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Active Control of Railway Bogies – Assessment of Control Strategies

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Abstract

A number of configurations for active control of railway vehicle bogies are assessed in a consistent framework to provide an effective comparison, using a typical modern bogie as a baseline. For each configuration appropriate control strategies are identified and their relative performances are assessed in terms of straight track stability, curving performance and control requirements.

Key words : Mechatronic, Active suspension, Active Steering, Active Guidance, Railway, Bogie, Control

1. Introduction

The scientific background relating to active or “mechatronic” bogies has been established for some time (Goodall and Kortum, 2002; Bruni et al, 2007). A mechatronic bogie solution is offered by Bombardier Transportation (Anon, 2014) which has not yet been used for service vehicles, but it seems that the industrial interest is now growing with specific references in both the European Commission’s Shift2Rail Master Plan (Shift^{2}Rail, 2014) and the UK’s Railway Technical Strategy (Future Railways, 2012).

A state-of-the-art review paper in 2009 (Bruni et al, 2007) identified five distinct mechanical/control configurations that could be considered for enhancing the stability and curving performance, i.e. concentrating upon controlling the lateral and yaw modes of the running gear. These are: Secondary Yaw Control (SYC), Actuated Solid-axle Wheelset (ASW), Actuated Independently-Rotating Wheelset (AIRW), Driven Independently-Rotating Wheelset (DIRW) and Directly Steered Wheels (DSW). Although this paper made reference to control strategies associated with each, they were not assessed in a consistent framework to quantify the relative merits in terms of capability for improved performance, sensing and actuation requirements, etc. The purpose of this paper is to examine in more detail the control system issues using parameters for a typical modern bogie as a baseline for comparison: a half-vehicle model involving two axles, the bogie frame and a half body is used. The control possibilities for each configuration are discussed, and the performance is assessed in terms of straight track stability, curving performance and control/actuation requirements.

Note that, although all these configurations could be applied to a bogie-less two-axle vehicle, for this paper the study is focused upon assessing performance benefits arising from the use of active bogies for a typical, four-axle, medium-to-high-speed passenger vehicle.

2. Nomenclature

Table 1 Physical parameters and values

Name	Symbol	Value	Units
Half vehicle body mass	m_v	15000	kg
Secondary yaw damper/actuator semi-spacing	A	1.25	m
Bogie semi-wheelbase	L	1.3	m
Bogie yaw inertia	I_{bz}	987	kgm^2

Radius arm length	D	0.45	m
Wheelset mass	m_w	1120	kg
Wheelset yaw inertia	I_{wx}	730	kgm^2
Wheelset pitch inertia	I_{wy}	30	kgm^2
Wheel rolling radius	r_0	0.45	m
Half gauge width	l	0.75	m
Load per wheelset	W	60000	N
Longitudinal creep coefficient	f_{11}	$10e^6$	N
Lateral creep coefficient	f_{22}	$8.8e^6$	N
Wheelset conicity	λ	0.25	-
Primary shear spring lateral stiffness	k_{wy}	$1e^6$	N/m
Primary shear spring longitudinal stiffness	k_{wx}	$1e^6$	N/m
Axlebox lateral semi spacing	c	1	m
Bush longitudinal stiffness	k_{wxb}	$14e^6$	N/m
Bush lateral stiffness	k_{wyb}	$4e^6$	N/m
Secondary shear spring lateral stiffness	k_{by}	$1.12e^6$	N/m
Secondary yaw stiffness	$k_{b\psi}$	$200e^3$	Nm/rad
Secondary lateral damper	f_{by}	$60e^3$	Ns/m
Secondary longitudinal yaw damper	$f_{b\psi lin}$	$250e^3$	Ns/m
Track radius of curvature	R	500	m
Track cant	θ_c	6	^{o}
Vehicle speed	V	31.6	m/s

3. Configurations and control for active bogies

This section provides an overview of the five configurations, and more detail can be found in the papers that are referenced. It also discusses control strategies for each and explains which of the options is analysed and simulated in the paper. The controller must provide stable running on straight track without unnecessarily responding to the track irregularities, and during curving must also avoid hard contact with the wheel flanges, minimize the longitudinal wheel-rail creep forces (ideally zero once the curve transition has been negotiated) and equalize the lateral creep forces between all axles. Some graphical results are included in the sub-sections that describe each configuration to illustrate the effect of the control action, but the quantitative results are brought together in a comparison table in Section 5.

