Data Acquisition and Its Relevance

Case Study:

Oscillation Trials of BEML Coaches for Kolkata East-West Metro

Field Trials Objectives

- *Estimate Sperling and ISO ride indices* under different loading (tare, crush), air spring conditions (inflated, deflated) and different speeds (low, high speeds), at different locations on coach floor. They must be below 3 to be fit to run as per RDSO norms
- *Monitor axle box and bogie frame vibrations*
- *Obtain draft gear compressions*
- *Monitor primary and secondary spring compressions*
- *Estimate natural frequencies and damping coefficients* for primary and secondary springs under different operating conditions
- *Estimate creepages* at rail-wheel contact through accurate estimation of wheel rpm on trailer and motor cars

Instrumented Coaches for Field Trials

A driver motor car at one end of a Kolkata metro train was instrumented. Trials were conducted on newly laid east-west corridor track in Kolkata from Salt Lake to Sec-5 stations.

Metro trains to ply on east-west corridor in Kolkata have 6 coaches: 2 driver motor cars (DMC), 2 motor cars (MC) and 2 trailer cars (TC) in DMC-TC-MC-MC-TC-DMC configuration. Each car/coach is around 20.8 meters long and it rests on two bogies.

Field Trials Route Map

City Center

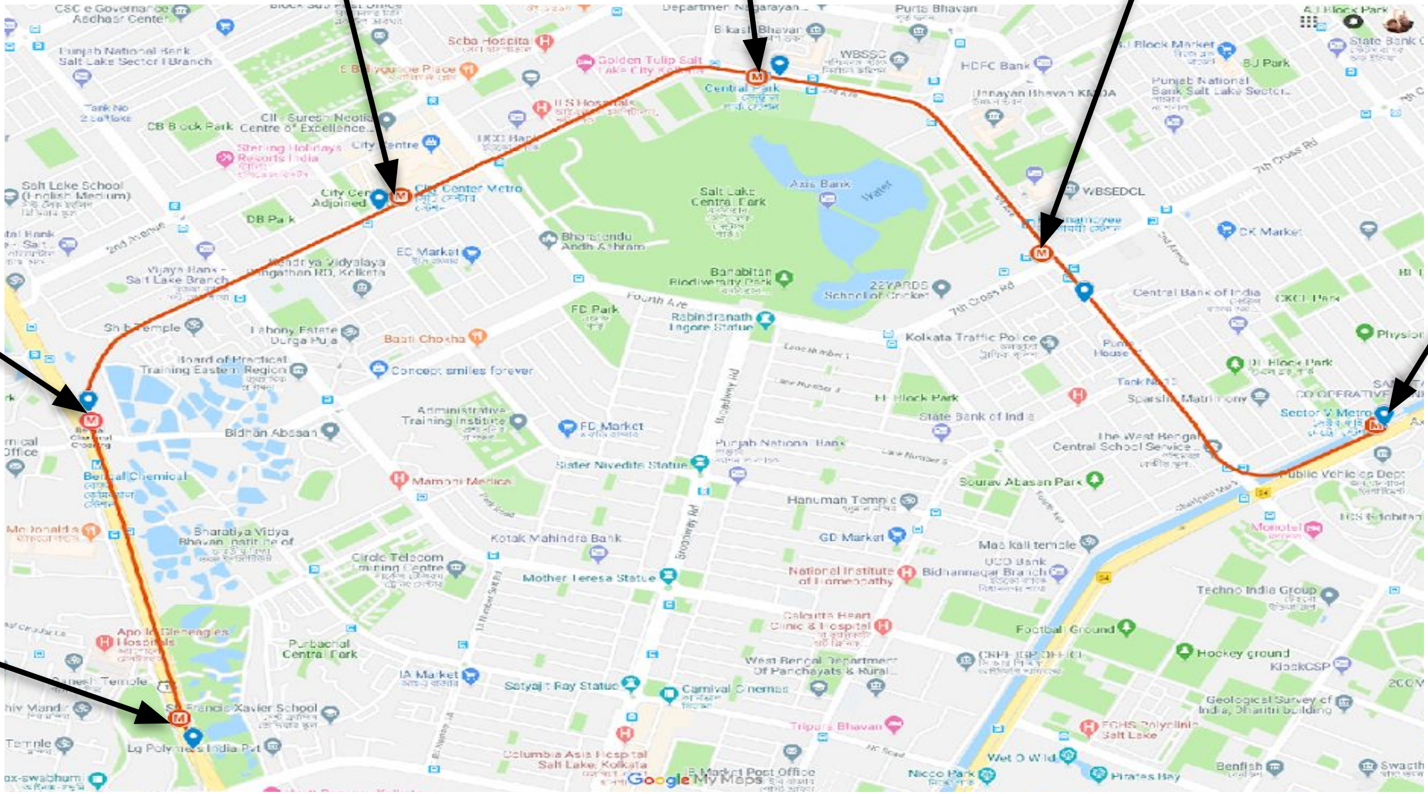
Central Park

Karunamoyee

Sector 5

Bengal Chemical

Salt Lake Stadium



Which Sensors are to be Used for Each of the Measurements?

Which Angular Speed Measurement Sensor Would be Ideal for this Application?

- Optical/Inductive Encoders: Cannot be used as it would require alteration of axle in the powertrain that cannot be done in this case.
- Laser tachometer: Easy to use. Laser mounted on an outside fixture. A reflective tape is to be stuck on wheel which is not an issue. Solution is also cost effective.
- IMU (Inertial Measurement Unit): Challenging to use as IMU needs to be mounted on rotating wheel while data acquisition system (DAQ) would be in coach. Either slip rings or wifi data transfer systems are needed making this option very challenging.

In this application, angular speed of wheelset (wheels rigidly mounted on axles) need to be measured.

Which Displacement Sensor Would be Ideal for this Application?

- Laser displacement sensor: Challenging for outdoor and reflecting surfaces
- Linear rheostat displacement sensor: Not suitable for high speed applications due to heat generation at sliding metal on metal contacts
- Capacitive displacement sensor: Not well suited for large displacement measurements
- Linear variable differential transformers (LVDTs): Well suited for this application. Can handle large displacements. Provides high resolution. Suitable for high speed applications too. They are cost effective too.
- Magnetic/Inductive/Eddy current sensors: Well suited for small gap variation measurements

In this application, change in distance across points that are at around 300-500mm distance is to be measured. Displacements are expected to be around a maximum of 10-30 mm.

Which Sensor Would be Ideal for Measuring Acceleration?

- MEMS based accelerometers: Better suited for lower frequencies up to 0 Hz. They can measure frequencies of up to 1 kHz. The readings are more accurate at lower frequencies. These are relatively cheap and easy to use.
- Piezoelectric accelerometers: Well suited for high frequency applications (e.g. up to 5-10 kHz). These are expensive and require expensive instrumentation.

