U.S. Department of Transportation
Federal Highway Administration

# Feasibility of Utilizing Intelligent Compaction Equipment to Ensure Uniformity and Quality of Pavement Foundation

WERIS

THE TRANSTEC GROUP
The World's Pavement Engineering Specialists

# 2. Project Overview and Technical Approach (George)

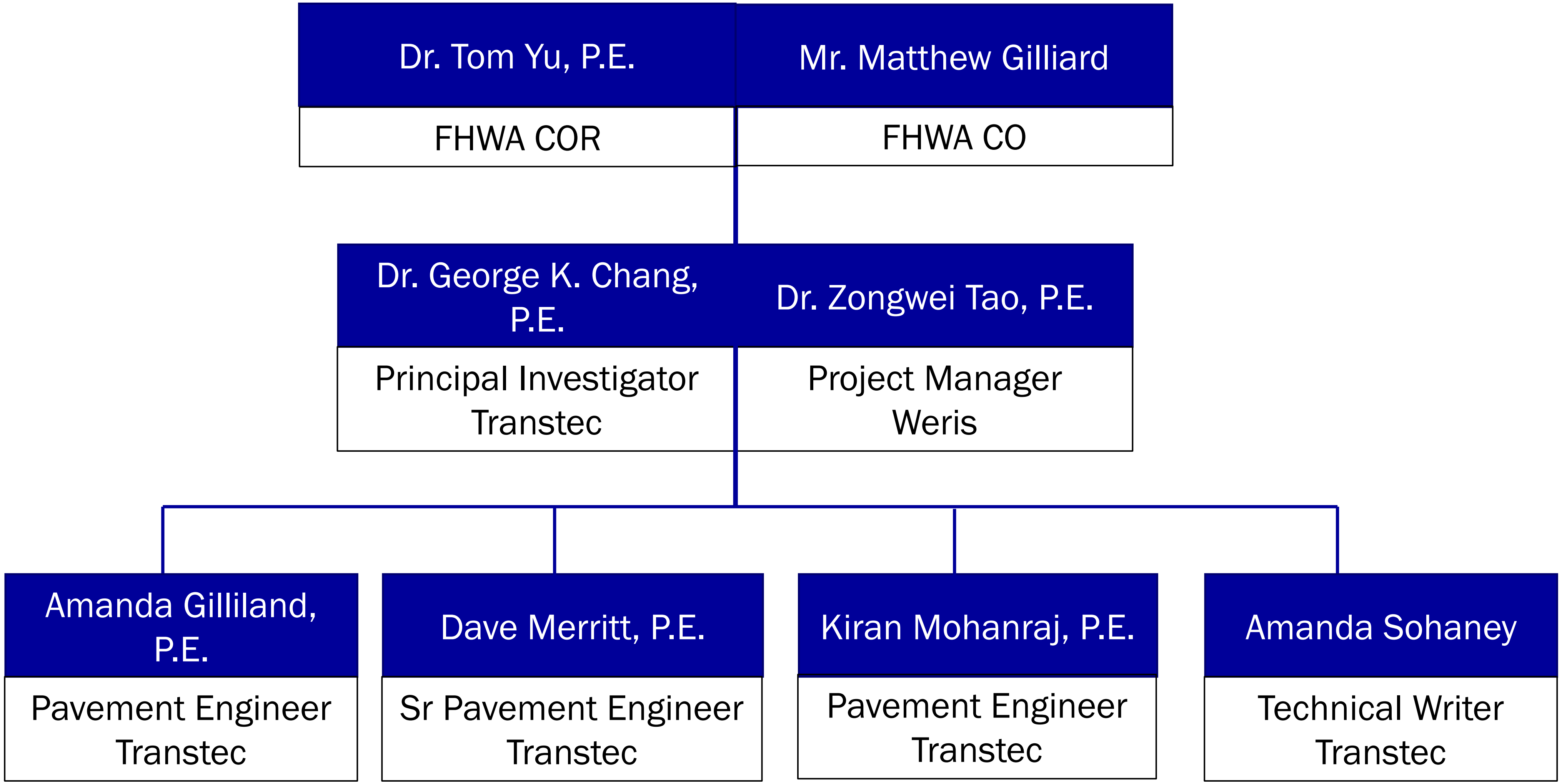
- Project Objectives
- Research Team Structure
- Industry Partners
- Levels of ICMV
- Characterizing Uniformity of Foundation with IC

# Project Overview

- FHWA Contract No. HIF190100PR
- Title: Feasibility of Utilizing Intelligent Compaction Equipment to Ensure Uniformity and Quality of Pavement Foundation
- Project Period: 36 Months
- Objectives

  Develop a procedure for ensuring **uniformity** and **adequacy** of pavement foundation using IC and demonstrating **feasibility**.

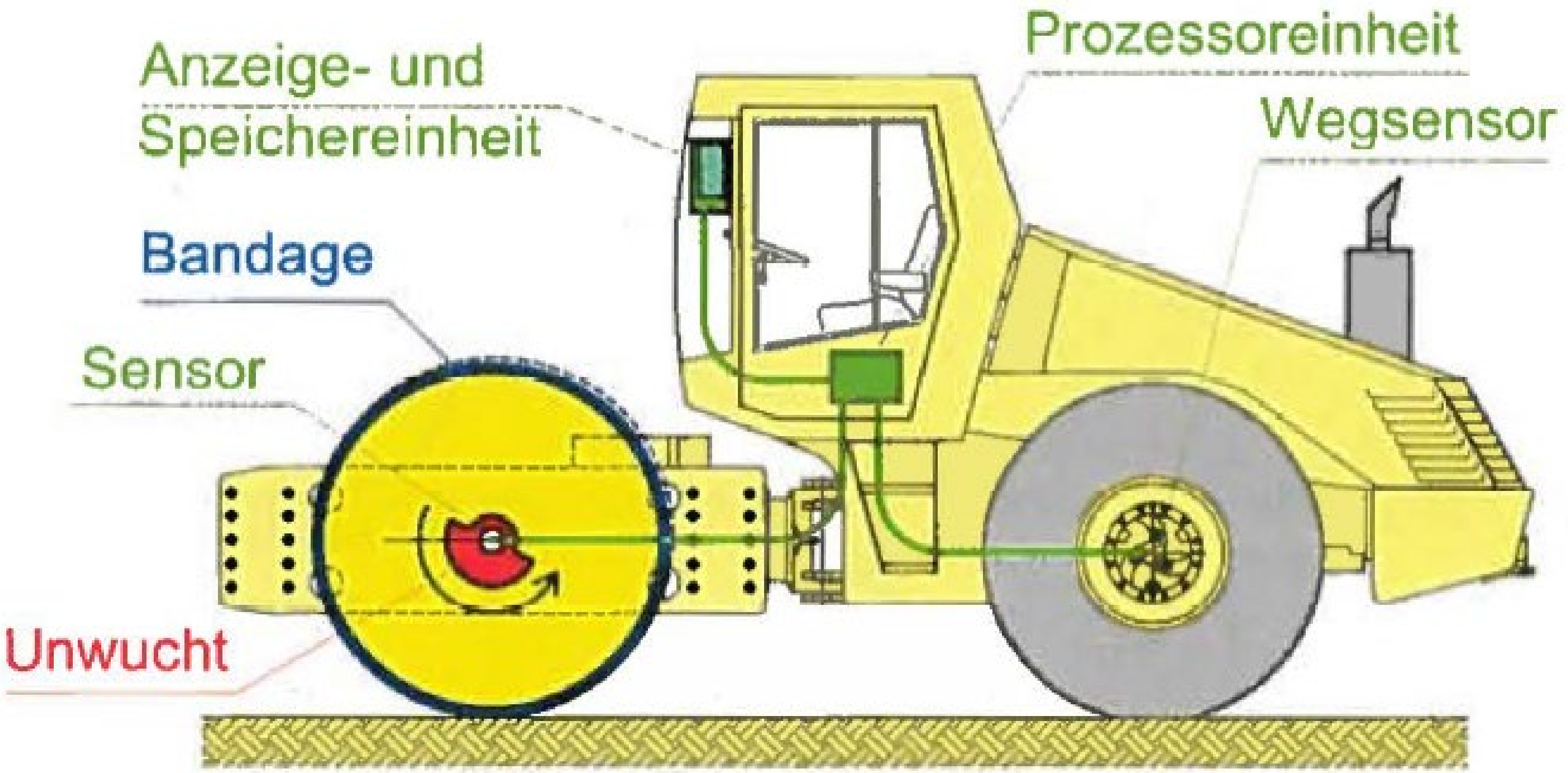
# Research Team Structure



# Industry Partners

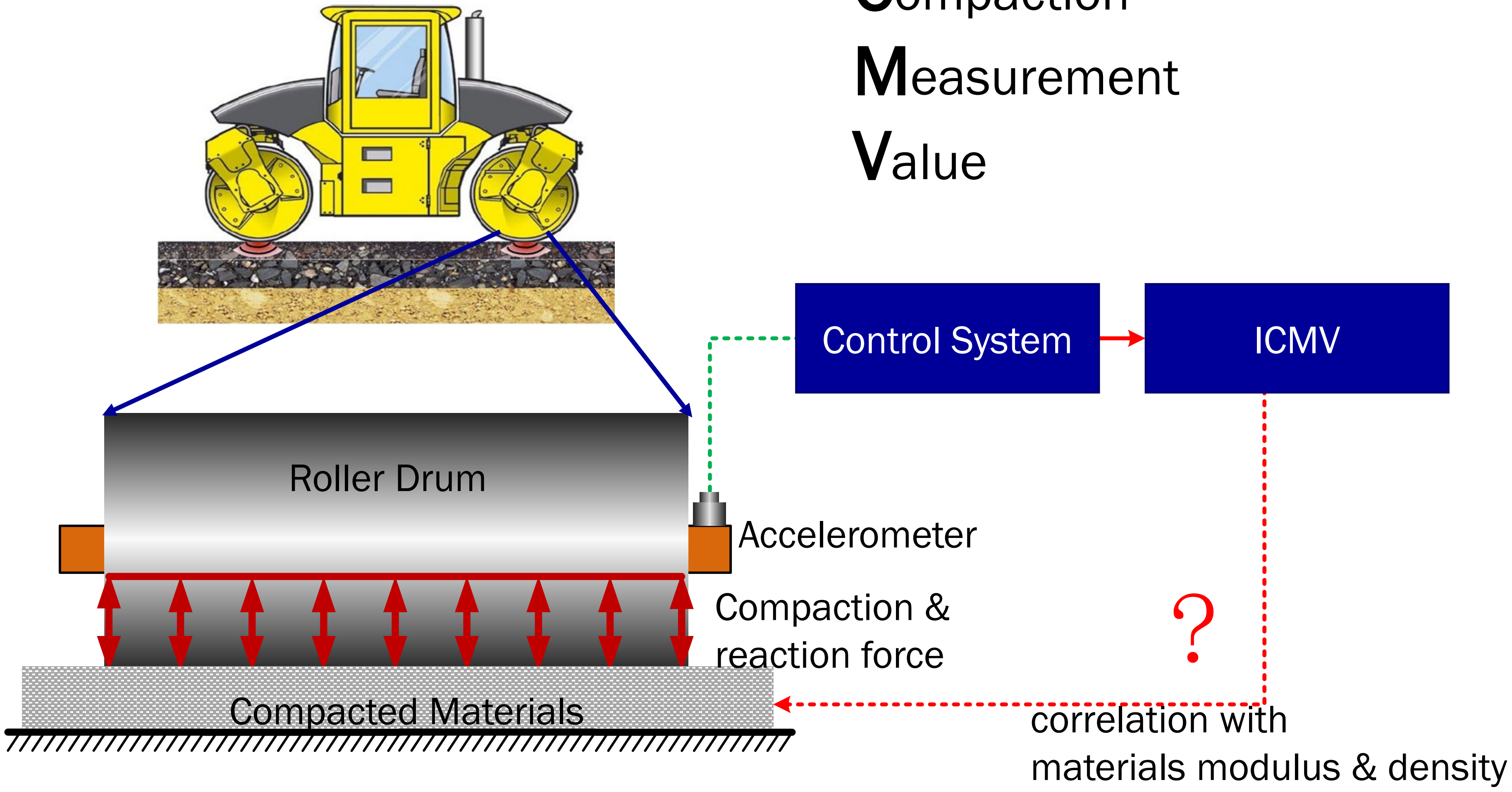
- MOBA
  - Provide an IC Retrofit with a Level 3 ICMV
- XCMG
  - Provide an OEM IC roller with a Level 3-4 ICMV


# First Generation of CCC

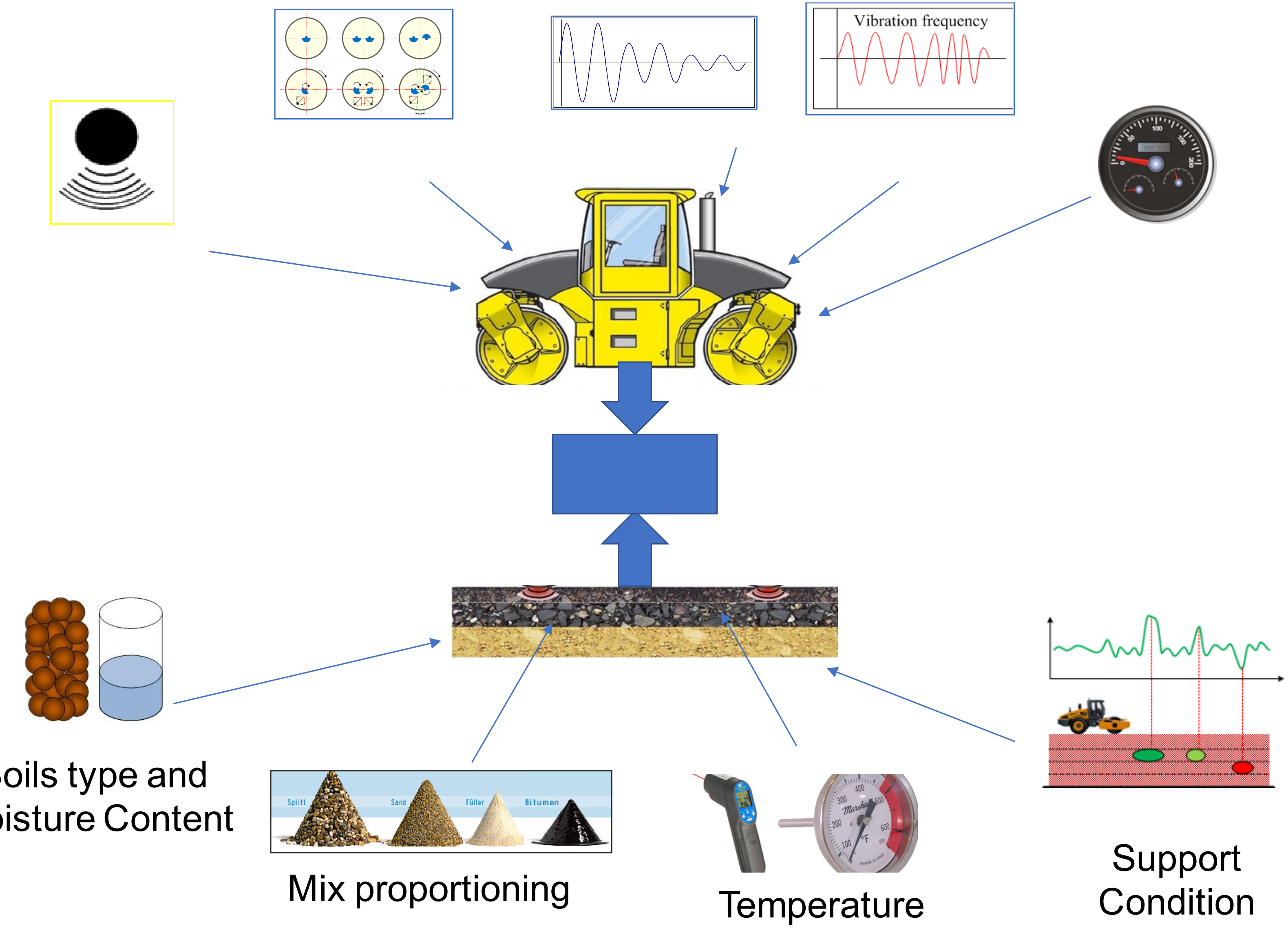


# ICMV Mechanism

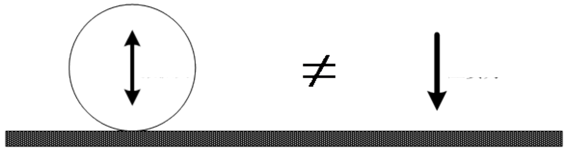
Intelligent
Compaction
Measurement
Value

