Technologies and solutions for future train suspension

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2 FUTURE TRAIN SUSPENSION SYSTEMS

2.1 EXECUTIVE SUMMARY

This report documents the application of a six-step Horizon Scanning process to identify technologies and solutions for future train suspension – see figure 1.

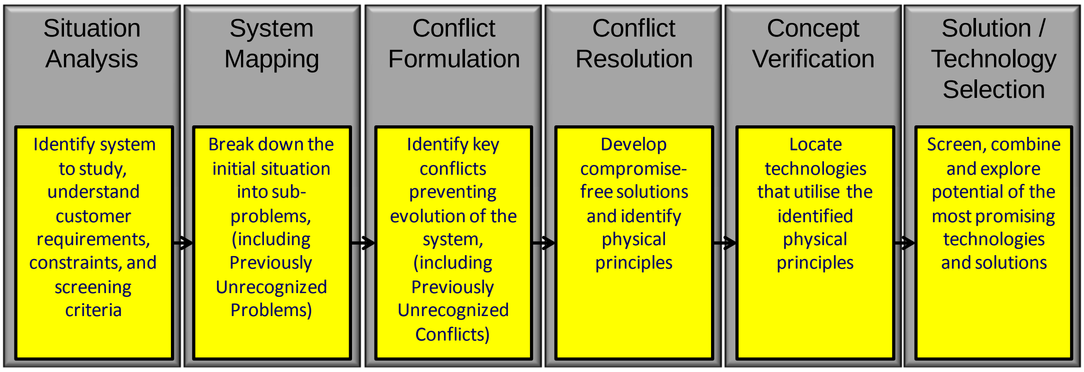


Figure 1: Six-step Horizon Scanning process

The report provides an overview of the process that was followed and highlights key insights into the future suspension challenge which emerged during the analysis. Here are the main findings:

- The current train suspension system is not keeping pace with the increasing demands of the modern rail industry – for example this report shows that increasing train speed has led to a reduction in track friendliness even for recently introduced trains (section 2.4.5).
- A modern train suspension system is a complex network of interacting elements which generally operate with fixed parameters. The suspension designer must trade-off to deliver the best overall compromise – for example, through yaw damping which is stiff enough to minimise “bogie hunting” but soft enough for acceptable curving performance. The ability of the suspension to adapt to changing conditions is severely limited as a result.
- In industry sectors such as automotive, there is a trend towards increased data transfer between vehicles and across the road system so that the car can better prepare to deal with approaching conditions. This trend could be applied in rail through increased information sharing within the train suspension (e.g. bogie to bogie) and between the train and the overall rail system.
- The train suspension has a negative impact on overall vehicle efficiency. As track variation is encountered, the suspension absorbs unwanted movement by dissipating some of the kinetic energy originally supplied by the train traction systems.

The report also summarises technologies and conceptual solutions to address the challenges described above. The most promising solution themes are:

- Information capture and transfer.
- Feedback and feed-forward control.
- Hybrid suspension using improved passive, semi-active and active elements.
- Simplified, reduced-mass suspension using composites and active steering control.
- Kinetic energy recovery.

2.2 BACKGROUND

Since the birth of rail travel, the train suspension system has continually evolved to meet the demand for faster, safer and higher-capacity transport. The suspension in today's trains play a critical role in delivering a safe, efficient and comfortable railway. Over the years, the train suspension designer's job has become far more demanding due to the need to manage competing requirements and the increasing complexity of the system. To deliver the Rail Technical Strategy and keep pace with changing industry and passenger expectations, future suspension systems must address many of the major issues highlighted by this study. This report details how the future challenges might be resolved by using technologies and solutions which are already applied in other industry sectors.

2.3 STEP 1: SITUATION ANALYSIS

2.3.1 PROJECT SCOPE

Figure 2 shows the areas of the rail system which were included within the scope of the study.

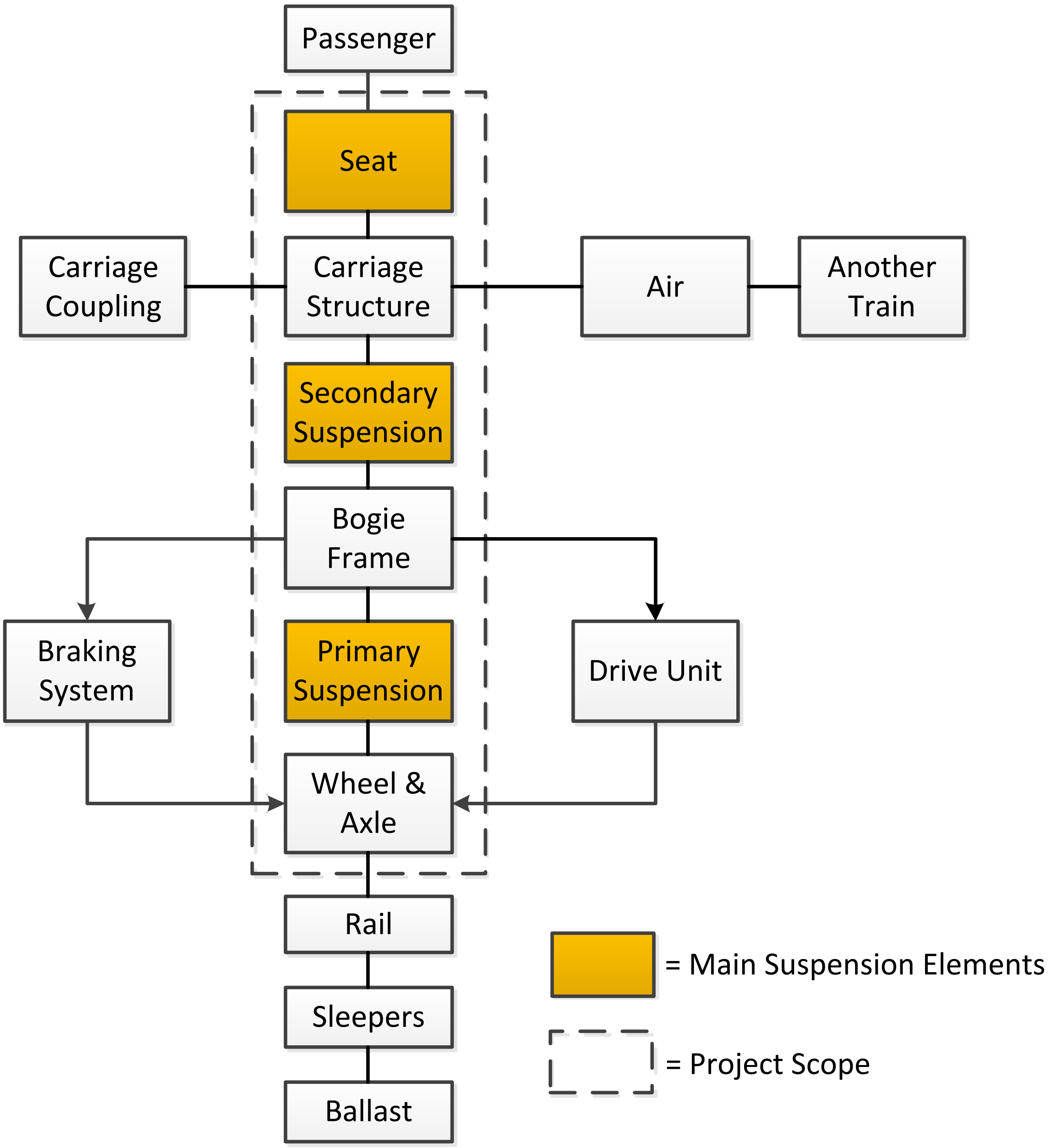


Figure 2: Project Scope diagram

This study will focus primarily on researching the main suspension elements (shown as orange in figure 2). The report will also consider other areas within the project scope (inside the dotted line in figure 2), if technologies and solutions are found to offer potential benefits.

2.3.2 FUNCTIONS OF A TRAIN SUSPENSION SYSTEM

The 2040 vision stated in the Rail Technology Strategy document **[1]** describes a railway which “sets the benchmark for service quality, customer satisfaction and value for money by being safe, reliable and resilient, meeting capacity and service requirements and contributing to the growth of the economy”. The train suspension system has a key impact on this vision. The system directly affects passenger comfort and safety in addition to enabling a reliable and resilient service.

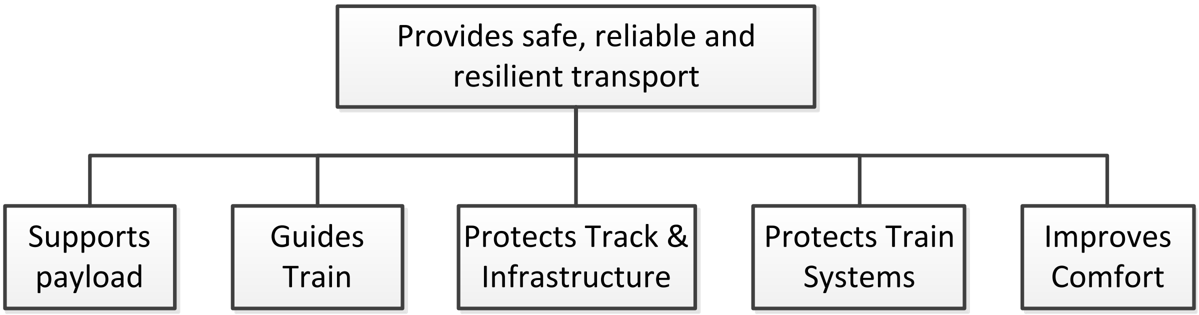


Figure 3: Main functions of the train suspension system

Figure 3 shows how these overall requirements are delivered though five main functions which are now detailed in priority order. Firstly, a basic expectation of the system is that it must support the train and its payload. Secondly, the suspension needs to provide the safety-critical function of train guidance, preventing derailment and ensuring safe operation under all expected conditions. Protection of the train, track and infrastructure is the next most important function. Train suspension design directly impacts the amount of damage caused to the track and rolling stock, leading to significant costs for the railway companies. Finally, the suspension improves comfort, contributing to a better passenger experience.

2.3.3 SUPPORTS PAYLOAD

A key priority for future railway is to increase capacity, leading to the need for the train payload (passengers and freight) to increase. The train suspension must distribute the weight of the train and payload uniformly to the rail and ballast.

2.3.4 GUIDES TRAIN

The suspension plays an important role in guiding the train along the track. In extreme cases, a lack of guidance might even lead to train derailment. The rail industry standard GM/RT2141 for the Resistance of Railway Vehicles to Derailment and Roll-Over **[2]** describes how rolling stock is tested to ensure adequate resistance to derailment. As a wheel flange contacts a rail there is a risk that it could climb onto the rail head and into derailment. This risk is dependent on the vertical and lateral forces acting at the point of contact – see figure 4. A high lateral force (Y) combined with a low vertical force (Q) increases the risk. Flange climbing is considered to occur when the ratio of the lateral Y and vertical Q forces exceeds a critical limit value for a sustained period. The critical limit depends only on the flange contact angle and wheel rail contact geometry/friction. GM/RT2141 details three test methods to derive the ratio of lateral to vertical force for a specific train design; the configuration of the train suspension has a direct impact on this ratio.

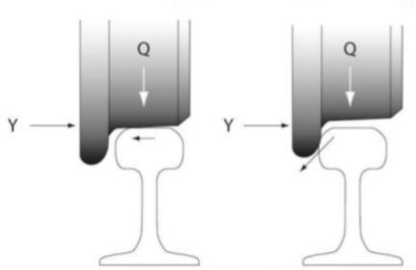


Figure 4: Vertical and lateral forces acting on the wheel rail contact

2.3.5 PROTECTS TRACK, INFRASTRUCTURE AND TRAIN

The UK rail industry has recognised that different train designs can have a different impact on the rail network. This has been formalised through the Variable Usage Charge (VUC) which recovers all operating, maintenance and renewal costs in line with track usage. The VUC is apportioned depending upon the “track friendliness” of specific trains. The “track friendliness” score is driven by four key vehicle characteristics:

- Axle load
- Operating speed
- Un-sprung mass
- Bogie primary yaw stiffness (indicative of its curving ability)

The higher the value of these parameters, the larger the resulting score and VUC. The design of the train suspension directly impacts these parameters. A low VUC is also likely to lead to a reduced level of noise and vibration transmitted to the surrounding area.

The train systems are also subject to wear and damage which incur maintenance costs. It is likely that a track friendly train will suffer less damage to its own systems.

2.3.6 IMPROVES COMFORT

The comfort of passengers is influenced by many different factors – e.g. temperature, noise and vibration. Rail suspension systems are assessed against EN12299 **[3]** – Ride Comfort for Passengers (Measurement and Evaluation), which considers the vibration and motion of the vehicle. EN12299 considers accelerations experienced by passengers in the vertical, longitudinal and lateral axes through various interfaces – e.g. the train floor or seat. The total acceleration energy is used to calculate a Comfort Index. The higher the Comfort Index, the less comfortable the train will be.

2.3.7 MAIN PARAMETERS OF VALUE (MPVS)

Main Parameters of Value (MPVs) are used to measure how well a system delivers its main functions. In addition to providing a useful metric to track how a system has developed over time, MPVs can give an indication of likely future development directions.

The following main parameters of value were identified for the train suspension system:

Train Speed. The maximum permissible speed for a train travelling on a track.

Payload. Maximum load capacity of the train.

Derailment Quotient. The ratio of the lateral Y and vertical Q forces.

$$Derailment\ Quotient = \frac{Y}{Q}$$

Track friendliness score. This metric is a function of the relative damage in both the vertical and lateral axes. The vertical damage metric is calculated using the following formula **[4]**:

$$Relative\ damage\ (per\ axle.mile) = 0.473e^{0.133A} + 0.015S.U - 0.009S - 0.284U - 0.442$$

Where:
A = Axle load (in tonnes – 5 to 25 tonnes)
S = Operating speed (in MPH – 25 to 100 mph)
U = Un-sprung Mass (tonnes per axle – 1 to 3 tonnes)

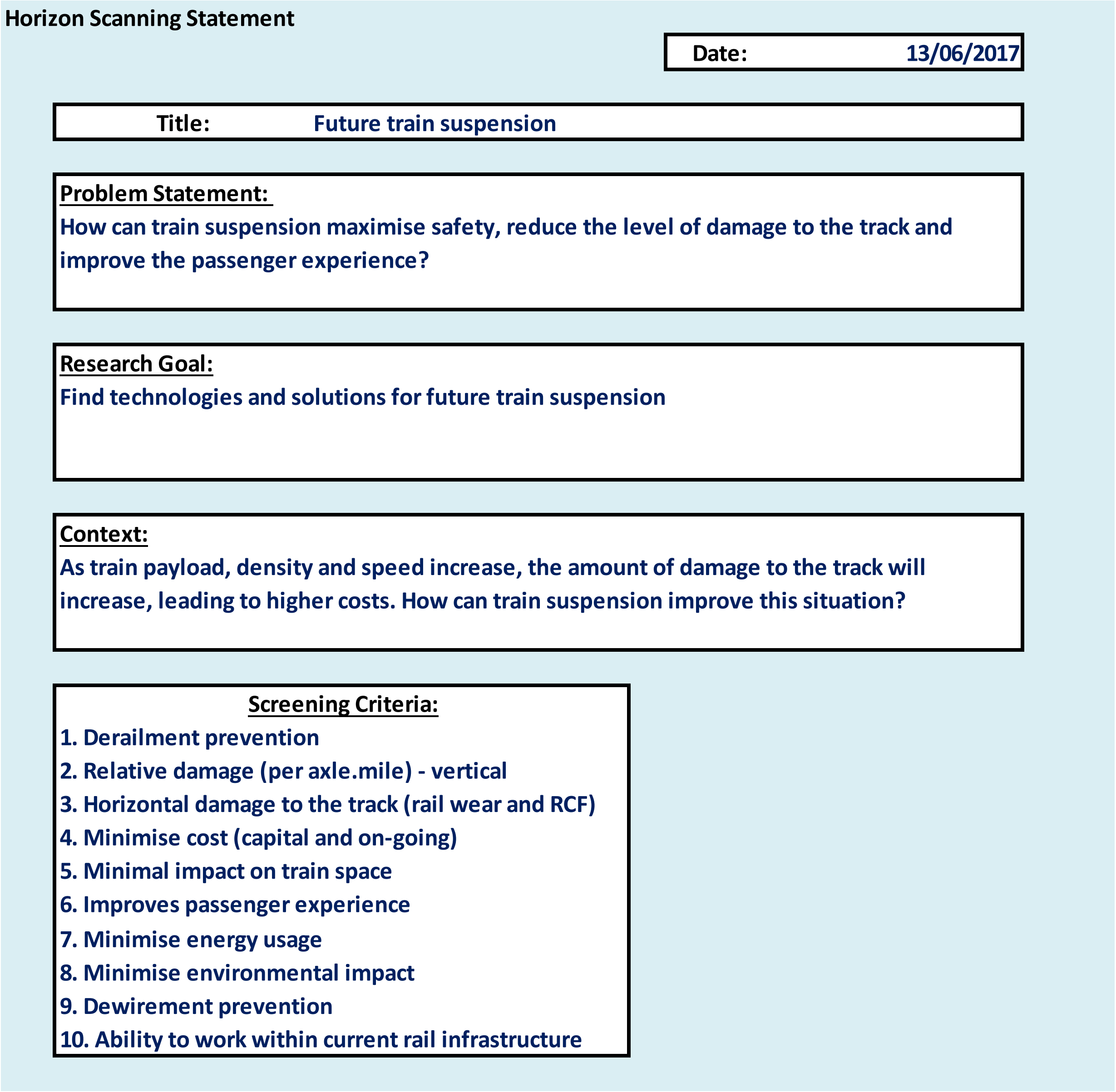
The horizontal damage metric is derived from Tɣ (T Gamma) which is a function of vehicle suspension type and certain track parameters.

Comfort Index. Related to the acceleration energy experienced by passengers in the vertical, longitudinal and lateral axes.

2.3.8 HORIZON SCANNING STATEMENT

It is important to define key screening criteria from the outset of the project which can be used to guide the analysis and identify relevant solutions. A horizon scanning statement captures evaluation criteria and other key outputs from the first stage of the study.

The analysis produced the following horizon scanning statement:



Horizon Scanning Statement

Date: 13/06/2017

Title: Future train suspension

Problem Statement:
How can train suspension maximise safety, reduce the level of damage to the track and improve the passenger experience?

Research Goal:
Find technologies and solutions for future train suspension

Context:
As train payload, density and speed increase, the amount of damage to the track will increase, leading to higher costs. How can train suspension improve this situation?

Screening Criteria:

1. Derailment prevention
2. Relative damage (per axle.mile) - vertical
3. Horizontal damage to the track (rail wear and RCF)
4. Minimise cost (capital and on-going)
5. Minimal impact on train space
6. Improves passenger experience
7. Minimise energy usage
8. Minimise environmental impact
9. Dewirement prevention
10. Ability to work within current rail infrastructure

2.4 STEP 2: SYSTEM MAPPING

2.4.1 PROCESS MAP

A process map was prepared to show the different states of train movement during a typical journey (see figure 5).

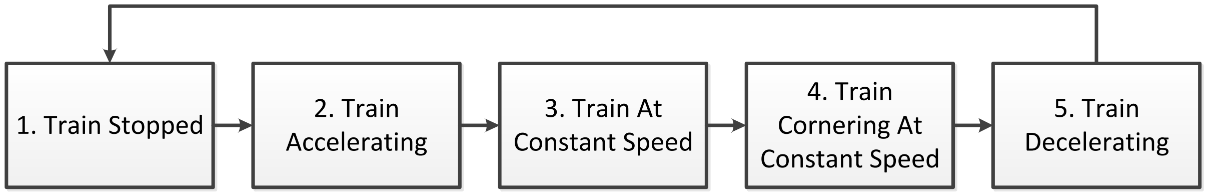


Figure 5: Train motion states

The following section describes these train states in more detail.

1. TRAIN STOPPED

The suspension supports the weight of the train. The secondary suspension also levels the train floor in response to changes in payload caused by passengers boarding or alighting from the train. Even after this levelling phase there is often a mismatch between the platform and the train carriage floor, resulting in a step and gap for the passengers to cross.

2. TRAIN ACCELERATING

As the train starts to leave the station, the drive units provide torque which is reacted through the traction between the wheel and the rail to accelerate the train. The suspension may play a small role in distributing the load more evenly across the driven wheels.

