Geometric Criterion of Flange Climb Derailment and IWS-based Implementation

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Background:

- Derailment prevention is always critical for railway safety
- A recent derailment at TTC shows that the current Lateral/Vertical load (L/V) ratio-based criteria may not be adequate to assess the risk of derailment in all circumstances
- Evaluation of derailment risk is still a challenge

Flange climb derailment at TTC in summer 2020

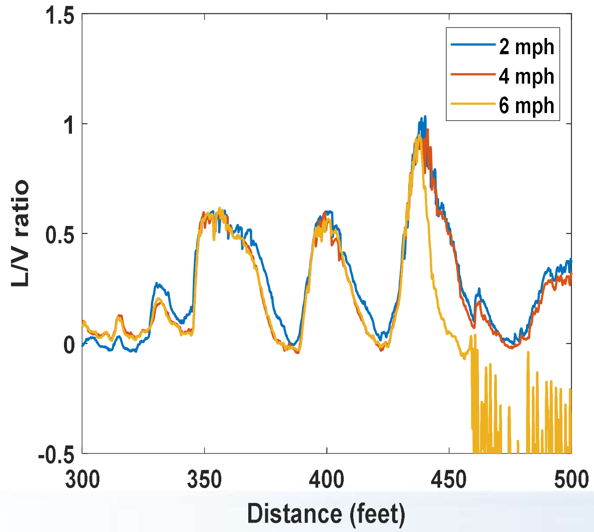
- The derailment occurred in a sharp curve
- The test vehicle passed through the curve at 2 mph and 4 mph without derailing, then derailed when passing through the same curve at 6 mph
- The measured friction coefficient is about 0.55

Methods to ensure safety

- Standards
  - AAR criteria: individual wheel L/V(1.0); time(50ms) and distance(3 ft) duration; nominal friction coefficient is 0.5
- Data comparison of subsequent runs when measured value is close to limit
  - Can eliminate the effect of some influence factors, like friction
  - More reliable, if key metric (L/V ratio time & distance duration) correctly represent risk

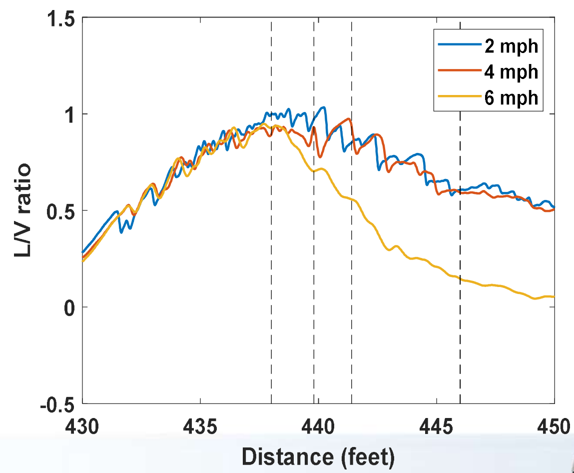
L/V Ratio criterion did not evaluate risk of derailment effectively

- Met standard and no obvious difference between L/V ratio of 2 mph and 4 mph run
  - Insensitive to real derailment risk



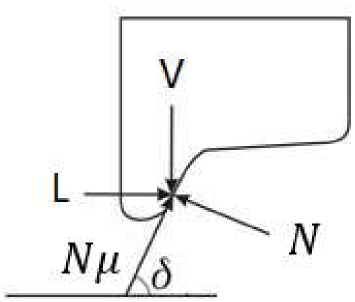
Data comparison does not effectively identify risk of derailment

- For the 4 and 6 mph runs, the L/V ratio time or distance-based parameter decreased
  - The test run that derailed at 6 mph trended in the opposite direction than expected based on data comparison, key metric does not represent risk correctly



Deep Analysis of L/V Ratio-based Criteria

- The classical Nadal criterion is generally considered conservative for safety



$$\frac{L}{V} = \frac{tan(\delta) - \mu}{1 + \mu \times \tan(\delta)}$$

$$\frac{L}{V} <= \frac{tan(\delta_{max}) - \mu_n}{1 + \mu_n \times \tan(\delta_{max})}$$

