TECHNICAL BRIEF

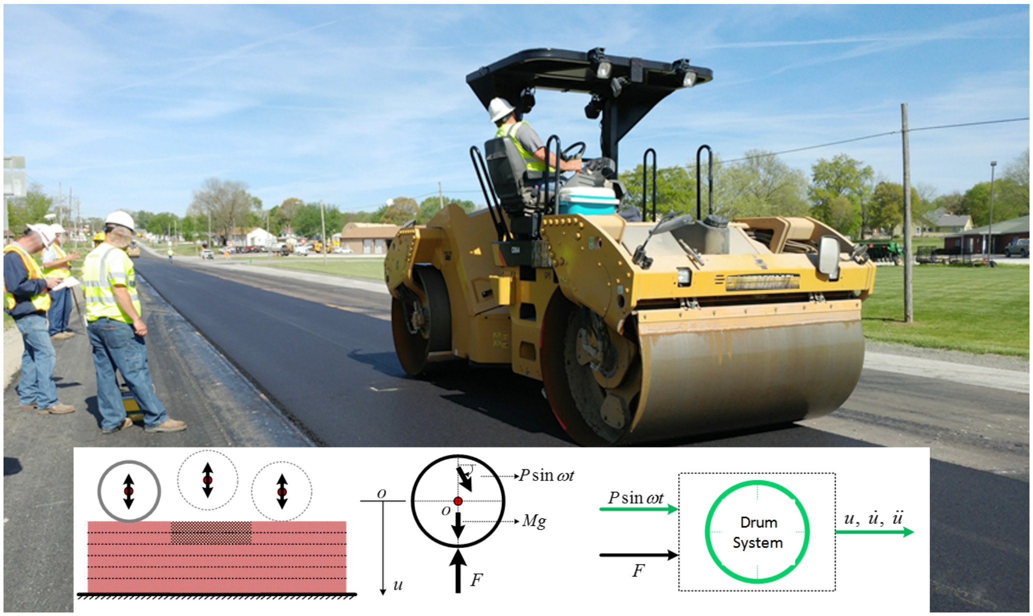
U.S. Department of Transportation
Federal Highway Administration

INTELLIGENT COMPACTION MEASUREMENT VALUES (ICMV)

A ROAD MAP

TECHNICAL BRIEF

SUMMER 2017



A Double IC Roller and A Diagram of ICMV Dynamic Model

WHAT IS ICMV?

Intelligent Compaction Measurement Value (ICMV) is a generic term for accelerometer-based measurement system instrumented on vibratory rollers as a key components of intelligent compaction systems. ICMV is based on the acceleration signals that represent the rebound force from the compacted materials to the roller drums. ICMV are in different forms of metrics with various levels of correlation to compacted material's mechanical and physical properties, such as stiffness, modulus, and density.

BACKGROUND

Intelligent compaction (IC) is an equipment-based technology to improve quality control of compaction. IC vibratory rollers are equipped with a high precision global positioning system (GPS), infrared temperature sensors, an accelerometer-based measurement system, and an onboard color-coded display. IC is used to improve compaction control for various pavement materials including granular and clayey soils, subbase materials, and asphalt materials. The accelerometer-based measurement system is a core IC technology that was invented in the early 80's and is still evolving today.

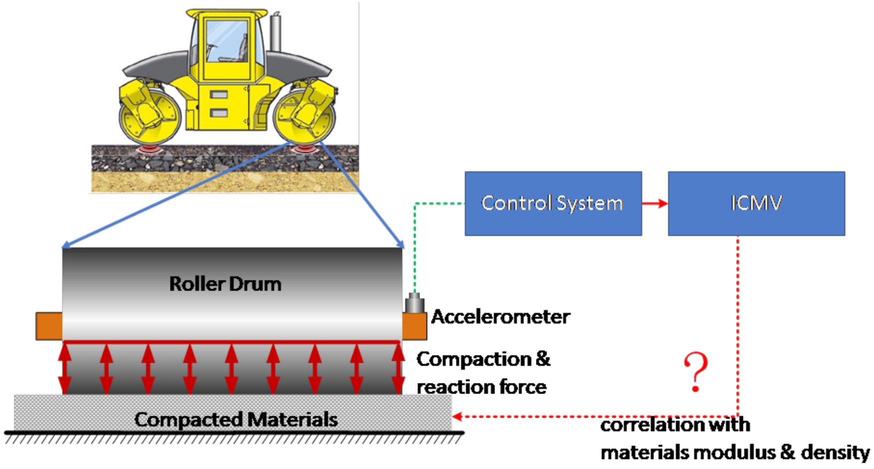
Intelligent Compaction Measurement Value (ICMV) is a generic term for a calculated value based on accelerometer measurements on vibratory roller drums. ICMV are in different forms of metrics with various levels of correlation to compacted material's mechanical and physical properties. The purpose of this document is to demystify ICMV by providing a comprehensive description on the mechanisms of ICMV and various levels of solutions as the road map for using ICMV towards compaction monitoring, control, and acceptance.