3. TRAIN AT CONSTANT SPEED

Once the train has completed its acceleration phase and is travelling at a constant speed on a straight track the suspension continues to support the weight of the train and minimises unwanted movement. Unwanted movement could result from variations in the rail flatness. Appendix A1 contains a detailed map of the actions of key suspension elements as the train passes over a vertical disturbance (a bump). Several conclusions can be drawn from this analysis:

- The location function between the wheel and rail is governed by the weight of the train and the geometry of the wheel and rail profiles. When the train suspension encounters a bump, energy is transferred into the vertical plane, temporarily reducing the apparent weight of the train and the effectiveness of the location function.

- The suspension is required to attenuate the vertical movement received from the rail, transmitting the minimum movement to the passenger. The stiffness of the suspension means that any vertical movement is resisted, increasing track loading.
- Un-sprung (e.g. wheel and axle) and partially sprung (e.g. bogie) elements of the suspension have significant inertia which impose their own loads on the track and require effective damping.
- Energy is lost due to the action of the suspension system e.g. heat generated in the dampers.
- There is a lack of control of energy within the suspension system e.g. conflicting requirements on damping for a smooth ride and effective un-sprung mass control.

4. TRAIN TURNING

This section considers the lateral movement of the train. As the train passes along a straight track, prior to cornering, the suspension components experience lateral forces and movements. As the train reaches the corner, the leading axle is directed by the rail to move the bogie which in turn moves the carriage. Once the train has fully entered the curve, the suspension system is in a steady state. Appendix A2 contains a detailed map of the actions of key suspension elements as the train transitions from straight line travel into cornering. Key points from this analysis are as follows:

- Disturbances in the rail cause movement in the bogie unit, potentially leading to hunting if the damping is insufficient.
- During the start of cornering, the bogie acts as a lever to move the carriage, reducing lateral wheel loading.
- An excessive level of damping between the carriage and the bogie could increase the risk of wheel “climbing” and derailment.

5. TRAIN DECELERATING

As the train slows, the brake units provide torque which is reacted through the traction between the wheel and the rail to decelerate the train. The suspension may play a small role in distributing the load more evenly across the braked wheels.

2.4.2 HISTORY OF TRAIN SUSPENSION SYSTEMS

Train suspension systems have evolved in parallel with the development of the railway system itself. A brief overview of the key evolutionary stages is shown in Table 1 below.

Year	Description	Suspension format	Benefit
1804	Trevithick's "Catch Me Who Can" locomotive was demonstrated operating on a circular rail track in Bloomsbury, London. The locomotive was too heavy for the cast-iron plateway track then in use and never got beyond the experimental stage.	Rigid 2 axles	
1813	Puffing Billy built by Christopher Blackett and William Hedley for the Wylam Colliery Railway. Maximum speed 5 mph, weighed 8 tons.	Rigid, multiple axles.	Weight carried over 4 axles reduced axle loading on the rails.
1815	Killingworth locomotives - Stephenson used the steam pressure of the boiler to provide 'steam spring' suspension for the engine. Maximum speed 4 mph, weight 6 tons. Payload – 8 wagons with 30 tons	Steam spring (primary suspension)	Increased cushioning to reduce track breakage.
1829	Stephenson's Rocket – had leaf spring primary suspension. First train for passengers rather than freight. Maximum speed 28mph, weight 4 tons.	Leaf springs (primary suspension)	Increased passenger comfort and reduced track breakage.
1837	Baltimore & Ohio Lafayette locomotive was the first to feature four-wheel bogie (4-2-0)	Bogie on locomotive	Improved ability to guide locomotive through curves, reduced track loading.
1840	Isaac Newton Stanley patent US1512	Bogies on carriages	Improved and higher speed cornering, reduced need for banking.
Early 1900's	Articulated cars where bogie is positioned between carriages.	Articulated bogies	Reduced cost, weight, noise, vibration and maintenance expenses.

1925	GB 232592 patent – Describes a system with a bogie suspended by a secondary frame.	Secondary suspension – Leaf spring	Reduced lateral loading and improved passenger comfort.
1936	J. Bugatti patent (US2034504) shows compliant rubber/hydraulic king pin mounting.	Secondary suspension – Rubber and/or hydraulic	Improved passenger comfort and suspension control.
1946	Firestone patent - US2537637 Continental Patent - US2920885 (1955)	Secondary suspension - Air suspension	Improved passenger comfort, potential to maintain same ride height for different loads.
1970s	BT10 Bogie fitted to British Rail MK3 coach capable of 125mph	Coil springs + damper (primary suspension), Air spring (secondary suspension)	Improved passenger comfort, potential to maintain same ride height for different loads.
1970s	Cross-anchor self-steering bogie introduced in South Africa	Self-steering bogie	Reduced lateral track loading during cornering.
1973	First tilting train in public service was the 381 series electric multiple unit train operated by Japanese National Railways (JNR).	Tilting train - Passive	Improved passenger comfort during cornering.
1984	The British Advanced Passenger Train was the first to implement active tilt. Maximum speed 155 mph, service speed was 125mph.	Tilting train - Active	Reduced lateral forces on passengers enabling increased speed on tight rail curves.
1997	Type 283 DMU (Japan) tilting train.	Assisted steering bogies using links	Reduced lateral forces on the track
2004	Shanghai Transrapid airport to city shuttle	Maglev	High speed travel in relative comfort.
2017	Mechatronic bogie – Bombardier Flexx Tronic Wako bogie fitted to Swiss SBB FV-Dosto double deck train.	Active radial steering (ARS), condition monitoring, roll compensation	Increased cornering speed (particularly double deck trains), increased track friendliness

Table 1: History of key changes in train suspension systems

2.4.3 PATENT ANALYSIS

Relevant rail industry patents were studied to show how train suspension systems have evolved over the years and to clarify the current state of the art.

PATENT CLASSIFICATION

The general patent classification for rail vehicle suspension (CPC B61F) was used to provide an overview of published patent activity for train suspension. Further analysis was conducted using search strings which combined the B61F classification with other search terms or codes. The search strings used are shown in Table 2 below.

CPC code	Sub code	Search term	Category description
B61F			Rail vehicle suspensions e.g. underframes, bogies or arrangements of wheel axles; rail vehicles for use on tracks of different width; preventing derailing of wheel vehicles; wheel guards, obstruction removers or the like for rail vehicles.
B61F		"Suspension"	Rail vehicle suspension with the word "suspension" in the abstract.
B61F	5/38		Arrangements or devices for adjusting or allowing self- adjustment of wheel axles or bogies when rounding curves, e.g. sliding axles, swinging axles
B61F		"Active"	Rail vehicle suspension with the word "active" in the abstract.
B61F		"Tilting"	Rail vehicle suspension with the word "tilting" in the abstract.

Table 2: CPC patent codes and search terms for train suspension

Figure 6 shows the number of published patents from 1840 to the current year.

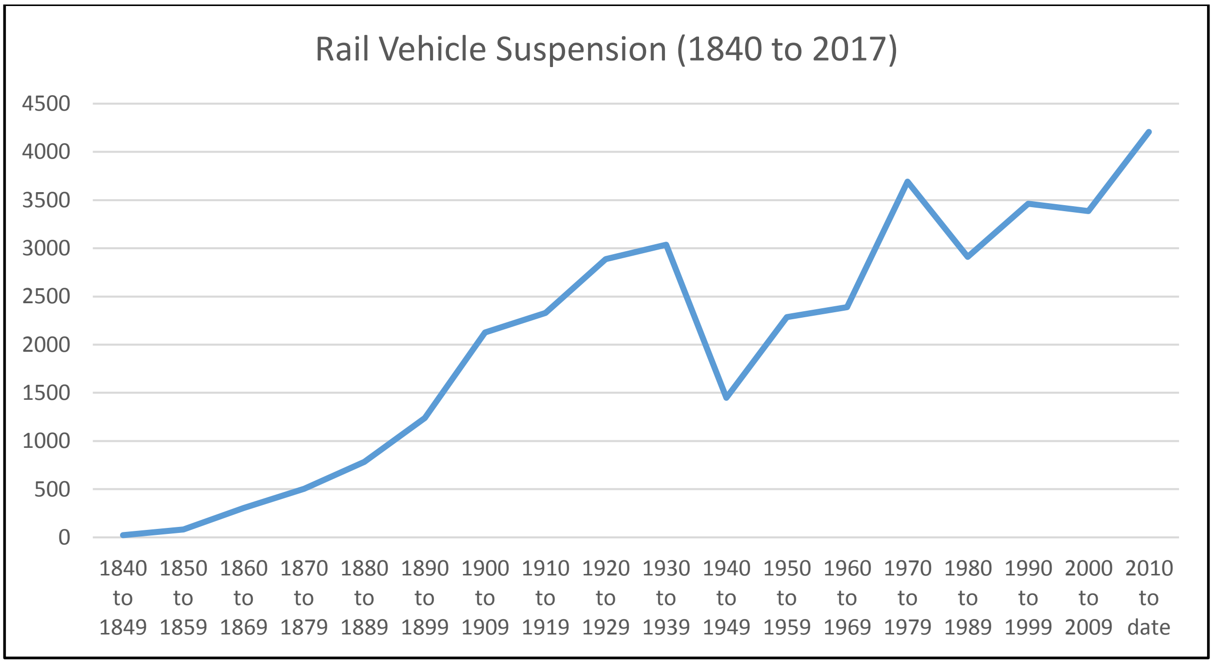


Figure 6: Train suspension patents 1950 to current CPC B61F

The graph illustrates several themes which played out in the development of train suspension systems:

Development of the (fully mechanical) bogie

- The bogie was first proposed in 1798 by William Chapman **[5]**.
- The first locomotive with leading swivelling bogie designed by Jarvis and Allen in the USA 1832.
- First bogie rolling stock patent was granted in 1840 **[6]**.
- Bogie format developed through 1850s and 1860s.
- Early attempts at implementing a tilting format from 1840, used the bogie turning moment to tilt the carriage but increased the risk of derailment.
- Self-steering bogies used linkages but reduced straight-line stability.
- Low level sub-system refinements continued to the 20th century; resolving problems such as axle lubrication, manufacturability, strength, spring durability, derailment risk and effects of poor track condition.
- Although bogies helped to improve curving performance they were often susceptible to dynamic oscillation (“hunting”) when travelling along straight track. Recently there has been patent activity around the use of inerters to address this conflict **[7]**.

Development of pneumatic secondary suspension

- First patent for a primary pneumatic suspension system was granted in 1905 **[8]**.
- In 1951 the Firestone tyre company patented a pneumatic primary and secondary suspension system
- During the 1950s, 1960s and 1970s various secondary problems of pneumatic suspension were addressed: provision of a reliable supply, configuration of the springs, controlling the level of the train, providing a failsafe system in the event of an airbag rupture and equalising the load between the suspension elements.
- The introduction of pneumatic suspension in trains has provided a step change in passenger comfort and is used throughout the industry, however, this form of suspension still represents a compromise with issues related to passenger comfort and rolling stability.

Development of tilting suspension

- First patent found for a passive tilting system using centrifugal force to tilt the train carriage and improve passenger comfort during cornering was granted in 1941 **[9]**.
- During the 1970s and 1980s patents were filed describing the mechanical elements of an active tilting system. Servo controlled hydraulic actuators were used to move the carriage body during train cornering, as described in reference **[10,11]**.
- A key patent emerged in the early 1980s which described a closed-loop control strategy to actively tilt the train to minimise lateral acceleration experienced by the passenger **[12]**.
- Further patents from the 1990s to present day describe improvements to the tilting control system **[13]**.

Horizon Scanning

- In the last few years patents have emerged describing various formats of kneeling train suspension to address the need for improved accessibility to and from the train **[14]**.

Increasing control of suspension parameters

- Patents describing more controllable component functionality e.g. magneto-rheological damping to adjust damping rates in response to changing conditions **[15]**.
- Patents have been published for adaptive suspension using a multitude of inputs including map information, train position, journey history, train weight, train condition data and meteorological information **[16]**.

Development of magnetic suspension

- First patent for magnetic levitation for train suspension was granted in 1912 **[17]**
- Various further patents described improvements to the system and methods to control its operation **[18]**.

2.4.4 TREND ANALYSIS

The purpose of trend analysis is to position the current rail industry technologies against various TRIZ trends of technical system evolution, developed from the study of successful innovations across a range of industries. The results can be used to make forecasts of likely future system developments in the rail industry. Table 3 contains an analysis of a current service train operating within the UK rail infrastructure.

	Trend of increasing flexibility	Transition to the super-system	Shortening of energy flow	Increasing controllability
Super-system Train, track, fixed infrastructure (e.g. platform, bridges, tunnels)	Rigid infrastructure, single hinge at points	Limited convolution of train within super-system	Unwanted energy is flowing into infrastructure in the form of vibration, noise heat (causing damage and other harmful effects)	Very limited interoperability between super-system and train e.g. points direct train to different tracks
System Train suspension	Multi-level discrete elements, multiple "hinges"	Two bogies, with two axles on multiple carriages, limited convolution across the train	Lengthening energy flow to dissipate harmful energy. N.B. harmful energy results from useful train kinetic energy being diverted by track variation	Passive suspension with limited control
Sub-system Primary suspension (spring + damper), Secondary suspension (air), wheels, axle, train body	Mismatched elements – rigid wheels and axles, elastomeric primary, fluidic secondary	Multiple elements with same properties e.g. primary and secondary suspension, some shifted properties e.g. damper and spring. Limited convolution	Mismatched energy flow (absorption) – rigid wheels, axles and bogies with inertia which must be managed.	Passive primary - stiff for stability in straight line. Other passive elements such as damping tuned to maintain stability. Secondary has limited control to maintain level. Active tilt control for cornering.

Table 3: Trend analysis of current UK Rail service train

Key trend analysis conclusions:

- The interaction between the train suspension and the infrastructure (super-system) is at an early evolutionary stage with very little co-ordination.
- There is little integration of control between the suspension elements in a train e.g. carriage to carriage.
- The trend mismatches between the different elements of the super-system, system and sub-systems of a train suspension must be managed by compensation systems e.g. yaw damping to control bogie "hunting".
- The suspension system must dissipate harmful energy resulting from useful train kinetic energy being diverted by track variation.

2.4.5 MPV MAPPING

In section 2.3.7, several potential Main Parameters of Value (MPVs) were defined.

One key train related MPV which directly drives the development of train suspension is speed. Figure 7 shows the progression of train speed through steam, diesel and electric propulsion.

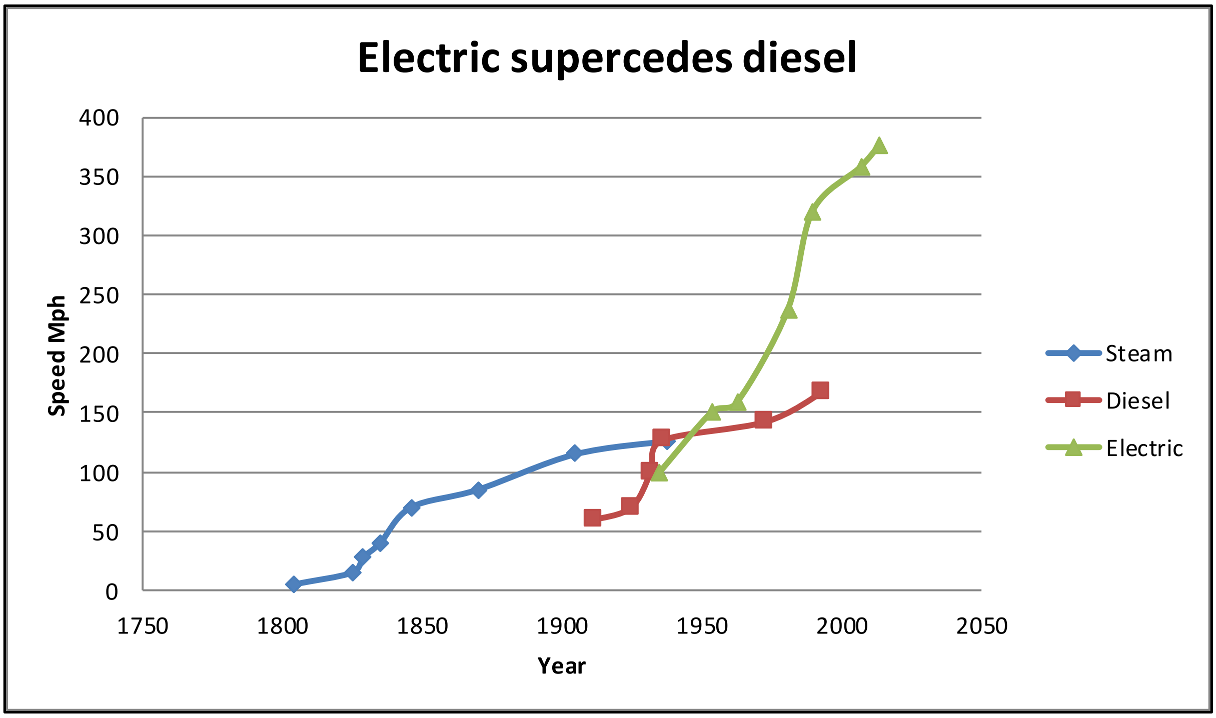


Figure 7: Main parameter of value – Train speed

Over the last two hundred years train speed has steadily risen, with significant continued growth over the last fifty years. Increasing speed puts additional demands on the train suspension and surrounding infrastructure.

The track friendliness score as described in section 2.3.7 is quantified as pence per mile. To convert this into an MPV the ratio is inverted i.e. miles per pence. Figure 8 shows the mile/pence value for all current passenger service trains mapped against the year of introduction. The data used was derived from the CP5 Track usage price list **[19]**.

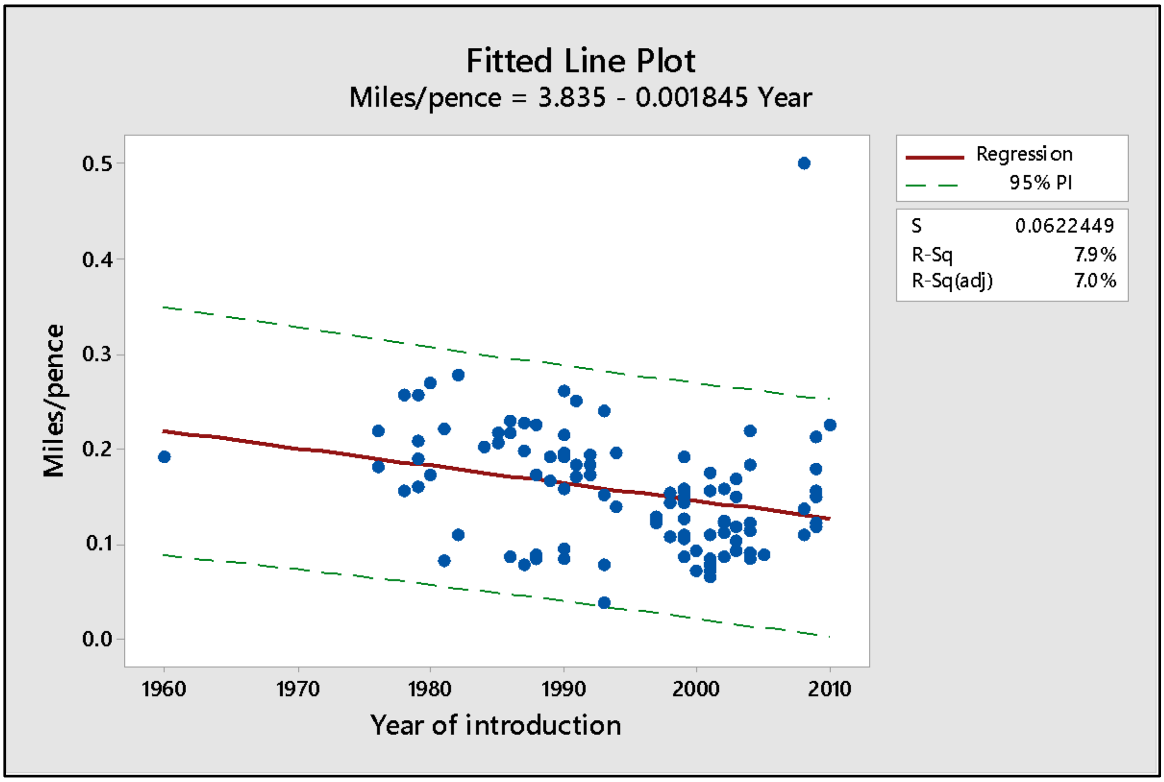


Figure 8: Main parameter of value – Miles/pence against year of introduction

In general, the MPV should increase over time, however, this chart shows that track friendliness has not increased and is possibly reducing. This would indicate that the train suspension system is not keeping pace with improvements occurring in the rest of the train e.g. train speed.