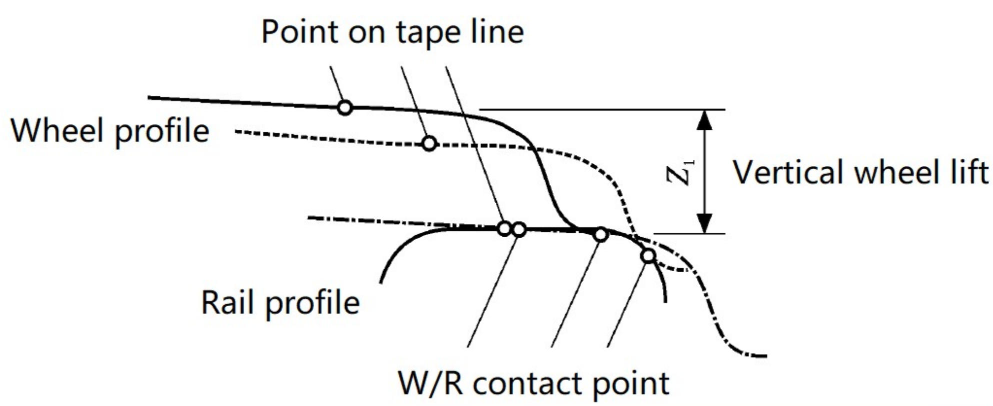
μ_n is the nominal friction coefficient

In practice

- Restrict the friction coefficient used in the Nadal criterion explicitly or implicitly
  - Adopt a nominal friction coefficient $\mu_n = 0.5$ to replace 0.6 (possible value in some scenarios) in safety standards
- The placement of the additional restriction of time or distance duration because flange climb derailment process is not instantaneous
  - It is impossible to find a limit to suit all situations

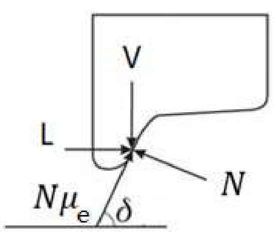
Concept to interpret derailment

- Vertical wheel lift-based geometric criterion
  - Distance between tape line and rail top, currently cannot be measured
  - Concept used in simulation and analysis of L/V ratio-based criterion



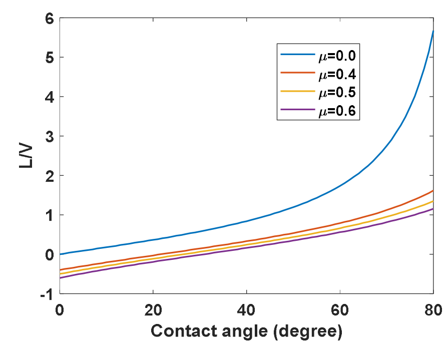
Facts behind measured L/V ratio

- Measured L/V ratio is function of contact angle and the equivalent friction coefficient (μ_e), can represent the contact angle if μ_e is known



$$\frac{L}{V} = \frac{(Normal\ Force) \times sin(\delta) - (Friction\ Force) \times \cos(\delta)}{(Normal\ Force) \times cos(\delta) + (Friction\ Force) \times \sin(\delta)}$$

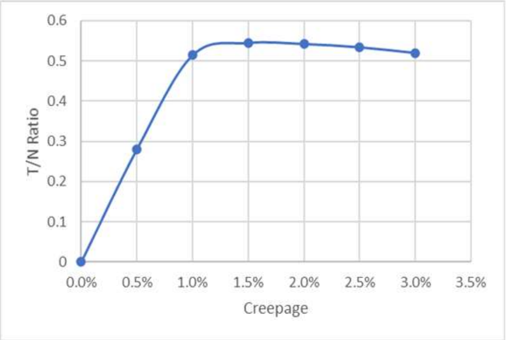
$$= \frac{N \times sin(\delta) - N \times \mu_e \times cos(\delta)}{N \times cos(\delta) + N \times \mu_e \times \sin(\delta)} = \frac{tan(\delta) - \mu_e}{1 + \mu_e \times \tan(\delta)}$$



N μ_e = W/R creep force on the Y-Z plane = Friction force in real time

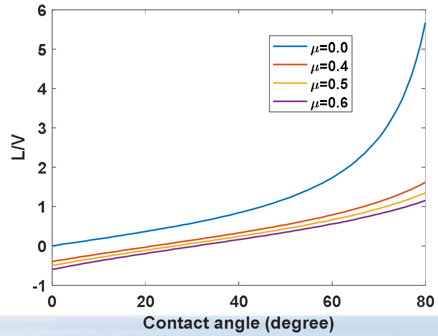
Facts behind measured L/V ratio cont.

- μ_e is affected by lots of factors (e.g., creepage) with the basic restriction $-\mu_a \leq \mu_e \leq \mu_a$, μ_a is actual sliding friction coefficient
  - It is the reason why measured L/V maybe larger than Nadal limit without apparent danger
  - μ_a is essential for using the L/V ratio criteria to ensure the safety but affected by surface status of wheel and rail, cannot be measured in real time



$$\frac{L}{V} = \frac{tan(\delta) - \mu_e}{1 + \mu_e \times \tan(\delta)} \geq \frac{tan(\delta) - \mu_a}{1 + \mu_a \times \tan(\delta)}$$

$$(\mu \geq 0 \; and \; 0 < \delta < \frac{\pi}{2})$$



Facts behind measured L/V ratio cont..