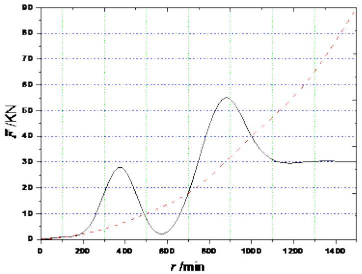


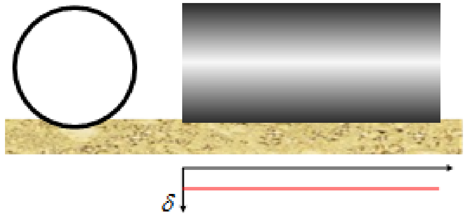
# Influence Factors on ICMV



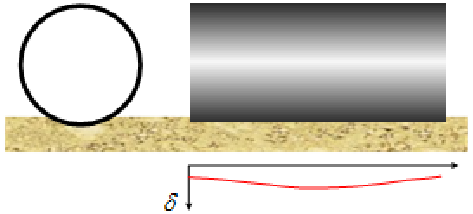
# Challenges for Measuring ICMV



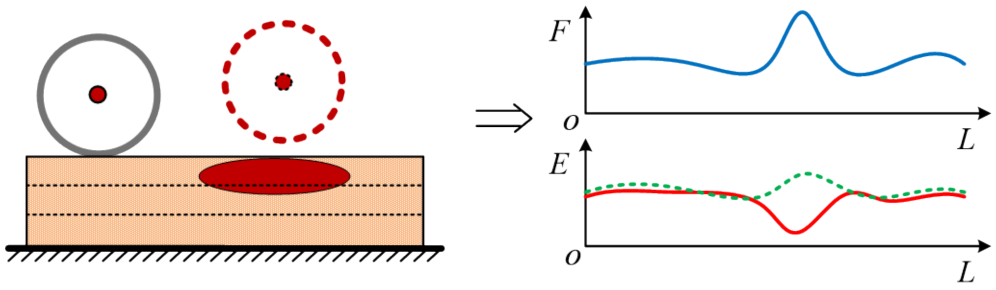




Actual measurement

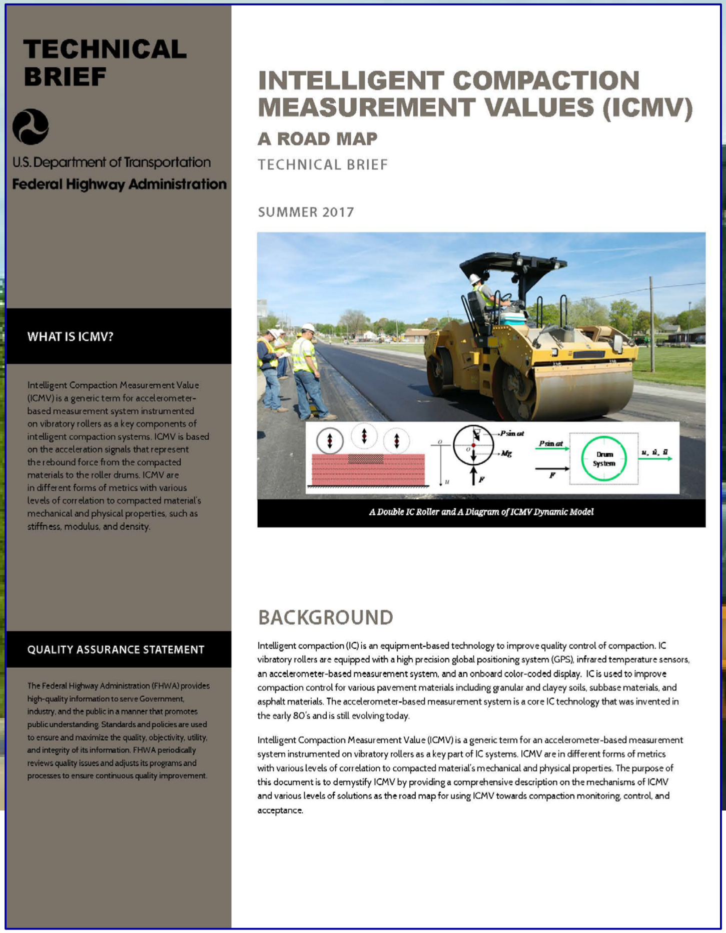



Theoretical computation



# Tech Brief - ICMV Road Map

FHWA-HIF-17-046

TECHNICAL BRIEF

U.S. Department of Transportation
Federal Highway Administration

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.

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INTELLIGENT COMPACTION MEASUREMENT VALUES (ICMV)

A ROAD MAP

TECHNICAL BRIEF

SUMMER 2017

A Double IC Roller and A Diagram of ICMV Dynamic Model

BACKGROUND

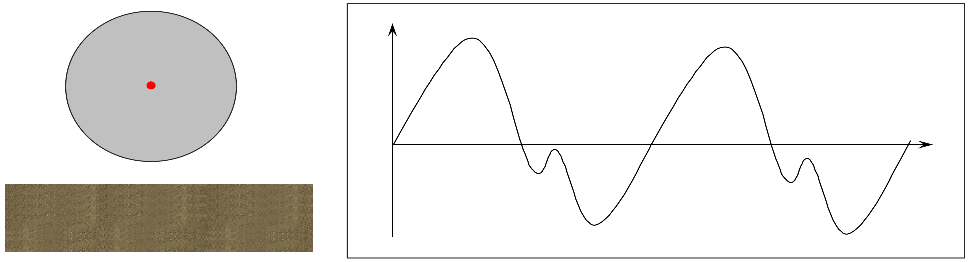
Intelligent compaction (IC) is an equipment-based technology to improve quality control of compaction. IC vibratory rollers are equipped with a high precision global positioning system (GPS), infrared temperature sensors, an accelerometer-based measurement system, and an onboard color-coded display. 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 an accelerometer-based measurement system instrumented on vibratory rollers as a key part of IC systems. 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.

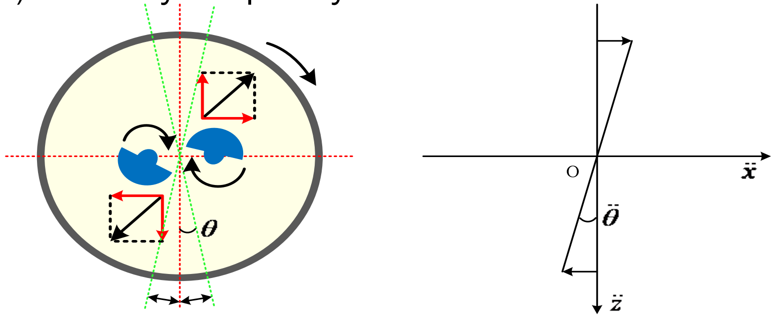
# ICMV Model and Methods

| Model | Methods | Mechanistic /Empirical | Dynamic/Static |
|---|---|---|---|
| A | Empirical Reactive Models | Empirical | NA |
| B | Continuous Roller and Half-space Layered System | Mechanistic | Dynamic/Static |
| C | Lump Model - Drum and Spring-Dashpot Coupled system | Mechanistic | Dynamic |
| D | Dynamic Impact Model for Decoupled Drum and Compacted Layer System | Mechanistic | Dynamic |
| E | Artificial Intelligence Method | Mechanistic | Dynamic data |

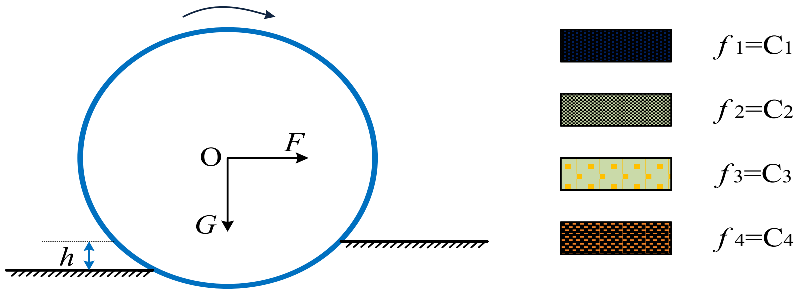
# Model A: Empirical Reactive Models



(A1) Vibratory Frequency Reactive Model

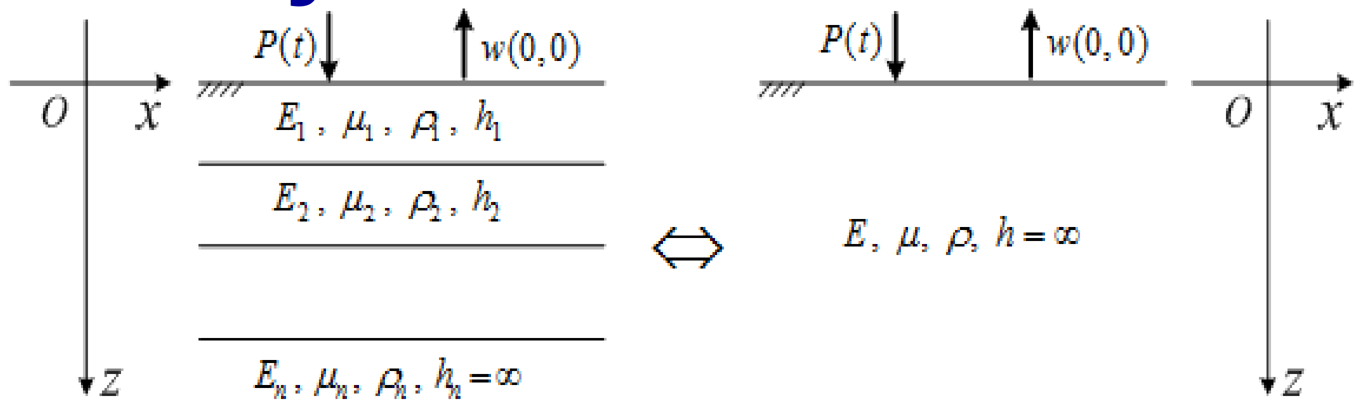



(A3) Oscillation Frequency Reactive Model



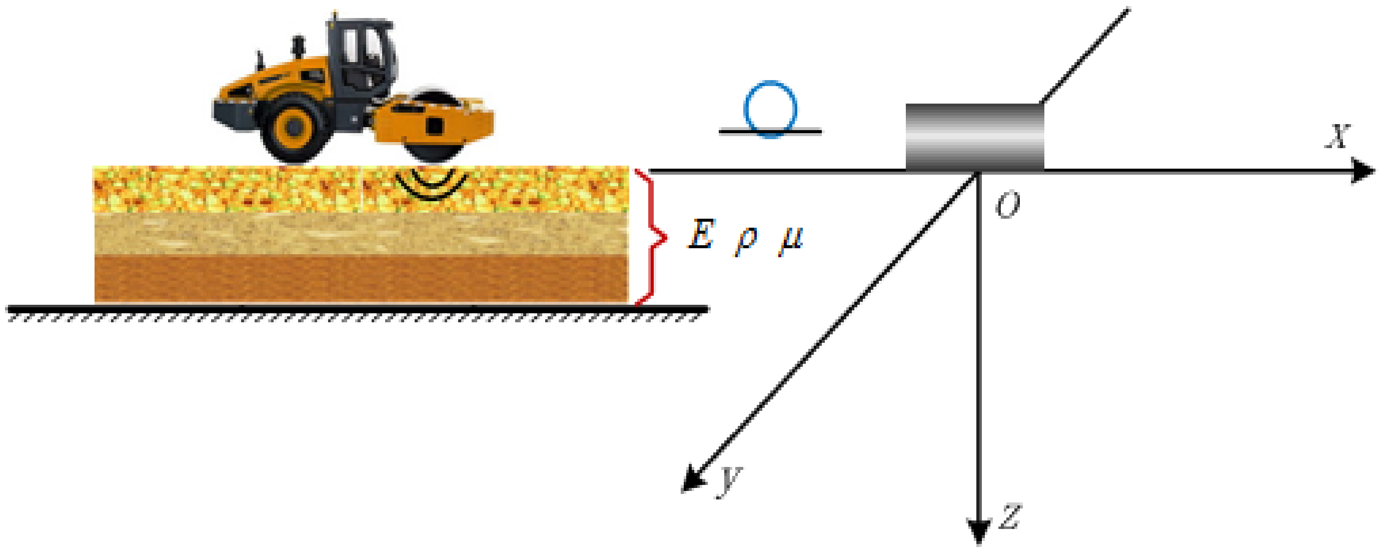

(A2) Static Rolling Resistance Reactive Model

# Model B: Layered System and Simplified Half-Space System



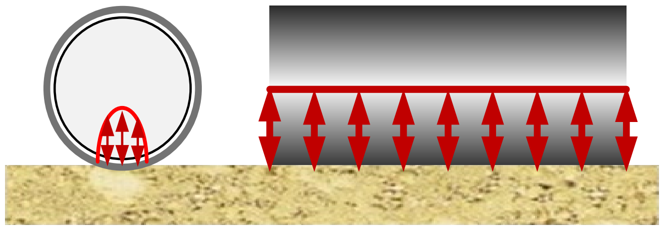

Elastic layered system

Elastic half-space system



# Model B: Dynamic & Static Solutions

## Dynamic Method



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

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

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

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

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

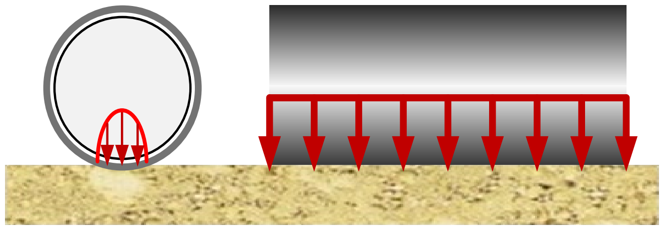
$$\varepsilon_z = \frac{1}{E}[\sigma_z - \mu(\sigma_x + \sigma_y)] \quad , \quad \gamma_{zx} = \frac{1}{G}\tau_{zx}$$