2.4.6 CAUSE AND EFFECT ANALYSIS

Based on the function analysis in section 2.3.2, train suspension should address several problems:

- Limited load carrying capacity
- Derailment (failure to guide train)
- Damage to track and train
- Passenger discomfort

For today's rail industry, track damage is viewed as the key priority. To uncover the underlying reasons behind this problem, Cause-effect analysis was used. This method enables the logic of the problem situation to be mapped and reviewed. Starting with the initial problem "train damages track", sub-causes were identified by reference to the track friendliness score (section 2.3.7). Where more than one cause is required to produce an effect, this is shown by using an "**AND**" gate. Where more than one causes could lead to an effect, an "**OR**" gate is used. Figure 9 shows the first part of the cause–effect analysis. Figure 10 analysed causes behind the problem "axle load is too high". Root problems (shown in boxes with a yellow fill) were identified for each of the branches of the analysis. Boxes with a dotted outline are out of scope.

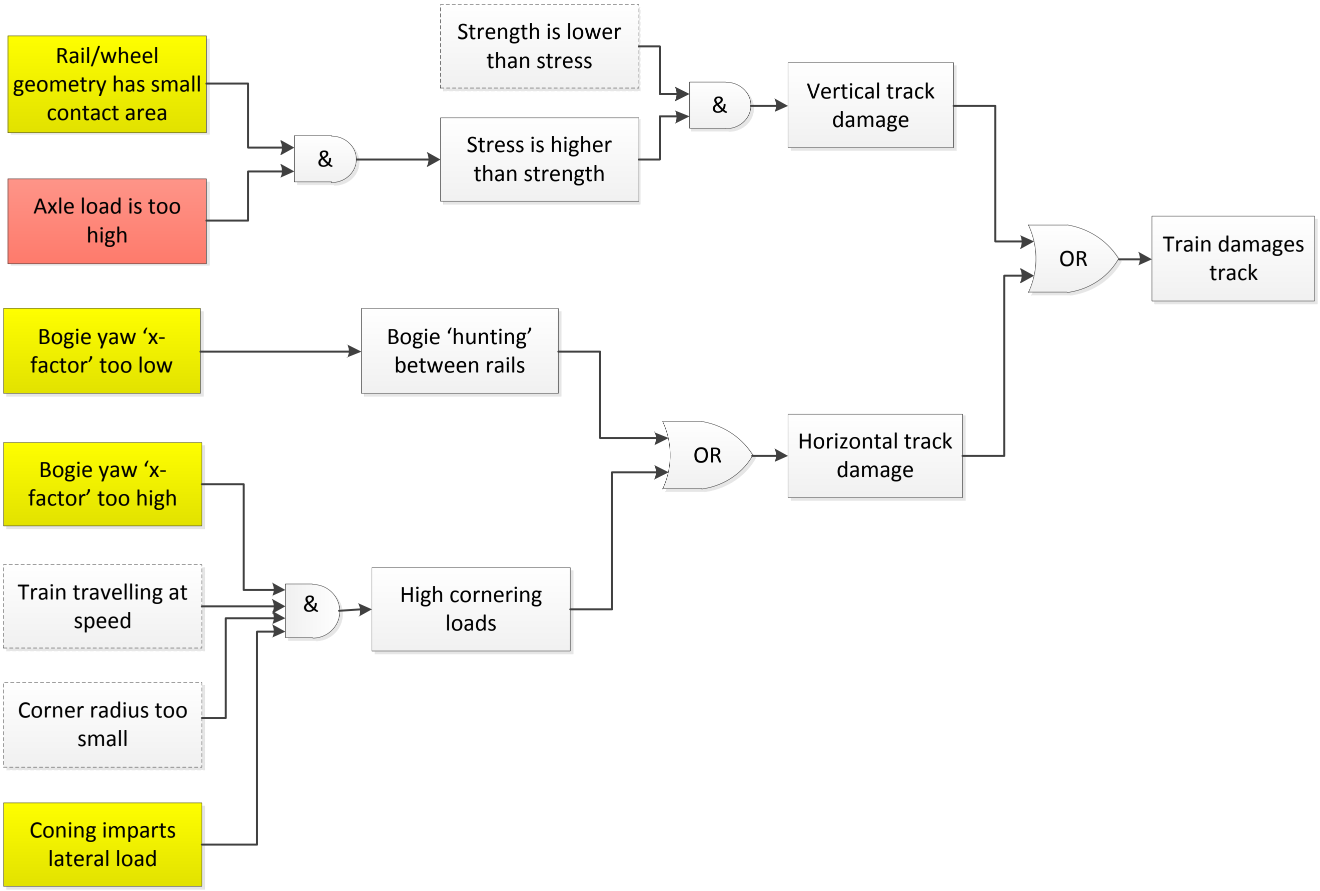


Figure 9: Cause effect analysis of train damages track

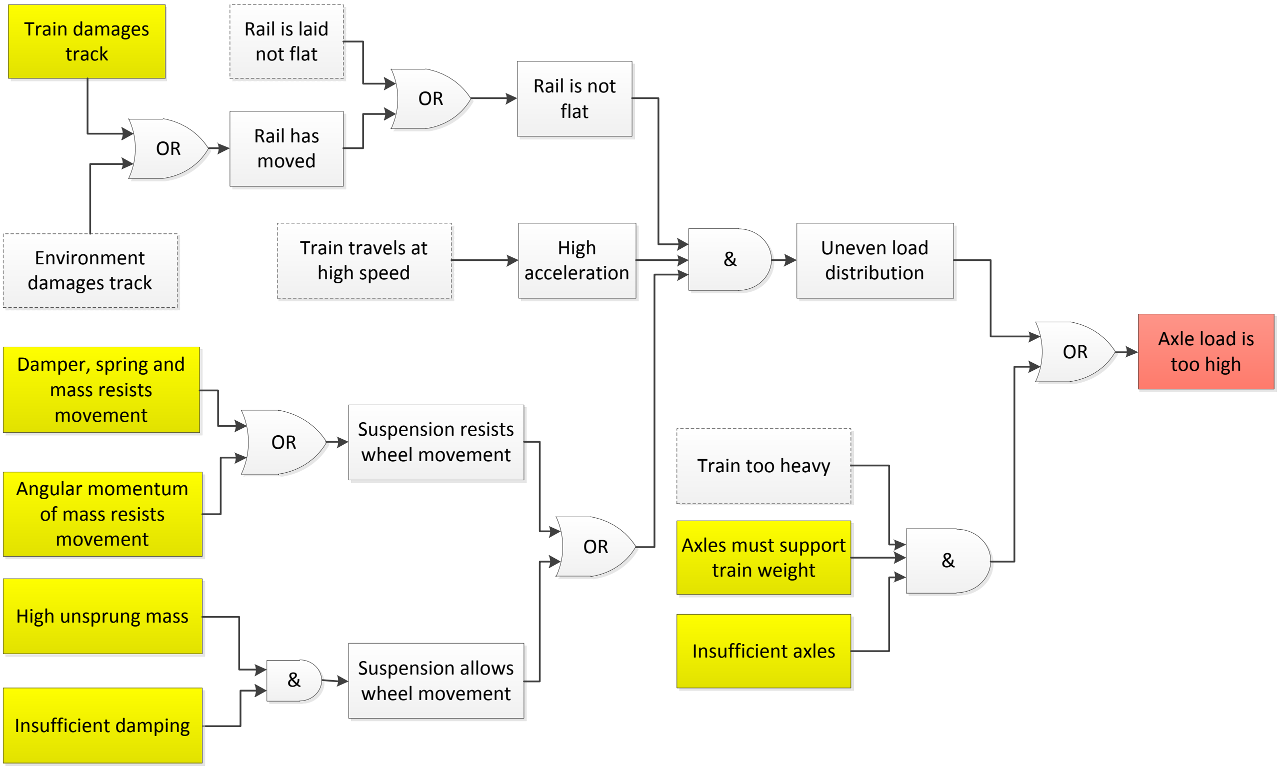


Figure 10: Cause effect analysis of axle load is too high

This analysis led to the following conclusions:

- Track damage is both a cause and an outcome – there is nothing in the current system to break the negative cycle of track damage leading to more track damage.
- The physical geometry of the current wheel and rail leads to a very high stress level in the contact area. A different geometry which minimised contact stress levels would negate the need to address lower level causes.
- There is a fundamental conflict between good curving performance (e.g. low bogie yaw factor) and straight-line stability (e.g. high bogie yaw factor).
- All the weight of the train passes through the axles to the wheel rail contact point – could some of this weight be distributed elsewhere?
- There is a conflict between the need to control the un-sprung mass (increased stiffness and damping) and the need for compliance when encountering track variations (reduced stiffness and damping).

2.4.7 NINE SCREEN MAPPING AND IDEAL OUTCOME

All technological systems exist within a hierarchy; that is, any system is part of a higher level system or super-system and is composed of lower level systems or sub-systems. For example, the train suspension system is part of the train and interacts with the track transportation and rail infrastructure super-system. On the other hand, the train suspension consists of sub-system elements including the wheel and axle, the bogie with yaw damping, the primary and secondary suspension. Typically, the needs of the super-system drive or constrain changes in the system while developments in the sub-system enable changes in the system.

While the TRIZ trends help to predict the next steps of evolution of a system, another important element of the analysis is a statement of the ultimate destination. The Ideal Outcome provides a way of stating the desired future state or end goal for the system, super-system and sub-system and often provides a powerful way to break current ways of thinking. Figure 11 shows a Nine Screen Map for the train suspension system, with the past situation showing an early stage rigid suspension. The future super-system is stated as a “Passengers travelling in comfort and safety at high speed with no track maintenance required”. The Ideal Outcome at the system level is stated in functional terms as “Supports the weight, guides and isolates from unwanted movement, with no loss of energy”. The future sub-system box identifies a need for new enabling technologies. Ideal Outcome statements are used to help formulate conflicts in the next stage of this project – step 3: Conflict Formulation.

	Past	**Present**	**Future (Ideal Outcome)**
Super System	Train, track, fixed infrastructure (e.g. platform, bridges, tunnels)	Train, track, fixed infrastructure (e.g. platform, bridges, tunnels)	Passengers travelling in comfort and safety at high speed with no track maintenance required
System	Rigid (no suspension)	Train suspension	Supports the weight, guides and isolates from unwanted movement, with no loss of energy
Sub-System	Wheels, axle, train body	Primary suspension (spring + damper), Secondary suspension (air), wheels, axle, train body	X-component(s) to deliver system’s ideal outcome

Figure 11: Nine screen map of train suspension system

2.5 STEP 3: CONFLICT FORMULATION

2.5.1 PROCESS OVERVIEW

Each root problem from the cause-effect map, detailed in section 2.4.6, was analysed using a conflict identification process. The analysis starts by stating both the root problem and corresponding Ideal Outcome (derived from the overall Ideal Outcome of “Supports the weight, guides and isolates from unwanted movement with no loss of energy” stated in section 2.4.7). The following Ideal Outcomes were derived from this analysis:

- Train only follows required movement with no damaging forces (vertical).
- Large contact area to support train weight.
- Perfectly guides train with no damaging forces (horizontal).

A full map of root problems and corresponding Ideal Outcomes is shown in Appendix A3. In the following section, specific barriers to the achievement of each Ideal Outcome will be briefly reviewed.

2.5.2 BARRIERS TO ACHIEVING “TRAIN ONLY FOLLOWS REQUIRED MOVEMENT WITH NO DAMAGING FORCES (VERTICAL)”

The vertical position of the train should follow the general elevation of the track, but should not follow any short-range deviations that might occur in the rails. The analysis revealed the following limitations in the current train suspension:

- Components have fixed parameters which often must be compromised e.g. the need for high stiffness to avoid derailment and low stiffness for comfort.
- The system cannot fully differentiate between wanted movement (changes in track elevation) and unwanted movement (track defects).
- There are several physical elements within the system that have high mass i.e. wheel, axle, bogie, and primary suspension components.
- Due to a conservative risk management approach within the rail industry, components which must withstand large loads are often heavy.

2.5.3 BARRIERS TO RESOLVING “LARGE CONTACT AREA TO SUPPORT TRAIN WEIGHT”

If the weight of the train could be borne across a larger area, the contact stress and loading on the track would be reduced. Three constraints were identified which prevent the rail system from moving in this direction:

- The current system is based on the use of hard wheels running on a hard rail; this leads to a very small localised contact between the wheel and the rail.
- Rolling resistance must be kept at a minimum, preventing the use of compliant or large contact area solutions.

- Increasing the number of axle/wheel combinations will increase complexity and may make cornering more difficult.

2.5.4 BARRIERS TO RESOLVING "PERFECTLY GUIDE TRAIN WITH NO DAMAGING FORCES (HORIZONTAL)"

The train should faithfully follow the path defined by the track, while preventing any harmful forces being exerted on the track or the passenger. The current train guidance solution has several drawbacks preventing the achievement of this goal:

- The wheel and axle is a one-piece rigid unit which prevents the two wheels rotating at different speeds.
- Wheel coning exerts a lateral force on the rail.
- The physical geometry of the wheel form, axle and bogie is fixed – it cannot respond to a wide range of track curvatures.
- The geometry and position of the rails is fixed.
- Components have fixed parameters which often must be compromised e.g. the need for high yaw stiffness to prevent hunting and low yaw stiffness to reduce cornering loads.

2.5.5 CONFLICTING REQUIREMENTS FOR TRAIN SUSPENSION ELEMENTS

The barriers described above highlight conflicting requirements for the current train suspension components e.g. the yaw damper must have high stiffness and low stiffness. A map of these "contradictions" is shown in Appendix A4.

2.6 STEP 4: CONFLICT RESOLUTION

2.6.1 PROCESS OVERVIEW

TRIZ tools were applied to identify strong solutions to each of the root problems outlined in section 2.4.6. The analysis also suggested three further solution directions which should be considered during the concept verification phase:

1. Simplification of the train suspension system.
2. Improve interaction between train suspension elements and the railway super-system.
3. Harness the energy currently wasted by the train suspension.

Functional search statements were prepared to enable research to find suitable technologies and solutions which are already in use in other industry sectors. The outputs of this section should be viewed as “partial solutions” to the complex problems which any future train suspension system should address. In practice, two or more conceptual solutions or technologies may need to be combined to provide a comprehensive answer to an issue. Possible options to combine solutions will be explored further in step 6 – Solution Selection. A more detailed review of the steps conducted in this analysis is outside of the scope of this report.

2.7 STEP 5: CONCEPT VERIFICATION

2.7.1 PROCESS OVERVIEW

Research was conducted to find technologies and concepts which answer the challenges stated in the previous step. Leading areas were identified where the underlying technologies found are already routinely used and well understood. Existing suspension resources were reviewed to find out if any of these could assist in providing the required functions. A list of potential technologies and solutions was generated and documented.

2.7.2 CONCEPT VERIFICATION OUTPUTS

Five main solution themes were identified by consolidating the Ideal Outcome statements with the additional three findings detailed in section 2.6.1. Figure 12 shows a summary listing of these solution categories.

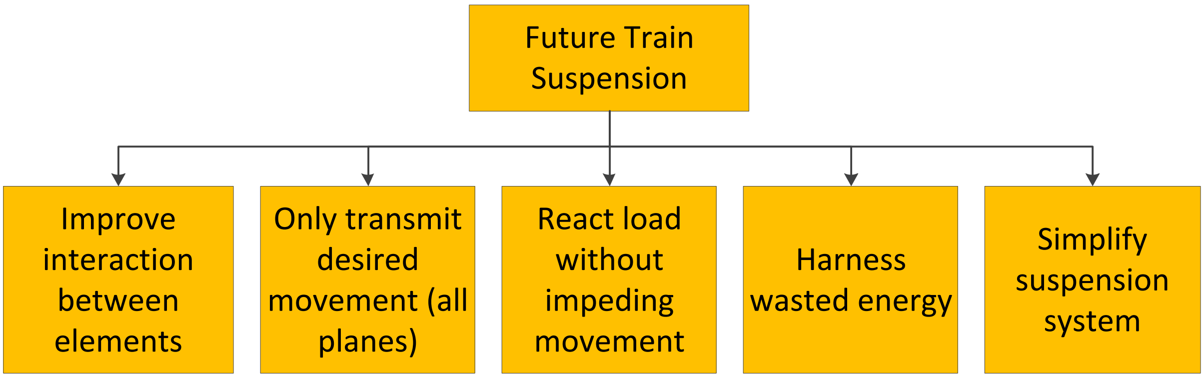


Figure 12: Summary listing of solution categories

Technology research was conducted within each of these areas. In the following sections of this report each of the technologies and solutions identified will be explored in further detail. The operating principle will be explained and the potential rail applications discussed. Where appropriate, evidence of the readiness of the solution for rail industry use will be provided.

2.7.3 IMPROVE INTERACTIONS BETWEEN ELEMENTS

During the analysis, it became clear that there is limited interaction between elements of present day train suspension systems.

In section 2.3.7, the MPV analysis showed that while the overall MPV of train speed was improving, a key suspension MPV related to the Variable Usage Charge, was getting worse. If there were good levels of interaction between the suspension system elements, train and rail system, both MPVs would be expected to improve together.

In section 2.4.4 the analysis highlighted significant trend mismatches between the different elements of the train suspension. The interaction between the train suspension and the infrastructure (super-system) is at an early evolutionary stage with very little co-ordination and there is little integration of control within the suspension elements within a train e.g. carriage to carriage.

As a result of the previous analysis, the solution category "improve interaction between elements" was selected. Figure 13 shows the technologies and solutions identified within this section.

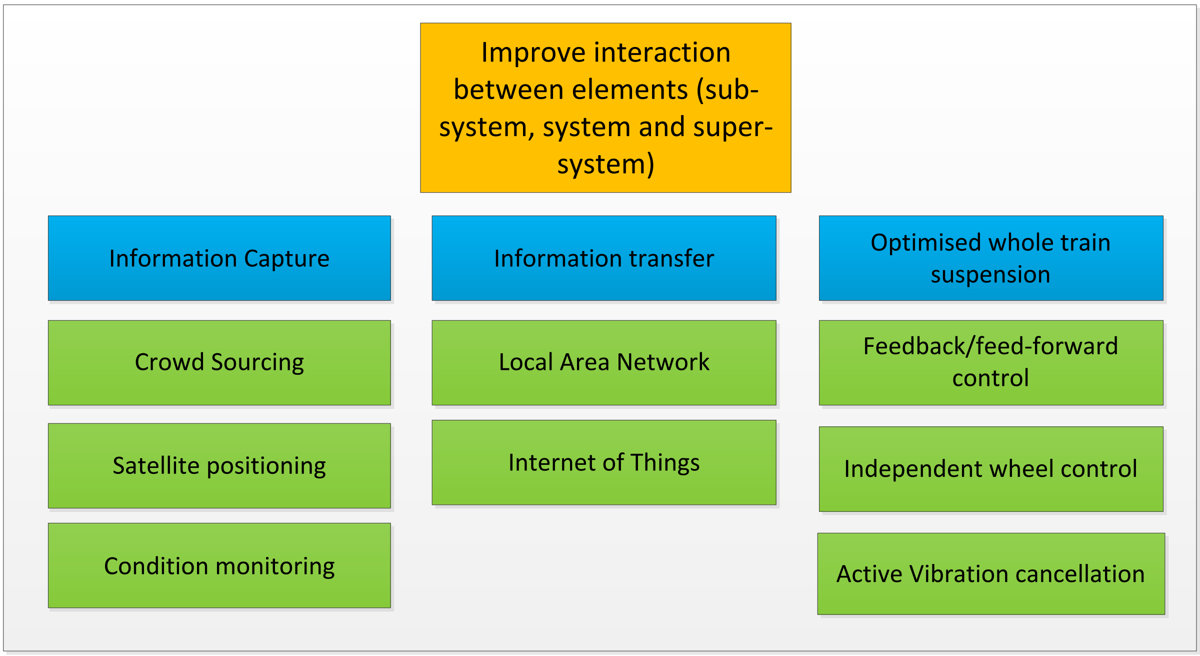


Figure 13: Technologies and solutions to improve interactions between elements

INFORMATION CAPTURE

To enable interaction within the suspension system it is first necessary to capture information. This section details examples of relevant technologies and solutions in this area.

