Wheel Rail Principles: Driving Factors, Results and Experience

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International Engineering

Understanding of the WRI: from the early days to the present

“From a small irregularity of the railway the wheels may be thrown a little to the right or a little to the left, when the former happens the right wheel will expose a larger and the left one a smaller diameter to the bearing surface of the rail which will cause the latter to lose ground…

…which will cause the wheels to proceed in an oscillatory but easy motion on the rails.”

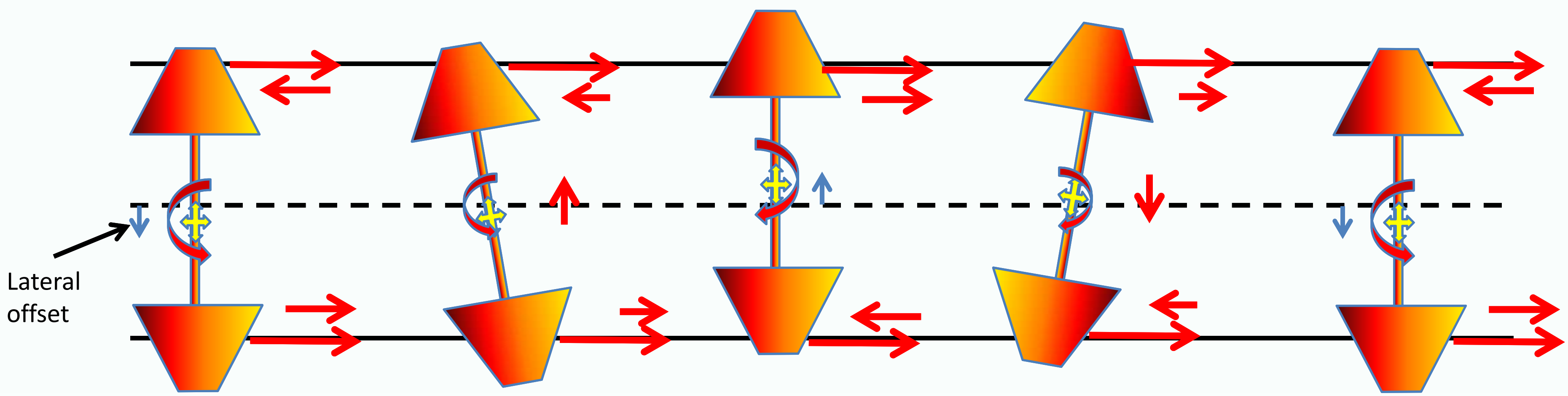
George Stephenson, 1827

The railway train running along a track is one of the most complex dynamical systems in engineering…the interaction between wheel and rail involves both complex geometry of wheel tread and rail head… and there are many non-linearities.”

Alan Wickens, 2002

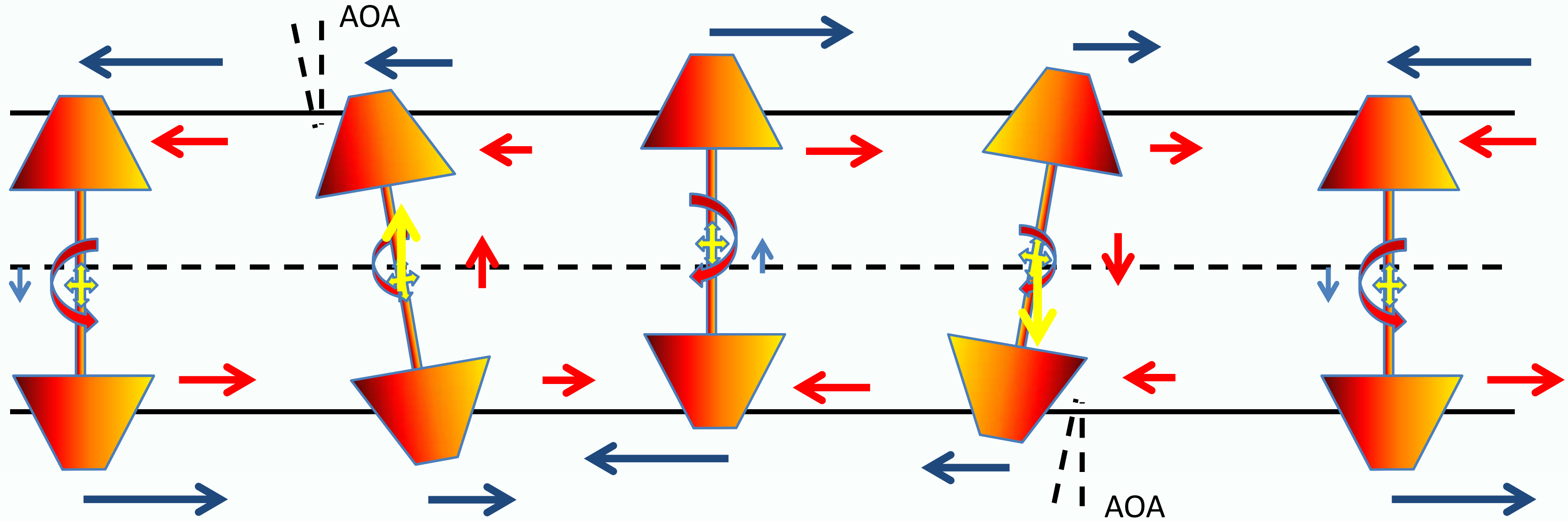
Stephenson's oscillation

- Stephenson's railway wheels were conic and had no bearings forcing both wheels to rotate the same
- Thus the difference in wheel radii (Rolling Radius Difference) caused by the lateral shift creates a difference in the velocities, both in longitudinal and lateral directions
- These in turn cause the axles to steer back toward track center



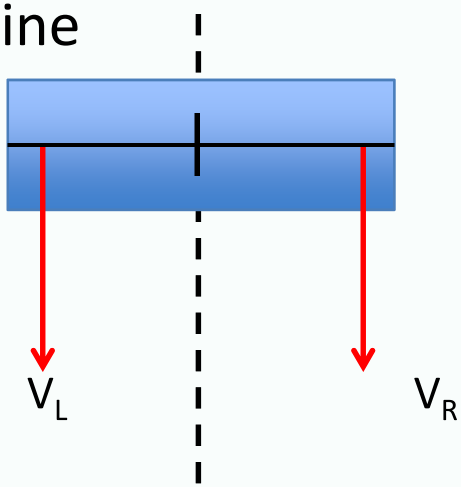
Steering velocities and forces

- The velocity differences cause changes in the trajectory of the axle which, by definition, are accelerations and hence related to forces
- These Longitudinal and Lateral forces are related to the velocity differences and are called Creep Forces
  - The Longitudinal forces are related to the axle lateral shift
  - The Lateral forces are related to the axle angle to the track (Angle-of-Attack)

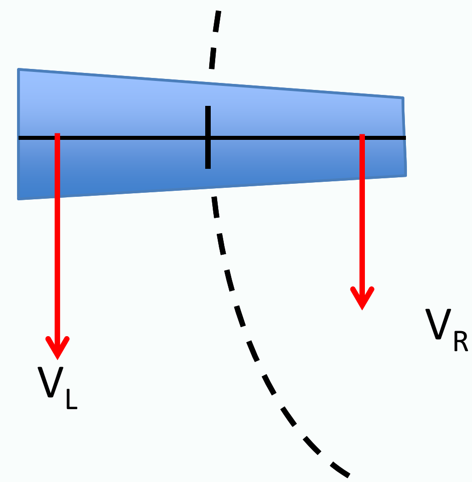


Kinematic Motion

- Cylinder: straight
  - Because $V_L = V_R$, the cylinder roles in a straight line



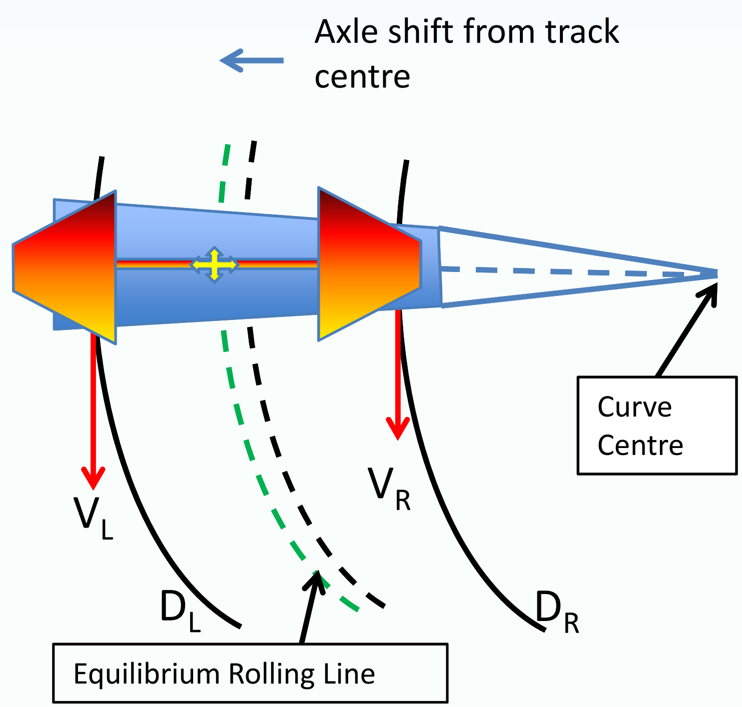
- Cone: curved
  - Because $V_L > V_R$, the cone roles in a curve to the right



- These trajectories are innate to the shapes and require no external forces

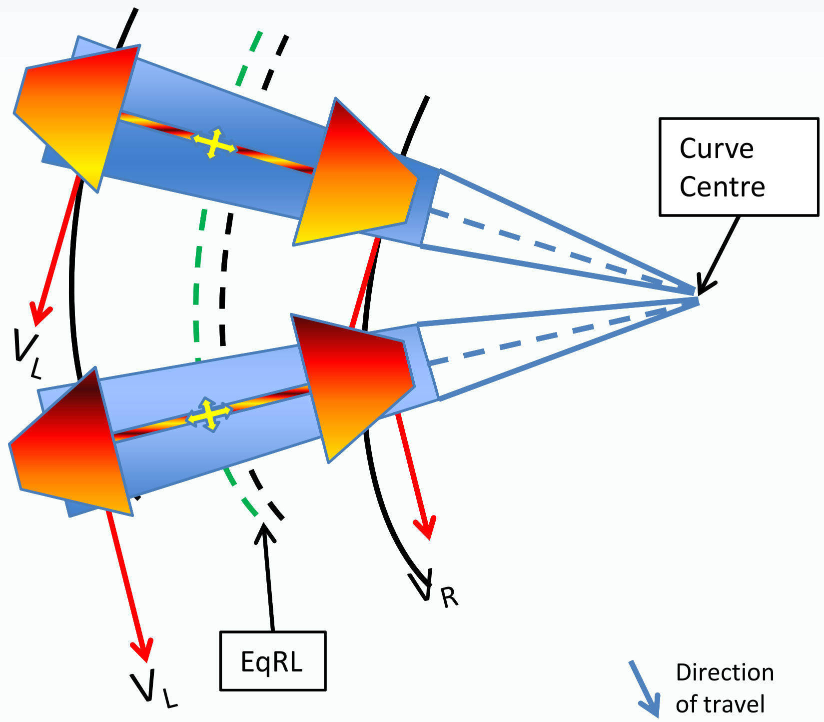
Axle Steering: Kinematic Curving

- If a railway wheel-set could appear as a cone relative to the track, then it could curve in a kinematic mode
- Because of the conic profiles and lack of bearings , this is possible
- An left shift allows the left wheel to be larger than the right to match the virtual cone terminating at the curve center
- Such an axle is said to exhibit an ideal “Rolling Radius Difference” and is centered on the Equilibrium Rolling Line (EqRL).



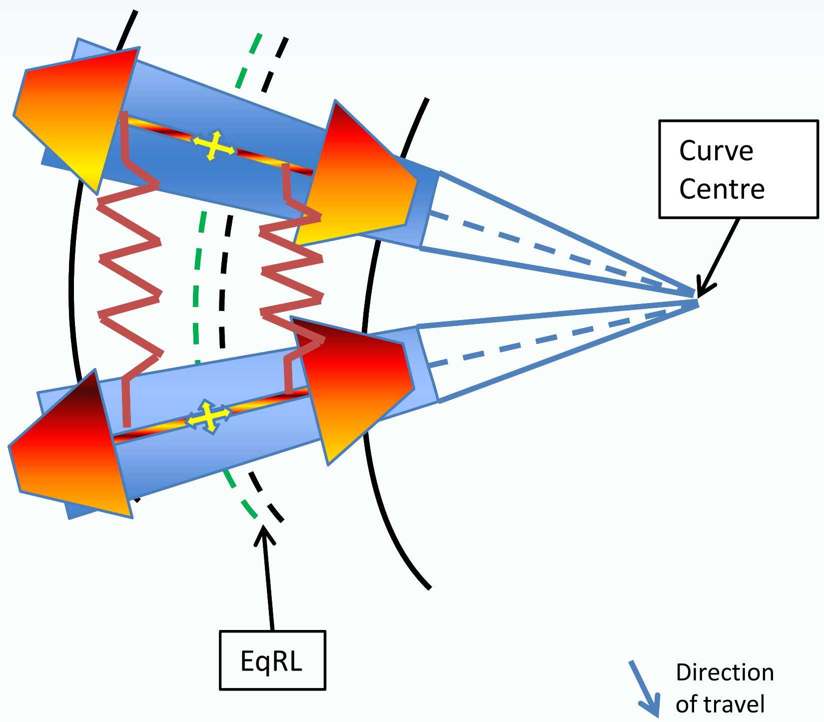
Bogie Steering: Kinematic Curving

- In order to a bogie to curve kinematically both axles will be :
  - shifted to the EqRL
  - oriented at a right angle to the track and have no AOA
- The bogey will negotiate the curve kinematically and with no external forces
- But is this possible?



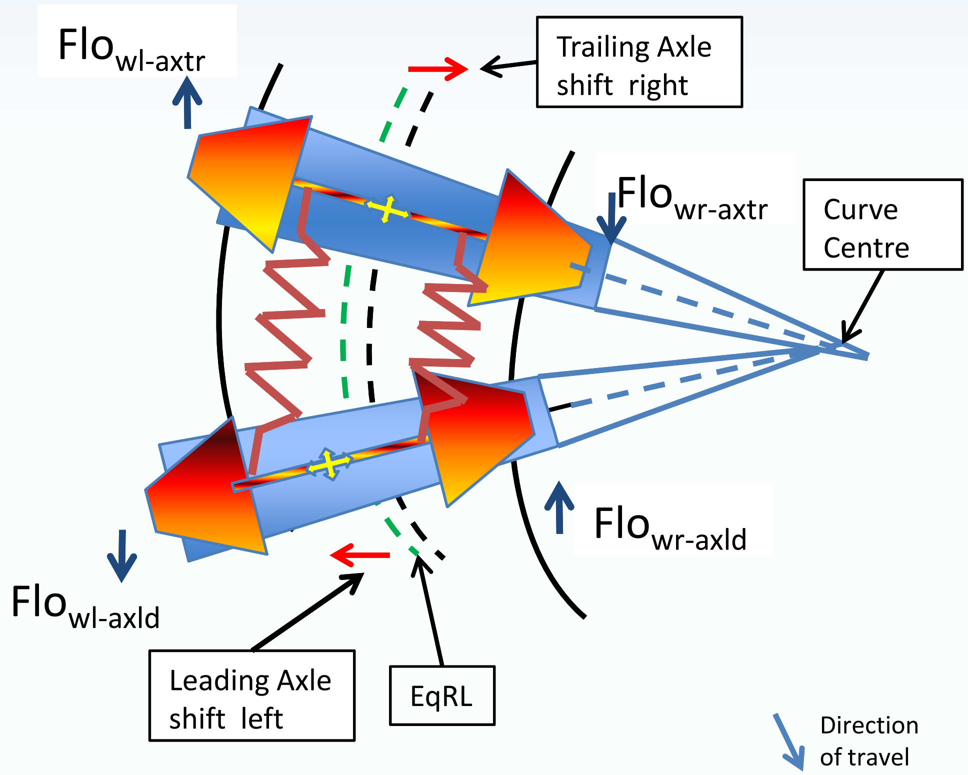
Bogie Steering: Kinematic or Not

- A bogey **can not** negotiate a curve kinematically because the axles are connected together by the suspension
  - The suspension can be depicted as a pair of virtual springs between the axles
  - The outer spring must be expanded and the inner spring must be compressed which requires forces
- Where do the forces come from?