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

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

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

## Static Method



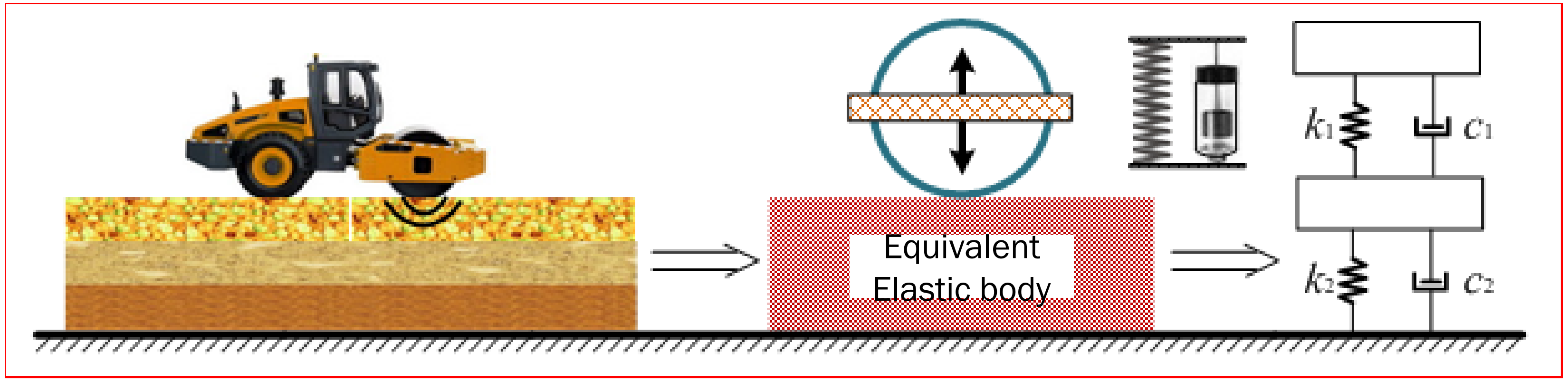
$$p(x,y) = \frac{2F}{\pi a L}\left(1 - \frac{x^2}{a^2}\right)^{1/2}$$

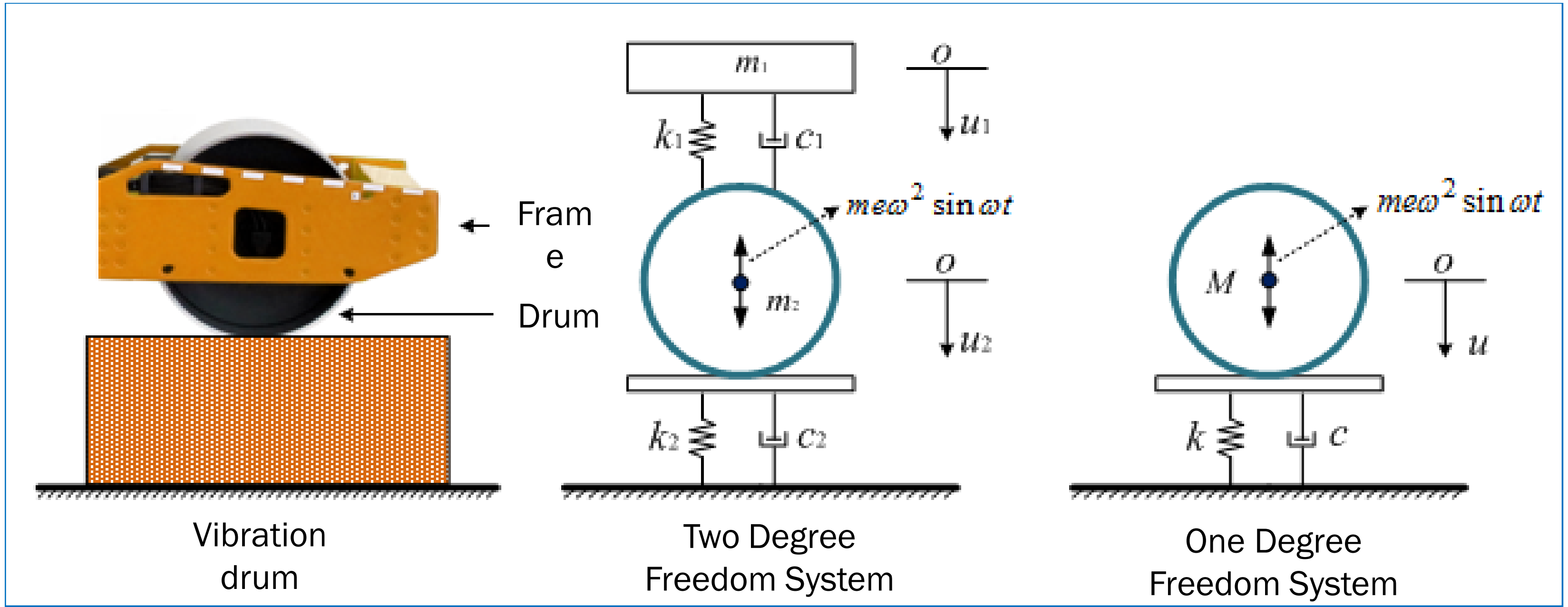
$$2a = \sqrt{\frac{16RF(1-\mu^2)}{\pi L E}}$$

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

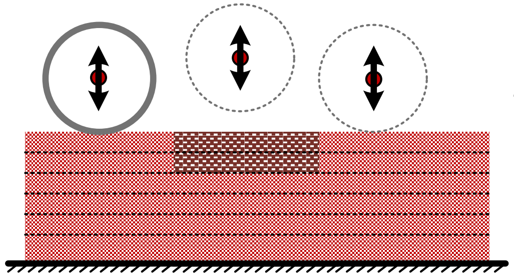
$$w(0,y,0) \approx w(0,0,0) - \frac{F(1-\mu^2)}{\pi L E}\ln[1-(2y/L)^2]$$

# Model C: Discrete Drum and Spring-Dashpot Coupled System

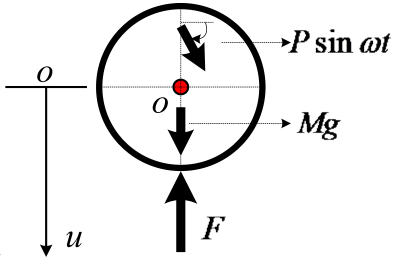


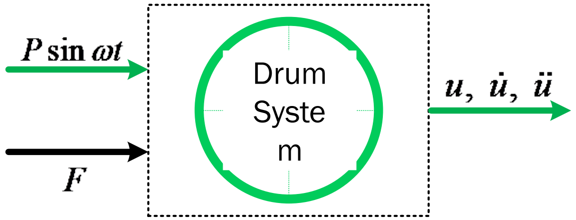
# Model D: Dynamic Impact Model for Decoupled Drum and Layer System



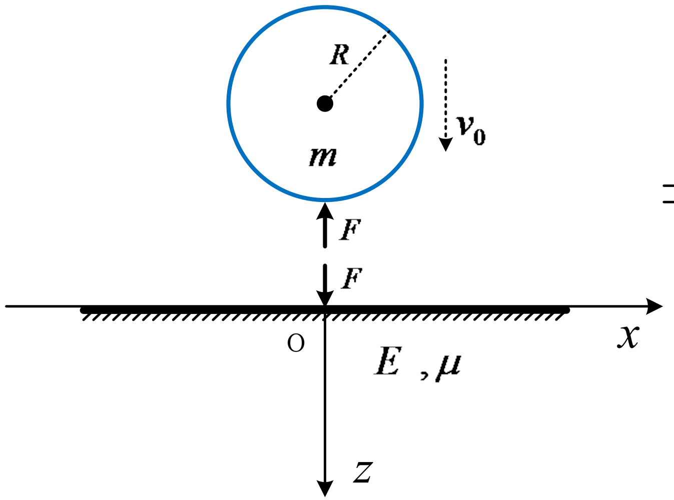
Drum impact movements




Force diagram

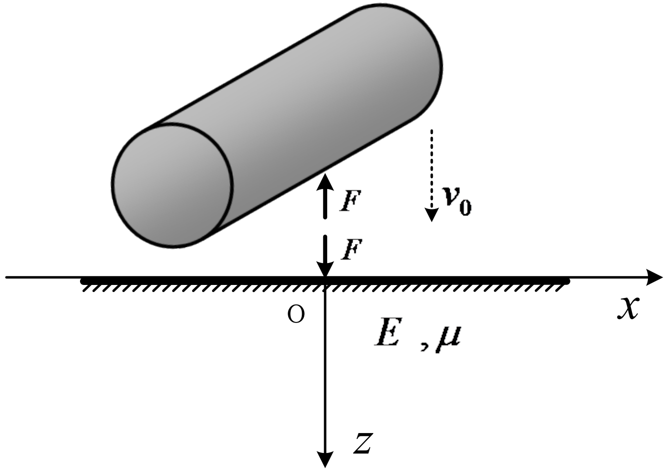



Compute reactive force



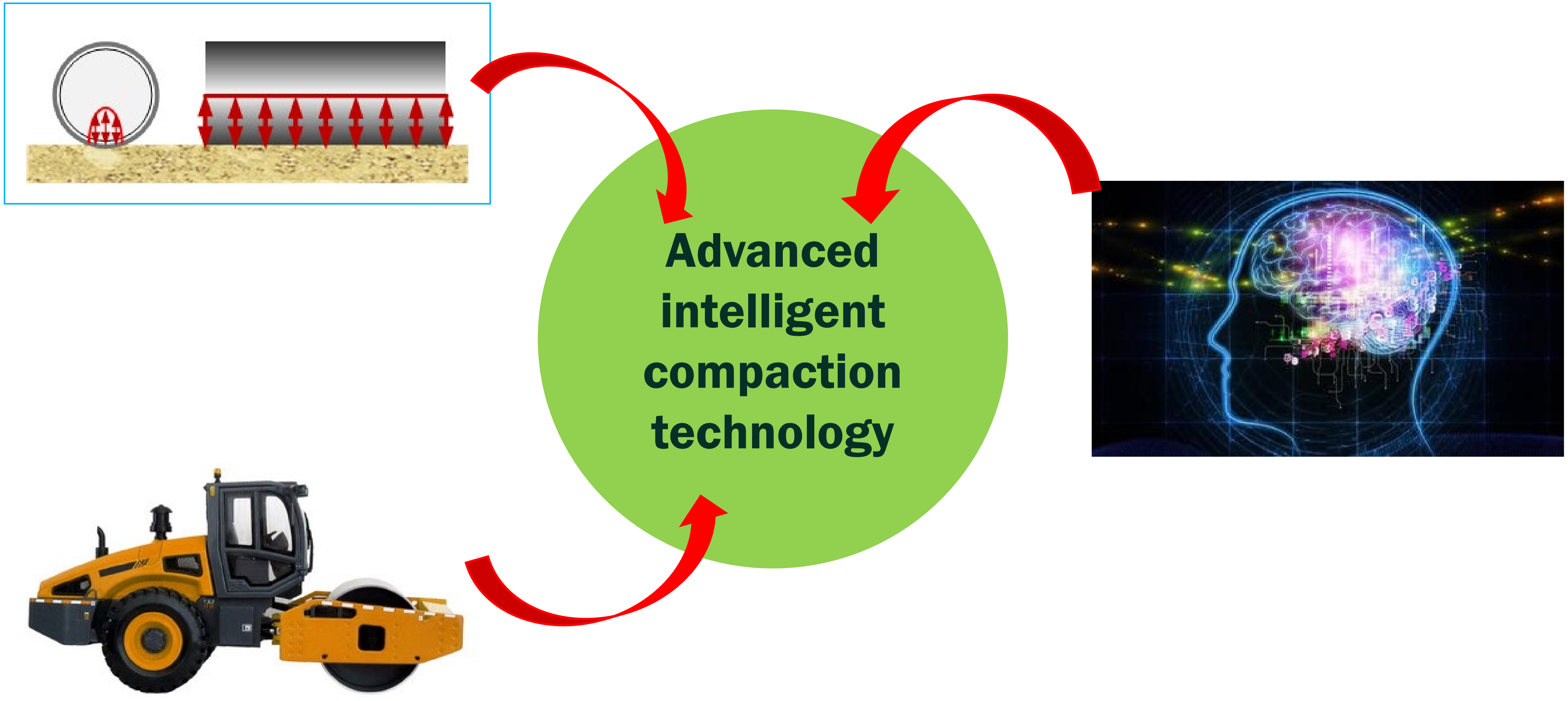

Simplified Ball Impact
on half-space body

⇒




Drum Impact
on half-space body

# Model E: Artificial Intelligence Method



# Criteria for Levels of ICMV

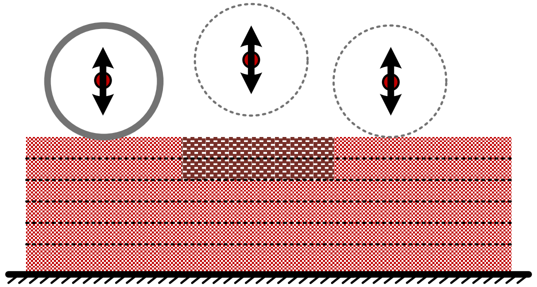
- Correlation: The threshold value for coefficient of correlation between ICMV and in-situ spot tests is generally accepted as R = 0.70 or R = 0.5.
- Decouple: Produce valid solution of ICMV during double-jump or decouple when the roller drum and compacted material lose contact.
- Layer Specific: Produce layer-specific ICMV values.
- Advanced IC: The ICMV can be combined with advanced technologies such as Artificial Intelligence and auto-feedback controls.

# Levels of ICMV

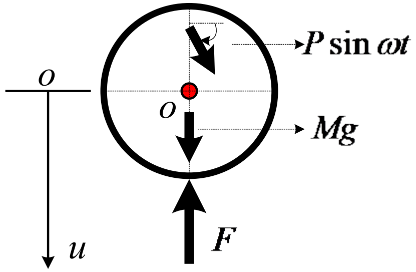
1. Correlation: The threshold value for coefficient of correlation between ICMV and in-situ spot tests is generally accepted as R = 0.70 or R = 0.5.
2. Decouple: Produce valid solution of ICMV during double-jump or decouple when the roller drum and compacted material lose contact.
3. Layer Specific: Produce layer-specific ICMV values.
4. Advanced IC: The ICMV can be combined with advanced technologies such as Artificial Intelligence and auto-feedback controls.
5. ×: No or Bad, O: Satisfactory, ?: Unproven; ✓: Yes or Good.

| Level | Model | Measurement Values | Correlation[1] | Decouple[2] | Layer Specific[3] | Advanced IC[4] |
|---|---|---|---|---|---|---|
| 1 | Empirical | Harmonic ratio | O | × | × | × |
| 2 | Energy | Energy index | ? | × | × | × |
| 3 | Discrete vibration | Stiffness Coefficient | ✓ | × | × | O |
| | Steel drum movement | Resistance force | ✓ | ✓ | O | O |
| | Continuous static | Modulus | ✓ | × | ✓ | ✓ |
| 4 | Hybrid | Resistance force, Modulus | ✓ | ✓ | ✓ | ✓ |
| 5 | Continuous dynamic | Density, Modulus | ✓ | ✓ | ✓ | ✓ |