In this application, while rigid body vibrations of coach and bogie are around <5 and <10 Hz, the vibrational frequencies associated with structural members e.g. springs, wheels, bogie would be of the order of around few hundred of Hz. The axle would also experience jerks to the range of around 50g which MEMS based accelerometers cannot capture.

Sensors Used

Sensor Type	Make	Model	Output	Associated NI Card	Input Power Supply (VDC)	Quantity	Quantity Measured
Remote Optical Tachometer	Monarch Instrument, NH, USA	ROS-W	TTL Pulse	NI 9401	3-15 VDC @40 mA	2	Wheel RPM
LVDT (Linear variable differential transformer)	Applied Measurements Limited, UK	AML/EU10+/-50mm-R0R-15-000	0-10 V, 100 mV/mm sensitivity	NI 9220	14-24 VDC (Regulated)	13	Primary suspension (8), secondary suspension (4) compressions and draft gear compression (1)
Tri-axial accelerometers	PCB Piezotronics, NY, USA	Model 356A16	100 mV/g, 0.5-5000 Hz range	NI 9232	20-30 VDC, 2-20 mA	4	Coach X, Y, Z floor accelerations in the middle and at an offset
Uni-axial accelerometers	PCB Piezotronics, NY, USA	Model 333B30	100 mV/g, 0.5 to 3000 Hz	NI 9232	18-30 VDC, 2-20 mA	3	Axle X, Z accelerations

Note that X, Y, Z correspond to longitudinal (travel direction), lateral, and vertical (downward positive)

ROS (Remote Optical Sensor): Threaded stainless steel remote optical sensors have a visible red LED light source and green LED 'On Target' indicator. Performs over a wide speed range and operating envelope.

Common usage: Wide range of general purpose applications in relatively clean environments.

Operating Distance	3 feet (1 m) and 45° from reflective tape
Speed Range	1-250,000 RPM
Operating Temperature	-14° to 158°F (-10° to 70°C)
Power Required	3.3 to 15 Vdc @ 45 mA
Output Signal	TTL Same as Source
Standard Cable	8 Feet (2.4 m)
Dimensions	2.9" (L) x 0.625" diameter (73 x 16mm)

APPLIED MEASUREMENTS LTD.

Transducer Specialists...

+44 (0) 118 981 7339

info@appmeas.co.uk

www.appmeas.co.uk

Specification:

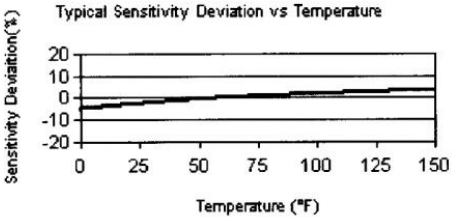
CHARACTERISTICS	AML/E---	AML/EJ---	AML/EU---	AML/EU10	AML/EI---	AML/ED---	UNITS
Stroke Measurement Range:	±0.5, ±2.5, ±5, ±10, ±12.5, ±15, ±25, ±50, ±75, ±100, ±125, ±150, ±175, ±200, ±250 ±300, ±400, ±500 (maximum stroke is ±100 for Sprung Loaded Core & Extension - Option S)						millimetres
Signal Output:	See Table Below		0-5volt	0-10volt	4-20mA	±2.5volt	
No. of Wires	6	4	3	3	3	4	
Supply Voltage (unregulated):	2 to 5Vrms @ 1 to 5kHz		10-24Vdc	14-24Vdc	14-24Vdc	12Vdc regulated	
Supply Current:	-		35mA @ 15V	35mA @ 15V	35mA typ.	35mA @ 12V	
Max. Loop Resistance:	-		-	-	300 @ 30V	-	ohms
Max. Output Sink Current:	-		0.5	1	-	0.1	milliamps
Non-Linearity:	<0.50 (<0.25 optional)						±% Stroke Range
Repeatability:	<0.10						±% Stroke Range
Output Bandwidth:	100		100	100	100	100	Hz
Output Ripple:	-		30mV max.	30mV max.	0.1% @ 20mA	30mV max.	
Operating Temperature Range:	AML/E & EJ: -30 to +85 Standard / -30 to +150 Optional				-20 to +85 on DC/DC models		°C
Zero Temperature Coefficient:	<0.020		<0.010				±%Stroke Range/°C
Span Temperature Coefficient:	<0.020		<0.030				±%Stroke Range/°C
Vibration Resistance:	20g up to 2kHz						
Shock Resistance:	1000g for 10milliseconds						
Construction Materials:	Body & Extension Rod: 303 St/Steel, Core: 416 St/Steel, Cable Gland: Nickel-Plated Brass, Spring: 316 St/Steel, Rod-End Bearings: Mild Steel						
Electrical Connection:	2 metre screened PVC cable* (*High-Temp Version = PTFE). Axial or radial exit available - see ordering codes for full details.						
Environmental Sealing:	IP54						

Note: On DC output version (0Vdc / 4mA) is given with the core in the extended / outwards position. This can be reversed if required, please request **Option Y** on your order.

Model Number 333B30	ICP® ACCELEROMETER	Revision: K ECN #: 25552

Performance	ENGLISH	SI	
Sensitivity(± 10 %)	100 mV/g	10.2 mV/(m/s²)	
Measurement Range	± 50 g pk	± 490 m/s² pk	
Frequency Range(± 5 %)	0.5 to 3000 Hz	0.5 to 3000 Hz	
Resonant Frequency	≥ 40 kHz	≥ 40 kHz	
Phase Response(± 5 °)(at 70°F [21°C])	2 to 3000 Hz	2 to 3000 Hz	
Broadband Resolution(1 to 10,000 Hz)	0.00015 g rms	0.0015 m/s² rms	[1]
Non-Linearity	≤ 1 %	≤ 1 %	[2]
Transverse Sensitivity	≤ 5 %	≤ 5 %	[3]
Environmental			
Overload Limit(Shock)	± 5000 g pk	± 49,000 m/s² pk	
Temperature Range(Operating)	0 to +150 °F	-18 to +66 °C	
Temperature Response	See Graph	See Graph	
Base Strain Sensitivity	0.01 g/με	0.1 (m/s²)/με	[1]
Electrical			
Excitation Voltage	18 to 30 VDC	18 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤ 300 ohm	≤ 300 ohm	
Output Bias Voltage	7 to 12 VDC	7 to 12 VDC	
Discharge Time Constant	1.0 to 3.0 sec	1.0 to 3.0 sec	
Settling Time(within 10% of bias)	<12 sec	<12 sec	
Spectral Noise(1 Hz)	39 μg/√Hz	380 (μm/s²)/√Hz	[1]
Spectral Noise(10 Hz)	11 μg/√Hz	110 (μm/s²)/√Hz	[1]
Spectral Noise(100 Hz)	3.4 μg/√Hz	33 (μm/s²)/√Hz	[1]
Spectral Noise(1 kHz)	1.4 μg/√Hz	14 (μm/s²)/√Hz	[1]
Physical			
Sensing Element	Ceramic	Ceramic	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	
Sealing	Hermetic	Hermetic	
Size (Height x Length x Width)	0.40 in x 0.63 in x 0.40 in	10.2 mm x 16.0 mm x 10.2 mm	
Weight	0.14 oz	4.0 gm	[1]
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack	
Electrical Connection Position	Side	Side	
Mounting Thread	5-40 Female	5-40 Female	
Mounting Torque	4 to 5 in-lb	45 to 56 N-cm	

