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Railway vehicle optimisation using the concept of "Design for Control"

PLEASE CITE THE PUBLISHED VERSION

<http://dx.doi.org/10.4203/ccp.104.321>

PUBLISHER

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VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

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Ward, Christopher P., Tian Xiang Mei, Peter D. Hubbard, and M. Mirzapour. 2019. "Railway Vehicle Optimisation Using the Concept of "design for Control"". figshare. <https://hdl.handle.net/2134/17443>.

Abstract

Design for control is an axiom extensively used in the aerospace and automotive industries that has proven highly beneficial both in terms of performance benefits but also in reducing unit costs and reducing maintenance burdens. To date in the railway industry, active control for vehicle suspensions has been used in a sparse manner operationally, and generally only as a performance improvement measure for essentially passive systems. There is a lack of in-depth understanding of broader benefits for both vehicle design/architecture and extended impact on rail infrastructure that could be brought about by this concept of design for control.

This paper presents a brief summary of the outcomes of a short study into the accumulative benefits of design for control if applied to future railway vehicles. The aim of the project was to determine a philosophy of vehicle architecture that would maximise the effect of the axiom in terms of: reduced unit purchase cost; reduced running costs; and improved overall system performance. The paper proposes an architecture for a mature mechatronic vehicle and dynamic studies show that significant reduction in track damage can be achieved with this thinking. A simple understanding of the cost implications is also explored which shows that the real benefits will come from operational cost reduction rather than from unit purchase cost.

Keywords: mechatronics, control, condition monitoring, creep forces, dynamics, railway vehicle

1 Introduction

“Design for control” is an axiom extensively used in the aerospace [1] and automotive industries [2] that has proven highly beneficial in terms of performance benefits but also in reducing unit costs and shrinking maintenance burdens. With this concept,

control engineering is a key technology that enables advanced solutions which are not possible with purely mechanical designs (such as relaxed stability aircraft like the Eurofighter Typhoon [3]).

To date in the railway industry, active control for vehicle suspensions has been used in a sparse manner in operational trains, and generally as a performance improvement measure for essentially passive systems, e.g. tilting control for increased train speed on curves (Pendolino, X2000, etc.), and lateral vibration control for improved passenger comfort on the series E2-1000 and E3 Shinkansen [4]. Those have been largely applied as add-on subsystems to passenger vehicles where the thinking has almost converged on a standard design: two bogies per vehicle; each with two wheelsets; and two related passive stages of suspensions.

There is a lack of in-depth understanding of the broader benefits for both vehicle design/architecture and extended impact on rail infrastructure that could be brought about by this concept of “design for control”. A number of control concepts present great potential to play an integrated part of vehicle design at the system level, such as: independently-rotating or steerable wheelsets [5]; a single active stage of suspension [6]; advanced condition monitoring as a core attribute of the vehicle operation [7]; etc.

This paper presents a summary of the outcomes of a short study into the accumulative benefits of “design for control” if applied to future railway vehicles. The aim of the project was to determine a philosophy of vehicle architecture that would maximise the effect of the axiom in terms of: reduced unit purchase cost; reduced running costs; and improved overall system performance.

Section 2 contains a proposal for how techniques from literature (and more speculative ideas) can be drawn together to create a potential end point design. Section 3 quantifies the benefits from this architecture type in dynamic studies. These assessed the level of creep forces produced by a benchmark contemporary vehicle running on a typical section of the UK network and compared this to creep forces predicted from the proposed mechatronic systems. Significant reductions in forces were shown, demonstrating the potential track friendly nature of this vehicle type.

Covered in Section 4 is the cost modelling that proved a more intractable issue with many facets of finance protected by commercial sensitivities. However it can be postulated that though it is difficult to show a reduction in the unit purchase cost, the mass reduction would lead to a lowering of track access charges in the UK, and there would be a significant reduction in traction energy consumed.

Finally Section 5 is a postulated concept of the steps required to implement these ideas over a long term time scale.

2 The railway vehicle of the future

There has been a substantial body of work in academia and research intensive parts of the rail industry that have postulated the potential of using ‘active control’ in mechanical designs. Mostly however these have been proposed as single entity additive

concepts or as additions to improve existing passive systems (with the exception of the work by DLR in Germany on the Next Generation Train (NGT) [8] and the European ‘mechatronic’ train project [5] [9] [10]) such as: tilt control; actively controlled independently rotating wheelsets; active pantograph uplift control; and advanced condition monitoring.

