Impact of running gear design on train energy consumption

Faculty of Civil and Industrial Engineering
Master's Degree in Transport Systems Engineering

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A.A. 2017-2018

SAPIENZA
UNIVERSITÀ DI ROMA

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INTRODUCTION

Railway vehicle is common vehicle that had been used wisely in many countries since the heavy industries began. Generally, railway vehicle consists of carriage, bogie frame, wheel set, and suspension system in a railway construction. Bogie is placed at the bottom of carriage, and the wheel sets relate to bearing attachment figure.I.1 shows one of the examples SF300 for railway bogie manufactured by company of Siemens Transportation Systems. Railway bogie is not only considered as a chassis to support the rail vehicle body, yet it is created to ensure the stability of the train on either straight track or curve track. Besides that, railway bogie provides ride comfort to the passengers through absorption of vibration and reducing the centrifugal forces especially when train is running at high speed corner. The types of railway bogies can be categorized into two features, articulated and non-articulated for the part of the railway bogie axles, generally it contains one or two axles. At the part of the axle, there will be axle box suspensions, also named as primary suspension systems which are attached between the wheel sets and the bogie frame. The axle box suspension allows the vertical movement between bogie frame and wheel sets to provide smoother ride. Besides the primary suspension system, there is a secondary suspension to absorb the vibration between bogie frame and the railway body, mostly coil springs is the main components in the suspension system. The bogie frame design of conventional railway vehicle is based on fixed wheel railway bogie system. Fixed wheel railway bogie could ensure the running stability on straight track; however, the curving performance is relatively low since the steering motion of wheel set is constrained by single rigid solid axle, this bring uncomfortable along the travel journey during the harsh interaction between wheel set and the track

In order to overcome the bad curving performance faced by the fixed wheel railway bogie, independent wheel railway bogie is introduced since it has an active element to control the wheel set motion according to track condition. A lot of experiments and simulation have been done to show the effectiveness of independent wheel railway bogie to bring smoothness and stability during high speed cornering on track, and better yaw motion of the railway vehicle. From the work of Bombardier transportation, it stated that the independent wheel set can run steadily even in high speed and smooth track cornering. With the invention of this bogie system, curving performance is considered upgraded without sacrificed the running stability of railway vehicle, the vibration of wheels and rail is also reduced to ensure the driving comfort. The independent wheel railway bogie has a simple linkage between wheel set and the bogie, by applying forces to the leverage to actuate the link for desired movement of wheel set. The independent wheel railway bogie includes wheel sets which are mounted separately near the end of side frame by connecting with a connector. Besides that, there are four solid bars joined with the bottom middle bar, this is a main bar to ensure the movement of wheel sets.

Fig.I.1: SF300 Running gear Siemens Transportation Systems

STATE OF ART

The use of new material for running gear such as composit material and single axle configurations (figure.I.2) in stand of conventional one (figure.I.3) is increasing for the new generation of rail vehicles in these days. In Europe there are many commercial uses of the single axle configurations for LRT, commuter trains and high-speed applications

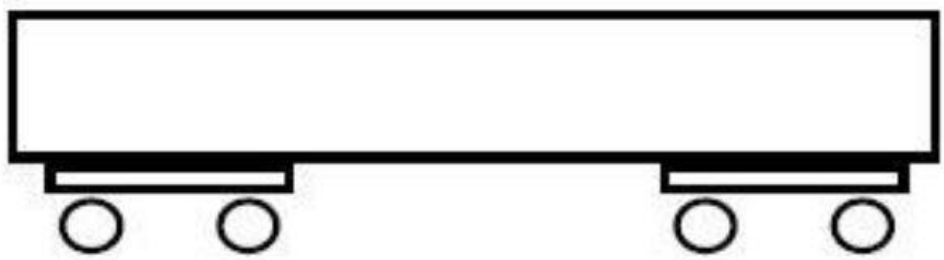

Fig.I.2: conventional running gear vehicle

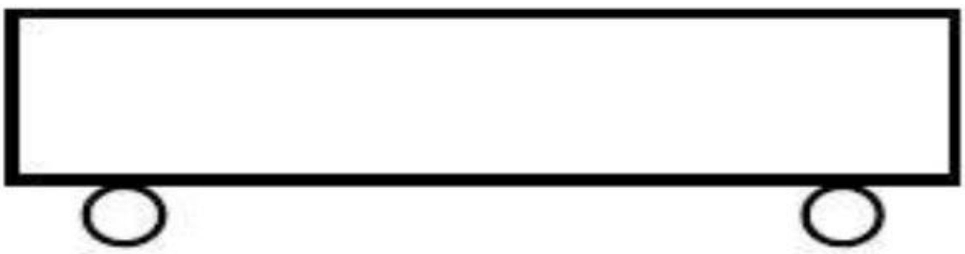

Fig.I.3: Single axle running gear vehicle

The simple structure leads to the expectation of low initial and running cost of vehicles. For LRT the relative ease with which low floor arrangements is very attractive for the accessibility of passengers. With this configuration the length of the car body should be shortened to keep the wheel load within the limits required by for track capacity. The short body enables a wider body because the amount (Figure.I.4) – (Figure.I.5) of over-hang [1]. Therefore, it contributes to higher capacity of the trains. Since bogies take a substantial share of overall train mass, single-axle bogies make an appreciable contribution to mass reduction. Single-axle bogies also have potential in freight services.

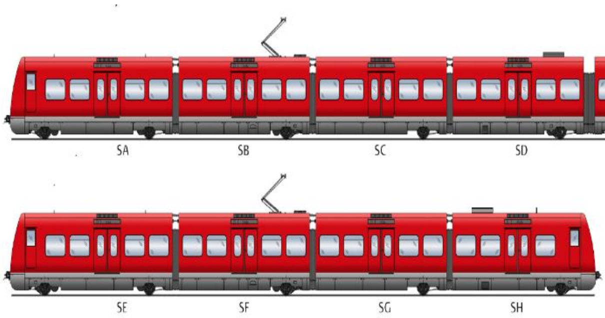

Fig.I.4: Copenhagen S train

Fig.I.5: High-speed train with bogie type locomotives and single-axle coaches

OBJECTIVES:

this thesis examines a case study with:

a single-axle vehicle with compiste material “light weight material” and considering the possibilities of benefiting

In practical terms, as a case study, single-axle train-set is hypothesized for operation on metro. The aim of this thesis is to understand the potential of reducing wheel-set maintenance costs and energy consumption and in particular:

1. to quantify, through assumptions, the mass reductions of running gear possible;
2. to quantify the corresponding energy consumption reduction on a hypothetical line;
3. to quantify, through assumptions, the effect on wheel-set maintenance costs of mass reduction and use of actively-steered wheels with the CAF series 8400.

The current solutions analyzed for reducing the mass is using composite materials such as kevler Fibre composite whose costs are high but the density of the material is less compared with steel’s. This light-weight material can be helpful in reducing pollution (environmental aspect) and can be supportive in reducing costs (economical aspect).

Being a new bogie concept produced in small numbers and tailored to specific vehicles, costs are still relatively high but are expected to drop as soon as bigger production number are achieved. Energy efficiency effects are especially high in local and regional transport.

Several European research projects, both within the Shift2Rail Programme but also outside of it have in recent years addressed running-gear innovation potential in some way. An on-going research project, in which SAPIENZA University is a partner, is RUN2RAIL (Innovative Running gear solutions for new dependable, sustainable, intelligent and comfortable RAIL vehicles) [5]. It is a Shift2Rail Open Call project within the Horizon2020 Programme of the European Commission. RUN2Rail is exploring several technical developments for future running gear.

1 THE ANATOMY OF RAILWAY RUNNING GEAR

1.1 MAIN FUNCTIONS OF THE RUNNING GEAR AND TERMINOLOGY

The principal difference between a railway vehicle and other types of wheeled transport is the guidance provided by the track. The surface of the rails not only supports the wheels, but also guides them in a lateral direction. The rails and the switches change the rolling direction of wheels and thus determine the travelling direction of the railway vehicle. The running gear is the system that provides safe motion of the vehicle along railway track. The running gear includes such components as wheelsets with axle boxes, the elastic suspension, the brakes, the traction drive, and the device to transmit traction and braking forces to the car body [2].

Its main functions are:

- Transmission and equalization of the vertical load from the wheels of the vehicle to the rails;
- Guidance of vehicle along the track;
- Control of the dynamic forces due to motion over track irregularities, in curves, switches and after impacts between the cars;
- Efficient damping of excited oscillations;
- Application of traction and braking forces;

Depending on the running gear, the vehicles may be described as bogied or bogie-less. In vehicles without bogies the suspension, brakes, and traction equipment are mounted on the car body frame. The traction and braking forces are transmitted through traction rods or axle box guides (sometimes known as “horn guides”). Conventional two-axle vehicles will generate larger forces in tight curves than the equivalent bogie vehicle; therefore, their length is limited. Running gear mounted on a separate frame that can turn relative to the vehicle body is known as a bogie (or truck). The number of wheelsets that they unite classifies the bogies. The most common type is the two-axle bogie, but three- and four-axle bogies are also encountered, often on locomotives.

Previously, the bogies simply allowed the running gear to turn in a horizontal plane relative to the car body thus making it possible for the wheelsets to have smaller angles of attack in curves. In modern bogies, the bogie frame transmits all the longitudinal, lateral, and vertical forces between the car body and the wheelsets. The frame also carries braking equipment, traction drive, suspension, and dampers. It may also house tilting devices, lubrication devices for wheel-rail contact and mechanisms to provide radial positioning of wheelsets in curves. Bogie vehicles are normally heavier than two-axle vehicles. However, the design of railway vehicles with bogies is often simpler than for two-axle vehicles and this may provide reliability and maintenance benefits.

1.2 BOGIE COMPONENTS

A. WHEELSETS

A wheelset comprises two wheels rigidly connected by a common axle. The wheelset is supported on bearings mounted on the axle journals.

The wheelset provides [2]:

- The necessary distance between the vehicle and the track
- The guidance that determines the motion within the rail gauge, including at curves and switches
- The means of transmitting traction and braking forces to the rails to accelerate and decelerate the vehicle

The design of the wheelset depends on:

- The type of the vehicle (traction or trailing)
- The type of braking system used (shoe brake, brake disc on the axle, or brake disc on the wheel)

- The construction of the wheel center and the position of bearings on the axle (inside or outside)

- The desire to limit higher frequency forces by using resilient elements between the wheel center and the tyre

The main types of wheelset design are shown in FIGURE.1.1. Despite the variety of designs, all these wheelsets have two common features: the rigid connection between the wheels through the axle and the cross-sectional profile of the wheel rolling surface, named wheel profile.

In curves, the outer rail will be a larger radius than the inner rail. This means that a cylindrical wheel must travel further on the outer rail than on the inner rail. As the wheels moving on the inner and outer rails must have the same number of rotations per time unit such motion cannot occur by pure rolling. To make the distances travelled by two wheels equal, one or both will therefore “slip” thus increasing the rolling resistance and causing wear of wheels and rails. The solution is to machine the rolling surface of wheels to a conical profile with variable inclination angle γ to the axis of the wheelset (FIGURE 1.2). The position of the contact point when the wheelset is at a central position on the rails determines the so-called “tape circle” where the diameter of the wheel is measured. On the inner side of the wheel, the conical profile has a flange which prevents derailment and guides the vehicle once the available creep forces have been exhausted [2].

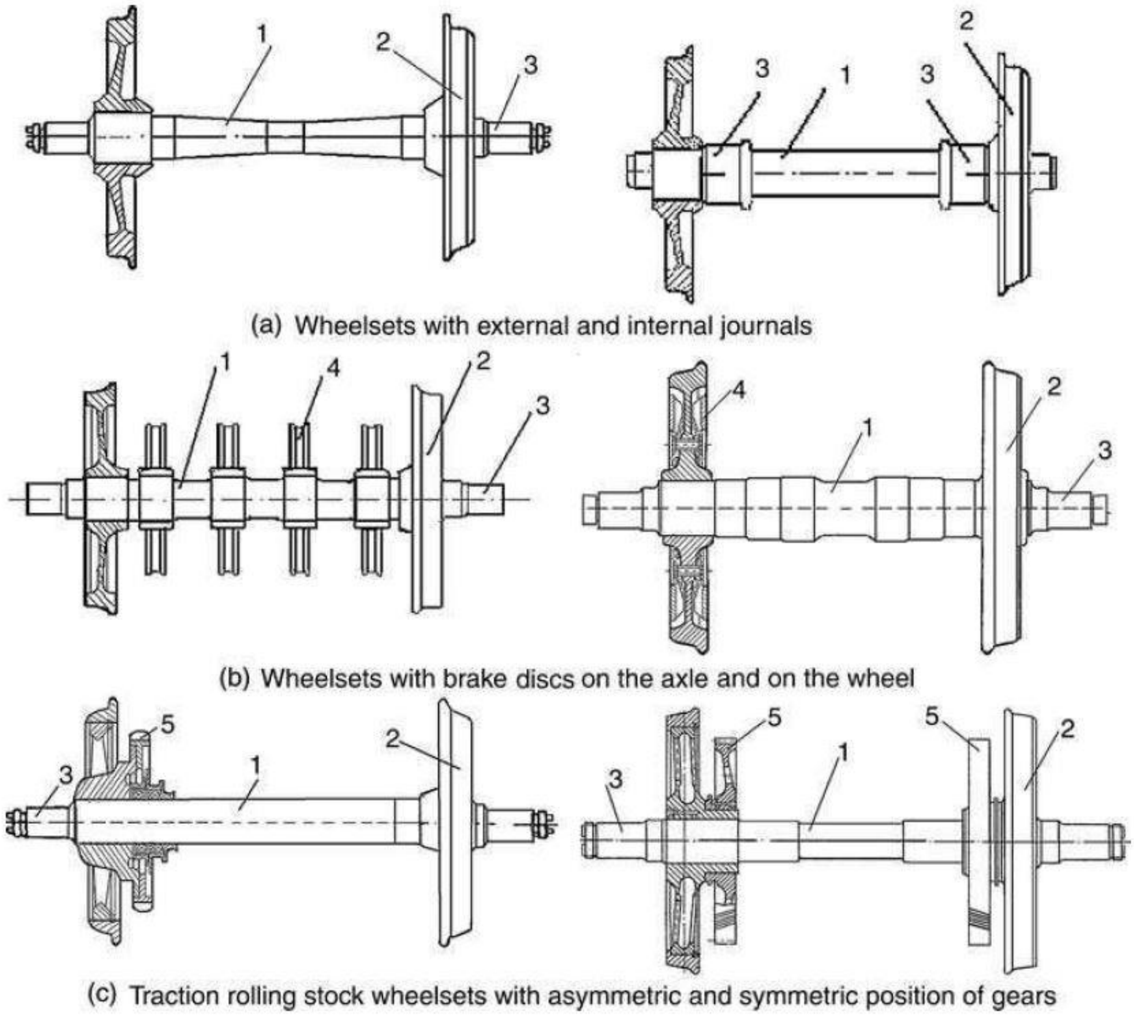

Fig.1.1: Wheelset typology

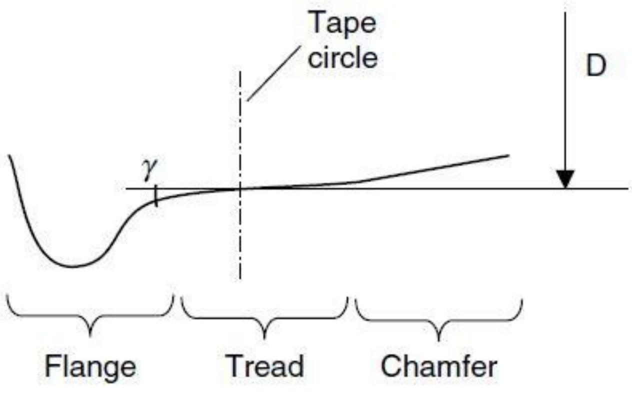

Fig.1.2: The rolling surface of wheels

B. AXLE BOXES

The axle box is the device that allows the wheelset to rotate by providing the bearing housing and the mountings for the primary suspension to attach the wheelset to the bogie or vehicle frame [2].