CE [4]



OPTIONAL VERSIONS

Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

T - TEDS Capable of Digital Memory and Communication Compliant with IEEE P1451.4
TLA - TEDS LMS International - Free Format
TLB - TEDS LMS International - Automotive Format
TLC - TEDS LMS International - Aeronautical Format
TLD - TEDS Capable of Digital Memory and Communication Compliant with IEEE 1451.4

Output Bias Voltage	7.5 to 13 VDC	7.5 to 13 VDC

NOTES:

[1] Typical.
[2] Zero-based, least-squares, straight line method.
[3] Transverse sensitivity is typically ≤ 3%.
[4] See PCB Declaration of Conformance PS023 for details.

SUPPLIED ACCESSORIES:

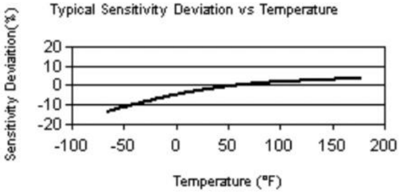
Model 080A109 Petro Wax (1)
Model 080A25 Adhesive base, 0.438" hex, 5-40 tapped hole, aluminum hardcoat. (1)
Model 080A90 Quick Bonding Gel (1)
Model 081A27 Mounting Stud (5-40 to 5-40) (1)
Model ACS-1 NIST traceable frequency response (10 Hz to upper 5% point). (1)
Model M081A27 Metric mounting stud, 5-40 to M3 x 0.50 long (1)

Entered:	Engineer:	Sales:	Approved:	Spec Number:
Date: 12-21-06	Date: 12/21/06	Date: 12/21/06	Date: 12/21/06	11827

Model Number 356A16	TRIAXIAL ICP® ACCELEROMETER	Revision: K ECN #: 28126

Performance	ENGLISH	SI	
Sensitivity(± 10 %)	100 mV/g	10.2 mV/(m/s²)	
Measurement Range	± 50 g pk	± 490 m/s² pk	
Frequency Range(± 5 %)(y or z axis)	0.5 to 5000 Hz	0.5 to 5000 Hz	
Frequency Range(± 5 %)(x axis)	0.5 to 4500 Hz	0.5 to 4500 Hz	
Frequency Range(± 10)	0.3 to 6000 Hz	0.3 to 6000 Hz	
Resonant Frequency	≥ 25 kHz	≥ 25 kHz	
Phase Response(± 5 °)	1.0 to 5000 Hz	1.0 to 5000 Hz	
Broadband Resolution(1 to 10,000 Hz)	0.0001 g rms	0.001 m/s² rms	[1]
Non-Linearity	≤ 1 %	≤ 1 %	[2]
Transverse Sensitivity	≤ 5 %	≤ 5 %	
Environmental			
Overload Limit(Shock)	± 7000 g pk	± 68,600 m/s² pk	
Temperature Range(Operating)	-65 to +176 °F	-54 to +80 °C	
Temperature Response	See Graph	See Graph	[1]
Base Strain Sensitivity	0.001 g/με	0.01 (m/s²)/με	[1]
Electrical			
Excitation Voltage	20 to 30 VDC	20 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤ 200 Ohm	≤ 200 Ohm	
Output Bias Voltage	8 to 12 VDC	8 to 12 VDC	
Discharge Time Constant	1.0 to 3.0 sec	1.0 to 3.0 sec	
Settling Time(within 10% of bias)	<10 sec	<10 sec	
Spectral Noise(1 Hz)	40 μg/√Hz	392 (μm/sec²)/√Hz	[1]
Spectral Noise(10 Hz)	10 μg/√Hz	98 (μm/sec²)/√Hz	[1]
Spectral Noise(100 Hz)	3 μg/√Hz	29.4 (μm/sec²)/√Hz	[1]
Spectral Noise(1 kHz)	1 μg/√Hz	9.8 (μm/sec²)/√Hz	[1]
Spectral Noise(10 kHz)	0.5 μg/√Hz	4.9 (μm/sec²)/√Hz	[1]
Physical			
Sensing Element	Ceramic	Ceramic	
Sensing Geometry	Shear	Shear	
Housing Material	Anodized Aluminum	Anodized Aluminum	
Sealing	Epoxy	Epoxy	
Size (Height x Length x Width)	0.55 in x 0.80 in x 0.55 in	14.0 mm x 20.3 mm x 14.0 mm	
Weight	0.26 oz	7.4 gm	[1]
Electrical Connector	1/4-28 4-Pin	1/4-28 4-Pin	
Electrical Connection Position	Side	Side	
Mounting Thread	10-32 Female	10-32 Female	
Mounting Torque	10 to 20 in-lb	113 to 225 N-cm	

CE [3]



All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
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OPTIONAL VERSIONS

Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

A - Adhesive Mount
Supplied Accessory : Model 080A109 Petro Wax (1)
Supplied Accessory : Model 080A90 Quick Bonding Gel (1)

T - TEDS Capable of Digital Memory and Communication Compliant with IEEE P1451.4
TLA - TEDS LMS International - Free Format
TLB - TEDS LMS International - Automotive Format
TLC - TEDS LMS International - Aeronautical Format
TLD - TEDS Capable of Digital Memory and Communication Compliant with IEEE 1451.4

Temperature Range(Operating)	-65 to +176 °F	-54 to +80 °C
Output Bias Voltage	8.5 to 13.0 VDC	8.5 to 13.0 VDC