Figure 1 is a pictorial representation of what a mature rail vehicle with the concept of ‘design for control’ at its core could look like. This concept is not far removed from the rail vehicles of today. The thinking is still constrained by the need to: travel along steel tracks; fit within a reasonable loading gauge; a full vehicle is still made up of a number of components (i.e. a train); and that electrical energy for traction is collected from overhead line equipment. What is being proposed here is how the concept of a Victorian age can be manipulated to generate economic and societal benefits from contemporary technology and concepts.

Figure 1: ‘Design for control’ railway vehicle concept

The proposed vehicle has the following key features:

- **‘Bogie-less’ operation**

- **Two decoupled actively guided wheelsets per vehicle.** This reduces the impact of contact forces on track wear and opens up a number of other benefits such as: as vehicle based track switching; the ability to design dynamically unstable vehicles; and removes the mechanical trade off constraint between straight line stability and curving performance.
- **Wheels that are flangeless.** Flangeless wheels would allow operation through simple fixed track infrastructure with the control system providing the necessary robustness and track feature following.
- **Single stage ‘active’ suspension.** A single stage of suspension has shown to be possible with an active solution [11]. This mechatronic concept can: maintain ride quality similar to that of two stage systems; reduce mass; save space; and avoid exciting flexible vehicle body modes.

- **In-wheel traction motors.** This (increasingly proven) technology will provide further space savings in this critical area and be one of the key factors in allowing torque vectoring guidance (in addition to yaw control).
- *Low floor carriages*
 - **Better packaging of the vehicle body interior.** Clever thinking on packaging may allow two-floor operation in the UK's small loading gauge or make more space available for goods carriage.
- *'Total' condition monitoring*
 - **Key parameter and state real time monitoring.** Advanced processing can be used to give a true indication of the system condition. This is due to making efficient use of the multiple sensors required for the actively controlled systems.
- *Adhesion dependent braking*
 - **Determine the actual adhesion level under the vehicle.** Vary the spacing between vehicles to make the most of the available adhesion profile. This could provide a useful improvement in the capacity available on existing lines, [7].
- *Active coupling*
 - **Removal of physical couplings between the vehicles.** This would allow better aerodynamic properties through reduced vehicle gaps on the straight track whilst allowing suitable articulation through curves. It also opens up the possibility of vehicles combining and even separating en-route.
- *Autonomous operation*
 - **Full automation potentially allows for safety, operational and capacity benefits.** This is the current trend in the aerospace and automotive sectors where in the former there is almost tacit acceptance from passengers that the pilot no-longer flies the aircraft.
- *Multiple closely coupled pantographs*
 - **Active position control.** This technology means that trailing pantographs are not disturbed by induced standing waves created by the leading pantograph.

(a) Passive vehicle primary suspension schematic (b) Passive vehicle secondary suspension schematic

Figure 2: Passive suspension model schematics

3 Dynamic benefits

Focus for the dynamic study was drawn on the control possibility that was perceived as to provide the largest transformation benefit; that of active guidance and stabilisation. The modelling consisted of: creating benchmark passive vehicle models; creating a number of active solutions; and testing these on representative sections of straight and curved track to determine effects on creep forces and vehicle body accelerations. The modelling in this paper is all carried out in the linear environment as a quantification of the macro effects of the ideas was sought.

3.1 Benchmark passive vehicle

The benchmark vehicle is modelled as a single carriage of a typical multiple unit used in the UK (and is loosely based upon the British class 158). This is a four axle, two bogie design, with typical contemporary thinking for the suspension layout. The vehicle is modelled in the plan view only with only the lateral and yaw movements considered. This is sufficient to understand the guidance mechanism [12]. The primary suspension consists of radius arms with a soft lateral coupling, Figure 2a. The secondary suspension is assumed to be by airbag springs with a viscous yaw damper, Figure 2b. Full details can be found in [13].

The vehicle was modelled in three mass conditions: 100% mass; 75% mass; and 50% mass. These were created so that effects of mass reduction with the mechatronic solutions could be discounted. Wheel/rail contact modelling was via Kalker theory and the gravitational stiffness was calculated assuming a linear conicity, again full

details can be found in [13].