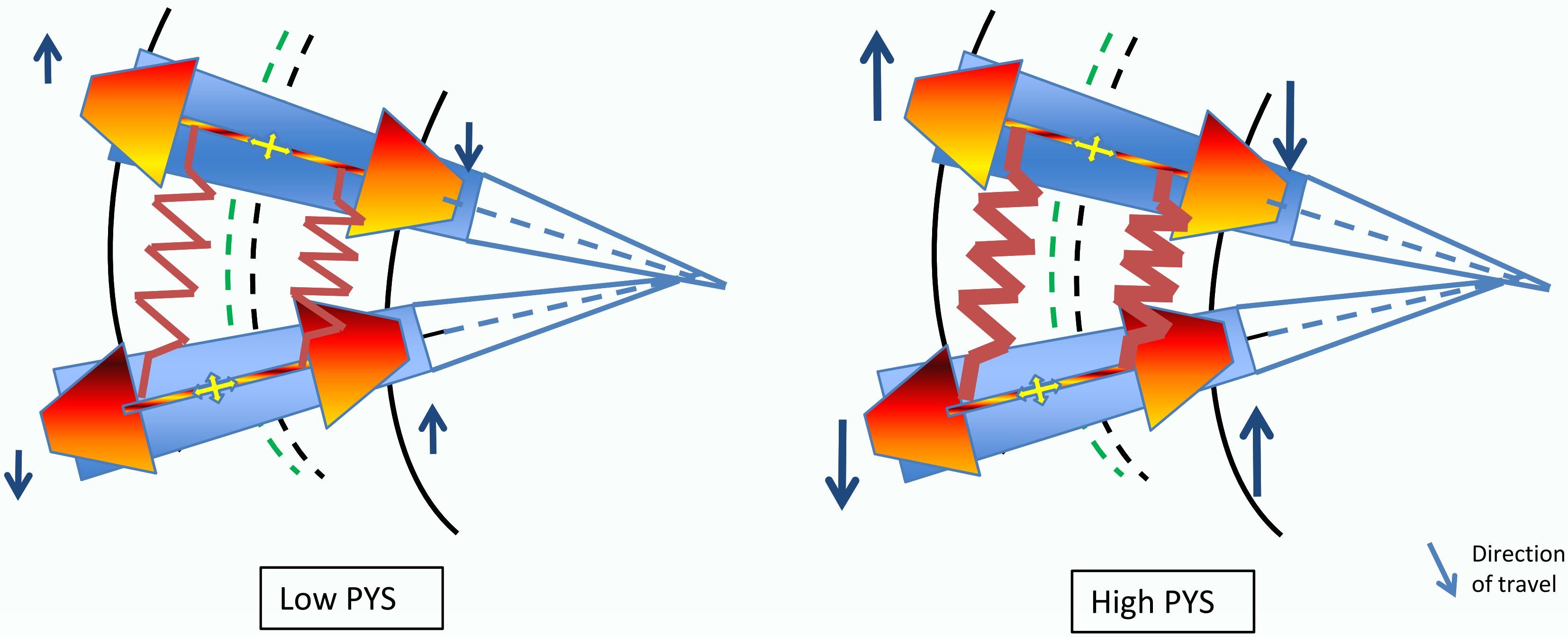
Bogie Steering: Non-Kinematic

- Forces required to stretch the outer and compress the inner springs must be longitudinal in direction
- The only Longitudinal forces available are Longitudinal Creep forces
- Thus, the axles must shift appropriately from the EqRl in the realistic energy state:
  - Lead: away from curve centre
  - Trailing: toward curve centre



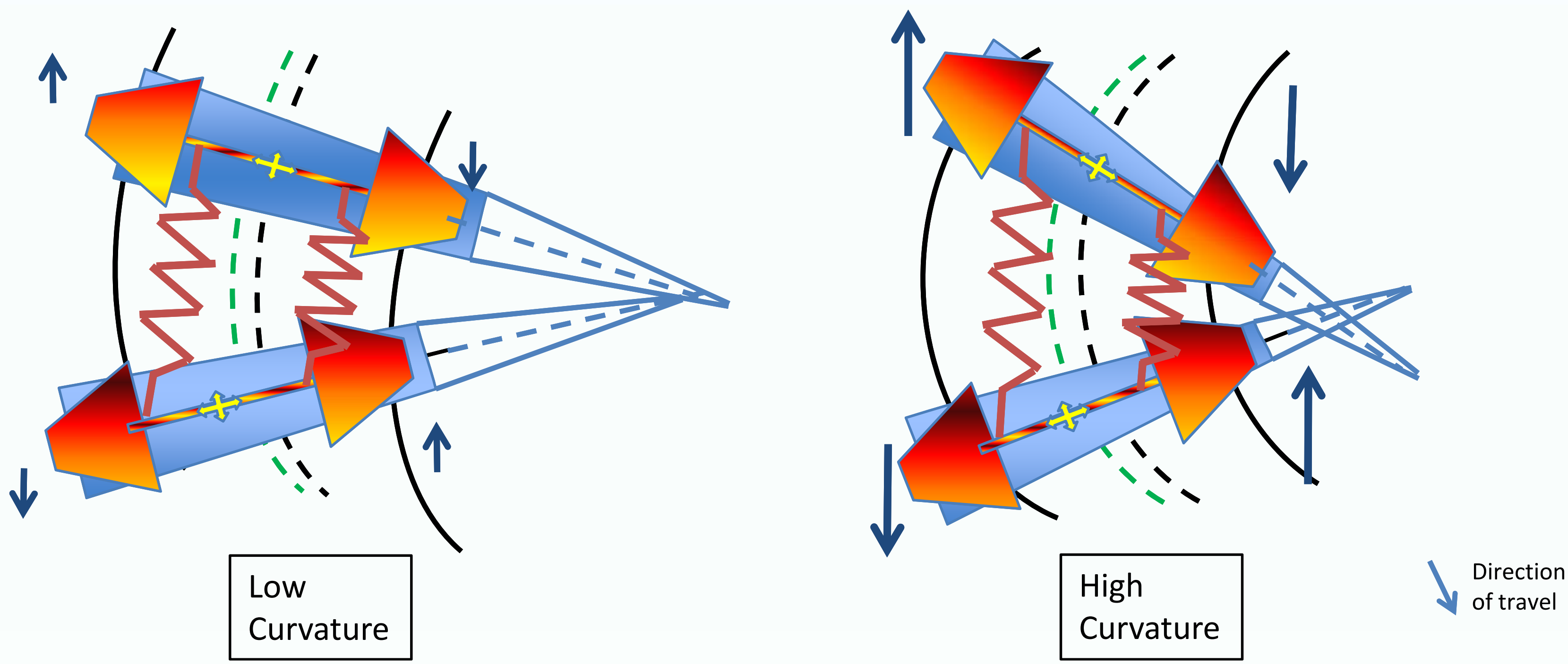
Bogie Steering: Axle Primary Yaw Stiffness (PYS)

- As the inter-axle spring stiffness increase in stiffness, a given deflection requires more Longitudinal creep force



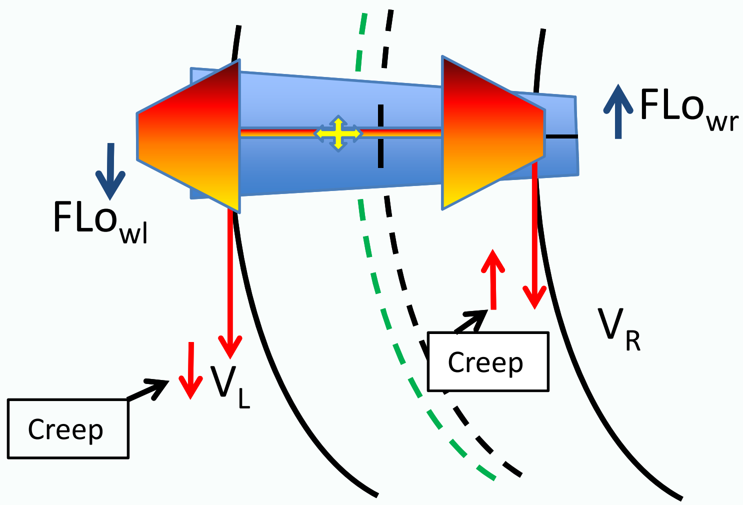
Bogie Steering: Curvature

- As the curvature increases (radius of curve decreases), the axles must rotate more, increasing virtual spring deflection and forces

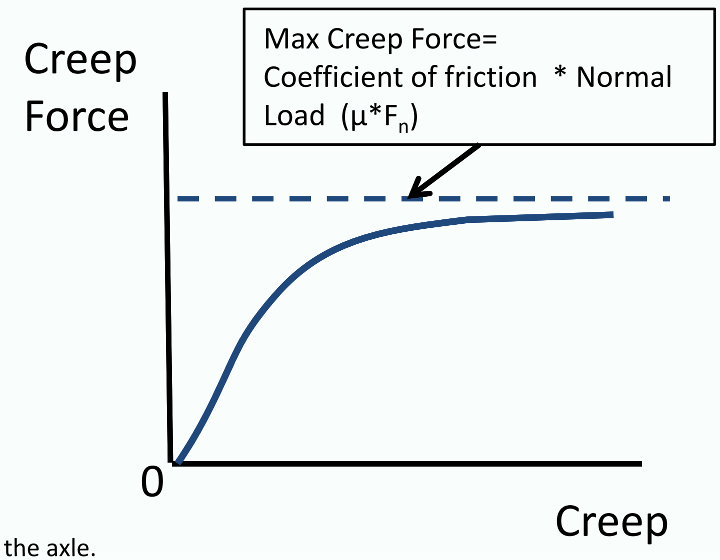


Creep Forces

- The difference between the actual and ideal velocities are known as slip or creep and generate forces



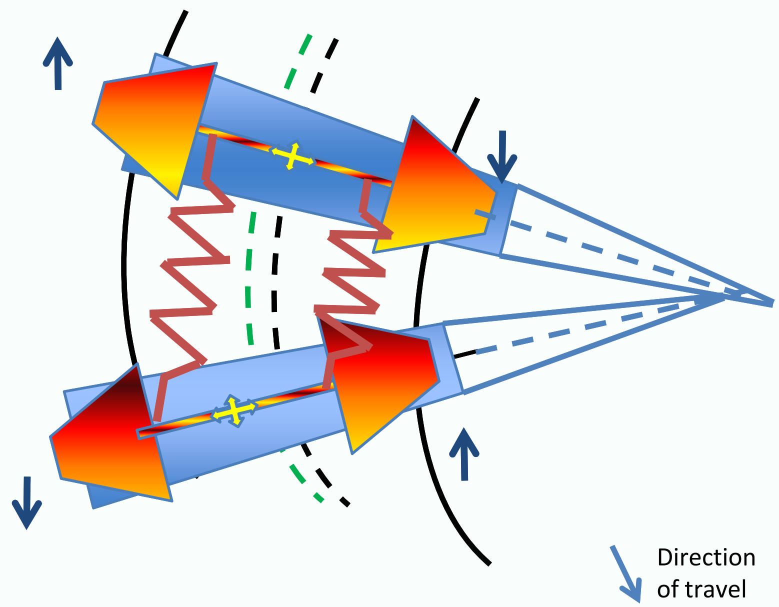
- The Creep Forces are a function of the amount of slip and saturate at the maximum allowed by friction & Load



Note: Forces shown are forces on the axle. Equal and opposite rail forces exist

Steering: 1st Summary

- A Bogie negotiating a curve does so via mechanisms described by Stephenson
- Bogie curving is non-kinematic and must have:
  - axle lateral shifts and Longitudinal forces
  - AOAs and Lateral forces



- The key factors which influence Lateral Shift and AOA are:
  - Vehicle Weight
  - PYS
  - Friction
  - Curvature

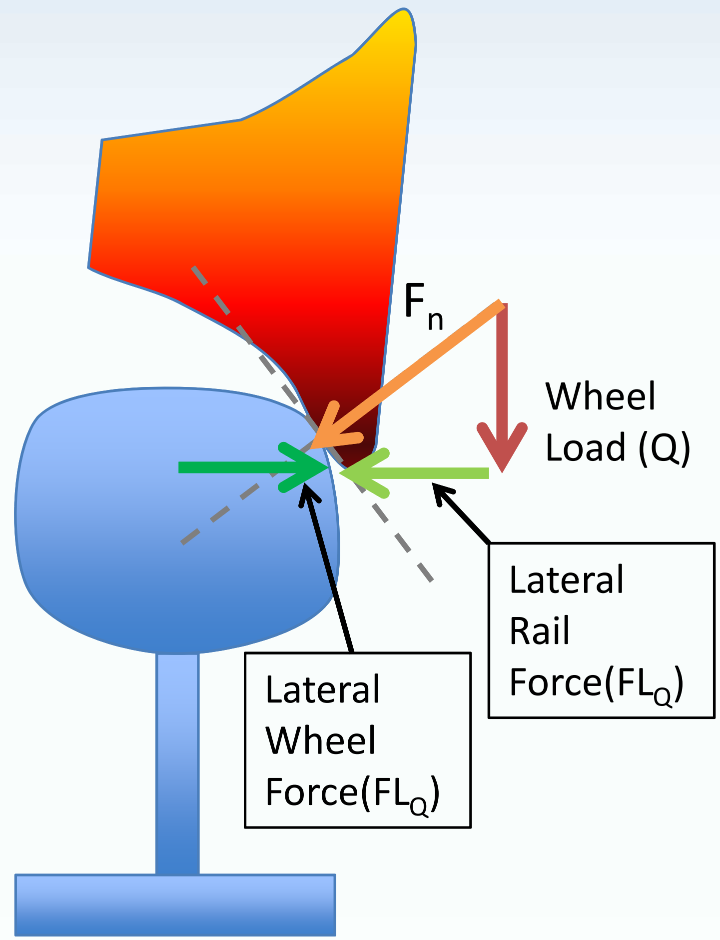
Vehicle

Shared

Track

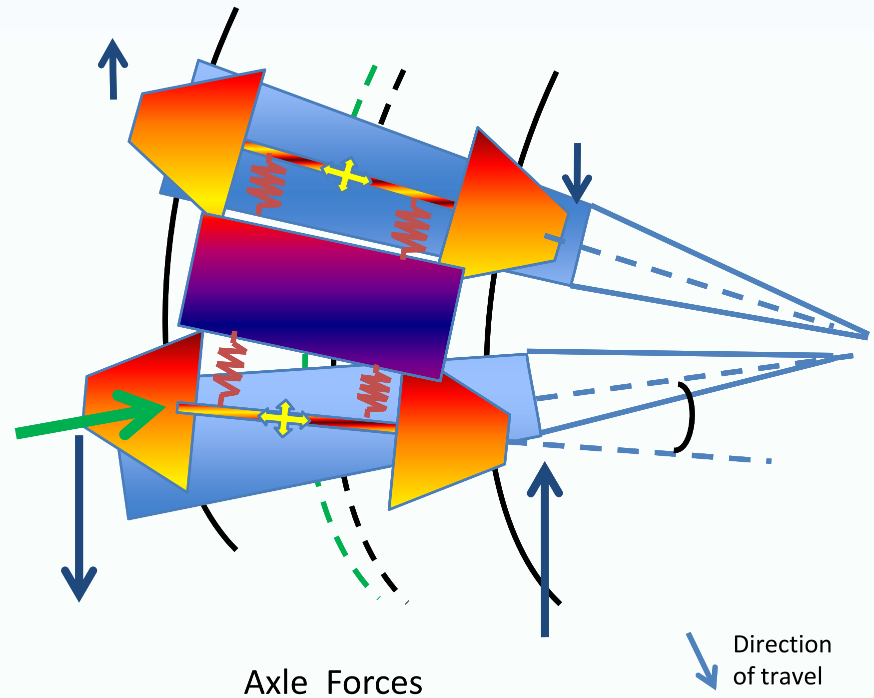
Conicity induced Lateral force

- Wheels are not simple cones but complex shapes with variable conicity
- When a wheel and rail are in non-horizontal equilibrium contact then:
  - A friction force must exist to maintain the equilibrium
  - This requires a normal force
  - The normal force in turn requires a lateral force
- The steeper the plane of contact, the greater the Lateral force
- From the intuitive point of view, the wheel and rail “push” against each other



Bogie Steering: the Bogie Mass

- Previous Slides ignored the Bogie mass
- In reality the virtual springs are not axle-to-axle but axle to Bogie
- For complex reasons, this tends to concentrate axle forces on the leading axle and reduce them on the trailing
- This is consistent with intuition which expects the leading axle to carry onward, not curve (Newton's laws of inertia)