- Nominal friction coefficient (μ_n) is a constant to represent μ_a in standard, simplify the implementation and balance the efficiency & risk

Conservativeness and risk of L/V ratio-based criteria

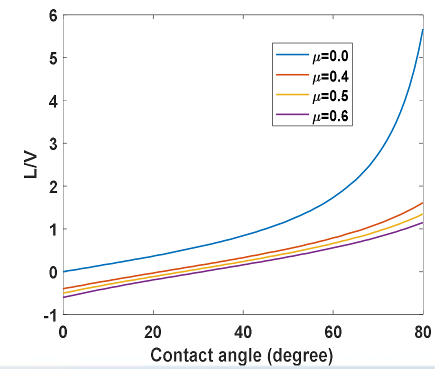
- The uncertain relationship between nominal friction coefficient (μ_n) and equivalent friction coefficient (μ_e) will cause both the conservativeness and risk of using L/V ratio-based criteria
  - $\mu_n = 0.5 < \mu_a\ (about\ 0.55)$ is the reason that current criteria did not identify the risk of derailment

$$\frac{L}{V} = \frac{tan(\delta) - \mu_e}{1 + \mu_e \times \tan(\delta)} \geq \frac{tan(\delta) - \mu_a}{1 + \mu_a \times \tan(\delta)}$$

Always correct

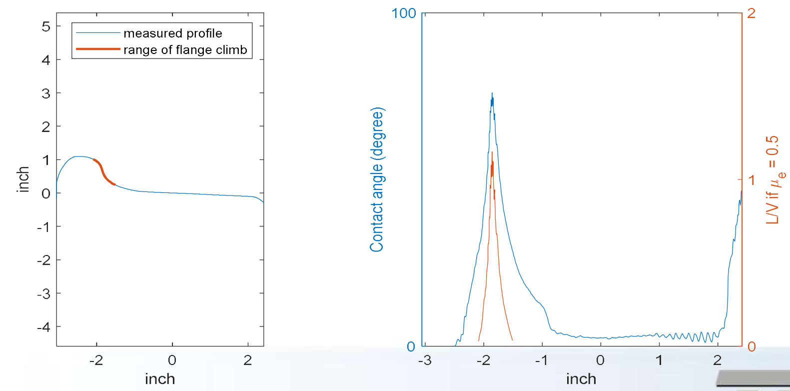
$$\frac{L}{V} = \frac{tan(\delta) - \mu_e}{1 + \mu_e \times \tan(\delta)} \geq \frac{tan(\delta) - \mu_n}{1 + \mu_n \times \tan(\delta)}$$

Maybe wrong



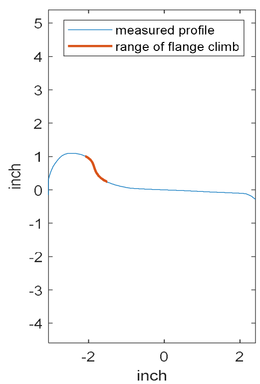
L/V ratio-based criteria lacks characteristics related to flange climb risk

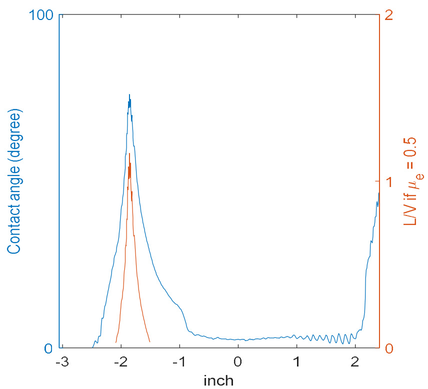
- L/V ratio-based criteria evaluate derailment risk through assessing contact angle
- But the contact angle is not a monotonically increasing function when the flange climbs

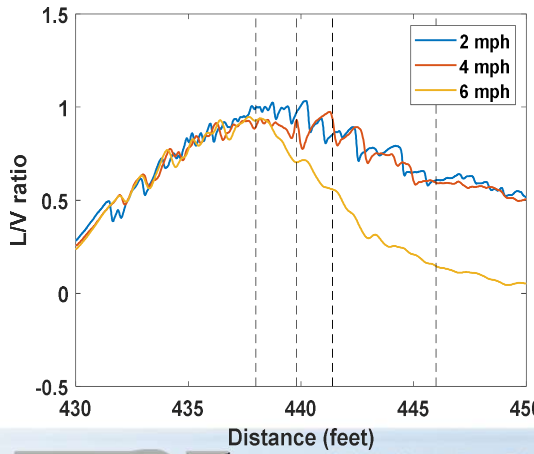


Significant consideration for L/V ratio-based criteria

- When the max contact angle of the wheel has been reached, the L/V ratio will decrease if the wheel either climbs toward the flange tip (more dangerous) or slips down to the wheel tread (safer)
  - The information is critical for real safety assessment







Significant consideration for L/V ratio-based criteria cont.