3.2 Mechatronic vehicle types

The mechatronic vehicle was selected to be two-axle with a single stage of suspension and a plan view diagram of the layout is shown in Figure 3. This vehicle configuration is mechanically simpler and lighter than the more standard layout of two bogies with two wheelsets on each bogie. The bogies are deleted and the wheelsets are mounted onto the vehicle body via the springs and dampers in the lateral and vertical directions. No longitudinal springs or dampers are included in the modelling, although in practice some form of longitudinal connection is needed to transmit traction and braking forces from the wheels to the vehicle body. The vertical suspension and associated roll suspension are not considered in this plan view design model because the study is focused on the active steering of the wheelsets only. The parameters for this vehicle scheme are based upon assumptions of the current trends of vehicle development around the world. This is mainly highlighted by vehicles such as the Japanese Shinkansen series being approximately half the mass per passenger compared to equivalent British vehicles [14].

Figure 3: Mechatronic guidance schematic

An actuator is placed between each ‘wheelset’ and the vehicle body in the yaw direction. Whilst it is possible to develop active steering schemes with actuators either in the yaw or in the lateral directions, the latter arrangement deteriorates the ride quality, due to the adverse effect on the body modes [9]. Dynamic equations for the system can be found in [13].

An analysis of independently rotating wheelsets shows that there is an issue of dynamic instability due to longitudinal contact force [15]. Stabilisation is therefore required from the control system, in addition to the guidance action necessary for the wheelsets to follow the track.

Two control methodologies are shown here for comparison. The first method uses a ‘practical’ sensor set, with measurements of the yaw velocity of each ‘wheelset’ axle and the relative rotational speed of each wheel on an axle. The former measure-

ments are used for wheelset stabilisation whilst the latter are used for track following purposes, [10].

The total control action torque is provided by

$$\tau_{w_1} = -C_w \left(\dot{\psi}_{w_1} - \frac{V_s}{R_1} \right) + K_w \dot{\phi}_{w_1} \quad (1)$$

$$\tau_{w_2} = -C_w \left(\dot{\psi}_{w_2} - \frac{V_s}{R_2} \right) + K_w \dot{\phi}_{w_2} \quad (2)$$

where τ_{w_1} and τ_{w_2} are the torque applied to the two wheelsets, C_w is the stabilisation damping level, $\dot{\psi}_{w_1}$ and $\dot{\psi}_{w_2}$ are the yaw rate measurements, V_s is the vehicle speed, R_1 and R_2 are the curve radius, K_w is the selected curve guidance coefficient, and $\dot{\phi}_{w_1}$ and $\dot{\phi}_{w_2}$ are the relative rotational speeds of the wheelsets. Applying a control action to a pure yaw velocity will have adverse effect during steady state curving therefore the sign first requires high pass filtering above 1 Hz, by

$$HPF = \frac{s^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (3)$$

where $\xi = 0.26$ and $\omega_n = 2\pi$. Using this simple system some form of adaptation will be required across the speed ranges to account for the trade-off in straight line performance and curving.

As a comparison, to eliminate the effects of the reduced measurement set, a full state feedback controller is used so that a single controller can be selected for several design goals such as: stabilisation; curving performance; and track guidance. The full state is assumed to be available either through measurement or through the use of an estimator [16].

A schematic of the system can be found in Figure 4. It is not necessary to minimise all of the states, in this case for stabilisation and curving performance this is only required of the lateral displacement and the angle of attack.

3.3 Dynamic evaluations

The three passive vehicles and the two active solutions were tested on identical ‘virtual test tracks’ that consisted of: a deterministic curved section; and a straight track section with stochastic track irregularities from data recorded on a British main line.

Two key items were compared between the dynamic models. The first is the sum of the creep forces created in the contact. This is used as an indication of how much force each vehicle puts into the track and is therefore a simple indication of the level of track damage. With the passive vehicles this is calculated as

$$F_{vecP} = \sqrt{(F_{xFF}^2 + F_{yFF}^2)} + \sqrt{(F_{xFR}^2 + F_{yFR}^2)} \\ + \sqrt{(F_{xRF}^2 + F_{yRF}^2)} + \sqrt{(F_{xRR}^2 + F_{yRR}^2)} \quad (4)$$

Figure 4: Full state feedback schematic

where F_{vecP} is the total vector summed creep force for the four axle passive vehicles, F_{LMN} is the creep force, where l is either longitudinal x or lateral y , M is the bogie, either F front or R rear, and N is the wheelset in the bogie, either F front or R rear. For the active vehicle this is calculated as

$$F_{vecA} = \sqrt{(F_{xF}^2 + F_{yF}^2)} + \sqrt{(F_{xR}^2 + F_{yR}^2)} \quad (5)$$

where F_{vecA} is the total vector summed creep force for the two axle active vehicles, F_{oP} is the creep force, where o is the either longitudinal x or lateral y , and P is the axle, either F front or R rear.

