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# CONTROL ALTERNATIVES FOR YAW ACTUATED FORCE STEERED BOGIES

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Abstract: A new design for actively steered bogies (Simson S., 2007) has been proposed for tractive rollingstock to improve not only wheel rail wear and rolling contact fatigue but to also improve wheel rail adhesion. The new bogie design features forced steering with active yaw control of the secondary suspension.

The control alternatives for the new bogie design are limited by the need for the control to act independently to wheel rail creep forces. Two control alternatives are presented, a full active method where the control is applied based on known track alignment and the vehicles position. And a semi active method where the track curvature is estimated from gyroscope inputs with no prior knowledge of the track and a target alignment is estimated. 

Keywords: Application of mechatronic principles; Mechatronic systems; Modelling; Railway Vehicle Dynamics; Train Dynamics.

## 1. INTRODUCTION

The steering task for traction curving of railway bogies is significantly different to the non-tractive or idle case. The difference is due to the large longitudinal creep forces from traction that saturate and diminish other creep force effects. Creep and creep forces is the phenomena of friction between rolling contacts such as a wheel and rail. Rolling contacts have creepage and creep forces in three directions, longitudinal, lateral and spin.

Under high traction loads for the rail friction the moment forces due to longitudinal creep force differences that provide steering and lateral forces due to spin creep that counter gravitational stiffness are diminished. The ideal for steering bogies "perfect steering" (Goodall R. M., Mei T. X. 2006; Goodall R. M., *et. al.* 2006) is no longer the minimal wear solution and is not applicable to hauling locomotives and the alternate concept of "ideal steering" has been proposed (Simson S. A., Cole C., 2007). Ideal steering allows for different longitudinal creep at the wheel contacts, which has minimal effect on the wheel rail wear rates, but allows offsetting of the lateral tracking position so that lateral forces can be balanced by the lateral components of the normal wheel rail contact forces instead of lateral creep forces. Ideal steering requires the bogie to control the steering angle and bogie yaw angle where as perfect steering requires additional control of the wheelset angle of attack or warp angle, (see Figure 1a).

A new design for actively steered bogies (Simson S., 2007) (see Figure 1b) has been proposed for tractive rollingstock to improve not only wheel rail wear and rolling contact fatigue but to also improve wheel rail adhesion. Adhesion being the amount of tractive force achieved by the locomotive and is often a limitation to train haulage performance. Improving wheel rail adhesion in curving requires the steering control to be independent of wheel rail creep forces so that all the available creep force can be used for traction. The new bogie design features forced steering with active yaw control of the secondary suspension. Forced steering is a linkage arrangement that forces the yaw angles of the wheelsets at the primary suspension to match the yaw angle of the secondary suspension in radial alignment of the bogie wheelsets.

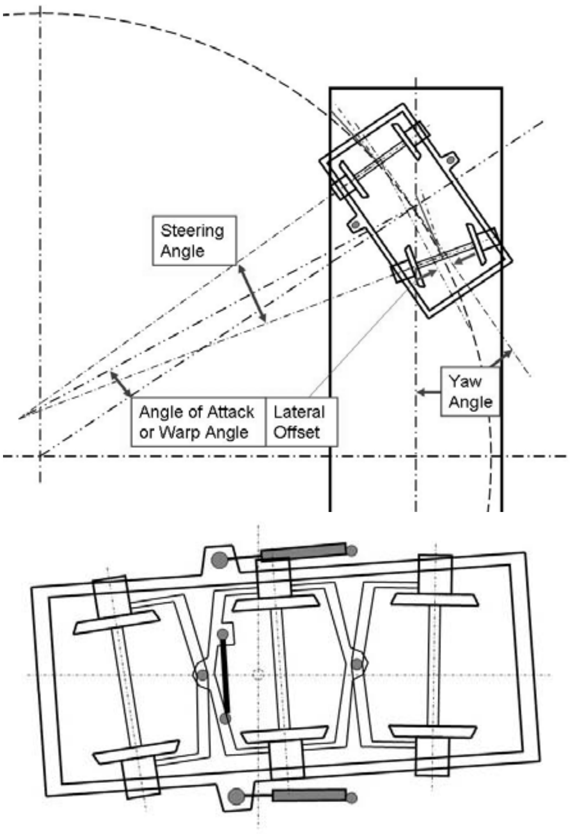


Figure 1 Bogie and wheelset angles involved in idealised steering and the three axle arrangement of a yaw actuated force steered bogie (Simson S., 2007).

