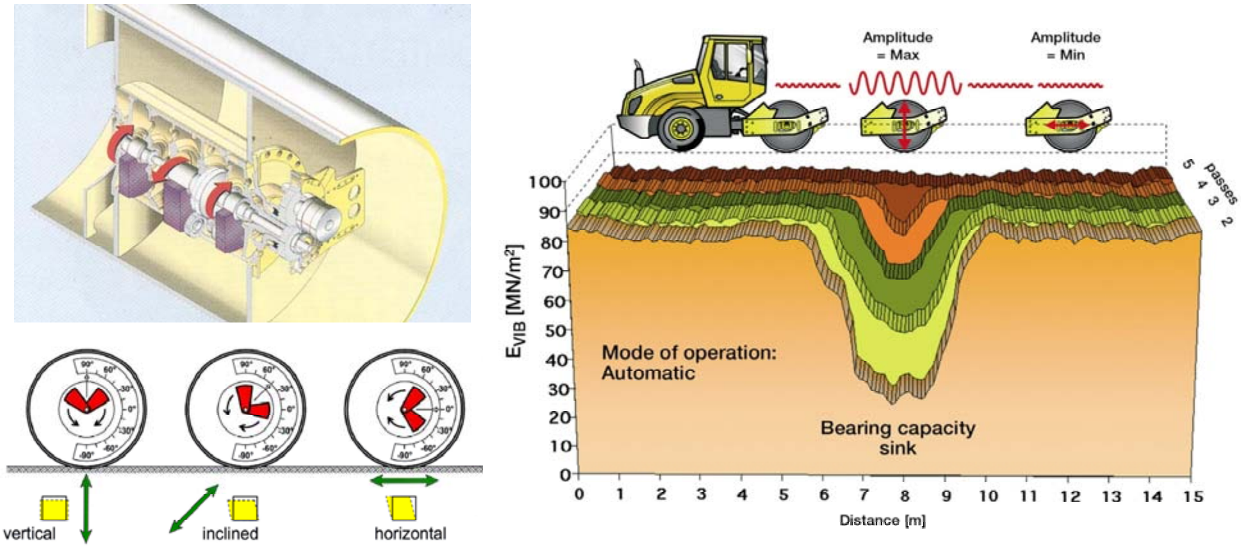


Figure 7. BOMAG roller eccentric mass assembly and vectoring to vary the vertical excitation force (left) and principle of BOMAG's automatic feedback control (AFC) system (right) (courtesy of BOMAG)

Machine Drive Power (MDP)

Machine drive power (MDP) technology relates mechanical performance of the roller during compaction to the properties of the compacted soil. Detailed background information on the MDP system is provided by White et al. (2005). MDP is calculated using Eq. 8.

$$\text{MDP} = P_g - Wv\left(\text{Sin}\alpha + \frac{A'}{g}\right) - (mv + b) \tag{8}$$

where MDP = machine drive power (kJ/s), P_g = gross power needed to move the machine (kJ/s), W = roller weight (kN), A' = machine acceleration (m/s^2), g = acceleration of gravity (m/s^2), α =

slope angle (roller pitch from a sensor), v = roller velocity (m/s), and m (kJ/m) and b (kJ/s) = machine internal loss coefficients specific to a particular machine (White et al. 2005). MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values indicate material that is more compacted than the calibration surface (i.e. less roller drum sinkage).

In a recent field study documented by White et al. (2009b) and field studies conducted as part of this pooled fund research project (Kansas and Mississippi field project from this research study), the MDP values are referred to as MDP_{80} or MDP_{40} depending on the modified settings. These modified values were recalculated to range between 1 and 150 using Eqs. 9 and 10.

$$MDP_{80} = 150 - 1.37(MDP) \tag{9}$$

$$MDP_{40} = 150 - 2.75(MDP) \tag{10}$$

For MDP_{80} calculation, the calibration surface with MDP = 0 kJ/s was scaled to MDP_{80} = 150, and a soft surface with MDP = 108.47 kJ/s (80000 lb-ft/s) was scaled to MDP_{80} = 1. For MDP_{40} calculation, the calibration surface with MDP = 0 kJ/s was scaled to MDP_{40} = 150 and a soft surface with MDP = 54.23 kJ/s (40000 lb-ft/s) was scaled to MDP_{40} = 1.

Influence of Drum Behavior on CCC/IC Values

Previous experimental and numerical investigations (e.g., Adam and Kopf 2004) on roller drum-soil interaction identified five different drum behavior modes which are dependent on the soil stiffness and roller operational settings (i.e., amplitude, frequency, and speed). These five modes include: continuous contact, partial uplift, double jump, rocking motion, and chaotic motion (see Figure 8). The accelerometer based CCC/IC values (i.e., CMV, RMV, Omega, E_{VIB}, and k_s) are influenced by these different drum modes (see Figure 9).