The tests also look at the lateral acceleration experienced in the carriage through the test sections. This is an indication of the acceptability of passengers to the varying vehicle types and control methods.

3.3.1 Straight track comparison

The straight track test used data captured by a track recording vehicle on the Great Western Railway (GWR) in the UK. Four sections of straight track were identified from this data and simulations were performed for each vehicle model upon these sections.

Each of the five vehicle types ‘traversed’ the test sections in the simulation environment at a constant 50 m/s. Additional this was performed with a conicity of $\lambda = 0.2$ and $\lambda = 0.05$. The creep forces and lateral acceleration for each test were capture and are summarised here.

Figures 5 and 6 draw together the average values of the contact forces and lateral acceleration experience on the four sections of track by the five vehicles, with a conicity of $\lambda = 0.2$. Some general conclusions can be drawn from these

- A reduction in weight with the two stage suspension vehicles results in a reduction in contact force . It is noteworthy that the reduction introduces no improvement in ride quality.
- The introduction of active suspension can be seen to outperform the traditional suspension design methods both in terms of a reduction in contact force and in terms of ride quality. In comparison to the 50% mass baseline vehicle, a reduction of creep force of around 20% of the original value with a non-optimal controller up to around 30% to an optimal controller.

Figure 5: Average contact force RMS for each model over the straight track sections with $\lambda = 0.2$

Figure 6: Average lateral acceleration RMS for each model over the straight track sections with $\lambda = 0.2$

Similarly, Figures 7 and 8 draw together the average values of the contact forces and lateral acceleration experience on the four sections of track by the five vehicles, with a conicity of $\lambda = 0.05$. The findings here demonstrate a different trend. Here, an reduction in contact force is only seen with an optimal control solution. The partial

state feedback method provides very similar results to the 50% mass passive vehicle. This highlights the need to re-assess the control at lower conicity levels. This lack of robustness in the control, is highlighted in the ride quality with slightly more than twice the baseline values being observed.

Figure 7: Average contact force RMS for each model over the straight track sections with $\lambda = 0.05$

Figure 8: Average lateral acceleration RMS for each model over the straight track sections with $\lambda = 0.05$

3.3.2 Curving comparison

Two deterministic curving scenarios were used: 1250m radius at a vehicle speed of 50 m/s; and a 350m radius at a vehicle speed of 25 m/s. Both these curves are subject to a 6 degree cant angle and contain no stochastic lateral irregularities. In each case there is a two second linear transition into and out of the curve, which itself lasts for 4 seconds.

Here the comparisons are of: leading wheelset lateral position; trailing wheelset lateral position; the vector sum of the creep forces of all wheelsets; and the vehicle body lateral acceleration. In the case of the passive vehicle, the leading wheelset refers to the foremost wheelset of the vehicle and the trailing wheelset to the rearmost.

The first scenario simulated is the 1250m curve at 50m/s and a conicity of 0.2. Figure 9 shows the time history of the lateral position of the leading wheelset through the curve. It can be seen that the largest lateral displacements occur for the 100% mass fully passive system at nearly 10mm. This suggests at this curve radius and speed the vehicle is likely to approach flange contact. Evident is the reduction in the lateral displacement with a reduction in the mass of the vehicle, 8mm with the 75% mass vehicle and 4mm with the 50% mass vehicle. The mechatronic solutions show a further reduction in the lateral displacement, with both down to the 1.5mm mark. The reduced measurement set active solution shows some oscillatory behaviour at the transitions in comparison to the full state feedback solution. This may be due to the sensitivity of the algorithm depending upon a displacement measurement from relative wheel speeds and knowledge of the conicity. Similar trends are shown for the trailing wheelset, but this is not shown here for brevity.