The axle box transmits longitudinal, lateral, and vertical forces from the wheelset on to the other bogie elements. Axle boxes are classified according to:

- Their position on the axle depending on whether the journals are outside or inside.
- The bearing type used, either roller or plain bearings.
- The external shape of the axle box is determined by the method of connection between the axle box and the bogie frame and aims to achieve uniform distribution of forces on the bearing.

Internal construction of the axle box is determined by the bearing and its sealing method. Axle boxes with plain bearing consist of the housing, the bearing itself which is usually made of alloy with low friction coefficient (e.g., bronze or white metal), the bearing shell which transmits the forces from the axle box housing to the bearing, a lubrication device which lubricates the axle journal. Front and rear seals prevent dirt and foreign bodies entering the axle box, while the front seal can be removed to monitor the condition of the bearing and add lubricant. Vertical and longitudinal forces are transmitted through the internal surface of the bearing and lateral forces by its faces.

Plain bearing axle boxes are now largely obsolete as they have several serious disadvantages:

- High friction coefficient when starting from rest
- Poor reliability
- Labour-intensive maintenance
- Environmental pollution

However, from a vehicle dynamic behavior point of view, axle boxes with plain bearings had certain positive features. In recent years, plain bearing axle boxes that do not require lubrication have been reintroduced on certain types of rolling stock though their use is still rare.

Axle boxes with roller type bearings (Figure.1.3) are classified according to:

- The bearing type (cylindrical, conical, spherical)
- The fitting method (press-fit, shrink-fit, bushing-fit)

The main factor that determines the construction of the axle box is the way it experiences the axial forces and distributes the load between the rollers.

Cylindrical roller bearings have high dynamic capacity in the radial direction, but do not transmit axial forces (Figure.1.3a). Experience in operation of railway rolling stock showed that the faces of rollers can resist lateral forces. However, to do this successfully it is necessary to regulate not only the diameter, but also the length of rollers, and the radial, and axial clearances.

Conical bearings (Figure.1.3b and c) transmit axial forces through the cylindrical surface due to its inclination to the rotation axis. This makes it necessary to keep the tolerances on roller diameters and clearances almost an order of magnitude tighter than for cylindrical bearings. In addition, conical bearings have higher friction coefficients compared to the radial roller bearings and therefore generate more heat. This not only increases traction consumption, but also creates difficulties for diagnostics of axle box units during motion.

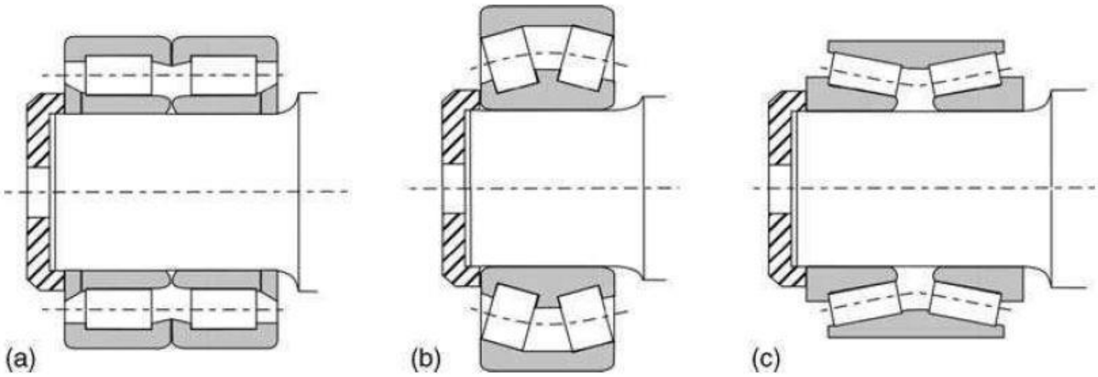

Fig.1.3: Axle boxes

Recently cartridge-type bearings have been widely used. Their special feature is that the bearing is not disassembled for fitting but is installed as one piece.

Spherical bearings have not been widely applied due to their high cost and lower weight capacity, although they have a significant advantage providing better distribution of load between the front and rear rows in case of axle bending. Ball bearings are, however, often combined with cylindrical bearings in railway applications to transmit axial forces. High speed rolling stock often has three bearings in the axle box: two transmitting radial forces and one (often a ball bearing) working axially [2] (Figur.1.4).

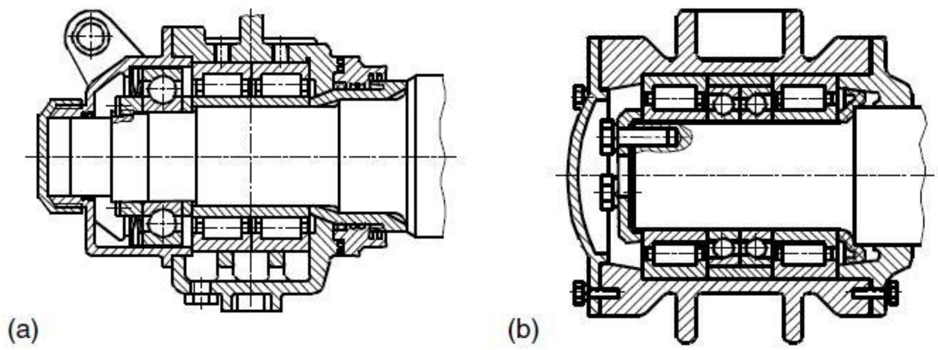

Fig.1.4: Axle boxes for high speed train

C. WHEELS

Wheels and axles are the most critical parts of the railway rolling stock. Mechanical failure or exceedance of design dimensions can cause derailment. Wheels are classified into solid, tyre, and assembly types as shown in Figure.1.5.

Solid wheels [2] (Figure 1.5a) have three major elements: the tyre, the disc, and the hub, and mainly differ in the shape of the disc.

Tyred wheels (Figure 1.5b) have a tyre fitted to the wheel disc that can be removed and replaced when it reaches its maximum turning limit.

Wheels may have straight, conical, S-shaped, spoked, or corrugated type discs when viewed in cross-section. A straight disc reduces the weight of the construction and can be shaped such that the metal thickness corresponds to the level of local stress. The conical and S-shape discs serve to increase the flexibility of the wheel, therefore reducing the interaction forces between the wheels and the rails. Corrugated discs have better resistance to lateral bending. The desire of reducing wheel-rail interaction forces by reducing the unspring mass has led to development of resilient wheels (Figure 1.5c) that incorporate a layer of material with low elasticity modulus (rubber, polyurethane). These help to attenuate the higher frequency forces acting at the wheel-rail interface.

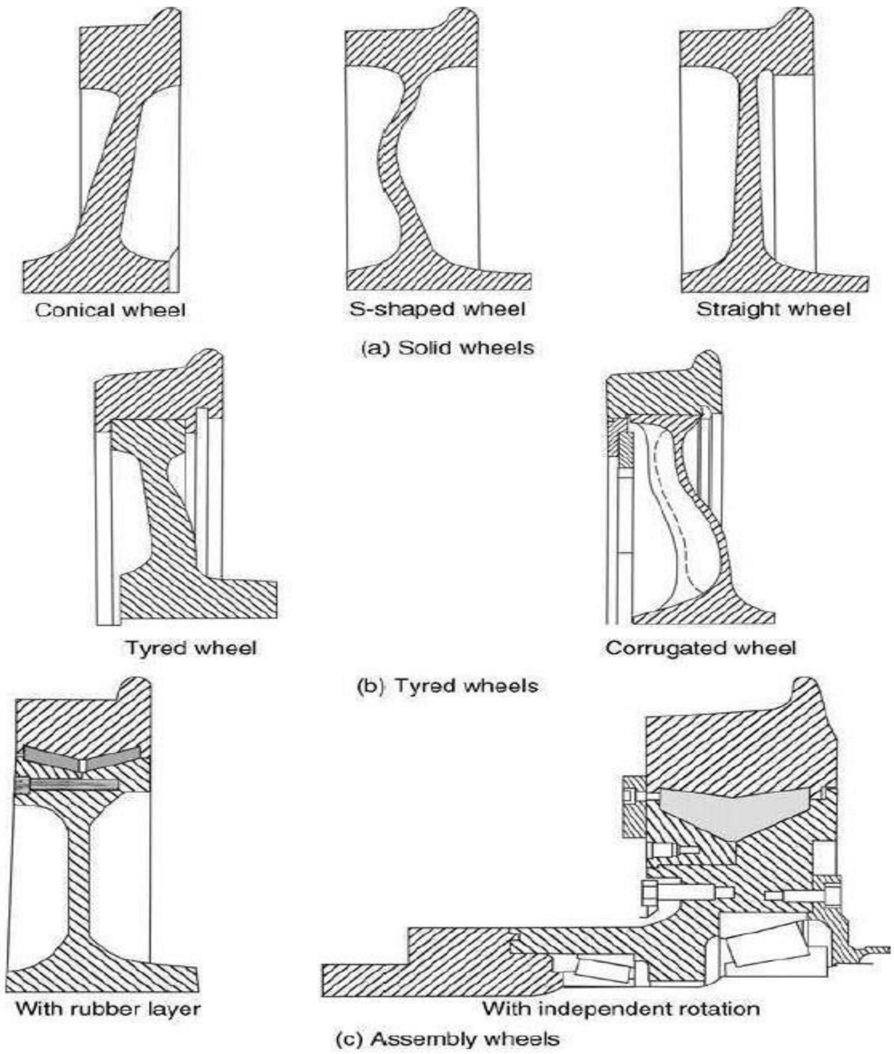

Fig.1.5: type of wheels

D. SUSPENSION

The suspension is the set of elastic elements, dampers and associated components which connect wheelsets to the car body. If the bogie has a rigid frame, the suspension usually consists of two stages: primary suspension connecting the wheelsets to the bogie frame and secondary suspension between the bogie frame and the bolster or car body. Such bogies are termed double suspended. Sometimes, typically in freight bogies, only a single-stage suspension is used. Where this occupies the primary suspension position it is often termed "axle box suspension" In the secondary suspension position, it may be termed "central suspension" [3].

The elastic element of a suspension, whether primary or secondary, can be composed of different materials. The combination of these materials and devices explained, makes a wide range of suspension possibilities. In this a variety of devices that are currently in bogies with different applications, is explained. The Figure.1.6 shows a classification of these devices and materials

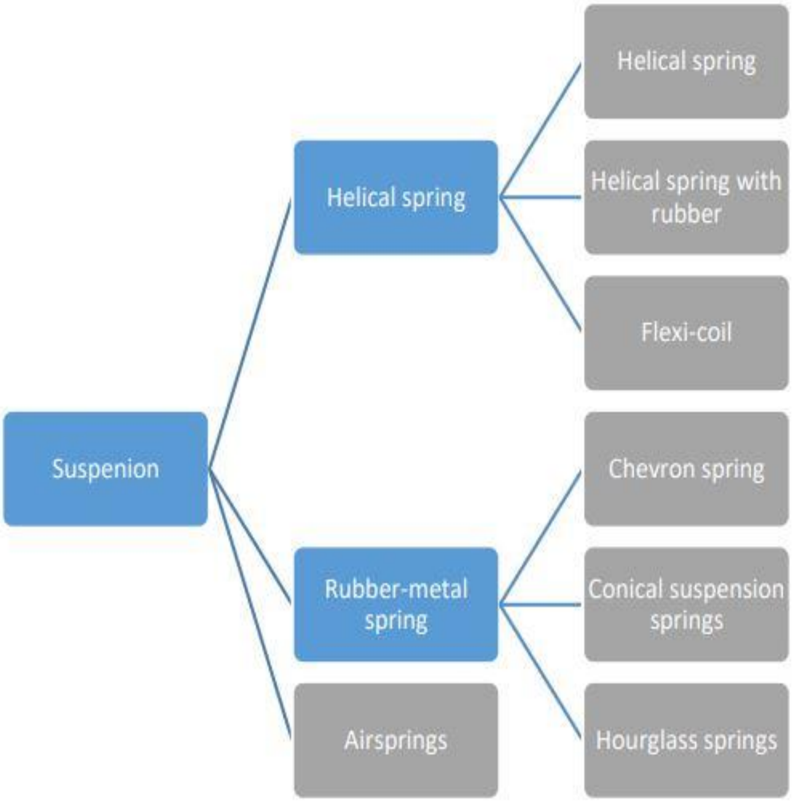

Fig.1.6: suspension classification

AIRSPRINGS

This is a modern device for vehicle suspension, typically adopted for the secondary suspension because it is more effective absorbing low-frequency oscillations an airbag works using the compressibility of air, filling and emptying to modify the height of the train [3]. The airspring itself is essentially a reinforced rubber laminate bellows Figure.1.7.

The system excels especially when there are torsional strain and large horizontal force solicitations. It also absorbs a portion of the vertical deflection. Airsprings can provide high ride comfort levels and provide isolation of structure-borne noise and vibration. A Drawback of this system is the increased complexity of the vehicle and the higher rate of compressed air consumption. However, airsprings can be mounted in serial with a rubber emergency spring. This ensures operation with maximum speed, even when the airspring is deflated. The airsprings can be arranged with no bolster, as it is explained in the subchapter Two dispositions more are possible, arranging the airsprings above or below the bolster.

Fig.1.7: Airspring

HELICAL SPRINGS

The helical steel springs are one of the simplest systems, also the most common, of suspension found on modern bogies. This spring may be present in both the primary and secondary suspensions. Very often, rubber elements are arranged inside the steel coils to improve the dynamic behavior, cushioning and give more rolling quality. An evolution of this is the Flexi-coil suspension, which is considered separately due to its differentiation and specific characteristics, explained in the next subchapter. Another common system with rubber elements is adding washers, for example, Hyrtel washers (thick rubber discs on both sides of the spring), this ensures an acoustical isolation between the bogie frame and the car body Figure.1.8. It is possible to combine this solution with others related with rubber, like mounting elastomeric springs in parallel to the steel coils, this provides a progressive suspension characteristic. This solution is used in the German train VT612 DMU [3]

Fig.1.8: Helical springs

Helical steel springs with low swiveling resistance fitted across the longitudinal axis of the vehicle prevent the introduction of torsional forces on the bogie frame.

FLEXI-COIL

Flexi-coil springs are commonly used in the secondary suspension stage. The springs in a flexi-coil suspension are made of steel, a spherical rubber dome protrudes from above and below from each spring and absorb some of the horizontal forces. These domes are connected firmly to the car body and the bogie frame. This system let lateral and longitudinal displacement thanks to the flexibility of the rubber domes Figur.1.9. The stiffness is influenced by the number of coils, height, mean diameter of coils, wire diameter etc [3]. The vertical forces are absorbed entirely by the steel springs. This type of suspension is most commonly used in modern rail passenger cars when air suspension is not required since it is cheaper to buy and to maintain than air suspension.