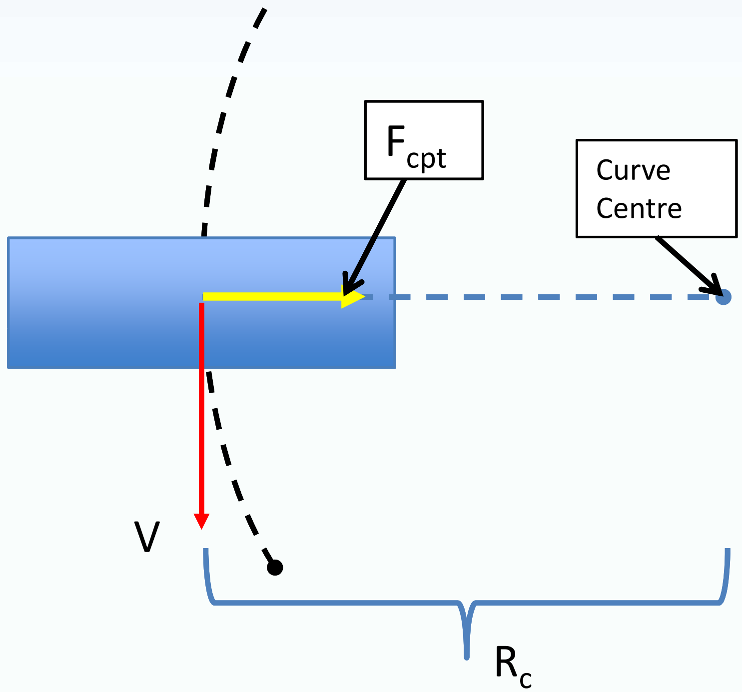


Non-Kinematic Curving: Centripetal and Lateral Forces

- For an object to curve, a force toward the curve center is required, the Centripetal Force (F_{cpt})

$$F_{cpt} = M * V^2 / R_c$$

- Wheel set F_{cpt} comes from lateral creep force and FL_Q.
- Therefore R_c & V influence both axle AOA and lateral shift



Plan View

Non-Kinematic Curving: Centripetal and Lateral Forces

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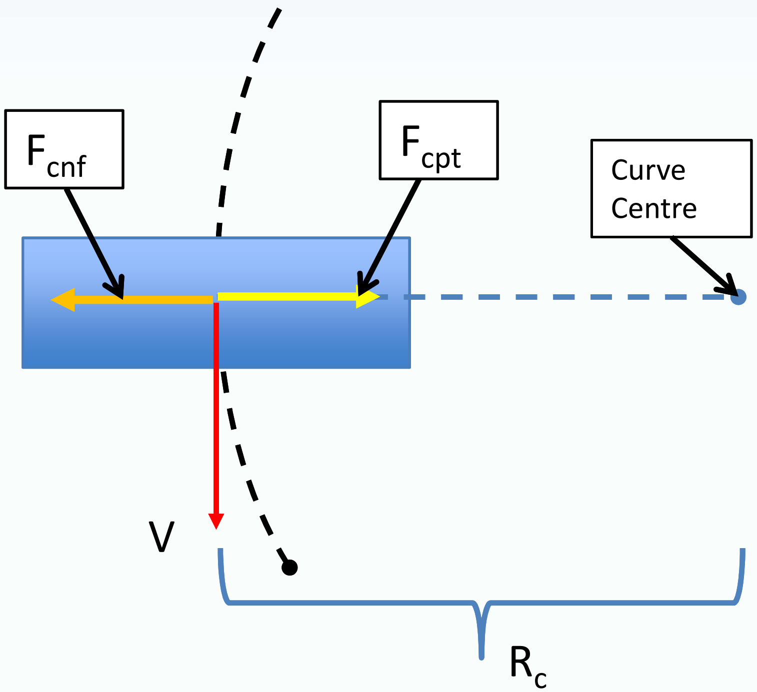
$$F_{cpt} = M * V^2 / R_c$$

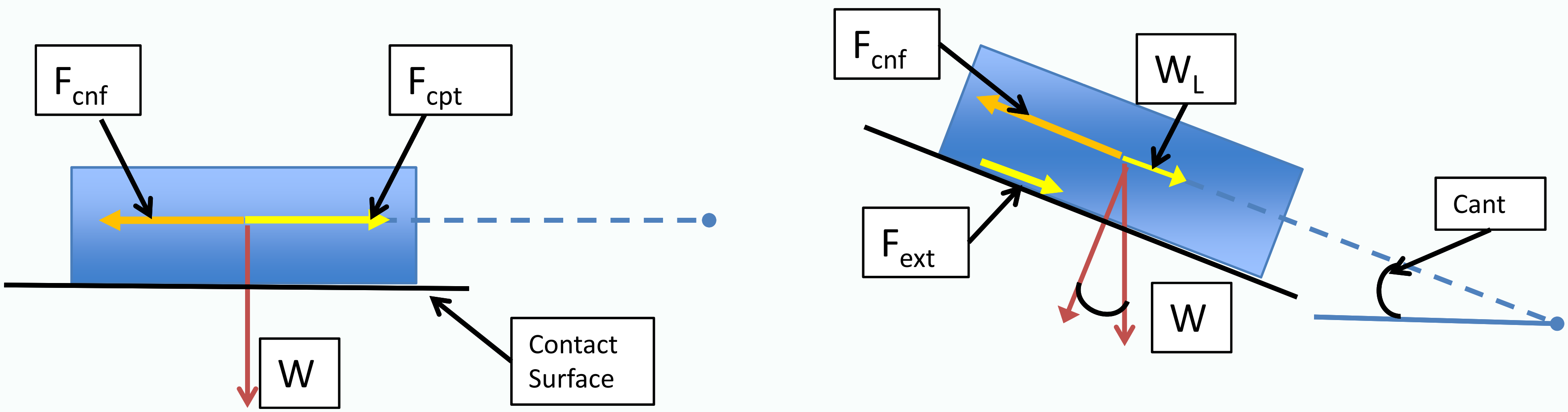
- Wheel set F_{cpt} comes from lateral creep force and FL_Q.
- Therefore R_c & V influence both axle AOA and lateral shift
- Centrifugal Force (F_{cnf}) is often depicted which is equal and opposite to F_{cpt}



Plan View

Centripetal force and Cant

- If the curving object is rolling on a Canted surface, then a component of its weight appears as a force in the same direction as F_{cpt}
- $W_L = W * \text{Sin}(\text{Cant})$
- Therefore: $|F_{cnf}| = |W_L + F_{ext}|$



Vertical Views

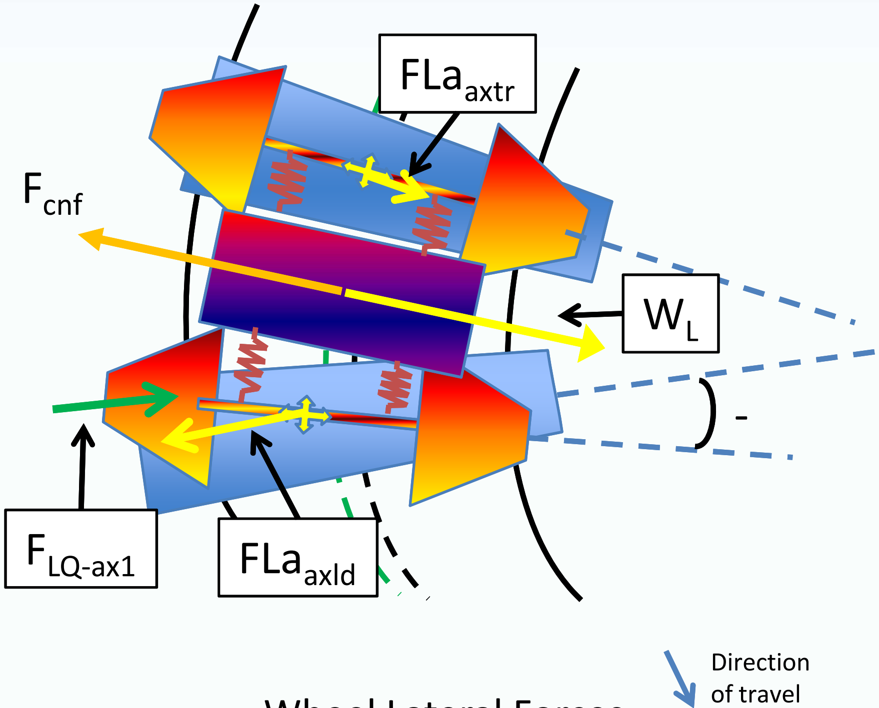
Bogie Steering: Cant Equilibrium

- Since at Cant Equilibrium $F_{cnf} = W_L$ the sum of the external forces must = 0
- In the case depicted:

  $F_{ext} = |\, Fla_{axld} \,| - |\, F_{LQ\text{-}ax1} + Fla_{axtr} \,|$

  $= \quad 0$

- Although in the past many curves were designed for Cant Equilibrium, it is not the most probable or desirable condition



Wheel Lateral Forces

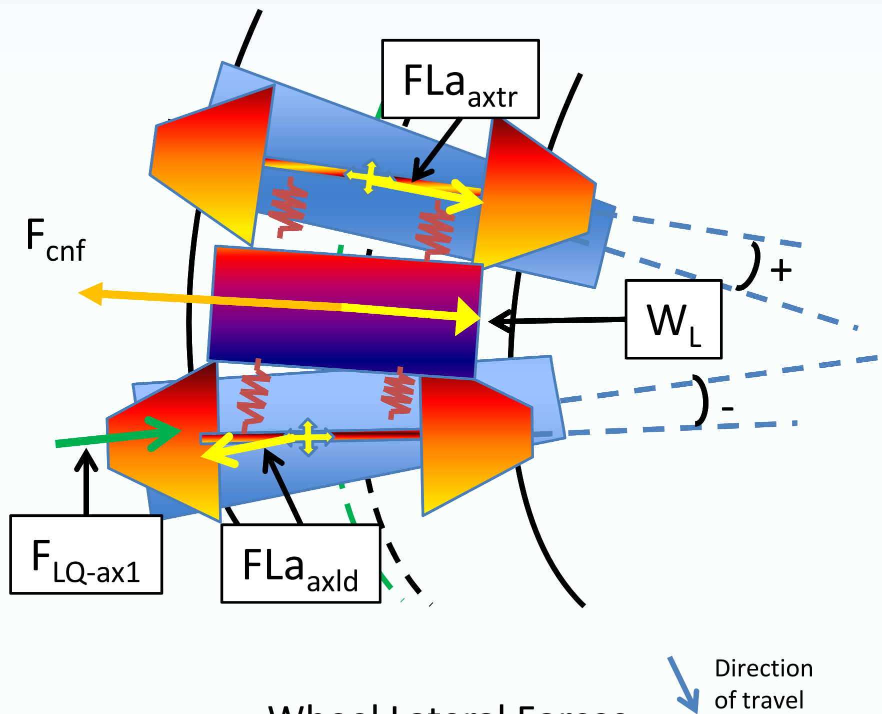
Note: For the sake of graphic simplicity, Lateral forces generated by AOAs are depicted as acting on the axle center. In fact they are generated at each wheel/rail interface.

Bogie Steering: Cant Deficiency

- Since at Cant Deficiency $F_{cnf} > W_L$ the sum of the external forces must point **toward** the curve centre
- The Bogie rotates **forward**, reducing the Leading - AOA and inducing a larger +AOA on the trailing axle.
- In the case depicted

  $F_{ext} = | F_{LQ\text{-}ax1} + Fla_{axtr} | - | Fla_{axld} |$

  >0
- The F_{ext} therefore adds to W_L equaling F_{cnf}



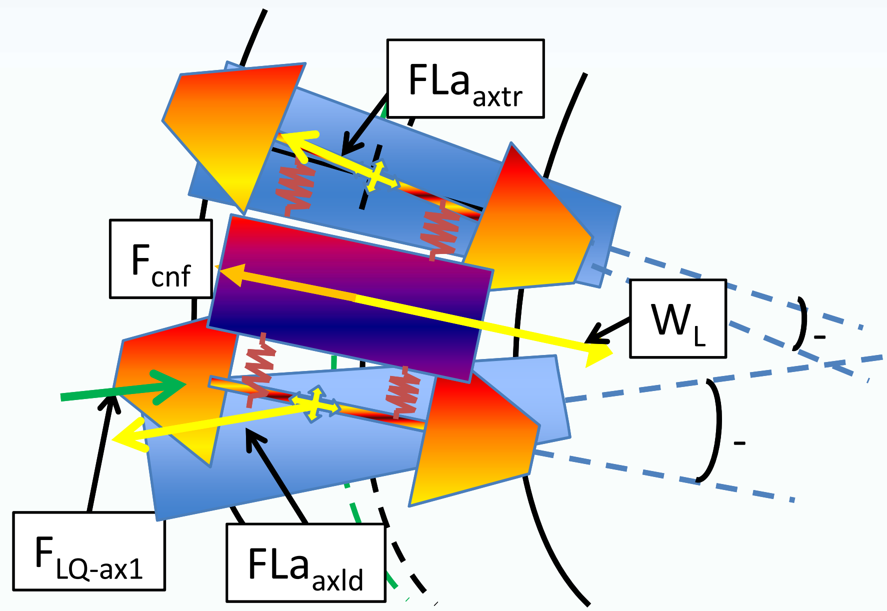
Wheel Lateral Forces

Bogie Steering: Cant Surplus

- Since at Cant Surplus $W_L > F_{cnf}$ the sum of the external forces must point **away** from the curve centre
- The Bogie rotates **backward**, increasing the Leading - AOA and inducing a -AOA on the trailing axle.
- In the case depicted

  $F_{ext} = |\, Fla_{axld} + Fla_{axtr} \,| - |\, F_{LQ\text{-}ax1} \,|$

  < 0
- F_{ext} subtracts from W_L equaling F_{cnf}



Direction of travel

Wheel Lateral Forces

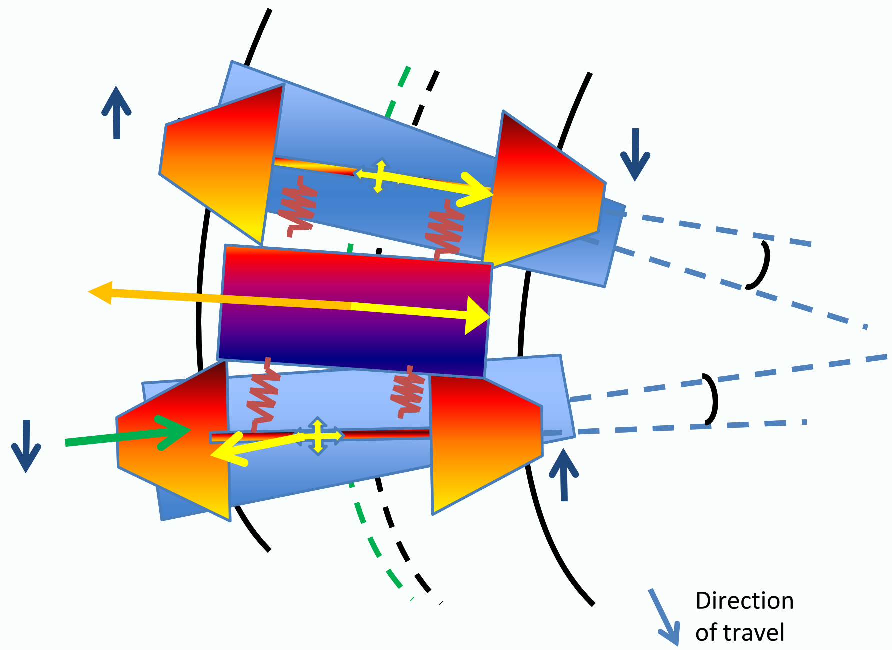
Steering: 2nd Summary

- A Bogie negotiating a curve must have:
  - AOAs and Lateral forces which balance Centrifugal force
  - axle lateral shifts and Longitudinal forces which attempt steer the axles to the Equilibrium Rolling Line
- The key factors which influence the AOAs and Lateral Shifts are:
  - Vehicle Weight
  - PYS
  - Friction
  - Conicity
  - Speed
  - Curvature
  - Cant

Vehicle: Vehicle Weight, PYS

Shared: Friction, Conicity, Speed

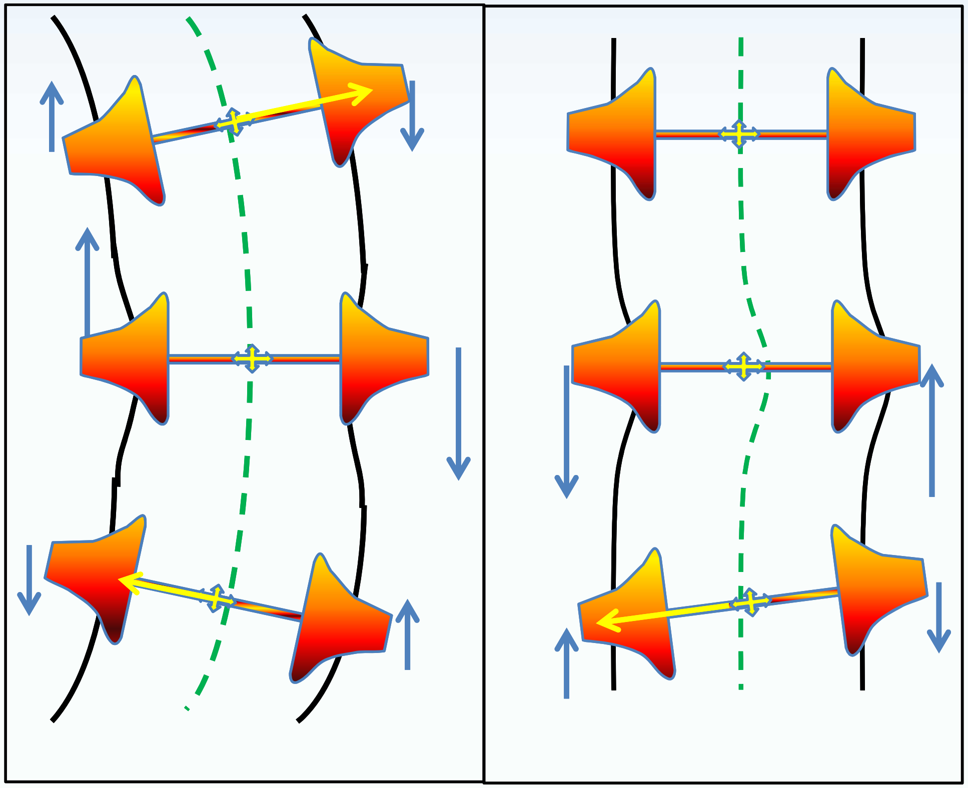
Track: Curvature, Cant



Wheel Forces

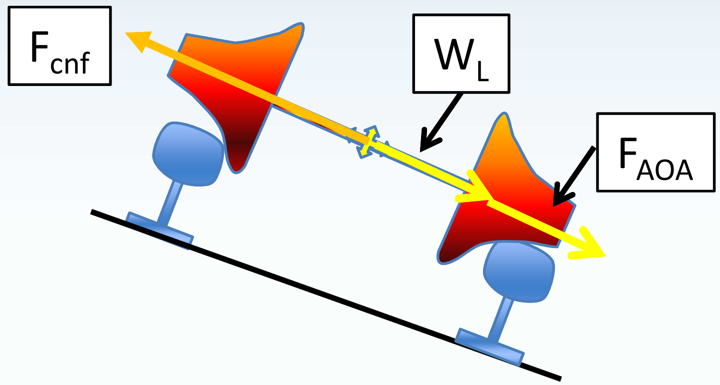
Rolling Radius Difference: Track Gauge & Alignment variations