CROWD SOURCING

Operating principle

Crowdsourcing is a specific sourcing model in which individuals or organizations use contributions from Internet users to obtain needed services, ideas or information. In crowdsourcing, organisations ask a group of individuals to contribute to a task. The undertaking of the task always entails mutual benefit; the contributor might receive money, social recognition, increased self-esteem, or personal development, the crowdsourcer gains advantage from the contributor's input.

An example of crowdsourcing in a transportation context is "Waze" from Google. According to the Waze website:

"Waze is a 100% free turn-by-turn GPS navigation application that provides real-time traffic updates, plus all kinds of cool social and geo-gaming elements that actually make commuting fun. Wazers can actively update one another on traffic, police traps, construction, speedcams, and more. And because it's user-generated, the more people who use it, the better (and more addictive) it gets!"

From the contributor's point of view, the benefit they get is a potentially shorter journey time; for Google, the benefit is extra information that can be used to enhance their products e.g. Google Maps.

Within public transport, the Moovit app provides users with up to date travel information as described below:

"By combining information from public transit operators and authorities with live information from the user community, Moovit offers travellers a real-time picture, including the best route for their journey. The Moovit community sends active reports about their travel experience, such as bus congestion levels, cleanliness, and more to help others have a better travel experience."

Railway solution – crowdsource train suspension information

Use the accelerometers and GPS capabilities of contributors' smart phones and other personal devices to collect information on the accelerations experienced by the user during their journey. This information is used to highlight the location of rail defects enabling appropriate action to be taken by the rail industry.

Potential benefits:

- Location and severity information on rail defects.
- Early indication of train defects.
- Opportunity to provide enhanced customer information e.g. advanced warning of sudden movement.
- Potential source of information for suspension system control optimisation.

Secondary considerations and research questions:

Potential questions to be addressed include:

- What benefits will motivate passengers to contribute to this solution?
- How accurate will this method of measurement be?
- Will the GPS provide an adequate measurement of position across the rail infrastructure e.g. tunnels, cuttings etc.?

Solution readiness

The civil engineering department at the University of Birmingham has recently published a paper describing how passengers' smart phones could be used to provide information on the ride quality of passenger trains **[20].** A key conclusion from the study was that the accelerometers found in modern smartphones are of sufficient quality to be used in evaluating ride comfort.

SATELLITE POSITIONING

Operating principle

The Global Positioning System makes use of satellites to measure location. The high accuracy achieved with modern receivers enable measurement of speed, distance and acceleration in all three planes. This is achieved using the Doppler shift in the GPS carrier signal which enables velocity and heading to be calculated directly.

The automotive industry is now making extensive use of this technology to log vehicle dynamic parameters for system development e.g. autonomous driving, suspension and braking development. One example of this technology is the VBOX system from Race Logic **[21].** Figure 14 illustrates the sensitivity of the VBOX system. The trace shows the velocity of a JCB during a braking manoeuvre, even recording the rocking motion of the vehicle cab after the JCB has come to rest.

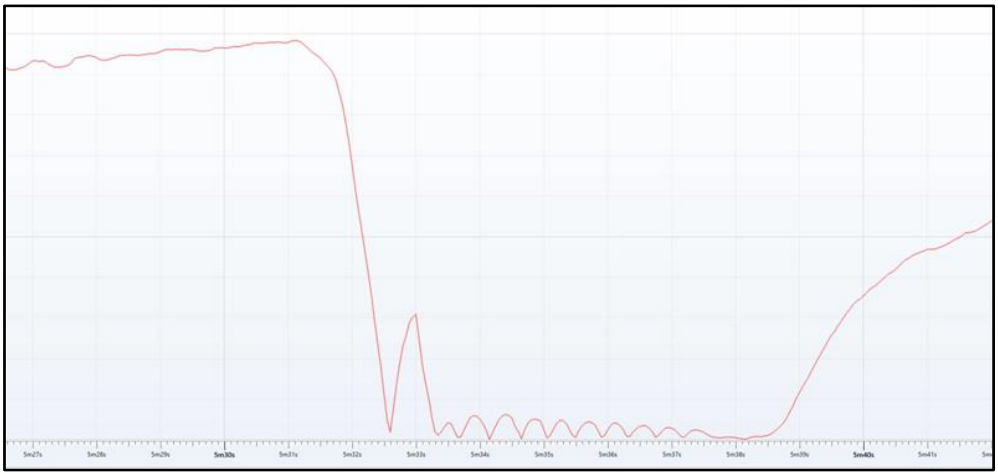


Figure 14: JCB decelerating and stopping with "rock back"

Railway solution – GPS provides inputs to control train suspension

GPS sensors could be deployed in multiple locations along the length of the train. The motion information gained could be used as a real-time input to a train suspension control strategy. In addition, this system could enable true train speed sensing and accurate train location in relation to track defects.

Potential benefits:

- Location and severity information on rail defects.
- Early indication of train defects.
- Potential source of information for suspension system control optimisation.
- True train speed can be utilised by wheel slip control system.
- Highly accurate train location could enhance existing methods of train position sensing e.g. track circuit.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Will the GPS provide an adequate measurement of position, velocity and acceleration across the rail infrastructure e.g. in tunnels, cuttings etc.?
- How easy will it be to integrate this technology on the trains?

Solution readiness

The technology is commercially available through several suppliers.

CONDITION MONITORING

Operating principle

Condition monitoring is the process of monitoring a parameter of condition in machinery (vibration, temperature etc.), to identify a significant change which is indicative of a developing fault. It is a major component of predictive maintenance. The use of condition monitoring allows maintenance to be scheduled, or other actions to be taken to prevent failure and avoid its consequences. Condition monitoring has a unique benefit in that conditions that would shorten normal lifespan can be addressed before they develop into a major failure.

A common condition monitoring method used with rotating machines is vibration analysis. Vibration measurements are taken on machine bearing casings with accelerometers and with eddy-current transducers that directly observe the rotating shafts to measure the radial (and axial) displacement of the shaft. The level of vibration is compared with historical baseline values such to assess any changes.

Railway solution – Condition monitoring on track and/or train to provide an indication of train suspension "health" with potential to provide an input to suspension control strategy

Multiple measuring techniques could be used to provide condition monitoring of the suspension and track. These might include:

- Vibration Analysis and diagnostics
- Lubricant analysis
- Acoustic emission
- Infrared thermography
- Pressure analysis (pneumatic and hydraulic systems)
- Environmental conditions

Potential benefits:

- Location and severity information on rail defects.
- Early indication of train defects.
- Potential source of information for suspension system control optimisation.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Which parameters would be the most appropriate to measure?

Solution readiness

Condition monitoring is a well-established and widely used technique. There is an ISO standard which describes how condition monitoring can be used on a range of common machine types **[22]** and the IMechE provides a training programme to apply these methods in the rail industry **[23].** A train mounted acoustic measuring system is available in the market under the trade name of ARRoW - “ARRoW records the noise (and vibrations) from the rolling wheels together with the train’s speed and geographical position. The noise levels that are measured fluctuate due to the changing properties of the railway track. By measuring the noise, one can chart the changes in typical rail properties such as rail roughness or rail defects”. **[24]**

INFORMATION TRANSFER

After acquiring relevant suspension system information, it is necessary to share this data with other system components. It is also necessary to send the corresponding control signals to other elements of the suspension system. This section details examples of relevant technologies and solutions in this area.

LOCAL AREA NETWORK

Operating principle

A local area network (LAN) is a group of computers and associated devices that share a common communications line or wireless link to a server. Typically, a LAN encompasses computers and peripherals connected to a server within a distinct geographic area such as an office or a commercial establishment.

An implementation of LAN in vehicles is known as the Controller Area Network (CAN bus). CAN is a robust vehicle standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer. It is a message-based protocol, designed originally for multiplex electrical wiring within automobiles to save on copper, but is also used in many other contexts.

Railway solution – Utilise available train networks to share suspension data and provide control to suspension system elements

To connect suspension system components to the existing train communication network to enable the transfer of suspension data and corresponding control signals between suspension elements.

Potential benefits:

- A means of communication between suspension components in different areas of the train.
- Potential source of information for suspension system control optimisation.
- Increased robustness to sub-system failure.

Secondary considerations and research questions:

Potential questions to be addressed include:

- What is the risk of sharing erroneous data across the entire train?
- Can information be shared at a rate to enable real time control?

Solution readiness

The use of local area networks is widely established in transportation applications including rail. For example, the CAN Bus protocol is used by most of the main automotive manufacturers. The train communication network standard IEC 61375 defines the Multifunction Vehicle Bus (MVB) for use in locomotives and across the whole train **[25].**

INTERNET OF THINGS

Operating principle

The Internet of Things (IoT) is the network of physical objects—devices, vehicles, buildings and other items—embedded with electronics, software, sensors, and network connectivity that enables these objects to collect and exchange data. The IoT allows objects to be sensed and controlled remotely across existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems.

A thing, in the Internet of Things, can be a person with a heart monitor implant, a farm animal with a biochip transponder, an automobile that has built-in sensors to alert the driver when tyre pressure is low – or any other natural or man-made object that can be assigned an IP address. Figure 15 shows a range of industrial and consumer devices connecting to the internet.

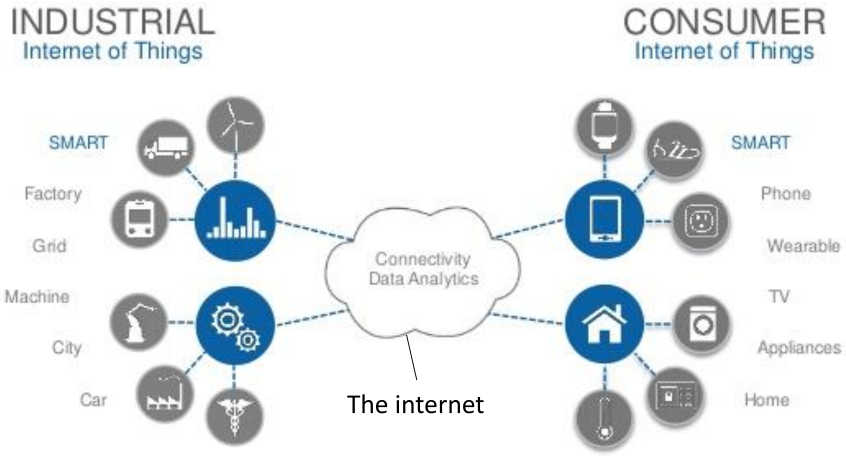


Figure 15: Industrial and consumer internet of things **[26]**

Railway solution

It is proposed to assign an IP address to every relevant component of the train suspension, enabling them to be sensed and controlled remotely. This extends the concept of a Train LAN described in the previous section to include wireless communication with the super-system e.g. a central rail controller or other trains.

Potential benefits:

- Enhanced communication with difficult to hard-wire components e.g. axles and wheels.
- Simplified connectivity within the train.
- Enables interaction between the super-system, suspension system and its components.
- Potential source of information for suspension system control optimisation.
- Increased robustness to sub-system failure.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How secure is the system to outside interference e.g. hacking?
- How robust is the radio communication in a hostile environment e.g. EMI?
- What is the risk of sharing erroneous data across the entire train and beyond?

Solution readiness

Siemens have recently described their Internet of Trains system which enables rail operators to connect their trains and physical infrastructure to the digital world **[27].**

As long ago as 2005, Hitachi filed a patent on adaptive suspension using a multitude of inputs including map information, train position, journey history, train weight, train condition data and meteorological information **[16].**

OPTIMISED WHOLE TRAIN SUSPENSION

The capability to acquire and share data between the super-system, system and sub-system enables the possibility of implementing whole train suspension control strategies. This section details examples of relevant technologies and solutions in this area.

Operating principle

In a closed loop control system, the output or response of the system to the control signal is fed-back and compared to the required or demanded output. This error between the actual and demanded output is used to modify the control signal in such a way as to minimise the error (see figure 16). This feedback control enables a system to be more robust and reliable to changing system and environmental conditions.

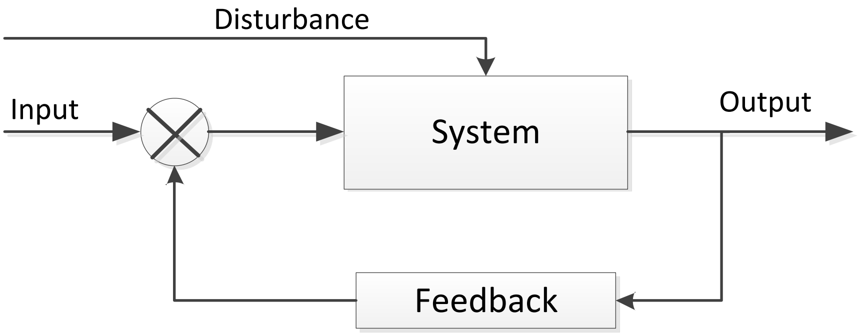


Figure 16: Closed loop feedback control system

An example of a suspension feedback control system is the “Active Roll Control” fitted to the new Audi SQ7. This system, from Schaeffler, “comprises of a transmission, an electric motor with electronic components, and an integrated torque sensor. The electric motor and its high transmission, three-stage planetary gear unit rotate the two halves of the roll control system in opposite directions, which produces a torque that has a stabilising effect on the vehicle body. A non-contact torque sensor accurately identifies this torque, which is used to quickly and precisely control the actuator.” **[28].** This feedback system prevents the rolling of the vehicle improving high speed cornering and passenger comfort.

In a feed-forward control system, the control signal adjustment is not based on measurement of the output but is based on a change in conditions which necessitates a pre-determined change in the controller (see figure 17).

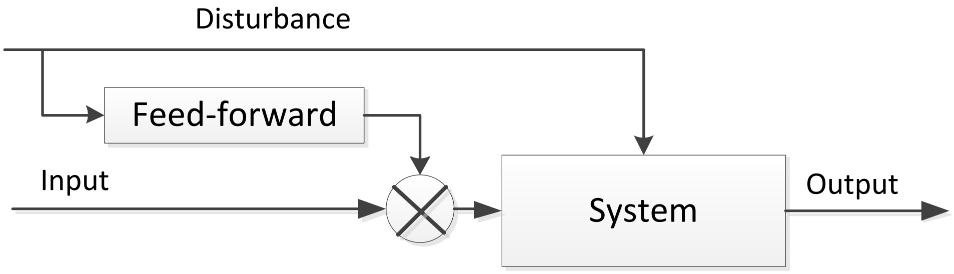


Figure 17: Feed-forward control system

An example of a suspension feed-forward control system is the “Magic Body Control” from Mercedes Benz **[29]**. This suspension system, fitted to the latest S-Class vehicles, incorporates a camera that is constantly scanning the road ahead. When it identifies a change in the road surface, it adjusts the vehicle suspension damping to the optimum setting for the coming conditions. This feed-forward of the road conditions enables the suspension to anticipate the disturbance, rather than having to react after the event.

Railway solution 1: The use of feedback control in train suspension in conjunction with semi-active or active train suspension components

It is proposed to use feedback control of semi-active or active components in the train suspension system enabling the suspension to adapt to changing track conditions. The semi-active or active suspension system might be an existing component such as the pneumatic suspension or a modified component such as an adjustable yaw damper. The feedback could be provided using appropriate sensors. For example, in the case of the pneumatic suspension, the state of the suspension could be measured by pressure transducers, level sensors or accelerometers.

Railway solution 2: The use of feed-forward control in conjunction with semi-active or active train suspension components

It is proposed to use feed-forward control to provide early information of changing track conditions to a semi-active or active component in the train suspension system. The track information could be provided in three different ways:

- Forward looking system mounted on the front of the train e.g. camera, LIDAR.
- Measurements from preceding axles within the train e.g. accelerometer mounted on leading axle.
- Historical information derived from previous trains.

The semi-active or active suspension system might be an existing component such as the pneumatic suspension or a modified component such as a yaw damper with adjustable damping.

Potential benefits:

- The suspension system can adapt its characteristics to changing track conditions, avoiding the need to compromise suspension settings.
- Increased safety and passenger comfort.
- Reduced track damage.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe behaviour be ensured?
- How much energy will be required to drive the semi-active or active elements?
- How quickly can the system respond to changing conditions?
- What is the optimal means of gather track information?

Solution readiness

Feedback and feed-forward suspension control systems are becoming widely introduced into the automotive sector **[28], [29].** One example from the railway industry is the control system for tilting trains – precedence control of tilting. As shown in figure 18, this incorporates both feed-forward (leading bogie sending information to following bogies) and feedback control (tilt angle sensors providing feedback to the actuators).

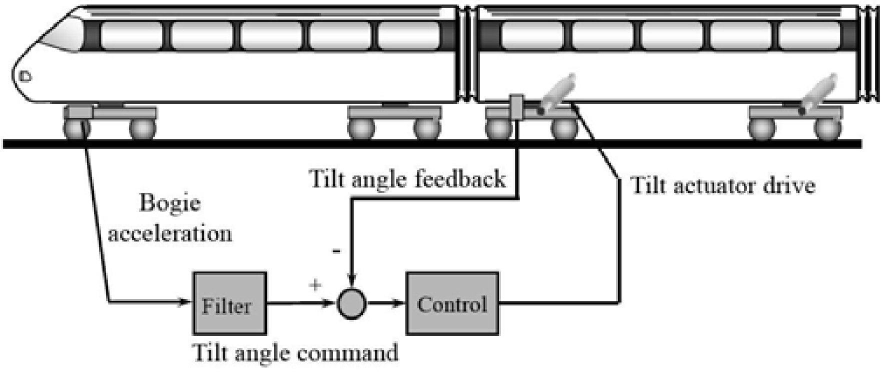


Figure 18: "Precedence" tilting control system **[30]**

INDEPENDENT WHEEL CONTROL

Operating principle

Train wheels are typically mounted rigidly to an axle, forming a wheelset. With a solid axle between the two wheels there is a natural mechanical guidance or steering action that enables the train to negotiate curves. Due to the coning of the wheels, if the wheelset moves sideways there is a larger rolling radius on the outer wheel compared to the inner wheel, which causes the wheelset to move back towards the centre line.

While this guidance action is useful during cornering, it can lead to problems of instability known as "hunting" when the train is travelling on a straight piece of track. To combat this instability, mechanical bogies use stiff yaw connections between bogie and wheelsets and secondary yaw dampers between the bogie and carriage to provide stability, but this leads to poor curving. There is therefore a fundamental trade-off between going quickly in a stable manner and negotiating curves which leads to wheel and rail wear, noise on curves, and other negative effects.

It may be possible to mitigate the trade-off between straight line stability and curving by allowing the wheels within an axle to rotate independently.

Railway solution

It is proposed to allow the wheels to rotate independently by splitting the axle and mounting each wheel with its own bearings. Independent wheel movement could be in response to track curvature (a passive independent system) or due to drive motor control for each wheel (an active independent system) **[30].**

Potential benefits:

- Improved cornering performance while maintaining bogie stability for all train speeds.
- Reduced wheel and rail wear on curves.
- Opportunity for lowering carriage floor.
- Reduced un-sprung mass.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Will independent wheels still provide sufficient guidance during cornering?
- Will independent wheels provide sufficient stability during straight line operation?

Solution readiness

- Independent wheel drive is already in use on some trams. An example of an independent wheel tram is the Siemens Avenio vehicle which has been in passenger service in Munich since September 2014 **[31, 32].**

ACTIVE VIBRATION CANCELLATION

Operating principle

Active noise cancelling headphones work by creating an anti-phase signal of the same amplitude and frequency as the noise to be cancelled. The two waveforms combine through a process of destructive interference to cancel each other out.

In the same way, unwanted vibrations can also be cancelled using active vibration cancelling. A force opposite to the vibration excitation (same frequency, same amplitude but opposite phase) is generated resulting in a destructive interference process at the location where the control force is applied.

Railway solution

It is proposed to use active vibration cancellation within train seats (or other selected areas e.g. driver’s seat, toilet, wheelchair space etc.) to provide an improved level of passenger comfort.

Potential benefits:

- Improved passenger/driver comfort.
- Opportunity to differentiate 1st Class.
- Less passenger fatigue and discomfort.
- Specialist seating for passengers with back problems or similar conditions.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How much energy will be required?
- Does the solution provide sufficient benefit for the increased cost?

Solution readiness

There is already a system in the market from BOSE (one of the leading manufacturers of noise cancelling headphones) called the “BOSE Ride System” **[33]** for truck seats.