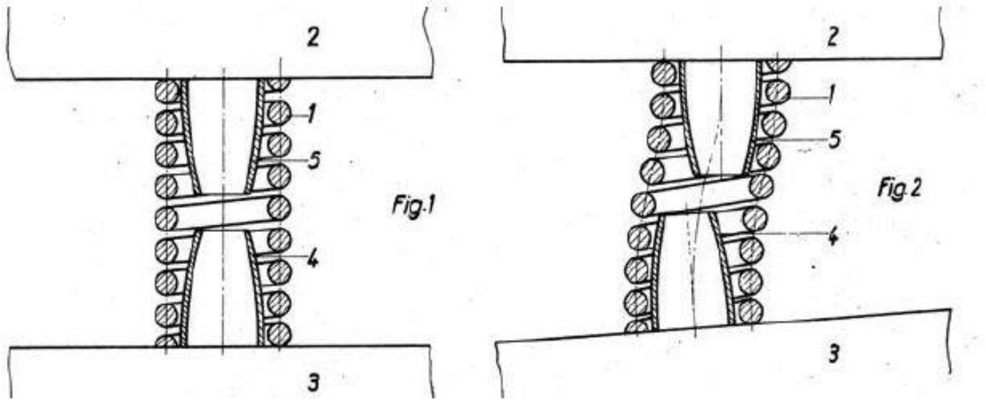

Fig.1.9: Flexi-coil

An analysis from the University of Pardubice (Czech Republic) summarized in the article “The effect of spring pads in the secondary suspension of railway vehicles on bogie yaw resistance” concluded:

“At a slow run in a curve, the bogie yaw resistance is low. However, the resistance is also low at the run of the vehicle in a straight track which can lead to worse riding stability characterized by a lower critical speed of the vehicle. In the case of a run in a curve at a high value of the cant deficiency, in which the need of a minimized bogie yaw resistance is the most important, the reduction of the bogie yaw resistance is not so significant, on the contrary.” [3]

RUBBER AND RUBBER-METAL SPRINGS

The elastomeric springs are suspensions made of rubber or composite materials that have an important natural hysteresis and are optimal to avoid high-frequency vibrations. The behavior of these materials varies according to their composition and its shape, presenting values of resilience, in general, higher than steel.

Conical rubber-metal springs provide an optimal filtration of vibrations in the axle box, avoids fatigue problems by transmission of vibrations to the axle. Conical rubber-metal springs also provide three linear modes of flexibility, lateral, longitudinal and vertical. Modifying the geometry, different properties are reached. Therefore, this suspension is used to provide a bogie with the axle guidance capability.

Fig.1.10: Rubber for primary and secondary suspension

The elastomeric materials of which these suspensions are composed have a natural tendency to flow or become unstable. They have a load memory produced by a change of properties permanent or semi-permanent by the result of applying continuous or undulatory loads. The temperature can produce changes in the height of the spring that, although being reversible, can produce changes of up to 12% variation with respect to the initial height with temperature variations of 30ºC [3].

This system is found both in primary and secondary suspension. A very common rubber-metal suspension system is the Chevron spring. Such system is a combination of elastomeric lays alternated with metal plates (Figure.1.10) Chevron springs provide lateral flexibility which improves the quality of the ride, especially on curves. Chevron springs applied on the primary suspension provides a lateral axle guidance widely used on metro bogies.

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Fig.1.11: Hourglass shape for secondary suspension

Lastly, there are elastomeric springs applied to the secondary suspension with an hourglass shape (Figure1.11). These springs allow lateral and longitudinal displacement. In addition, rubber provides advantages such as their simplicity of manufacturing, low maintenance cost, less weight than steel and a long service life. This type of suspension offers a high load capacity and can store more elastic energy per unit volume than metals [3].

CLASSIFICATION OF SUSPENSIONS SYSTEMS ACCORDING TO THE GEOMETRY

The primary suspension should connect the axlebox to the bogie frame. This should be an elastic connection due to the axlebox must have a stroke. The different systems that allow this movement are classified (figure.1.12)

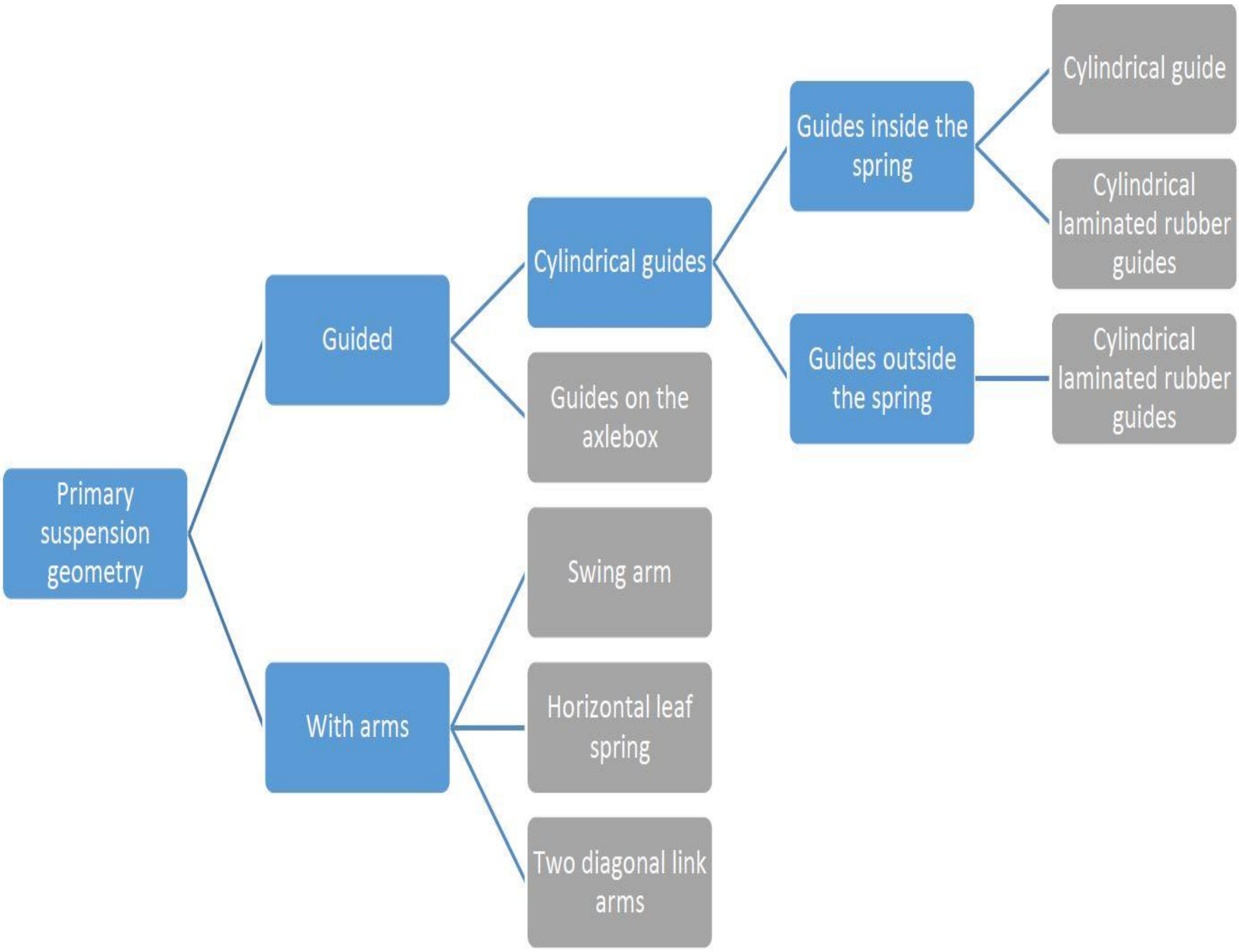


Fig.1.12: Classification of suspensions systems according to the geometry

CYLINDRICAL GUIDES INSIDE THE SPRING

This consists of a barrel inside the helical spring attached to the axlebox and a guide that slides inside of it attached to the bogie frame (Figure.1.13). The barrels are attached to the axlebox with rubber coaxial bushings, therefore, provides some flexibility between the wheelset and the bogie frame in the longitudinal and vertical directions. Due to the axial symmetry of the rubber bushes, the stiffness in longitudinal and vertical directions in the same [3].

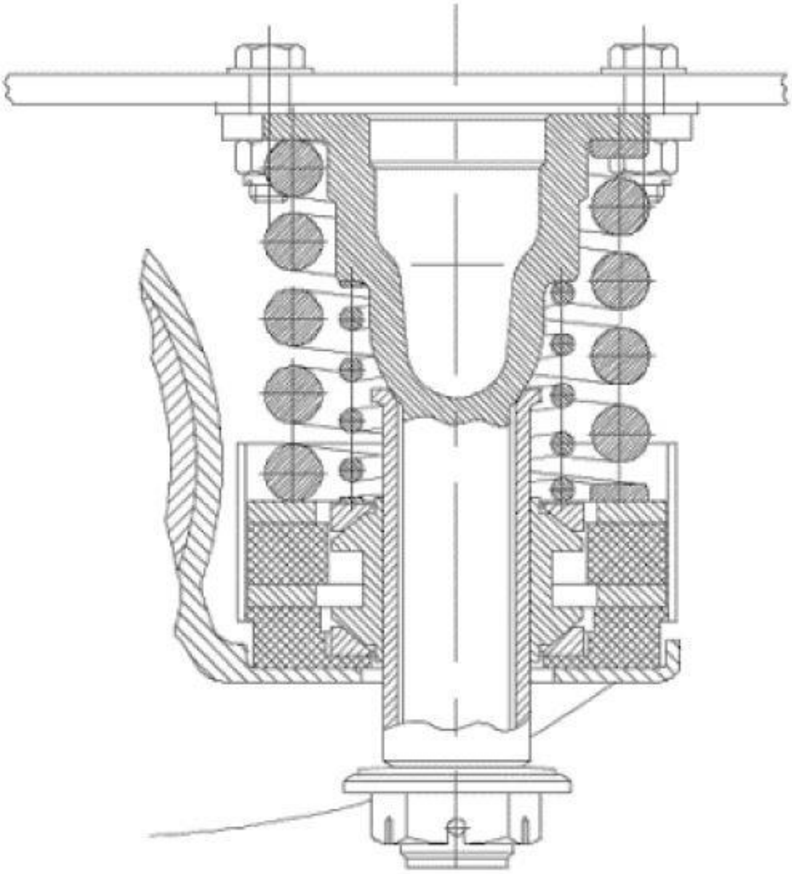


Fig.1.13: Cylindrical guides inside the spring

Another system of guides are the ones with cylindrical laminated rubber achieved concentrically inside the helical spring (Figure.1.14). This arrangement allows lateral and longitudinal movement of the axlebox due to the flexibility of the rubber. This system is more compact than the system with the cylindrical rubber guides outside the spring (explained below). Due to the rubber guide should be inside the helical spring, this has a limited space, consequently, the transmitted forces are lower.

In comparison with the guides inside the spring mentioned above, the cylindrical laminated rubber guides get an excellent vibration isolation that provides more comfort on the train.

This solution is widely used in the Japanese high-speed railways called Shinkansen. A bogie from this line who use this suspension is the *DT200* [3].

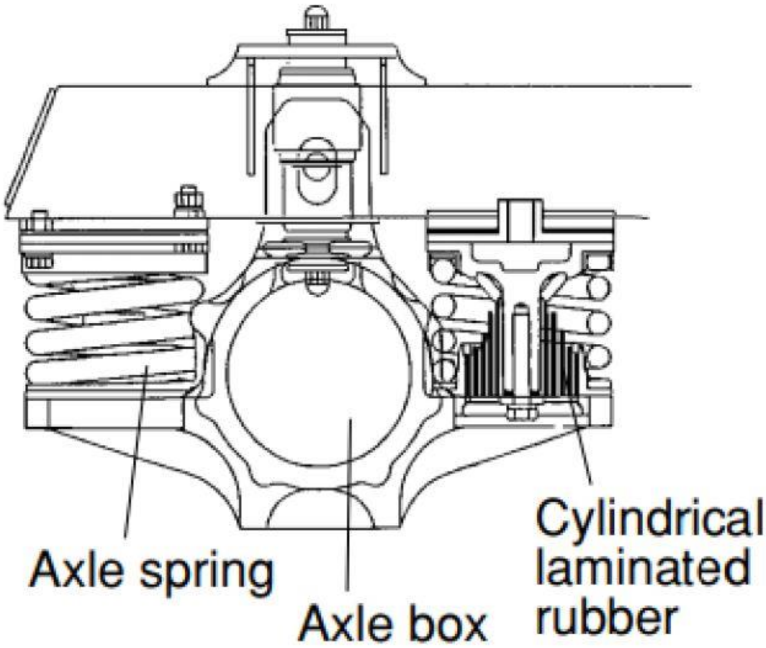


Fig.1.14: DT200 suspension

CYLINDRICAL LAMINATED RUBBER GUIDES OUTSIDE THE SPRING

This kind of axlebox guides design could be found on high-speed trains such as the French *TGV Y2-30* [3]. Now the guide itself is outside the spring (Figure.1.15), the displacement of the axlebox along the guides occur by shear deformation of multi-layer rubber-metal block, and it is free from disadvantages. In order to obtain the optimum relationship of horizontal and vertical stiffness this block consists of two longitudinally oriented sections. This provides the bogie an excellent guidance on curves due the axlebox is free to move in yaw and adapt to the curve.

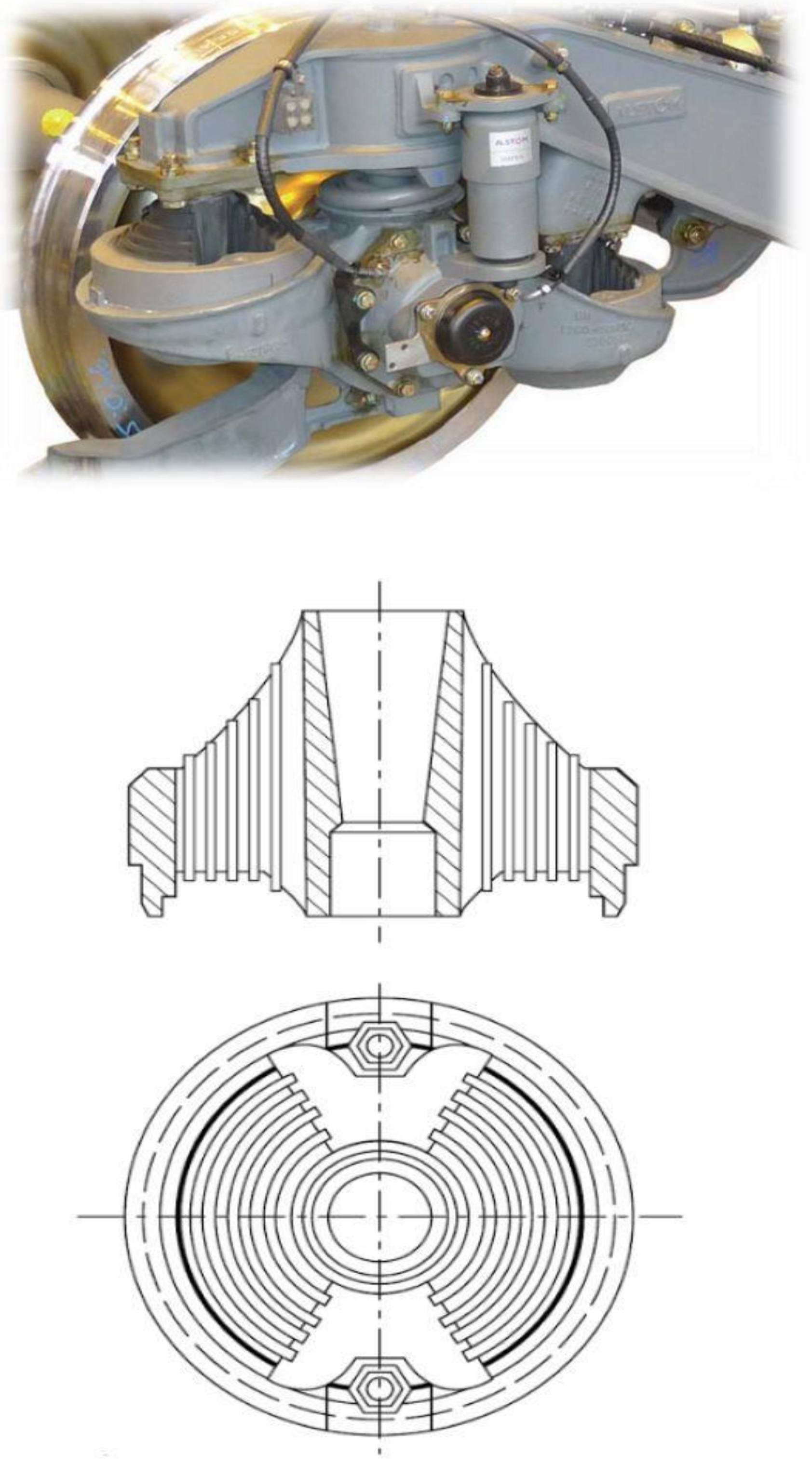


Fig.1.15: Cylindrical laminated rubber

SWING ARM

In this configuration, the axlebox has a rod hooked to the chassis by bearings. This allows a circular movement where the center of the circle is the point of union between the arm and the bogie frame. A spring, typically a helical steel coil, completes the structure (Figure.1.16).