QUALITY ASSURANCE STATEMENT

HOW TO MEASURE AND CALCULATE ICMV

COMMON MECHANISM

The common mechanism for calculating all types of ICMV is to measure the vertical acceleration at the center of the vibrating drum and compute ICMV using various models and methods. The concept is simple and ingenious; measuring the properties of compacted materials during compaction allows real time compaction monitoring and control. The following figure illustrates how ICMV is measured. The roller drum exerts compaction force on the compacted materials and the compacted materials react the force back to the roller drum. The harder the compacted materials, the larger the reactive force. The reacted force is captured by the accelerometer in terms of acceleration. The control system will then process the acceleration signals and compute ICMV.



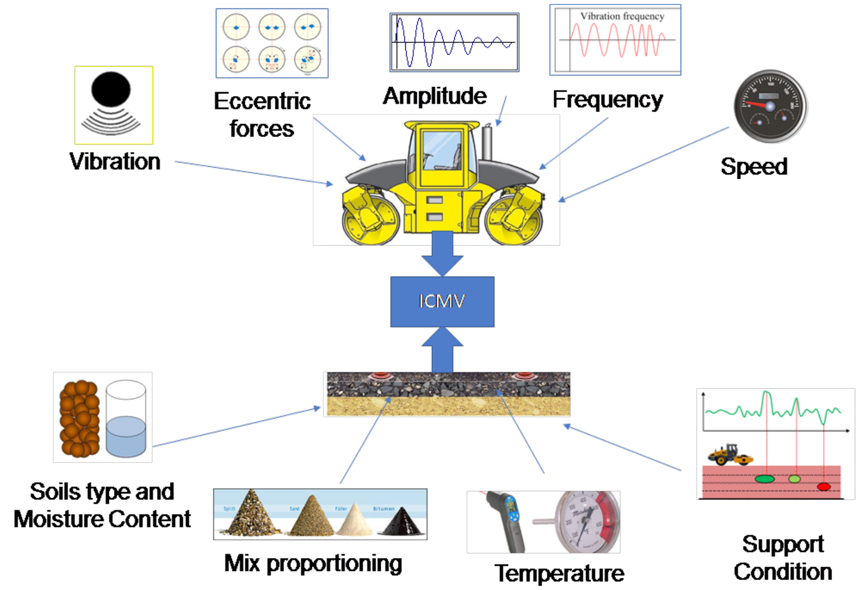
Common Mechanism of ICMV

CHALLENGES

The complexity of roller-material's interaction during dynamic, vibratory, contact, decouple, and impact rolling movements makes it challenging to produce accurate measurements. The following is just a brief list of challenges for ICMV:

- Complex Interaction between rollers and compacted materials
- Difficulty of solving ICMV due to variances of field measurements
- Differences between ICMV and conventional spot tests (footprint size and influence depth)

FACTORS THAT AFFECT ICMV



Factors that Affect ICMV

There are numerous factors affecting ICMV computation. Major factors from the roller side include vibration types, eccentric force, vibration amplitude and frequency, and roller speed. Major factors from the compacted materials side include soils types and moisture content, asphalt mixture proportioning, asphalt mix temperatures, and underlying support condition.

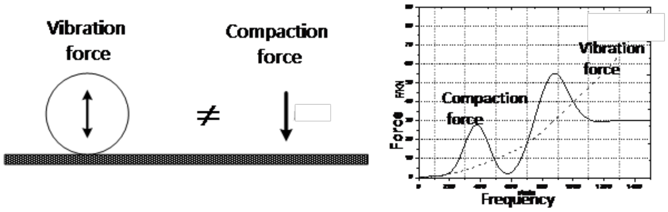
CHALLENGES FOR COMPUTATION OF ICMV

There are many challenges to producing ICMV.

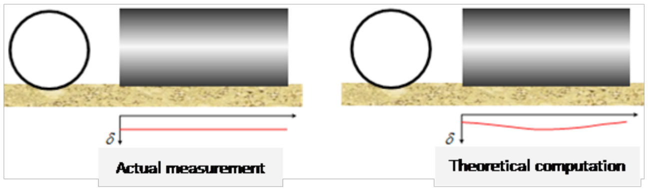
1. Vibration force is not equal to compaction force: The vibration force from the eccentric weight in the drum is not equivalent to the effective compaction force that asserts on compacted materials. The compaction force fluctuates as the vibration frequencies increase. On the other hand, the vibration force increases monotonically with increase of frequencies. This is a frequent mistake for researchers who start modeling the drum and material interaction.

2. Actual strain measurement is different from theoretical compaction: The actual strains and displacement under a drum is constant. However, the computed theoretical strains and displacement are variable across a drum width based on Lundberg's and Hertz's theories to solve the contact problem of cylindrical drum of finite length on compacted materials. The error is due to the incorrect assumption of theoretical contact area of the models to mimic the field drum contact condition. Therefore, the theoretical computation needs corrections to match actual field measurements.