- L/V Ratio-based criteria are not always positively correlated with the risk of derailment
  - The traditional concept that the longer the duration of L/V ratio exceedance, the higher the probability of having a flange climb derailment is not always correct
  - "L/V ratio and relevant duration is not a monotonically increasing with derailment risk" is the reason that the comparison method did not identify the risk of derailment

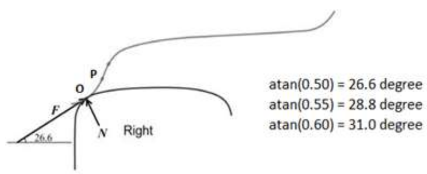
A new and implementable derailment criterion is needed which is independent of friction coefficient and can represent real risk effectively

W/R Contact Position-based Geometric Criterion

- Directly compare the W/R contact position with the wheel profile
- The geometric criterion identifies when the wheel has climbed past the position of the maximum contact angle making the contact angle less than a specified angle
  - Once the wheel has climbed past this point, derailment could be imminent
  - The specified angle should be larger than $\mathrm{atan}(\mu_n)$, and can be defined according to the conditions and requirements of the railway system

Inspiration

- The idea was proposed by TTCI's VTI expert to develop L/V distance-based criterion 20 years ago
- Limited by the technology at the time, the assessment has never been fully realized



Idea

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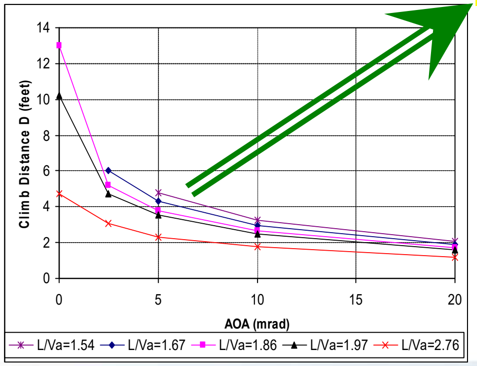
NUCARS



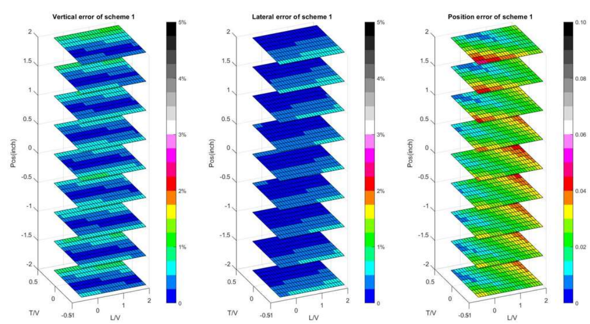
$$D < \frac{1}{0.001411*AOA+(0.0118*AOA+0.1155)*L/V-0.0671}$$

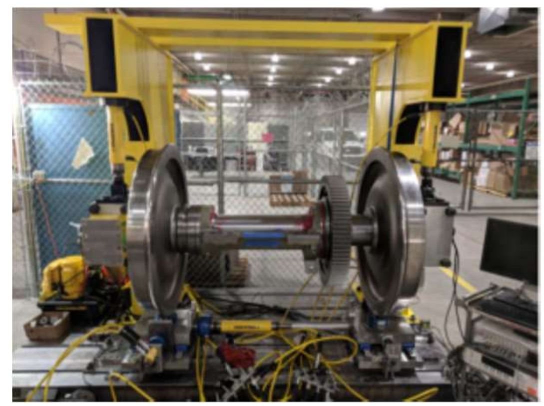
IWS for W/R contact position measurement

- The derailed vehicle mentioned above was equipped with TTCI's latest high accuracy IWS that output individual W/R force and lateral contact position
  - Made it possible to investigate whether the geometric criterion would identify the risk of derailment to TTCI's test team

History and new progress

- Under development more than 30 years
- Refined the framework in resent years, highly accurate even in extreme situations such as wheel-lift, derailment



