TECHBRIEF

U.S. Department of Transportation
Federal Highway Administration

Intelligent Compaction

CASE STUDY • SPRING 2014

SUMMARY OF INTELLIGENT COMPACTION ON SOIL AND SUBBASE

ABSTRACT

This Tech Brief represents the second in a series of three tech briefs that are targeted at sharing information about intelligent compaction (IC) technology and helping to promote its use throughout the U.S. The first Tech Brief provides an Executive Summary that provides background information, a detailed description of the technology, and identifies the advantages and implementation considerations. It is applicable to IC for both soil/subbase and hot-mix asphalt/warm-mix asphalt (HMA/WMA) construction. Using the findings of recent demonstration projects, this Tech Brief provides information that demonstrates the field application of this technology for soil and subbase materials.

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INTRODUCTION

Intelligent compaction (IC) refers to an innovative pavement construction technology in which conventional rollers are equipped with instrumentation that is used to monitor and control the material compaction process. The technology, which is applicable to both soil/subbase and hot-mix asphalt/warm-mix asphalt (HMA/WMA) compaction, provides graphical information that a roller operator can use to better manage his roller operations. This, in turn, ensures that the target properties of the layer are achieved in a more uniform and efficient fashion.

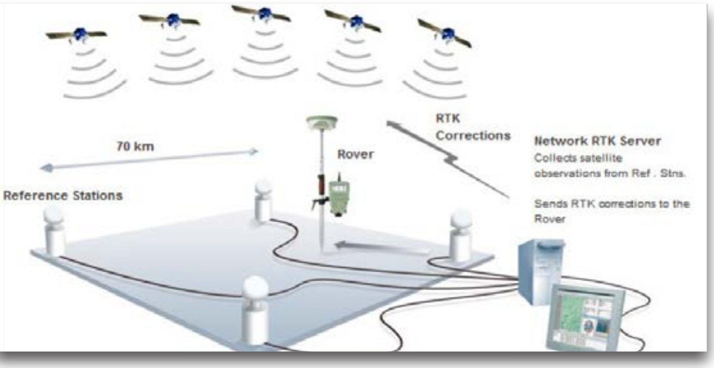
IC technology was developed in Europe in the 1980s and has proven to be an effective construction practice in many European countries. IC arrived in the U.S. roughly 10 years ago and, despite its proven success and demonstrated benefits, it is only slowly being implemented into U.S. practice.

DESCRIPTION OF IC FOR SOIL/BASE CONSTRUCTION

A single-drum Dynapac roller equipped with roller-integrated CMV measurement system.

OVERVIEW: When conventional roller compaction equipment and techniques are used for pavement construction, roller operators are essentially blind to what is happening to the underlying materials. To achieve adequate compaction, the operators must rely heavily on the application of pre-established roller patterns and the use of portable gauges that measure density at spot locations. In contrast, the continuous graphical (and numerical) information produced by IC-equipped rollers create a window into the layer compaction process.

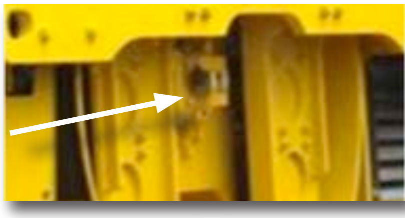
INSTRUMENTATION: The rollers used for IC on soil and subbase materials are basically the same as those used for conventional compaction techniques. The primary difference is the instrumentation system that is attached to measure, display, and record the compaction effects. The key components of this system are described below:

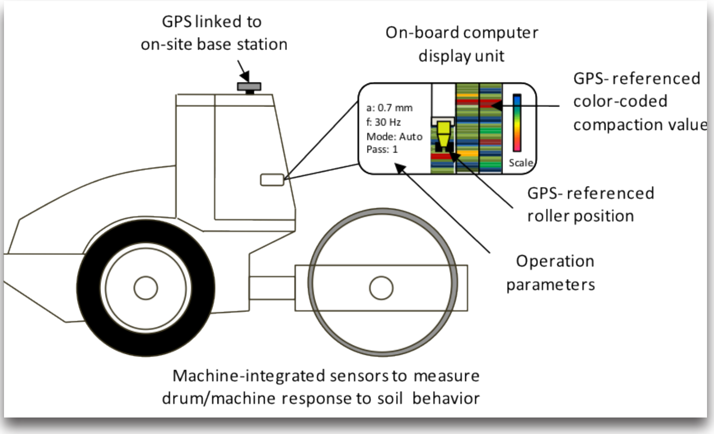


RTK using a Handheld rover/receiver with a reference network

- **GPS** – Global positioning systems are used to accurately locate the roller on the project. A real-time kinematic (RTK) GPS capable of providing the highest level of precision location (within 1 to 3 cm) is required for IC operations. This level of precision is achieved through the use of single or multiple RTK on-site GPS base stations or virtual reference stations (VRS), depending on the terrain. If the line of sight is unobstructed, the effective range of a GPS station on the project is approximately 2 miles. On IC rollers, the GPS antenna is mounted on the top of the cab.