For CMV measurement technology the drum jump behavior is assessed using the RMV or BV measurements. According to Adam and Kopf (2004), RMV or BV = 0 indicates that the drum is in a continuous contact or partial uplift mode. For RMV or BV > 0, the drum enters double jump mode and transitions into rocking and chaotic modes with increasing soil stiffness. Based on numerical studies, Adam and Kopf (2004) demonstrated the change in CMV relative to soil stiffness and drum behavior as shown in Figure 9. For E_{VIB} measurement technology, the drum behavior is assessed using Jump value. Jump = 0 indicates the drum is in continuous contact or partial uplift mode and Jump > 0 (1 or 2) indicates the drum is in either in double jump, rocking, or chaotic mode. AFC systems should help control the drum behavior to prevent the drum jumping by automatically adjusting the vibration amplitude and/or frequency.

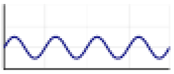
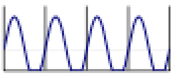
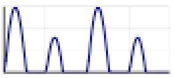
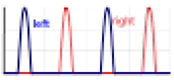
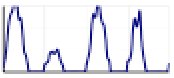
drum motion	Interaction drum-soil	operating condition	soil contact force	application of CCC	soil stiffness	roller speed	drum ampli-tude
periodic	continuous contact	CONT. CONTACT		yes	low	fast	small
	periodic loss of contact	PARTIAL UPLIFT		yes			
		DOUBLE JUMP		yes			
		ROCKING MOTION		no			
chaotic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

Figure 8. Influence of soil modulus and drum behavior on IC-MVs (from Adam and Kopf 2004)

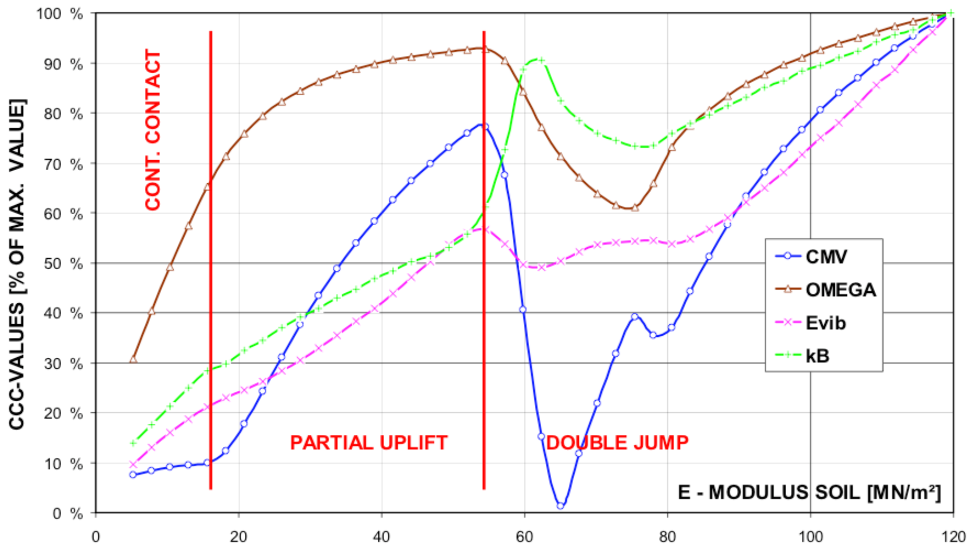


Figure 9. Influence of drum behavior on IC-MVs relative to soil modulus (based on numerical simulations from Adam and Kopf 2004) (Note $k_B = k_s$)

Manufacturers, Roller Types, and Documentation Systems

Currently, at least six manufacturers (Ammann, BOMAG, Case/Ammann, Caterpillar, Dynapac, and Sakai) offer CCC/IC on their machines (note that Case uses Ammann CCC/IC technology on their rollers). All the manufacturers employ proprietary data filtering, recording, and display methods using proprietary software's. A summary of key features from each manufacturer is presented in Table 1. Figure 10 to Figure 15 show different roller configurations and display software's by different manufacturers.

