From Reactive to Predictive: AI-Driven Optimization for ATE Performance & Reliability

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February 11, 2026

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Agenda

- **Reactive Automated (ATE) application**
  - Pre-emphasis setting optimization
- **Predictive Automated (ATE) application**
  - Improvement in ATE maintenance

Reactive: Automated Pre-Emphasis Setting

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Reactive: Automated Pre-Emphasis Setting

- **Objectives**
  - Provides a structured, automated method to select optimal pre-emphasis settings.
  - Combines simulation, measurement, and software-guided testing.
  - Supports a wide range of probe card and load board configurations.
  - Ensures robust performance across varying operating conditions.
- **Background**
  - High-speed digital signals suffer from signal loss, skin effect, and dielectric losses, causing inter-symbol interference (ISI).
  - Pre-emphasis compensates ISI by applying delayed and inverted signal components with proper weighting.
  - Finding the optimal Transmitter (Tx) settings usually requires time-consuming trial-and-error sweeps for every new operating condition.

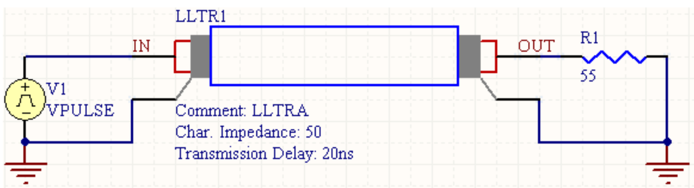
Pre-Emphasis Setting Challenges

Too Many Settings

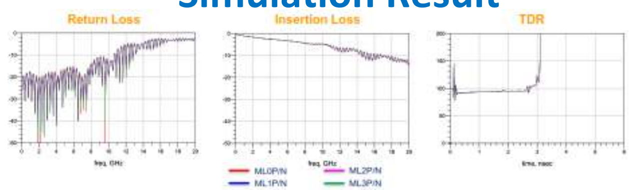
- There are 3 knobs for pre-emphasis setting
  - Pre-1
  - Post-1
  - Post-2
- Each knobs has 32 settings
  - A combination of 32K settings with 3 knobs
  - To determine the optimum setting will be time consuming and challenging without oscilloscope
- Pre-emphasis use model concept
  - Automate the pre-emphasis setting through engineering characterization
  - API with selection of most optimum pre-emphasis setting based on software-based optimization

Hardware Characterization

Signal Integrity Simulation



Simulation Result



Channel	Frequency Bandwidth(GHz)	
	S_{dd11}@-10dB	S_{dd21}@-3dB
ML0P/N	10.66	4.85
ML1P/N	10.66	5.12
ML2P/N	10.66	5.12
ML3P/N	10.66	5.12

Channel	Spec TDR	TDR(ns)
ML0P/N	<1.8ns	1.45
ML1P/N		1.45
ML2P/N		1.45
ML3P/N		1.45

Scope-Based Validation

- To reduce the number of settings
- Create Final Setting Table

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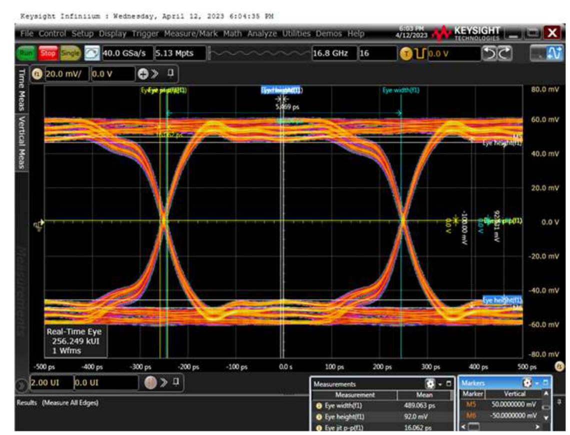
Preliminary Setting Table