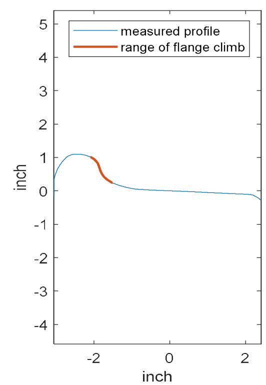


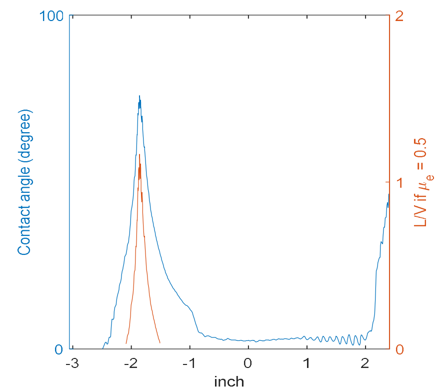
New direction of derailment investigation

- Focused on the output of the W/R lateral contact position after it was determined that the L/V ratio-based criteria were not as effective at showing the risk of derailment

$$\frac{L}{V} = \frac{tan(\delta) - \mu_e}{1 + \mu_e \times \tan(\delta)} \geq \frac{tan(\delta) - \mu_n}{1 + \mu_n \times \tan(\delta)}$$

Maybe wrong

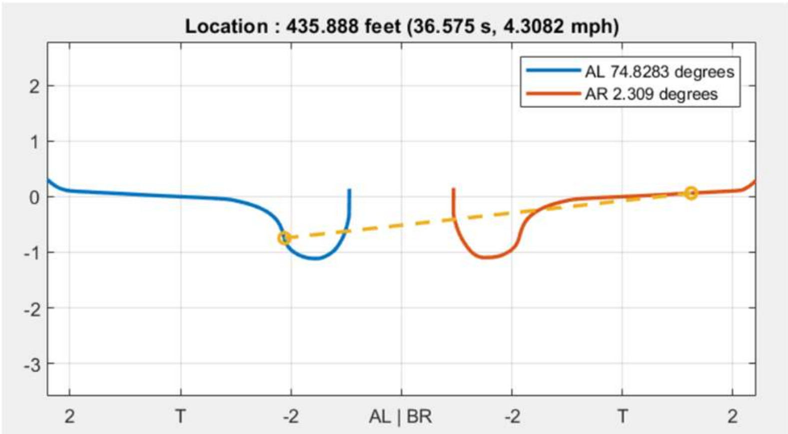




not always positively correlated with the risk

New output based on the needs

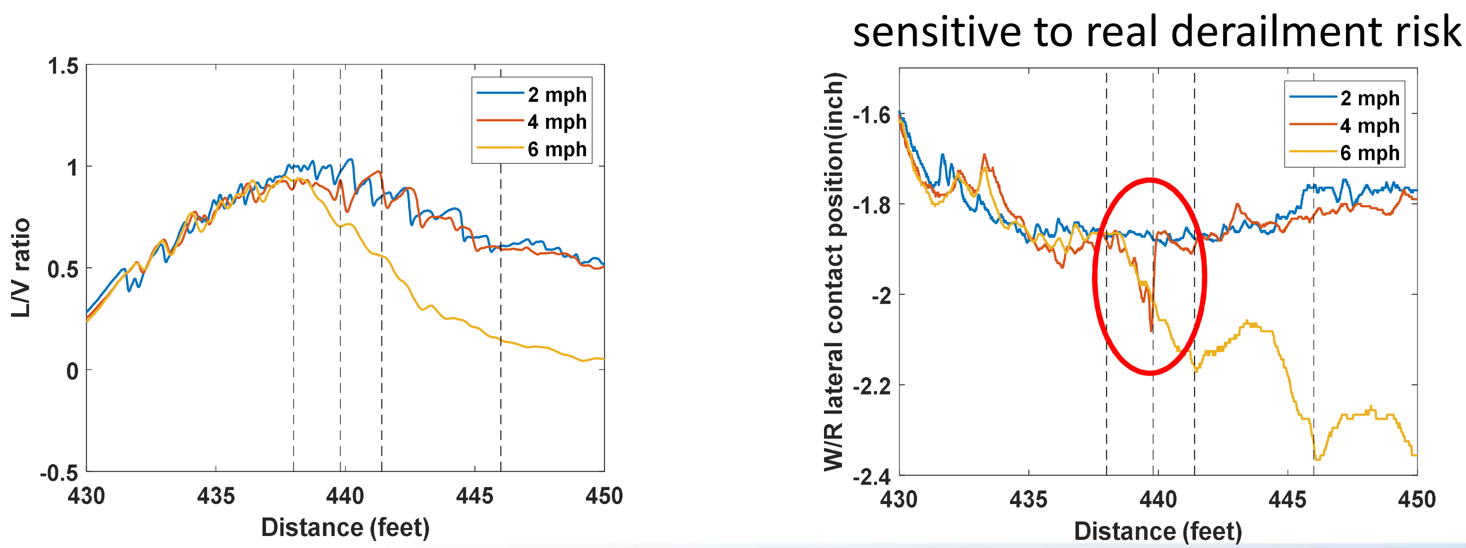
- Updated IWS processor to output the W/R vertical contact position and contact angle by adding in the wheel profile information of the IWS