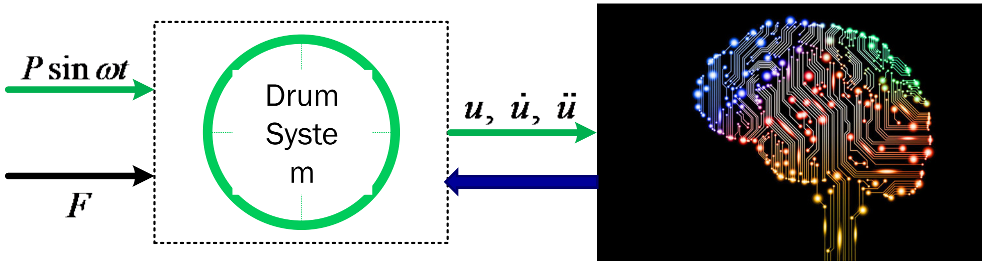
# Ultimate Goal – Level 5 ICMV



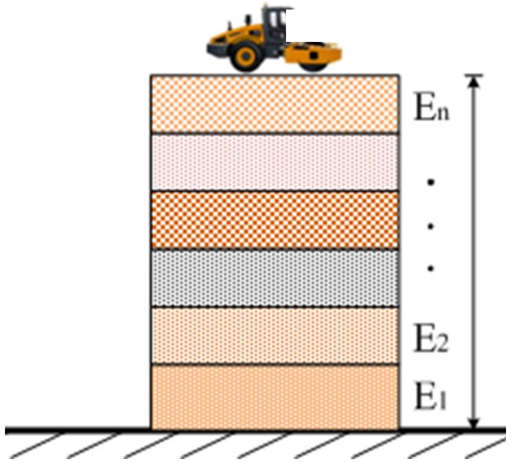
Drum impact movements




Force diagram



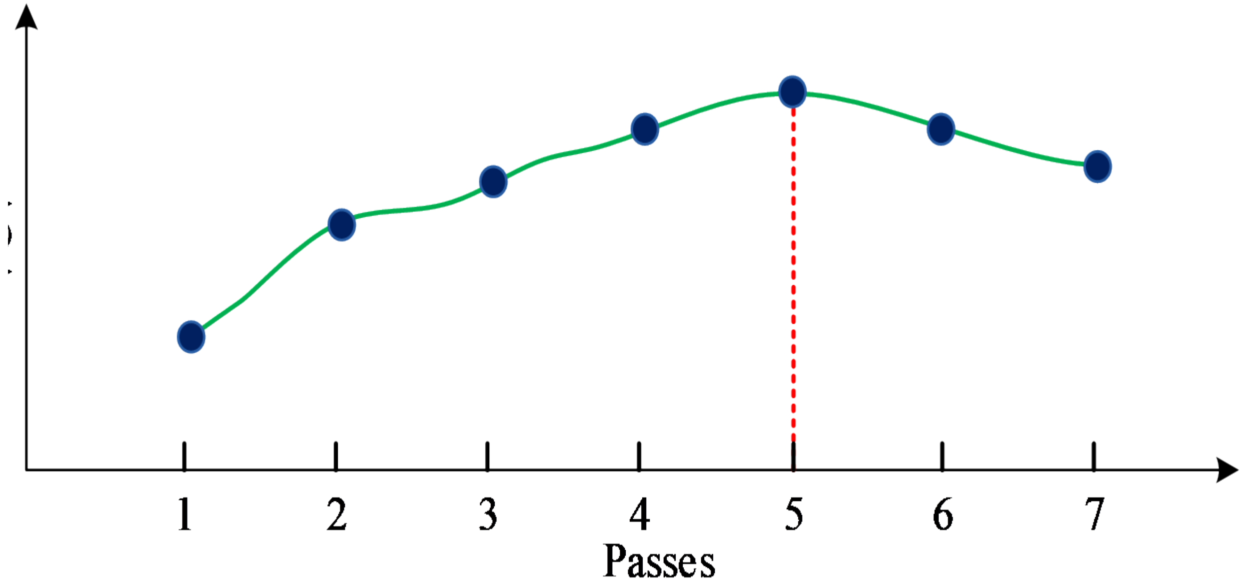

Compute reactive force




$E_n$-ICMV

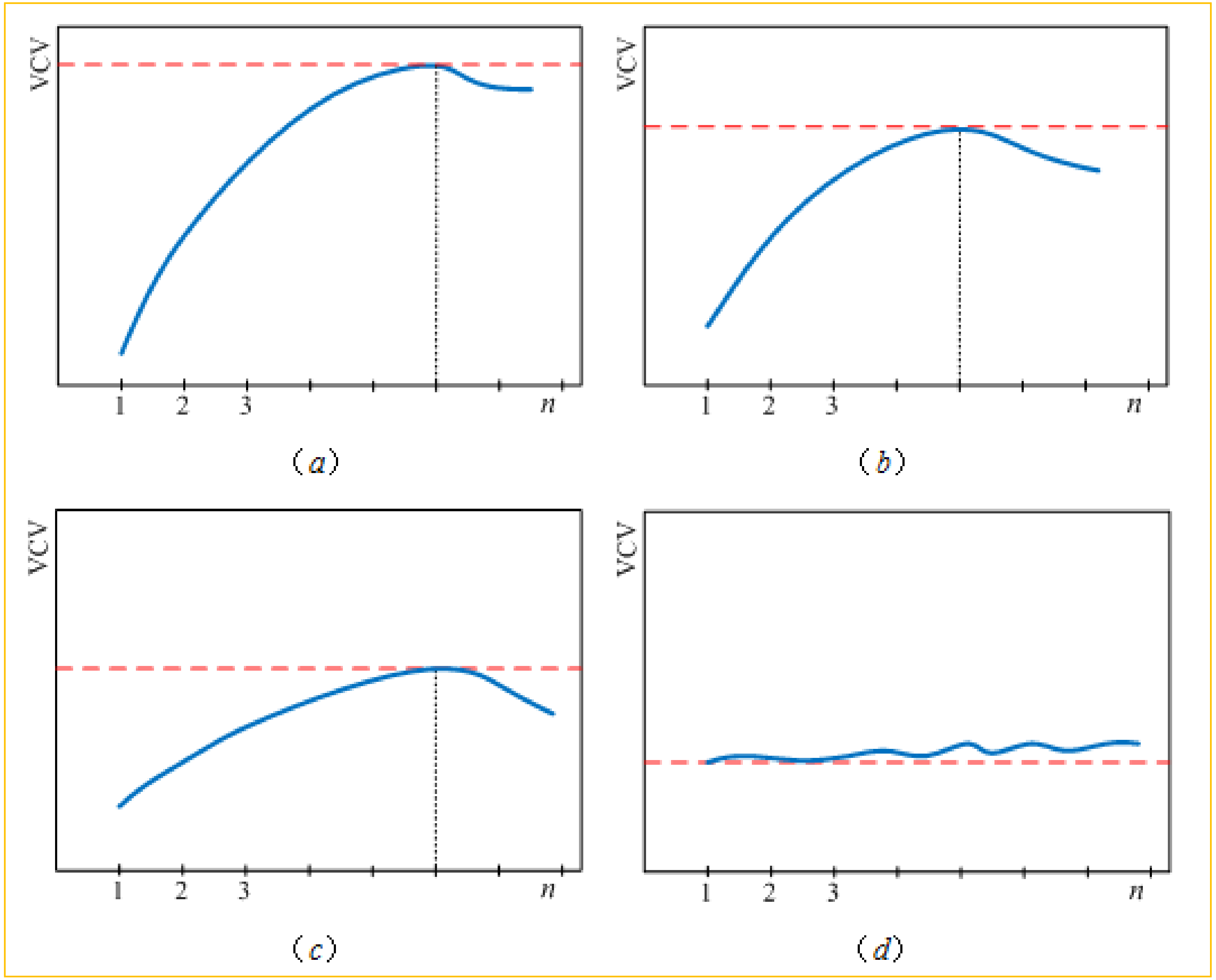
$\rho_n$-ICMV

# Good Example of ICMV Compaction Curve

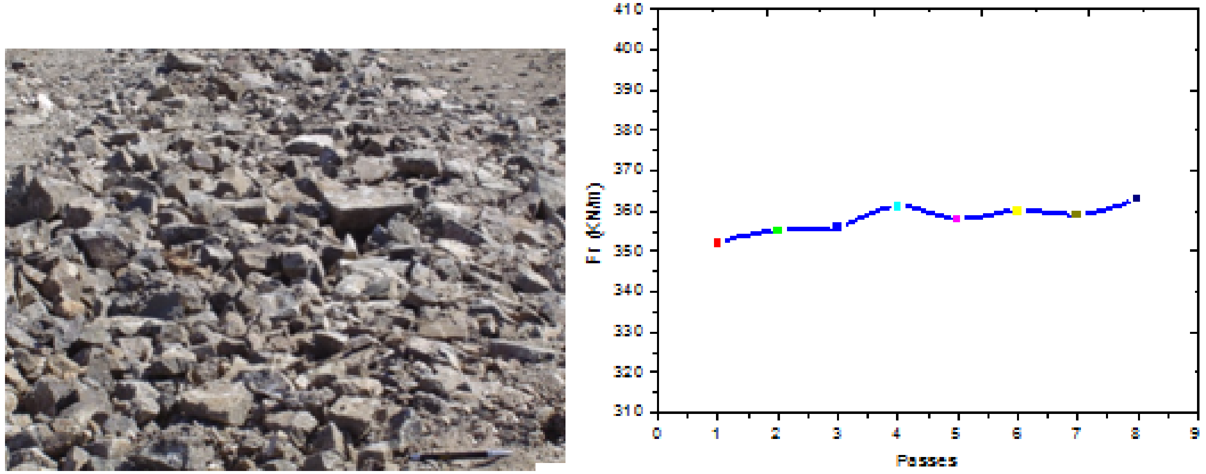

Xu, GH (2017)

# Various Compaction Curves

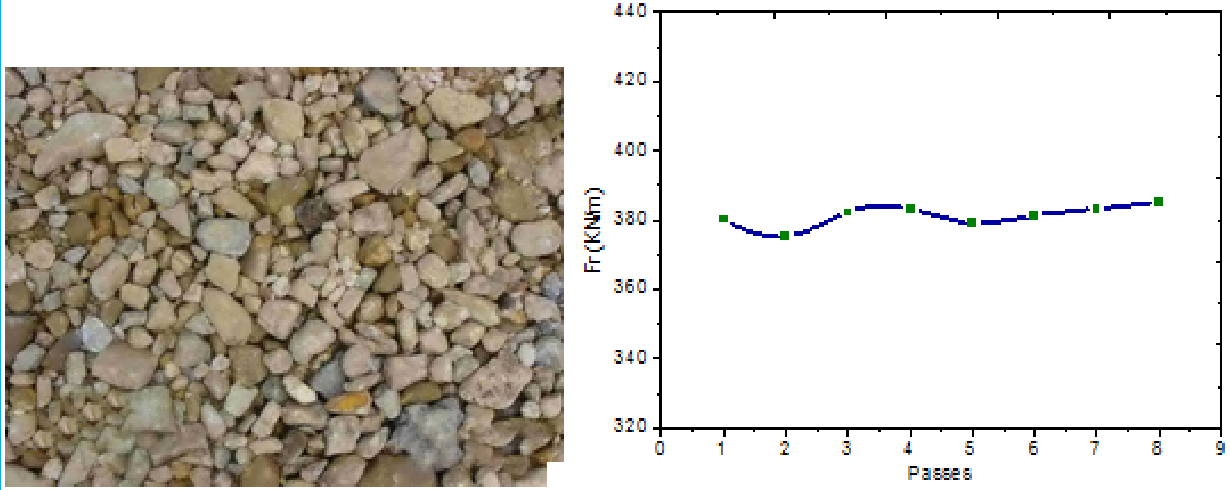



Xu, GH (2017)

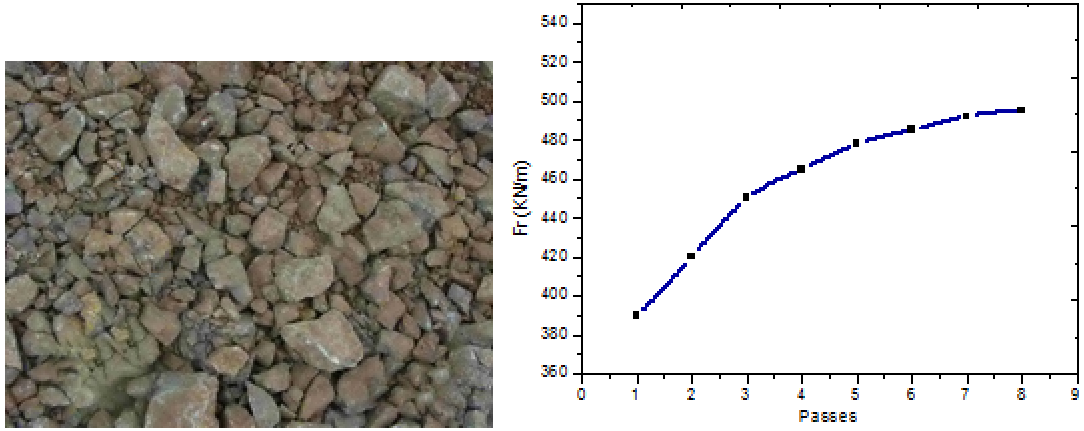
# Compaction Curves of Granular Materials




(a) poor-graded



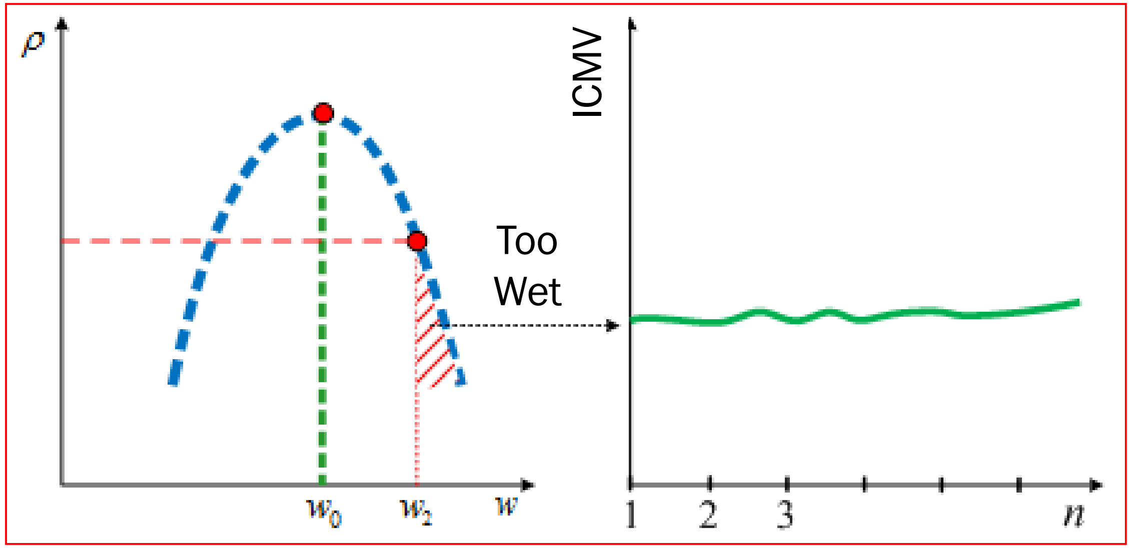

(b) rounded gravel

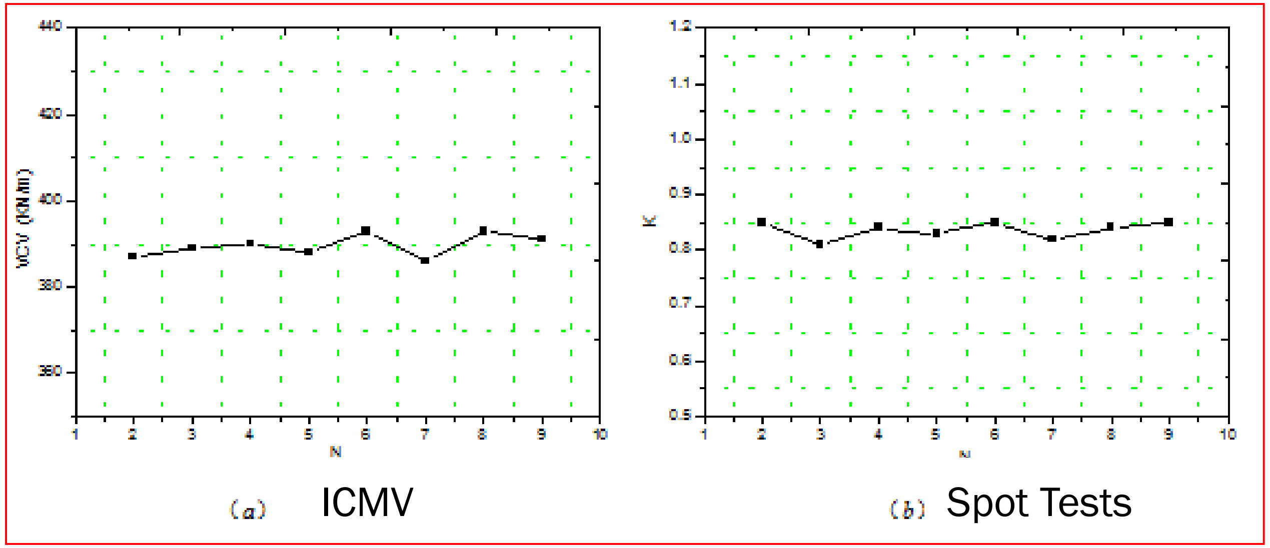



(c) well-graded

Xu, GH (2017)