Table 1. Key features of different CCC/IC systems (as of 2009)

Feature	Ammann/Case	BOMAG	Caterpillar	Dynapac	Sakai	Trimble
CCC/IC Value	k_s (MN/m)	E_{VIB} (MPa)	MDP_{40} (shown as CCV in the output) and CMV	CMV	CCV	CMV
Drum Configuration	Padfoot, Smooth Drum	Smooth Drum	Padfoot and Smooth Drum	Padfoot and Smooth Drum	Smooth Drum	(Retrofit) Smooth Drum
Display Software	ACE-Plus ®	BCM05®	AccuGrade®	DCA®	Aithon MT®	AccuGrade®
Output Documentation	Date/Time, Location (Latitude/ Longitude/ Elevation), Machine length/width, Direction (forward/ backward), Vibration (On/Off), Stiffness (k_s), Amplitude (actual), Speed, Frequency	Date/Time, Location (Northing/ Easting/ Elevation at center of the roller drum), E_{VIB}, Frequency, Amplitude (actual), Speed, Jump	Date/Time, Location (Northing/Easting/ Elevation of left and right ends of the roller drum), Speed, CCV, CMV, RMV, Frequency, Amplitude, Direction (forward/ backward), Vibration (On/Off)	Location (Latitude/ Longitude/ Elevation), Direction (forward/ backward), CMV, Bouncing, Frequency, Speed, Amplitude	Date/Time, Location (Northing/ Easting/ Elevation), CCV, Temperature, Frequency, Direction (forward/ backward), Vibration (On/Off), GPS Quality	Date/Time, Location (Northing/Easting/ Elevation of left and right ends of the roller drum), Speed, CCV, CMV, RMV, Frequency, Amplitude, Direction (forward/ backward), Vibration (On/Off)
Output Export File	*.txt	*.csv	*.csv	*.txt	*.csv	*.csv
Automatic Feedback Control (AFC)	Yes	Yes	No	Yes	No	No

Figure 10. Ammann and Case rollers (padfoot and smooth rum) equipped with roller-integrated k_s measurement system on-board display units with ACE-Plus® software

Figure 11. BOMAG rollers (padfoot and smooth rum) equipped with roller-integrated E_{VIB} measurement system on-board display units with BCM-05® software

Figure 12. Caterpillar rollers (padfoot and smooth rum) equipped with roller-integrated MDP and CMV measurement systems on-board display unit with AcuGrade® software

Figure 13. Dynapac rollers (padfoot and smooth rum) equipped with roller-integrated CMV measurement system and on-board display unit with DCA® software

Figure 14. Sakai rollers (padfoot and smooth rum) equipped with roller-integrated CCV measurement system and on-board display unit with Aithon-MT$^{®}$ software

Figure 15. Trimble CB430 on-board display unit with roller-integrated CMV measurement system

FIELD CORRELATION STUDIES

Correlation studies relating different CCC/IC measurements to soil dry unit weight, strength, and stiffness/modulus properties in-situ are documented in the technical literature. A variety of in-situ test QC/QA devices have been used in the documented correlation studies (Figure 16):

- Density and moisture content — nuclear gauge (Figure 16a), electrical density gauge (Figure 16b), water balloon method, sand cone replacement method, radio isotope method, and drive core method.
- Stiffness or Modulus — light weight deflectometer (LWD) (Figure 16c), soil stiffness gauge (SSG) (Figure 16d), static plate load test (PLT) (Figure 16e), falling weight deflectometer (FWD) (Figure 16f), Briaud compaction device (Figure 16g), dynamic seismic pavement analyzer (D-SPA) (Figure 16h), Clegg hammer (Figure 16i), pressure meter, and screw plate.
- Strength or California bearing ratio — shelby tube sampling and laboratory testing (Figure 16j); dynamic cone penetrometer (DCP) (Figure 16k), cone penetration testing (CPT) (Figure 16l), rut depth measurements under heavy test rolling (Figure 16m)
- Other — surface settlement monitoring under compaction passes using GPS or total station surveying, etc.

A summary of field correlation studies documented in the literature is provided in Table 2. A comprehensive correlation study involving field evaluation of five different CCC/IC technologies on 17 different soil types from multiple project sites is documented in NCHRP 21-09 (2010). A list of factors that commonly affected the correlations between CCC/IC and in-situ test measurements are identified from that study are as follows:

1. Heterogeneity in underlying layer support conditions
2. High moisture content variation
3. Narrow range of measurements
4. Machine operation setting variation (e.g., amplitude, frequency, speed) and roller "jumping")
5. Non-uniform drum/soil contact conditions
6. Uncertainty in spatial pairing of point measurements and roller MVs
7. Limited number of measurements
8. Not enough information to interpret the results
9. Intrinsic measurement errors associated with the roller MVs and in-situ point measurements

Of all the factors above, heterogeneity in support conditions of layers underlying the compaction layer is identified as the major factor that affects the correlations (NCHRP 21-09 2010). This is largely due to differences in measurement influence depths between the roller and the in-situ point-MVs (see Figure 17). An approach of using the underlying layer CCC/IC measurements and in-situ point-MV information, and incorporating those into multiple regression analysis is described in NCHRP 21-09 (2010).