Active control offers the possibility to receive “feed-forward” information that defines the design alignment; while this may often be advantageous it implies high-accuracy, high-integrity data from the infrastructure which is not currently available. Hence this paper only considers strategies based upon feedback control from sensors fitted to the vehicle itself. In addition it is assumed that appropriate variables can be either sensed or estimated, even though the provision of accurate reliable sensing is a key aspect of mechatronic design. For example to achieve guidance the lateral wheel-rail displacement is a particularly valuable measurement which may be practically difficult to measure, but various approaches for estimating this have been proposed. Similarly idealized actuators are assumed, i.e. using no particular actuator technology, the effect of which has been considered elsewhere (Md. Yusof et al, 2010). The rationale is that it’s first important to understand what can be achieved without considering the practicalities of sensing and actuation – at a later stage such practicalities can be brought into the design process.

It is also important to allow for the multi-variable nature of the problem, because the two wheelsets are strongly coupled in a dynamic sense via their connections to the bogie frame. However a simple, practical method for minimizing the control complexity is to take advantage of the essential symmetry and introduce modal control such that sum and difference of the lateral wheel-rail displacements to provide sum and difference control commands for the two axles, respectively: this enables the two (lateral and yaw) control loops to be designed relatively independently of each other. This approach is used for all the configurations except SYC.

3.1 Secondary Yaw Control (SYC)

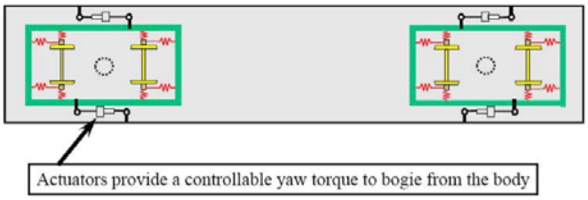

Fig. 1 Basic configuration for Secondary Yaw Control

Actuators between the body and bogie frame are used to provide a controllable yaw torque onto the bogie, as shown in Fig. 1. Although the actuation operates at the secondary suspension level, the aim is to improve vehicle running dynamics rather than ride comfort. The actuators will normally be designed to replace the pair of conventional (passive) yaw dampers so that active control of the running gear can be introduced without a substantial redesign of the bogie. Control action may be applied either at low frequencies (<0.5 Hz) to enhance curving (Braghin et al, 2007) or at higher frequencies (2-10 Hz) for stability control. The latter is of less immediate interest because stabilization is the function of the passive yaw dampers which have been replaced, but there is the potential for stabilizing a bogie with a much softer primary yaw suspension which will also give improved curving (Prandi et al, 2015). However in this paper the primary yaw stiffness (PYS) is kept the same as for the passive vehicle.

The strategy adopted is that proposed by Braghin et al (2007), in which stability is provided by emulating the yaw damper characteristics via the actuator(s), with an additional force to provide enhanced steady-state curving. One approach would be to equalize lateral wheel-rail displacements of the leading and trailing wheelsets, but the longitudinal creep forces would produce yaw torques equal in both magnitude and sign, certainly not a good steady-state curving situation. The ideal strategy is to minimize the total creep forces for the two wheelsets but this potentially represents a complex strategy, and so a simpler approach which on steady curves equalizes the lateral forces at the two wheelsets of the bogie is used. The error between the two forces can be processed via a proportional plus integral (PI) controller to determine the required yaw torque, which can then be added to the higher-frequency stabilizing forces that emulate the passive damping. Another possible strategy is to equalize the yaw moments applied to two wheelsets on steady curves: this will potentially reduce the total wear work on curves, but of course this can only be achieved by having unequal lateral forces.