GHz	Target Swing mV	Programed swing mV	pre 1 dec	post 1 dec	post 2 dec
2	500	700	4	-12	0
2.5	500	780	4	-16	0
3	500	900	4	-20	-2
4	500	700	4	-12	0
5	500	780	4	-16	0
6	500	900	4	-20	-2
7	500	700	4	-12	0
8	500	700	4	-12	0
10	500	780	4	-16	0
12.8	500	900	4	-20	-2
2	100	140	1	-2	0
2.5	100	156	1	-3	0
3	100	180	1	-4	0
4	100	140	1	-2	0
5	100	156	1	-3	0
6	100	180	1	-4	0
7	100	140	1	-2	0
8	100	140	1	-2	0
10	100	156	1	-3	0
12.8	100	180	1	-4	0
2	50	70	0	-1	0
2.5	50	78	0	-2	0
3	50	90	0	-2	0
4	50	70	0	-1	0
5	50	78	0	-2	0
6	50	90	0	-2	0
7	50	70	0	-1	0
8	50	70	0	-1	0
10	50	78	0	-2	0
12.8	50	90	0	-2	0

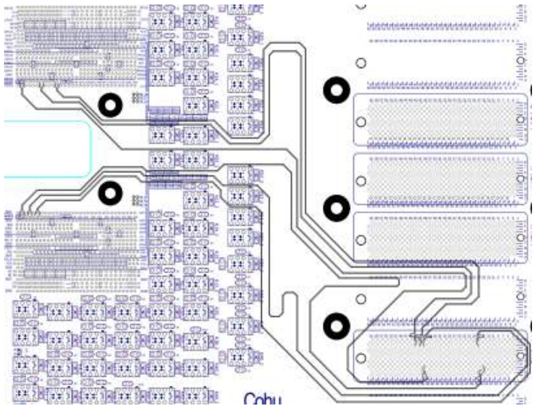
Scope-Based Validation



Software-Based Optimization

- On the user load board, select an unused TX (transmit) lane that is routed similarly to other high-speed lanes. This ensures it accurately reflects the overall high-speed channel characteristics.
- Create a loopback connection by routing the selected unused TX lane into an RX (receive) channel
- Refer to the hardware characterization's pre-emphasis setting table and use those values to perform tests and capture eye diagrams
- The pre-emphasis settings used in the loopback test will be selected based on user-defined parameters.
- Multiple pre-emphasis settings will be tested in sequence.
- System to select most optimum settings based on eye-height and eye-width

PCB Trace Routing



Instrument RX Channel Eye Opening

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The Methodology

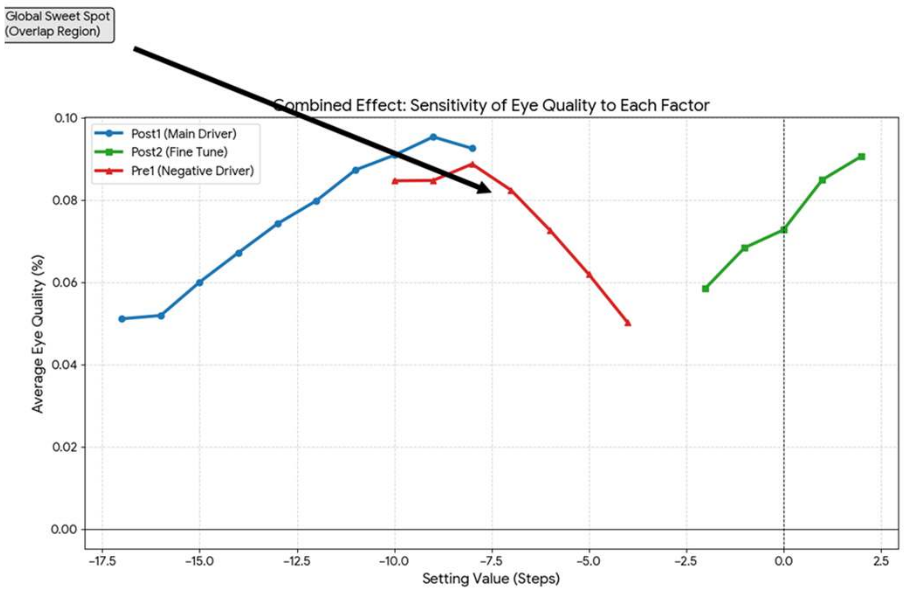
The base: Real world data collection

The Scaling Rules

- **Half Rate Rule:** If speed drops by 50% (6.25G), loss drops by ~50%. Steps scale by 0.5.
- **Voltage Ratio Rule:** If swing drops by 50% (200mV), the required cancellation voltage drops by 50%. Steps scale by 0.5.