Figure 16. Various in-situ QC/QA test measurements: (a) nuclear moisture-density gauge; (b) electrical density gauge; (c) light weight deflectometers; (d) soil stiffness gauge; (e) static plate load test; (f) falling weight deflectometer; (g) Briaud compaction device; (h) seismic pavement analyzer; (i) Clegg hammer; (j) shelby tube sampling; (k) dynamic cone penetrometer; (l) static cone penetrometer; and (m) heavy test rolling

Table 2. Summary of field correlation studies

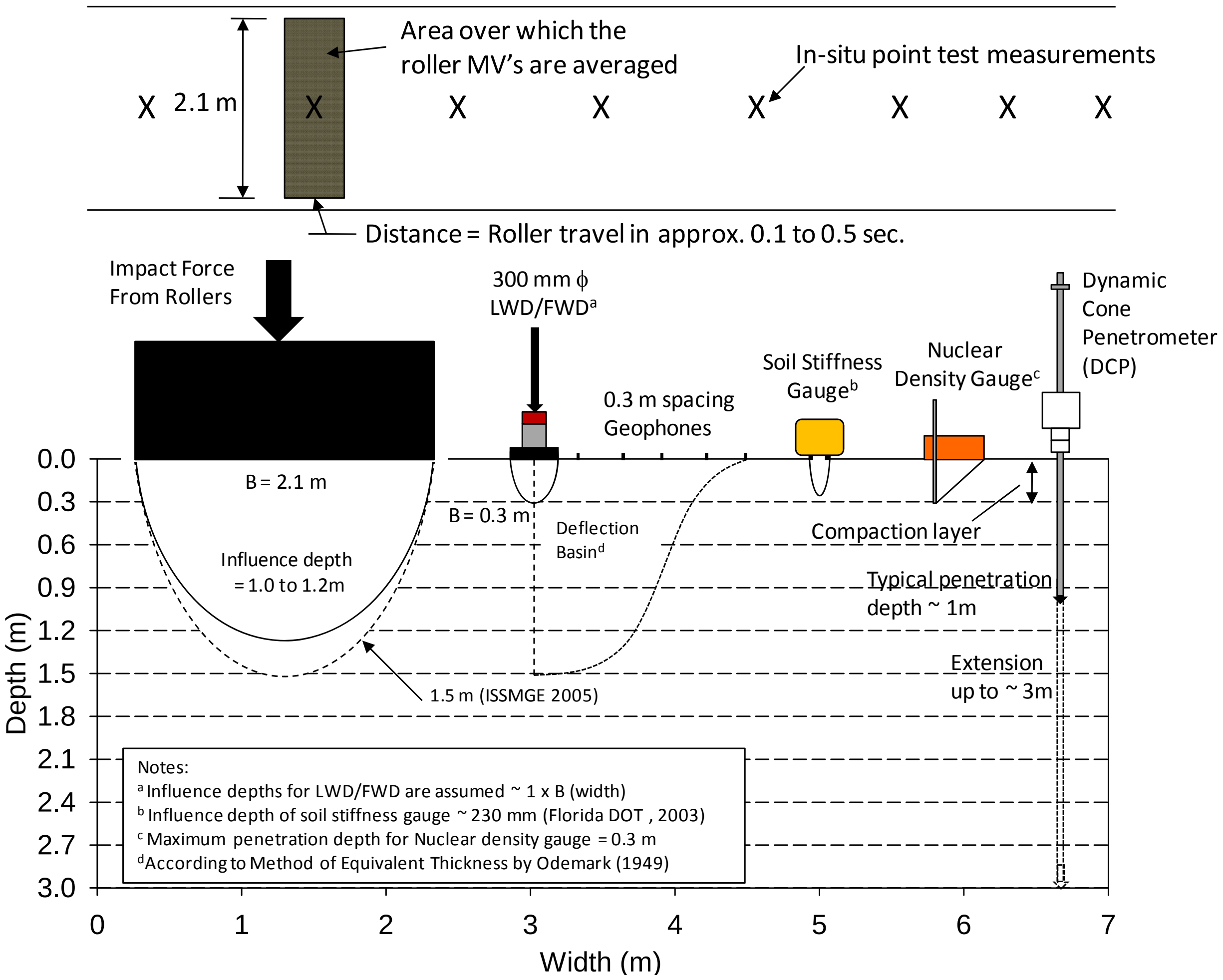
Reference	Project location	Roller Type; CCC/IC	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
Forssblad (1980)	Sweden	Dynapac SD; CMV	Morainic soil, fine rock fill, and coarse rock fill	Water balloon volumeter (for density), PLT, FWD, and surface settlement	Linear correlations have been observed between CMV and Point-MVs. Moisture content should be considered in correlations for fine grained soils. Roller results in a composite value in layered soil condition. CMV measurements are affected by roller speed (higher speeds result in lower CMV).
Hansbo and Pramborg (1980)	Stockholm, Sweden	Dynapac SD; CMV	Gravelly sand, silty sand, and fine sand	Sand cone (for moisture and density), pressuremeter, PLT, screw-plate, CPT, and DCP	Compaction growth curves showed improvement in CMV and other mechanical properties (i.e., modulus and cone resistance) with increasing pass. Relative compaction measurement was not sensitive to changes in compaction.
Floss et al. (1983)	Munich II airport, Munich, Germany	Dynapac Dual SD; CMV	Sandy to silty gravel fill	Bentonite displacement, water balloon method, and sand cone (for moisture and density), PLT, and DCP	Correlations generally showed increasing CMV with increasing density, modulus, and DCP penetration blows (per 0.6 m penetration). Correlations with modulus and penetration blows were generally better than density. CMV measurements are dependent on speed, vibration frequency and amplitude, type of soil, grain composition, water content, and strength of subsoil.
Brandl and Adam (1997)	—	BOMAG SD; CMV	—	PLT	Correlation between CMV and PLT modulus (initial) showed different regression trends for partial uplift and double jump operating conditions. Regressions in partial uplift and double jump conditions yielded $R^2 = 0.9$ and 0.6, respectively.
Nohse et al. (1999)	2nd Tomei Exp. way, Japan	Sakai SD; CMV	Clayey gravel	Radio-isotope (for density)	On calibration test strips, average dry density and CMV increased with increasing roller passes. Linear regression relationships with $R^2 > 0.9$ were observed for correlations between dry density and CMV.
Kröber et al. (2001)	—	BOMAG SD; E_{VIB}	Silty gravel	PLT	Correlations from calibration test strips between E_{VIB} and PLT initial and reload modulus (E_{V1} and E_{V2}) showed strong correlation with $R^2 > 0.9$.
Gorman and Mooney (2003); Mooney et al. (2003)	Oklahoma	Ingersoll Rand SD; Total harmonic distortion (THD)	Well-graded sand	DCP	Trends in relationship between THD and DPI generally showed decreasing penetration resistance with increasing THD. Strength of the correlations improve significantly if the sub-lift material was stiffer.