3.2 Actuated Solid-axle Wheelset (ASW)

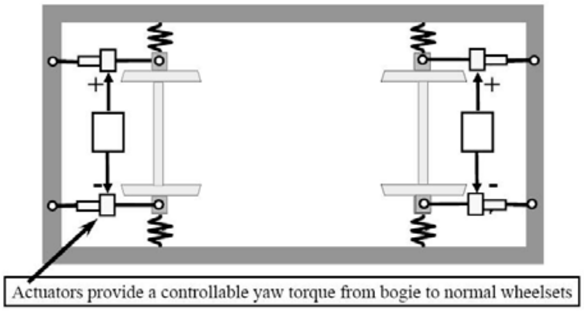

Fig. 2 Basic configuration for Actuated Solid-axle Wheelset

Figure 2 shows how in this configuration a yaw action is applied onto a solid-axle wheelset in a manner that affects the plan view dynamics of the two wheelsets and the bogie. This will often be achieved using a pair of linear actuators working in opposition from the bogie frame to each axle box. As before, control can be aimed towards either stability or curving (or both). Bombardier’s mechatronic bogie project (Pearson et al, 2004) achieved bogie stability with a soft primary yaw suspension so that the natural steering action of the wheelset is more effective, although it’s also possible to further improve curving ability (Shen et al, 2004).

For this study the concept of active yaw relaxation described by Shen and Goodall (1997) is used. This has actuators with longitudinal series stiffness equal to that for the passive vehicle so as to ensure dynamic stability, but the two actuators' lengths are altered at low frequencies during curving so as to bring the longitudinal actuator forces to zero – see Fig. 3.

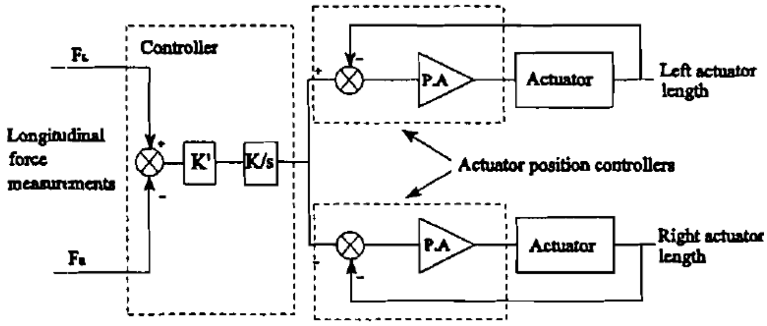

Fig. 3 Active yaw relaxation control scheme (from Shen and Goodall 1997)

Although the diagram shows a scheme applied separately to each wheelset, a modal approach applied at a bogie level can also be used. A further refinement is to counteract the longitudinal primary stiffness that arises from the primary vertical suspension. Details for both can be found in the quoted reference.

3.3 Actuated Independently-Rotating Wheelset (AIRW)

As can be seen from Fig. 4, this configuration is similar to ASW, but in this case the actuation effort is onto an axle with independently-rotating wheels; this is a logical progression because the natural steering action associated with solid-axles can be provided by the yaw actuation. Again the aim is to affect the plan view dynamics. Achieving kinematic stability is no longer a problem so a strategy to provide either 'steering' or 'guidance' is required. 'Steering' is a strategy in which knowledge of the curves and their transitions is used, either from a track database or from a "look ahead" sensing system. In contrast 'guidance' is a strategy that keeps the wheelset closely aligned with the track such that curving is implicit, and usually involves some form of feedback. Various strategies have been suggested (Mei and Goodall, 2003; Perez et al, 2004), a key issue being the provision of practical and appropriate sensors.