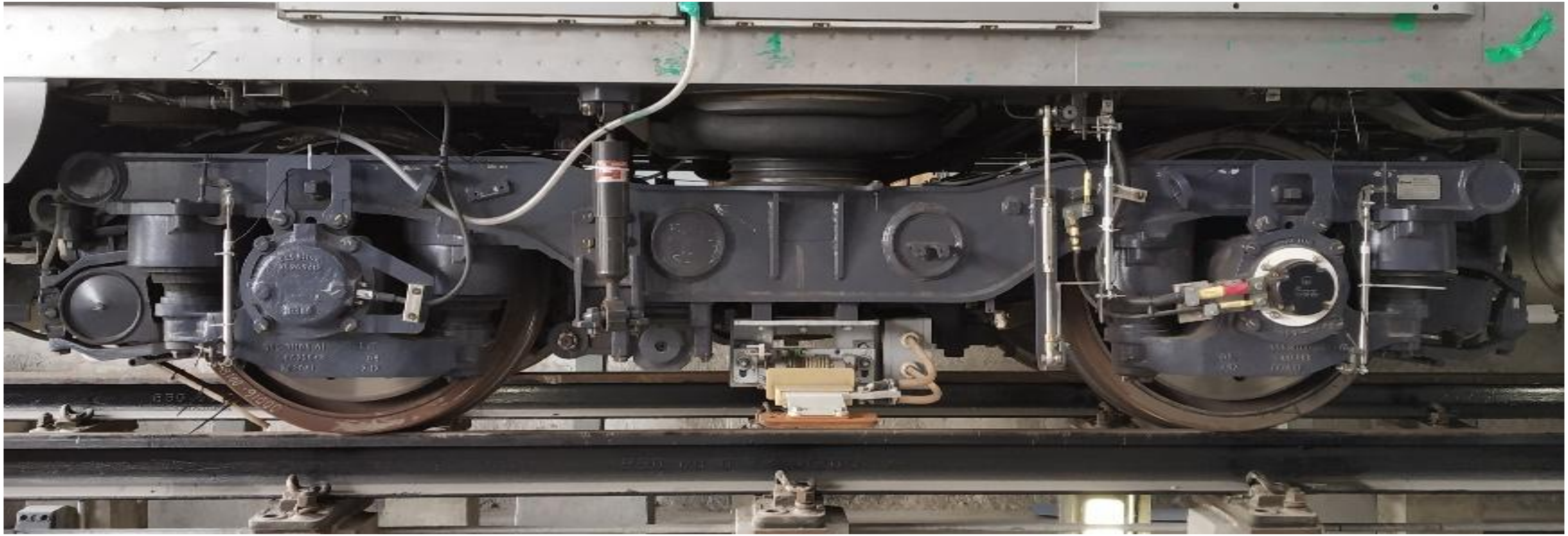
NOTES:
[1]Typical.
[2]Zero-based, least-squares, straight line method.
[3]See PCB Declaration of Conformance PS023 for details.

SUPPLIED ACCESSORIES:
Model 080A109 Petro Wax (1)
Model 080A12 Adhesive Mounting Base (1)
Model 081B05 Mounting Stud (10-32 to 10-32) (1)
Model ACS-1T NIST traceable triaxial amplitude response, 10 Hz to upper 5% frequency. (1)
Model M081B05 Mounting Stud 10-32 to M6 X 0.75 (1)

Entered:	Engineer: SDS	Sales:	Approved: BAM	Spec Number:
Date:	Date: 2/11/2008	Date:	Date: 2/11/2008	**10330**

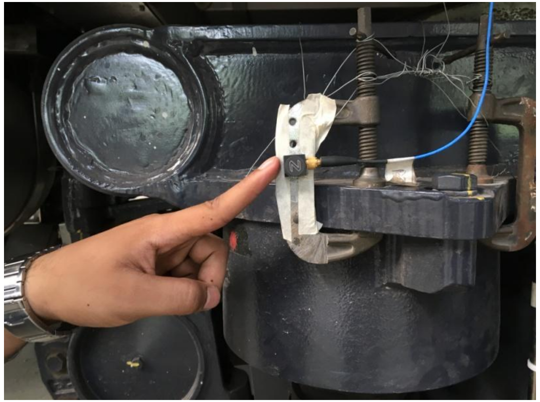
PCB PIEZOTRONICS
3425 Walden Avenue, Depew, NY 14043
Phone: 716-684-0001
Fax: 716-684-0987
E-Mail: info@pcb.com

Sensor Locations: LVDTs

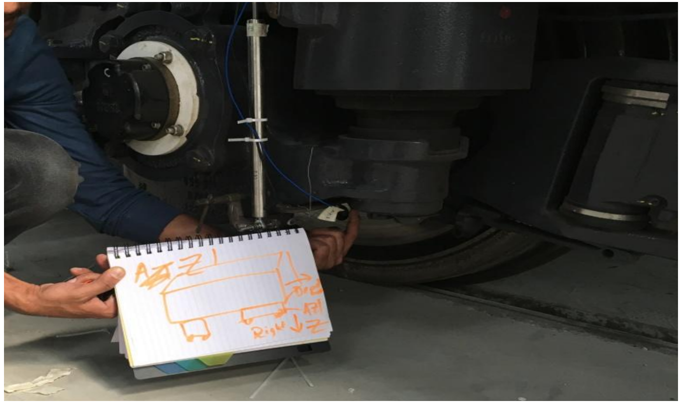


8 LVDTs were used to monitor primary spring compressions in the two bogies and 4 LVDTs were used to monitor air spring compressions