Figure 9: Time history of the lateral position of the leading wheelset through the curve

The vector sum of the contact forces through the curve are shown in Figure 10 and shows a reduction in force from a peak of 120kN for the 100% mass passive system to approximately 40kN for the 50% mass passive system. The active solutions demonstrate a further reduction in the contact forces to a peak of around 20kN. There is very little difference between the two active solutions in this metric.

The lateral acceleration felt at the vehicle body level is shown in Figure 11, note that the centrifugal equivalent force is not included in the body acceleration here. This shows that passengers would experience higher transient accelerations for the passive vehicle systems than the active. There is very little effect of mass reduction in this. The full state feedback control adds an element of delay to the accelerations experienced but the magnitudes are a similar magnitude as for the reduced sensor set solution.

The time response for the remaining test are again not shown for brevity but show similar trends to the previous Figures. Details can be found in [13].

Figure 10: Time history of the contact force through the curve

Figure 11: Time history of the lateral acceleration experienced through the curve

3.3.3 Dynamic benefit comparison

Overall it can be seen that mechatronic solutions offer a number of advantages over the fully passive systems. It can be seen that the lateral displacements are reduced as are the contact forces experienced in the wheel/rail interface, producing track-friendly trains.

What is also shown is the algorithms need to be selected carefully and that they need to be shown to be robust to parametric and structural uncertainty that they will inevitably encounter through an operational life. Careful selection of the frequency response to expected track irregularities is also paramount.

4 Cost benefits

The cost analysis work shown here is a first phase quantification (and mostly qualification) of the possible technology benefits. The modelling is based on guideline assumptions from selected literature sources and it is provided only as an indication

of the macro financial possibilities.

Reliance is upon a small number of published and unpublished articles. The first [17] is the outcome of a seminar held at Loughborough University in 2006 to determine the costs associated with typical vehicles. This was used to establish a base purchase cost. The second publication [18] is an extensive study carried out for RSSB into the benefits of lowering the mass of railway vehicles and is the basis for track access and energy saving calculations.

Covered are a number of considerations: vehicle type; capital costs; running costs; maintenance costs; and cost of failure.

4.1 Comparison vehicle type

Cost models and operational issues will be different for varying fleet types; a benchmark ‘modern’ vehicle was required, the Siemens Desiro class 450.

The vehicle is: electrical multiple unit (DC); four cars per train (two power cars and two trailing cars); ‘modern’ suspension design; each vehicle has two bogies with two wheelsets per bogie. Information is available in [18] for the vehicle type with full parameters highlighted in [13]. This train would have tare mass of 172.18 tonnes and a gross mass of 194.58 tonnes.

The future vehicle postulated in Section 2 is: two ‘axles’ with independently rotating wheels; independent torque control; ‘active’ steering; and ‘total’ condition monitoring. It is postulated that this architecture would create weight savings in line with those achieved by two axle vehicles already in service (such as the British Rail class 142 DMU) where 25% saving in mass can be seen over regular vehicles, [11]. Projecting further into the future it can be postulated that a 50% weight reduction is possible based upon trends from the Japanese Shinkansen system, and use of composite materials. Cost reductions are therefore calculated with two vehicles at 75% and 50% of today's representative mass. The 75% mass train has a tare mass of 129.04 tonnes and a gross weight of 151.44 tonnes, with the 50% mass train having a tare mass of 87.03 tonnes and a gross mass of 109.43 tonnes.

4.2 Capital costs

Initial purchase cost of the vehicle can often be the driver for the selection of a vehicle, but may actually be a small proportion of the overall cost associated with a vehicle in its life. The concept being proposed need a major change in production and estimates of initial capital cost would be useful.

Representative information was taken from [17] and is indicative of a train similar to the Class 450. The guidance and propulsion mechanism only makes up a relatively modest proportion (approximately 17%) of the overall purchase cost. It could be postulated that a 50% reduction in material quantity alone is possible, potentially creating a 83k saving.

This saving would be offset by the initial generations of vehicles needing more intense engineering input. The greatest benefits potentially will come from realigning the architecture of the vehicle to make the use of the space saved from changing the guidance mechanism. This would require a more far reaching design study than is possible here. Therefore this type of technology is difficult to justify on an initial purchase basis alone.

4.3 Running costs

The guidance from [18] suggests that running costs can be broken down into two areas: track damage; and energy consumption. The document proposes values that can be used to calculate savings based upon mass reduction.