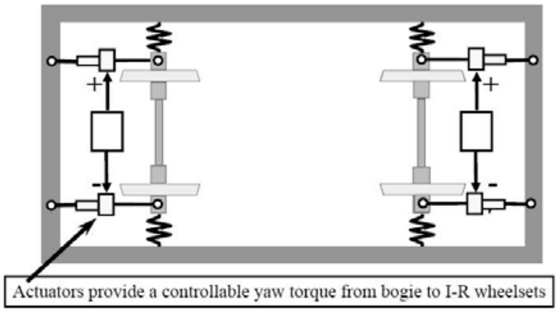

Fig. 4 Basic configuration for Actuated Independently-Rotating Wheelset

A high value of PYS is no longer required with IRWs, but there will still be a longitudinal stiffness arising from the primary vertical suspension. For this study a basic guidance control strategy is used in which a yaw torque applied to each wheelset is adjusted via a PI controller on the basis of the lateral wheel-rail displacement, thereby keeping the wheelset centralized with respect to the rail. The figure shows by a pair of actuators being used in opposition to generate a yaw torque onto the wheelset, but a single actuator with a suitable mechanism can also be used – see for example (Pearson et al, 2004). This can either be applied independently for each wheelset, or using a strategy in which the sum and difference of the displacements of the two wheelsets within a bogie are used to control the sum and difference (respectively) of the two wheelset torques, i.e. providing a modal approach which enables more effective tuning of the PI controllers. The basic arrangement for modal control is shown in Fig 5.

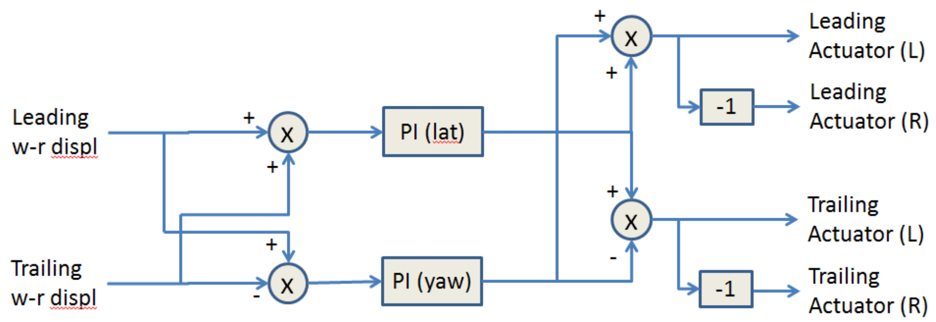

Fig 5 Modal control scheme for AIRW

3.4 Driven Independently-Rotating Wheelset (DIRW)

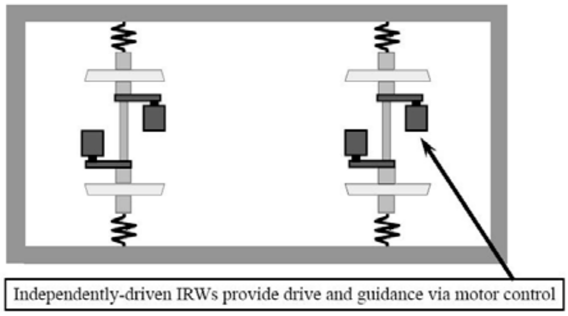

Fig. 6 Basic configuration for Driven Independently-Rotating Wheelset

This configuration is a development of AIRW, but the control action is instead provided by control of the differential torque of motors driving the two adjacent wheels – see Fig. 6. If the motors are also providing traction and braking then of course the steering/guidance control must be integrated with that of the traction/braking. The strategy will also be similar to AIRW, i.e. to provide steering or guidance, although a key decision is whether the motor should be speed-or current/torque-controlled. Caution is needed with speed control because this has the effect of introducing an "electronic axle" and a consequent pseudo-kinematic instability (Mei et al, 2001). A strategy involving torque controlled motors has been described which also includes state estimation to provide simplified sensing requirements (Mei and Goodall, 2003). It should be noted that the simplified diagram of the mechanical arrangement doesn't indicate any longitudinal stiffness arising from the primary vertical suspension, which may need to be carefully considered to take full advantage of this configuration in tighter curves.