Reference	Project location	Roller Type; CCC/IC	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
Preisig et al. (2003); Anderegg and Kaufmann (2004)	Bern, Switzerland	Ammann dual SD; k_s	Eight project sites with sandy gravel materials	PLT	Correlations between ks and PLT initial and reload (E_{V1} and E_{V2}) modulus showed $R^2 = 0.68$ and 0.56, respectively. If only data points with E_{V2}/E_{V1} ratio < 3.5 (i.e., areas with less plastic deformation during reloading) are considered, the R^2 values improve to about 0.80.
White et al. (2004, 2005)	Edwards, Illinois	Caterpillar PD; MDP	Lean clay	NG, Drive core, DCP, and Clegg hammer	Correlations between MDP and in-situ test measurements using simple and multiple regression analyses are presented. MDP correlated relatively better with dry unit weight ($R^2 = 0.86$) than with DCP ($R^2 = 0.38$) or CIV ($R^2 = 0.46$). Including moisture content via multiple regression analysis greatly improves the R^2 values for DCP and CIV ($R^2 > 0.9$). These results were developed by averaging data over 20m long strip per pass.
Camargo et al. (2006)	Atwater test site, Minnesota	BOMAG SD; E_{VIB}	Select granular subbase	LWD, DCP, and SSG	No statistically significant correlation between Point-MVs and E_{VIB} values, however, the COV observed in LWD and SSG measurements were similar to COV in E_{VIB} measurements. Narrow range of measurements contributed to weak correlations.
Hossain et al. (2006)	US65 and I-70, Kansas	BOMAG SD; E_{VIB}	Well-graded silty sand	NG and DCP	E_{VIB} measurements are sensitive to soil moisture content. Weak correlation was observed between E_{VIB} and CBR determined from DCP, and NG. (E_{VIB} measurements obtained in AFC mode which are influenced by changing amplitude).
Peterson et al. (2006)	MnRoad, Albertville, Minnesota	BOMAG SD; E_{VIB}	Silty sand, railroad ballast, and well-graded granite	DCP, SSG, LWD, PLT, FWD, NG, and sand cone (for moisture and density)	Influence of applied stress on soil modulus determined by different test methods, and influence of measurement influence depth and differences between different test methods are discussed in this paper.
Petersen and Peterson (2006)	TH53, Duluth, Minnesota	Caterpillar SD; CMV and MDP		LWD, DCP and SSG	Weak correlations were obtained on a point-by-point basis comparison between in-situ test measurements and roller measurements, likely due to the depth and stress dependency of soil modulus, and the heterogeneity of the soils. Good correlations were obtained between CMV values and DCP measurements for depths between 200 and 40 mm depth.