Parameters & Relationships based on real world data

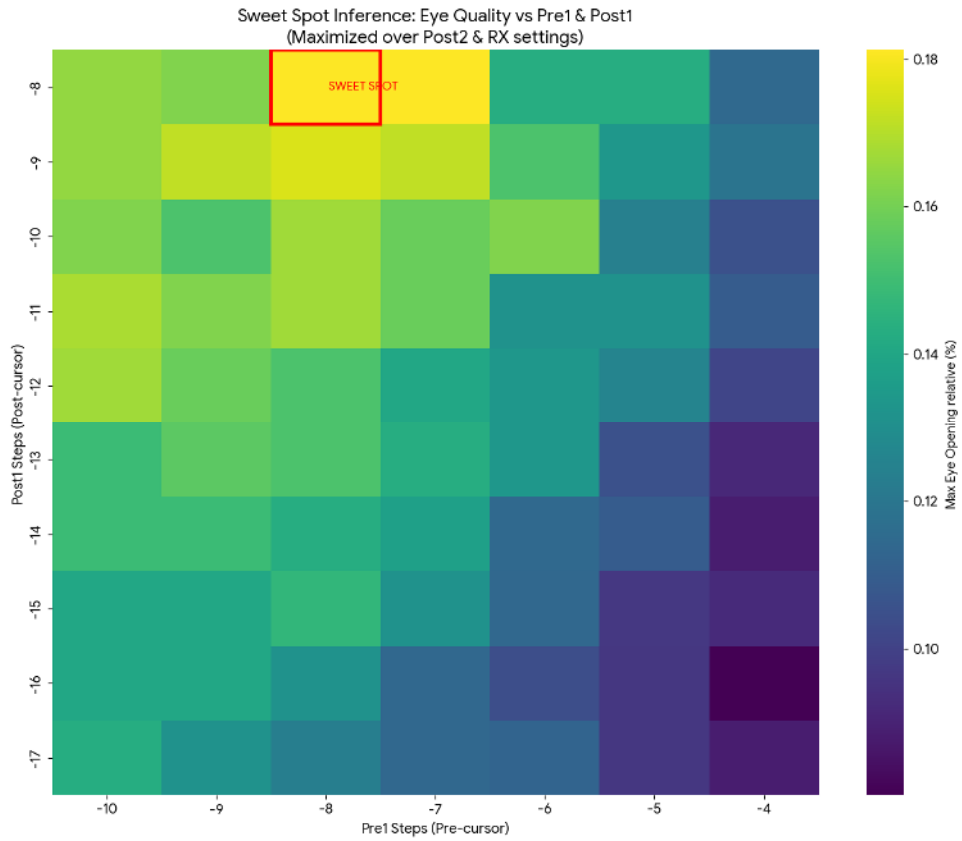
- Pre-setting
  - Optimum setting peaks around 4 to 8 steps
- Post1-setting
  - Strongest driver of performance range from 8 to 17 steps
- Post 2-setting
  - Fine tune control optimal range is from 0 to 2 steps



Note: Specific to 12.5G/400 mV on a given reference board.

The "Sweet Spot" Chart

- The map visualizes the Maximum Eye Quality achievable for every combination of Pre1 and Post 1.
- By collapsing the other dimensions (Post2, RX settings), we can clearly see the "mountain peak" of signal integrity
  - Yellow/Green areas: High Eye Quality (the optimal zone)
  - Purple/Blue areas: Poor Eye Quality (the signal is closed)
  - Red Box: The absolute peak (global sweet spot)
- **Estimated Sweet Spot Analysis**
  - Based on the chart and data inference:
  - The "Peak" Location (Optimum)
    - Pre1 (pre-cursor): -8
    - Post 1 (post-cursor): -8
    - Post2 (fine tune): +2