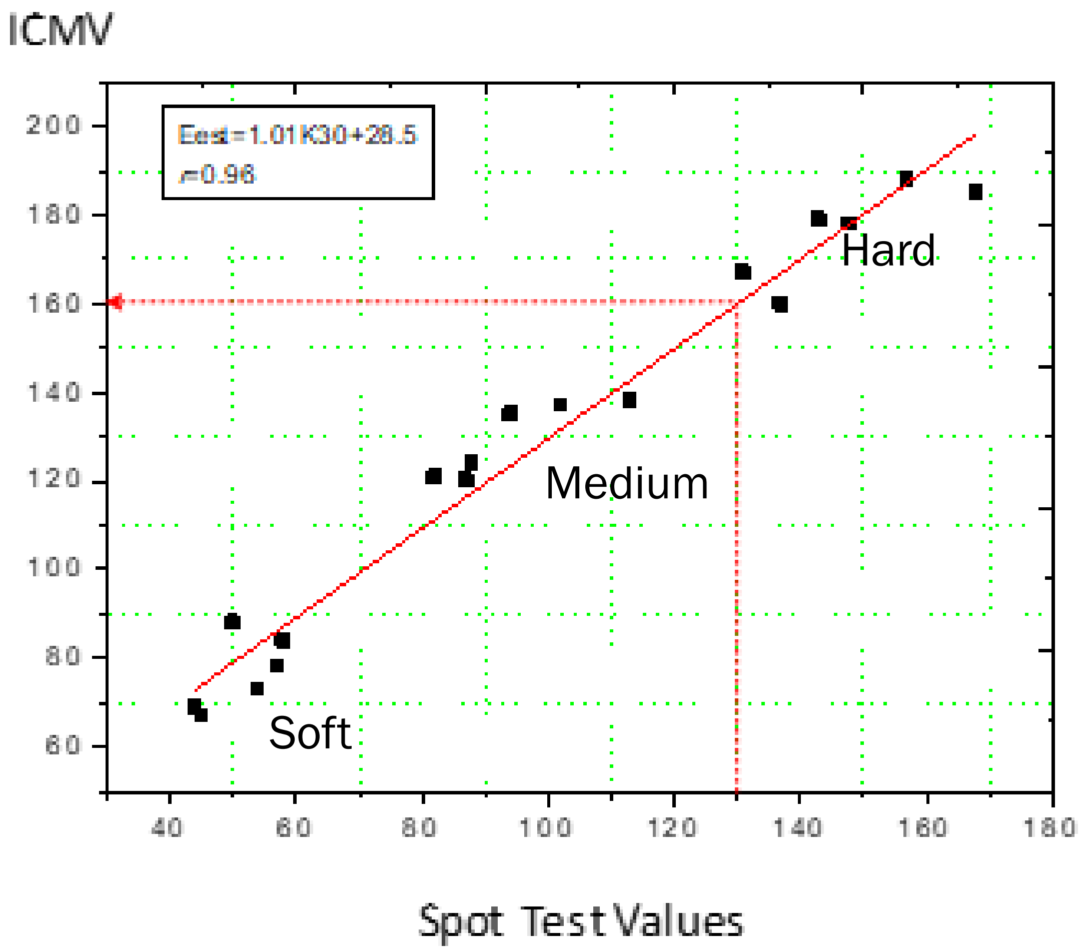
# Effects of Moisture Contents on Compaction Curves




Xu, GH (2017)

# Correlation b/w ICMV and Spot Tests

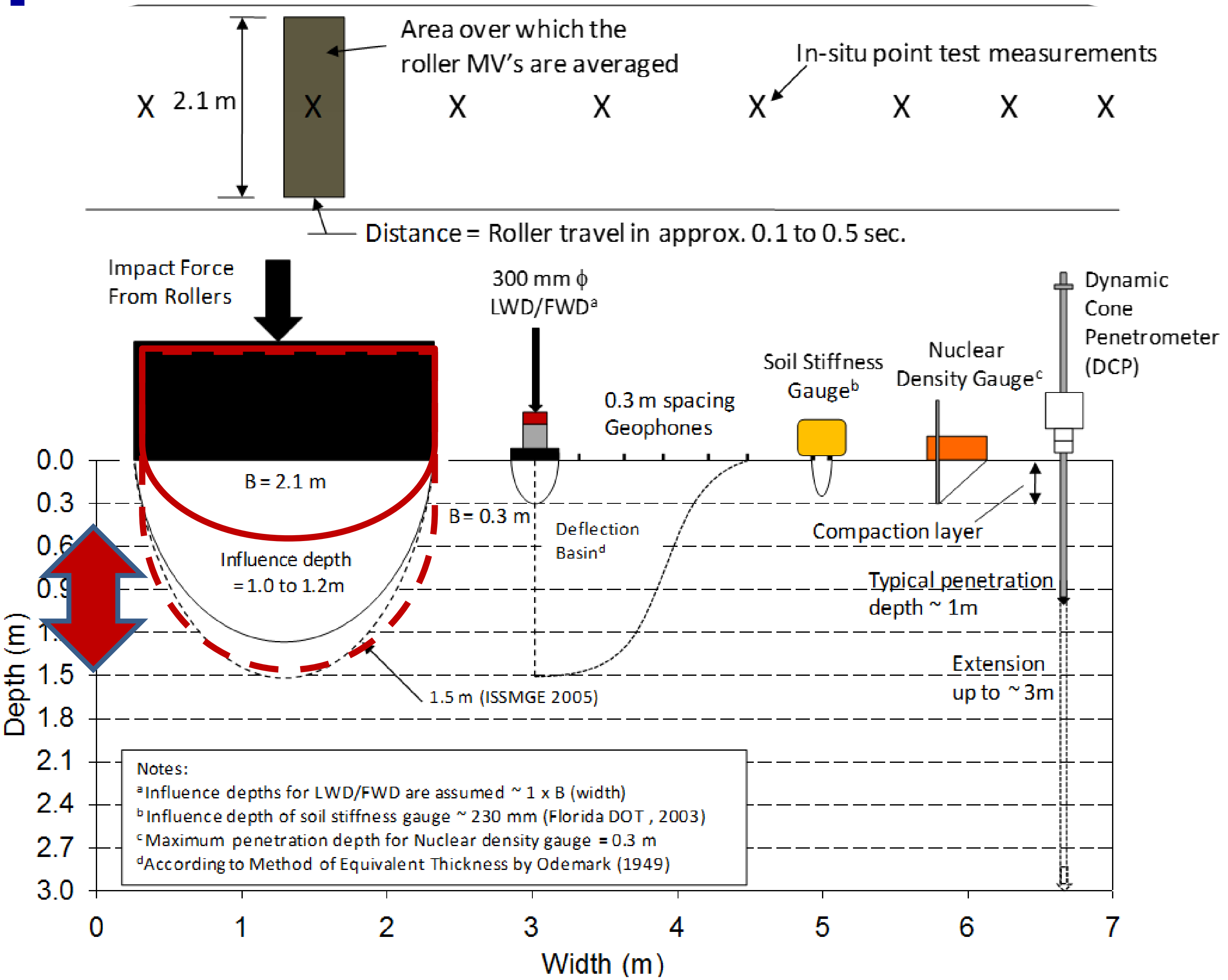



Xu, GH (2017)