Reference	Project location	Roller Type; CCC/IC	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
White et al. (2006a, b)	Edwards, Illinois	Caterpillar PD; MDP	Well-graded silty sand	NG and DCP	Average machine power values showed a decreasing (logarithmic) trend, dry unit weight values showed an asymptotic increase, and DCP index showed an asymptotic decrease with increasing roller pass. Correlations between MDP and Point-MVs showed good correlations ($R^2 = 0.5$ to 0.9). Incorporating moisture content into analysis is critical to improve correlations for dry unit weight.
White et al. (2006b); Thompson and White (2008)	Edwards, Illinois	Caterpillar PD; MDP	Silt and lean clay	NG, DCP, Clegg Hammer, and LWD	Correlations between MDP and Poin-MVs are presented using simple and multiple regression analysis. Averaging the data along the full length of the test strip (per pass) improved the regressions. Multiple regression analysis by incorporating moisture content as a regression parameter further improved the correlations.
Thompson et al. (2008) and White et al. (2007a)	US14, Janesville, Minnesota	Ammann SD; k_s	Sandy lean clay subgrade, and poorly graded sand base layer	LWD, PLT, DCP, Clegg Hammer, and NG	k_s correlated well with PLT with $R^2 = 0.80$ and the R^2 values with other measurements ranged from 0.30 to 0.61 on subgrade. Poor R^2 values were observed on the e base layer due to narrow range of measurements.
White et al. (2007a); White et al. (2008b)	TH64, Ackley, MN	Caterpillar SD, CMV	Poorly graded sand and well-graded sand with silt	LWD, DCP, and NG	Project scale correlations by averaging data from different areas on the project are presented, which showed R^2 values ranging from 0.52 for density and 0.79 for DPI. Correlations with LWD showed poor correlations due to the effect of loose surficial material. The COV observed in the CMV data was similar to DCP and LWD measurements but not to density measurements.
White et al. (2007b); White and Thompson (2008)	Edwards, Illinois	Caterpillar SD; MDP and CMV	Reclaimed asphalt, clayey gravel, silty gravel, poorly graded gravel, and silt	NG, DCP, Clegg hammer, and LWD	Averaging the data along the full length of the test strip (per pass) improved the correlations between MDP, CMV, and Point-MVs. The relationships were independent of soil type. Compaction curves of MDP, CMV, and Point-MVs showed improvement in soil compaction with increasing roller pass. CMV measurements reflected the properties of the underlying subgrade layer.
White et al. (2007b)	Edwards, Illinois	Caterpillar PD; MDP	Sandy lean clay	NG and DCP	Based on average measurements over the length of the test strip (~20 m); correlations between MDP and Point-MVs ($R^2 = 0.87$ for density and 0.96 for DCP)

Reference	Project location	Roller Type; CCC/IC	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
White et al. (2008c); Vennapusa et al. (2009)	Edwards, Illinois	Caterpillar PD; MDP	Crushed gravel base	DCP and LWD	Correlations were obtained on a test bed with multiple lifts placed on a concrete base and a soft subgrade base. Correlations between MDP and Point-MVs yielded R^2 = 0.66 to 0.85 for spatially nearest point data, and R^2 = 0.74 to 0.92 for averaged data (over the length of concrete or soft subgrade).
White et al. (2009a, b)	TH60, Bigelow, Minnesota	Caterpillar PD; MDP_{80} and Caterpillar SD; CMV	Sandy lean clay to lean clay with sand	Heavy test roller, DCP, LWD, and PLT	Correlations were obtained on multiple calibration test strips and production areas from the project. MDP_{80} and LWD modulus correlation showed two different trends (R2 = 0.35 and 0.65) over the range of measurements as the MDP_{80} reached an asymptotic value of about 150 which is the maximum value on the calibration hard surface. CMV correlation with LWD modulus produced R^2 = 0.70, and with rut depth produced R^2 = 0.64.
White et al. (2009b)	TH36, North St. Paul, Minnesota	Caterpillar SD; CMV	Granular subbase and select granular base	DCP, SSG, Clegg Hammer, LWD, PLT, FWD, and CPT	Correlations between CMV and Point-MVs from calibration and production test areas based on spatially nearest point data are presented. Positive trends are generally observed with R^2 > 0.5 (for LWD, FWD, PLT, SSG, and Clegg) with exception of one test bed (FWD, LWD, and CPT) with limited/narrow range of measurements.
White et al. (2009b)	US10, Staples, Minnesota	Caterpillar SD; CMV	Poorly graded sand with silt to silty sand	LWD, PLT, and DCP	Correlations between CMV and Point-MVs from calibration and production test areas based on spatially nearest point data are presented. Correlations between CMV and Point-MVs showed R^2 value ranging from 0.2 to 0.9. The primary factors contributing to scatter are attributed to differences in measurement influence depths, applied stresses, and the loose surface of the sandy soils on the project. Correlations between CMV and LWD or DCP measurements improved using measurements at about 150-mm below the compaction surface.