Figure 19: BOSE RIDE Truck seat with active vibration cancelling **[33]**

2.7.4 SIMPLIFY SUSPENSION SYSTEM

The trend analysis in section 2.4.4, revealed that the suspension system is made up of many discrete elements with similar properties e.g. primary and secondary suspension and some shifted properties e.g. damper and spring. From the TRIZ perspective, this level of complexity would be expected to reduce in future systems as the elements of the suspension system combine.

The analysis showed that in a modern train suspension, there are many compensation systems at the sub-system level which are intended to correct issues that have been designed into the basic system e.g. yaw damping to correct bogie “hunting”. These corrective systems should be trimmed from the overall train suspension, with their function delegated to other existing components or resources. In some cases, the need for compensating systems might be eliminated completely through mass reduction.

These findings support the need to simplify the train suspension systems; various options to achieve this goal will be discussed in the following sections.

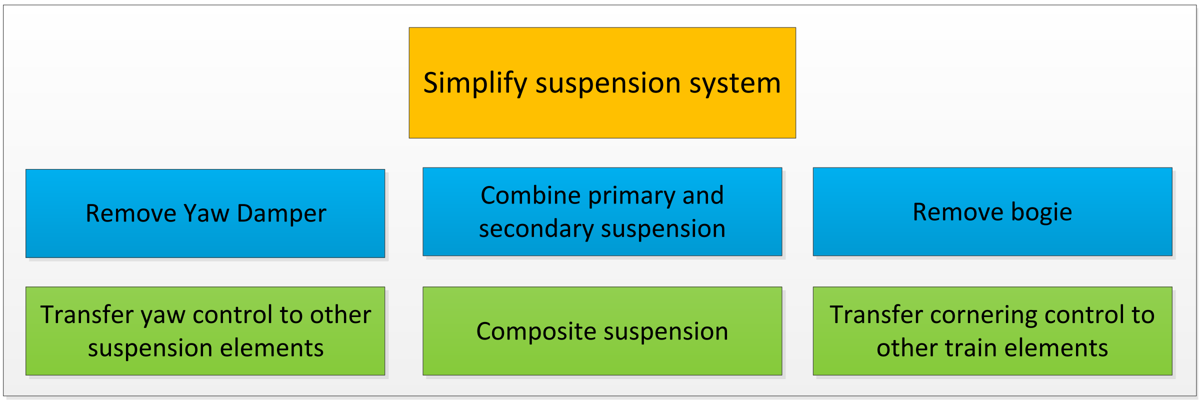


Figure 20: Technologies and solutions to simplify suspension system

REMOVE YAW DAMPER

The secondary suspension yaw damper is mounted between the bogie and the carriage and is designed to prevent the “hunting” instability that can occur when a train is travelling on straight track above a critical speed. This is a form of compensation system, in that its main function is to compensate for the poor functioning of another system (the bogie). The yaw damper does not contribute directly to the useful function of guiding the train, but corrects for the inability of the bogie to guide the train in a straight line. Compensation systems add cost and complexity and will have their own reliability and maintenance issues.

To simplify the suspension, we should consider removing the yaw damper. There are two strategies that we can employ to achieve this:

- Transfer the function of the yaw damper to another train system or component.
- Remove the need for a yaw damper e.g. remove the bogie (this will be discussed later in this report).

TRANSFER YAW CONTROL TO OTHER SUSPENSION ELEMENTS

Operating principle

Provide yaw damping using a controllable train suspension element which is configured to give an appropriate level of resistance to bogie rotation.

Railway solution

It is proposed to utilise the active tilting system or the compliance in the pneumatic secondary suspension to change the bogie yaw resistance.

Potential benefits:

- Removal of yaw damper leads to reduced cost, weight, maintenance and improved reliability.

- Active yaw control leads to improved cornering while maintaining straight line stability at high speed.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe behaviour be ensured?
- How much energy will be required to control the yaw resistance?
- How quickly can the system respond to changing conditions?

Solution readiness

The concept of active yaw control has been discussed in several research papers **[30].** This study has not identified any systems currently in use in the rail industry which make use of other suspension components to perform yaw damping.

COMBINE PRIMARY AND SECONDARY SUSPENSION

COMPOSITE SUSPENSION

Operating principle

Conventional suspension systems consist of a rigid supporting structure combined with compliant components such as springs and dampers. Modern carbon fibre composite materials can provide structures with very high strength but with a controlled amount of flexibility and internal damping. Composite materials offer reduced mass compared with steel structures of similar strength.

Railway solution

It is proposed to replace the primary suspension on the bogie, by utilising a very stiff but flexible bogie structure constructed from carbon fibre composite materials.

Potential benefits:

- Reduced weight leading to less track damage and energy saving.
- Improved reliability through part count reduction and elimination of moving parts.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Is composite technology appropriate for train suspension?

Solution readiness

Composite springs are already being used in mass produced automotive applications **[34]**. A car suspension concept has been proposed in which flexible composite wishbones replace conventional springs and dampers. A demonstrator is currently under development by a UK-based engineering consortium. The ‘Lightweight Innovative Flexible Technology’ (LIFT) system is claimed to save about 40% of a conventional double wishbone system’s weight. The project is part-funded by Innovate UK **[35].**

REMOVE BOGIE

A further step towards simplifying the suspension system is to remove the bogie entirely. The primary function of the bogie is to follow a curved track. The next section describes an option to provide this cornering function without a bogie.

TRANSFER CORNERING CONTROL TO OTHER TRAIN ELEMENTS

Operating principle and railway solution

The bogie is replaced by an “axle” which is comprised of two decoupled actively guided wheels. This provides the means to steer each wheel, enabling the cornering function. Each wheel is suspended by a single stage ‘active’ suspension unit and is driven by an in-wheel traction motor. This concept is described in more detail in a paper from Loughborough University **[36]**

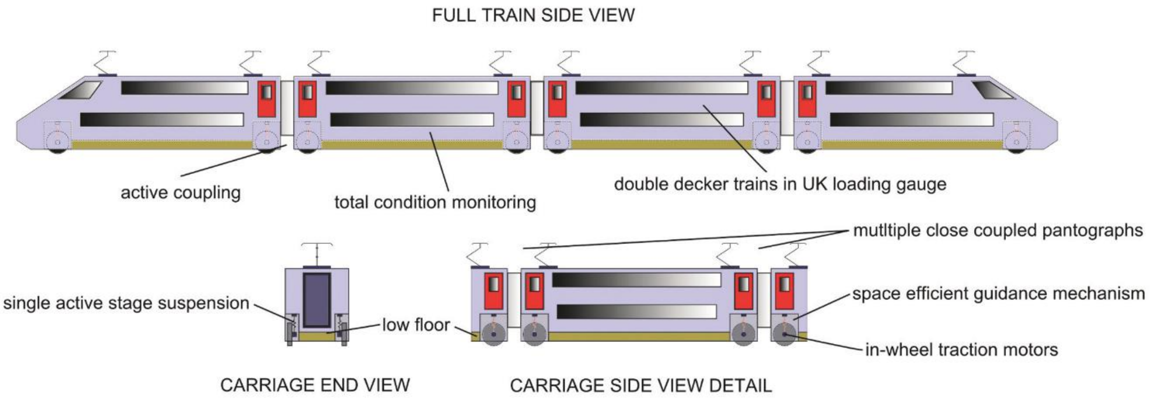


Figure 21: Future train concept **[36]**

Potential benefits:

- Reduces the impact of contact forces on track wear.
- Removes the mechanical trade off constraint between straight line stability and curving performance.
- Reduced suspension mass.
- Increased space availability, possibly allowing lower carriage floor.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe behaviour be ensured?
- How much energy will be required to control the suspension system?
- Does the system need to be fully active?

Solution readiness

The concept described above is still at the research stage for the rail industry, however, in aerospace and increasingly automotive the control strategies needed for this form of operation are already being applied **[37]**.

2.7.5 HARNESS WASTED ENERGY

In section 2.4.4 the trend analysis of energy flow highlighted that the suspension system is an energy absorption system. The suspension must dissipate harmful energy that results from useful train kinetic energy being converted into vertical movement because of track variation. The harmful energy which is not absorbed by the suspension causes damage to the track and train, noise, and vibration. The energy absorbed by the suspension is currently unused. The next section describes options to recover this energy.

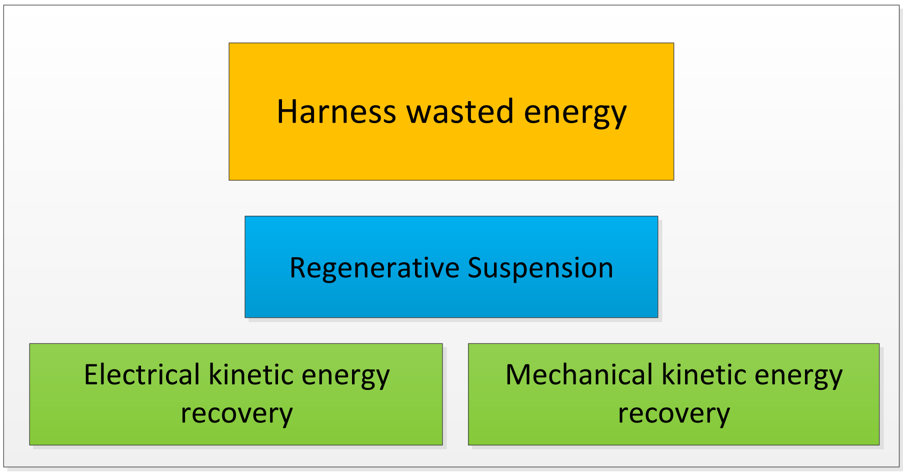


Figure 22: Technologies and solutions to harness wasted energy

REGENERATIVE SUSPENSION

Regenerative braking systems recover the kinetic energy of the train that would normally be lost as heat and noise in conventional friction braking. In a similar way, a regenerative suspension system would attempt to recover or harvest kinetic energy from unwanted train movements in the vertical or lateral planes. This would potentially have two benefits; firstly, removing the energy from the unwanted movement will have the effect of “damping” the movement, secondly, the recovered energy can be used to provide some useful function e.g. actuate active suspension components.

ELECTRICAL KINETIC ENERGY RECOVERY

Operating principle

Kinetic energy from a vehicle's suspension movement is converted by various suspension components (e.g. regenerative dampers) into electricity. The electricity is then used to recharge the on-board energy store, reducing the amount of energy required to drive the vehicle.

Railway solution

It is proposed to use regenerative damping components within the existing train suspension system to harvest wasted energy.

Potential benefits:

- Reduce overall energy consumption.
- Potential for additional control of suspension components.
- New energy source for suspension actuation or control.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How much energy could this concept recover?

Solution readiness

Research has been conducted by academics and industry with the focus on automotive and wave energy applications **[38, 39, 40, 41]**.

MECHANICAL KINETIC ENERGY RECOVERY

Operating principle

Kinetic energy from a vehicle's movement is captured during braking and stored. The energy is then used to provide additional power boost to drive the vehicle forwards as required. This form of system is used in Motorsport e.g. Formula 1 (see Figure 23).

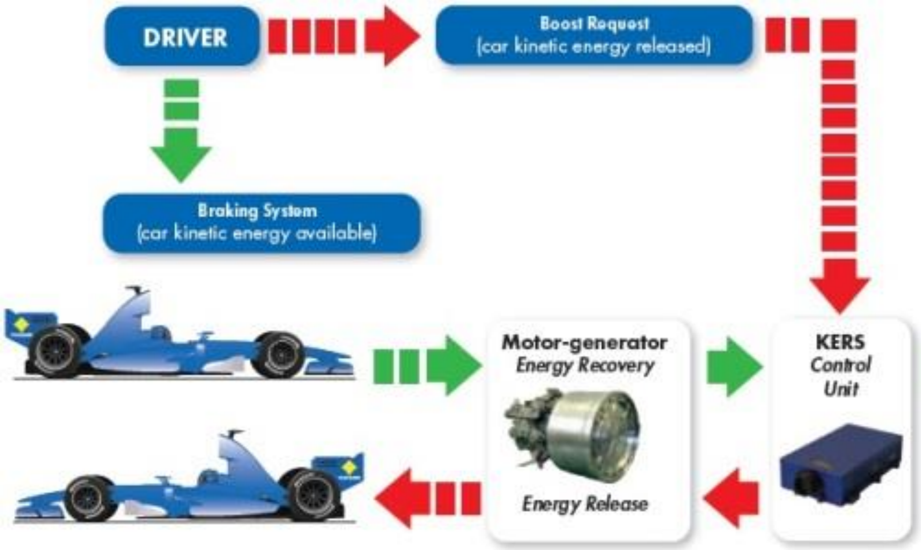


Figure 23: Kinetic energy recovery system operation

Railway solution

It is proposed to recover the kinetic energy from suspension movement and store it using a flywheel. The stored energy could then be released to assist the train acceleration.

Potential benefits:

- Reduced energy consumption.
- Potential to boost train acceleration if needed e.g. in tunnels and bridges with no electrification access.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How much energy would this concept recover?
- What is the most effective format to capture the kinetic energy of suspension movement?

Solution readiness

This form of technology is already in use in Motorsport. Flywheel systems have been used experimentally in small electric locomotives for shunting or switching, e.g. the Sentinel-Oerlikon Gyro Locomotive **[42]**. Larger electric locomotives, e.g. British Rail Class 70, have sometimes been fitted with flywheel boosters to carry them over gaps in the third rail **[43]**.

2.7.6 REACT LOAD WITHOUT IMPEDING MOVEMENT

To minimise the stress on the track the contact area should be large, but this conflicts with the need to keep rolling resistance to a minimum (see section 2.5.1 & 2.5.3). Strong solutions to this conflict should satisfy both requirements, resulting in a solution theme for this area of "React load without impeding movement".

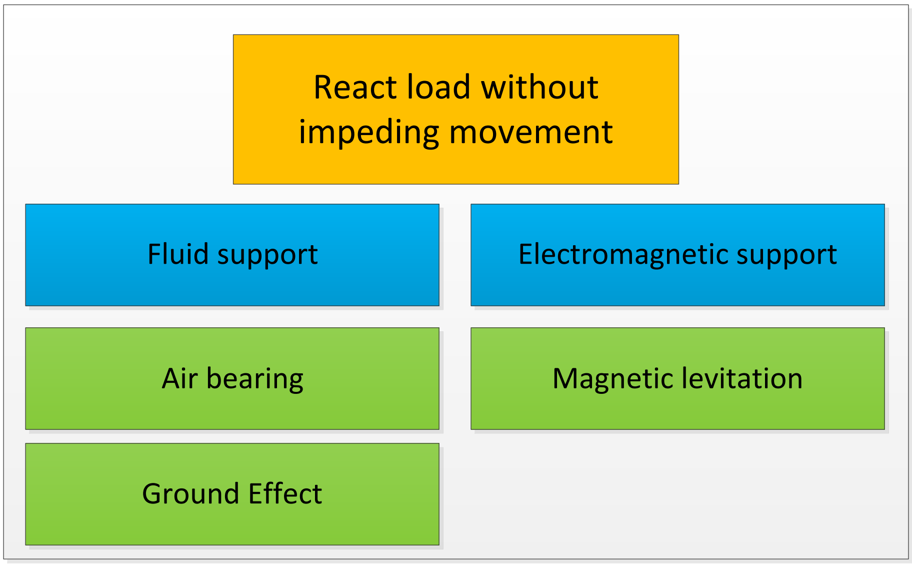


Figure 24: Technologies and solutions to react load without impeding movement

FLUID SUPPORT

AIR BEARING

Operating principle

An air bearing has two surfaces between which air is forced, via a restrictive orifice, so that it keeps them apart. If the gap between the surfaces reduces then the outflow via the edges of the bearing is reduced and the pressure goes up, forcing the surfaces apart again very strongly, giving excellent control of the gap and giving low friction. Air bearings are used in applications where there is a need to minimise frictional resistance to movement. Figure 25 shows an example of an air bearing application.

Figure 25: Air “hockey” table

Railway solution

It is proposed to reduce the force acting through the wheel rail contact by incorporating an air bearing system into the train. Compliant air bearings could be mounted between the two axles of one bogie and would act directly onto the rail surface **[44]**.

Potential benefits:

- Reduced force acting through the wheel rail contact.
- Reduced rolling resistance.
- May provide additional compliance to primary suspension.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How much force can be supported by this form of bearing?
- How much air would be lost and what level of energy consumption would be required?
- Will this solution be sufficiently robust for the rail industry?

Solution readiness

This form of bearing is already in use for applications in which it is necessary to move heavy items with relatively low force **[45]**.

GROUND EFFECT

Operating principle

A wing generates lift by deflecting the oncoming airmass. The deflected or "turned" flow of air creates a resultant force on the wing. Depending on the shape of the wing, the resultant force can provide lift. Flying close to a surface increases air pressure on the lower wing surface and thereby improves the lift-to-drag ratio of the wing. The closer the wing is to the ground, the more pronounced the ground effect becomes.

Railway solution

It is proposed to utilise ground effect when a train is travelling at high speed to provide a vertical force to react some of the weight of the train. The ground effect could be delivered by passive or active aerodynamic devices e.g. wings.

Potential benefits:

- Reduced force acting through the wheel rail contact.
- Reduced rolling resistance.
- Potential to reduce risk of derailment at high speed (with active control).

Secondary considerations and research questions:

Potential questions to be addressed include:

- How much force can be generated by ground effect?
- Will there be any effect on train energy consumption?
- Will this solution be sufficiently robust for the rail industry?
- How will failsafe operation be ensured?

Solution readiness

Ground effect is already commonly used in racing cars and some high-performance road cars.

ELECTROMAGNETIC SUPPORT

MAGNETIC LEVITATION

Operating principle

Magnetic levitation, or maglev, is a method by which an object is suspended with no support other than magnetic fields. Magnetic force is used to counteract the effects of the gravitational acceleration and any other accelerations. The magnetic field can be generated by using permanent magnets or electromagnets and the forces generated can be attractive or repulsive depending upon the configuration of the system.

Figure 26 shows a coil wrapped around an iron core, placed over a metal plate. When current flows through the coil, the iron core is induced with a magnetic field. The magnetic field induces a magnetic field in the metal, but in the opposite direction. As a result, both fields repel each other and the iron core is lifted upwards.

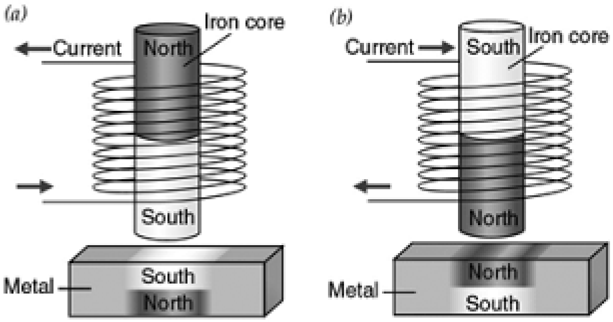


Figure 26: Electromagnetic levitation

In figure 27, a permanent magnet replaces the coil and iron core. When the magnetic flux is changed by moving the magnet, a magnetic field is induced in the metal plate which repels the permanent magnet.

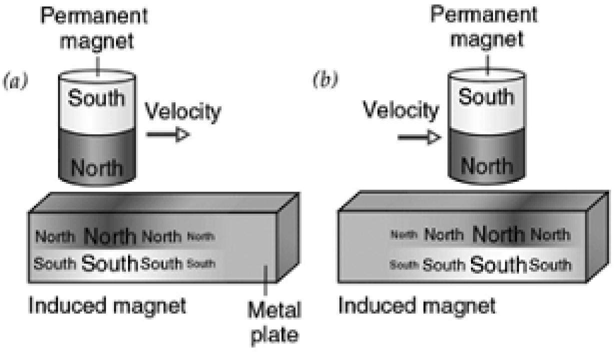


Figure 27: Electrodynamic levitation

Various options for magnetic levitation have been proposed and demonstrated **[46]**:

- Electromagnetic suspension
- Electrodynamic suspension
- Inductrack

Railway solution

It is proposed to use a train based magnetic levitation system to assist the weight carrying and guidance roles of the train suspension.

Potential benefits:

- Reduced loads transmitted through the wheel rail contact resulting in improved track friendliness.
- Reduced likelihood of flange climbing derailment.
- Potential to improve passenger comfort.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Which type of magnetic levitation will give the best benefits?
- Is it possible to combine the levitation function with train braking and traction?
- How will failsafe operation be ensured?
- How much power will be required to achieve the required control?