Accelerometers



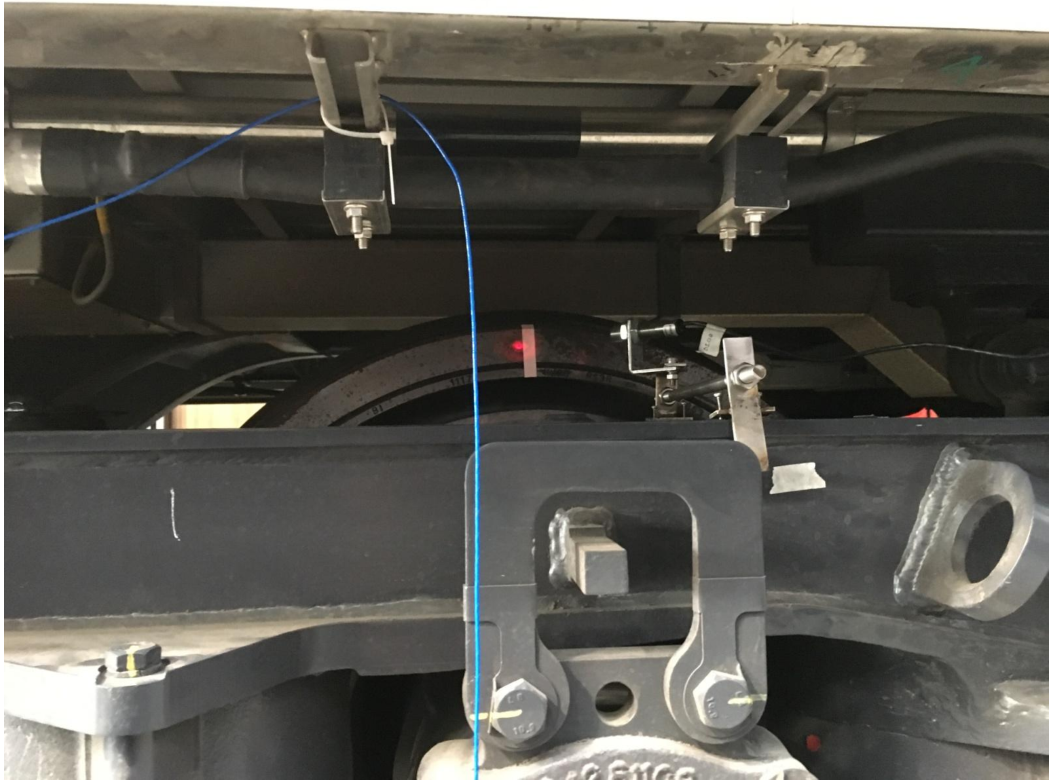
Tri-axial accelerometer on bogie frame



Uni-axial accelerometer on axle box

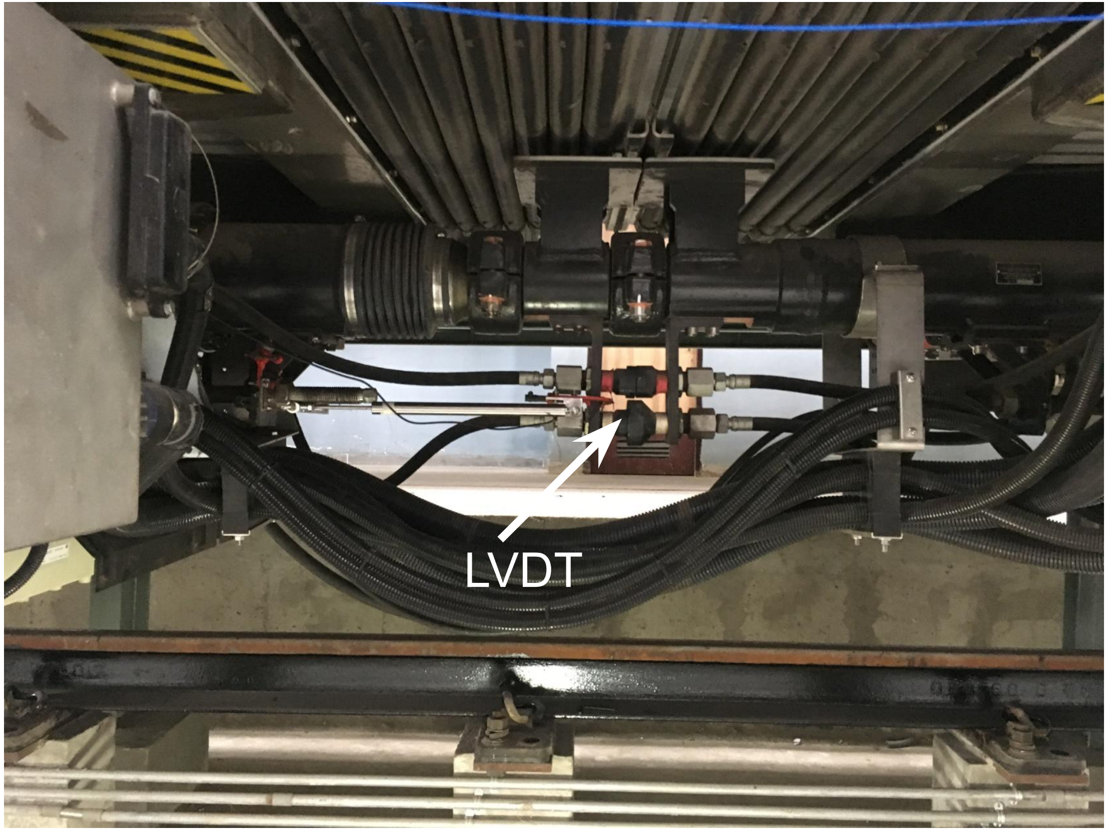
Tri-axial accelerometer on coach floor in the middle of the coach

Laser Tachometers



Laser tachometers are used for precise measurement of wheel rpm on driver motor and trailer cars

Draft Gear Compression



Forces exerted between DMC and TC are monitored through draft gear compression

How are the sensors powered?
How is the data collected?
What dictates rate of data collection, resolution of acquired data, and number of sensors that can be connected?

National Instruments Compact Rio cRIO-9035 Controller

Item details

Number of Ethernet Ports on Controller: **2**

Slot Count: **8**

Conformal Coated: **No**

FPGA: **Kintex-7 70T**

GigE Vision Support: **Yes**

Operating Temperature Range: **-20 °C to 55 °C**

Processor Core: **1.33 GHz Dual Core Intel Atom**

RAM Size: **1 GB**

Hard Drive Memory Size: **4 GB**

Programming Method: **LabVIEW FPGA**

NI 9401 Module for Analysing Signals from Laser Tachometer

Item details

Number of Bidirectional Digital Channels: **8**

Current Flow Direction: **Sinking Input, Sinking Output, Sourcing Input, Sourcing Output**

Enclosed: **Yes**

Digital I/O Logic Levels: **5 V TTL**

Digital I/O Isolation: **60 VDC Ch-Earth Ground Isolation**

Front Connection Type: **D-SUB**

Number of Digital Input Only Channels: **0**

Number of Digital Output Only Channels: **0**

Maximum Update Rate: **100 ns**

Supported Hardware Platform: **C Series**

NI 9220 Module for Analysing Signals from LVDTs

Item details

Maximum Number of Differential Analog Input Channels: **16**

Analog Input Voltage Range: **-10 V to 10 V**

Enclosed: **Yes**

Analog Input Resolution: **16 bits**

Maximum Sample Rate: **100 kS/s/ch**

Maximum Number of Single-Ended Analog Input Channels: **0**

Simultaneous Sampling: **Yes**

Supported Hardware Platform: **C Series**

NI 9232 Module for Powering and Analysing IEPE Accelerometers

Item details

Maximum Number of Differential Analog Input Channels: **3**

IEPE Excitation: **4 mA**

Analog Input Voltage Range: **-30 V to 30 V**

Enclosed: **Yes**

Maximum Sample Rate: **102.4 kS/s/ch**

Analog Input Isolation: **60 VDC Ch-Earth Ground Isolation**

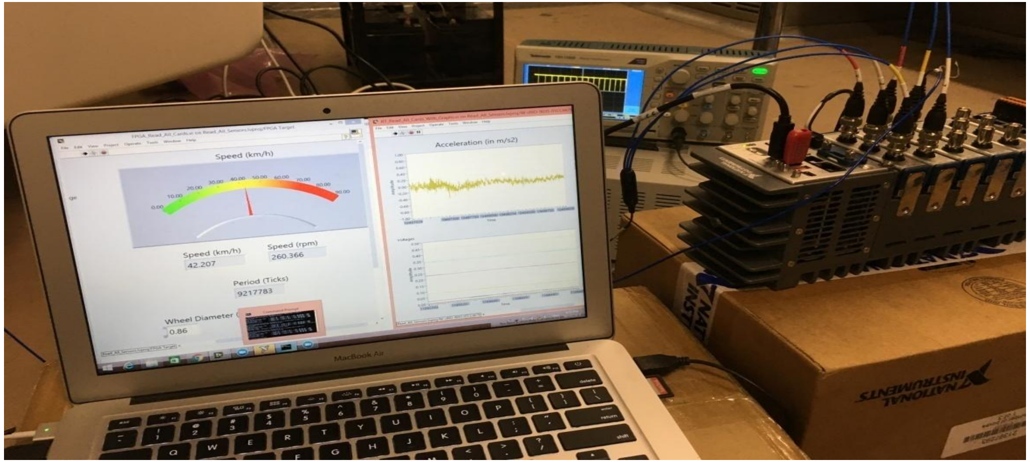
Supported Hardware Platform: **C Series**