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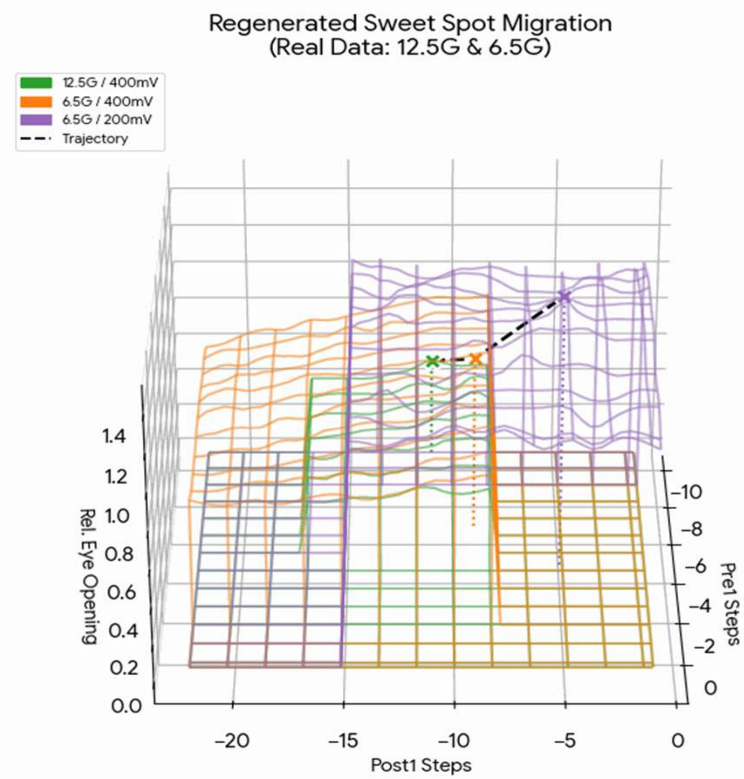
Signal Integrity Landscape

- Based on the data points we have analyzed and the physical scale rules. The optimal emphasis setting (for both Pre1 and Post1) is directly proportional to the product of the Data Rate and Voltage Swing

- The Wire mesh represents the "Eye Quality" for a specific condition (Data rate from 6.5 Gbps to 12.5 Gbps)

- The "Black Dash Line" represents the path of the "Sweet Spot"

Visualization of 5 Conditions



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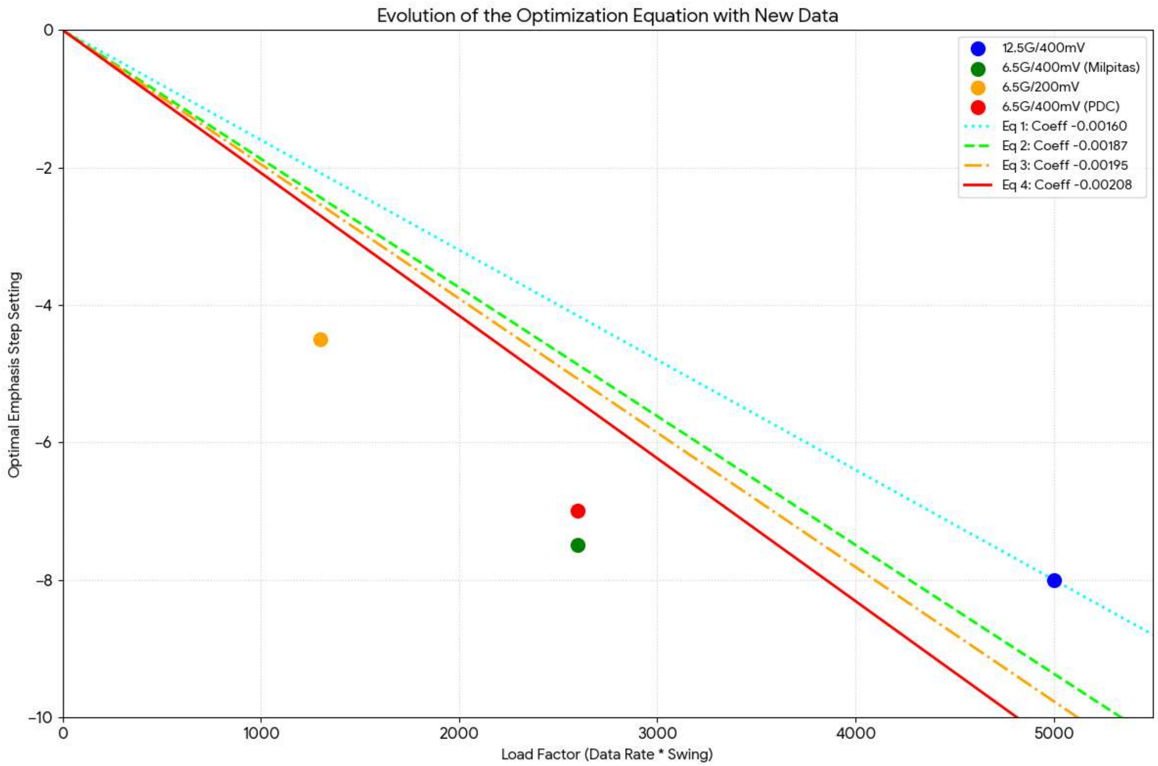
Figuring Out the Formula