Solution readiness

The first passenger carrying magnetic levitation train was introduced at Birmingham airport in 1984 **[47]**. A 30km maglev track opened for commercial service in 2004 running between the airport and city of Shanghai **[48].** There is a maglev test facility in Japan that recently set the speed record for this form of transport of 600kph **[49].**

2.7.7 ONLY TRANSMIT DESIRED MOVEMENT (ALL PLANES)

Section 2.5.1 stated that an ideal suspension system should transmit the desired movement (track position) to the train and passengers, while totally removing all undesired movement (track defects and variations). This section explores technologies and solutions which can help a train suspension system reach this goal.

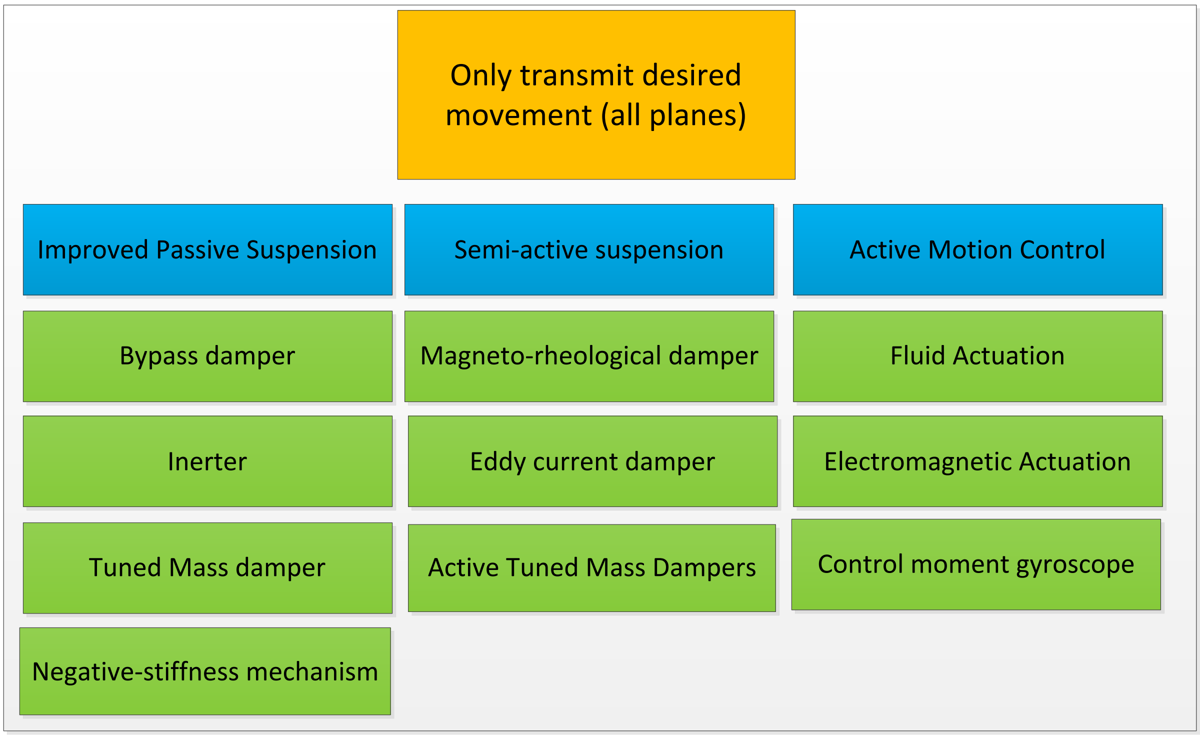


Figure 28: Technologies and solutions to only transmit desired movement

IMPROVED PASSIVE SUSPENSION

Operating principle

Any mechanical system subject to vibration can be described in terms of a mass, spring and damper (see figure 29). The mass has inertia that will resist change in velocity, the spring has an elastic characteristic which provides increasing resistance to displacement and the damper resists movement with a force that is proportional to the rate of change of velocity. In a suspension system the spring and damping parameters are tuned to improve the stability of the mass in response to vibration. In a passive system the spring and damping parameters are fixed which prevents the suspension from being optimised for all operating conditions. The following technologies provide ways to enhance the performance of a passive suspension system.

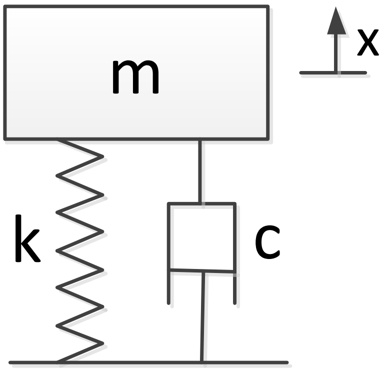


Figure 29: Mass spring damper system

BYPASS DAMPER

Operating principle

A damping system which uses a valve and bypass channel to provide amplitude-dependent damping giving a lower damping force for small bumps and a greater damping force for large movements.

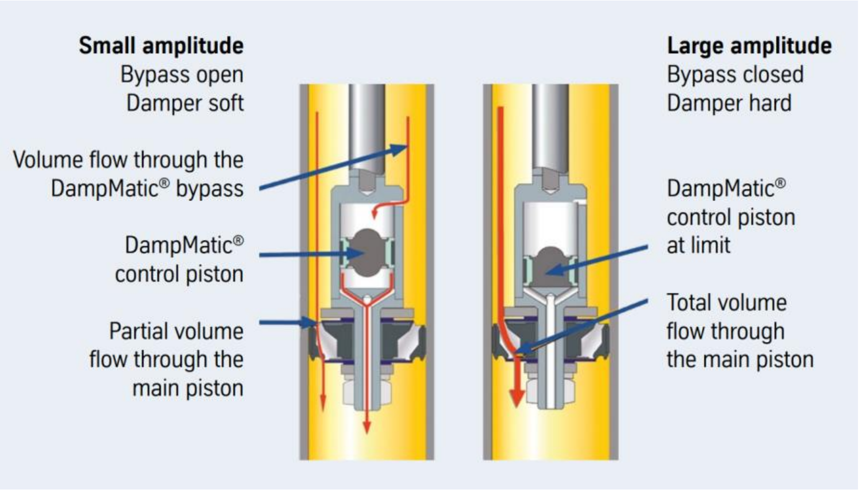


Figure 30: Bypass damper system **[50]**

Railway solution

It is proposed to incorporate bypass damper systems into the current train suspension system.

Potential benefits:

- Could provide more comfortable and forgiving primary and secondary suspension, while still maintaining train stability.
- Could enable two stage yaw damping e.g. high yaw resistance for straight line travel and low yaw resistance for cornering.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe operation be ensured?
- Is this technology sufficiently robust for railway application?

Solution readiness

This is a mature technology in use for many years in the automotive market **[50]**.

INERTERS

Operating principle

An inerter stores kinetic energy derived from motion rotationally using a flywheel. By gearing up the flywheel to increase its speed, a greater amount of energy can be captured without increasing the mass of the device and its inertia in space. The inerter enables the suspension system to have a high effective mass (for good control of rate of change of velocity) but with a low actual mass to minimise impact on vehicle speed, space and safety. Figure 31 shows a mass spring damper suspension with an inerter.

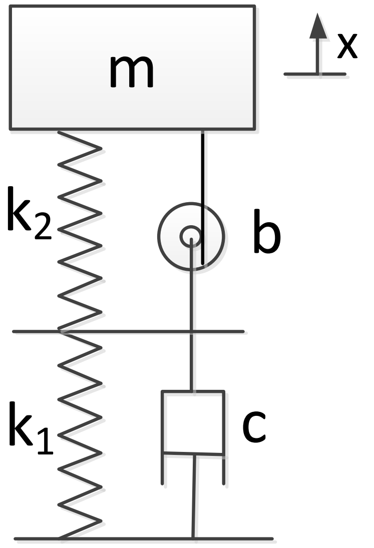


Figure 31: Mass spring damper and inerter system

Figure 32 provides more detail of the internal elements of a typical inerter which uses a rack and pinion to translate linear motion to rotary, a gearing arrangement to increase rotational speed and a flywheel to store rotational kinetic energy.

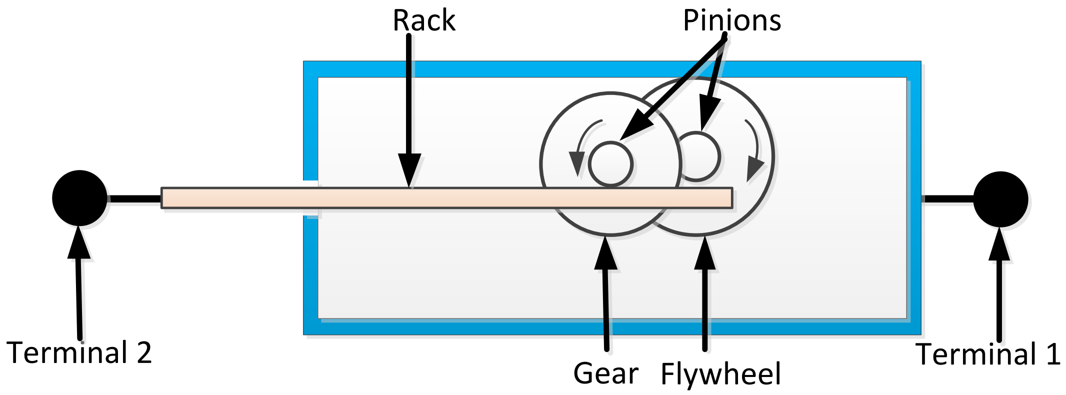


Figure 32: Section view of an inerter **[51]**

Railway solution

It is proposed to use inerters within the train suspension systems.

Potential benefits:

- Could provide more comfortable and forgiving primary and secondary suspension, while still maintaining train stability.
- Could enable improved yaw damping.
- Could improve pantograph stability.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe operation be ensured?
- Is this technology sufficiently robust for railway application?

Solution readiness

This technology is already in use in motorsport e.g. Formula 1 **[51]**. The University of Huddersfield is currently running a study into the use of inerters in the rail industry **[52]**.

TUNED MASS DAMPER

Operating principle

A tuned mass damper is a device intended to reduce the amplitude of mechanical vibration in structures. They are commonly used to prevent discomfort, damage, or structural failure. A tuned damper reduces the vibration of a system using a small additional spring mass damper system to absorb vibratory energy from the overall structure. Tuned mass dampers can be used to prevent resonance in structures which otherwise would be difficult or expensive to damp directly. Figure 33 shows a typical tuned mass damper system.

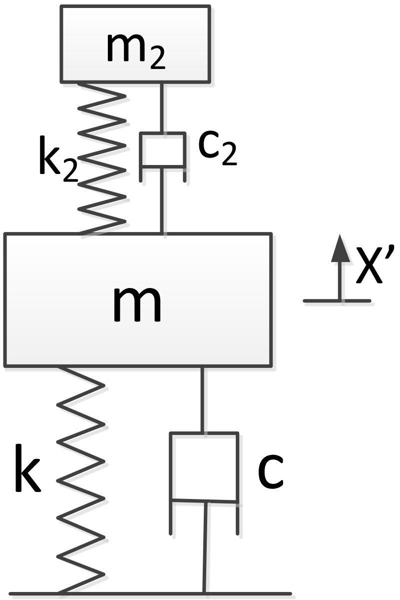


Figure 33: Tuned mass damper (m_2)

Railway solution

It is proposed to use passive tuned mass dampers to prevent resonance in train suspension when it is hard to establish an optimum damping value e.g. avoiding hunting due to poor yaw damping.

Potential benefits:

- Could provide improved train stability.
- Potential to reduce track damage.
- Prevents bogie hunting.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe operation be ensured?

Solution readiness

Tuned mass dampers are widely used in automotive applications. They are also commonly used in civil engineering, for example protecting tall buildings from damage during earthquakes and eliminating harmful resonance in bridges. Figure 34 shows a seismic mass used as part of a tuned mass damper system to prevent earthquake damage to a 101-storey skyscraper in Taipei **[53]**.

Figure 34: 660 tonne tuned mass damper system in 101 storey Taipei skyscraper **[53]**

NEGATIVE-STIFFNESS MECHANISM

Operating principle

Whereas in a normal spring support system, force increases with spring deflection, in a negative stiffness mechanism the resistance decreases with deflection. A negative stiffness mechanism comprises two flexures, loaded in compression. Negative stiffness mechanisms are used as part of a vibration isolation system. In a vibration isolator, isolation is provided by a stiff spring that supports a weight load, combined with a negative-stiffness mechanism. The net vertical stiffness is made low without affecting the static load-supporting capability of the spring. A typical vibration isolator is shown in Figure 35.

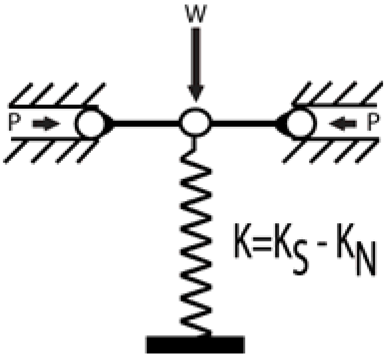


Figure 35: Negative stiffness isolator

Figure 35 shows a system with a conventional spring connected to a negative stiffness mechanism. The spring is compressed by weight W to the operating position of the isolator. The stiffness of the isolator is K=KS-KN where KS is the spring stiffness and KN is the magnitude of a negative stiffness which is a function of the design of the flexures and the load P. The isolator stiffness can be made to approach zero while the spring supports the weight W.

Railway solution

It is proposed to use negative-stiffness mechanisms in combination with the primary or secondary suspension springs to reduce the net vertical stiffness of the train suspension without affecting the static load-supporting capability.

Potential benefits:

- Significant improvement in suspension compliance leading to improved passenger comfort and reduced train system damage.
- Potentially reduced track damage.
- Passive solution which does not require any energy input.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How might this solution be integrated into a train suspension system?
- How will failsafe operation be ensured?

Solution readiness

Negative stiffness mechanisms are currently being used for mechanical vibration suppression in applications requiring a very high degree of stability such as the mounting of precision measuring equipment **[54].**

SEMI-ACTIVE SUSPENSION

In a passive suspension system, the spring and damping parameters are fixed which prevents the suspension from being optimised for all operating conditions. A semi-active suspension enables these parameters to be adjusted to meet changing operating conditions, without the higher energy requirements of a fully active system. The following technologies provide ways to provide semi-active train suspension.

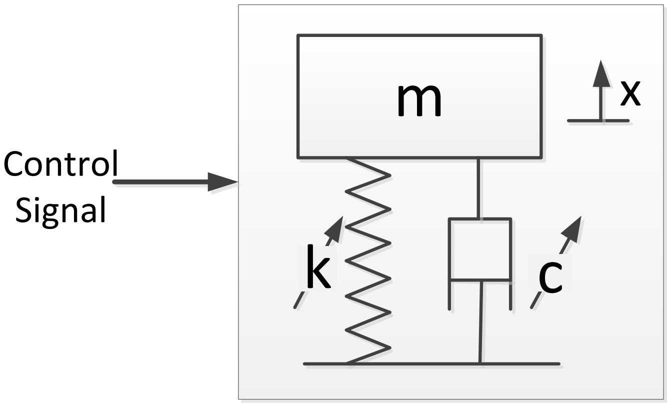


Figure 36: Semi-active suspension system

MAGNETO-RHEOLOGICAL DAMPERS

Operating principle

A magneto-rheological fluid (MR fluid) is a type of smart fluid composed of very small ferrous particles in a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity. A magneto-rheological damper or magnetorheological shock absorber is a damper filled with MR fluid. The damping characteristics of the shock absorber can be continuously controlled by varying the power of an electromagnet. Fluid viscosity increases within the damper as the electromagnetic intensity increases. This type of shock absorber has several applications, most notably in semi-active vehicle suspensions which can adapt to changing road conditions **[55].** Figure 37 shows a typical magneto rheological damper from an automotive application. The electromagnetic field within the damper is varied by a central control unit which can change the damping characteristics from soft to very firm in milliseconds.

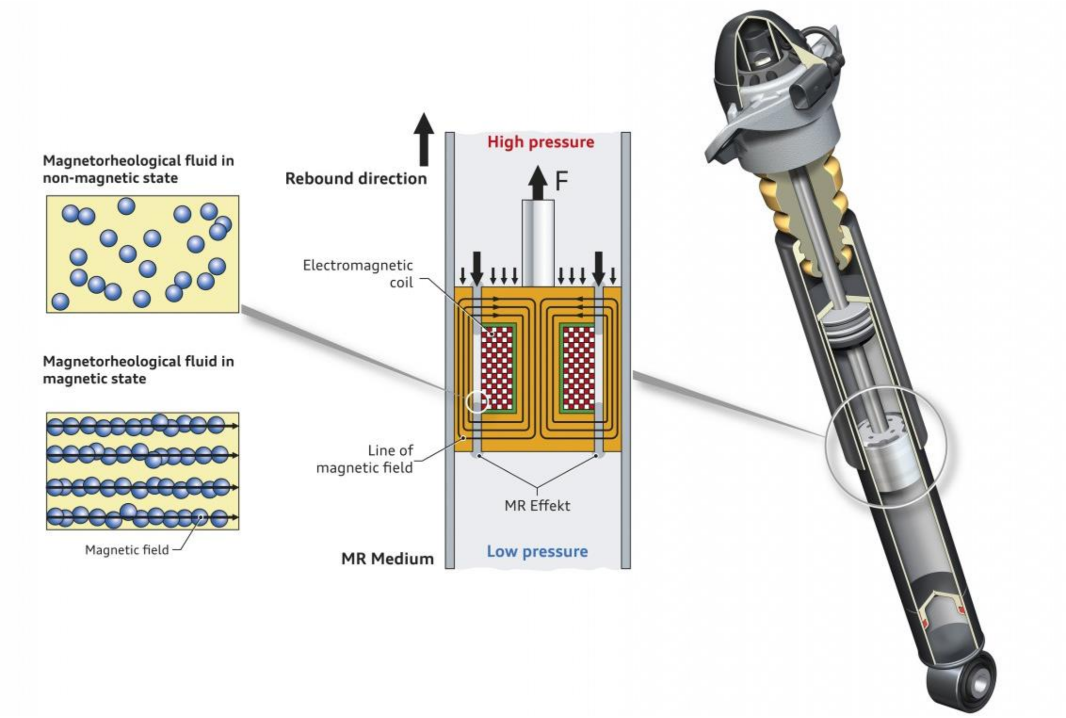


Figure 37: Magneto rheological damper **[55]**

Railway solution

It is proposed to use magneto-rheological damping within the train suspension systems.

Potential benefits:

- Enables suspension parameters to be optimised to deal with different track conditions.
- Potential to reduce track damage.
- Improved passenger comfort.
- Reduced risk of hunting and improved curving.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How might this solution be integrated into a train suspension system?
- How will failsafe operation be ensured?

Solution readiness

This technology has been in use for 15 years in the automotive industry. Applications to the train suspension have been discussed in academic papers **[56]**.

EDDY CURRENT DAMPING

Operating principle

When a conducting material is exposed to a varying magnetic field, a voltage difference and hence current is induced in the conductor. The faster the rate of change of the magnetic field, the greater the induced voltage and current in the conductor.

Under certain conditions, the induced electric current in a conductor may circulate in the form of "eddies". The circulating eddy currents heat the conductor and induce their own magnetic fields which resist the motion of the applied field. This resistive force means that eddy currents are often used for braking; since there is no contact with a brake shoe or drum, there is no mechanical wear.

Eddy current damping uses this principle to provide a variable means for motion control. Figure 38 shows a linear eddy current damper using permanent magnets. Resistive force can be changed by altering the magnetic field e.g. by use of an electromagnet or by changing the conductor resistance e.g. by replacing the conductor with a switchable coil arrangement.

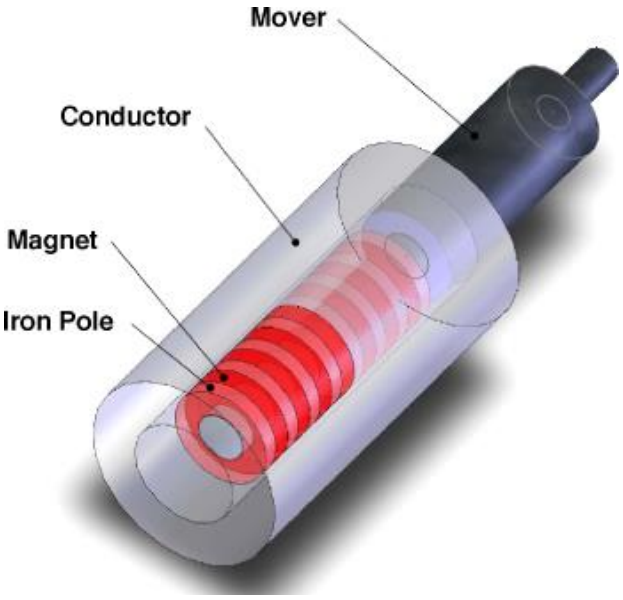


Figure 38: Passive linear eddy current damper

Railway solution

It is proposed to use semi-active eddy current damping within the train suspension systems.