The strategy employed for this study is essentially the same as for AIRWs, except that the wheelset yaw torque is the result of differentially driving the two motors in each wheelset, and of course the modal approach shown in Fig.5 is equally applicable.

3.5 Directly Steered Wheels (DSW)

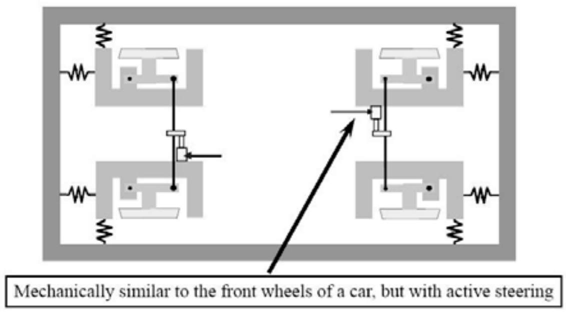

Fig. 7 Basic configuration for Directly Steered Wheels

In the DSW configuration (Fig. 7) a pair of independently-rotating wheels on stub axles and connected by a steering/track linkage is actively steered. The control could again be aimed towards steering or guidance, although the latter is probably the more obvious approach and strategies to achieve this have been studied previously (Wickens, 1994).

This is a straightforward strategy with feedback of wheel-rail lateral displacement providing a steering angle command for the actuation system, in practice requiring an inner steering angle loop controlling the actuators.

4. Modelling and assessment

A half-vehicle model involving two axles, the bogie frame and a half body forms the basis for the assessment. The passive arrangement is shown in Fig. 8, where the principal parameters and values that have been used are listed in Section 1. This is representative of a modern European railway vehicle, with typical parameters for a 160km/h passenger vehicle.

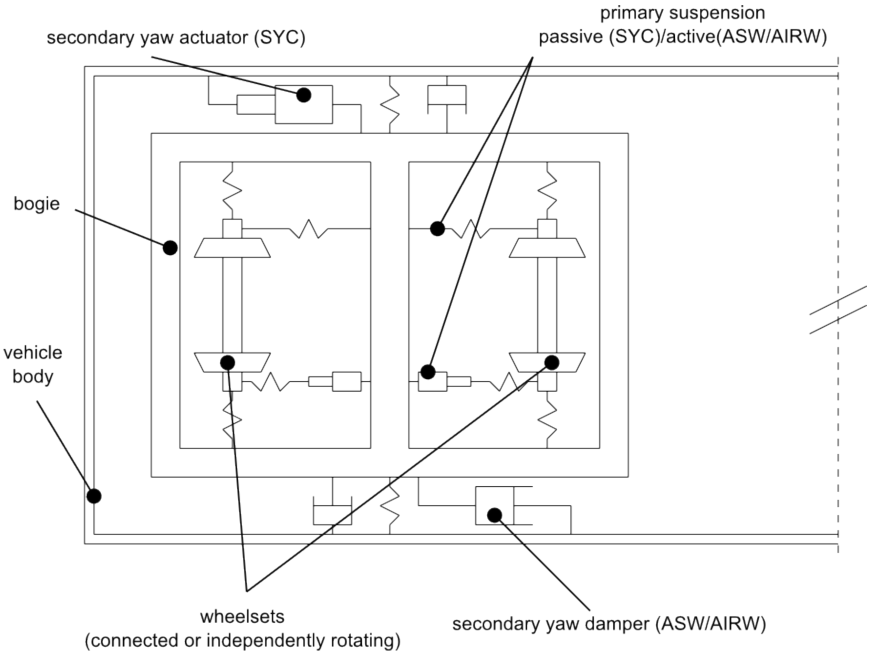

Fig. 8 Plan-view vehicle model (showing actuator positions)