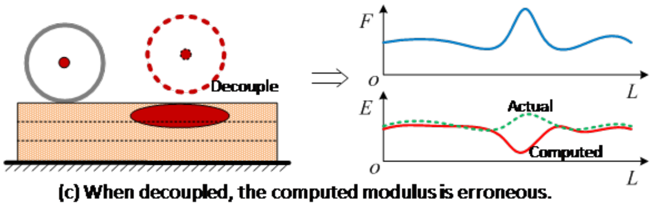
3. When decoupled, the computed modulus is erroneous: When a drum and compacted materials lose contact or are decoupled, the computed modulus are often too low or non-obtainable. The actual modulus should be high, based on the reactive force, in comparison with the computed values. Therefore, the technique of using the impact model and reactive force can overcome the difficulties of computing ICMV during double-jump movements of the roller drums.



(a) Vibration force is not equal to compaction force



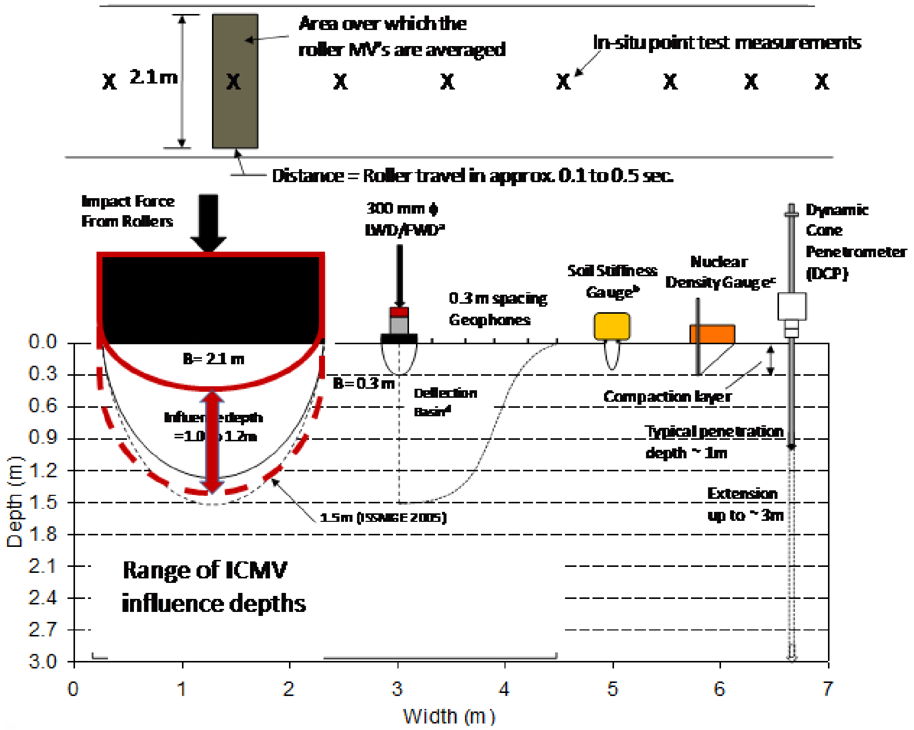
(b) Actual strain measurement is different from theoretical computation



(c) When decoupled, the computed modulus is erroneous.

Various Challenges for Measuring ICMV

DIFFERENCES BETWEEN ICMV AND CONVENTIONAL SPOT TESTS



Differences between ICMV and Conventional Spot Tests

The major differences between ICMV and conventional spot tests, such as lightweight deflectometer (LWD), soils stiffness gauge, nuclear density gauge, and dynamic penetrometer (DCP), are in their measurement footprint sizes, influence depths, and measurement depths. The ICMV footprint is normally rectangular-shaped (approximately 2 m by 0.3 m) and is much larger than those of spot tests, and its influence depths (approximately 0.5 m to 1.6 m) are much deeper than those of spot tests. The range of ICMV influence depth depends on the roller operating weight, vibration frequency, vibration amplitude, and the stiffness of compacted materials.

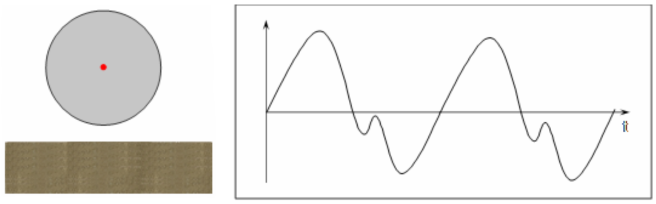
MODELS FOR SOLVING ICMV

There are several models for solving ICMV with various levels of applicability to overcome the challenges stated above. The list of the models is summarized below. There are five different models with several types of solution methods; dynamic, static, empirical, and mechanistic.