Reference	Project location	Roller Type; CCC/IC	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
White et al. (2009b)	CSAH 2, Olmsted County, Minnesota	Caterpillar PD; MDP_{80}	Sandy lean clay	LWD	MDP_{80} values were influenced by the travel direction of the roller due to localized slope changes and roller speed. Correlations between MDP_{80} and LWD generally showed $R^2 > 0.6$ (with exception of one case) when regressions were performed by separating data sets with different travel directions and speed. Data was combined by performing multiple regression analysis incorporating travel speed and direction which showed correlations with $R^2 = 0.93$.
NCHRP 21-09 (2010)	Minnesota, Colorado, North Carolina, Florida, and Maryland	Caterpillar (PD and SD; MDP and CMV), Dynapac (PD and SD; CMV), Sakai (SD, CCV), BOMAG (PD, SD, E_{VIB}), Case/ Ammann (SD, k_s)	Two types of cohesive subgrade materials, five types of granular subgrades, and six types of granular base materiasl	NG, DCP, LWD, FWD, PLT, Clegg hammer, SSG	Simple linear correlations between CCC/IC and compaction layer point-MVs are possible for a compaction layer underlain by relatively homogenous and stiff/stable supporting layer. Heterogeneous conditions in the underlying layers, however, can adversely affect the relationships. A multiple regression analysis approach is described that includes parameter values to represent underlying layer conditions to improve correlations. Modulus measurements generally capture the variation in CCC/IC values better than traditional dry unit weight measurements. DCP tests are effective in detecting deeper "weak" areas (at depths > 300 mm) that are commonly identified by CCC/IC values and not by compaction layer point-MVs. High variability in soil properties across the drum width and soil moisture content contribute to scatter in relationships. Averaging measurements across the drum width, and incorporating moisture content into multiple regression analysis, when statistically significant, can help mitigate the scatter to some extent. Relatively constant machine operation settings are critical for calibration strips (i.e., constant amplitude, frequency, and speed) and correlations are generally better for low amplitude settings (e.g., 0.7 to 1.1 mm).



Notes:
[a] Influence depths for LWD/FWD are assumed ~ 1 x B (width)
[b] Influence depth of soil stiffness gauge ~ 230 mm (Florida DOT , 2003)
[c] Maximum penetration depth for Nuclear density gauge = 0.3 m
[d] According to Method of Equivalent Thickness by Odemark (1949)

Figure 17. Illustration of differences in measurement influence depths for different measurements (modified from White 2008)

SPECIFICATIONS

Overview of Current Specifications

Some agencies (Swedish Road Administration, Federal Ministry of Transport of the Federal Republic of Germany, The Austrian Federal Road Administration, International Society for Soil Mechanics and Geotechnical Engineering, and Mn/DOT) have developed specifications to facilitate implementation of CCC/IC into earthwork construction practices. Table 3 provides a summary of key elements of the current CCC/IC specifications. A brief review of these specifications is presented by White et al. (2008b). The specifications typically require performing either PLT or LWD on calibration strips to determine average target values (typically based on 3 to 5 measurements) and use the same for quality assurance later in production areas. The German specification suggests performing at least three PLTs in locations of low, medium, and high degree of compaction during calibration process. Further, it is specified that linear regression relationships between roller measurement values and plate load test results should achieve a regression coefficient, $R \geq 0.7$.

White and Vennapusa (2009) documented the following as the key attributes required in CCC/IC specifications and noted that the largest dissimilarities exist in the current specifications with the attribute item number 10.

1. Descriptions of the rollers and configurations,
2. Guidelines for roller operations (speed, vibration frequency, vibration amplitude, and track overlap),
3. Records to be reported (time of measurement, roller operations/mode, soil type, moisture content, layer thickness, etc.),
4. Repeatability and reproducibility measurements for IC measurement values (IC-MVs),
5. Ground conditions (smoothness, levelness, isolated soft/wet spots)
6. Calibration procedures for rollers and selection of calibration areas,
7. Regression analysis between IC-MVs and point measurements,
8. Number and location of quality control (QC) and quality assurance (QA) tests,
9. Operator training, and
10. Acceptance procedures/corrective actions based on achievement of minimum MV-TVs (MV target values) and associated variability.