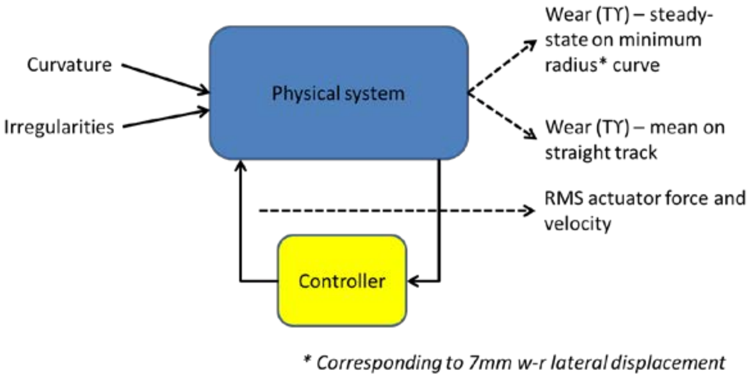

Fig. 9 Assessment approach

Figure 9 illustrates the assessment approach, in which both track irregularities and curving inputs are applied to the vehicle model. Since improvements in wheel-rail interaction are the principal benefit arising from active control, the "Tγ" values are used as indicative of wheel and rail wear (Burstow, 2012), calculated both for a curve and on straight track to indicate the "background level" wheel-rail contact interaction. A single curve radius of 500m with a cant of 6°, cant deficiency of 1 m/s^2 has been used for this study (a speed of 32m/s) – this has been selected on the basis of the limit for the passive bogie before flange contact starts to occur. The straight track Tγ has been included principally to ensure there are no detrimental wheel-rail interaction effects arising from the active control, and the values have been derived for a 10s simulation using measured track irregularities. These criteria provide a comparison of the basic suspension performance, but also RMS values for the actuation requirements on straight track and the peak torque on curves are assessed, which together help to quantify the trade-off between performance and actuation effort. Note that the actuator requirements are theoretical figures based upon idealized actuators because neither actuation technology nor associated actuator control implications have been incorporated in the study (Yusof et al 2010).

5. Results

Some graphical results have been presented to illustrate key aspects of the control strategies for the configurations, but the main numerical results that provide the comparison are given in Table 2 at the end of this section.

5.1 Curving results for SYC scheme

Figure 10 demonstrates that for SYC the lateral creep forces of the leading and trailing wheelsets are equalized on steady curves through the application of torque at the bogie level. This is compared to the difference in these lateral creep forces for the passive vehicle. However during tight cornering the longitudinal creep forces increase meaning an increasing in ‘energy’ transmission to the contact patch, and (as mentioned in Sect 3.1) another possible strategy is to equalize the yaw moments applied to two wheelsets on steady curves: this will potentially reduce the total wear work on curves, but of course this can only be achieved by having unequal lateral forces.