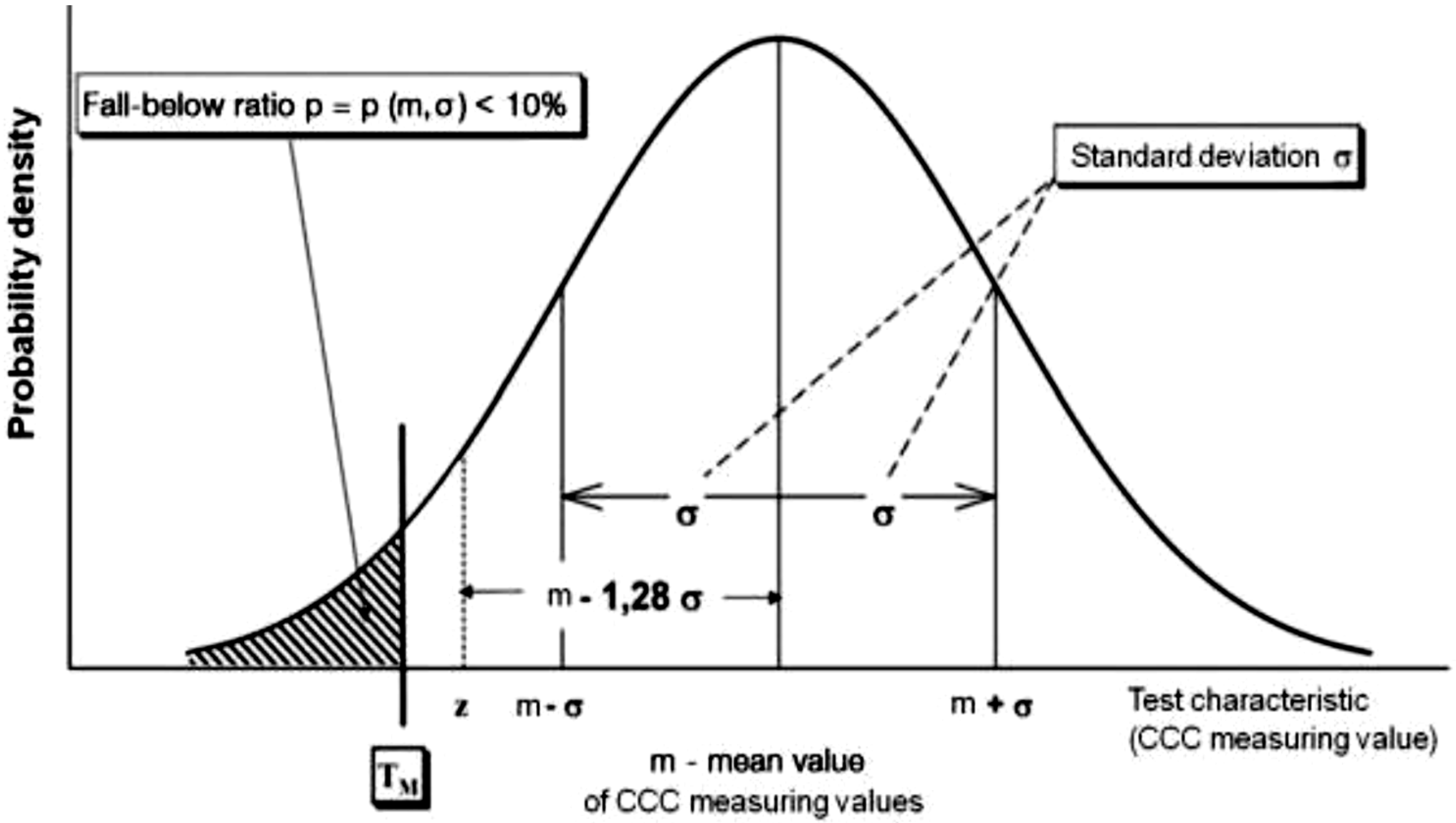
# ICMV vs. Spot Tests

0.5 m **20 in.**

1.2 m **5 ft**

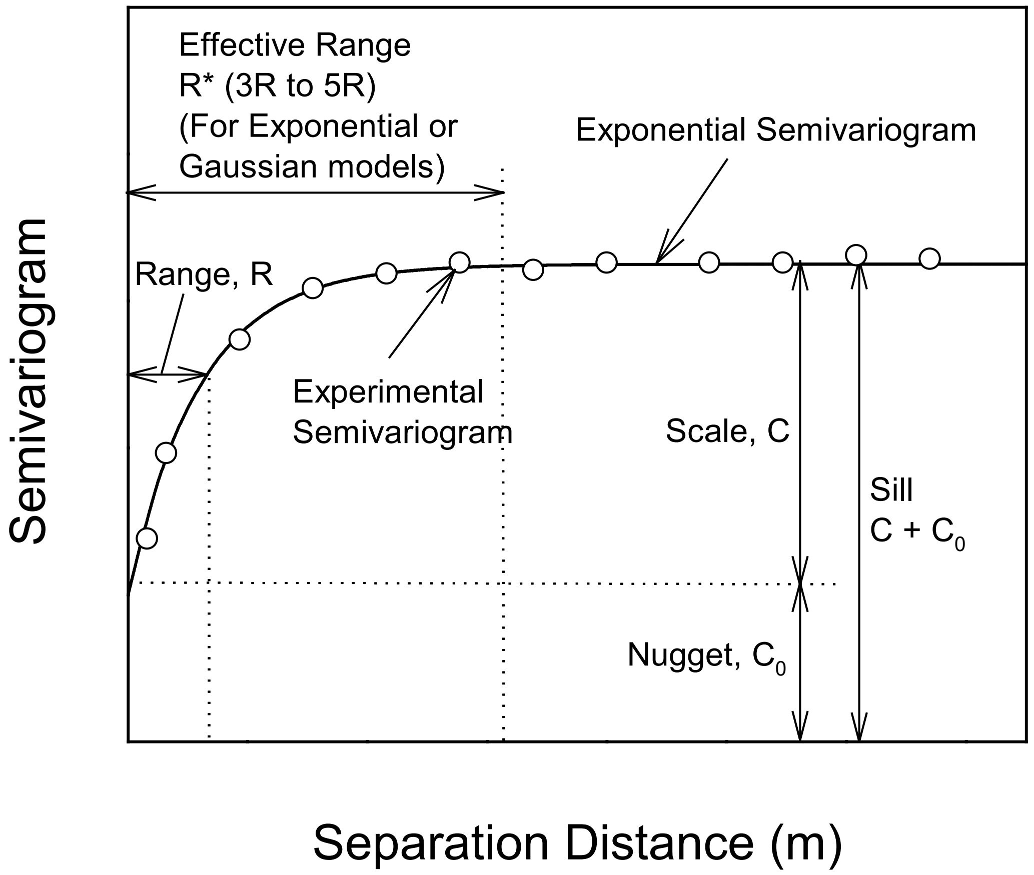


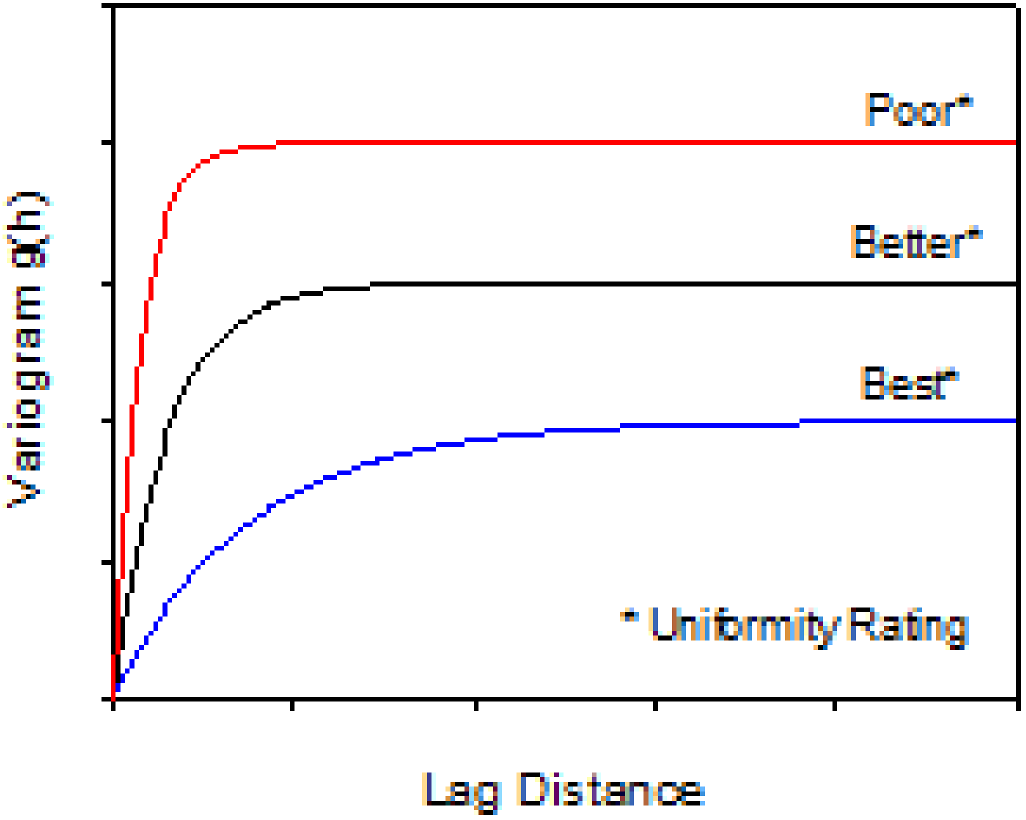
# Statistical Distribution of ICMV

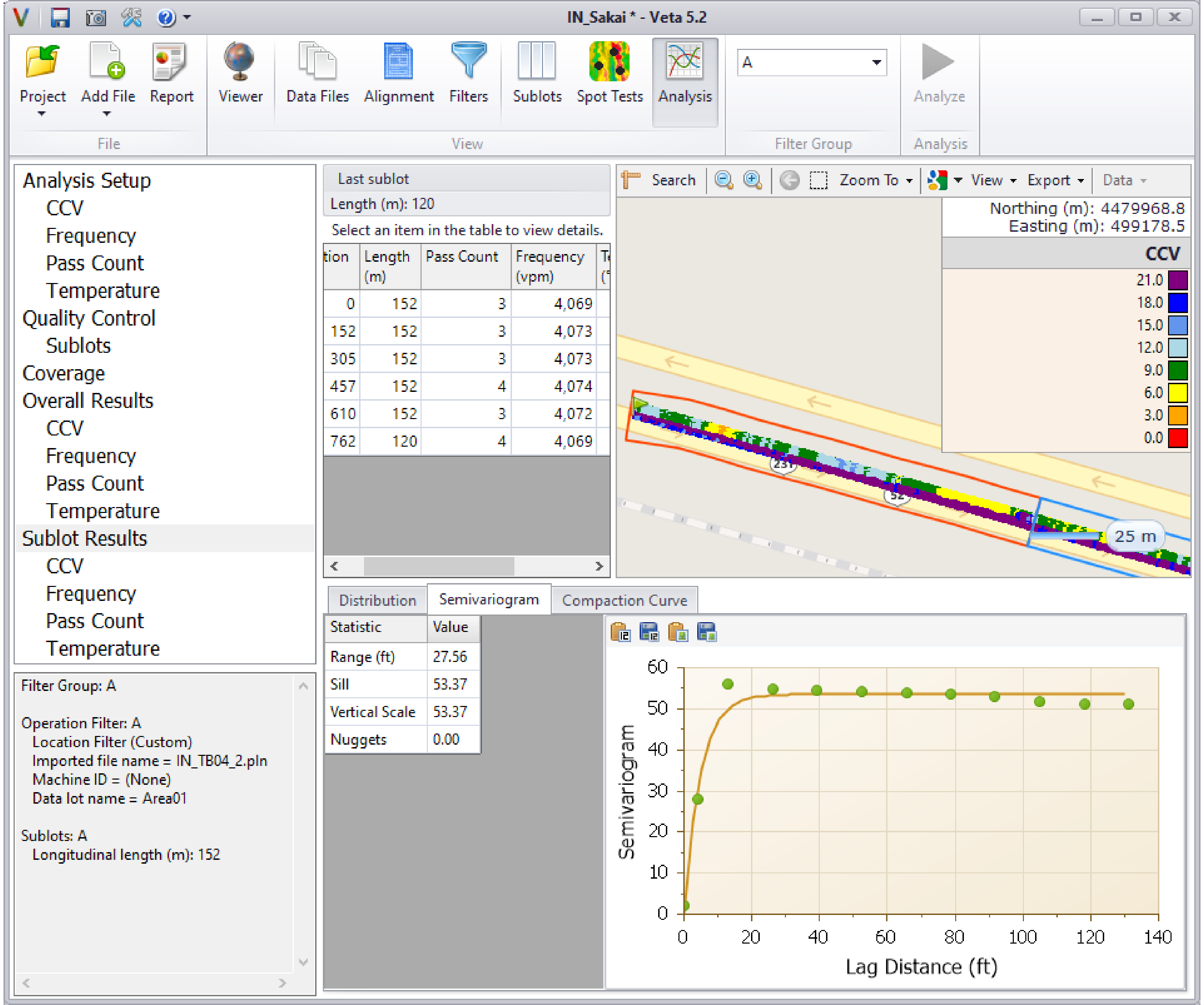



EU IC Standard (2016)

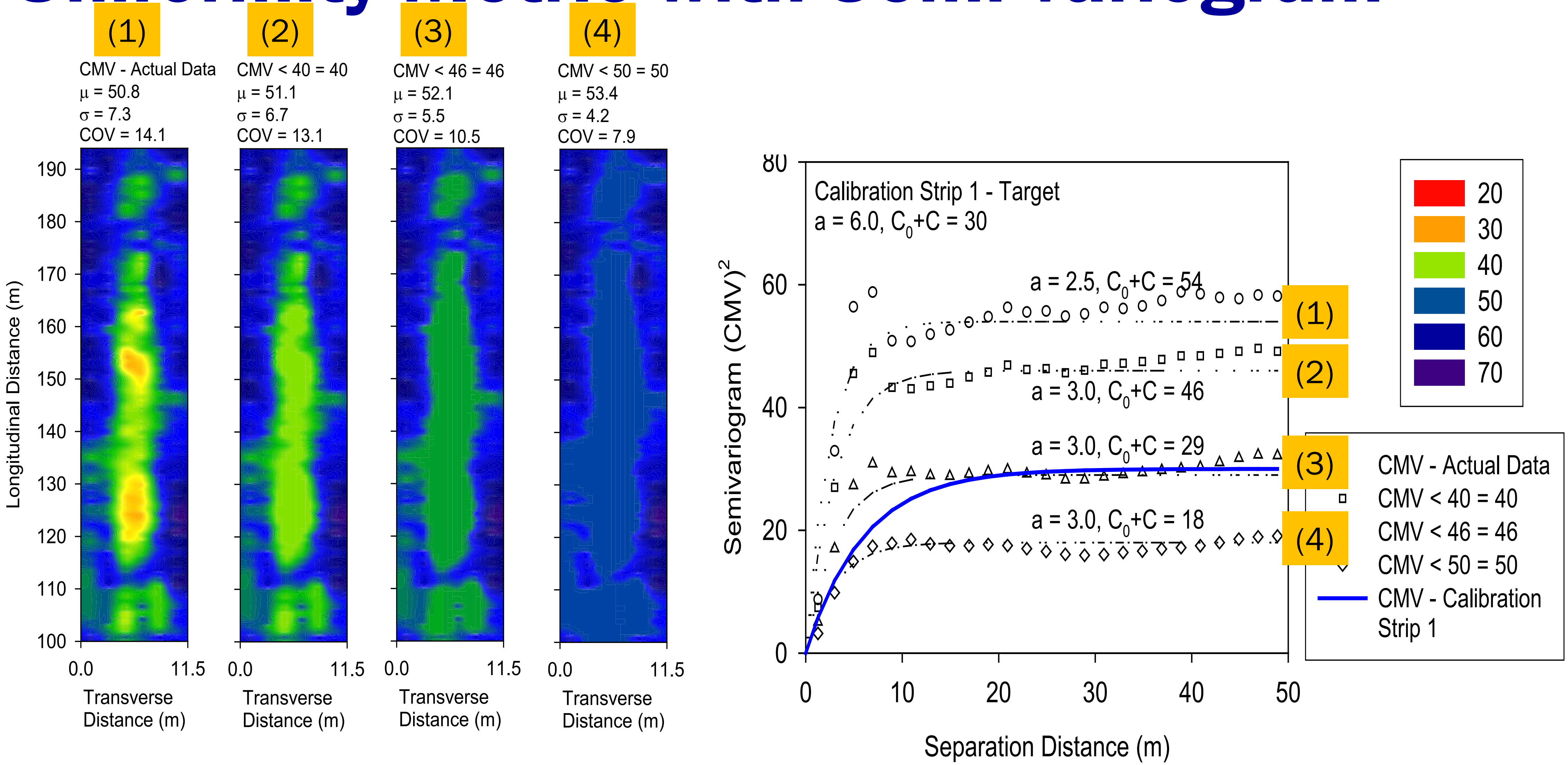
# Semi-Variogram




IN_Sakai * - Veta 5.2
Project
Add File
Report
Viewer
Data Files
Alignment
Filters
Sublots
Spot Tests
Analysis
A
Analyze
File
View
Filter Group
Analysis
Analysis Setup
CCV
Frequency
Pass Count
Temperature
Quality Control
Sublots
Coverage
Overall Results
CCV
Frequency
Pass Count
Temperature
Sublot Results
CCV
Frequency
Pass Count
Temperature
Last sublot
Length (m): 120
Select an item in the table to view details.
tion | Length (m) | Pass Count | Frequency (vpm)
0 | 152 | 3 | 4,069
152 | 152 | 3 | 4,073
305 | 152 | 3 | 4,073
457 | 152 | 4 | 4,074
610 | 152 | 3 | 4,072
762 | 120 | 4 | 4,069
Search
Zoom To
View
Export
Data
Northing (m): 4479968.8
Easting (m): 499178.5
CCV
21.0
18.0
15.0
12.0
9.0
6.0
3.0
0.0
25 m
Filter Group: A
Operation Filter: A
Location Filter (Custom)
Imported file name = IN_TB04_2.pln
Machine ID = (None)
Data lot name = Area01
Sublots: A
Longitudinal length (m): 152
Distribution
Semivariogram
Compaction Curve
Statistic | Value
Range (ft) | 27.56
Sill | 53.37
Vertical Scale | 53.37
Nuggets | 0.00
Semivariogram
Lag Distance (ft)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140

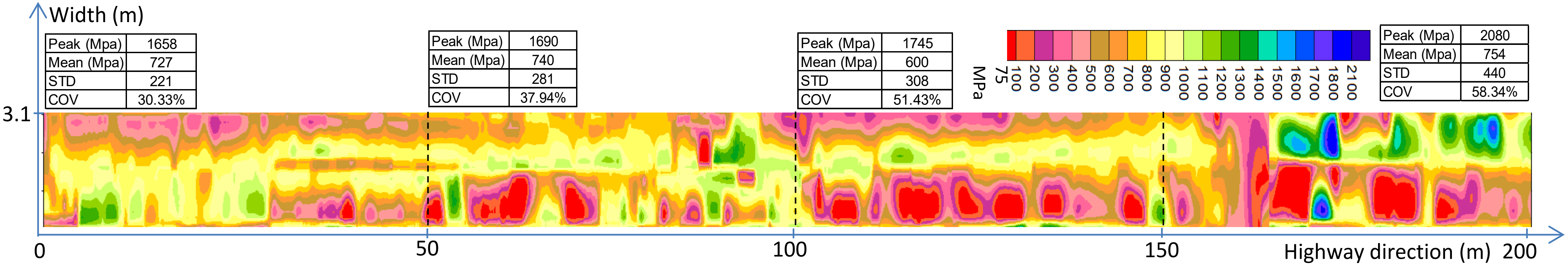
# Uniformity Metric with Semi-variogram



# Uniformity of ICMV

Evib – Level 3 ICMV

**Characterize Uniformity with Intelligent Compaction**




| | |
|---|---|
| Peak (Mpa) | 1658 |
| Mean (Mpa) | 727 |
| STD | 221 |
| COV | 30.33% |

| | |
|---|---|
| Peak (Mpa) | 1690 |
| Mean (Mpa) | 740 |
| STD | 281 |
| COV | 37.94% |

| | |
|---|---|
| Peak (Mpa) | 1745 |
| Mean (Mpa) | 600 |
| STD | 308 |
| COV | 51.43% |

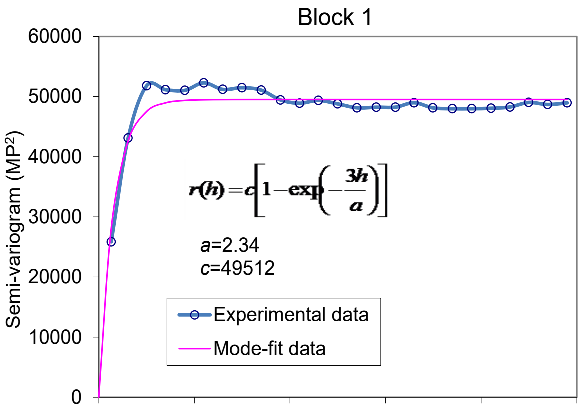
| | |
|---|---|
| Peak (Mpa) | 2080 |
| Mean (Mpa) | 754 |
| STD | 440 |
| COV | 58.34% |

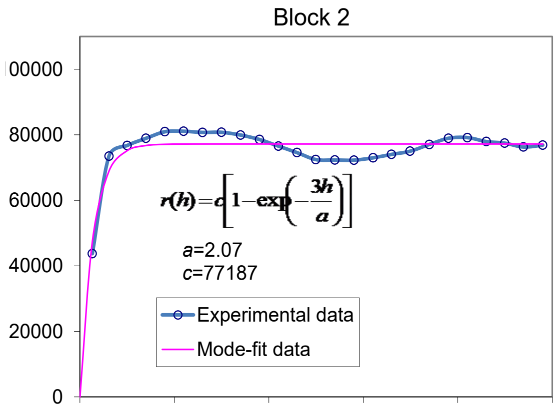
| | |
|---|---|
| Still ($MP^2$) | 4.95E+04 |
| COVA | 30.60% |

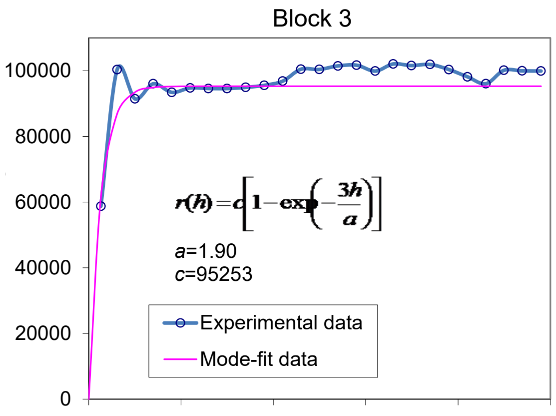
| | |
|---|---|
| Still ($MP^2$) | 7.72E+04 |
| COVA | 37.53% |