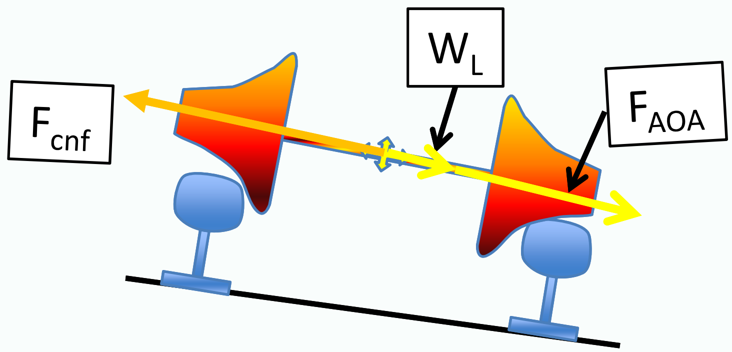
- When curving axles shift laterally relative to the track
- The contact position of the wheels/track can also change due to changes in gauge or alignment
- This can create
  - Rolling Radius Differences
  - Axle oscillations
  - Transient Longitudinal & Lateral Forces



Cant Variations and AOA

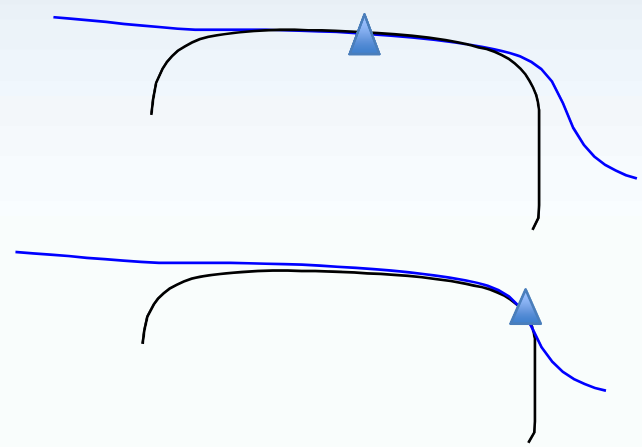
- When negotiating a curve, normally a bogie is in a state of equilibrium where the lateral shifts and AOAs are constant
- But an abrupt change in cant will alter the Lateral force due to gravity
- This can create
  - Different AOA
  - Axle oscillations
  - Transient Longitudinal & Lateral Forces



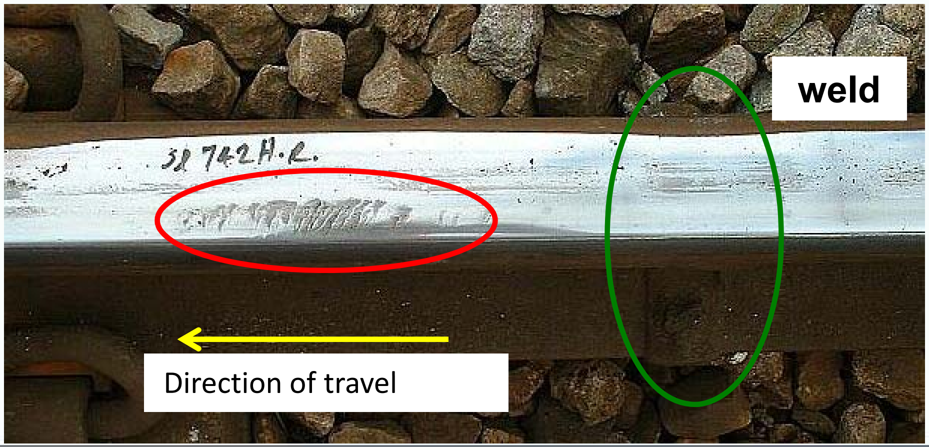


Rolling Radius Difference: Conformal Profiles

- Wheel and rail profiles that are very similar in shape (conformal) can cause large changes in RRD with a very slight lateral shift



- Slight changes in Rail profile associated with welds can cause large changes in RRD and generate instability and track damage



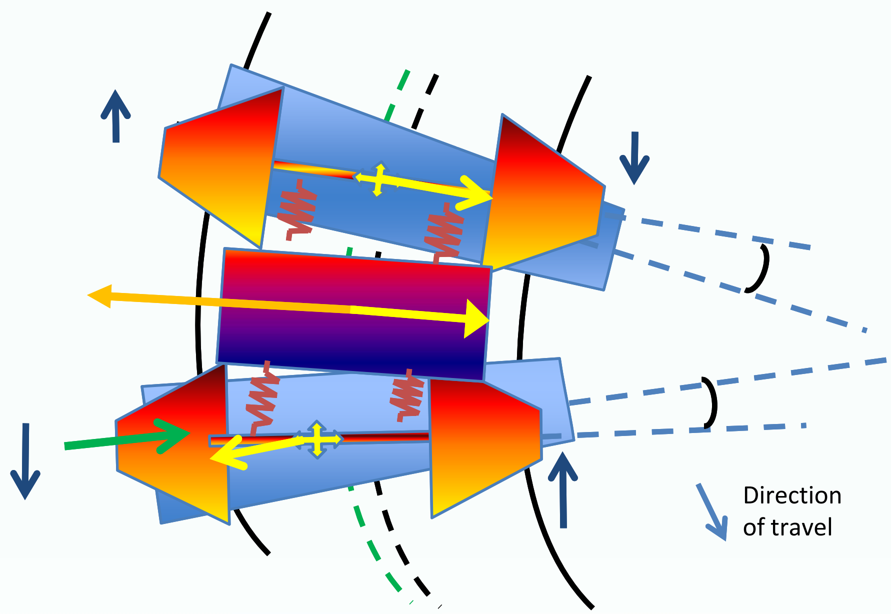
Steering: 3rd Summary

- A Bogie negotiating a perfect curve will establish AOAs and lateral Shifts to establish Lateral and Longitudinal Force equilibrium
- But variations in track geometry can lead to instability and transient forces
- The key factors which influence the AOAs and Lateral Shifts are:
  - Vehicle Weight
  - PYS
  - Friction
  - Conicity
  - Speed
  - Curvature
  - Cant
  - Alignment variations
  - Gauge variations
  - Cant variations

Vehicle (Vehicle Weight, PYS)

Shared (Friction, Conicity, Speed)

Track (Curvature, Cant, Alignment variations, Gauge variations, Cant variations)

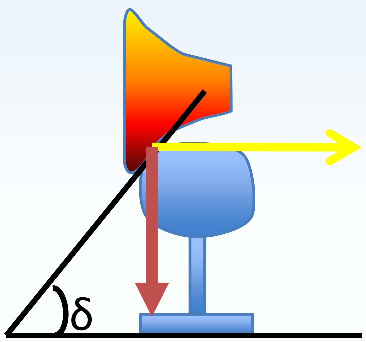


Managing the WRI

- Bogies negotiating a curve must generate:
  - Lateral Forces to satisfy Centrifugal force demands
  - Longitudinal Forces to attempt to deflect the axles to align with the curve
- Managing the WRI means managing those factors which influence the magnitude of the Lateral and Longitudinal forces
- Since these key factors are either owned by the vehicle or track stakeholder or are shared, a Systems approach is needed
- There are many reasons to manage the WRI:
  - Overall Safety
  - Resonance
  - Rail Damage control
  - Wheel damage control
  - etc

Safety: WRI derailments

- Excessive Lateral forces can cause derailments:
  - **Flange Climb**: Various formulas exist which relate Y (Lateral Force) and Q (nominal Wheel Load), the best known is Nadal's Limit:



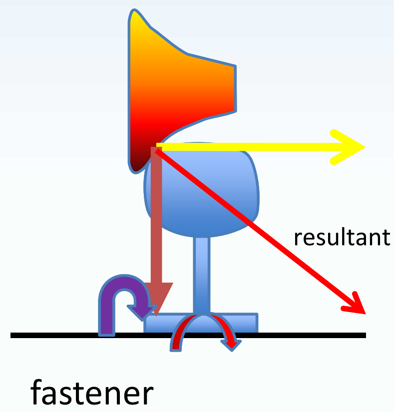
$$\frac{Y}{Q} = (\tan(\delta) - u)/(1 + u\tan(\delta))$$

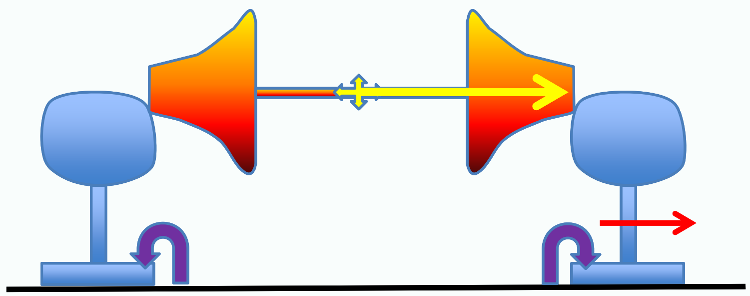
where: δ is the flange contact angle
u is the coefficient of friction

- If Y/Q exceeds this limit, derailment is possible
- Generally speaking the probability of derailment increases as friction increases or the contact angle decreases

Safety: WRI derailments

- Excessive Lateral forces can cause derailments:
  - **Rail Roll Over**: If the resultant of Y and Q (a line of action) is beyond the base of the rail and the outside rail/sleeper fasteners are weak, then the rail can roll over
  - **Gauge Widening**: If Y is very large and the track fasteners are weak on one/ both rails then the axle may drop down off the rails





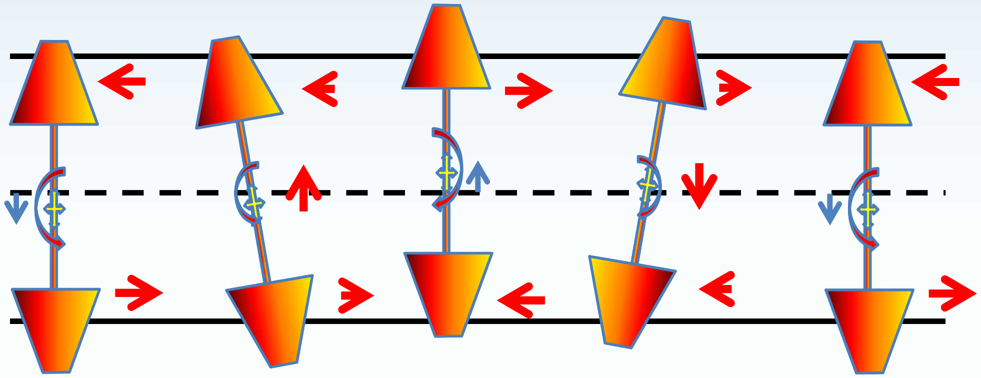
WRI and Resonance: Hunting

- Wheel sets naturally oscillate
- Klingel predicted their wavelength:

$$W = C * \sqrt{\frac{G}{\lambda}}$$

where: G = gauge

λ = conicity

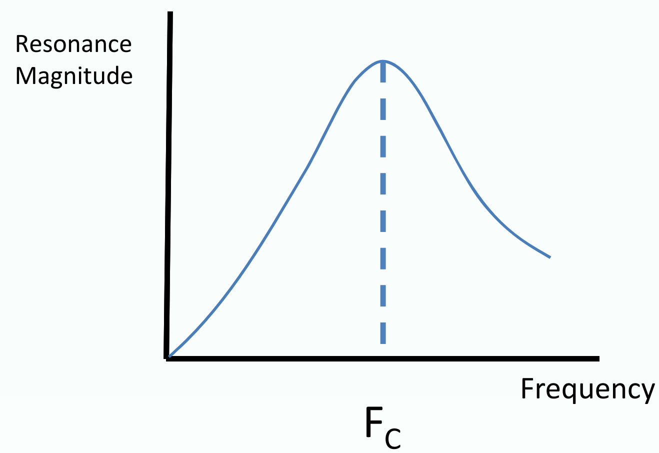


- A simple mechanical system has a Critical Frequency where the resonance reaches a maximum:

$$F_c = c * \sqrt{\frac{k}{m}}$$

where: K = stiffness

m = mass



WRI and Resonance: Hunting

- The wheel set oscillation and bogie resonance are tied together via speed because:

  F = S/**W** where: S: Speed & W: wavelength

- Combining this equation and that for the Critical Frequency and the Klingel Wavelength results in a Critical Speed equation:

  $S_C = c * \sqrt{G * k/\lambda}$ where: G = Gauge

  k = Primary Yaw Stiffness

  λ = Wheel/Rail set Conicity

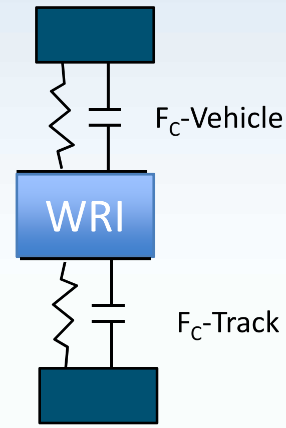
- Therefore any bogie operating at or above S_C will oscillate in a sustained manner (Hunting) creating excessive Longitudinal and Lateral forces

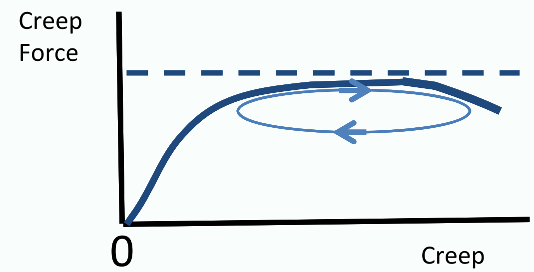
Curving & Hunting: the first 2 industry conundrums

- In general Curving forces are lowest (a good thing) when:
  - Conicity is high
  - Primary Yaw stiffness is low
- In general Hunting is minimized (a good thing) when:
  - Conicity is low
  - Primary Yaw stiffness is high
- Thus the industry is faced with 2 conflicting phenomena which effect track and vehicle design, safety and maintenance
- These conundrums are inherent but their impact can be reduced by managing the pertinent key factors.

WRI and Resonance: Corrugations

- The vehicle above the WRI and the track structure below the WRI can be depicted as systems capable of resonating
- There are several Corrugation mechanisms
- In some cases the Creep Forces are highly saturated such that a “slip-slide” occurs which is bi-stable

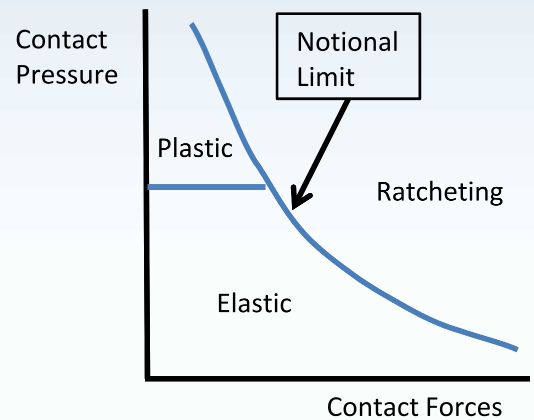




- If the resultant frequency is near the critical frequencies, corrugations may result

Rail Damage

- Rail damage is found in several forms
- It is generally caused by cyclical loads whose contact pressure and force magnitudes exceed a limit allowing "ratcheting"



Simplified Shakedown Diagram

Studs ?