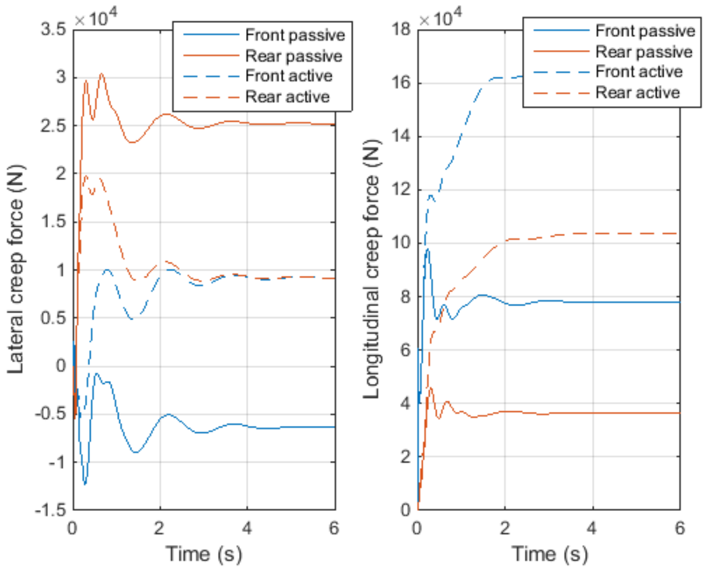

Fig. 10 SYC creep force comparisons with the passive vehicle during curving

5.2 Curving results for ASW scheme

Figure 11 shows how the longitudinal creep forces are driven to zero for the ASW system with the application of control torque at the wheelsets. The lateral creep forces in the wheel-rail contact remain unbalanced between leading and trailing wheelsets which does not represent the ideal response, but sub-section 5.4 shows that the longitudinal force reductions provide valuable improvements in wear performance.

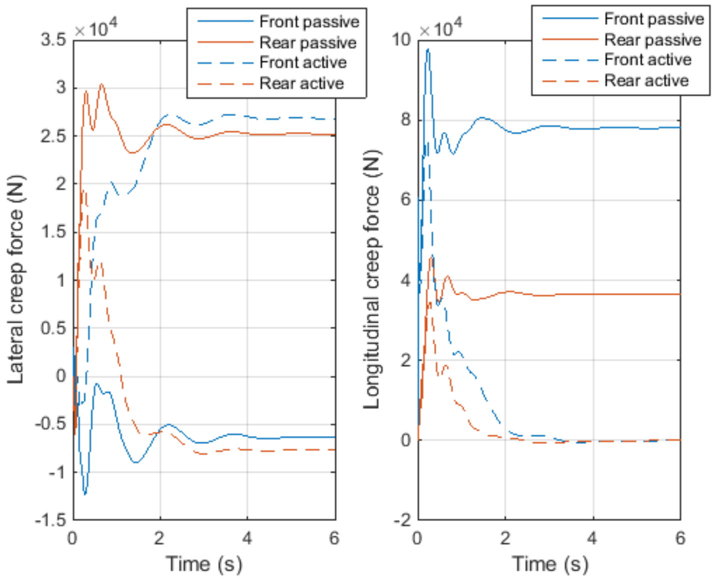

Fig. 11 ASW creep force comparison with passive vehicle during curving

5.3 Curving results for the three IRW schemes

Analysis of the three schemes involving independently-rotating wheels revealed that their basic control and resulting performances are very similar, hence only one set of curving responses is given.

Fig. 12 presents results for the AIRW scheme, from which it can be seen that the longitudinal creep forces are insignificant in comparison with the passive bogie. The lateral creep forces are the result of a design a compromise between cornering and straight track running, particularly relating to the integral action in the PID controller, and the curving response shows a substantial difference in leading v. trailing wheelset forces, only slightly changed compared with the passive responses. A more sophisticated strategy, perhaps involving additional sensing, could of course produce a different result. However the authors expect that the wear predictions will be broadly similar to those predicted.