- **Accelerometer** – The key component of the IC system is a small device that is mounted on the roller frame near the vibratory drum (see image to right). Double vibratory drum rollers may have two accelerometers, one mounted near both vibratory drums. The accelerometers measure the vertical acceleration of the roller frame as it moves down the road project.





Overview of ICMV compaction monitoring systems

- **Processing** – The software for processing the IC data is proprietary and manufacturer dependent. Each software product is capable of conducting a real-time analytical process in which the acceleration is converted to downward displacement and then combined with other roller information (such as amplitude, frequency, and speed) to produce a continuous profile of the level of compaction achieved in the soil/subbase layer. The software also uses information from the accelerometers to indicate whether there is a problem with drum bouncing or soft spots in either of these layers.

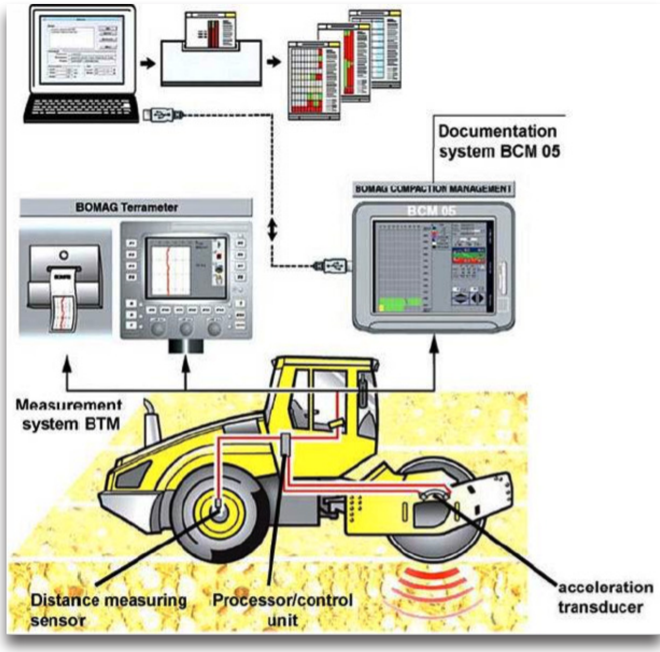
- **Automatic Feedback Control** – AFC refers to a feature available from some IC roller manufacturers in which the vibration amplitude and/or frequency are automatically adjusted if "drum jumping" above a certain threshold is detected. This phenomenon can occur when the dynamic reaction of the soil or base becomes synchronized with the frequency of the roller. By reducing or eliminating drum jumping, the compaction process can become more efficient and more uniform.

Caterpillar on-board display unit with AcuGrade® software.

- **Visual Display** – A monitor located in the cab displays real-time compaction information in both numerical and graphical format so that roller operators can make appropriate corrections or adjustments to the roller operation. The displayed information includes roller amplitude, frequency, GPS location, and speed. The effects of a roller pass are displayed in varying colors (or shades of color) so that the operator can track his location along the project, monitor the increase in layer stiffness, and ensure uniform coverage.

- **Data storage** – The system produces a complete digital record of the compaction process. The stored data can be downloaded at any time for analysis and documentation.

Each of the components is part of an overall IC system. The system does require routine inspection and calibration checks; however, it is relatively reliable and robust considering the construction conditions under which it must operate.



Bomag Vario Control System

EQUIPMENT MANUFACTURERS: Ammann, Bomag, Case/Ammann, Caterpillar, Dynapac, and Sakai are the primary manufacturers of single-drum IC rollers for soil and subbase compaction. Currently, all six produce IC rollers that are available in the U.S. Of the six manufacturers listed, four of them (Ammann, Bomag, Case/Ammann, and Dynapac) offer the AFC capability.

The primary vendors for GPS equipment including base stations and virtual reference stations include Trimble, TopCon, and Leica. Trimble also offers equipment and software for retrofitting IC on an existing roller.

INTELLIGENT COMPACTION MEASUREMENT VALUE: A standard measure for reporting the compaction results of IC rollers has not been established. Accordingly, each IC equipment manufacturer has developed its own unique method for characterizing the level of soil/subbase layer compaction (which in turn is incorporated into its own proprietary software for data processing and display). Since no standard exists, the term intelligent compaction measurement value (ICMV) is used to represent (collectively) the compaction measures produced by the different IC roller equipment. Following is a brief description of the five ICMVs currently used.