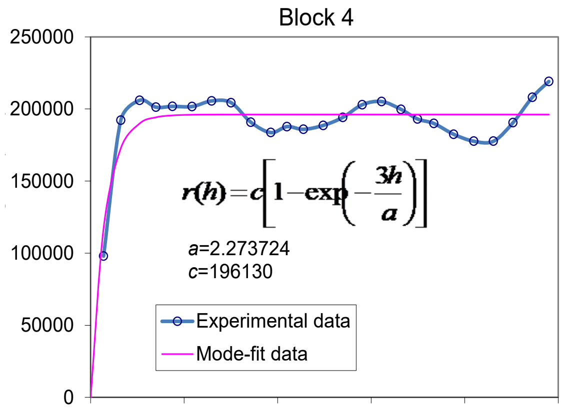
| | |
|---|---|
| Still ($MP^2$) | 9.52E+04 |
| COVA | 51.46% |

| | |
|---|---|
| Still ($MP^2$) | 1.96E+05 |
| COVA | 58.74% |



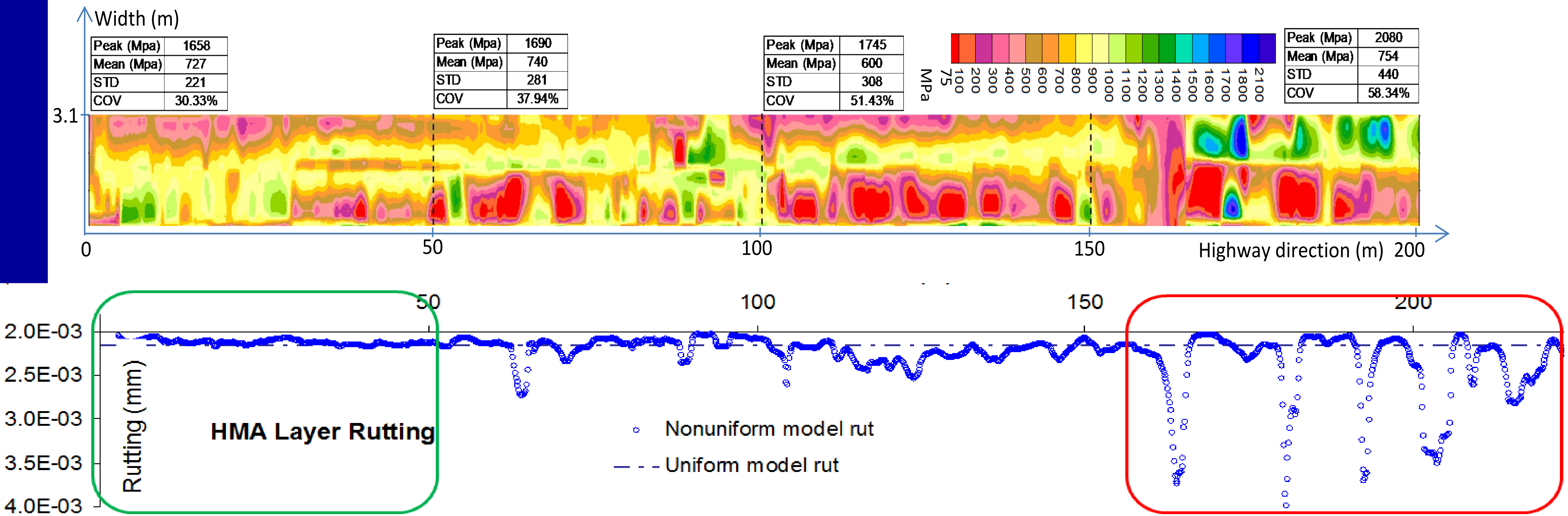




Xu and Chang (2014)

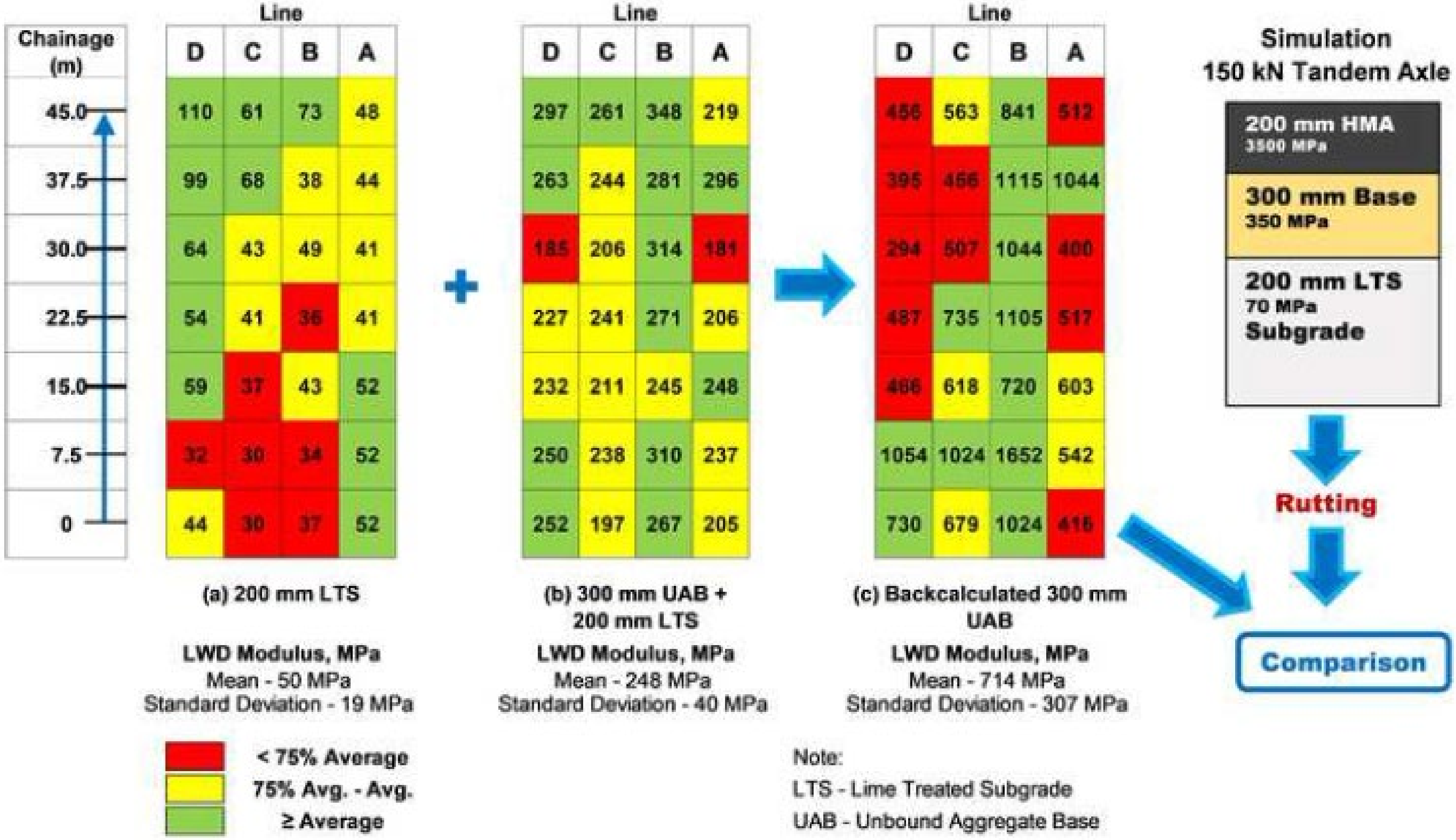
# Simulation of ACP Performance

**Impact of Uniformity On Pavement Performances**




Xu and Chang (2014)

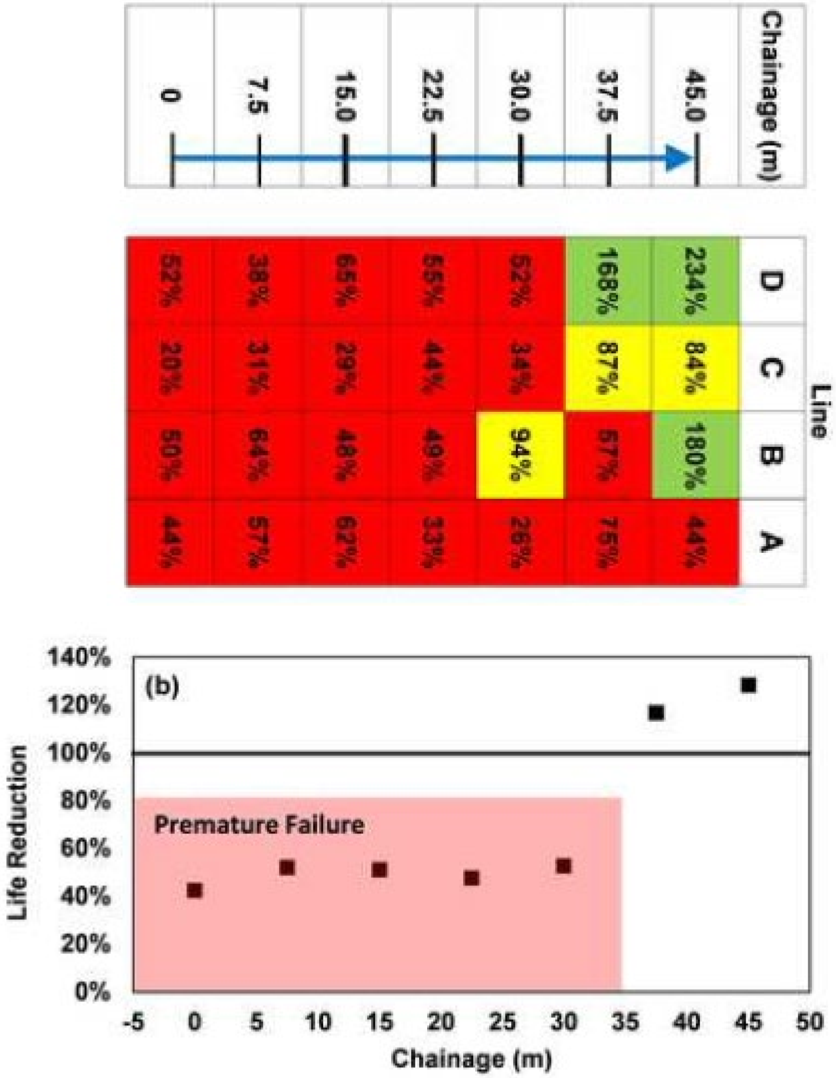
# Predicted Expected Pavement Life (1/2)




Adequacy of Foundation ?

Nazarian et al. (2019)

# Predicted Expected Pavement Life (2/2)




Adequacy of Foundation ?

Nazarian et al. (2019)

# 3. Work Plan (George)

- Overall Schedule of Tasks and Deliverables
- Meetings and Progress Reporting
- Task 1 – Detailed Work Plan
- Task 2 – State-of-Technology Review
- Task 3 – Field Demonstration
- Task 4 – Documentation

# Schedule of Tasks and Deliverables

| Task No. | Task Description | 2019 | | | 2020 | | | | | | | | | | | | 2021 | | | | | | | | | | | | 2022 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
| 1 | Detailed Work Plan | XX | FR | RD | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | State-of-Technology Review | XX | XX | XX | XX | XX | XF | RR | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Field Demonstration | | | | | | | | XX | XX | XX | XX | XX | XX | XX | XX | XX | XX | XX | | | | | | | | | | | | | | | | | | |
| 4.1 | Documentation (final report) | | | | | | | | | | | | | | | | | | | XX | XX | XX | XX | XX | FR | RR | RX | XD | | | | | | | | | |
| 4.2 | Documentation (tech brief) | | | | | | | | | | | | | | | | | | | | | | | | | | | F | RR | RR | XD | | | | | | |
| 4 | FHWA publication requirements | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X |
| | Quarterly Reports | | | X | | | X | | | X | | | X | | | X | | | X | | | X | | | X | | | X | | | X | | | X | | | X |
| | Web meeting/Conf call | | 1 | | | | | 2 | | 3A | | 3B | | 3C | | | | | | | | | | | | | | 4 | | | 5 | | | | | | |

*Legends:*

*X: Contractor effort*

*F: draft deliverable*

*R: FHWA Review*

*D: Final deliverable*

*Q: Quarterly Reports*

Web meeting/Conf call:

*1: Work plan meeting with the COR within 2 weeks of the project "kickoff" meeting*

*2: After the review of interim report*

*3: After site visit for each case-study project*

*4: After the review of the project report*

*5: After the review of the Tech Brief*

# Meetings and Progress Reporting

- Project kickoff Meeting with 14 days following TO award
- Work plan meeting with the COR within 2 weeks of the project “kickoff” meeting
- After the review of interim report
- After site visit for each case-study project
- After the review of the project report
- After the review of the Tech Brief


Deliverable: Project meetings and quarterly reports

# Task 1 – Detailed Work Plan

- Task 1.2  Identify Level 3-4 ICMV solutions and Level 1-2 solutions for comparison and to refine work plan for selected test sites.
- Within 1 month of NTP, the research team will identify Level 3-4 ICMV solutions and Level 1-2 solutions for comparison and for refining the work plan.


Task 1 Deliverable: Detailed work plan within 45 days

# Task 2 – State-of-Technology Review

- Thorough review of the state-of-technology of IC, including the capabilities of the available equipment, past implementation efforts, and on-going research.
- develop a procedure that could be used to fulfill the objectives of this TO: demonstrate the feasibility of utilizing IC device to ensure

    uniformity of pavement foundation, and

    adequacy of the foundation support

- Document appropriate procedures for identifying and correcting various types of problems that could be encountered


Task 2 Deliverable: Interim report within 6 months

# Task 3 – Field Demonstration

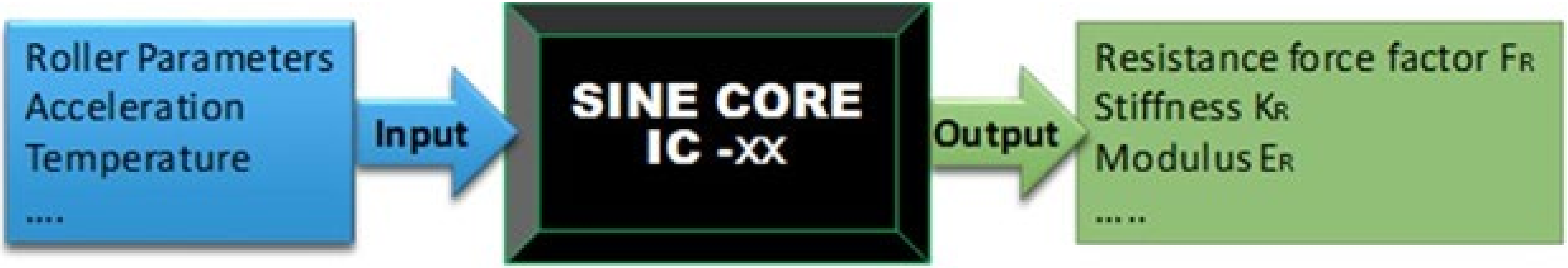
- Conduct field demonstrations at three (3) different sites to demonstrate the feasibility of utilizing IC device to ensure uniformity and quality of pavement foundations.
  - New concrete pavement project
  - New AC pavement project
  - AC pavement rehabilitation project