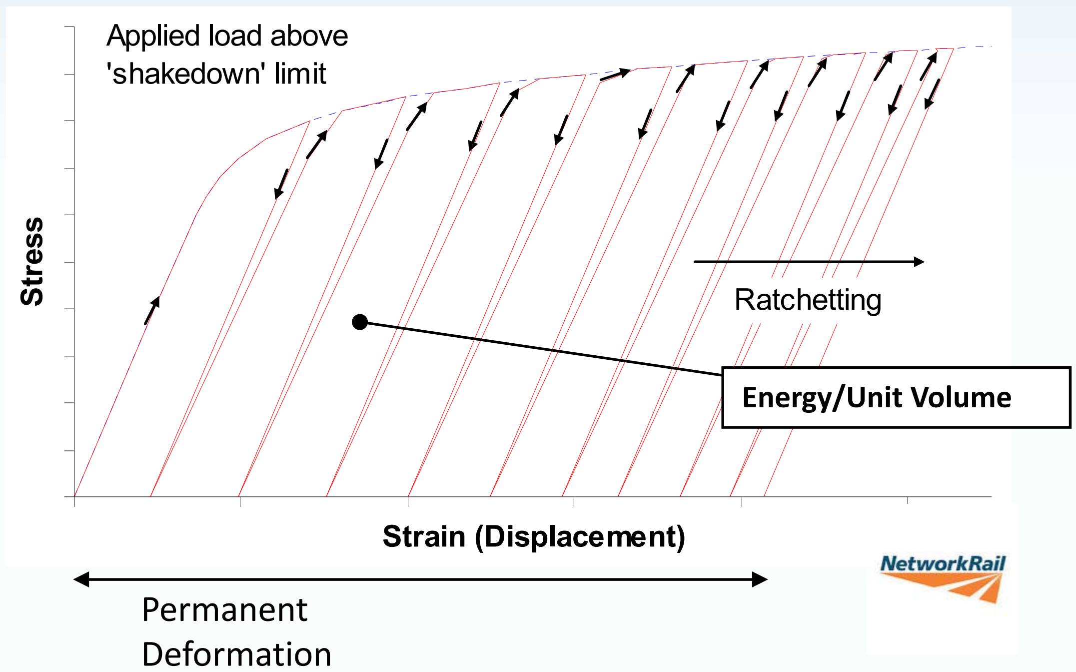
High Rail RCF

Low Rail RCF

Squats

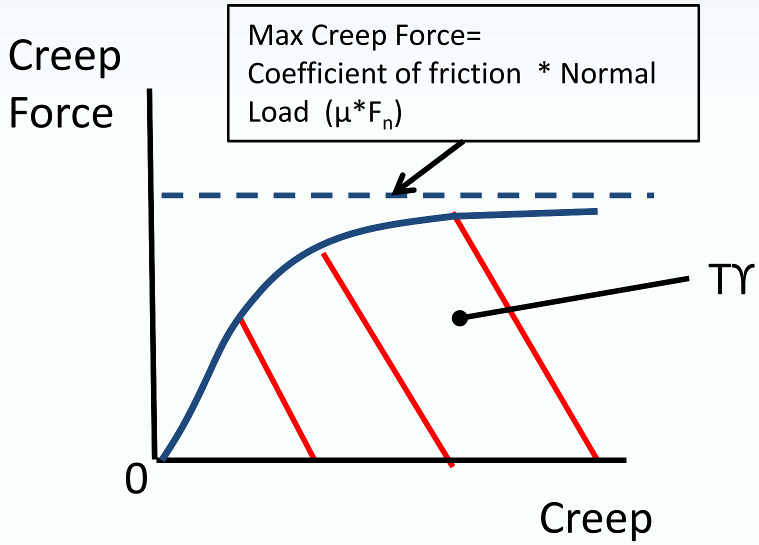
Rail Damage: Ratcheting

- The Ratcheting occurs when each cycle of a cyclical load at the point of contact creates a small increment of plastic deformation
- The area under the stress-strain curve is an energy term
- Eventually the material can absorb no more energy and cracks occur



Rail Damage: The Whole Life Rail Model (WLRM)

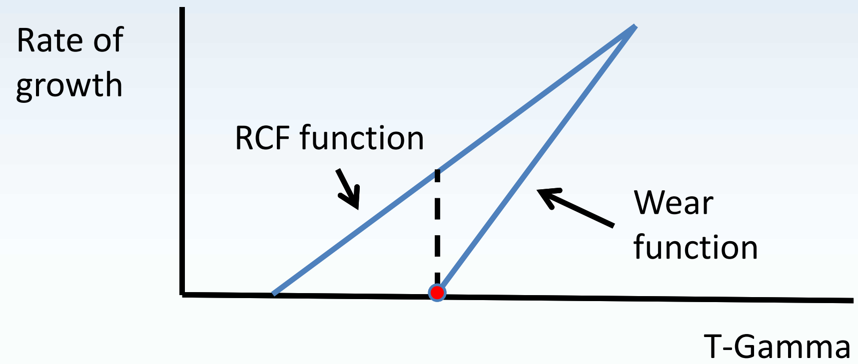
- The WLRM is based upon the Tϒ (T-Gamma) concept of contact patch energy developed by BR research in the 1970s
  - T-Gamma is the area under the Creep Force – Creep curve and has units of Energy/Unit Length
  - It was originally intended to predict wear of rails and wheel

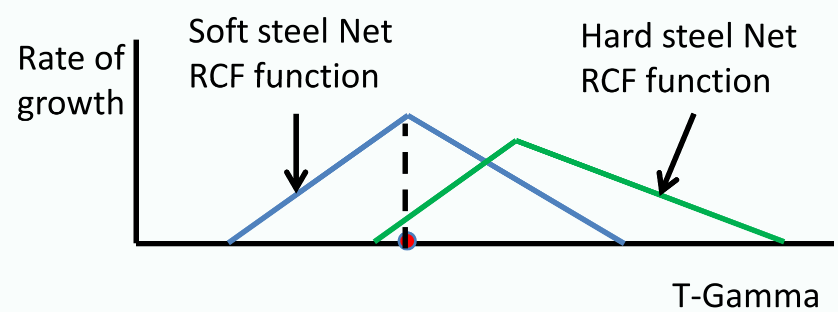


- The WLRM exploits the fact that the area under the stress-strain curve is an energy term also
- It is essentially a transfer function relating force and ratcheting

Rail Damage: WLRM

- The Whole Life Rail Model (WLRM) assumes that cracking and wear are separate phenomena, the former starting at lower energies than the latter
- By combining the 2, a T-Gamma exists that represents maximum RFC

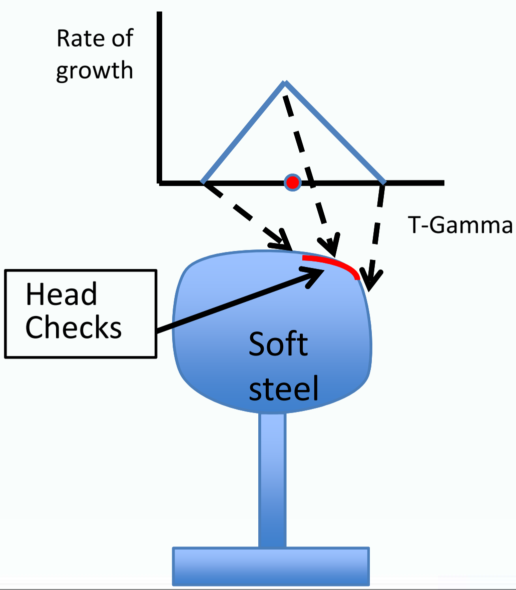


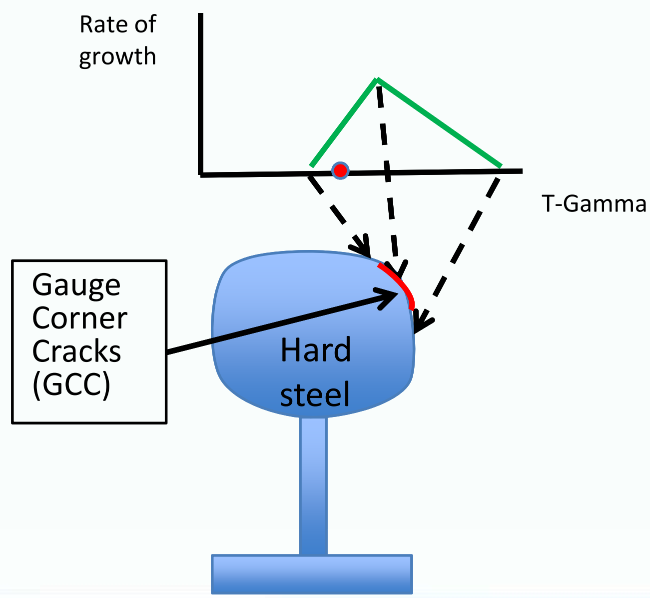


- Since cracking and wear are functions of material properties, separate WLRM functions exist for different steels

Rail Damage: WLRM

- In general, as the wheel and rail contact position moves toward gauge face/flange contact, T-Gamma increases
- This means soft and hard steel will exhibit RCF at different locations on the rail head





Rail Damage: RCF crack angles

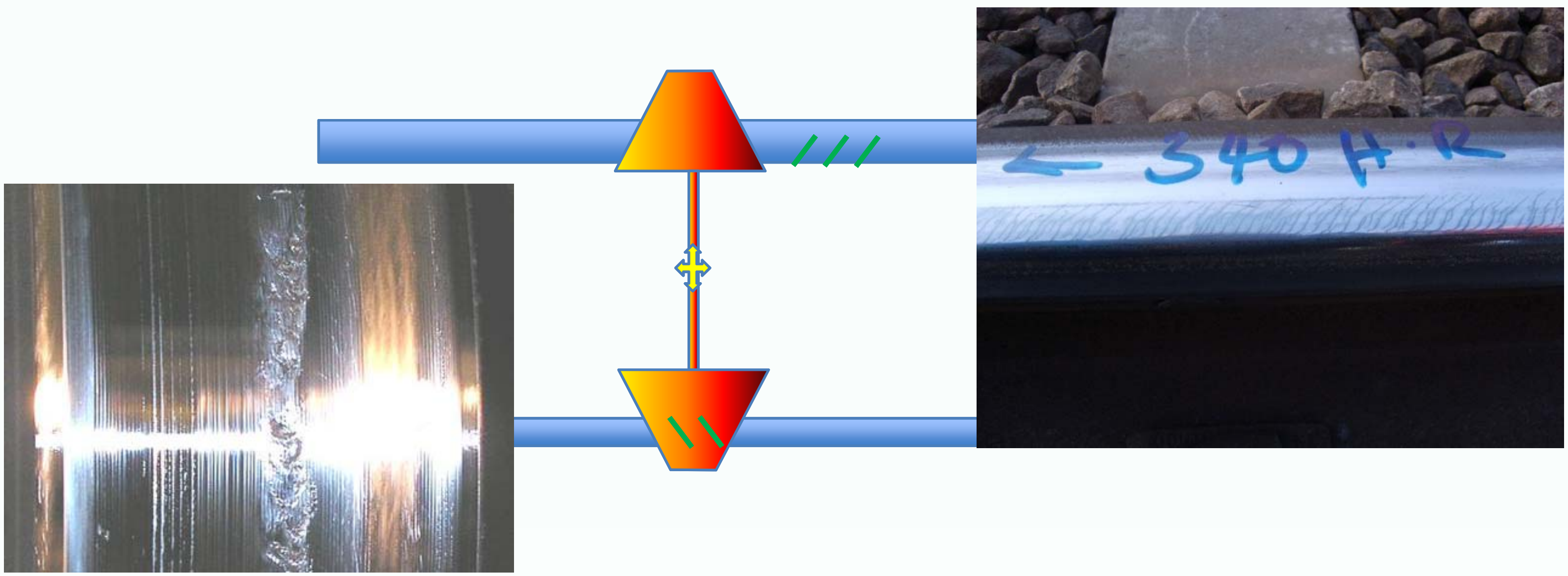
- Because of the nature of crack propagation, the RCF cracks observed on rail are largely at right angles to the resultant of the Lateral and Longitudinal Creep forces

- Crack angles, position on the rail head and location down the track are indicators of the dynamic behavior of the bogies causing the damage

Rail Forces

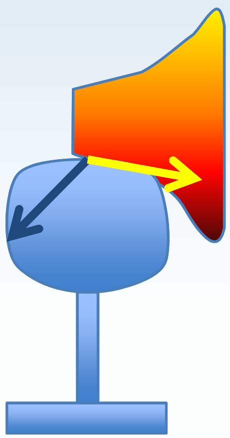
Wheel & Rail Damage: RCF

- Because of crack growth mechanisms, RCF tends to appear:
  - On the High rail of curves on the gauge shoulder/ face region
  - On the Low wheel on the field side of the tread
- Reducing T-Gamma will reduce damage on both wheel and rail in most cases

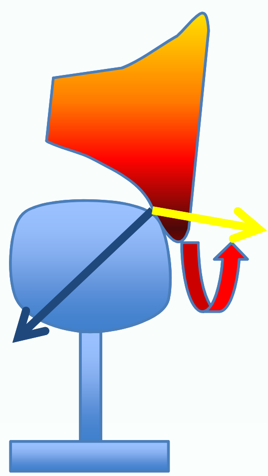


Wheel & Rail Damage: Wear

- When the wheel is in contact with the top of rail, the tread of the wheel is essentially "rolling"
  - Longitudinal and Lateral creep forces dominate

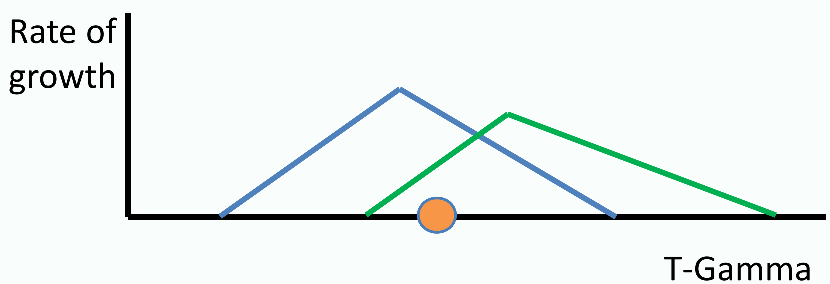


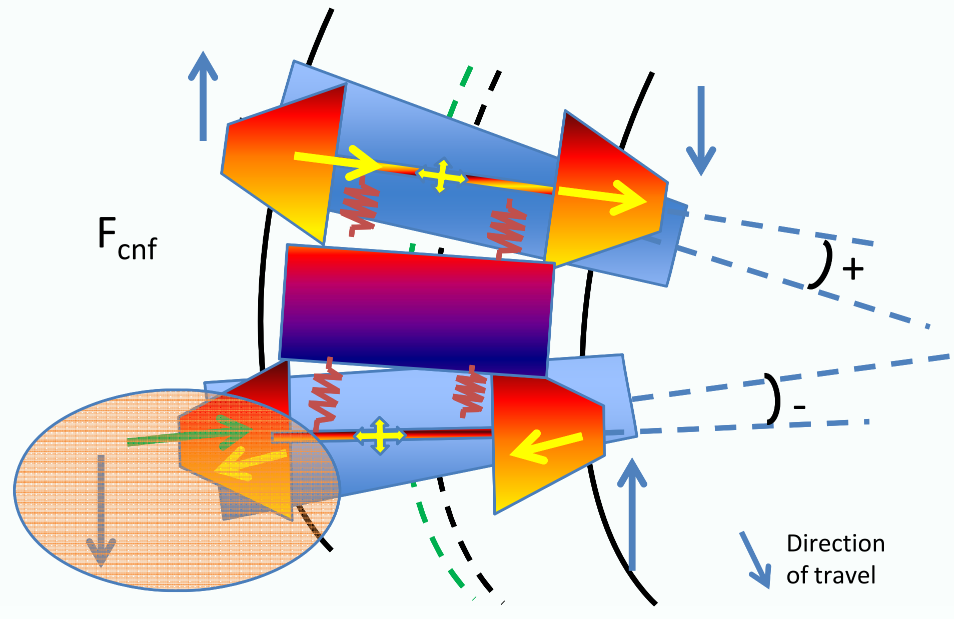
- When the wheel is in contact with the gauge face, a sliding motion of flange relative to the gauge face exists
  - The Spin Creep creates a corresponding moment
  - The wheel is starting to act like a "grinding stone"
- This Spin Moment is highly undesirable and is a main source of gauge face and flange wear



High Rail RCF

- High Rail RCF is caused by excessive T-Gamma on the leading axle whose Longitudinal force direction promotes RCF
- Corresponding Low Wheel RCF is also generated