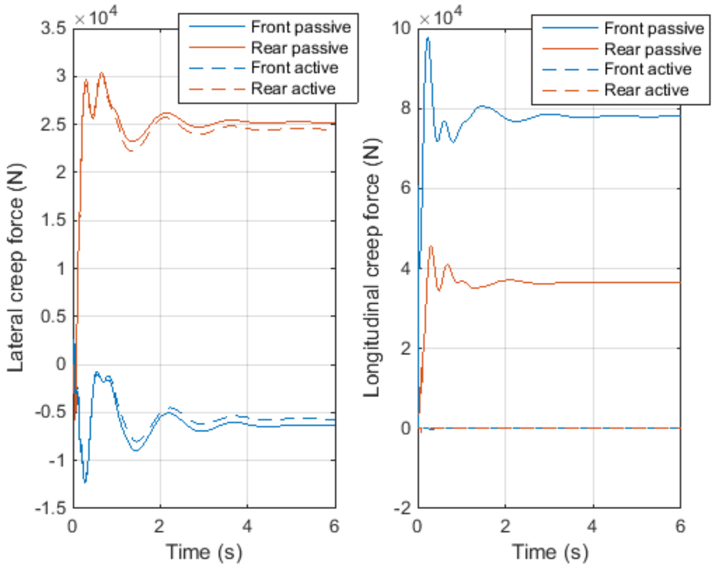

Fig. 12 AIRW creep force comparison with passive vehicle during curving

The basic control action of a DIRW configuration, and consequently its curving response and straight track performance, are the same. However means of applying a controllable yaw torque to each wheelsets is different, i.e. via differential wheel drive torques rather than direct actuation. The detail of actuation requirements for DIRW therefore depends upon how the controlled torques are applied: if some kind of differential mechanism with a single motor is used then the requirements are exactly the same as for AIRW, and these figures have therefore been included in the tabular comparison later. However if the guidance/steering control is integrated with traction/braking control then the situation is different, in fact the additional power requirements may be minimal.

Study of the DSW arrangement showed that, although what could be achieved is very similar to the AIRW and DIRW schemes (as observed already), the actuation detail depends very much upon the geometry of the steering mechanism, in particular the length of the stub axle, whether there is any “trail” provided, where the axis of rotation is, etc (Wickens 1994). Hence for this paper the authors have used the same performance results as for the other two IRW schemes, but have not provided any analysis of actuation requirements.

5.4 Comparison of results

The paper’s principal purpose is to contrast the relative performance of the active control options, and Table 2 provides this comparison using the conditions and criteria identified previously. The table also presents “baseline” results for the passive vehicle, and for the Tγ wear results both the absolute values and the percentage wear compared with the passive option are listed.

Table 2 Performance table

	Vehicle performance				Actuation requirements (straight track)			(Curved track)
Config.	Tγ (curves) (J/m)	%	Tγ (straight) (J/m)	%	RMS torque (Nm)	RMS vel (mrad/s)	Rated Power (W)	Max torque (kNm)
Passive	818	100	4.6	100	-	-	-	-
SYC	3875	474	4.08	88	1889	5.8	10.89	156
ASW	88.1	11	4.57	98	785/484	8.1/5.4	6.4/2.6	104/39
AIRW	72.4	9	0.45	10	283/288	4.9/2.0	2.0/1.3	1.2/1.2
DIRW	72.4	9	0.45	10	283/288	4.9/2.0	2.0/1.3	1.2/1.2
DSW	72.4	9	0.45	10	?	?	?	?

Note: where there are two entries these refer to leading/trailing actuation requirements

In general the performance improvements become larger with the more sophisticated mechanical configurations, i.e. further away from current technology, without requiring larger actuation effort. In fact all of the configurations based upon independently-rotating wheels require significantly smaller actuation than for the passive configuration and offer substantial reductions in wear. It’s worth noting that the calculation of rated actuation power, i.e. product of RMS torque and angular velocities are relatively simple indications of requirements, and any rigorous on-going study of one or more of the schemes needs to include actuator technology implications in order to give a practical evaluation.

6. Conclusions

The paper has shown what might potentially be achieved in terms of performance benefits for a variety of active bogie configurations based upon a published categorization.

The analysis has necessarily been limited to a selection of performance aspects, and although these are expected to be indicative the work needs to be extended to a more complex, nonlinear model assessed under a wider range of conditions. An extended study should also include practicalities, in particular to include appropriate sensing and actuator technologies. Also, in the case of DSW, more detailed consideration of the steering geometry is necessary.

Nevertheless the comparison provides an assessment that both identifies candidate control strategies and helps to guide potential exploiters towards the most appropriate engineering-based solution. Some of the detail of the results would change if more detailed investigation of different control options had been included, but the overall trends of the results are realistic.

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