Data Acquisition System Details

DAQ and Modules	Specifications
Compact Rio cRIO-9035	Controller, 1.33 GHz Dual Core, 8-slot, Kintex 7.70T FPGA
NI 9401	8 DIO, 5V/TTL, Bidirectional, 100 ns
NI 9220	16 Analog Inputs, +-10 V, 16 Bit, 100 kS/s/ch Simultaneous
NI 9232 (5 Units)	3 AI, +-30 V, 24 Bit, 102.5 kS/s/ch Simultaneous

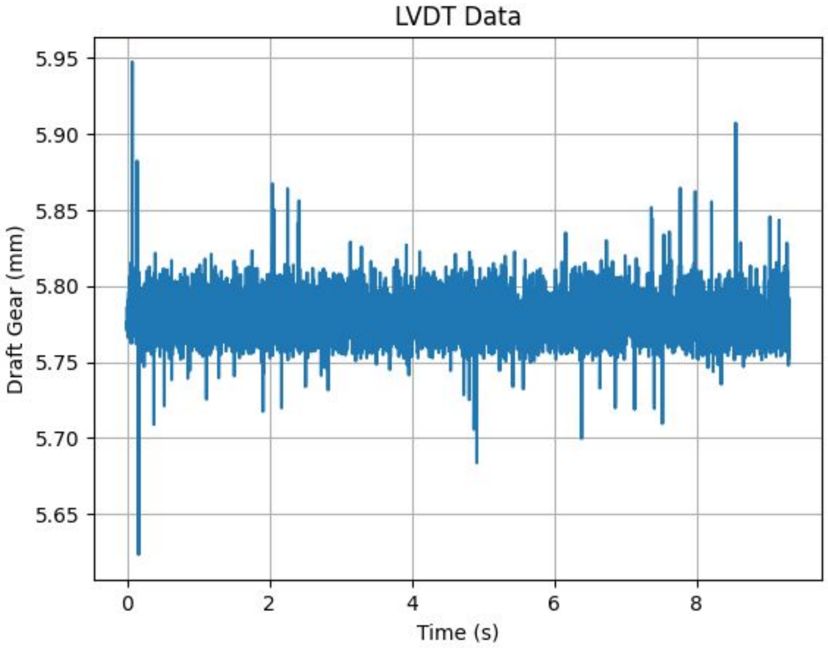
Acquisition rate used ~ 500 samples/s/channel

Maximum acquisition rate achieved ~ 80,000 samples/s/channel



Photograph of the data acquisition system and the laptop used for data acquisition in the field trials

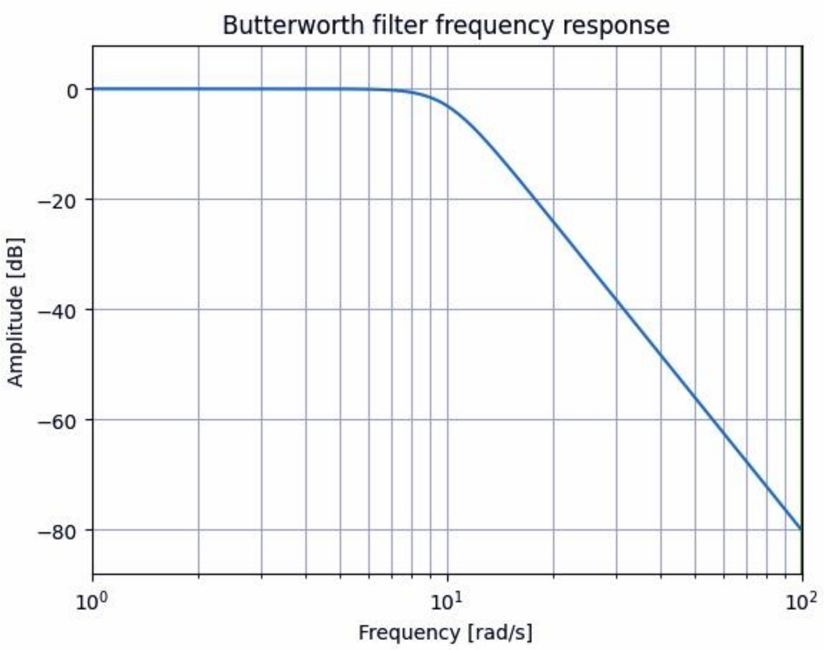
LVDT Signal for Draft Gear Compression for Train at Rest

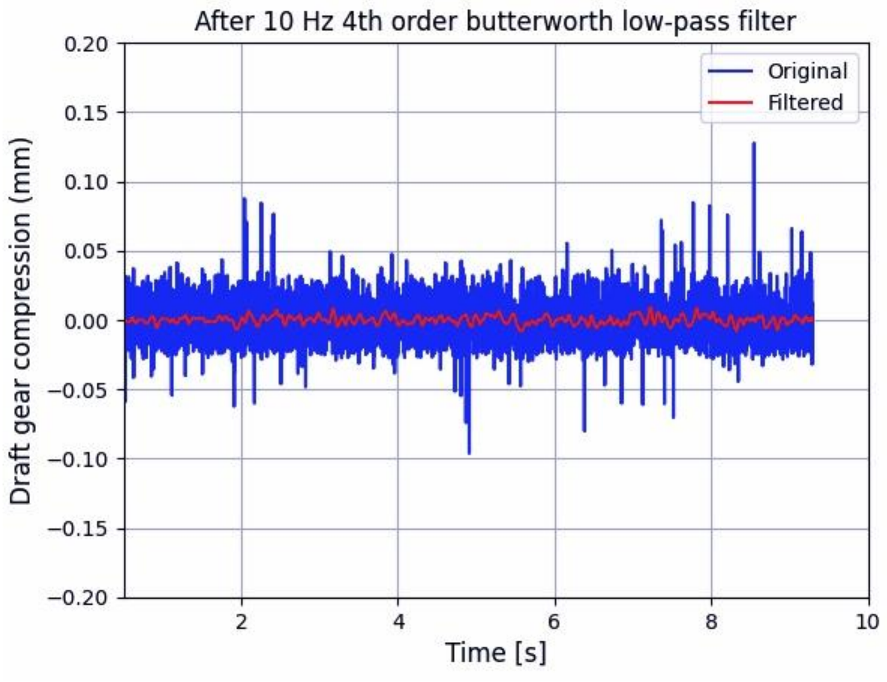


Measurement resolution:

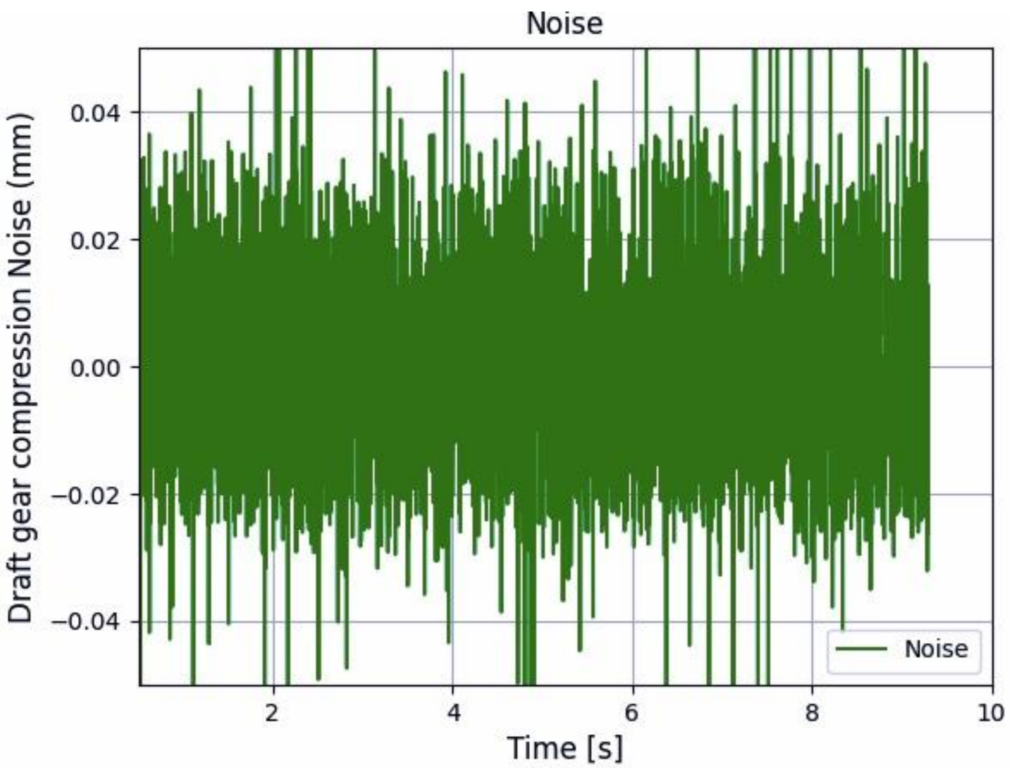
- Since 16-bit ADC was used for 50mm movement, sensitivity of measurement in this case is 0.76 microns
- Noise in signal was around 50 microns.

Original and Filtered Signal





Noise and Signal-to-Noise Ratio

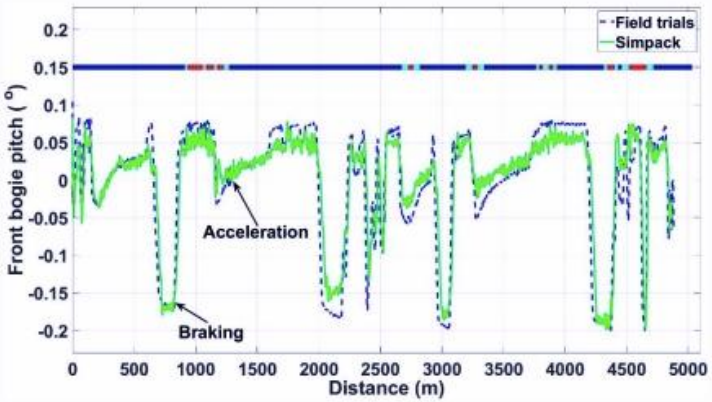


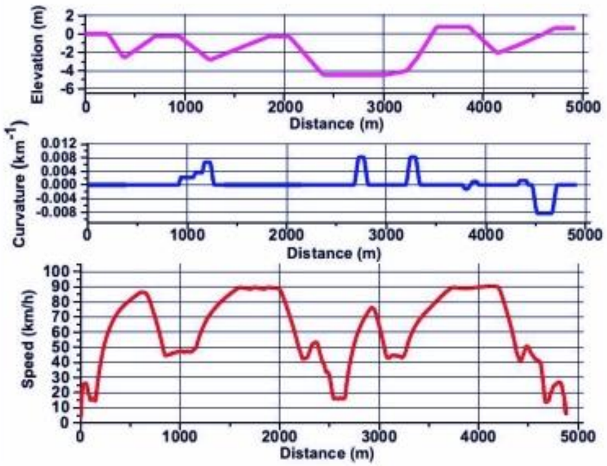
Amplitude of Noise (RMS of Noise): 16 microns

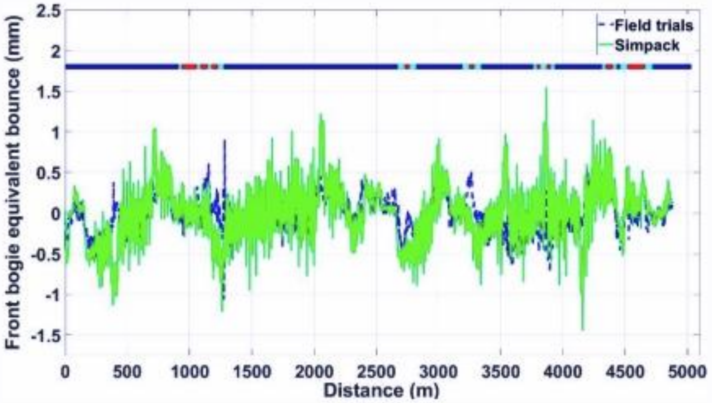
Ratio of Amplitude of Noise (ANoise) to Signal Sensitivity ~ 20

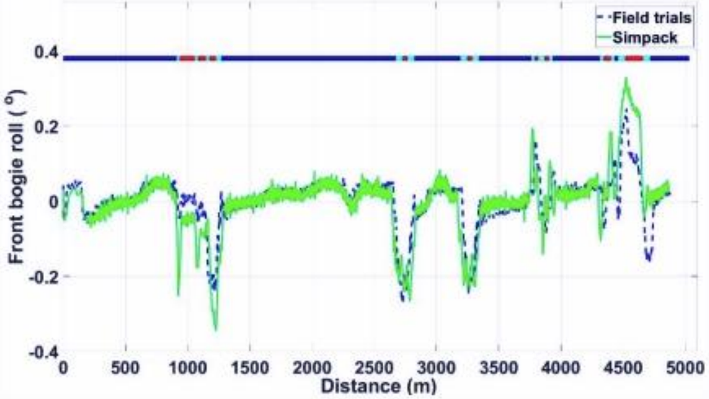
Signal to Noise Ratio ($ASignal^2/ANoise^2$) = 136061