Forced steering bogies are only partially dependant on creep forces for steering, (Simson S. A., Cole C., 2008a; Simson S. A., Cole C., 2008b). As such the wear rate on tight radius curves under traction with forced steered bogies only deteriorates slightly from the performance of ideal steering (Simson S. A., Cole C., 2008b). Early linear modelling investigation of the stability of self steering and forced steering bogie designs identified a low frequency instability mode associated with low wheel conicities (Wickens A. H., 2003). Recent studies of force steered bogies have identified improvements in lateral wheel forces from increasing the steering angle produced from bogie yaw rotation to exceed radial steering, (Sato E., *et. al.* 2003).

### *1.1 Active Steering*

Research on active steering (Goodall R. M., Mei T. X. 2006; Goodall R. M., *et. al.* 2006) has focused on actuated wheelset yaw (Schneider R., Himmelstein G., 2004) and secondary yaw activation (Braghin F., *et. al.* 2006) with prototype developments seen on both concepts targeting high speed passenger operations. Theoretical research has looked at the capabilities of independent wheel designs and directly steered wheels (Goodall R. M., *et. al.* 2006). Previous investigations on active steering have not considered high traction curving cases where creep forces become saturated. Hunting instability which any mode of wheelset lateral oscillation those stability decreases with wheel conicity and train speed. Hunting is major limitation to the maximum safe running speed of trains. The control task in active steering is both curve steering and vehicle stability.

Secondary yaw activation control is a system which controls the bogie yaw angle by moving either the bolster or bogie frame with no change in the steering angle of the wheelsets. It can therefore be used to stabilise bogie hunting modes permitting the use of shorter bogie axle spacings. The main advantage in curve steering in secondary yaw activation control is the reduction in peak lateral track shifting forces by balancing the lateral wheel forces on the two or more wheelsets in the bogie. Lateral track shifting forces are the gross lateral forces transmitted to the rails by a wheelset that can cause rail sleepers to move.

For secondary yaw activation total creep forces causing wheel rail wear are not greatly altered (Goodall R. M., Mei T. X. 2006) though there is likely to be some improvement in traction adhesion due to reduced creepages present on the front wheelset. Studies on curving adhesion performance of this concept have not been conducted.

Actuated wheelset yaw control is a system which controls the wheelset steering angle with no direct control of the bogie yaw angle. It would also be possible to have a design that controls wheelset warp angle Figure 1. The authors are not aware of any actuated wheelset yaw controller design that makes use of warp angle. The traction steering performance of actuated wheelset yaw bogie depends on the controller used and the reliance on creep forces to generate control. Controllers that are dependant on creep force inputs perform similarly to self steering bogies (Simson S. A., Cole C., 2008b). Alternatively actuated wheelset yaw controllers can be made to imitate forced steering bogies by eliminating the dependence on creep forces as a control input.

## 2. ACTUATED YAW FORCE STEERED (SIMSON) BOGIES

A provisional patent for a force steered bogie with a secondary yaw control system has been made (Simson S., 2007) covering two and three axle variations. The general configuration of a three axle, yaw actuated, force steered bogie is shown in Figure 1b. The design features actuators on either side of the bogie that control the yaw movement of the secondary suspension and force steering linkages that control the yaw movement of the end axles to match the yaw movement of the secondary suspension. Three axle force steering can be implemented in two alternative forms, the difference in the two bogie designs is the stiffness in the lateral connection of the middle axle to the steering arm. Options range from a stiff connection (e.g solid bar) to soft connections including free floating.