How is W/R contact position-based geometric criterion more advanced in assessing the risk of flange climb derailment?

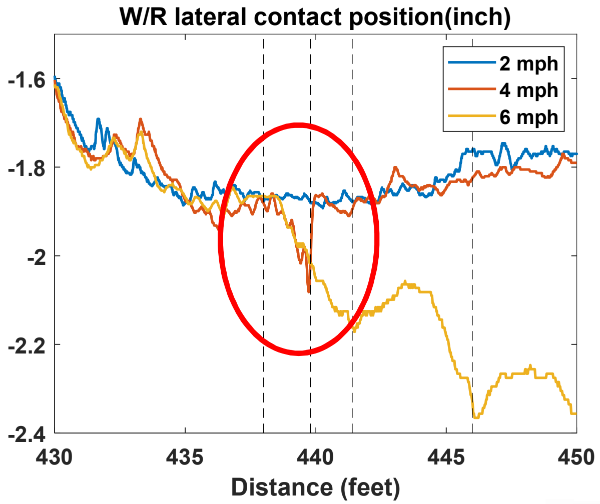
Strength of W/R Contact Position-based Criterion

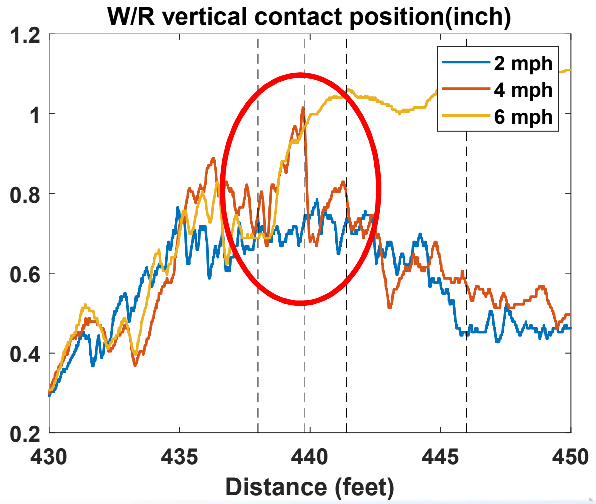
- Comparison between L/V ratio and lateral contact position
  - The trends are quite a bit different

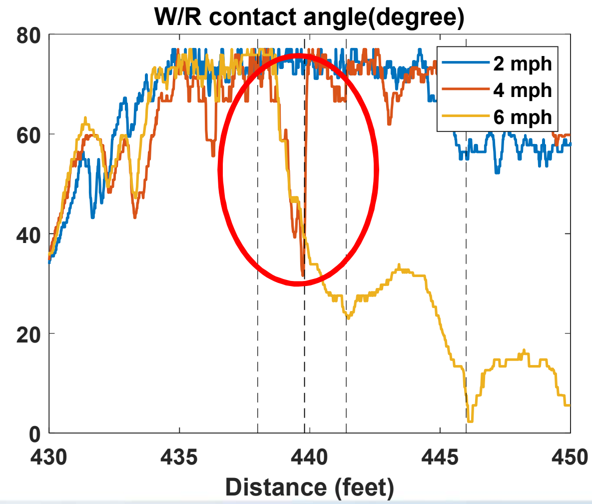


Results of new contact position-based evaluation

- Assess risk of derailment correctly even when the coefficient of friction is unknown