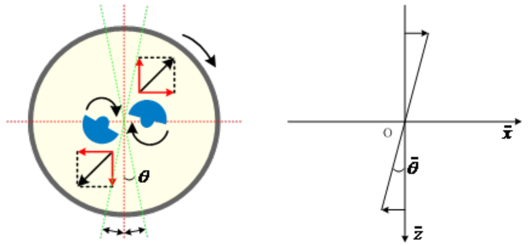
Summary of Models for Solving ICMV

Model	Description	Mechanistic/ Empirical	Dynamic/Static
A	Empirical Reactive Models	Empirical	N/A
B	Continuum Roller and Half-Space Layered System	Mechanistic	Dynamic/Static
C	Discrete Drum and Spring-Dashpot Coupled System	Mechanistic	Static
D	Dynamic Impact Model for Decoupled Drum and Layer System	Mechanistic	Dynamic
E	Artificial Intelligence Method	Mechanistic	Dynamic

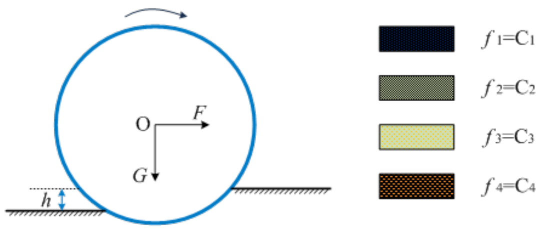
MODEL A: EMPIRICAL REACTIVE MODELS



(A1) Vibratory Frequency Reactive Model



(A3) Oscillation Frequency Reactive Model



(A2) Static Rolling Resistance Reactive Model

Model A: Empirical Reactive Models (with A1, A2, A3 Submodels)

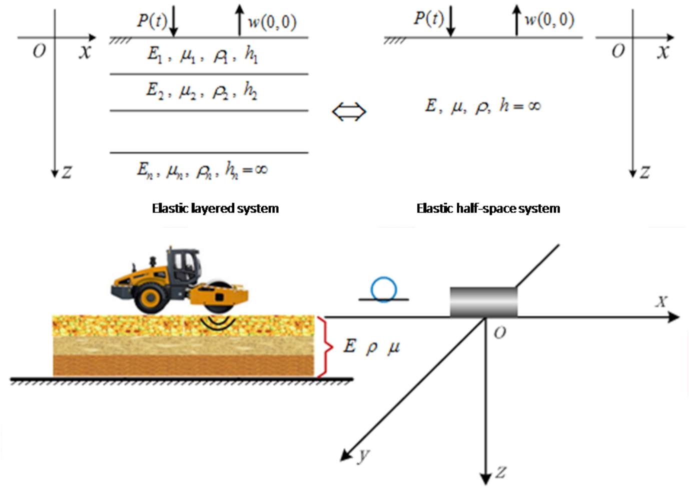
The reactive models include three types of submodels.

- Model A1: Vibratory Frequency Reactive Model is based on the ratio of frequency responses from the reactive force.
- Model A2: Oscillation Frequency Reactive Model is based on areas of "8-shape" plots to reflect the levels of compaction.
- Model A3: Static Rolling Resistance Reactive Model is based on the rolling resistance coefficient of different types of compacted materials and associated machine driver power.

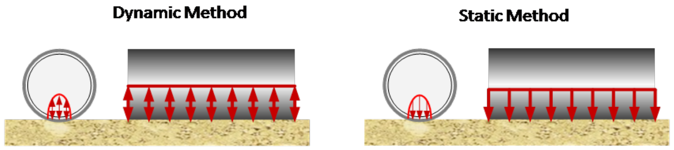
MODEL B: CONTINUUM ROLLER AND HALF-SPACE LAYERED SYSTEM

Using simplification, a pavement layered system can be transformed into to a half-space. The compaction force and reactive force are equivalent for both systems. The effective and equivalent modulus, density, and displacement can be computed.

The governing equations for the dynamic method are partial differential equations that are difficult to solve. The static method is simplified by assuming all acceleration terms are zero. However, simplification will depart from the actual condition and require a semi-empirical solution to approximate field measurements.



Model B: Continuum Roller and Half-Space Layered System



$$\begin{cases}\frac{\partial\sigma_x}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}=\rho\frac{\partial^2 u}{\partial t^2}\\ \frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\sigma_y}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}=\rho\frac{\partial^2 v}{\partial t^2}\\ \frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\sigma_z}{\partial z}=\rho\frac{\partial^2 w}{\partial t^2}\end{cases}$$

$$\varepsilon_x=\frac{\partial u}{\partial x}\ ,\quad \varepsilon_y=\frac{\partial v}{\partial y}\ ,\quad \varepsilon_z=\frac{\partial w}{\partial z}$$

$$\gamma_{xy}=\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y},\quad \gamma_{yz}=\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z},\quad \gamma_{zx}=\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}$$

$$\varepsilon_x=\frac{1}{E}[\sigma_x-\mu(\sigma_y+\sigma_z)]\ ,\quad \gamma_{xy}=\frac{1}{G}\tau_{xy}$$

$$\varepsilon_y=\frac{1}{E}[\sigma_y-\mu(\sigma_z+\sigma_x)]\ ,\quad \gamma_{yz}=\frac{1}{G}\tau_{yz}$$

$$\varepsilon_z=\frac{1}{E}[\sigma_z-\mu(\sigma_x+\sigma_y)]\ ,\quad \gamma_{zx}=\frac{1}{G}\tau_{zx}$$