- Compaction Meter Value (CMV) was the first ICMV. It was established in 1976 by Geodynamic (a Swiss company) in cooperation with the Dynapac Research Department. CMV is an indicator of the soil/subbase layer's stiffness/modulus and is dimensionless. Dynapac, Caterpillar, and Trimble report CMV.

- Vibratory Modulus (EVIB) is a measure of the compacted layer's stiffness as produced by Bomag IC rollers. Its units are in mega pascals (MPa).

- Roller Integrated Stiffness (k_b) is the measure of the compacted layer's stiffness as reported by Ammann/Case rollers. Its units are in mega-Newtons per meter (MN/m).

- Machine Drive Power (MDP) basically defines the amount of additional power required (in kJ/s) by the roller to compact a given soil (or subbase layer) over the power level required to compact the calibration layer. Thus, a positive MDP means that the layer being compacted has not yet reached the level of compaction associated with the calibration layer. Similarly, a negative MDP means that the layer being compacted has achieved a higher level of compaction than the calibration layer because it requires less power to move the roller. MDP may also be reported as an index property (either MDP80 or MDP40) in which the power required is rated on a scale of 1 to 150, where 150 corresponds to the compaction level of the calibration layer.
- Compaction Control Value (CCV) is a measure of the compacted layer's stiffness as produced by Sakai's IC rollers. Like CMV, CCV is dimensionless.

KEY FINDINGS OF THE FHWA/TPF DEMONSTRATION IC PROJECTS FOR SOIL AND SUBBASE

PROJECT OVERVIEW: Between 2008 and 2010, 13 states participated in an FHWA-sponsored, Transportation Pooled Fund (TPF) study entitled "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials." The primary purpose of the study was to demonstrate and evaluate IC technologies through the execution of multiple field projects. Of the 13 states, 6 participated in the soil/subbase field demonstration projects (or case studies). These included Indiana, Kansas, Mississippi, North Dakota, New York, and Texas. Following is summary information on each demonstration project.

	Location and Year	Highway	Layers Compacted Using IC	Machine(s)	In-situ Tests*
	W. Lafayette, IN	SR 25	Sandy embankment fill and silty clay	Caterpillar (single drum)	LWD, DCP, FWD
	Pleasanton, KS (2008)	US 69	Weathered shale and clean clay fills on subgrade and stiff weathered shale on clean clay subgrade	Caterpillar and Sakai (single-drum padfoot)	LWD, DCP, NG, FWD, PLT
	Waynesboro, MS (2009)	US 84	Granular base, cement treated granular base, granular subgrade, and cement treated granular subgrade	Caterpillar and Case/Ammann (AFC and manual)	LWD, DCP, NG, FWD, PLT
	Marmarth, ND	US 12	Silty subgrade and salvage base	Caterpillar (padfoot and smooth drums)	LWD, DCP, CBR, NG, FWD, BST
	Springville, NY (2009)	219	Embankment, embankment (with underlying tire fill), and gravel subbase	Caterpillar and Bomag (AFC and manual)	LWD, DCP, NNG, FWD, PLT, BCD
	Fort Worth, TX (2008)	FM 156	Subgrade, lime stabilized subgrade, and flex base	Case/Ammann and Dynapac (smooth and padfoot drums)	LWD, DCP, NG, FWD, PLT, PSPA

*Test Codes: BST-Bore Hole Shear Test, CBR-California Bearing Ratio, DCP-Dynamic Cone Penetrometer, PSPA-Portable Seismic Pavement Analyzer, FWD-Falling Weight Deflectometer, LWD-Light Weight Deflectometer, NG-Nuclear Density Gauge, NNG-Non-nuclear Density Gauge, PLT-Plate Load Test.

SUMMARY OF KEY FINDINGS: The use of IC was demonstrated to be a success in all six states. The following table provides a summary of some of the more significant findings from each state's demonstration project.