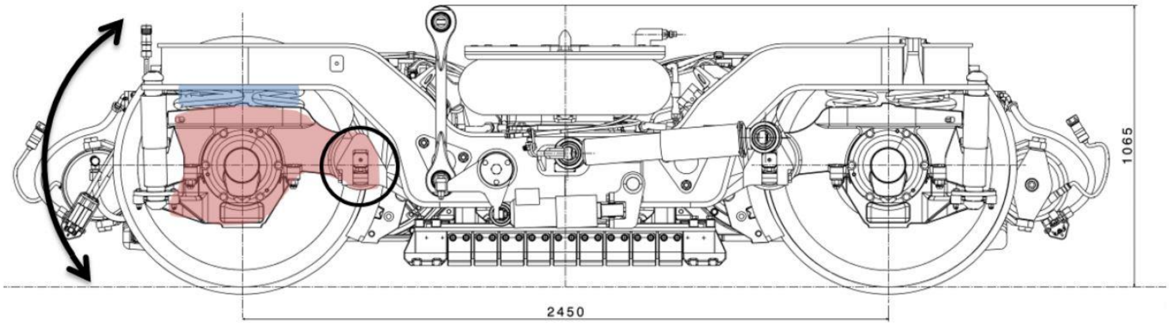


Fig.1.16: Swing arm

The swing arm system has several functions including the support of the axlebox, connection of the bogie and axlebox, and also transfers brake and traction force in the longitudinal direction from the axle to the bogie. Elastic bearings can be arranged on the link between the bogie and the swing arm to provide lateral free movement. This allows the bogie axle guidance on curves. The system's vertical, longitudinal, and lateral stiffness can be adjusted according to design requirements and operating conditions to prevent derailment and ensure stable operation during high speed. This configuration is found in metros and intercity trains, but also on high-speed trains like CRH-1A in China (figure.1.17) [3].

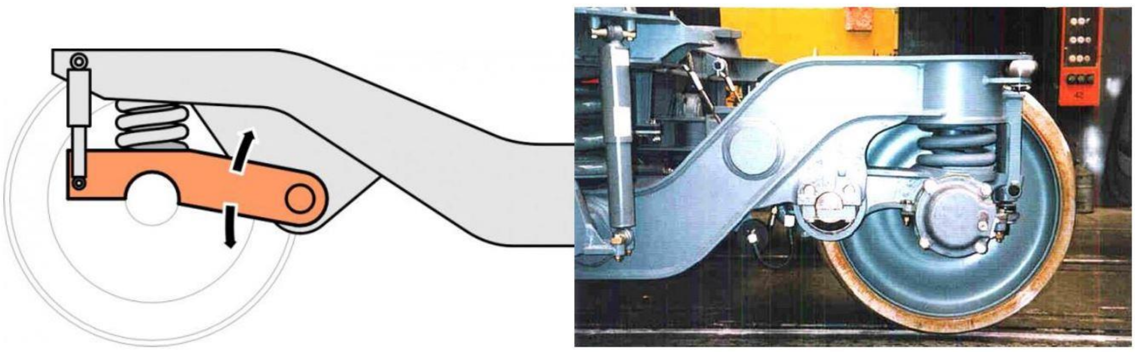


Fig.1.17: Swing arm on CRH-1A train

HORIZONTAL LEAF SPRINGS

In this configuration, a horizontal leaf spring connects the axlebox and the bogie. The idea is very similar as the swing arm system, but instead of a rod. There is a plane horizontal leaf which is linked also to the axlebox, it is not a part of it (Figure.1.18). The connection of the steel leaf in both extremes is made by rubber elements allowing yaw movement of the leaf and consequently, lateral movement of the axlebox. It is another system to provide axle guidance to the bogie.

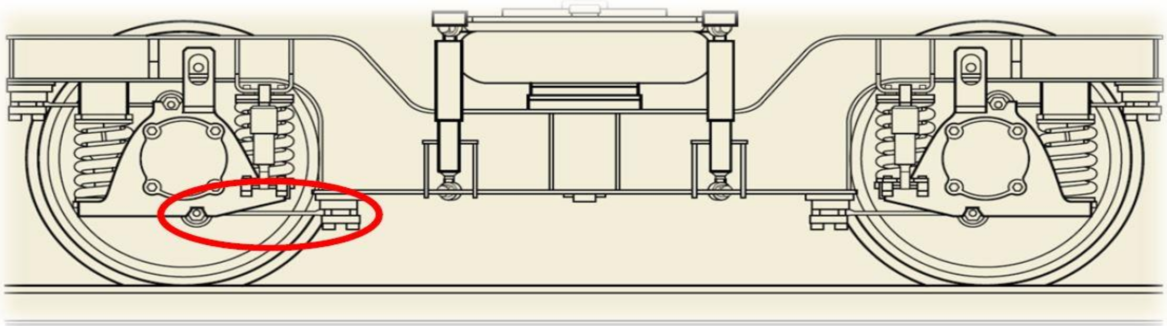


Fig.1.18: Horizontal leaf springs

Two parallel horizontal leaf springs instead of one is also a possibility to guide the axlebox. Again, the extremes of the two pairs of leaves are connected by rubber bushings. This arrangement is used in the *MD-522* by *Bombardier* [3] which is used in the ICE (German High-speed trains) trailer bogies (Figure.1.19).

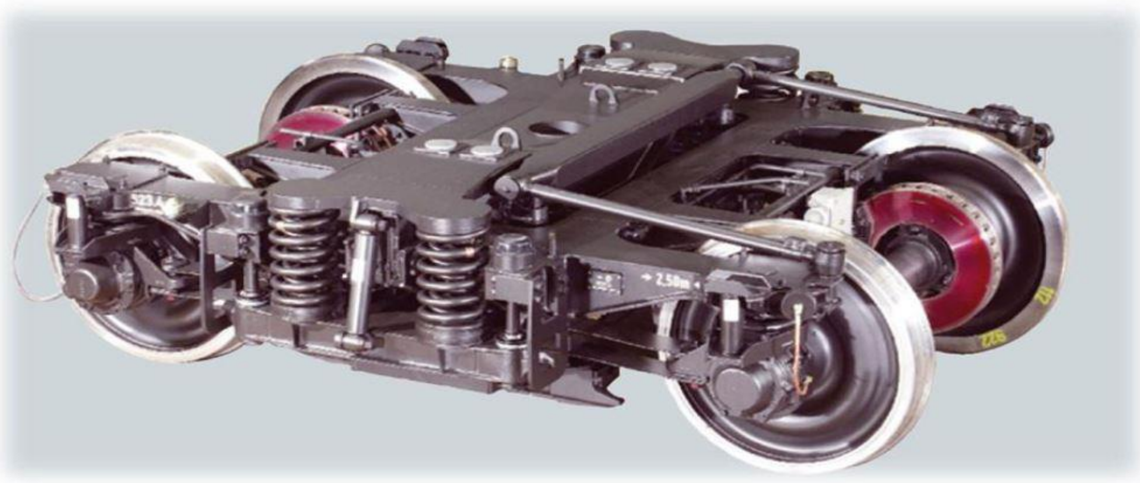


Fig.1.19: MD-522 Bogies by Bombardier

TWO DIAGONAL LINK ARMS

This system consists of two arms connected from one side to the axlebox and the other the bogie frame, arranged in a diagonal position (Figure.1.20). All the connections are done by rubber elements or elastic bearings to let flexibility enough and avoid friction surfaces. The main problem is obtaining linear motion of the axlebox when the arms rotate. The problem can be solved increasing the longitude of the arms, but this is committed to space.

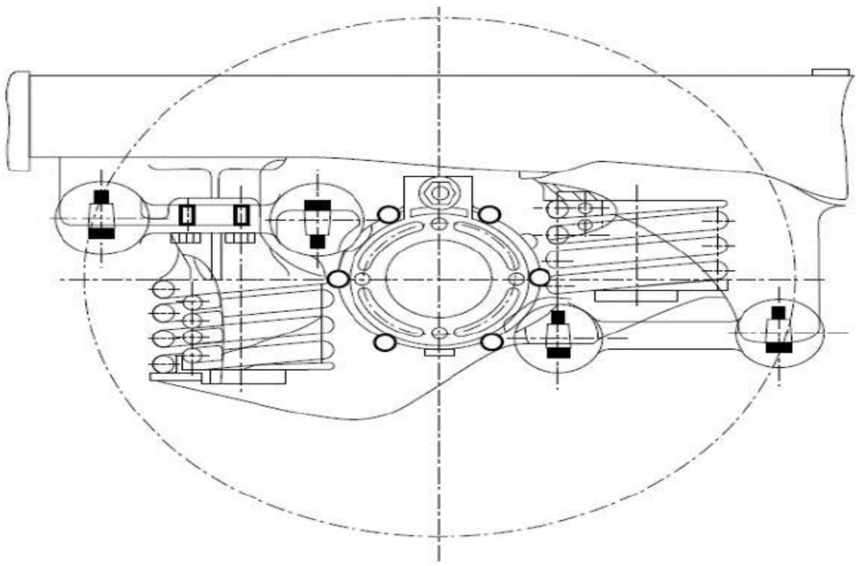


Fig.1.20: Two diagonal link arms

This configuration is widely used by *Alstom* for example in the *CL 624* showed in the (Figure.1.21).

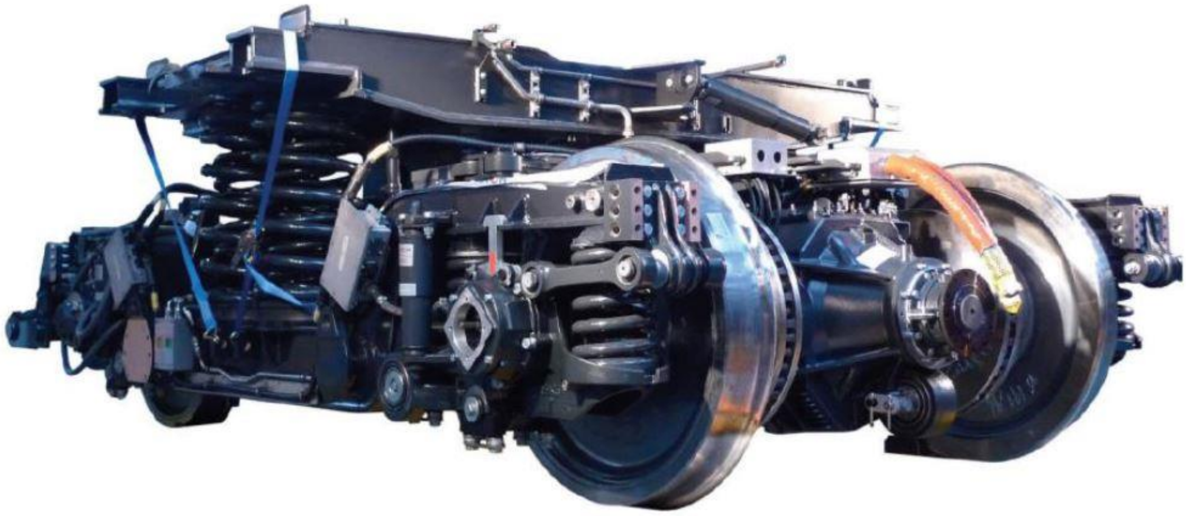


Fig.1.21: CL 624 Bogies by Alstom

HORN LINER GUIDES

On this configuration, the axlebox is linked to the chassis through guides in the own frame of the bogie allowing a vertical movement [3]. This system is also known as *horns* and is the simplest way to arrange the axlebox (Figure.1.22). Transmits more vibrations than other systems due there are no intermediate elements between the axle and the bogie frame as there are in the swing arm system for example. It is more compact but very limited in terms of movements refers, only allows vertical movement. It is used for its simplicity and low cost.

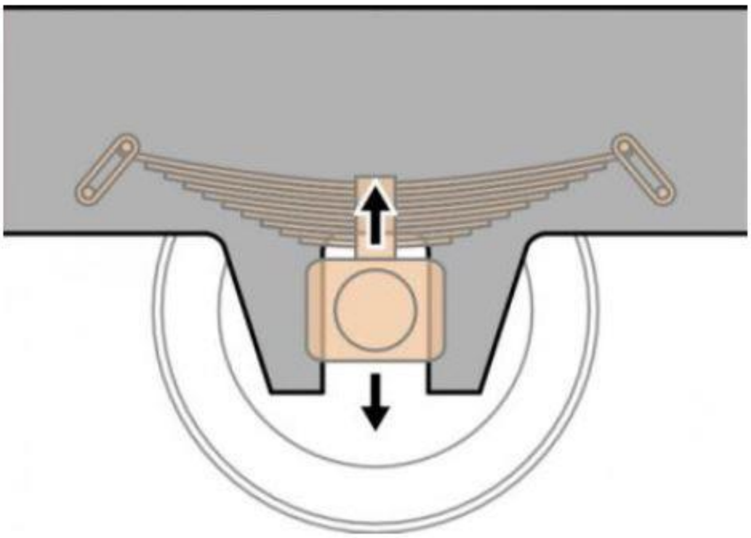


Fig.1.22: Horn liner guides

The main disadvantage of this layout stands the hard pressure of the axlebox against the horn during the braking or the acceleration. Therefore, a high rate of wear on the sliding surfaces occur prematurely, moreover, stresses on the base of the horn are created accelerating the creation of cracks

CYLINDRICAL STUBS

This is an evolution of the system explained above *Horn liner guides* [3]. The axlebox slides up and down guided by two stubs bolted to the bogie frame (Figure.1.23). Has the same disadvantage as the Horn system but with the friction surface is reduced, therefore there is less wear

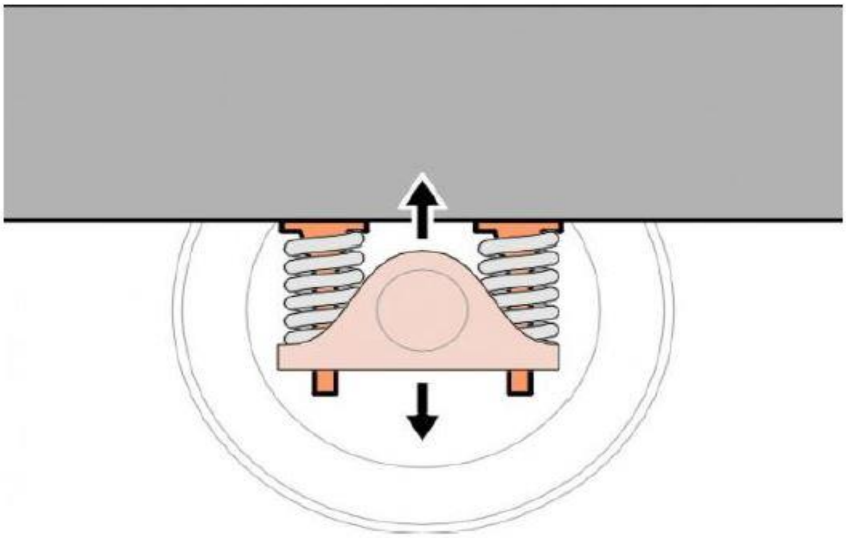


Fig.1.23: Cylindrical stubs

DAMPERS

The function of the damping elements is to absorb the oscillations produced by the elastic suspension elements in the shortest possible time. Dampers absorb the kinetic energy that is transmitted to the suspended mass and reduce the time in which the wheel-rail adhesion varies due to the oscillations produced by the elastic elements. They also break the oscillations produced in the suspended mass and in the non-suspended mass. Dampers aim to provide the necessary comfort to the passengers of the vehicle and limit the carbody movements.