Potential benefits:

- Enables suspension parameters to be optimised to deal with different track conditions.
- Potential to reduce track damage.
- Improved passenger comfort.
- Reduced risk of hunting and improved curving.
- Potential for energy generation (see section 2.7.5).

Secondary considerations and research questions:

Potential questions to be addressed include:

- How might this solution be integrated into a train suspension system?
- How will failsafe operation be ensured?

Solution readiness

Semi-active eddy current damping systems have been described in research papers **[57]**.

ACTIVE TUNED MASS DAMPERS

Operating principle

A passive tuned mass damper (TMD) is made-up of an inertia element (mass) suspended by an energy dissipating (damping) device and a restoring (resilient) element. The size of a TMD is characterized by its mass ratio of M2/M1. The effectiveness of a TMD can be enhanced by addition of an active element, e.g., a linear actuator, into its make-up transforming it into an active TMD (ATMD). An ATMD can also be tuned to more than one frequency eliminating the need for using multiple TMDs tuned to multiple frequencies.

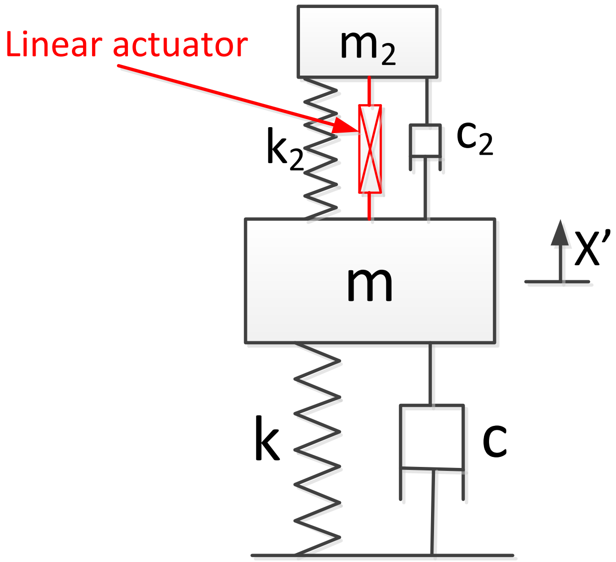


Figure 39: Active Tuned Mass Damper (TMD with added actuator)

Railway solution

It is proposed to use active tuned mass dampers to prevent resonance in train suspension when it is hard to establish an optimum damping value e.g. avoiding hunting due to poor yaw damping.

Potential benefits:

Same benefits as tuned mass damper, with the following additional benefits over that solution:

- Reduced mass.
- Able to deal with multiple resonances.
- Can adjust to changing parameters over time.

Secondary considerations and research questions:

Potential questions to be addressed include:

- How will failsafe operation be ensured?

Solution readiness

Active tuned mass dampers are being used in several industry sectors to provide noise and vibration control **[58]**.

ACTIVE MOTION CONTROL

In a passive or semi-active suspension system, the operational parameters are limited by the characteristics of the system elements e.g. spring stiffness and damper characteristics. An active suspension system uses power to "artificially" extend the design parameters of the system. The control system constantly monitors the changing conditions and drives elements of the suspension as needed. Figure 40 shows a schematic of a typical active suspension system. The following technologies provide ways to provide active train suspension.

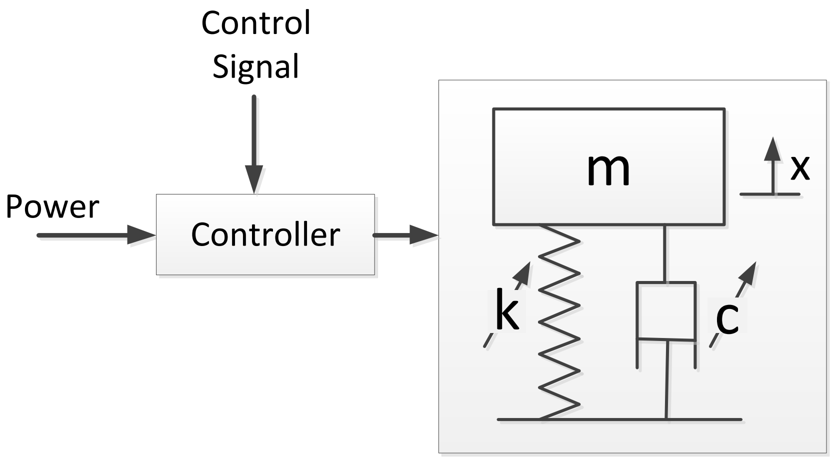


Figure 40: Active suspension system

FLUID ACTUATION

Operating principle

A fluid actuation system comprises a pressure source, a servo valve, an actuator and a controller. The pressure source provides a supply of operating fluid to the servo valve. The controller adjusts the servo valve output which controls the position of the actuator, moving the load. To provide closed control the position of the actuator is fed back to the controller. The operating fluid can be either pneumatic or hydraulic. Figure 41 shows a typical fluid actuation system with closed loop control.

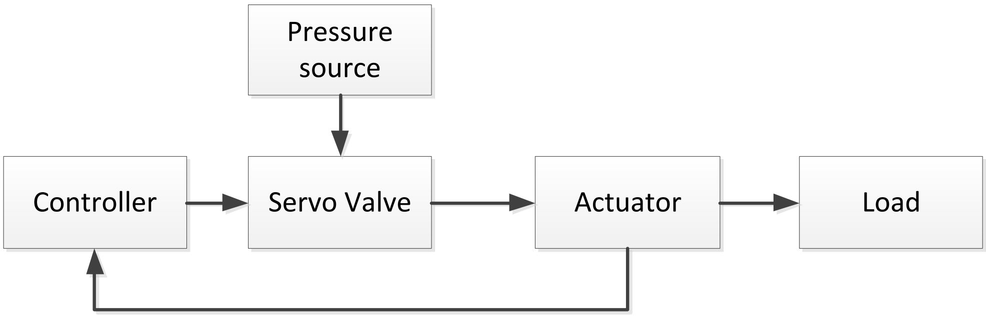


Figure 41: Fluid actuation system

Railway solution

It is proposed to use the existing pneumatic secondary suspension with improved control e.g. using a servo valve to provide active control of the train suspension.

Potential benefits:

- Very high actuation forces with precise control of train body leading to improved comfort and reduced track damage.
- Potential to improve platform to train gap and step.
- Well proven robust technology.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Which areas of the train suspension would benefit most from this form of actuation?
- How quickly can this form of actuation respond?
- How will failsafe operation be ensured?
- How much power will be needed to achieve the required active control?

Solution readiness

Pneumatic suspension is already used routinely in train suspension systems under the control of the levelling valve.

ELECTROMAGNETIC ACTUATION

Operating principle

An electromagnetic actuation system comprises an electrical power source, an actuator and a controller. The power source provides a supply of electricity to the actuator which generates a torque or linear force depending upon the type of actuator. The controller adjusts the level of power to the actuator, moving the load to the desired position. To provide closed-loop control, the position of the actuator (or sometimes load) is fed back to the controller. Figure 42 shows a typical electromagnetic actuation system with closed loop control.

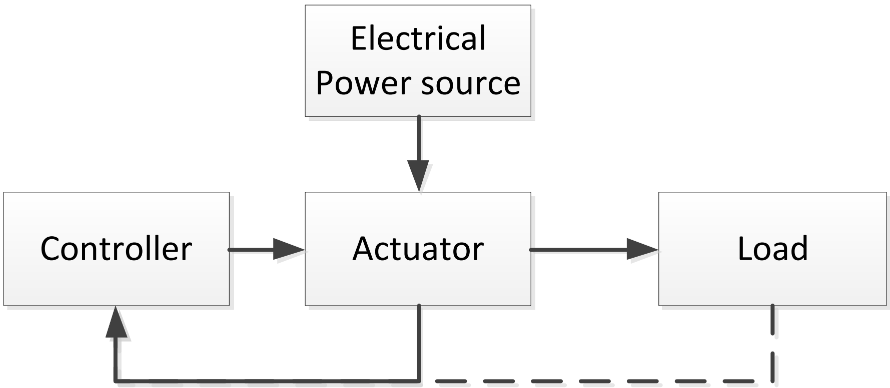


Figure 42: Electromagnetic actuation system

Railway solution

It is proposed to use electromagnetic actuation to provide an element of active control within the train suspension systems.

Potential benefits:

- Very precise and rapid control of train body, leading to improved comfort and reduced track damage.
- Well proven robust technology.
- More energy efficient than hydraulic actuation.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Which areas of the train suspension would benefit most from this form of actuation?
- How will failsafe operation be ensured?
- How much power will be needed to achieve the required active control?

Solution readiness

Electromagnetic actuation is already used in some rail applications e.g. Pendolino train has electric actuators to provide the tilting function **[59]**.

CONTROL MOMENT GYROSCOPE

Operating principle

A control moment gyroscope (CMG) is an attitude control device generally used in spacecraft attitude control systems. A CMG consists of a spinning rotor and one or more motorized gimbals that tilt the rotor's angular momentum. As the rotor tilts, the changing angular momentum causes a gyroscopic torque that rotates the spacecraft. CMGs can produce a large amount of torque, for example, an input power of a few hundred watts can produce thousands of newton meters of torque.

Railway solution

It is proposed to use a train based CMG system to assist the stabilisation and guidance roles of the train suspension.

Potential benefits:

- Reduced loads transmitted through the wheel rail contact resulting in improved track friendliness.
- Reduce the potential for flange climbing derailment and bogie hunting.
- Potential to improve passenger comfort.

Secondary considerations and research questions:

Potential questions to be addressed include:

- Where would be the best CMG mounting location?
- How much space would be required?
- How will failsafe operation be ensured?
- How much power will be required to achieve the required control?
- What level of benefits could be delivered by a CMG?

Solution readiness

Control moment gyroscopes are currently used for attitude control and stabilisation in spacecraft **[60]**, and boats **[61].**

2.8 STEP 6: SOLUTION SELECTION

2.8.1 PROCESS OVERVIEW

The twenty-seven technologies and solutions described in section 2.7 were reviewed against the evaluation criteria listed in the original project horizon scanning statement section 2.3.8. An additional criterion of “Rail industry development time” was added to provide an indication of implementation timescale. Concept illustrations were prepared to show how selected technologies and concepts might be combined to deliver future train suspension and to expose secondary problems which might need to be solved to realise the proposed concept.

2.8.2 TECHNOLOGY AND SOLUTION EVALUATION

Strong negative impact	🟥
Moderate negative impact	🟧
No impact	⬜
Moderate positive impact	🟨
Strong positive impact	🟩

	1. Derailment prevention	2. Relative damage (per axle.mile) - vertical	3. Horizontal damage to the track (rail wear and RCF)	4. Minimise cost (capital and on-going)	5. Minimal impact on train space	6. Improves passenger experience	7. Minimise energy usage	8. Minimise environmental impact	9. Dewirement prevention	10. Ability to work within current rail infrastructure	11. Rail industry development time
Crowd sourcing	🟨	🟨	🟨	🟨	⬜	🟨	⬜	🟨	⬜	🟨	🟩
Satelite positioning	🟨	🟨	🟨	🟨	⬜	🟨	⬜	🟨	⬜	🟨	🟩
Condition monitoring	🟨	🟨	🟨	🟨	⬜	🟨	⬜	🟨	⬜	🟨	🟩
Local Area Network	🟨	🟨	🟨	⬜	⬜	🟨	⬜	🟨	⬜	🟨	🟩
Internet of Things	🟨	🟨	🟨	⬜	⬜	🟨	⬜	🟨	⬜	🟨	🟨
Feedback control	🟨	🟩	🟩	🟧	⬜	🟩	🟧	🟨	🟨	🟨	⬜
Feed-forward control	🟩	🟨	🟨	🟧	⬜	🟩	🟧	🟨	🟩	🟩	⬜
Independent wheel control	🟩	⬜	🟩	🟥	🟨	🟨	⬜	🟨	⬜	⬜	🟧
Active Vibration cancellation	⬜	⬜	⬜	🟧	⬜	🟩	🟧	⬜	⬜	⬜	🟨
Transfer yaw control to other suspension systems	⬜	⬜	🟨	🟨	🟨	⬜	⬜	⬜	⬜	⬜	🟧
Composite suspension	⬜	🟨	⬜	🟨	🟨	🟨	⬜	🟨	⬜	⬜	🟥
Transfer cornering control to other train elements	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟨	🟨	⬜	🟥
Electrical kinetic energy recovery	⬜	⬜	⬜	🟧	⬜	⬜	🟩	⬜	⬜	⬜	🟧
Mechanical kinetic energy recovery	⬜	⬜	⬜	🟧	🟧	⬜	🟩	⬜	⬜	⬜	🟧
Air bearing	🟧	🟨	⬜	🟥	🟧	🟨	🟥	🟨	⬜	🟧	🟥
Active Ground Effect	🟨	🟨	⬜	🟥	🟧	🟨	🟧	🟨	⬜	🟧	🟥
Magnetic levitation	🟩	🟩	🟩	🟥	🟧	🟩	🟥	🟨	🟨	🟥	🟥
Bypass damper	🟨	🟨	🟨	⬜	⬜	🟨	⬜	🟨	⬜	🟨	⬜
Inerter	🟨	🟨	🟨	🟧	🟧	🟨	⬜	🟨	🟨	🟨	🟧
Tuned Mass damper	🟨	🟨	⬜	🟧	🟧	🟨	⬜	🟨	⬜	🟨	⬜
Negative-stiffness mechanism	⬜	🟩	🟨	⬜	🟧	🟩	⬜	🟨	⬜	🟨	🟧
Magneto-rheological damper	🟨	🟩	🟩	🟧	⬜	🟩	⬜	🟨	⬜	🟨	⬜
Eddy current damper	🟨	🟩	🟩	🟧	⬜	🟩	⬜	🟨	⬜	🟨	🟧
Active Tuned Mass Dampers	🟨	🟨	⬜	🟧	🟧	🟨	⬜	🟨	⬜	🟨	🟧
Servo controlled pneumatic suspension	🟨	🟩	🟩	🟧	⬜	🟩	🟧	🟨	🟨	🟨	⬜
Electromagnetic Actuation	🟨	🟩	🟩	🟥	⬜	🟩	🟥	🟨	🟨	🟨	🟥
Control moment gyroscope	🟩	⬜	🟨	🟥	🟥	🟩	🟧	⬜	🟨	🟨	🟥

Table 4: Evaluation matrix and colour code key for future train suspension technologies and solutions

The purpose of this evaluation is to provide a first-pass indication of the suitability of each option to provide benefits in a future train suspension system. For more detail on the specific criteria applied, see Appendix A5. At this stage in the study it is common for the options presented to offer "partial solutions" to the overall requirement and it is therefore important to understand their potential strengths and weaknesses. This analysis can then be used to provide a framework to highlight potentially strong solutions created from combinations of the options presented.

The evaluation resulted in several conclusions:

- There are passive suspension solutions that warrant further investigation i.e. bypass damper, inerters and negative-stiffness mechanism.
- The information capture and transfer solutions (crowd sourcing, satellite positioning, condition monitoring and local area network) offer a range of moderate benefits with little harmful impact. In addition, some of these solutions are already being implemented in the rail industry.
- Future use of feedback and feed-forward control could positively impact suspension performance. Particularly significant benefits could result when both solutions are used in combination with information capture.
- Semi-active solutions appear to offer significantly improved suspension performance without the increased cost, complexity and energy consumption of a fully active system.
- The first applications for fully active suspension are likely to be in non-weight bearing areas such as anti-roll and yaw control.
- In the long term the option of transferring cornering control to other train systems (removing the bogie), offers major benefits across all suspension performance criteria. At the same time, this solution will require extensive research and development to be proven suitable for use in rail.
- There may be longer term opportunities to simplify train suspension using composite materials.
- The concept of electrical kinetic energy recovery could mitigate the increased energy usage of semi-active suspension components.

2.8.3 CONCEPT ILLUSTRATIONS OF SELECTED COMBINATIONS OF TECHNOLOGIES AND SOLUTIONS

The concept illustrations presented in this section are not intended to be exhaustive; other combinations of two or more of the options listed in section 2.7 may offer further advantages for specific UK rail applications. The purpose of these illustrations is to show how the technologies and solutions might be combined to provide increased benefits and to address some of the drawbacks highlighted in the previous section.

CONCEPT 1: SIMPLIFIED SUSPENSION

A typical modern train suspension system is based on a complex combination of several elements optimised to operate together to satisfy conflicting requirements. The resulting system is heavy, expensive and requires significant maintenance. This concept aims to simplify the suspension by using composite elements for the primary suspension and an adaptive pneumatic secondary suspension which also provides yaw control and energy recovery. Figure 43 shows one way these elements might be combined to deliver a simplified suspension system.

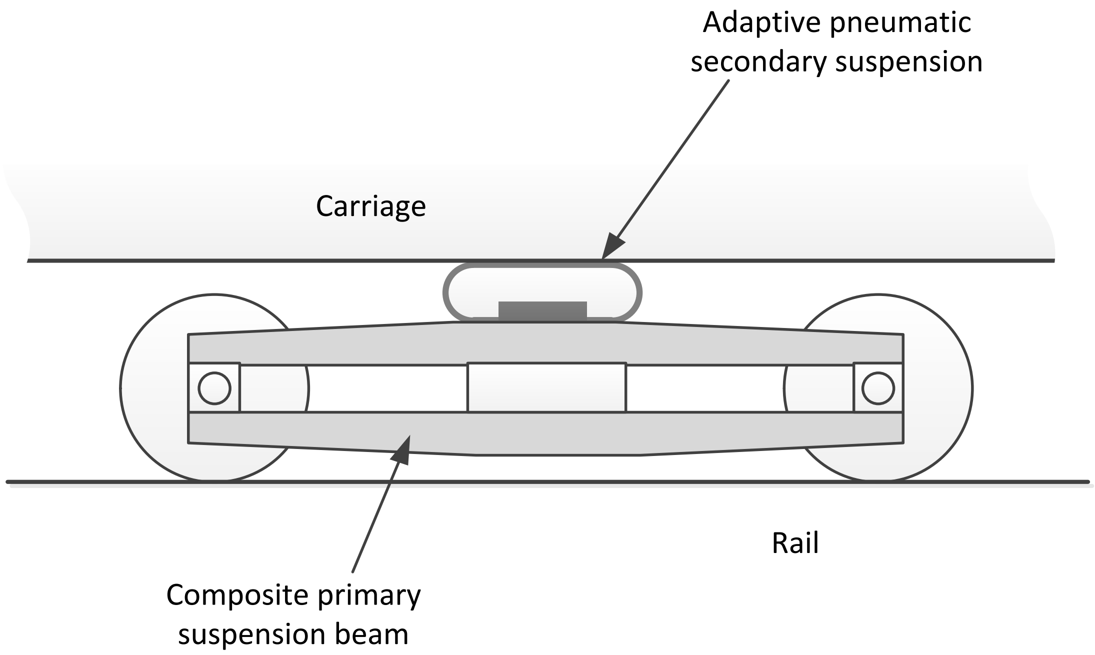


Figure 43: Simplified suspension using composite materials

CONCEPT 2: SEMI-ACTIVE SUSPENSION WITH INFORMATION CAPTURE

This concept combines semi-active suspension with information capture and sharing solutions to enable the suspension to match the current track and infrastructure conditions. Train location information allows feed-forward suspension parameters to be set based on historical track data. Real-time data of suspension performance is fed back to further optimise suspension parameters. Figure 44 shows a schematic diagram of this concept. For more detail on the specific technology options which might enable this solution, see section 2.7.