Equation Scenario	Data Included	Coefficient (k)	Change
Eq 1 (Baseline)	12.5G/400mV	**-0.00160**	-
Eq 2 (+ 6.5G Old)	... + 6.5G/400 (Milpitas)	**-0.00187**	+17% Aggressive
Eq 3 (+ 6.5G Low)	... + 6.5G/200	**-0.00195**	+4% Aggressive
Eq 4 (+ PDC New)	... + 6.5G/400 (PDC)	**-0.00208**	+6% Aggressive

The data that generated the coefficient is accumulative

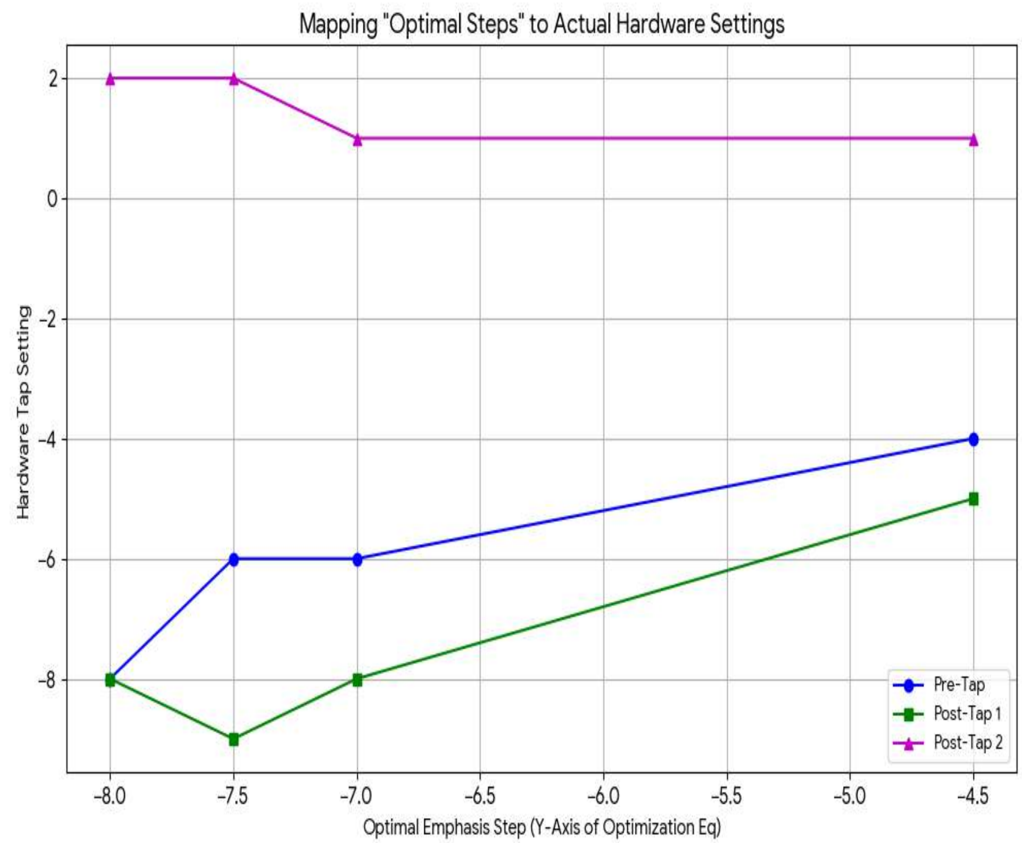
For instance:

Coefficient -0.0016 is calculated using dataset1.
Coefficient -0.00187 is using dataset1 + dataset2