$$\frac{\partial^2\varepsilon_y}{\partial x^2}+\frac{\partial^2\varepsilon_x}{\partial y^2}=\frac{\partial^2\gamma_{xy}}{\partial x\partial y}\qquad \frac{\partial}{\partial x}(\frac{\partial\gamma_{zx}}{\partial y}+\frac{\partial\gamma_{xy}}{\partial z}-\frac{\partial\gamma_{yz}}{\partial x})=2\frac{\partial^2\varepsilon_x}{\partial y\partial z}$$

$$\frac{\partial^2\varepsilon_z}{\partial y^2}+\frac{\partial^2\varepsilon_y}{\partial z^2}=\frac{\partial^2\gamma_{yz}}{\partial y\partial z}\qquad \frac{\partial}{\partial y}(\frac{\partial\gamma_{xy}}{\partial z}+\frac{\partial\gamma_{yz}}{\partial x}-\frac{\partial\gamma_{zx}}{\partial y})=2\frac{\partial^2\varepsilon_y}{\partial z\partial x}$$

$$\frac{\partial^2\varepsilon_x}{\partial z^2}+\frac{\partial^2\varepsilon_z}{\partial x^2}=\frac{\partial^2\gamma_{zx}}{\partial z\partial x}\qquad \frac{\partial}{\partial z}(\frac{\partial\gamma_{yz}}{\partial x}+\frac{\partial\gamma_{zx}}{\partial y}-\frac{\partial\gamma_{xy}}{\partial z})=2\frac{\partial^2\varepsilon_z}{\partial x\partial y}$$

$$p(x,y)=\frac{2F}{\pi aL}(1-\frac{x^2}{a^2})^{1/2}$$

$$2a=\sqrt{\frac{16RF(1-\mu^2)}{\pi LE}}$$

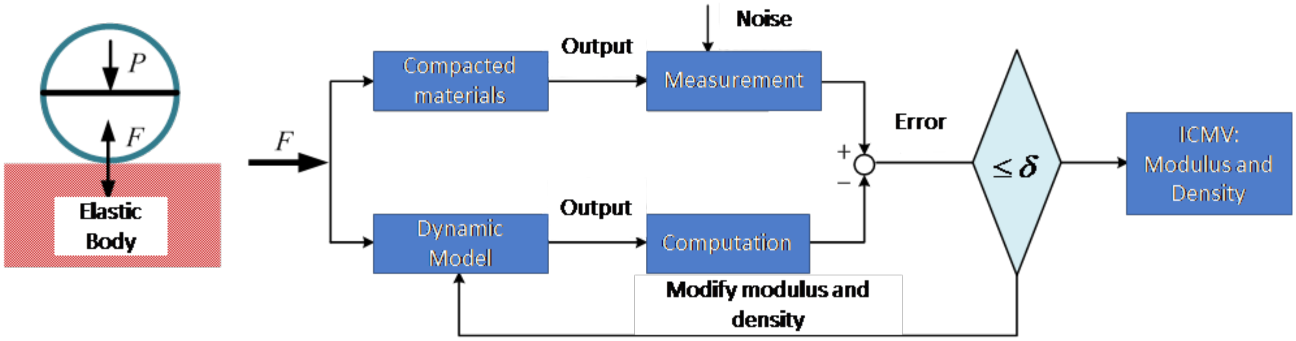
$$w(0,0,0)=\frac{2F(1-\mu^2)}{\pi LE}[\ln(\frac{L}{2a})+1.886]$$

$$w(0,y,0)\approx w(0,0,0)-\frac{F(1-\mu^2)}{\pi LE}\ln[1-(2y/L)^2]$$

Model B: Solutions based on Dynamic or Static Methods

The flow diagram for computing ICMV with a dynamic model begins from left to right and loops around if the error check is not satisfied. The check is to compute the differences between the actual measured force with the computed theoretical force with assumed modulus. The analytical solution is challenging because the displacements of compacted materials cannot normally be measured.

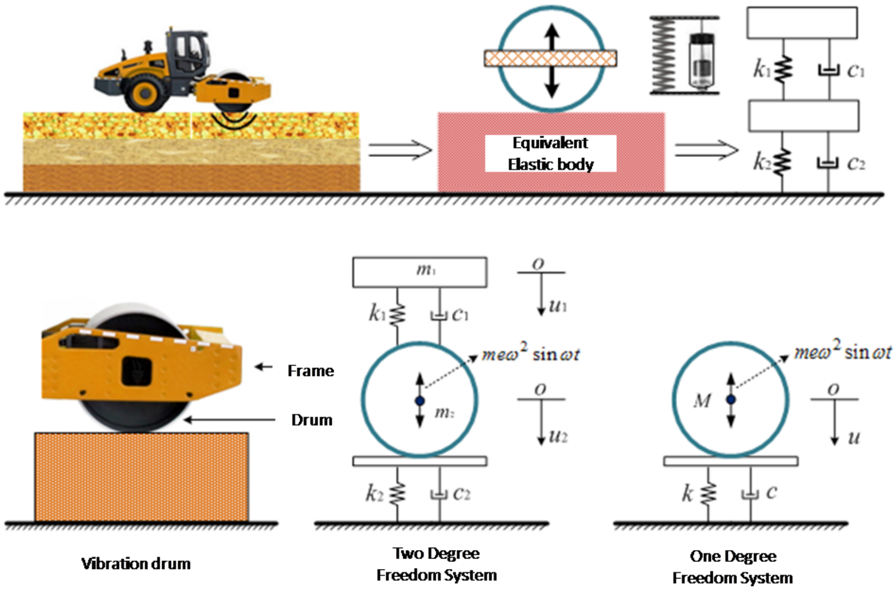
It requires a tremendous amount of field measurement to provide dynamic correction. Using a numerical solution is also challenging due to the lengthy computing time required. In additional, back-calculated parameters are not always a unique and exact solution.