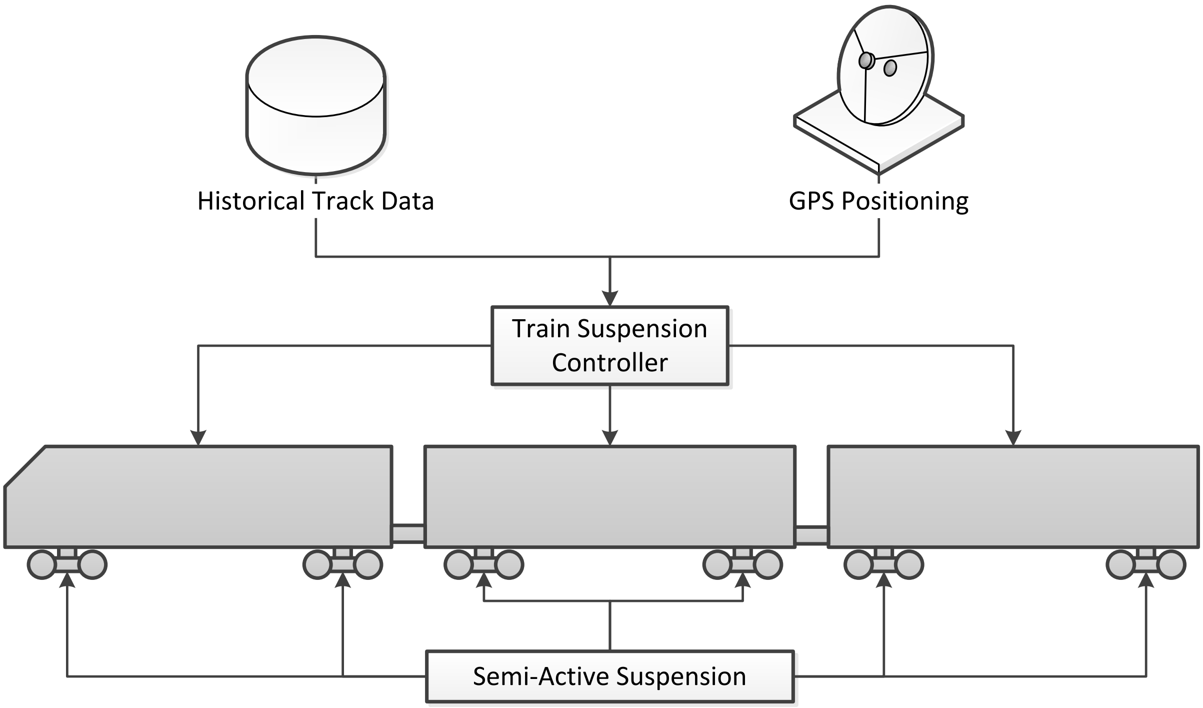


Figure 44: Semi-active suspension with information capture

2.9 CONCLUSIONS

It is hard to optimise current train suspension systems because of conflicting requirements and the limitations of existing components. In some cases, solutions which improve performance only do so at the expense of increased complexity. There is a lack of connectivity between suspension elements and to the broader rail infrastructure, leading to a reactive rather than proactive response to track variations. As train speed increases, the suspension system struggles to keep pace (evidenced by the increasing variable usage charge for more recent trains, section 2.4.5). The efficiency of the overall train is reduced because some of the traction energy is lost when unwanted movement is absorbed by the suspension.

This report details solutions ranging from relatively simple short-term improvements to more radical long-term options. The solutions address the limitations of the existing suspension systems, enabling greater adaptability, more proactive operation, higher train speed and reduced track damage. In addition, this report describes how some of the energy currently dissipated by the suspension might be recovered, increasing train efficiency.

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4 APPENDICES

4.1 APPENDIX A1

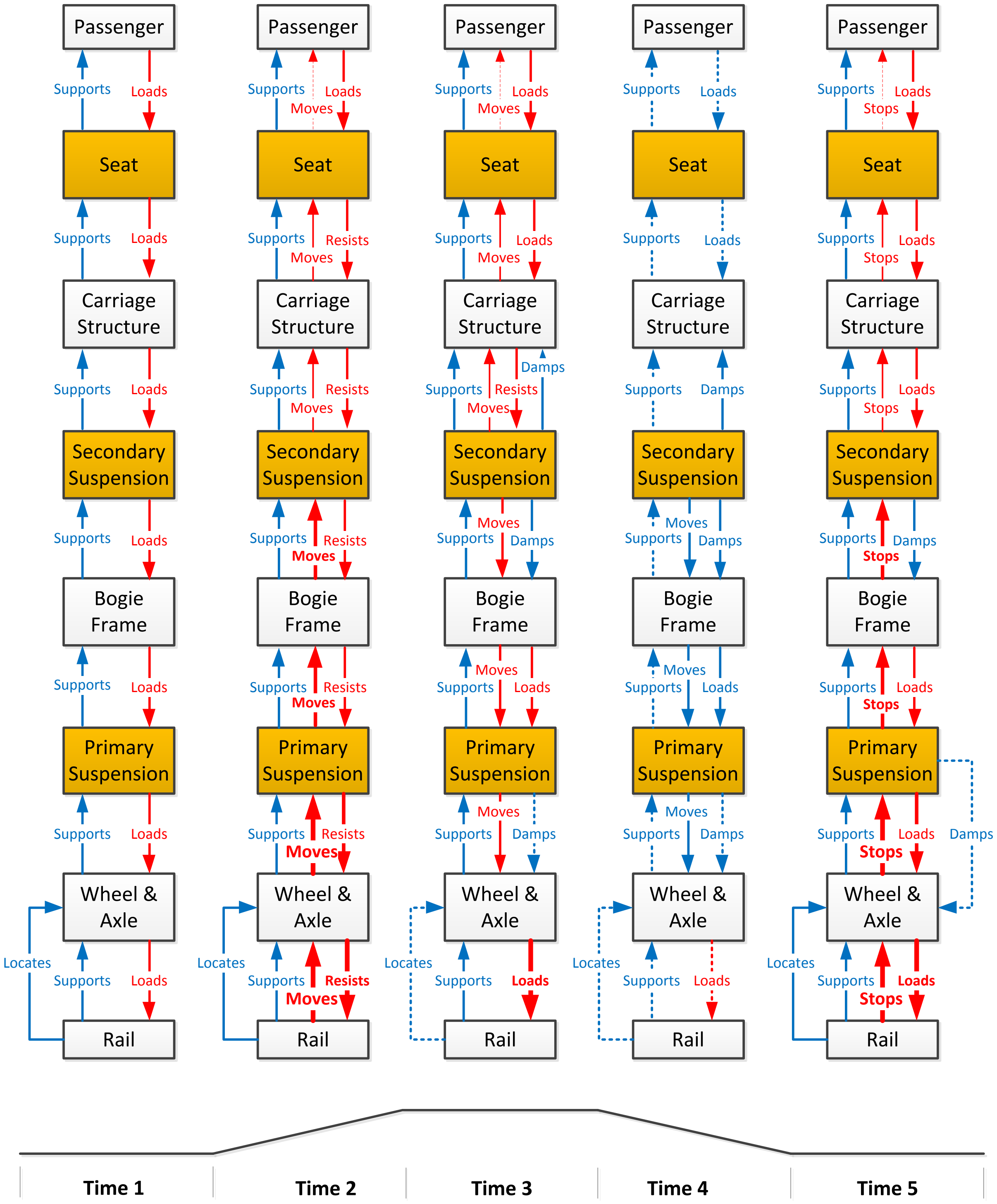

Figure A1: Action diagram of train suspension encountering a rail disturbance

Key points

Time 1 – The suspension locates the wheels in relation to the rail and supports the weight of the train.

Time 2 – The rail moves the wheel and axle, which through its inertia resists the movement, the suspension also resists the movement but attenuates the movement such that it is reduced by the time it reaches the passenger. The suspension continues to maintain the correct positioning of the wheel in relation to the rail.

Time 3 – At the top of the “bump” the wheel becomes partially unloaded, reducing the level of location between the rail and the wheel. The load that has been built up within the suspension is released, accelerating the wheel and axle towards the rail. Assuming this is insufficiently damped, the rebound combined with the inertia of the wheel and axle subjects the rail to increased load.

Time 4 – As the rail returns to its original level, the wheels become partially unloaded again, reducing the level of location between the wheel and the rail. The harmful effect of the wheel and axle loading the rail is momentarily reduced.

Time 5 – As the rail reaches its original level, the inertia of the wheel and axle inertia combined with the inertia of the rest of the train (via the suspension), excessively loads the rail. The effect of the change in acceleration is attenuated by the suspension, minimising the effect on the passenger and train systems. The wheel is now well located in relation to the rail and the train weight is supported, subject to sufficient damping of the wheel and axle.

4.2 APPENDIX A2

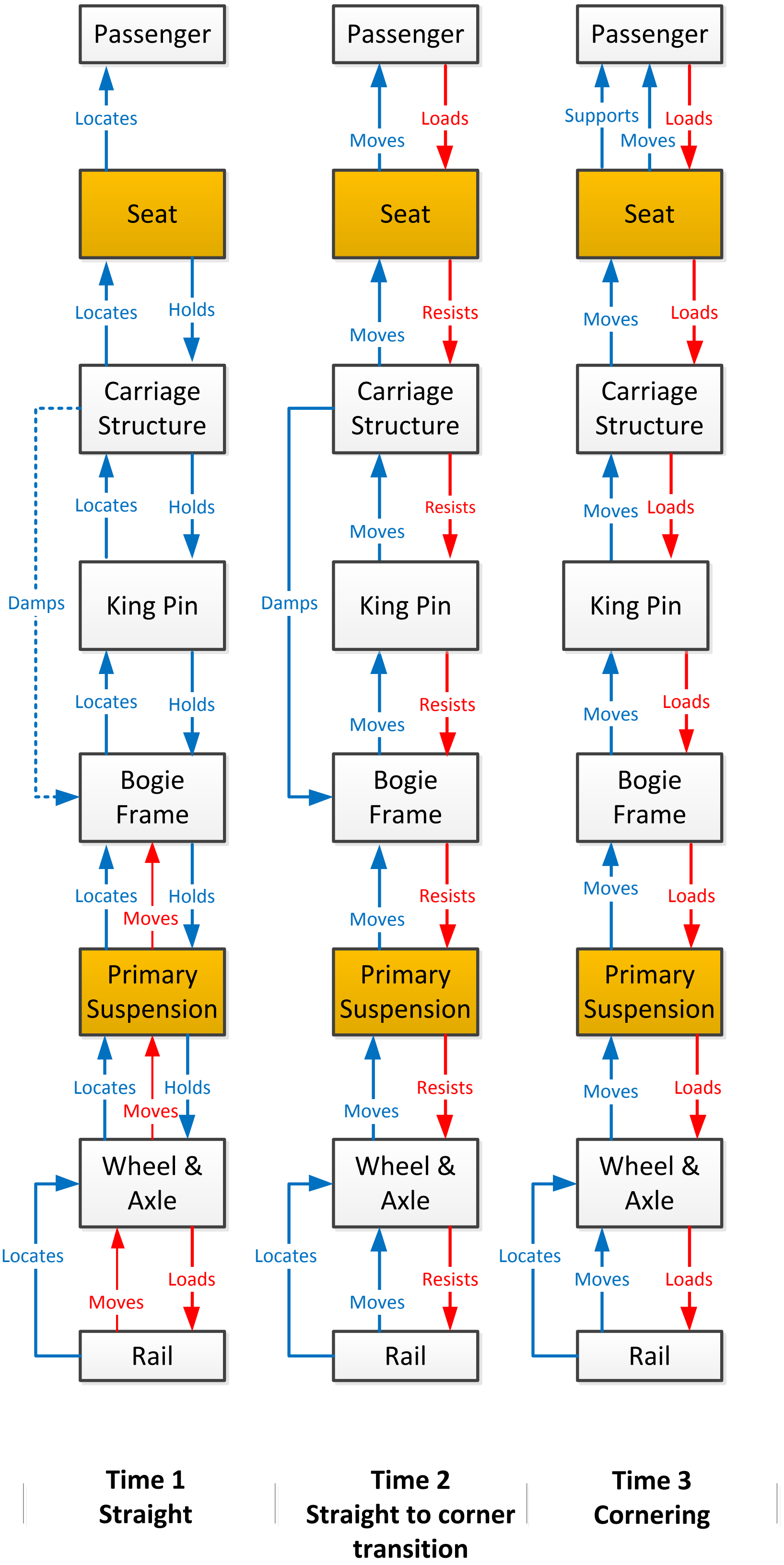

Figure A2: Action diagram of train suspension during cornering

Key points (Lateral plane only)

Time 1 – The suspension locates the wheels laterally in relation to the rail. Disturbances in the rail will cause movement in the wheel, axle, primary suspension and bogie potentially leading to hunting with insufficient damping.

Time 2 – The rail moves the wheel and axle which, through its inertia resists the movement. The primary suspension transfers the movement of the wheel and axle to the bogie, which in turn rotates in relation to the carriage via the king pin, exerting a turning moment on the carriage. The movement of the bogie in relation to the carriage is damped – an excessive level of damping would resist bogie movement with a risk of wheel “climbing”. The carriage has its own inertia which also resists movement.

Time 3 – During steady state cornering there is no relative movement between the bogie frame and carriage. The train loads the rail horizontally due to cornering.

4.3 APPENDIX A3

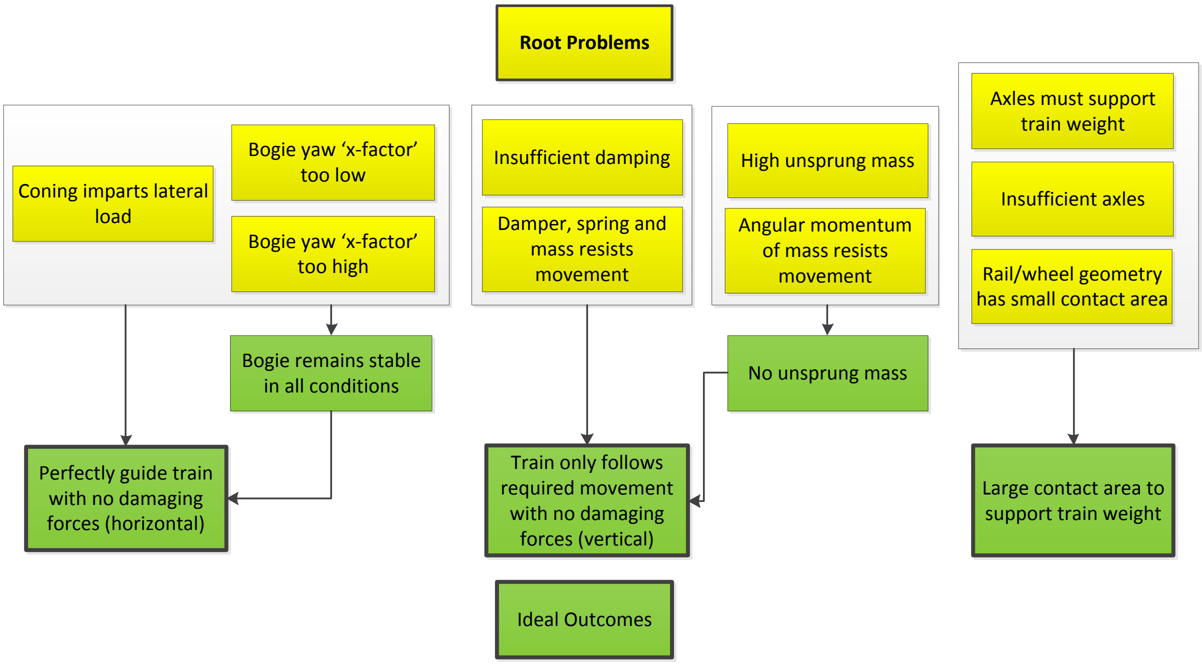

Figure A3: Root problems and ideal outcomes (ref section 2.5)

4.4 APPENDIX A4

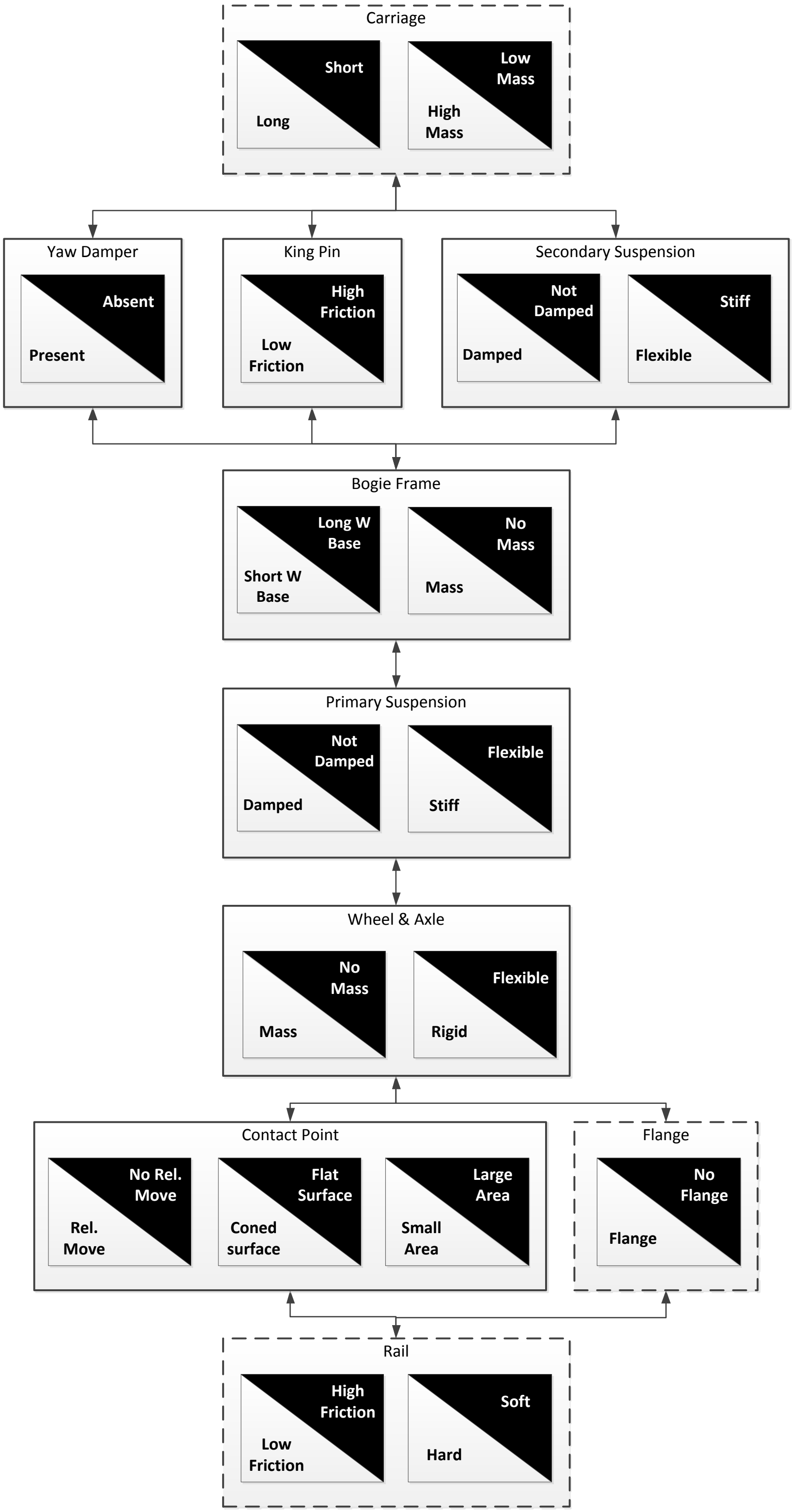

Figure A4: Conflicting requirements for train suspension elements (ref section 2.5.5)

4.5 APPENDIX A5

Criterion	**Target**
Derailment prevention	Significant improvement in robustness to derailment (Y/Q Quotient significantly improvement)
Relative damage (per axle mile), vertical	Break the relationship between train speed and track damage. Match best current VUC
Horizontal damage to the track (rail wear and RCF)	Break the relationship between train speed and track damage. Match best current VUC
Minimise cost (capital and on-going)	Reduced total cost
Minimal impact on train space	Reduced space taken up by suspension system
Improves passenger experience	Significant improvement in comfort index (NMW < 1.5 = Very comfortable, ref BS12299)
Minimise energy usage	Reduced energy usage
Minimise environmental impact	Reduced noise and vibration
Dewirement prevention	Train carriage roll as current or better
Ability to work within current rail infrastructure	Enable longer usage of existing infrastructure
Rail industry development time	Short term improvement in performance possible

Figure A5: Detail of targets for evaluation criteria (ref section 2.8.2)