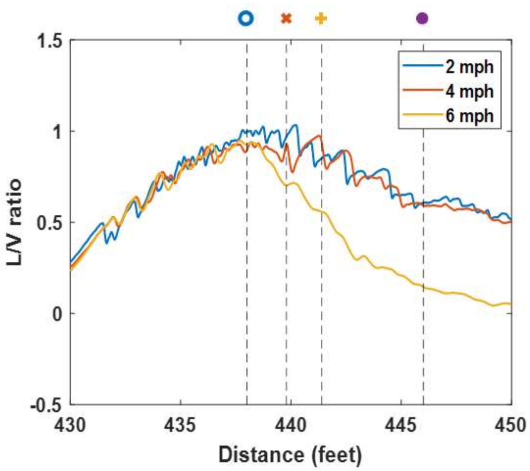


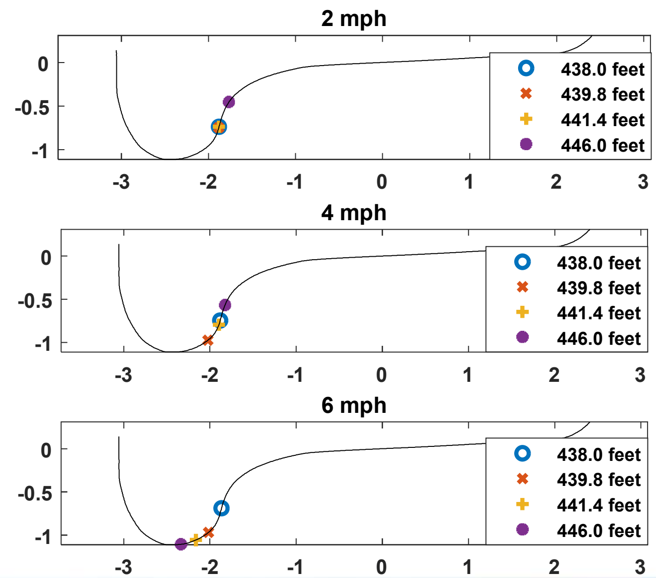




W/R contact position

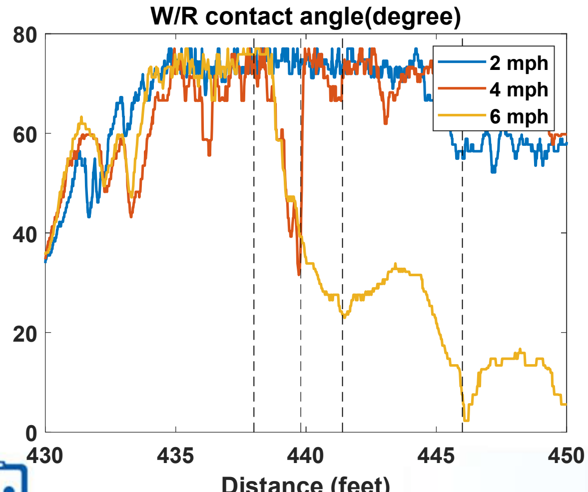
- Describe the whole derailment process clearly and assess risk of derailment correctly

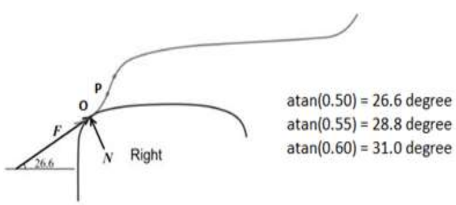


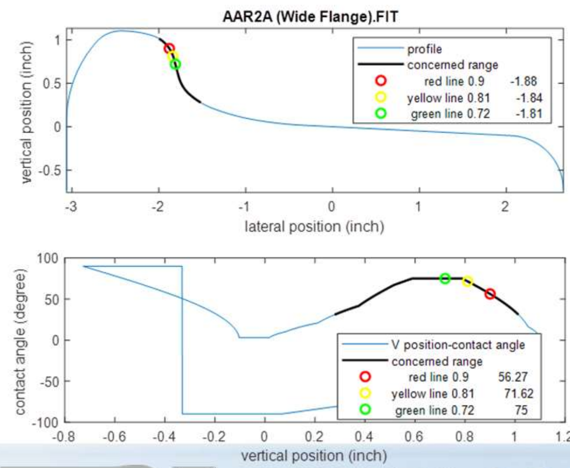


Derailment prevention

- For the 4-mph run, the contact angle was 32 degrees after passing the maximum contact angle
  - If above information was known at that time, the test would have been stopped at 4 mph to ensure safety