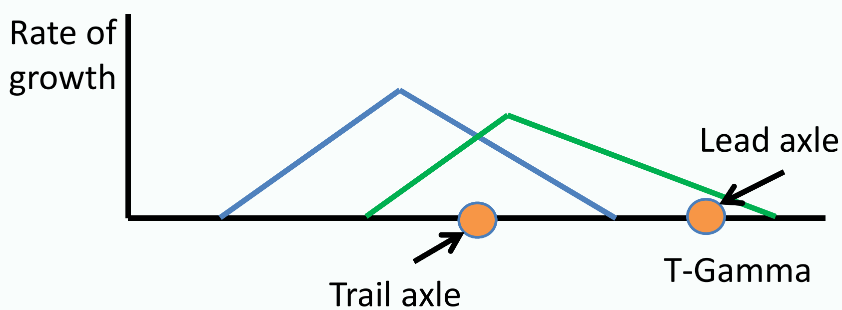


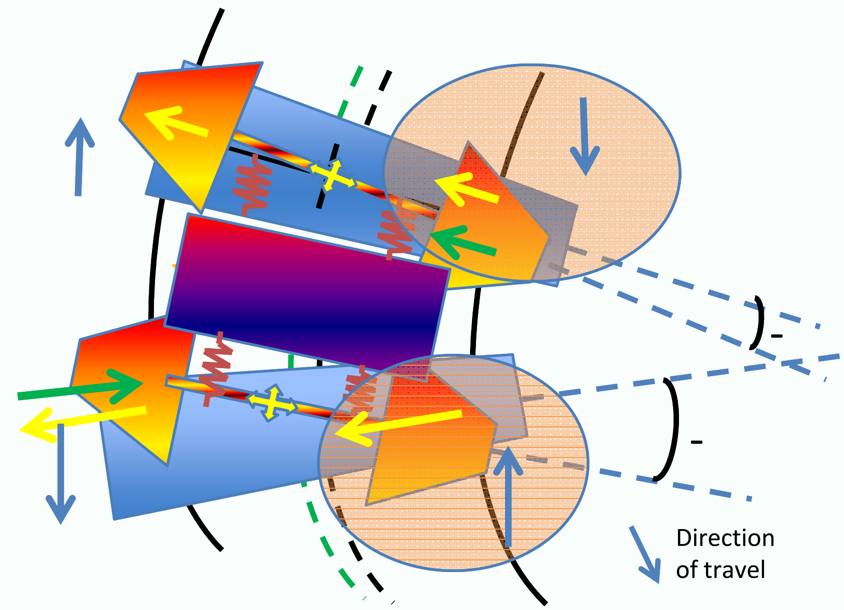
Wheel Forces

Note: Previous slides showed a single Lateral force generated by AOA acting on the axle center rather than the wheels. That was done for graphical simplicity

Low Rail RCF

- Low Rail RCF is caused by Excessive T-Gamma:
  - On the leading axle whose Longitudinal Force direction promotes wear and metal flow
  - On the trailing axle whose Longitudinal Force direction cause RCF
- It usually occurs with extreme Cant Surplus

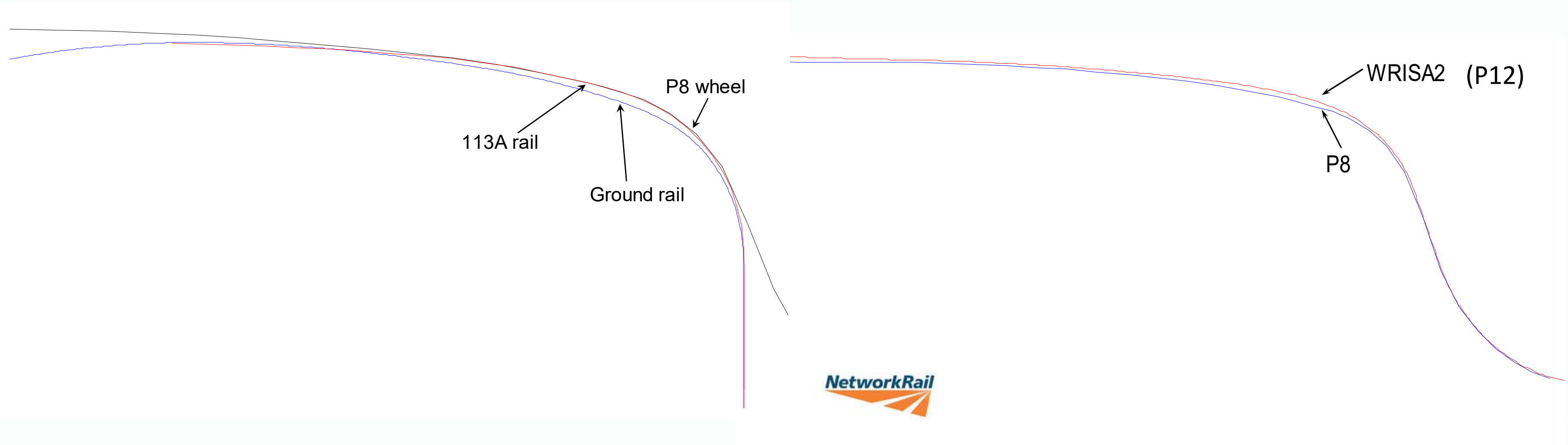




Wheel Forces

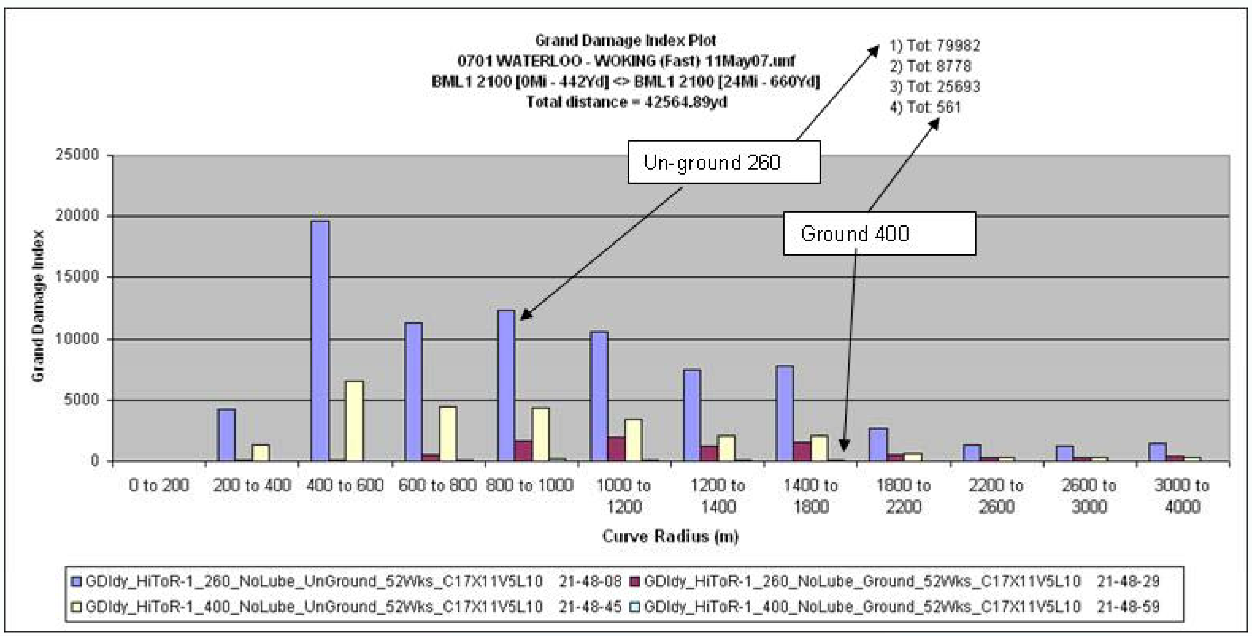
Managing WRI Damage: profiles

- One means of suppressing Outside rail RCF is to preclude contact on the rail shoulder where RCF is likely to appear for standard rail. This can be done by:
  - grinding the rail shoulder (a form of artificial wear)
  - Using a less conformal wheel profile



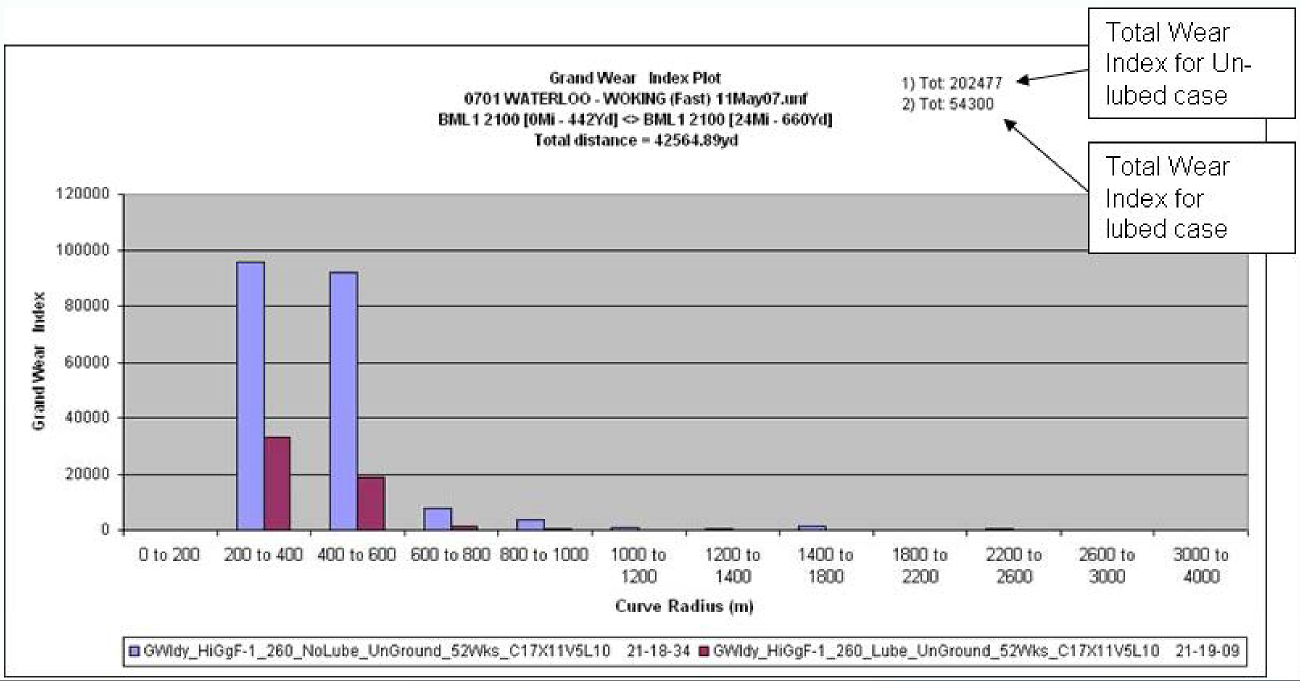
Managing WRI Damage: rail grinding and premium rail

- Grinding reduced the base case RCF by ~90%
- Unground premium rail reduced the base case RCF by ~70%
- Ground premium rail reduced the base case RCF by ~99%



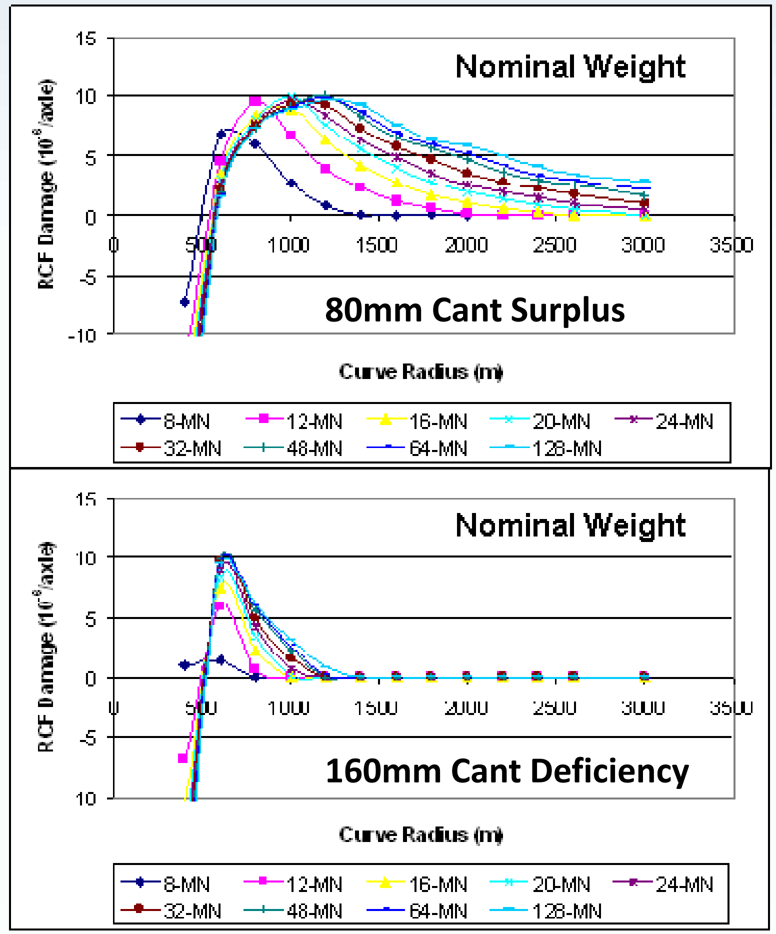
Managing WRI Damage: Lube

- Route-Fleet Analysis models a fleet traversing a route
  - It totals the damage for the entire route and distributes it in a histogram based upon curve radius
- In this case, lubrication reduce gauge face wear by ~75%



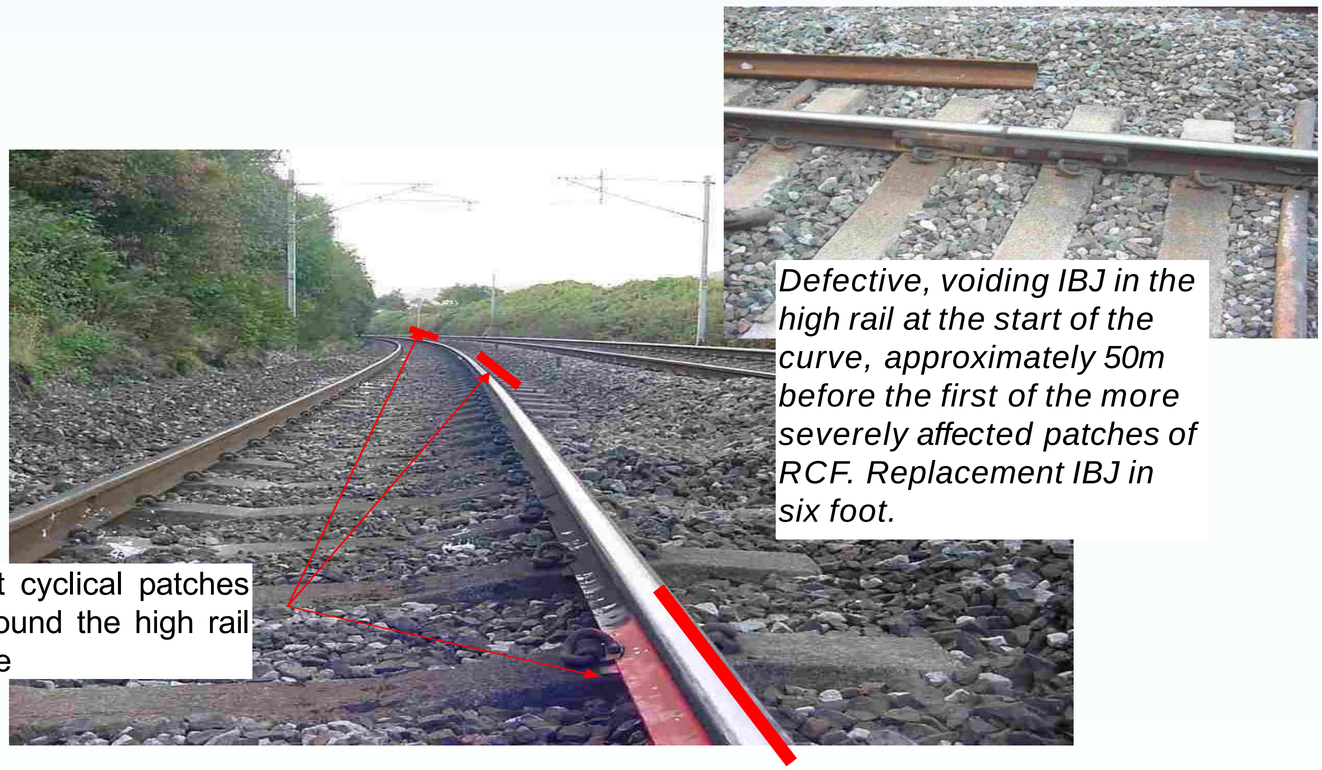
Managing WRI Damage: Cant Deficiency

- Cant deficiency can greatly reduce RCF damage especially in medium-shallow curves
- The effect is most pronounced for bogies with high PYS
- This means trains that stop on curves are prone to generate rail and wheel damage