Under ideal steering, correct bogie tracking in a curve is achieved with a combination of wheelset steering angles and bogie yaw angle (see Figure 1a). The yaw actuated force steered bogie (Simson S., 2007) has direct control of the bogie yaw angle and the force steering linkages set the wheelset steering angle. This is achieved with the placement of actuators at or above the vehicle's secondary suspension and with potential redundancy from duplicate actuators giving a significantly more robust design than actuated wheelset yaw permits.

*2.1 Eigen Mode Analysis*

An Eigenvalue analysis has been conducted on the linearised vehicle models for Simson bogie without actuator control. The Eigenvalue analysis identified numerous distinct modes involving yaw or lateral movement of the wheelsets across the rails. Selected results form the Eigenvalue analysis are given in Table 1. It was noted that not all of these modes can be described as hunting modes and only those modes that become unstable with changes in running speed or conicity are termed hunting modes. The unstable modes identified can be broadly classified as: vehicle hunting; bogie hunting; primary suspension hunting. All of these modes occur with frequencies under 7 Hz for the modelled vehicle. Additional modes involving bogie sway and yaw oscillations of the wheelsets and steering linkages where identified at frequencies above 12 Hz. None of these higher frequency modes were unstable for speed or conicities tested.
The vehicle hunting mode, Table 1 (note: conicities reported are 0.005 and 0.05 for this mode), can be dismissed in that it is unstable only at low wheel profile conicities and then only if the bogie rotation friction is made very low as was the case in the linearised model. The vehicle hunting mode operates well below the frequencies of kinematic wheelset oscillation described by Klingel (Wickens A. H., 2003). The vehicle hunting mode was previously identified by Wickens Table 1. At lower speeds and conicities bogie hunting modes for front and rear bogies, are the same and are so heavily damped that they do return eigenvalues for the model evaluated. As speed and conicity increase the rear bogie mode becomes distinct with a higher frequency than the front bogie hunting. Hunting of the front and rear bogies are different as the force steering linkage to the vehicle body on the rear bogie steers the axles in the opposite direction to the bogie yaw motion. Consequentially both bogie hunting modes yaw the vehicle body with limited connection to the body sway motions. The Eigen values for bogie hunting vary between 2 – 4 Hz for a wide range of train speeds (50 – 300 kph), with the critical speed being dependant on wheel conicity.

There are several primary suspension hunting modes all of which either correspond or closely match the natural frequency for longitudinal oscillations of the end axles on the steering linkages. That frequency for the tested vehicle model is approximately 5 Hz. All of these modes go unstable at close to 250 kph in the linearised model except for the case when the middle axle is disconnected to the steering links which hunts at a lower speed. Active control of any of these instability modes with linkage based forced steering is unlikely as they are essentially oscillations of the steering linkage connection stiffness.

*2.2 Control Task Simson Bogie*

As with any actively steered bogie the controller has two primary functions which are curving and stability. The control target during curving for the Simson bogie (Simson S., 2007) is to keep the bogie yaw position tangential to the rails. The controller must also control hunting and bogie oscillations with frequencies up to 4 Hz for the modelled vehicle.

Table 1 Eigenvalue analysis, undamped natural frequencies and damping ratio

| **Mode** | **50 kph, λ = 0.05** | | **50 kph, λ = 0.50** | | **260 kph, λ = 0.05** | | **260 kph, λ = 0.50** | |
|---|---|---|---|---|---|---|---|---|
| | [Hz] | [%] | [Hz] | [%] | [Hz] | [%] | [Hz] | [%] |
| Vehicle Hunting [*1] | 0.071 | -65 | 0.111 | 33 | 0.182 | -86 | 0.170 | 57 |
| Front Bogie Hunting | - | | 3.47 | 32 | 2.25 | 18 | 4.57 | -11 |
| Rear Bogie Hunting | - | | 4.00 | 33 | 3.51 | 44 | 4.85 | -13 |
| Primary Hunting A type | 5.0 | 6 | 5.0 | 6 | 5.0 | -2 | 5.0 | -2 |
| Primary Hunting B type | 5.29 | 36 | 5.58 | 27 | 4.8 | 1 | 5.4 | -5 |
| End axle longitudinal oscillation | 4.71 | 0 | 4.71 | 0 | 4.71 | 0 | 4.71 | 0 |

[1] The conicity (λ) for the vehicle hunting mode are 0.005 and 0.05

The vehicle hunting mode, which has frequencies under 0.2 Hz for the simulated speeds, can probably be ignored as it likely that passive friction in the bogies secondary yaw suspension in real bogie systems will be sufficient to control this mode.