Only a very crude approximation of the saving possible with actively controlled wheelsets can be shown with these figures as there is an assumption that the reduced mass vehicle will have traditional guidance. The architectures proposed here have a greater reduction in the creep forces and as such could potentially generate greater savings.

Cost savings were calculated for a range of operating conditions and mileages for individual vehicles and for a representative fleet size (127 of the Class 450 were procured). Over a 35 year life of a fleet potential savings of £227,000,000 are possible for a 75% mass train and £448,000,000 for a 50% mass train assuming the cost modelling for track access charges remains the same. This offers a far more convincing case for the adaptation of these concepts than on purchase cost alone.

Also in [18] are figures to quantify the traction energy savings with mass reduction. This calculation is independent of the guidance mechanism and will be representative of mass savings proposed by the new vehicle architectures only. The level of electricity used is dependent upon the route of the vehicle. Commuter style stop/start traffic takes a great deal more energy to accelerate and brake on a regular basis in comparison to sustaining the much higher speeds. However, as the commuter traffic covers less distance the comparison is far from trivial.

Over a 35 year life of a fleet potential savings of £117,000,000 for the 75% mass vehicle and £230,000,000 for the 50% mass vehicle. Again this adds to the case that these technologies potentially add higher savings to the running costs than any initial purchase cost reduction.

Track access and energy saving can be combined to give a total saving for the dynamic changes. Cumulative figures for individual vehicles and the total fleet are shown in Table 1 for 15 and 30 years of operation. It is worth pointing out that the author postulate this is potentially the minimum saving (especially due to track access charges) as the cumulative effects of changing the vehicle architecture will only become evident when designers begin to realise the full potential of releasing space inside the vehicle.

	15 years			30 years		
Route category	Track save	Elec save	Total save	Track save	Elec save	Total save
Inter urban (75%)	£766k (£97m)	£394k (£50m)	£1,160k (£147m)	£1,532k (£195m)	£788k (£100m)	£2,320k (£295m)
Inter urban (50%)	£1,512k (£192m)	£777k (£99m)	£2,289k (£291m)	£3,025k (£384m)	£1,555k (£197m)	£4,580k (£582m)
Outer sub-urban (75%)	£217k (£27m)	£186k (£24m)	£403k (£51m)	£435k (£55m)	£372k (£47m)	£807k (£102m)
Outer sub-urban (50%)	£429k (£55m)	£367k (£47m)	£796k (£101m)	£858k (£109m)	£735k (£93m)	£1,593k (£202m)
Inner sub-urban (75%)	£167k (£21m)	£203k (£26m)	£370k (£47m)	£334k (£42m)	£406k (£52m)	£740k (£94m)
Inner sub-urban (50%)	£329k (£42m)	£401k (£51m)	£730k (£93m)	£659k (£84m)	£802k (£102m)	£1,461k (£186m)

Table 1: Total saving based upon mass reduction only

4.4 Maintenance costs

The area of maintenance finance is difficult to penetrate with clarity due to many of the costs and procedures being less than forthcoming from industrial sources. This has proved the case for other research projects such as [19], where lack of information on maintenance meant the project was not continued.

‘Total’ advanced condition monitoring is proposed in this project as a consequence of the control methods. Control relies on high integrity measurements of key states or parameters. These signals (from sensors such as: accelerometers; yaw rate gyroscopes; and linear differential transformers) when placed on the running gear can be used with advanced processing to infer the condition of the vehicle and track [7].

Qualitative justification for the use of ‘total’ condition monitoring can be shown in [20] and [21]. The former identified standardisation and simplification of design, intelligent monitoring and analysis, and electrification as key drivers for systems im-

provement. Each area could provide a greater than 20% reduction in failures per million miles. The simplification of mechanical systems is a key driver behind control systems and condition monitoring has proven itself in many transport sectors. A key example is the Rolls Royce Engine Health Monitoring system, which has proven itself to such a degree that the whole cost model changed from Rolls Royce from selling engines to selling availability of engines to operators.

The latter study [21] shows the business case for a number of condition monitoring systems. These monitoring systems could be seen as ‘first generation’ systems, with the ideas proposed in this current study improving the level of obtainable performance and the level of useful information to the user. The systems would also allow the transition to total preventative maintenance due to the condition of components being known, and not when they are at fault. So they can be replaced before failure occurs and at the most economically viable instance.