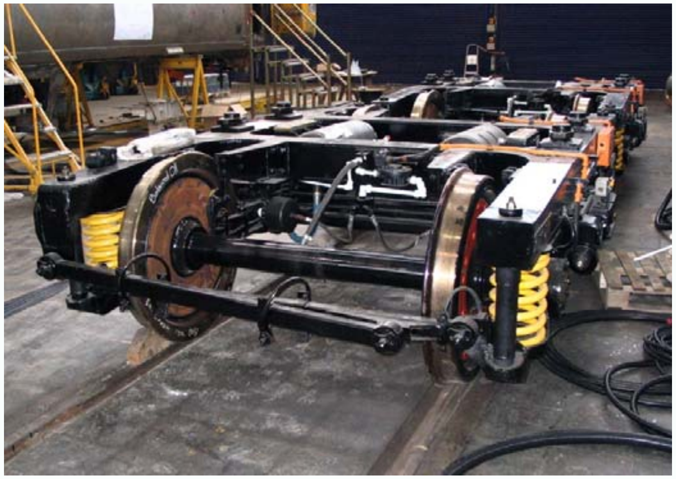
Managing WRI Damage: Track quality

- RCF in “clusters” may be caused by variations in track that satisfy most current track standards



Managing WRI Damage: PYS

- Most contemporary bogies are designed for simplicity to support ease of manufacturing and maintenance
- Vendors supply bogies with a variety of PYS
- In the past, bogies have been designed to minimize forces by adding suspension elements in order to reduce PYS

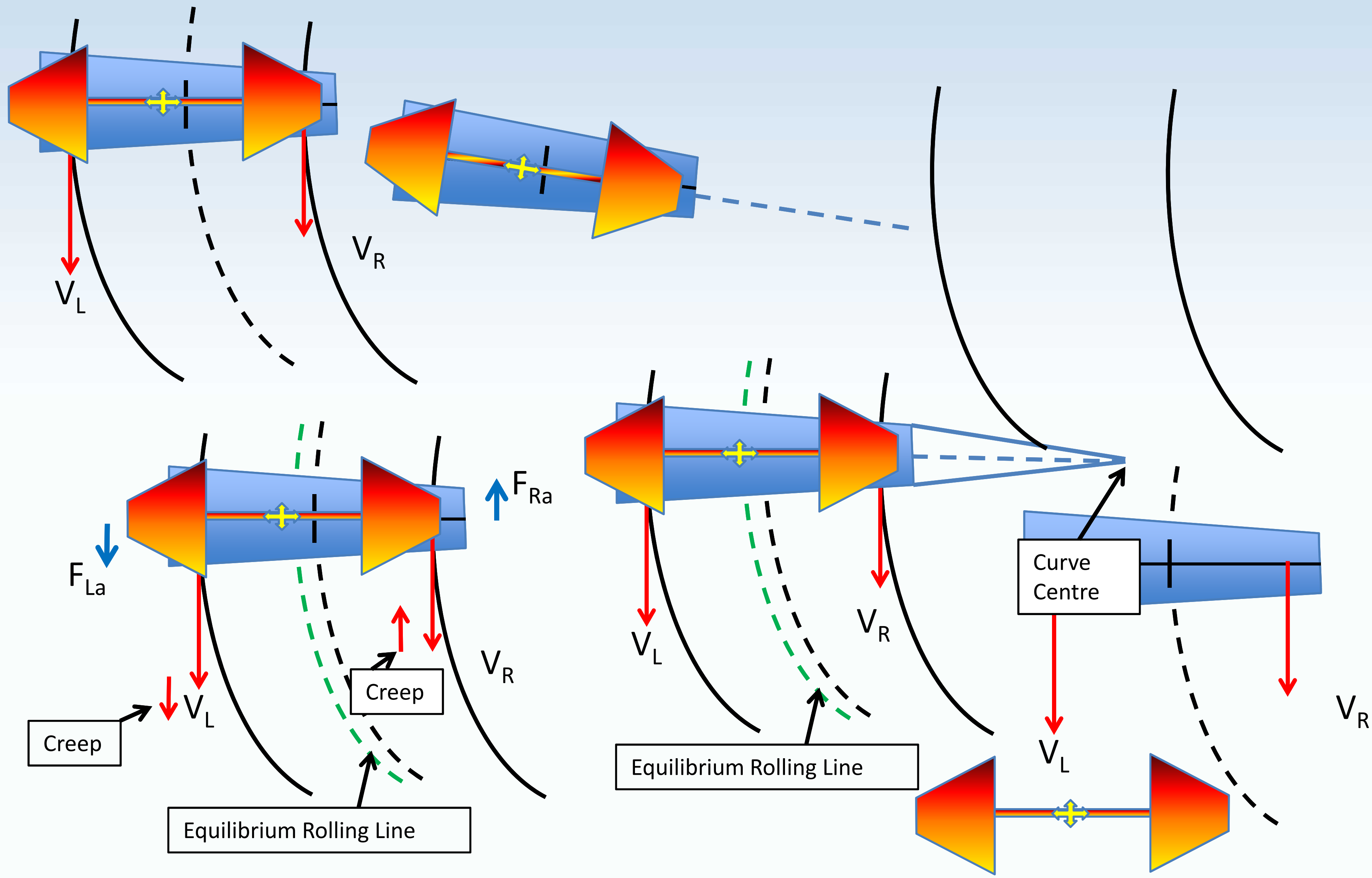


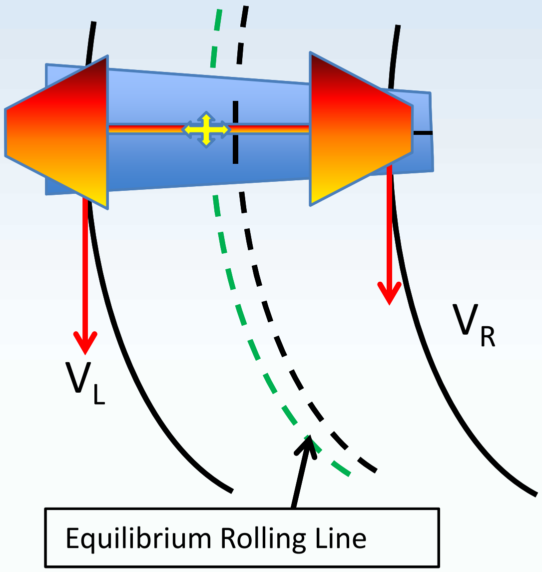
Observations

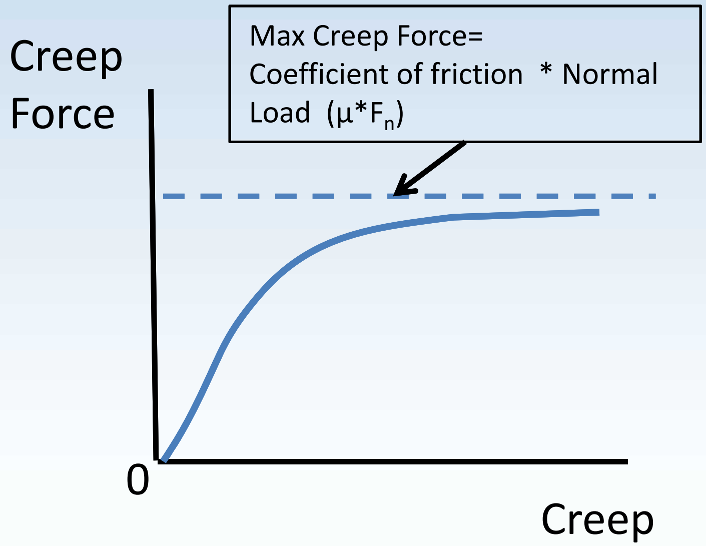
- The WRI is an intangible asset owned by both track and vehicle stakeholders
- The quest to understand the WRI began in the earliest days of the industry but has advanced greatly in the past decades
- But has the current understanding permeated the ranks of industry?
  - Is understanding of the WRI and its implications for safety and cost containment common at all levels?
  - Has this knowledge been translated into appropriate management tools at all levels?
  - Are WRI issues balanced with financial and political points of view?
- Perhaps not

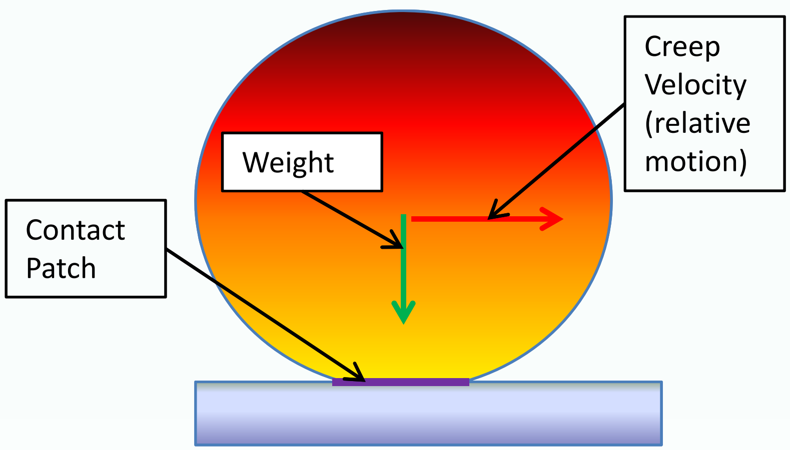
Conclusions

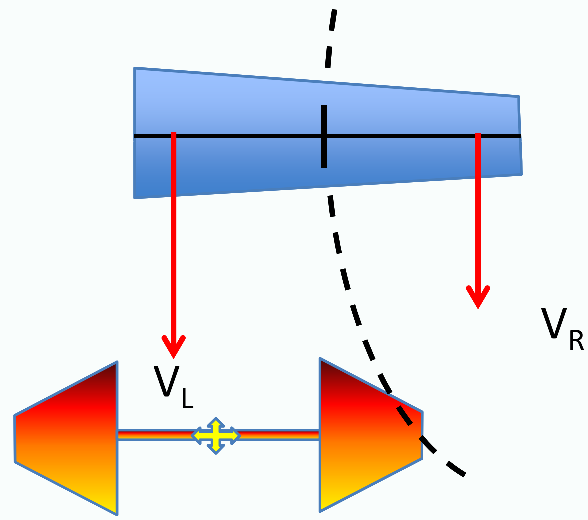
- The industry will continue to progress whether WRI becomes part of the core or not
- But the industry will not become truly optimal unless appropriate WRI knowledge does become common place
- Who will make this happen?

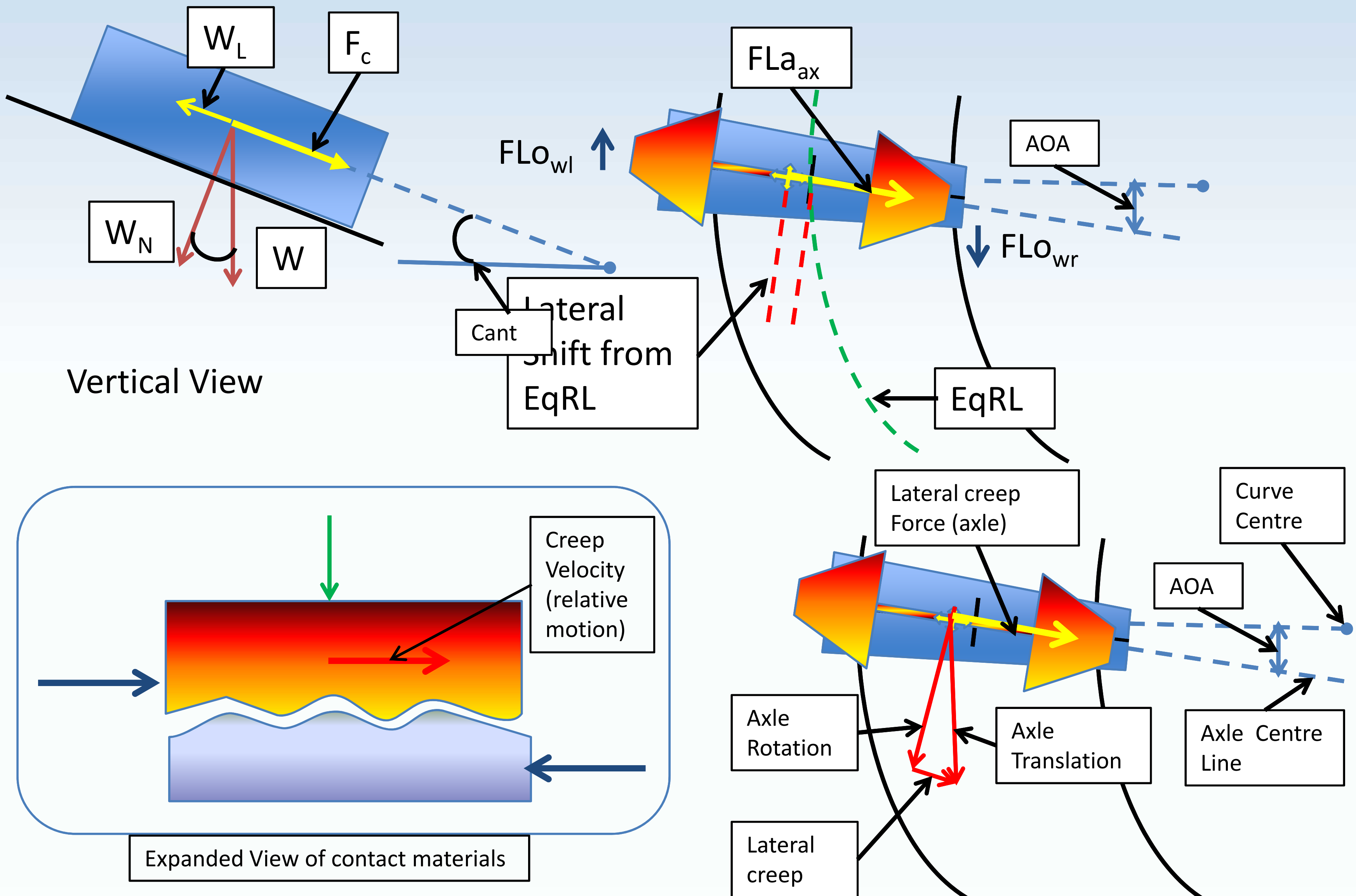

V_L
V_R
F_Ra
F_La
Creep
Creep
V_L
V_R
Equilibrium Rolling Line
V_L
V_R
Equilibrium Rolling Line
Curve
Centre
V_L
V_R


V_L
V_R
Equilibrium Rolling Line

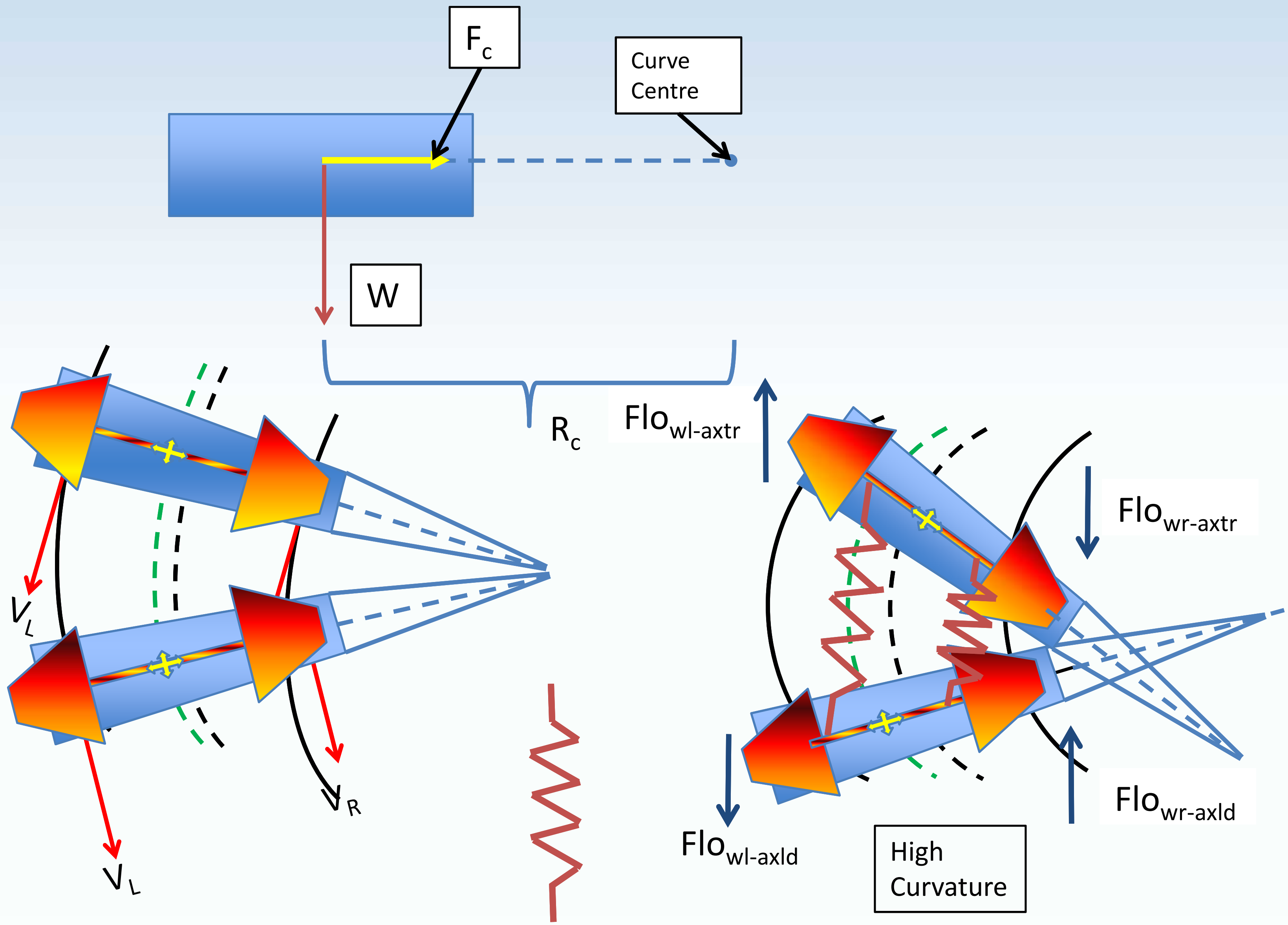

Creep Force
Max Creep Force= Coefficient of friction * Normal Load (μ*F_n)
0
Creep