Flow Diagram for Computing ICMV with a Dynamic Model

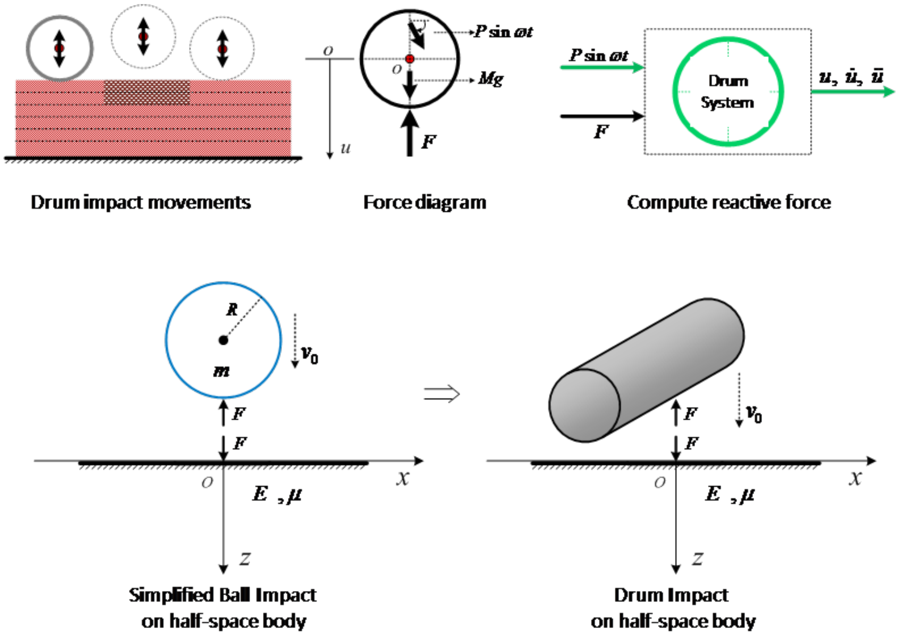
MODEL C: DISCRETE DRUM AND SPRING-DASHPOT COUPLED SYSTEM

The discrete drum and spring-dashpot coupled system is governed by differential equations, slightly simpler than the solutions for partial differential equations for the continuum models. The layer system is simplified to an equivalent elastic body that is then further modeled with elastic spring and dashpot in parallel based on the modulus-stiffness conversion theory. The vibration drum (including the frame and drum) can be modeled by a two-degree-freedom lump model or further simplified to a one-degree-freedom model. The solution methods include linear and nonlinear ones.