Pre-Emphasis Setting Formula

X-Axis	Value from the equation (e.g., -8.0)
Y-Axis	The specific setting for each tap
	Key Relationships
Post-Tap 1 (Green)	Tracks the "Optimal Step" almost 1:1. If the equation says -8, set Post1 to -8.
Pre-Tap (Blue)	Tracks closely but is slightly weaker. If the equation says -8, set Pre to -6 to -8.
Post-Tap2 (Purple)	Stays in the **+1 to +2** range.
	Rule of Thumb Setting
Calculate Target	$T = -0.0021 \times Rate \times Swing$
Set Post1	$\approx T$ (The main driver).
Set Pre	$\approx 0.8 \times T$ (Slightly less than Post1).
Set Post2	Fixed at +1 or +2 (less impact)



Initial Results (based on actual data collected)

TX Ch	TX pair	alt TX name	Data Rate, Gbps	UI, ps	native UI. ps	Requested Swing, mV	Pre1 Emphasis steps	Post1 Emphasis steps	Post2 Emphasis steps	RX Gain setting	RX Equalization setting	EyeWidth, ps	EyeHeight, mV	Eye Opening relative (%)
7	TX_7/8	TX4_P/N	6.5	153.8	153.8	400	-4	5	0	4	15	122.553	410	81.7%
7	TX_7/8	TX4_P/N	6.5	153.8	153.8	400	-4	5	-1	4	15	120.15	410	80.0%
7	TX_7/8	TX4_P/N	6.5	153.8	153.8	400	-4	5	1	4	15	120.15	400	78.1%
7	TX_7/8	TX4_P/N	6.5	153.8	153.8	400	-4	5	-2	4	15	122.553	390	77.7%
7	TX_7/8	TX4_P/N	6.5	153.8	153.8	400	-4	5	2	4	15	115.344	390	73.1%
7	TX_7/8	TX4_P/N	6.5	153.8	153.8	400	-4	5	-3	4	15	120.15	370	72.2%

Data was manually collected using multiple pre-emphasis settings, data rates, and voltage swings

Data Rate, Gbps	UI, ps	Requested Swing, mV	Suggested Pre1 Emphasis steps	Suggested Post1 Emphasis steps	Suggested Post2 Emphasis steps	EyeWidth, ps	EyeHeight, mV	Eye Opening relative (%)
6.5	153.8462	200	-2	2	1	112.7	200	73%
6.5	153.8462	400	-4	5	1	117.4	400	76%
6.5	153.8462	500	-5	6	1	117.4	490	75%

Pre-emphasis settings were recommended by an AI model using the collected data. Validation results indicate strong correlation between the AI-suggested and manually determined settings.

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Predictive: Improving Cpk Value

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Predictive: Process Stability Monitoring

Use Case

- High-speed digital instrument: Low Cpk in voltage swing test

Potential Impact

- Difficulties in manufacturing
- Out of box quality
- Tester-to-tester or site-to-site variation
- Insufficient design margin
- Parameter sensitivity
- Corner condition not fully covered

Reason for Low Cpk (<2.0)

Process Mean is Shifted Toward Upper Limit

- The mean is closer to the upper specification limit than to the center of the specification range
- This asymmetry causes the upper capability to be the limiting factor

High Process Variation (Sigma)

- The standard deviation is relatively large compared to the specification window
- The 3-sigma spread consumes ~30% of the total specification range

Test Condition Sensitivity

- This is the lowest swing volt age test point (example of test point) in the swing verification test
- Looking at the source code (specific test source code) at low swing values:
  - The signal-to-noise ratio is lower
  - Hardware calibration effects are more pronounced (see line xxxx & yyyy for more detail)
  - The measurement is more sensitive to offset errors

Calibration Margin

- The test uses percentLimRange (50%) and offsetLimRange for limit calculations
- At the lowest test point, these margins have proportionally greater impact

Key Message:

AI Helps Identify Root Cause by Exploring Multiple Possible Paths

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Recommendations to Improve Cpk

Center the Process Mean

- Adjust calibration offset to shift the mean closer to center of spec
- This would balance CPU and CPL, improving overall Cpk

Reduce Process Variation

- Investigate sources of variation in the swing measurement at low voltage
- Consider increasing average count or this test point
- Review hardware calibration data for outlier channels

Review Specification Limits

- The current limits are overly conservative for test point, consider widening them based on actual hardware capability

Hardware Investigation

- Potential hardware-related issues at low swing values that may need addressing

Key Message:

AI Delivers Data-Driven Recommendations to Improve Cpk

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Thank you

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