Dampers can be classified into two groups: friction dampers and hydraulic dampers:

- Friction dampers
- Hydraulic dampers

The friction dampers (Figure.1.24) the simplest ones but widely used on freight vehicle or on bogies where the comfort is not essential

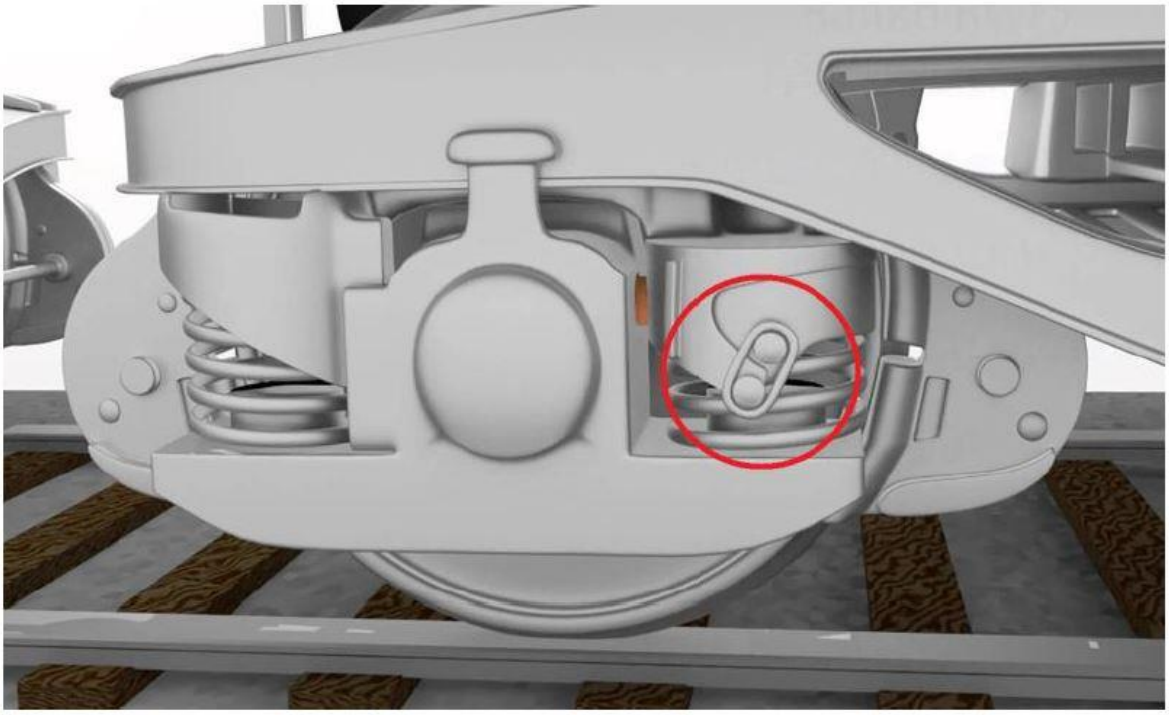


Fig.1.24: Friction dampers

Principal problem is that the damper starts working when the friction force is exceeded, so the vehicle starts from an initial situation of blocked suspension. Once the friction force is overcome, the damping force decreases with the speed instead of increasing with it. In addition, continuous maintenance is necessary due to the wear and tear suffered.

Hydraulic dampers (Figure.1.25) are the ones that use the viscosity of a fluid or the compressibility of a gas to absorb the kinetic energy. There are basically two different hydraulic dampers, monotube and double tube shock absorbers being the second the most common for their best behavior. Hydraulic dampers are the most common shock absorbers used on passenger bogies. Those can be used in both primary and secondary suspension. Dampers arranged in parallel to the primary suspension system ensure an optimal vibration and sound decoupling. This solution is extended used in Siemens bogies for passengers like the SF 200.

Hydraulic dampers are also used to dampen the yaw and the tilting, also the axle guidance (lateral movement) if the bogie is provided with it.

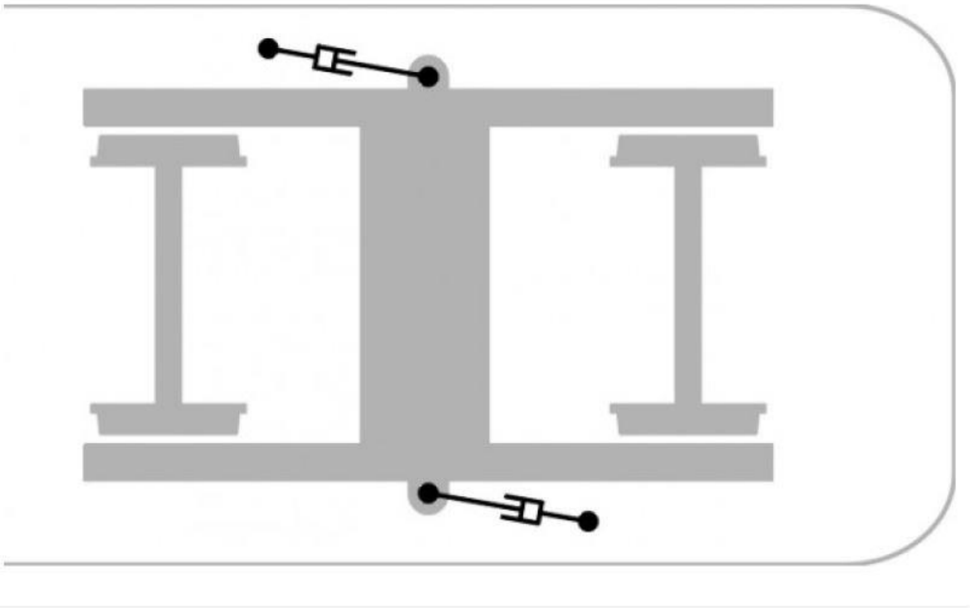


Fig.1.25: Hydraulic dampers

The correct usage of dampers is relevant to obtain a good comfort in the carbody, that's why many arrangements are available on the market in the sense of getting specific properties according to demand. For example, the SF 600 made by Siemens, which is defined as a high-comfort bogie for passenger's train, has a yaw damper system fitted with hydraulic dampers, which can be automatically activated depending on the vehicle speed to improve the stability of the carbody

Nevertheless, using an active stabilization of the wheelsets negates the need for yaw dampers between bogie and carbody, which, in the case of conventional bogies are required to stabilize the sinusoidal movement of the bogie. Furthermore, lower weight designs are possible due to potential elimination of intervehicle dampers, that means less material required.

E. BOGIE FRAME SHAPE

The bogie frame is the bogie chassis, where all the components are linked. There is not a specific design or shape; it changes depending on the demands of each usage. It is made, in most designs (Figure.1.26), of high strength steel, connecting each part by welding. Each part can be made of steel sheets, forged or cast pieces

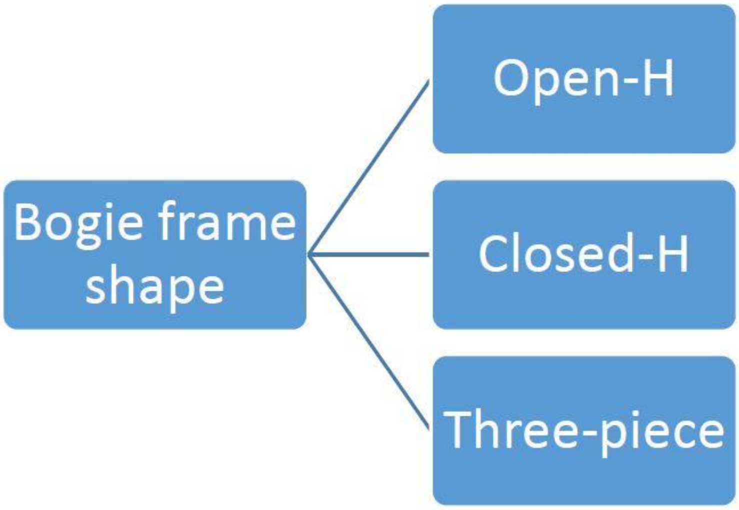


Fig.1.26: Designs of bogie frame

OPEN H-FRAME

The most common design is the open H-frame (Figure.1.27). It is a light design widely used in high-speed trains like the *ICE 3 – DB, AVE S103 – RENFE, Velaro RUS – Russia*. All these trains use the First-Class Siemens SF 500 bogie [3], which is robotically welded. This frame shape is commonly combined with a swing arm with helical springs as the elastic element.

Fig.1.27: Open H-frame

The bearings can be located inboard with the bogie frame lying between the wheels as shown in the lower image of the Figure.1.28, or outboard, keeping the wheels in the inner part, top image of the Figure.1.28. Inboard bearings make the frame lighter and more compact. This last configuration is used on regional passenger trains and trams whose modest travel speed is unlikely to result in bearing failure

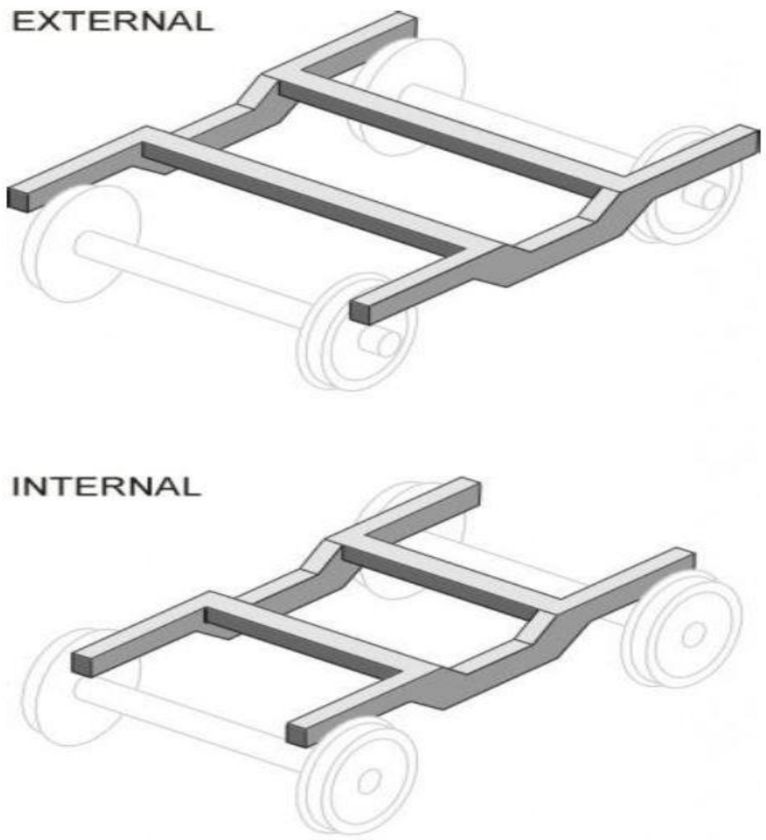


Fig.1.28: External & Internal Open H-frame

CLOSED H-FRAME

There exist also a closed H-frame that links the extremes of the *H* with a bolster (Figure.1.29). This provides more torsional resistance, consequently, it has a higher weight. This bogie frame is found on locomotives like the *CL 622* from *Alstom*. However, it is also rarely found on bogies for high-speed trains like the *SF 500 DSW* from *Siemens* [3].

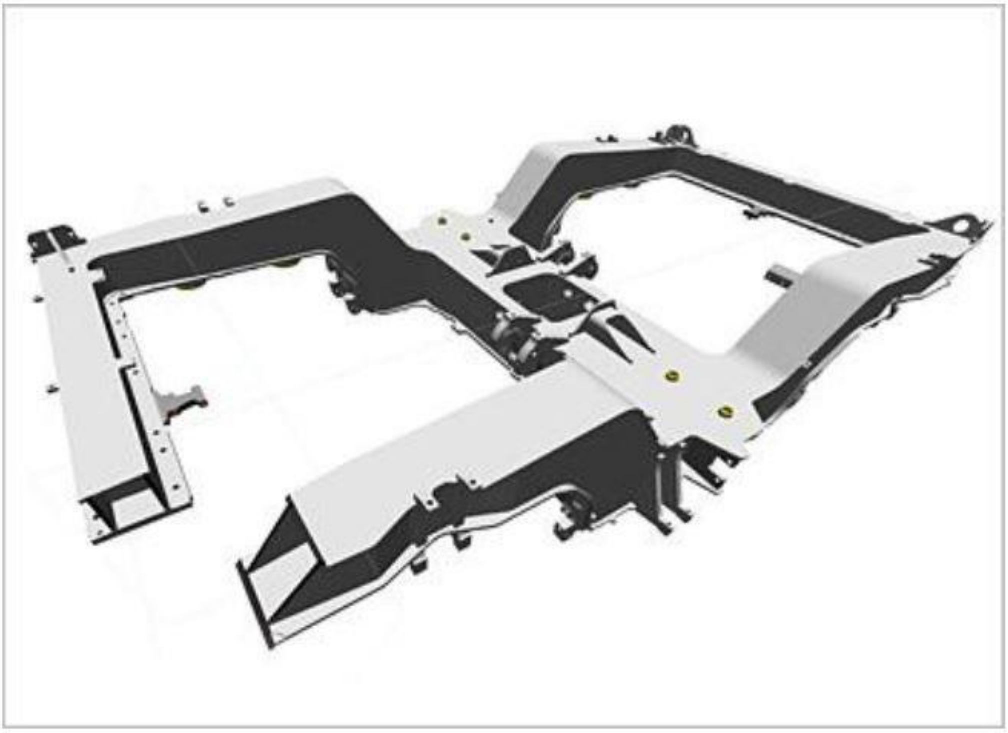


Fig.1.29: Open H-frame

A well-known railway manufacturing company as Siemens, inform that their bogie frame on the *Vectron* is welded almost entirely with the use of robots, and does not incorporate any castings or forged parts because of their bad mechanical properties

THREE-PIECE FRAME

This type of chassis consists, as the name suggests, of three pieces, two side frames linked to the central bolster by the secondary suspension as shown on the (Figure.1.30). The connection from the bolster to the car body is via a central pivot and side bearers with sliding surfaces. There is no primary suspension between the wheels and the side frames in the most of these bogies. The three-piece bogie is not common in Western Europe, is widely used in North America, Australia, Africa and Russia and a modern version is currently being introduced into Great Britain [3]. Three-piece bogie frames are widely used on freight bogies due to their low cost, inherent simplicity and ability to articulate in poor track conditions

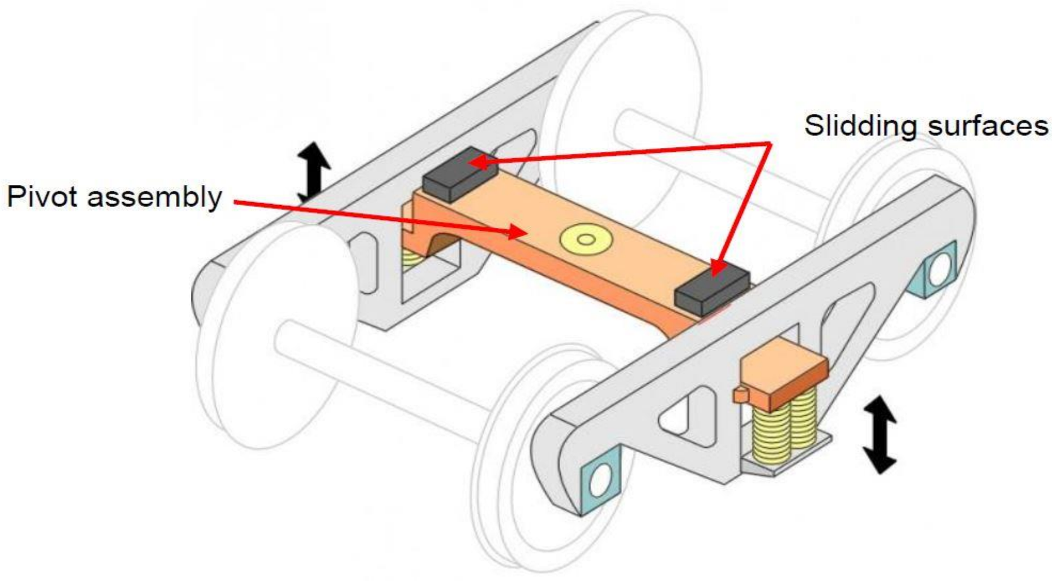


Fig.1.30: Three-piece frame

F. BRAKING SYSTEM

The principal function of the braking system is to reduce the speed of the train. The weight, axle load and maximum speed are decisive parameters when choosing one of these systems [3]. Braking can be achieved by the systems explained in this subchapter which are classified in the (Figure.1.31).