Task 3 Deliverable: Three (3) field demonstrations

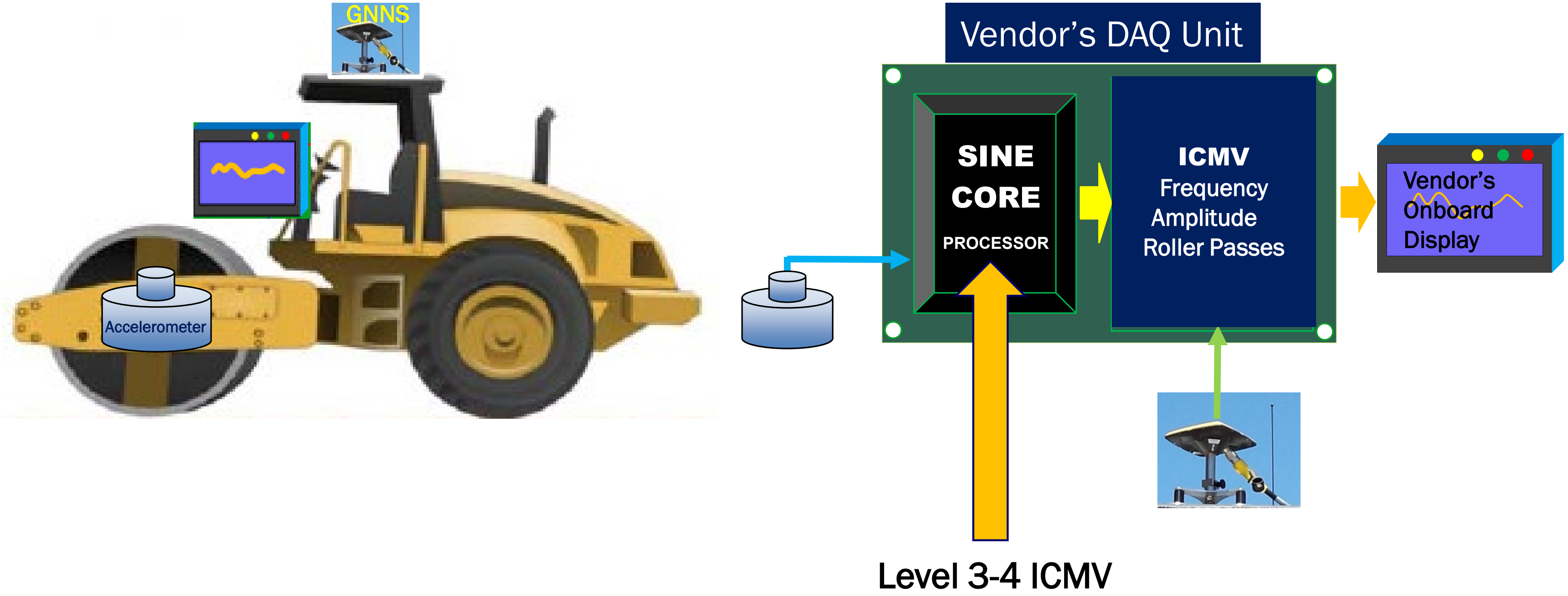
# Candidate Level 3-4 ICMV Systems

- MOBA IC retrofit system prototype with SINE CORE Level 3 ICMV module
- XCMG OEM IC system prototype with SINE CORE Level 3-4 ICMV module

# SINE CORE ICMV Inputs and Outputs



# Integration of Level 3-4 ICMV



# Candidate Test Sites (Discussion)

- Field sites with Subbase construction
  - New concrete pavement project
  - New AC pavement project
  - AC pavement rehabilitation project (FDR)
- Candidate States:
  - MN
  - TX
  - MO
- Redundancy of Candidate Field Sites

Timing - Weather – Contracting consideration

# Field Schedule and Activities (1/2)

1. Identification of a Subbase Test Section.  The team members from research team, DOT and Contractor will coordinate and identify a 250 ft (minimum) long and full width (or minimum of 25 ft wide) test section.
2. Set up of GPS. DOT or contractor’s base station will be used.
3. Set up of IC Roller. The research team will setup the IC roller. The IC roller will be checked for proper data collection and all settings including roller speed, and vibration frequency and amplitude.

# Field Schedule and Activities (2/2)

4. Conduct Construction as normally done.  It is at the discretion of the contractor to use a regular or an IC roller (the latter is preferred).  The research team may observe the construction but will not become involved in or interfere with the operation.
5. Conduct Mapping and Spot Tests. The research team will map the test section using one forward pass of the IC roller.  research team will carry out spot tests at a minimum of eighteen (18) points for correlation testing shortly after compaction. These activities will be carried out at a time that is least disruptive to the contractor. The proposed NDT devices for these tests include:
    - Nuclear Density and Moisture Gauge (NDG)
    - Light Weight Deflectometer (LWD)
    - Falling Weight Deflectometer (FWD)
    - GPS Rover (for positioning)

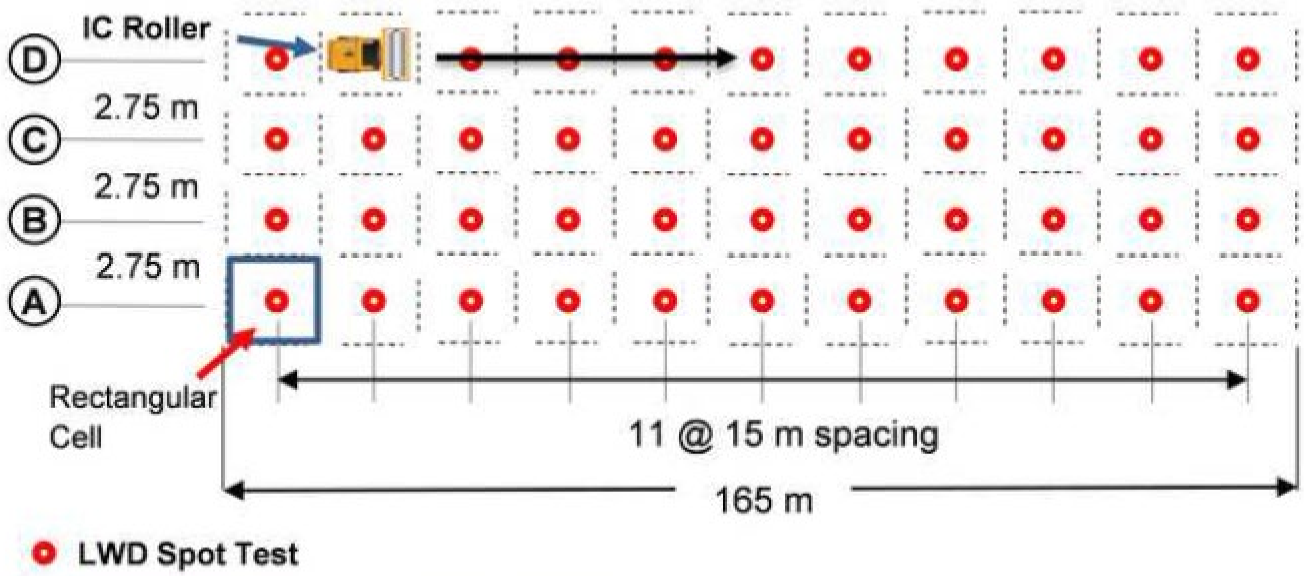
| Time | Tasks | Activities |
| --- | --- | --- |
| **Prior to Field Demonstration** | Coordination | • Identify field project and select the test section (DOT, contractor, research team)<br>• Arrange for spot test equipment and operators (DOT, contractor, research team)<br>• Arrange for roller instrumentation (contractor, industry partner, research team) |
| Day 1 | Initial Set up and trial runs | • Identify and mark the test section (DOT, contractor, research team)<br>• Initial setup of IC roller and GPS validation (contractor, industry partners, research team)<br>• Dry runs with the IC roller to collect, record, save, download and transfer data for this project (Contractor, industry partners and research team)<br>• Trial tests with spot test equipment (DOT, contractor and research team) |
| Day 2 | Subbase compaction and tests | • Pre-map subgrade within the test section (Contractor, research team)<br>• Prepare and compact subbase within the test section (Contractor)<br>• Map the top of subbase with IC roller (Contractor, research team)<br>• Select locations for spot tests based on ICMV map (research team)<br>• Conduct spot testing with NDG/LWD/FWD/GPS (DOT, research team) |
| Day 3 | Map subbase and tests | • Identify and mark other existing or completed subbase sections (DOT, Contractor, research team)<br>• Map the top of subbase with IC roller (Contractor, research team)<br>• Select locations for spot tests based on ICMV map (research team)<br>• Conduct spot testing with NDG/LWD/FWD/GPS (DOT, research team) |

# Instrumentation of an IC Roller


# Instrumentation of an IC Roller

# Spread Subbase Materials and Compact with IC Roller

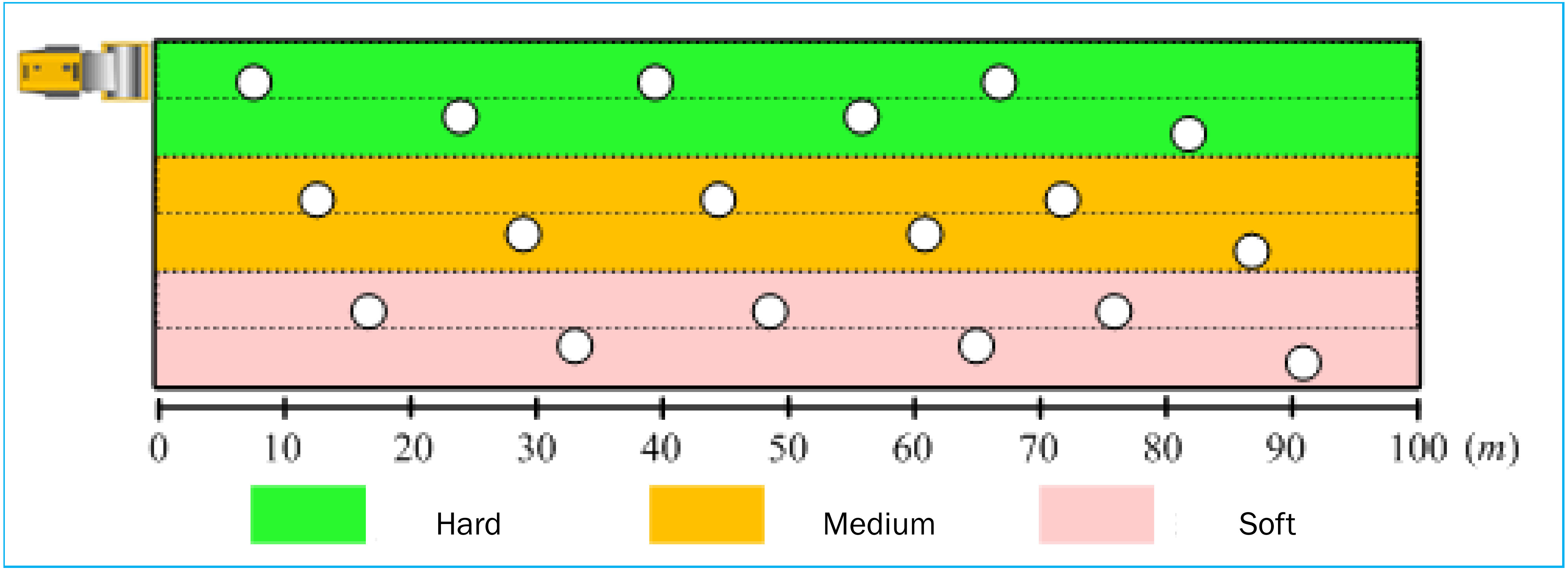
# Grid Pattern for Spot Tests





Nazarian et al. (2019)

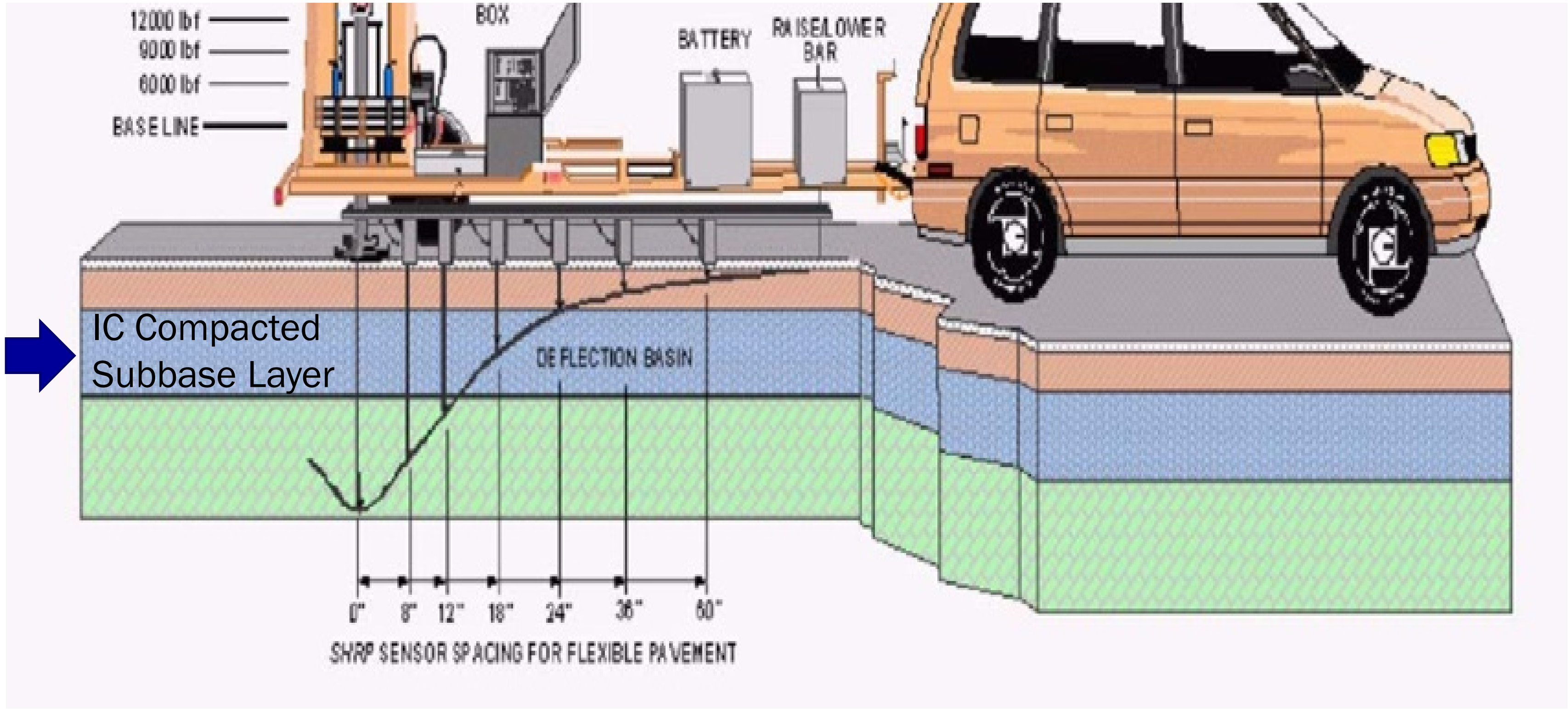
# Spot Test Locations based on IC Map




Xu, GH (2017)

# Spot Tests

# DOT's FWD Tests on Finished Pavements



# Task 4 – Documentation

- Task 4.1 Project Report

  document the work conducted under this TO, including the state-of-technology review conducted under Task 2, data, findings, demonstration projects, and any discussions of the recommendations included in the Technical Brief developed under Task 4.2.

- Task 4.2 Technical Brief

- Task 4 Deliverable: Project Report (within 24 months) Tech Brief (within 27 months)


FHWA publication requirements

U.S. Department of Transportation
**Federal Highway Administration**

# THANK YOU!

WERIS

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*The World's Pavement Engineering Specialists*