Validation of Simpack Model: Bogie Motion

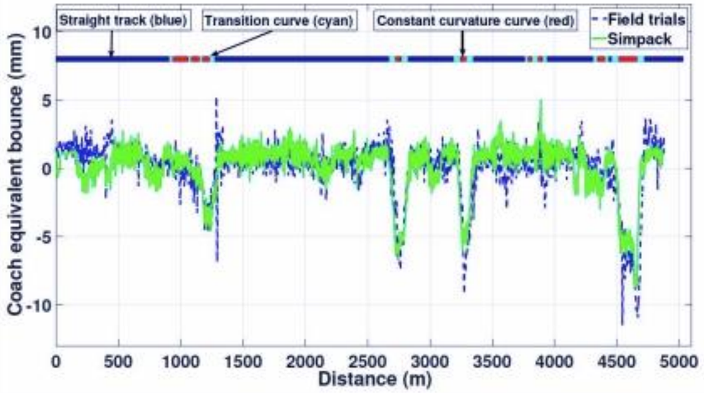






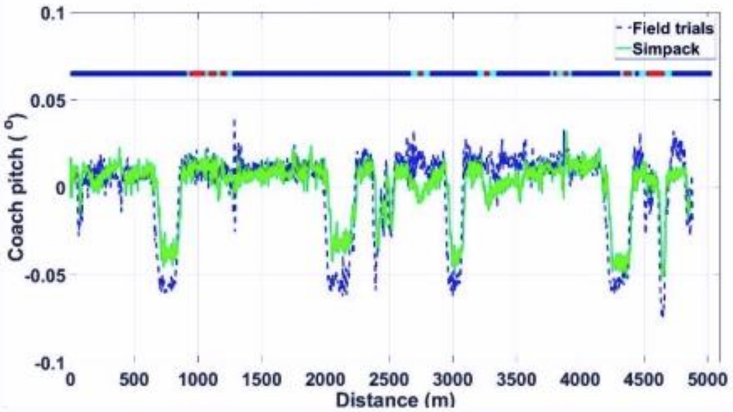


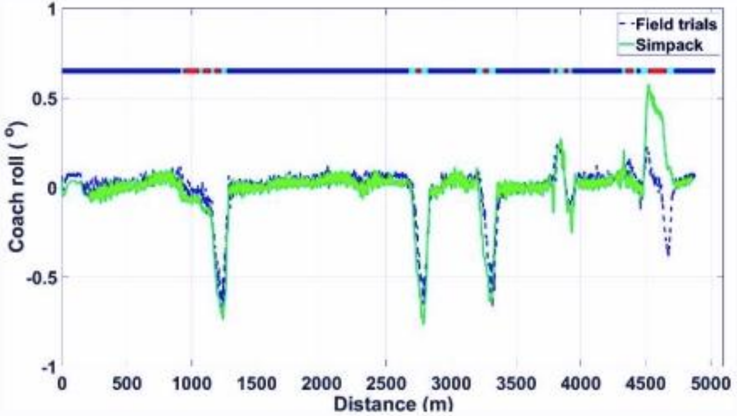
Validation of Simpack Model: Coach Motion



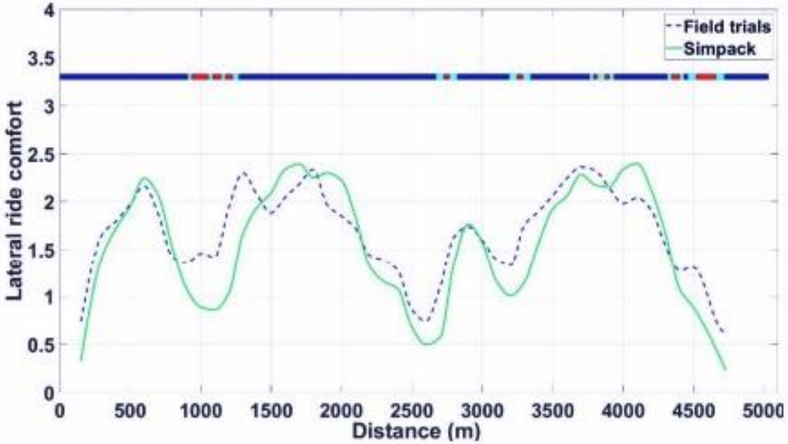
For equivalent bounce and pitch motion, following transformation is used

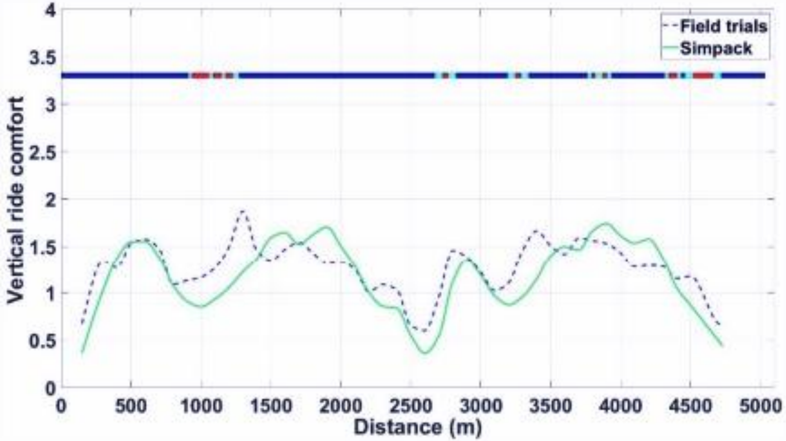
$$\begin{bmatrix} \delta_{SF} \\ \delta_{SR} \\ \delta_{BFF} \\ \delta_{BFR} \\ \delta_{BRF} \\ \delta_{BRR} \end{bmatrix} = \begin{bmatrix} -1 & -L^{CS} & 1 & L^{BS} & 0 & 0 \\ -1 & L^{CS} & 0 & 0 & 1 & -L^{BS} \\ 0 & 0 & -1 & -L^{BP} & 0 & 0 \\ 0 & 0 & -1 & L^{BP} & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & -L^{BP} \\ 0 & 0 & 0 & 0 & -1 & L^{BP} \end{bmatrix} \begin{bmatrix} w^{C} \\ \theta^{C} \\ w^{B1} \\ \theta^{B1} \\ w^{B2} \\ \theta^{B2} \end{bmatrix}$$





Validation: Vertical and lateral ride comfort





Sperling Index correlates quantitative acceleration measurements taken from the coach floor to subjective parameter of ride comfort. RDSO specifies that it be ***estimated over 200m*** blocks using a 4^{th} order band pass filter over 0.4 to 10 Hz frequency range

Sperling Index: 1 → Very good, 2 → Good, 3 → Satisfactory, 4 → Acceptable for running, 4.5 → Not acceptable for running, 5→ Dangerous

Parametric Study: Why do it?

- Identification of influential parameters
- Optimization of parameters
- Limiting values and extreme scenarios
- Design modification
- Testing of new design

Parameters Considered

- **Operating Conditions**
  - Vehicle speed
  - Friction at the rail-wheel contact
  - Axle load
- **Suspension Elements**
  - Horizontal stiffness of primary springs
  - Horizontal stiffness of air springs
  - Lateral damper damping
  - Effective area of air springs

Effect of Operating Parameters on Wear Index and Derailment Coefficient