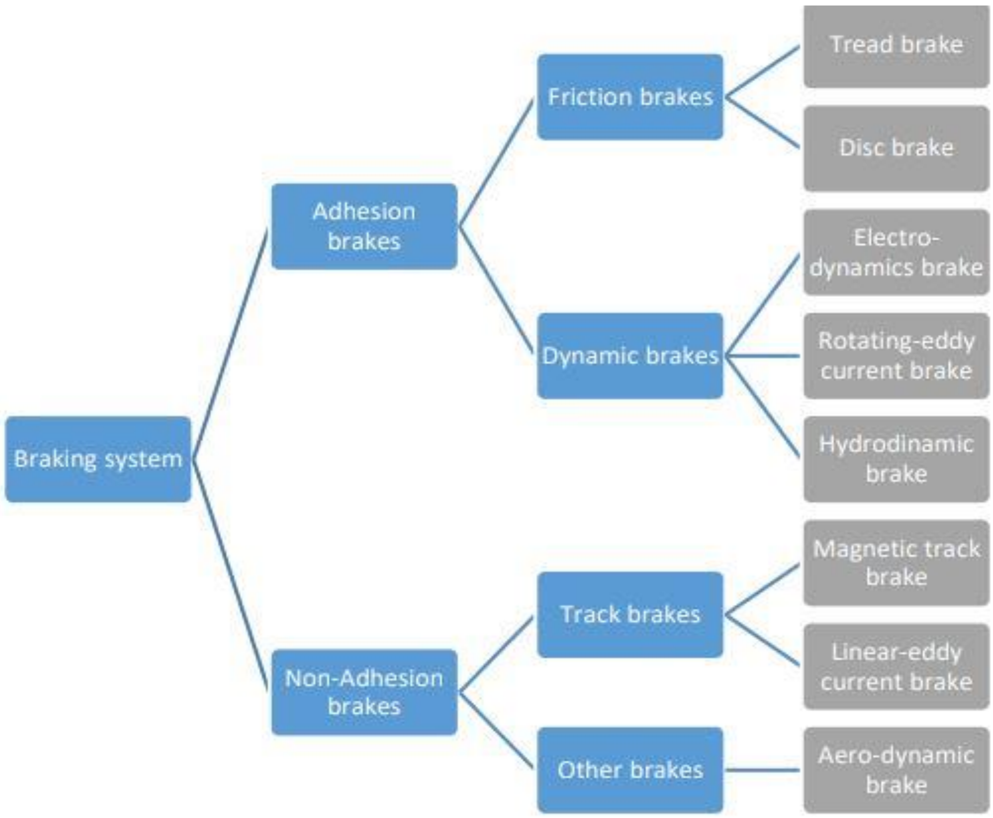


Fig.1.31: Classification of braking system

TREAD BRAKES

Mostly used in non-tractive units, this brake uses the friction between a brake shoe and the running surface of the wheel to create braking force. The wheel must be designed to evacuate the heat and avoid thermal overstress. The main problem of this system is the considerable wear that occurs on the wheel. Over the time this system has been replaced by disc brakes, however, these braking systems still used in freight bogies [3].

DISC BRAKE

The braking effect is created by the friction of the brake shoe on the brake disc (Figure.1.32) [3].

Fig.1.32: Disc brake

There is produced a transformation of the energy into heat and it is removed via cooling fins. The most common designs are ventilated axle-mounted brake discs. This system is the most common braking system used in all the bogies due to the simplicity and good braking power which can be increased just adding more discs in the same axle as needed Disc brakes can also be mounted on the inner part of the wheel saving space on the axle box (Figure.1.33).The system is called wheel-mounted brake discs. These are usually low-maintenance disc to reduce the life cycle costs.

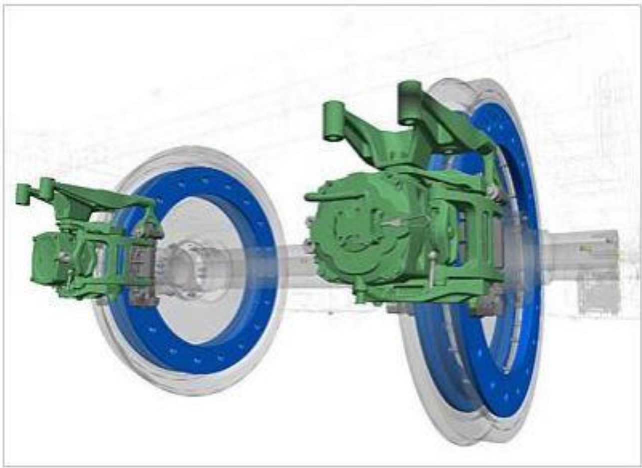


Fig.1.33: Wheel-mounted brake discs

ELECTRO-DYNAMIC BRAKE

This system consists on using an electric traction motor as a generator when slowing the vehicle, it is understood that is a brake for electric tractive units. The drive motor switches on and turns generators during the braking, transforming kinetic energy of the train into electrical energy. This is a wear-free braking system and it's very effective at high speeds. It is assumed that the motor bogies integrate this type of brakes [3].

ROTATING-EDDY CURRENT BRAKE

Consists of a conductive non-ferromagnetic metal disc attached to the axle, with an electromagnet with its poles located on each side of the disk, so the magnetic field passes through the disk (Figure.1.34). The electromagnet allows the braking force to be varied. This system is wear-free due there is no physical contact between the poles and the disco [3].

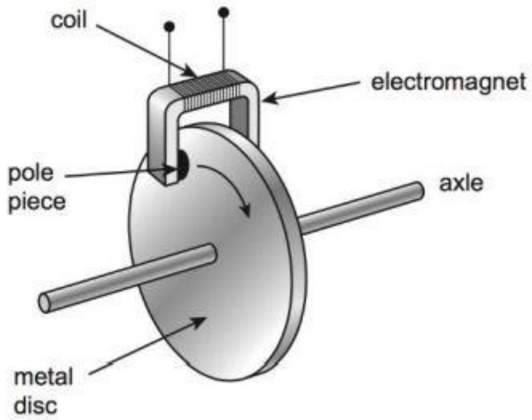


Fig.1.34: Classification of braking system

MAGNETIC TRACK BRAKES

This system consists of two brake shoes magnetically attracted to the rails generating friction directly on them (Figure.1.35). When using a sintering friction material, the maximum speed at which this brake can be applied is up to 350 km/h. This system is powerfully braking but causes considerable wear, which is why this system is mostly used for emergency brake applications [3].

Fig.1.35: Magnetic track brakes

G. CAR BODY CONNECTION

Car body connection the efforts generated by the bogie to pull or brake the train must be transmitted to the car body. This is done through the systems discussed in this subchapter. The car body connection is not only a point of union between the bogie frame and the car body, but it is the connecting link through which all the forces are transmitted. The possibile systems are classified in the (Figure.1.36).

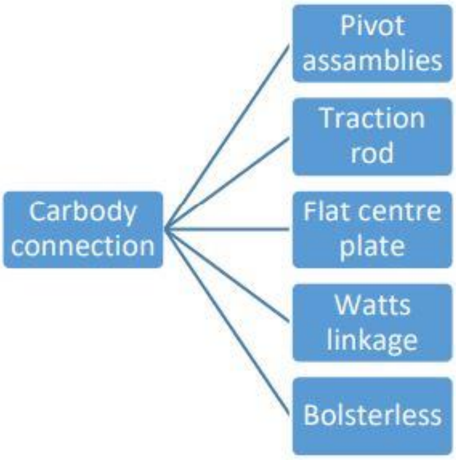


Fig.1.36: Classification of carbody connection

The designs generally attempt this connection as simple as possible using as fewer elements as possible and reducing the elements that work on friction [3].

THE PIVOT ASSEMBLY

Transmits traction and braking forces from the bogie to the car body, moreover, is the point about which a bogie undergoes rotational movement in the horizontal plane to the car body [3].

According to their relative position, pivot assemblies can be classified into two types:

- High location of the pivot point: the forces transmitted to the car body are located above wheelset in the horizontal plane as shown in the (Figure.1.37).
- Low location of the pivot point: the forces transmitted to the car body are located below the wheelset in the horizontal plane as shown in the (Figure.1.38).

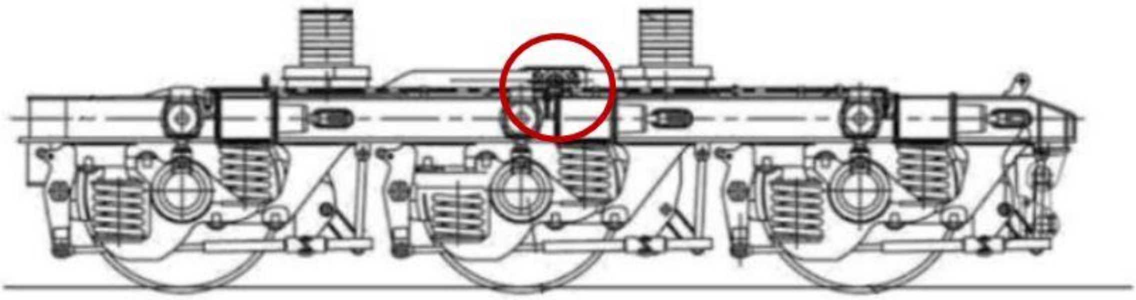


Fig.1.37: High location of the pivot point

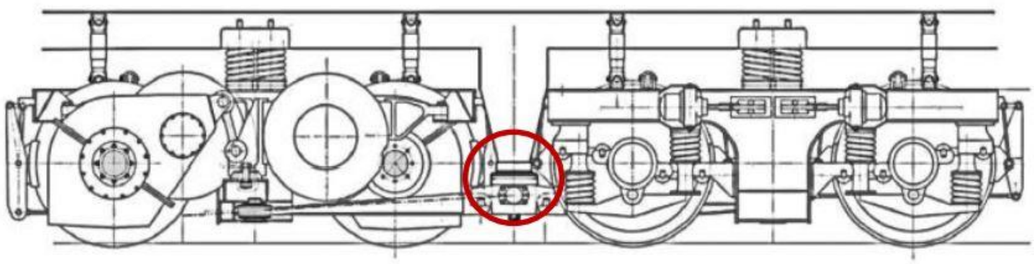


Fig.1.38: Low location of the pivot point

The low location of pivot point achieves higher values of tractive and brake efforts on a bogie than another with the same design but a high pivot point. Pivot assemblies can be designed with additional gaps that allow some small motion in the horizontal plane. The ones with spherical joints allow the bogie to carry out a rotational movement [3]. In addition, these can have movement in the vertical plane and partial displacement in the horizontal plane. From the design point of view, the pivot assembly consists of a pin rigidly fixed to the bogie frame on one end, while, on the other end, a pin is inserted in the pivot yoke which is fixed to the frame of the bogie or the bolster.

The advantages of a rigid pivot are the simplicity of their design and low-cost manufacturing. This system allows lateral motions, therefore, have better dynamics in comparison with rigid joints. In addition, this with spherical joints can provide improved dynamic behavior for a traction bogie in comparison to other designs.

A disadvantage are the clearances in longitudinal and lateral directions this system has. Nevertheless, this design provides enough ride quality only for bogies having low lateral stiffness of the secondary suspension [3].

FLAT CENTER PLATE

It is the most common connection for low speed and freight bogies. Consist of a plate in charge of transmitting the weight of the bogie and both lateral and longitudinal forces. It is normally located over the bolster, fitted in a crown bearing (Figure.1.39). A pin pivot on the center always secures the structure. The pin pivot has clearances on the yoke thus only provides emergency restraint. The center plate allows the bogie to rotate in curves and creates a friction torque that resists bogie rotation, therefore, the circular center plate provides a connection between the bogie and the car body in all directions. This arrangement to join the car body and the bogie frame is the simplest and low cost [3]. Logically it has disadvantages, the most significant is that the rotary movement occurs under a high contact pressure and, therefore, the surfaces are subject to significant wear. On modern designs, it is being used a flat central plate combined with elastic side supports that resist the rolling motion of the body and reduce the load on the central plate

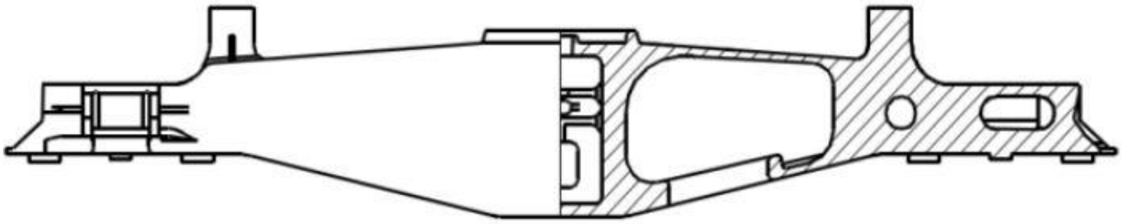


Fig.1.39: Flat center plate

WATTS LINKAGE

Watts linkage (Figure.1.40), also known as “Z link”, is a design that can be understood as an evolution of the pivot assemble since it consists of a central pivot and two others on both sides of it. These two on the sides join with the central one by a connecting rod [3].

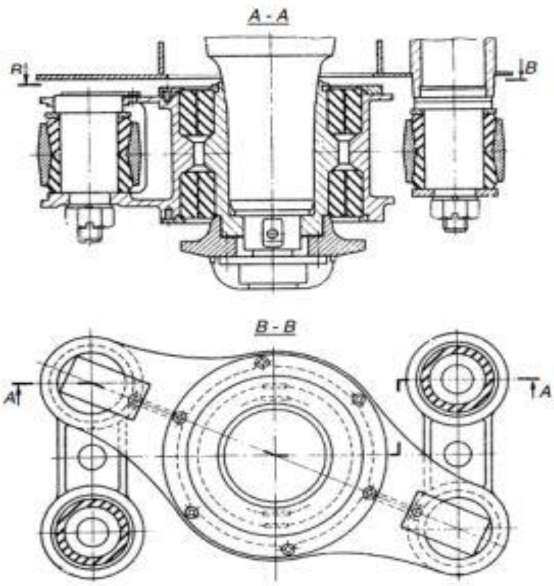


Fig.1.40: Watts linkage

This configuration allows the bogie to rotate and move laterally while longitudinal movement is guided by the geometry (Figure.1.41). In addition, the pivots in the linkage are provided with rubber washers and bushes to prevent the transmission of high frequency vibrations through the mechanism and improve the driving comfort

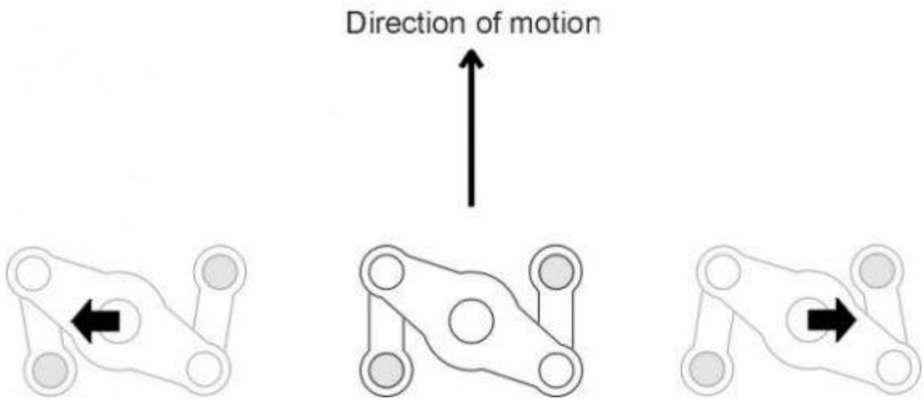


Fig.1.41: Watts linkage configuration

BOLSTER LESS CONNECTION

A typical bogie design has a bolster joining transversely the springs of the secondary suspension from one side to the other of the bogie frame. In the middle of the bolster, there is the connection between the bogie and the car body. In the bolster less designs, this bolster is missed and the link between the bogie and the body rests only on the springs and a center pivot to transmit the forces. The bogie rotates under the car body using the flexibility of secondary suspension. This requires that the suspension used allows both longitudinal and lateral movements for the correct turning of the bogie. Such requirement is solved with airsprings or flexi-coil springs [3].