## 3. CONTROL SYSTEMS

Two control approaches are reported on in this paper.

- Full active control method (has prior knowledge of the track alignment) sensing bogie frame misalignments to a predetermined target yaw.
- Semi active control method that uses a track curvature estimate based on sensing bogie angular velocity with train speed and determining misalignments to a calculated target yaw which is set by the track curvature estimate.

The control feedback loop for both the full active and semi active control methods used in simulation testing includes low pass filters to model sensor and actuator delays that would occur in actual implementations. Both the control input and output signals are filtered with a 3 pole 16 Hz low pass filter. Simulations have also been done using a feed forward controller to determine the bogies ultimate capability.

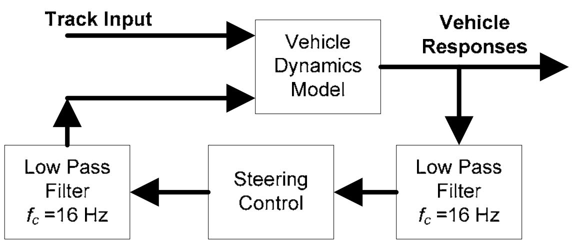


Figure 2 Control feedback for active steering simulations

The final control equation (Equation 1) is based on the calculated yaw misalignment of the bogie to the rails.

Equation 1 Final control equation.

$$X_i = G_p \times \psi_i + G_d \times \frac{d\psi_i}{dt} + G_i \int_{t-s}^{t} \psi_i \cdot dt$$

Where:

| | |
|---|---|
| $X_i$ | Control for bogie i |
| $\psi_i$ | Misalignment yaw bogie i |
| $G_i$ | Gain integral |
| $G_t$ | Gain derivative |
| $G_p$ | Gain proportional |
| $t$ | time |
| $s$ | Integral time |

### *3.1 Full Active Curvature Misalignment*

Under full active control track geometry data, determined for the track position is used to determine a target yaw angle required for each bogie. Control is then determined by Equation 1 based on the misalignment to the target yaw, (Equation 2). The stability of this control method depends on the phase shift position of the control in relation to the oscillation response, (Tananifuji K., *et. al.* 2003). Damping of the response is achieved with the actuator force being ¼ wavelength behind the yaw misalignment. The authors (Tananifuji K., *et. al.* 2003) use a half wavelength of kinematic oscillation for a phase shift delay of the control. Signal processing and actuator responsiveness mean a proportional control input has a small phase shift delay to the yaw misalignment and increases the hunting instability. Stability of the Simson bogie (Simson S., 2007) is thus obtained with a damping force opposing the yaw misalignment velocity (i.e derivative control). The derivative control used has a negative gain setting compared to proportional gain on the steering control. The stability control feature therefore has a direct and negative impact on steering control responsiveness.

Equation 2 Full active misalignment.

$$\psi_i = \varphi_i - \varphi_{ti}(x)$$

Where:

| | |
|---|---|
| $\psi_i$ | Misalignment yaw bogie i |
| $\varphi_{ti}(x)$ | Yaw target alignment bogie i, a function of x |
| $\varphi_i$ | Measured yaw alignment bogie i |
| $x$ | positon along the track |

The steering task changes in curve transitions requiring good steering responsiveness, so it is in curve transitions where stability control competes with steering control. The use of a yaw velocity derivative (yaw acceleration) can improve the responsiveness of the stability control but a derivative can not be applied to the steering control. Determining a target yaw for use in the curve transition is more difficult than in the regular part of the curve. Articulated or force steered bogies are notable for the curving difficulty they experience in transition curves. The bogie yaw angle required for tangential alignment in transition curves is dependant on the changing curvature between the bogies and the resulting steer angle of the wheelsets do not match the present curvature. To minimise creep forces the Simson bogie (Simson S., 2007) needs some angle of attack during the transition in order to change the lateral position of the wheelsets to and from a curving alignment.