Table 3. Summary of current CCC/IC specifications (modified from White et al. 2008a)

Reference	Equipment	Field Size	Location Specs	Documentation	Compaction Specs	Speed	Freq.
Mn/DOT (2007a, b)	Smooth drum or padfoot vibratory roller (25,000 lbs.)	300 ft x 32 ft (minimum 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 (2005)	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 E_{v1}, 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)
Austria — RVS 8S.02.6. (1999)	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 E_{v1}, 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)
Germany — ZTVE StB/TP BF-StB (1994)	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	
Sweden — ROAD 94 (1994)	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	—

New Developmental Specifications and Concepts

The following specification options and concepts (Options 1 to 5) were discussed at a national level workshop participated by representatives from many state and federal agencies, contractors, and manufacturers (see White and Vennapusa 2009). These specification options differ in the required level of upfront calibration work, data analysis, and the level of confidence in the quality of the completed work.

Option 1: Roller based QC with pre-selected CCC/IC target values

For this specification option, an appropriate MV-TV is pre-selected based on documented case histories/literature, a database of information from local projects, laboratory tests, calibration tests on test beds of known engineering properties, mechanical apparatus simulating a range of soil conditions, and/or numerical modeling. The contractor uses the preselected MV-TV primarily for QC. QA is evaluated using a combination of IC-MVs and in situ QA point measurements. This option will become more beneficial as experience and data become available through implementation of IC on earthwork projects.

Option 2: CCC/IC maps to target locations for QA test measurements

IC-MV geo-referenced maps are used in this specification option to identify “weak” areas to focus on QA point measurements. Proper QC measures (e.g., controlling moisture content, lift thickness, etc.) should be followed during compaction. The contractor should provide the IC-MV map to the field inspector for selection of QA test locations. Judgment is involved with selecting the number of tests and test locations. Acceptance is based on achievement of target QA point measurement values in roller identified “weak” areas. If in-situ test QA criteria are not met, additional compaction passes should be performed and/or QC operations should be adjusted (e.g. moisture, lift thickness, etc.) and retested for QA.

Option 3: CCC/IC target values from compaction curves to target locations for QA point measurements

This specification option evaluates the change in IC-MVs with successive passes as an indicator of compaction quality. As the number of roller passes increases, the change in MV between passes normally decreases. A production area is monitored by evaluating the percent change in IC-MVs between successive passes. Once the percent change of ≤ 5% over 90% (these percentages can be adjusted based on judgment and field experience) of the production area between roller passes is achieved, the production area is considered fully compacted. This option is more effective for controlled field conditions with relatively uniform materials, moisture content, and lift thickness and serves as a QC process control for the roller operator. Judgment is involved with selecting the number of tests and test locations. Acceptance is similar to Option 1, in that QA testing is targeted in areas with relatively low IC-MVs.

Option 4: Calibration of CCC/IC measurements to QA point measurements

This specification option requires calibration of IC-MVs to QA point measurements from a representative calibration test strip prior to performing production QA testing. The MV-TV is established from project QA criteria through regression analysis and applying prediction intervals. For modulus/strength measurements simple linear regression analysis is generally suitable, while for correlation to dry unit weight/relative compaction measurements, multiple regression analysis including moisture content as a variable may be needed. If underlying layer support conditions are heterogeneous, relationships are likely improved by performing multiple regression analysis with IC-MV or point measurement data from underlying layers. Acceptance of the production area is based on achievement of MV-TV at the selected prediction interval (80% is suggested) and achievement of target QA point measurement values in the areas with MVs < MV-TV.

Option 5: Performance based QA specification with incentive based payment

One of the shortcomings of the existing CCC/IC specifications might be that the acceptance criteria (specifically the target limits) are dependent on specific IC technology. This specification option, although requires a more rigorous statistical analysis framework (see White et al. 2009b), could provide a consistent means for specifying acceptance criteria. The acceptance criteria for this option are: (a) the overall level of critical soil engineering properties over an area achieve the MV-TV, and (b) the variability of critical soil engineering properties over an area is no more than some specified maximal amount (e.g., COV%). These acceptance criteria are established based on regression analysis from calibration, applying prediction intervals, accounting for the repeatability and reproducibility errors associated with IC-MVs and point measurements, and a selected probability or risk level in acceptance decisions. This approach could provide a link to performance-based specifications and a quantitative mechanism to define incentive-based payment.

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