This design should use yaw dampers fitted longitudinally between the bogie and the carbody to assure stability in a straight line.

TILTING

The tilting trains arise from the need to reduce the centrifugal forces in curves at high speed [3]. This force pushes the passenger toward outside of the curve, hence comfort is reduced. To solve this problem, some trains are equipped with a hydraulic or electric system that makes the carbody tilt to the side where the center of the curve (Figure.1.42).

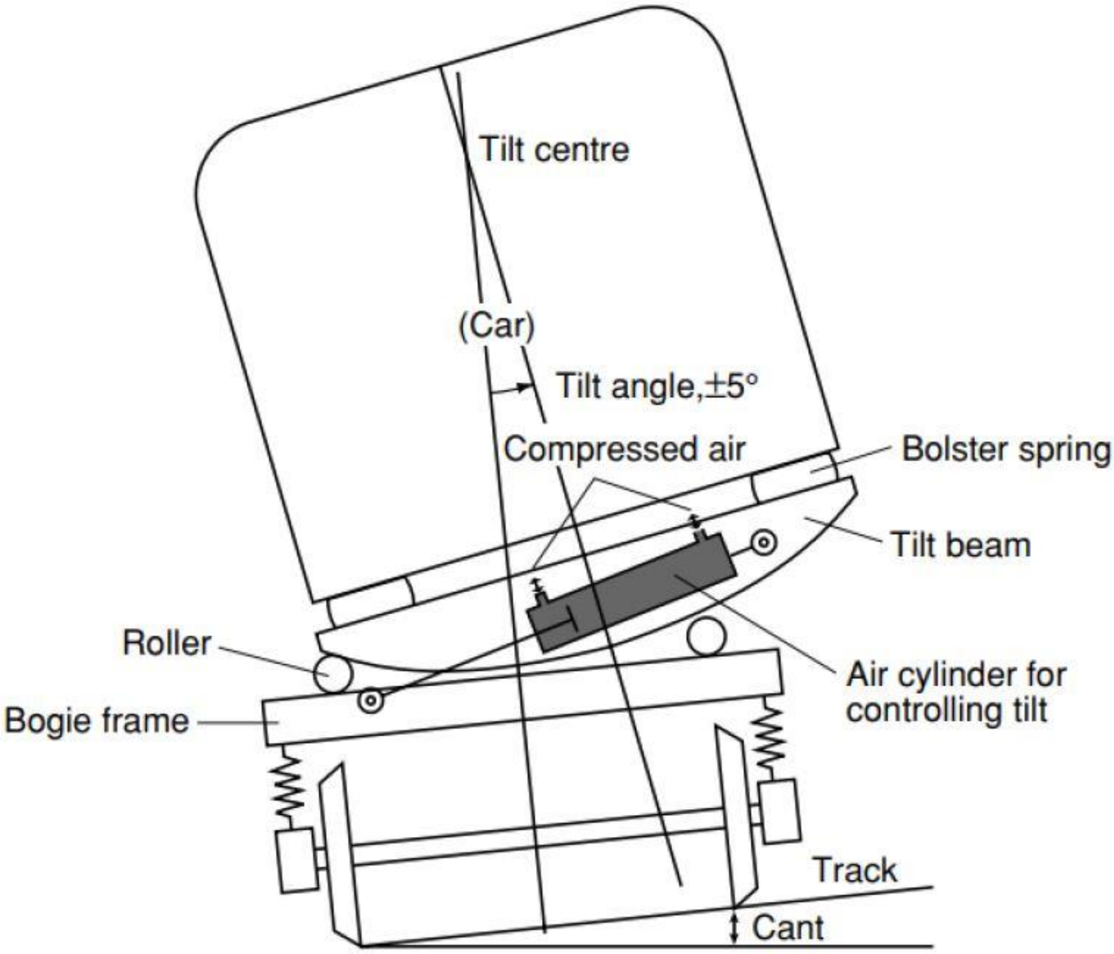


Fig.1.42: Watts linkage

A tilting system (Figure.1.43) simulates a cant effect in railways which do not have, thus a train can drive through places where initially were not designed for high-speed. Even if the railway track is equipped with a cant, may not enough for a high-speed train to run on it, hence the inclination helps to improve comfort and drive faster.

An example of a bogie that uses a tilting system, is the *CL 624* produced by *Alstom* and used by *RENFE* or *Trenitalia*. This bogie is used in high-speed trains with an operation speed around 225-250 km/h. The manufacturer *Alstom* specifies that “has an active hydraulic tilting system (+/- 8º) to enable to do high-speed curves on conventional lines”.

There are four ways to tilt the carbody; two with no bolster, one just elevates the secondary suspension and let the carbody naturally swings outwards the curve. The other way is to actuate directly to the secondary suspension to make it tilt, for example, applying differential control to the air springs. The other two systems that use a bolster are the most complicated but also most effective tilting systems. They are differentiated because one has the bolster above the secondary suspension and the other below, this last avoids the increasing of the curving forces, and this is probably the most common of all schemes. These two last are active ways to tilt in the sense on there are arranged actuators (hydraulics or electrics) that force the car body to tilt.

Tilting systems for high-speed trains is widely used due to their comfort gain. In Japan for example, a passive system is used, in Italy, *Pendolino* trains have an active control system, in Spain a completely different passive system had been developed for the *Talgo*, however, in France and Germany, the high-speed lines are being built on new alignments that don’t justify the expense and complication of tilt technology

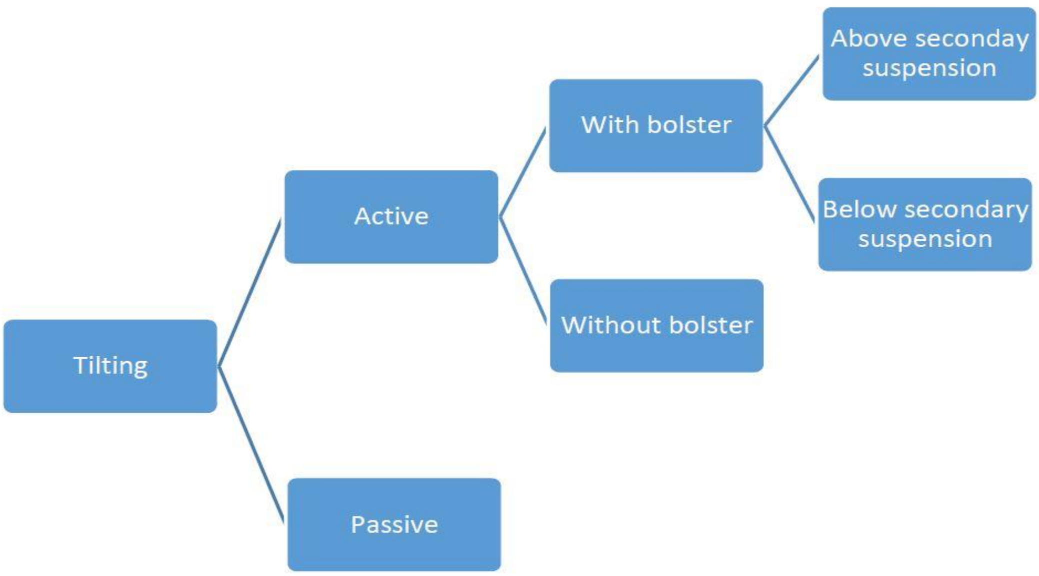


Fig.1.43: Classification of tilting

WHEELSET STEERING

The steering is the capacity that the bogies have on the wheelset to adopt a radial position in curves (Figure.1.44). This brings a significant decrease of flange wear "**10 time wear reduction**"and lower track forces that will prolong the life of the track and postpone the need for rail replacement. It provides a better behavior on sharp curves, on a tram railway for example. Finally, the curve squeal noise is eliminated or partially eliminated.

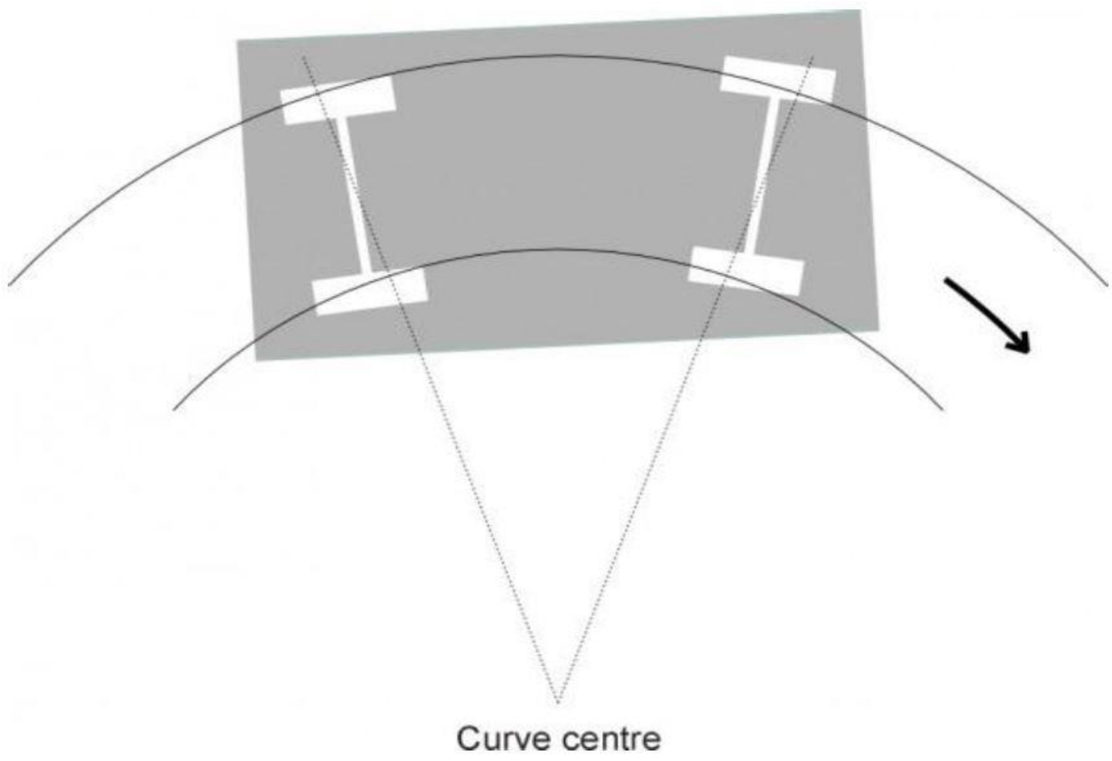


Fig.1.44: Steering

There are three different ways to get steering of the wheelset. The first is the one that gets the yaw of the wheelset through the interaction between the rail and the wheel. The second system, the yaw angles of the wheelsets are determined by the angle of the bogie relative to the vehicle body, the wheelsets are forced to get radial position due to the linkages between the wheelset and the vehicle body. This second system has been used successfully on the Japanese *Railways Hokkaido Series 283* [3] passenger diesel motor units, where tests have shown that it reduces lateral forces on the rail by a half or more. The last system integrates sensors and actuators, either hydraulic or electric, that force the axlebox to adopt radial position.

This is the most complicated system, but also the most effective. The two first systems are passive ways of self-steering due there is any actuator that controls the yaw of the wheelset.

To summarize, wheelset steering axel guidance (Figure.1.45) can be classified into the following three groups:

• Wheelsets yawed by the wheel-rail contact forces.

• Wheelsets yawed by the relative rotation between the bogie frame and vehicle body.

• Wheelsets yawed by an external energy source (electric, hydraulic, or pneumatic actuators, steering linkages (Figure.1.46)).

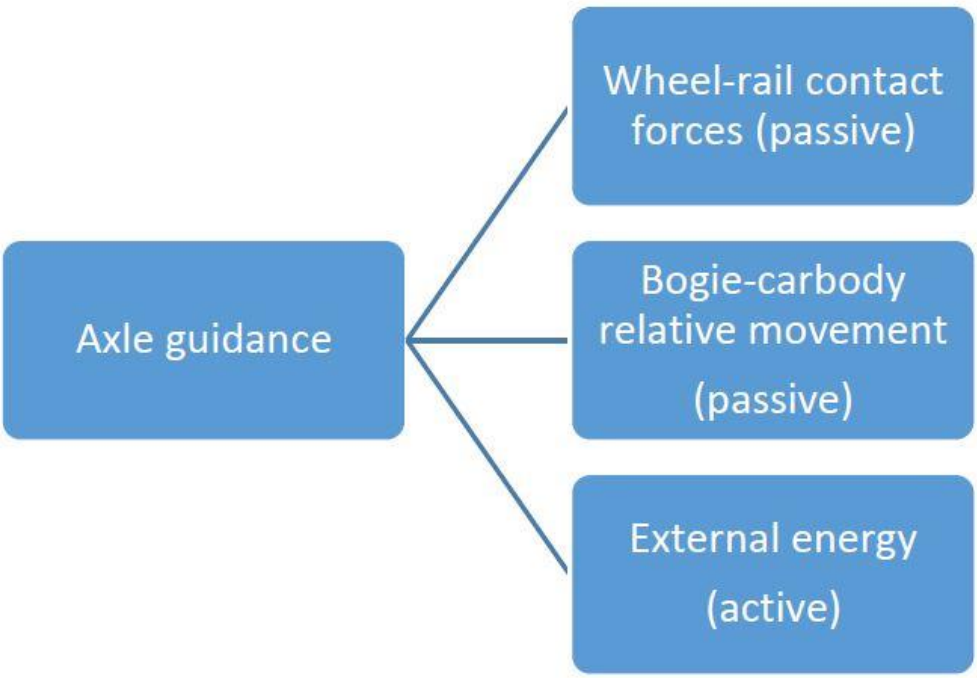


Fig.1.45: Classification of axel guidance

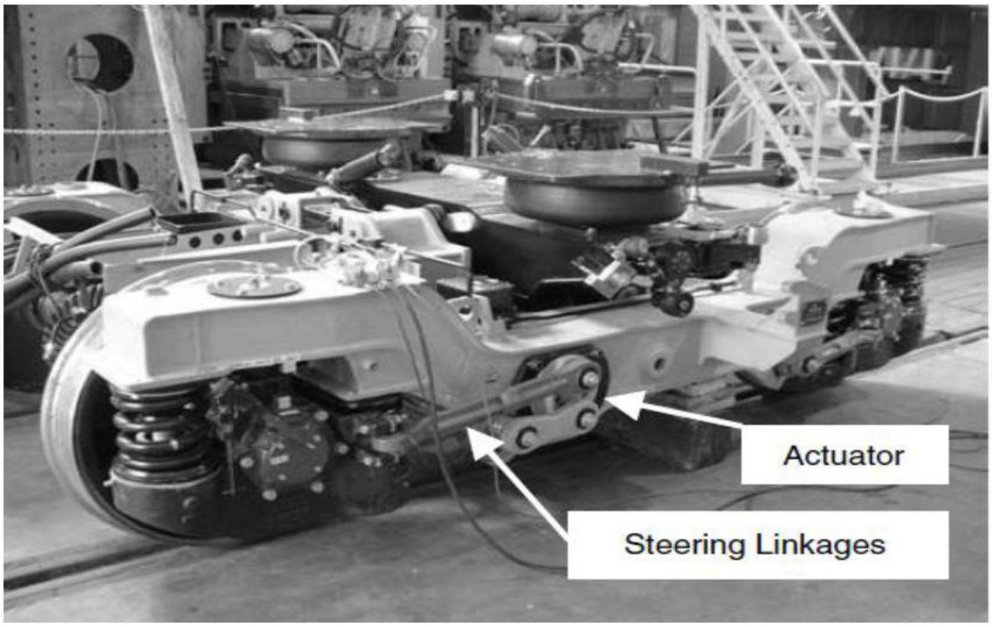


Fig.1.46: Steering linkages & Actuator

To understand how the axle can have yaw freedom to adopt radial position, the (Figure.1.47) explains four different systems. The axlebox yaw must be compatible with the primary suspension, which is joining the axlebox to the bogie frame, hence the suspension must provide freedom in lateral and longitudinal directions. This is not achieved by all the suspensions. To provide a bogie with axle guidance, the selected suspension system should allow the lateral and longitudinal displacement [3].