4.5 Cost of incidents

An attempt has been made to quantify the cost of incidents in [22]. Of interest to this project from the study is the number of running gear related incidents that occur each year. In particular those of derailment; where 2112 were logged and these tend to come down to: the mechanical failure of the train; the mechanical failure of the infrastructure; or a human operator failure. It is suggested that the first of these issues could be mitigated somewhat with the ‘total condition monitoring’ concepts suggested here. The infrastructure would also potentially be monitored with the systems on the train looking ‘down’ to the track as well as ‘up’ to the vehicle. The latter point of human operator failure would also be covered in a similar way to the aviation industry. Flight control systems are designed such that the pilot cannot make an overly ambitious manoeuvre with the aircraft. This thinking could be built in a more comprehensive manner that is possible today into the train control system to prevent drivers from executing overly ambitious manoeuvres.

4.6 Cost analysis conclusion

Any engineering changes suggested by this project were required to be evaluated in terms of their cost impact. It has proven difficult in a number of areas to get definite quantitative information due to commercial boundaries and the complexity of the systems interactions. Benefits in terms of capital cost reductions are hard to quantify, and in the short term the mechatronic bogie may actually increase the purchase cost for early adopters. However in the longer term these costs would reduce as designers and engineers become used to the systems integration possibilities of designing in such systems. The true benefits come in terms of the running costs (track damage and electrical energy). The level of longitudinal creep forces of the guidance mechanism can be greatly reduced through mechatronic systems opening up the possibility of track friendly trains. It is postulated that this will also be accompanied by a reduction of

the overall mass of vehicles due to the simplified and space efficient mechanical design possibilities. Using today's cost modelling this means a reduction in track access charges and reduced use of electrical energy. Maintenance and incident cost analysis proved more challenging in a quantitative sense but qualitative benefits can be shown from the near universal adaptation of the mechatronic ideas and condition monitoring in other transport sectors. This is already being adapted in rail.

5 Implementation strategy

It is realised that the deployment of this technology may be initially fraught in today's environment where safety qualification of new technology is intensely difficult and driven by decades of hard won and painful experience. Due to this position, the industry can appear overly conservative in the adoption of new technologies.

The railway industry is not unique in having a conservative outlook. In aerospace 'fly-by-wire' is currently considered the only method by which to design flight controls for both high-performance military fighter jets and civilian airliner applications. This is now proven technology that is used for performance, economic and safety reasons. However when first proposed a substantial component of the aerospace design community claimed that the concept would never work due to performance, economic and safety reasons [23]! The aircraft industry's steady adoption of this technology was due to a number of key champions proving the benefits of this concept over more than a decade. This iterative proving method persuaded enough key engineers to provide a critical mass of positive opinion to diminish the effect of the 'naysayers'.

A similar approach will most likely be needed in the rail industry. The timeline in Figure 12 is a simplistic (and probably optimistic) estimation of how the technology could be adopted if the industry pursued this as a common agenda.

Figure 12: Timeline for implementation

5.1 Stage 1 - Vehicle adaptations

There will inevitably be a transition period and as such the mechatronic vehicle concepts would need to work on existing infrastructure. The element to adopt first would be active single stage of suspension and the actively guided independently rotating

wheelsets. This would bring many benefits in terms of capacity within the vehicle and the wear impact upon the fixed infrastructure.

5.2 Stage 2 - Command and control adaptations

Once a critical level of vehicles adapted to the new technology are operational on the network their full potential can begin to be realised. Such as: driver-less operation; vehicle based route selection; vehicle co-operation/planning; and platooning of vehicles for energy conservation.

5.3 Stage 3 - Infrastructure adaptations

The changes up to this stage could essentially be achieved through application to existing infrastructure. The vehicle centric route selection opens the possibility of fixed infrastructure with all the associated maintenance and operational benefits.

6 Conclusion

Design for control when applied to railway vehicles can be justified on many fronts. The potential is to produce track friendly trains that have increased performance and reduced down time compared to today's vehicles. This paper showed the former in a quantitative sense where large reductions in guidance forces can be found and the latter was justified qualitatively through the examples of other transport sectors. In addition a cost justification was developed for adopting this approach primarily through the operational cost reductions rather than through unit purchase costs. The key task will be to promote the ideas to a rail industry that is cautious of new concepts and create an effective plan for implementing the change management that has been postulated here.

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