Weight
Creep Velocity (relative motion)
Contact Patch

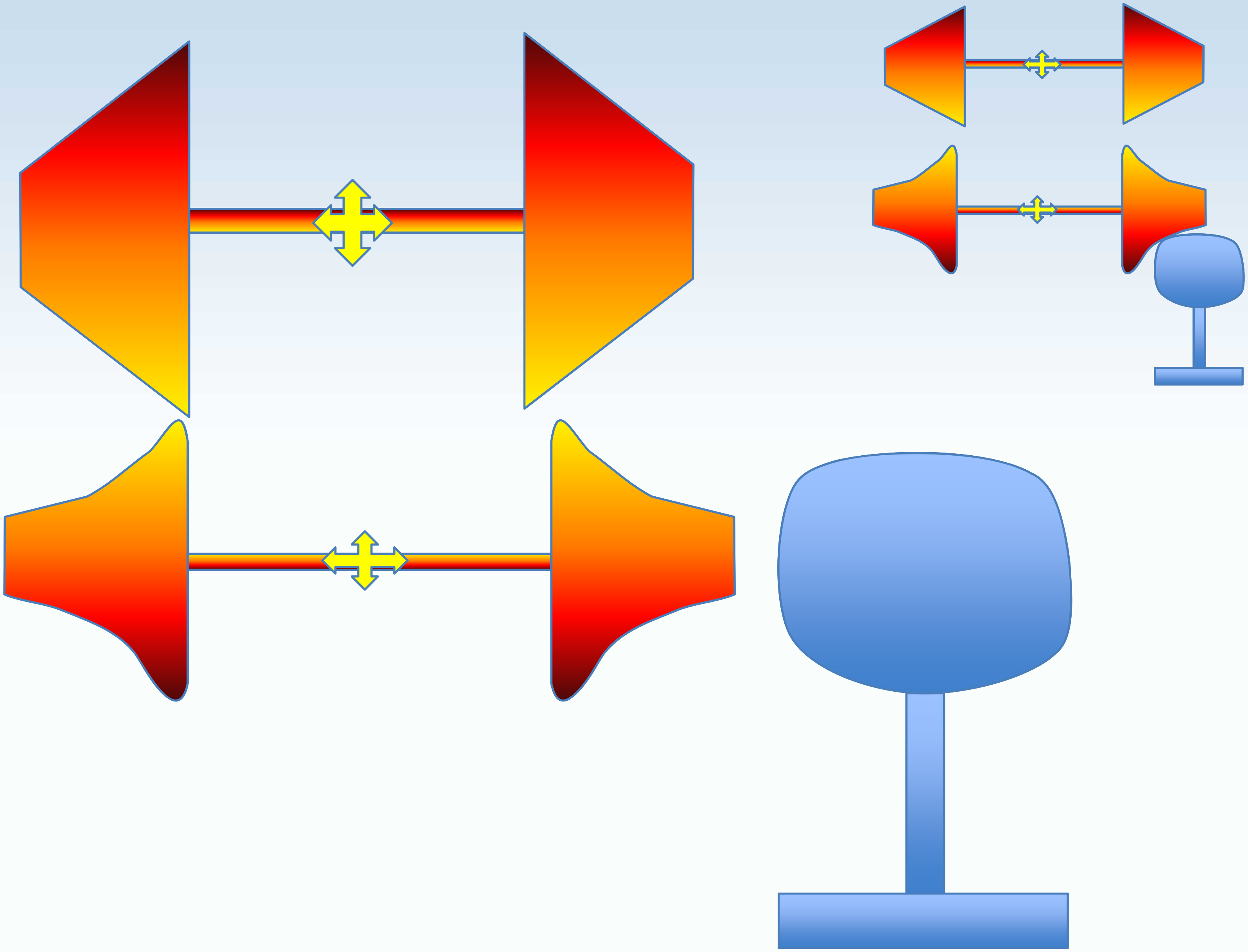

V_L
V_R

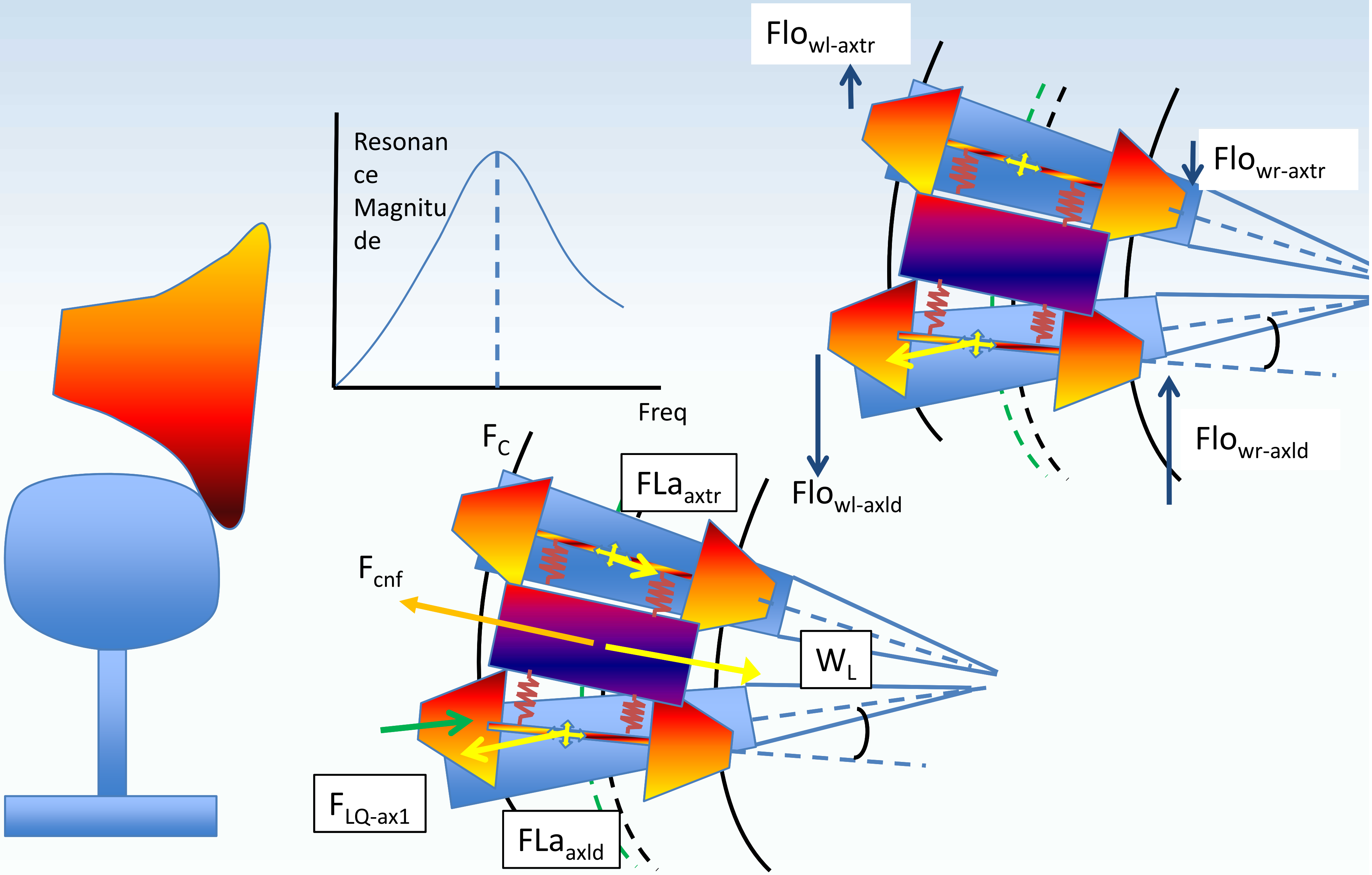


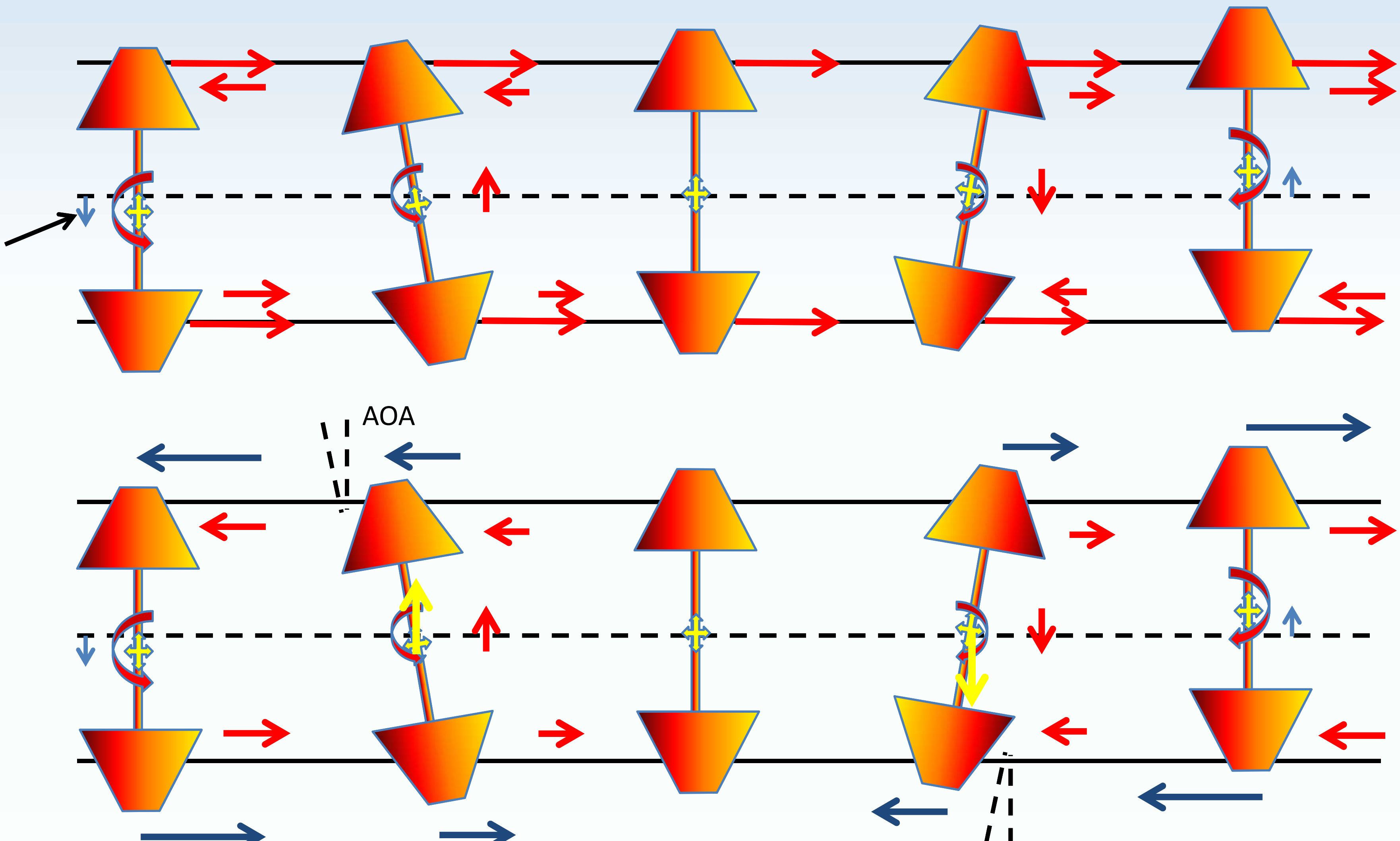
W
L
F
c
W
N
W
Vertical View
FLa
ax
FLo
wl
FLo
wr
AOA
Cant
Lateral shift from EqRL
EqRL
Creep Velocity (relative motion)
Expanded View of contact materials
Lateral creep Force (axle)
Curve Centre
AOA
Axle Rotation
Axle Translation
Axle Centre Line
Lateral creep

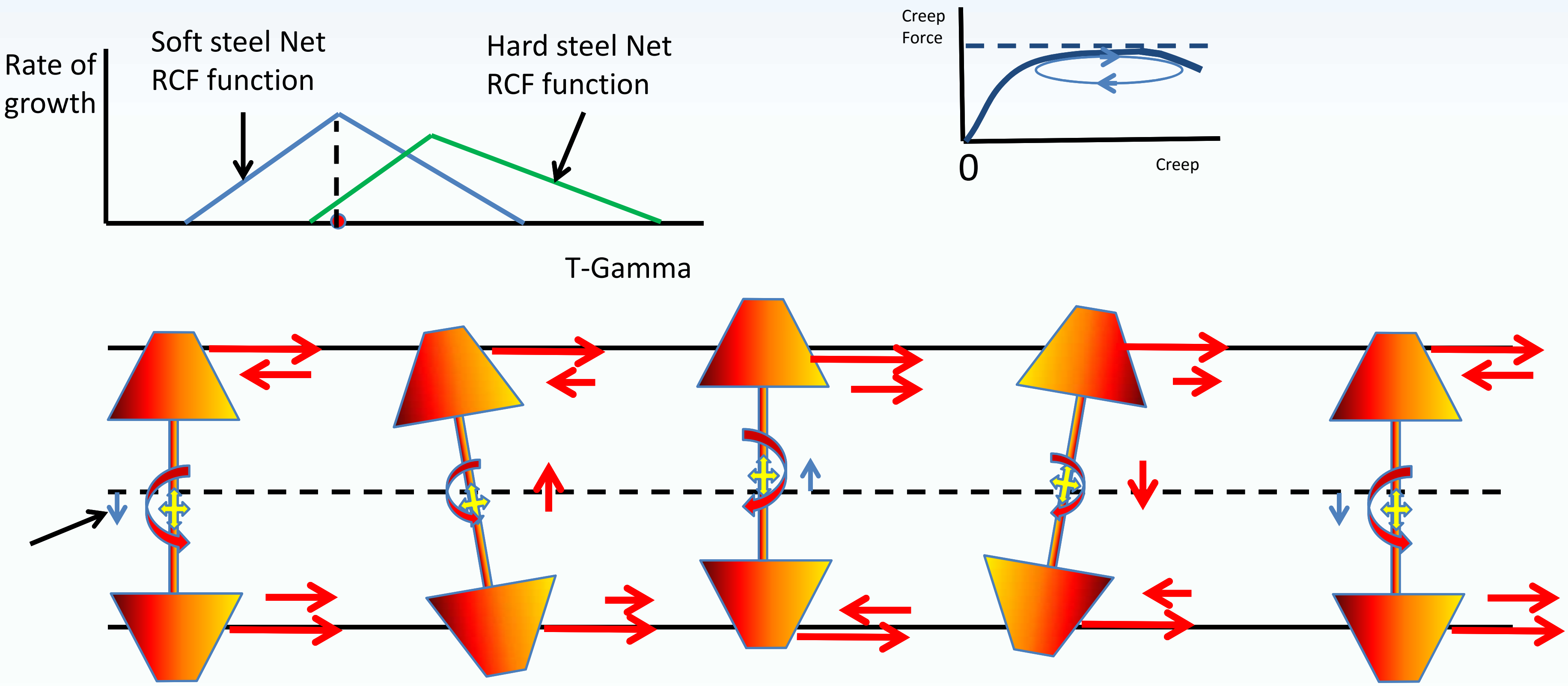


F_c
Curve Centre
W
R_c
$Flo_{wl-axtr}$
$Flo_{wr-axtr}$
V_L
V_R
V_L
$Flo_{wr-axld}$
$Flo_{wl-axld}$
High Curvature




Resonan
ce
Magnitu
de
Freq
F_C
FLa_{axtr}
F_{cnf}
W_L
$F_{LQ\text{-}ax1}$
FLa_{axld}
$Flo_{wl\text{-}axtr}$
$Flo_{wr\text{-}axtr}$
$Flo_{wl\text{-}axld}$
$Flo_{wr\text{-}axld}$


AOA


Rate of growth
Soft steel Net RCF function
Hard steel Net RCF function
T-Gamma
Creep Force
0
Creep