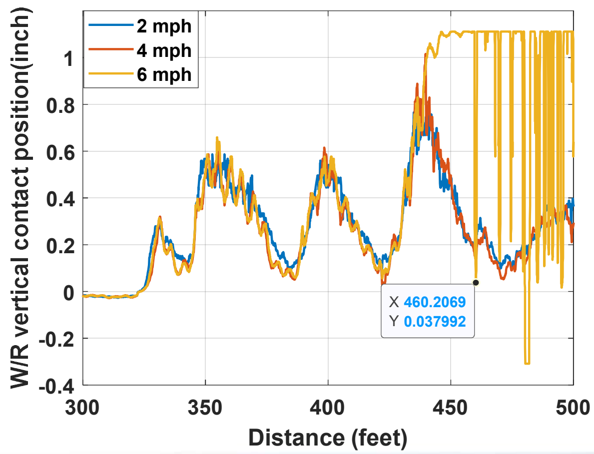




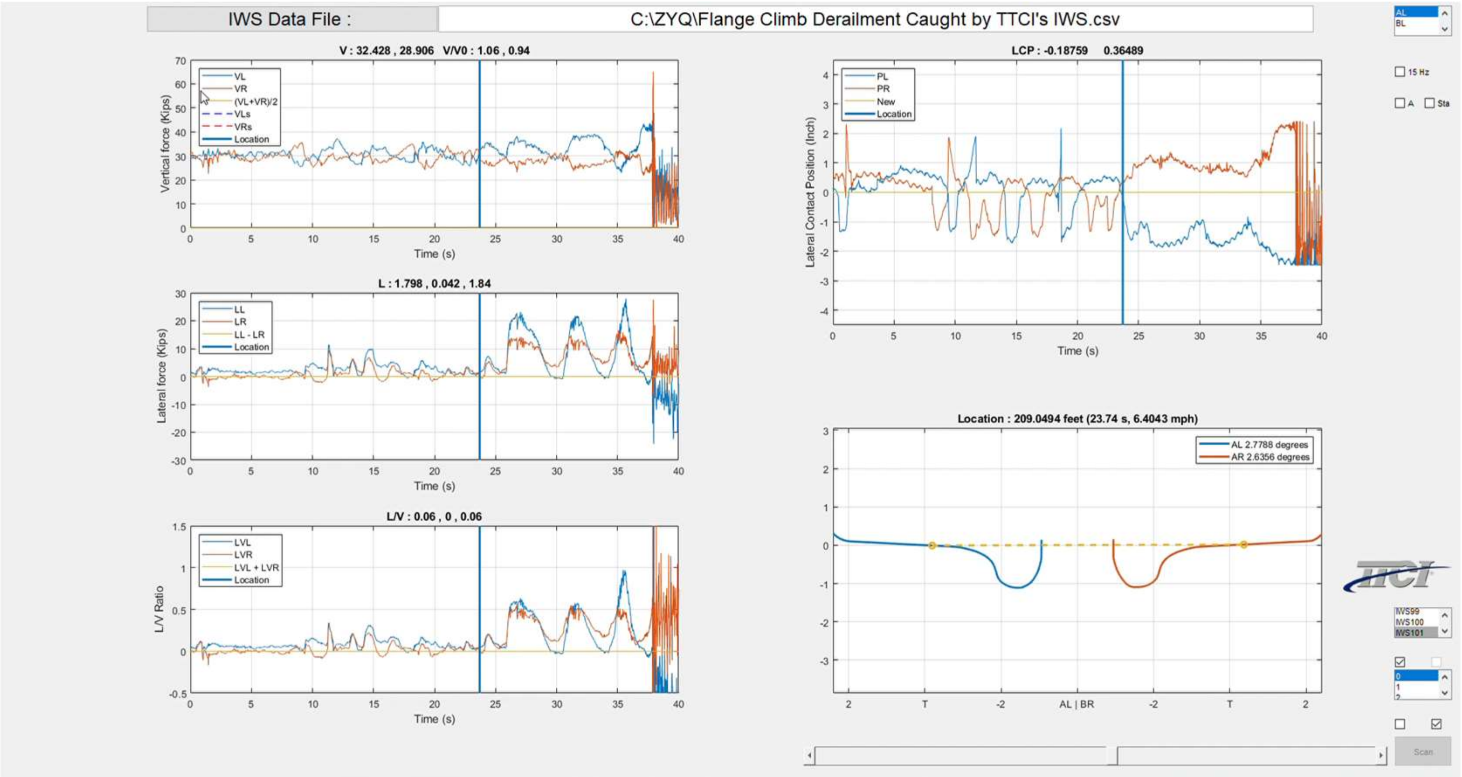


Possibility to mitigate the loss

- On the 6-mph run, there was about 20 feet and over 2 seconds of time between the 1.0-inch vertical contact position and derailment location



Whole process of the derailment



Conclusions:

- Independent of the W/R frictional coefficients and positively correlated with the risk of derailment, the W/R contact position-based geometric criterion is an effective method to determine the risk of flange climb derailment
- High accuracy IWS is critical to relevant implementation
- TTCI is now implementing this method to help assess derailment risk during testing
- The W/R contact position is recommended as an index for derailment risk assessment in the future

This speech is dedicated to the memory of Wil Lundberg whose contributions to this work were invaluable