The transitional curve control can be implemented with a weighted curvature assessment where the curvature at each bogie is used to determine a target yaw (see Equation 3, Figure 3). This method can be further adapted with a delay factor where the curvature is determined for a point ahead of the vehicles current position thus giving the bogie an angle of attack throughout the curve transition. On a short transition (~6 times the bogie semi spacing) using a weighting ratio (n) of 3 and a delay factor of 1.3 times, the bogie semi spacing of X m, has given minimum wear energy in simulation using "ideal steering" as the control target. Further work is required to assess the optimal steering target yaw for a range of transition curves.

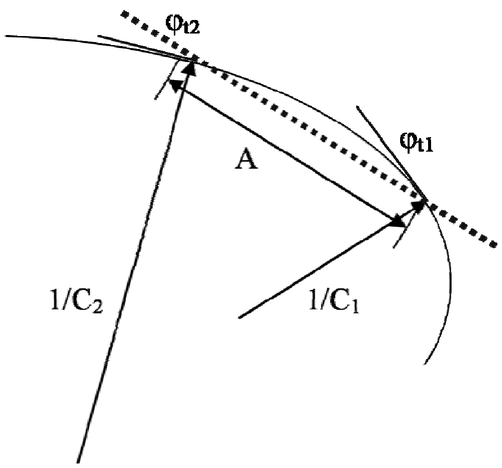


Figure 3 Target yaw calculation

Equation 3 Bogie 1 target yaw angle.

$$\varphi_{t1} = A \times \left(n \times C_1(x) + C_2(x)\right)/(n+1)$$

Where:

| | |
|---|---|
| $\varphi_{ti}$ | Target yaw bogie i (1 or 2) |
| $A$ | Bogie semi spacing |
| $C_i(x)$ | Curvature at bogie i (1 or 2) centre position, a function of track position |
| $n$ | weighting ratio for bogie curvature |

### *3.2 Semi Active Estimated Curvature Misalignment*

Active steering with curvature estimation has been implemented in a simulation of a prototype secondary yaw control bogie (Braghin F., *et. al.* 2006). In practice gyroscopes can be mounted to provide the yaw velocity of the bogie and the vehicle body so these measurements, together with the train speed, allow the instantaneous curvature to be estimated. The control can then be applied based on the bogie misalignment to a estimated target yaw, Equation 4. In such as system, there is the problem that bogie yaw velocity could also be due to lateral bogie frame oscillations or a hunting instability described in section 2.1 giving a unstable feedback loop. The presence of yaw velocity dependent term in Equation 4 creates additional feedback to the full active method.

During curving, the lateral oscillations on the front bogie are detrimental to the control as additional yaw is required in the same direction to match a calculated target yaw. The rear bogie hunting mode, however, is damped by the steering control as the steering yaw angle is opposite to the curvature. The vehicle hunting mode (section 2.1) is also not excited by the curving estimates as the yaw velocities are to low. At very high speeds, vehicle hunting could be excited by the curving control however such speeds are unlikely, for the locomotives simulated, due to primary suspension hunting modes.

Equation 4 Semi active misalignment.

$$\psi_i = \varphi_i - \varphi_{ei}\left(\frac{d\varphi_i}{dt}\right)$$

Where:

| | |
|---|---|
| $\psi_i$ | Misalignment yaw bogie i |
| $\varphi_{ei}$ | Yaw alignment estimate bogie i |
| $\varphi_i$ | Measured yaw alignment bogie i |
| $x$ | positon along the track |
| $t$ | time |

Yaw velocity oscillation for: the vehicle body; the front bogie; and the rear bogie are shown in Figure 4 together with the bogie yaw oscillations during high speed hunting instability simulation. A modified yaw oscillation for each bogie is also shown in Figure 4 which is bogie yaw velocity with the bogie to body relative yaw angle velocity subtracted.