Model C: Discrete Drum and Spring-Dashpot Coupled System

MODEL D: DYNAMIC IMPACT MODEL FOR DECOUPLED DRUM AND LAYER SYSTEM

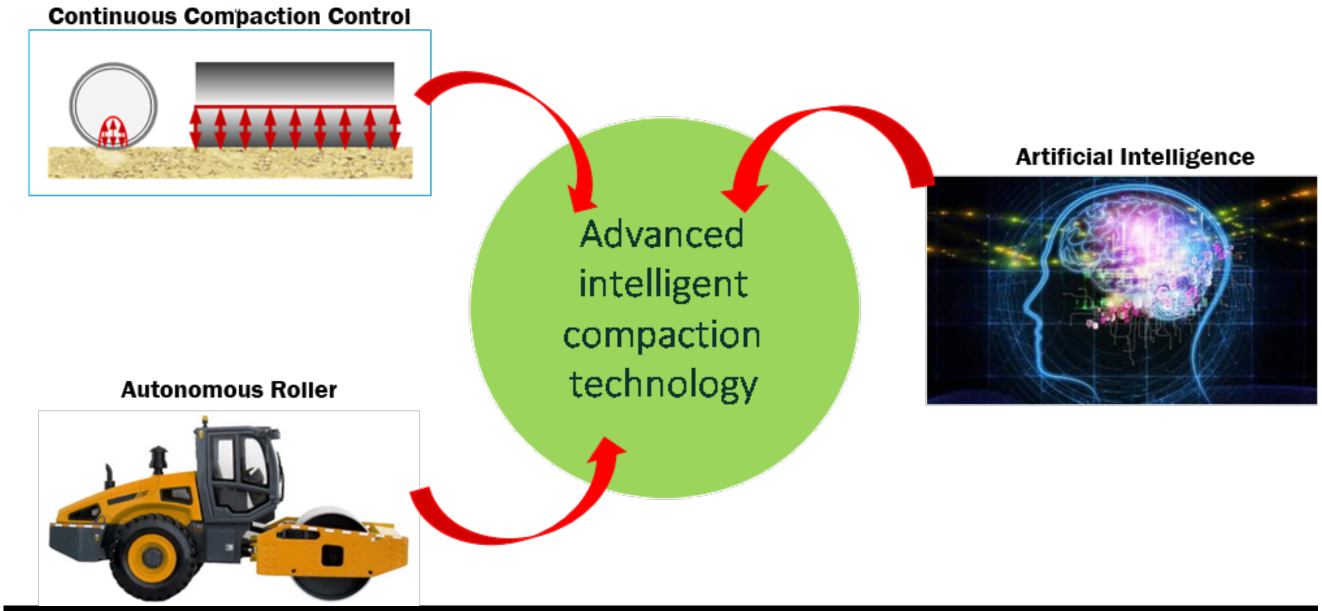


Model D: Dynamic Impact Model for Decoupled Drum and Layer System

Based on the dynamic impact model for a decoupled drum and compacted layer system, the reactive force and modulus can be computed even when double jumps occur. The drum impact movements can be analyzed with a force diagram to calculate the reactive force. Using a simplified ball impact on the half-space body to emulate the drum impact, the modulus of compacted materials can be calculated either by the displacement method or the impact time method.

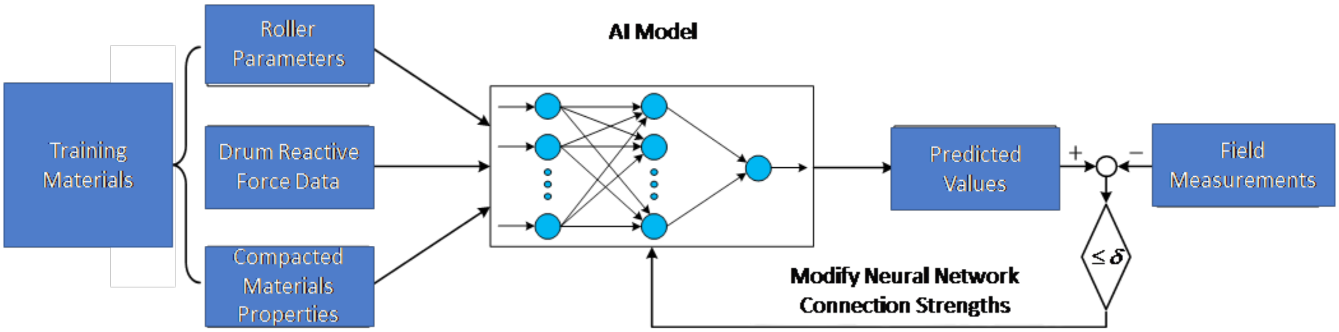
MODEL E: ARTIFICIAL INTELLIGENCE METHOD

The Model E: Artificial Intelligence (AI) model uses Artificial Neural Network (ANN) and Genetic Algorithm (GA). The key is to use sufficient and accurate roller parameters, field measurements of reactive forces, and compacted material's properties to train the AI model. The training methods may include Hebbian, Delta rule, and Least Mean Squared (LMS) methods.



Model E: Artificial Intelligence Method

The flow diagram for computing ICMV with an artificial intelligence model begins from left to right and loops around if the error check is not satisfied. The check is to compute the differences between the actual measured force with the computed theoretical force with assumed modulus. The analytical solution is challenging because the displacements of compacted materials cannot normally be measured. It requires a tremendous amount of field measurement to provide dynamic correction.



Model E: Artificial Intelligence Method

LEVELS OF ICMV – A ROAD MAP

There are currently solutions of ICMV based on the above models. There are also next generation ICMV under development. The following describe the "Levels of ICMV" in terms of applicability to a variety of pavement materials, correlation with material's mechanical (modulus) and physical (density properties, validity during decoupling (when a drum loses contact with compacted materials), and applicability to obtain layer-specific mechanical and physical properties of compacted materials. This lays out the road map for past, present, and future ICMV development.

LEVEL 1 – EMPIRICAL SOLUTIONS BASED ON FREQUENCY RESPONSES

The Level 1 ICMVs are empirical solutions based on frequency responses represented by frequency ratios. It is computed based on the Model A1: Reactive Models with frequency responses or Model A2: Oscillation Frequency Reactive Model.

LEVEL 2 – EMPIRICAL ENERGY AND ROLLING RESISTANCE SOLUTIONS

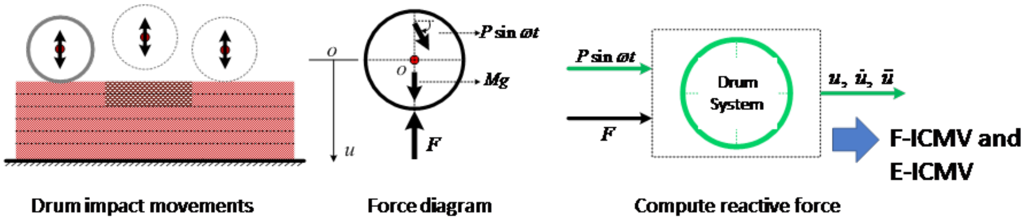
The Level 2 ICMVs are empirical energy and rolling resistance solutions. It is computed based on Model A3: Reactive Models with rolling resistance principle. The computation requires machine specific parameters and measurements such as machine movement angle and energy loss coefficients.