State	Most Significant Findings
Indiana	• Granular embankment fill Machine Drive Power generally increased with the number of passes, but no significant differences were detected using different amplitudes. • MDP values are generally repeatable in both forward and reverse passes. • WD modulus values correlated best with MDP values.
Kansas	• Sakai CCV and Caterpillar MDP measurements are repeatable. • Color-coded maps of the IC data with 100 percent coverage information provided the opportunity to visualize compaction quality over a production area or at a given point. • Linear regression analysis produced poor to good correlations between IC and point measurement values.
Mississippi	• Empirical correlations between ICMVs and different in-situ measurements were weak sometimes. • ICMVs generally correlated better with modulus-based and CBR in-situ measurements than with dry density in-situ measurements. • IC data indicated that the response distance for altering the amplitude and/or frequency was about 1 to 2 m for a roller speed of about 4 km/hr. The Case/Ammann roller on this project reported ICMVs every 1 m. A higher sampling rate is required to accurately evaluate the response distance.
North Dakota	• MDP increases with pass count, and high-amplitude setting results on lower MDP than low-amplitude setting.
New York	• Good correlation between ICMVs and in-situ point tests can be obtained (as long as both tests are conducted properly). • More testing is necessary to evaluate the AFC mode compaction operations with variable subsurface conditions
Texas	• IC rollers can effectively identify soft spots (e.g., wet zones) and hard materials (e.g., box culverts). • Padfoot rollers were demonstrated to produce excellent compaction curves. • Results of in-situ NG, DCP, and LWD did not match well with ICMVs. PLT and FWD results correlated better with ICMVs. • ICMVs resulting from automatic feedback control and manual control exhibited a similar trend; however, the AFC resulted in higher ICMVs.

Additional findings from the FHWA/TPF Demonstration projects fall under three categories: compaction curves, compaction uniformity, and correlation studies. Compaction curves refers to the two-dimensional graphs of a layer's level of compaction versus the number of roller passes. They are typically used to determine the number of roller passes that are required to achieve the target level of compaction. Compaction uniformity is important because of its impact on pavement performance. If the layers of the pavement structure are not compacted uniformly, the pavement is more likely to perform poorly, because of all the weak spots associated with poor uniformity. Correlation studies refer to the work done to develop meaningful relationships between ICMVs and other in-situ measurements, such as moduli, density, and CBR. Following are tables that summarize the key findings for these factors as they pertain to IC.

Key Findings for Compaction Curves

- Generally, ICMV and in-situ measurements increase with increasing number of passes; however, the rate of increase gradually decreases until close to being constant.
- In some cases, the ICMV may drop during the first and second pass before increasing.
- For some materials, the ICMV may increase and then decrease with each roller pass.
- Compaction curve results are material dependent.
- Compaction curve is affected by material moisture condition, with the dry and optimum moisture resulting in higher ICMV with each roller pass.
- The grade of the compaction area may affect the compaction curve.

Key Findings for Compaction Uniformity

- A higher vibration amplitude usually results in a lower compaction uniformity.
- With each roller pass, the compaction uniformity may increase or decrease.
- There was no consistent proof that either manual or AFC mode achieves higher uniformity.
- Materials that require curing typically exhibit more non-uniformity.

Key Findings from Correlation Studies

- ICMV increases with in-situ measurements. ELWD and EFWD had a good linear correlation; however, others (Plate Load Test results, CBR (from DCP), and non-nuclear density) were generally poor.
- Depending on the material, the linear relation may be either direct or logarithmic.
- There was no evidence that machine settings such as frequency, amplitude, and speed will affect the correlation quality.
- Separate trends were observed for different materials.

CONCLUSIONS

1. The primary conclusion that can be drawn from the FHWA/TPR study is that IC is an effective method for achieving the target level of soil and subbase compaction. Each of the IC rollers (and their respective instrumentation) worked satisfactorily in the demonstration projects where it was applied. There was no attempt in the study to compare the different IC rollers.
2. Both flat and padfoot steel wheel drum rollers were effective in their respective applications. With the exception of one state (Texas) reporting that padfoot rollers produced excellent compaction curves, there was no indication that one roller type was more effective for IC than the other.
3. Because of the ability to visually monitor compaction with each pass, IC rollers do increase the level of compaction uniformity as compared to conventional roller operations. However, there was no data to indicate that changing the roller settings (amplitude, frequency, or speed) results in improved uniformity during an individual pass.
4. Automatic feedback control was not demonstrated to improve compaction uniformity (as compared to rollers that were not equipped with the feature).
5. IC equipment can be used effectively to develop compaction curves and to determine the optimum number of roller passes.
6. The correlation studies showed some correlation between the ICMVs and the in-situ measurements. However, there was generally a lot of variability. The correlations between ICMVs with deflection-based moduli produced the best results.

AVAILABLE RESOURCES

The best source of information currently available on IC is the website: www.intelligentcompaction.com. In addition to providing valuable up-to-date information on most IC topics, it also identifies sources of information from previous and currently ongoing research efforts and case studies and provides links to other useful websites.

In addition to the Transportation Pooled Fund project (TPF-5(128)), there are two other recent studies that address intelligent compaction of soils and subbases:

NCHRP Report 676, Intelligent Soil Compaction Systems, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., 2010.

Evaluation of Intelligent Compaction Technology for Densification of Roadway Subgrades and Structural Layers, Draft Final Report, Wisconsin Highway Research Program, WHRP Project ID #0092-08-07, June 2010.

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