The body yaw velocity is the most stable curve estimate input to the front bogie hunting. The alternative would be to filter input for curve sensing with a low pass filtering to remove the 2-4 Hz frequency of the bogie hunting modes. All these curve sensing approaches place considerable delay to determining the start of curve transition for the lead bogie.

The body yaw acceleration can be used with a low pass filtering to remove instability effects, to identify the change in curvature during the curve transition. The yaw acceleration has to be divided by train velocity to give change in curvature per unit length. Together with the body yaw velocity used to identify the track curvature under the vehicle we can now estimate the change in curvature under the vehicle. The target yaw for each bogie can then be set based on the estimated current track curvature and estimated change in track curvature. The filtering required on the estimate of change in curvature will cause some tracking errors at the ends of the transition curve.

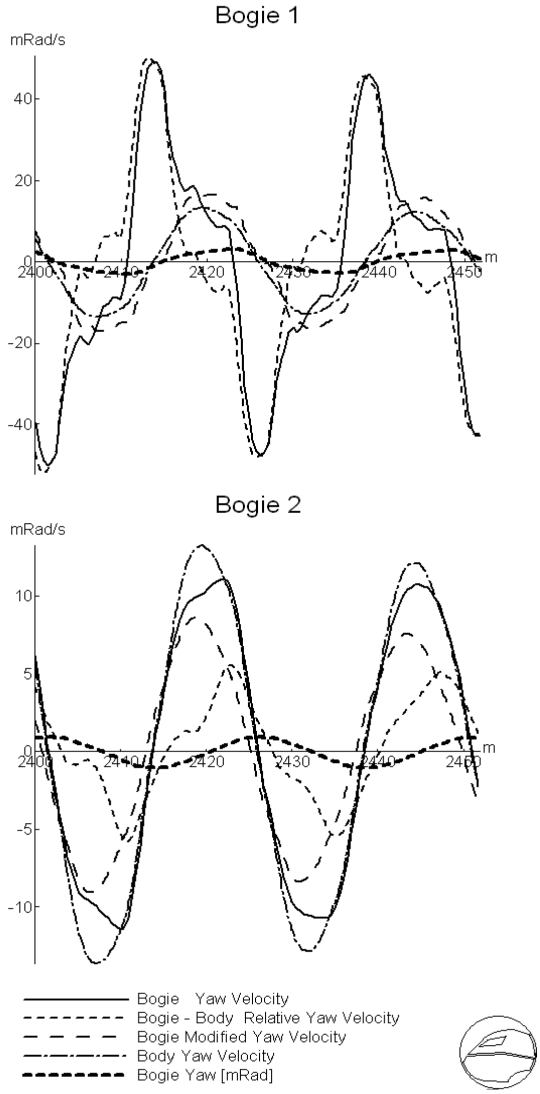


Figure 4 Bogie and Body Yaw Velocity During Hunting

## 4. CONCLUSIONS

The control problem for all steering bogie designs must be a trade-off between the lateral stability performance and the curve transition performance. Lateral stability of actuated yaw force steered bogies at high speeds requires the bogie hunting mode to be controlled. To control bogie hunting the yaw velocity of the bogie has to be damped. The front bogie of a actuated yaw forced steered vehicle, the same yaw damping resists bogie alignment on the curve entrance transition. Semi active control faces added challenges of detecting curve transitions and distinguishing curving from lateral instability movements. Improved steering control is achieved with systems that estimate both the curvature and the change in curvature using the vehicle body yaw acceleration. Front bogie hunting instability requires the use of low pass filtering of the change in curvature estimations based on body yaw accelerations. The filtering delays this input signal reducing steering performance on curvature entrances and exits.

## ACKNOWLEDGEMENTS

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