LEVEL 3 – SIMPLIFIED STATIC MECHANISTIC SOLUTIONS

The Level 3 ICMVs are simplified static mechanistic solutions. It is a static solution based on Model B: Continuum Roller and Half-Space Layered System or based on Model C: Discrete Drum and Spring-Dashpot Coupled System. Due to its static solution and simplified method, the solution is invalid when double jumps (or loss of contacts) occur.

LEVEL 4 – DYNAMIC MECHANISTIC SOLUTIONS

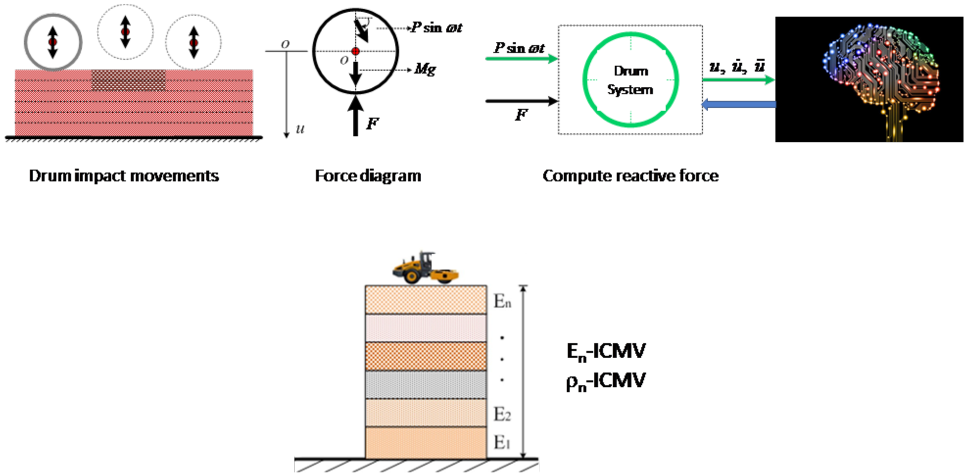
The Level 4 ICMVs are dynamic mechanistic solutions. They are dynamic solutions based on Model D: Dynamic Impact Model for Decoupled Drum and Layer System. The reactive force ICMV (F-ICMV) can be computed based on roller vibration acceleration, velocity, and displacement. It also requires dynamic correction factors and phase lags to account for actual field condition. The modulus ICMV (E-ICMV) can be computed either based on the reactive force or based on the time duration of impact.



Level 4 Reactive Force ICMV (F-ICMV) and Modulus ICMV (E-ICMV) and their Computation Method

LEVEL 5 – DYNAMIC MECHANISTIC AND ARTIFICIAL INTELLIGENCE SOLUTIONS

The Level 5 ICMVs are a combination of dynamic mechanistic solutions and artificial intelligence solutions. Layer-Specific Modulus ICMV (E_n-ICMV) and Density ICMV (P_n-ICMV) are based on a combination of Model D: Dynamic Impact Model for Decoupled Drum and Layer System Model E: Artificial Intelligence Method. Though still under development, it is envisioned that both models can be fused and field measurement methods can include layer by layer mapping to measure E_n-ICMV and P_n-ICMV. A true real-time auto-feedback system can then be deployed to optimize compaction without human intervention. Then, an autonomous compaction machine can be realized.



Level 5 Layer-Specific Modulus ICMV (E_n-ICMV) and Density ICMV (P_n-ICMV) and Its Computation Method

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IC WEBSITES

FHWA TSSC IC SUPPORT SITES
http://www.fhwa.dot.gov/construction/ictssc/support.cfm

ONE STOP-SHOP FOR INTELLIGENT COMPACTION
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SUMMARY OF ALL ICMV LEVELS

1	A1, A2	Weak or Poor	No	No
2	A3	Weak or Poor	NA[4]	No
3	B + C	Satisfactory	No	Difficult
4	D	Good	Yes	Yes
5	D + E	Excellent	Yes	Yes

1. Correlation with mechanical and physical properties of various compacted materials.
2. Valid measurement when drum and compacted materials are decoupled.
3. Allows layer-specific measurements of compacted material's mechanical and physical properties.
4. Model A3 functions in static rolling.

A Double Drum IC roller Compacting an Asphalt Pavement and the ICMV Road Map.

SUMMARY AND CONCLUSIONS

Intelligent Compaction Measurement Values have been demystified in this comprehensive tech brief. Further details of the model equations and solutions can be found in the references. Solutions for ICMV are never an easy task. Research communities and the industry have put in heroic efforts since the 1980s to invent various ICMVs to meet the demand of real-time compaction monitoring, control, and ultimately acceptance. The road map of ICMV levels shows the path of the ongoing efforts and points to future solutions that will measure true mechanical and physical properties of any compacted layers to allow true real-time feedback system control and autonomous operation.

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