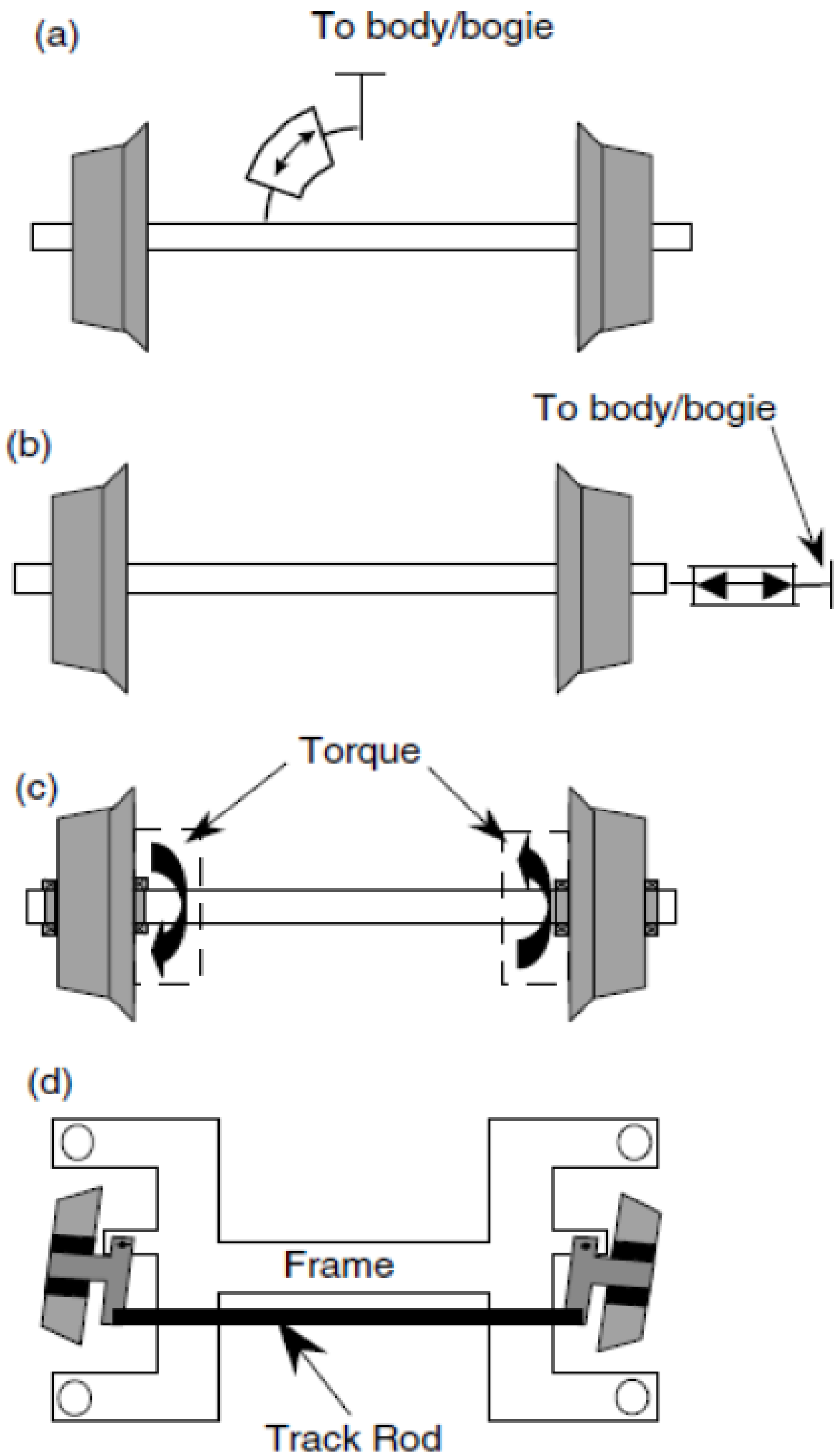


Fig.1.47: different systems of an axle

2 IMPACTS OF INNOVATIVE RUNNING GEAR WITH COMPOSITE MATERIAL

2.1 OVERVIEW OF A SINGLE AXEL RUNNING GEAR

Common running gears (Figure.2.1) consisting of a bogie with wheelsets are well proven in railway practice. However, they have disadvantages in two areas: Under special running conditions very high speed and in narrow curves running stability problems or high wear can occur. Also, the bogies restrain some aspects of the vehicle design. Therefore, typically vehicle layouts are long single coaches with two bogies or articulated trains with Jacobs-bogies and a shorter carbody.

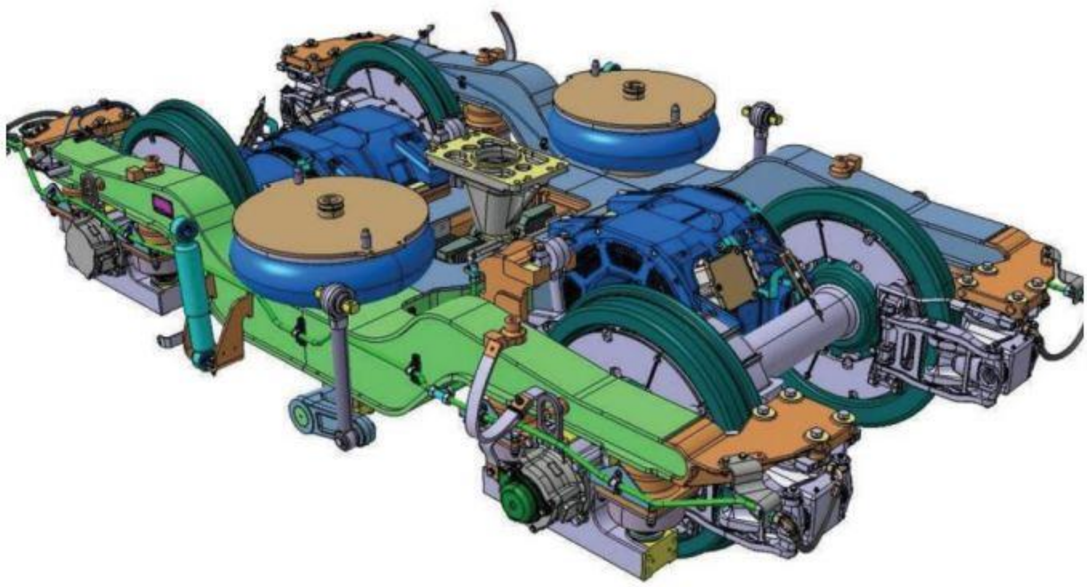


Fig.1.47: Running gear – case study

A novel train concept [4] is developed consisting of a high-speed double-decker trainset with continuous floors and two axle center coaches. With a length of 20 m, the singel axle coaches offer a very high light-weight potential, but special running gears are needed with a controlled pair of independently rotating wheels, which can be arranged as single wheel pairs or in a bogie. In order to enable a lower floor over the running gears, both wheels are connected by a cranked beam. Each wheel has a traction motor, which is also used as actuator for the track guiding and radial steering in curves. This mechatronic running gear should offer a better running performance than a conventional running gear under all operation conditions in combination with a low maintenance effort.

The challenges for the development of a mechatronic track guidance system are to find a robust sensor to detect the current lateral position of the wheels relative to the track, which can be placed in a real running gear, a robust control algorithm, which is able to adjust itself to alternating operation conditions and a powerful actuator to realize the commands of the control system.

The basic idea of the novel mechatronic running gear concept consists of independently rotating wheels with a mechatronic guidance system to overcome the disadvantages of conventional wheelsets under certain operating conditions. At most operation conditions a conventional wheelset offers a good guidance quality, but at very high speed and in narrow curves problems can occur on vehicles with conventional wheelsets, for instance instability (high speed) or high wear and vibrations (curves). In principle, the problems should disappear by using independently rotating wheels (IRW).

Otherwise, vehicles with independently rotating wheels – without an active guidance system – often need a higher maintenance effort to ensure low wear at the wheels, because of the reduced centering effect of independently rotating wheels.

The aim is the development of a running gear, which offers gear under all operation conditions in combination with a low maintenance effort a better running performance than a conventional running. This means a lower emission level of vibrations to the ground and the air as well as less friction at curves and therefore a lower need of traction energy. Additionally, the running gear concept enables more comfortable train concepts such as low floor trams or double deck trains with two continuous decks. The principle is applicable to bogies as well as running gears with a single pair of wheels.

These features are preconditions for the realization of “Next generation Train” - NGT, (Figure.2.1). The NGT is a research project and was started in 2007 [4]. Eight institutes are engaged in different rail specific topics such as aerodynamics, structural design, energy systems, new materials, passenger comfort, running dynamics and vehicle concepts.

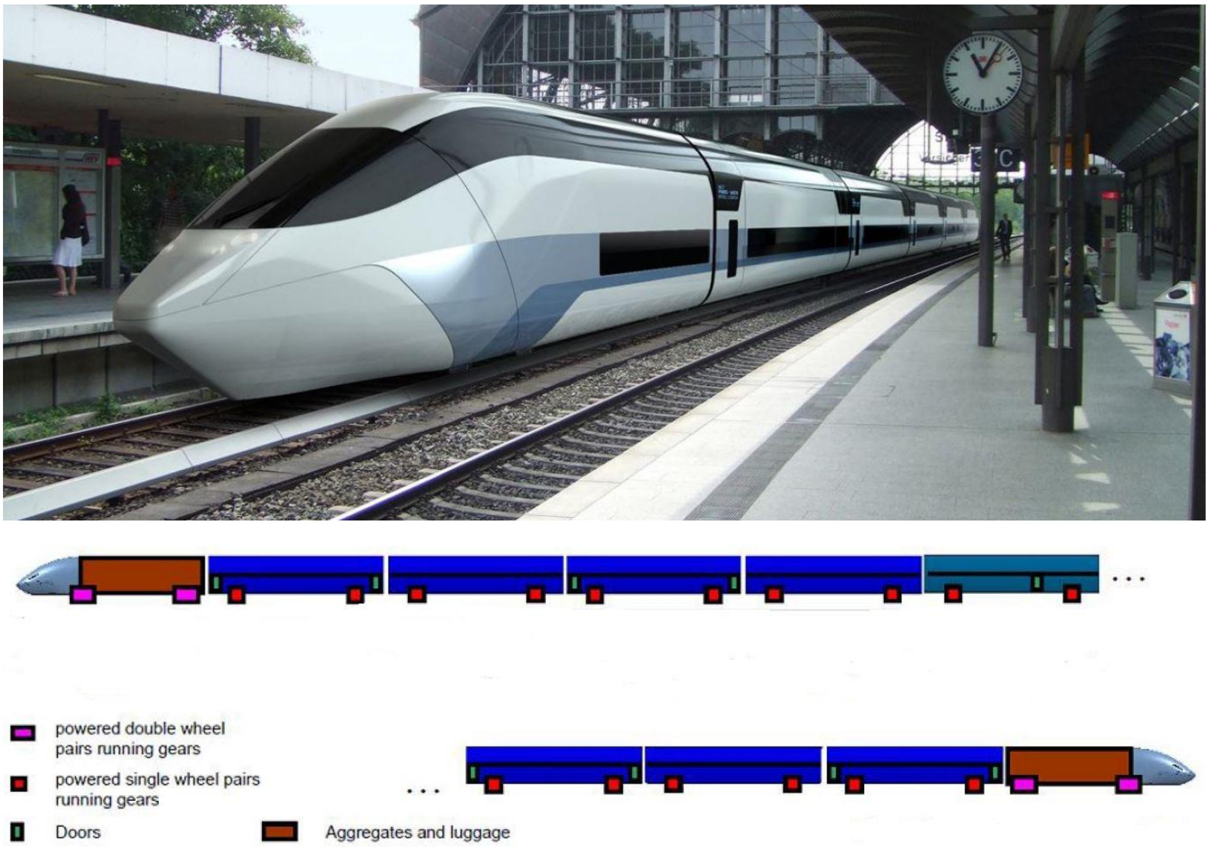


Fig.2.1: DLR Next Generation Train (NGT) (design study by ids, Hamburg)

The concept of the NGT [4] consists of a high-speed. The center coaches are a specialty of the train concept. They are planned as two axle vehicles. Continuous floors allow the passengers to easily walk through the train. Therefore, the independently rotating wheels with a mechatronic track guidance system are one of the main features. Many good concepts for mechatronic track guidance systems are published, yet. However, only a few were tested in vehicles. The main challenge is adequate and robust sensors in combination with an intelligent control system for a mechatronic track guidance system.

Especially in a high-speed train, an active track guidance system is a very ambitious challenge and requires high demands of the sensor and control system. For instance, the sensor must be able to identify the position of the wheels relative to the track and the control system must be fast enough to avoid flange contact even at highly disturbed tracks at high speed.

At the end this novel mechatronic running gear will increase the competitiveness and acceptance of the railway by a cost-effective and low emission running gear.

The mechatronic wheel pairs, which are an enhancement of the mechatronic wheelset, are the main issue of the running gear. the following classification of the concepts for steering of IRW, is suggested [4]:

- Driven independently rotating wheels (DIRW)
- Directly steered wheels (DSW)
- NGT CONCEPT

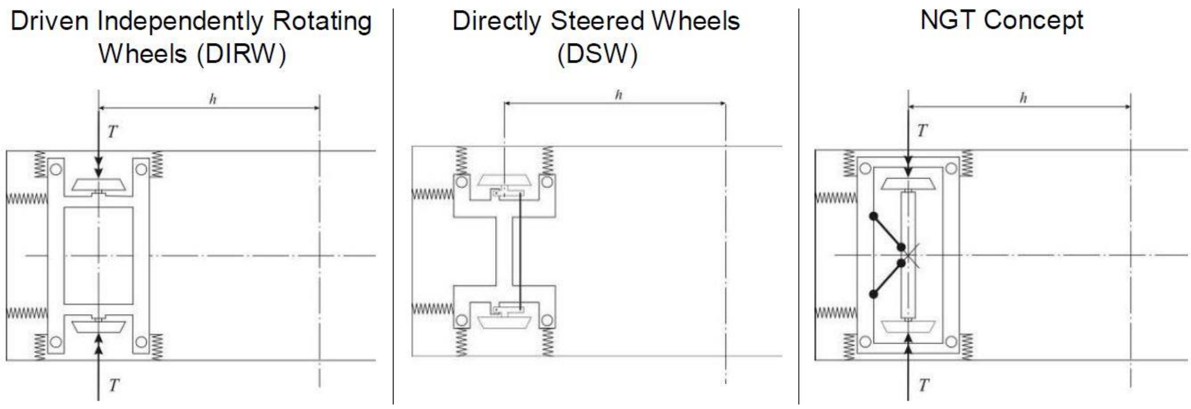


Fig. 2.2: streeing principles for independently rotating wheels

The concept of the driven independently rotating wheels (Fig.2.2) consists of two wheels mounted at a frame. The wheels are steered by applying differential traction or braking torques on both wheels. The springs between the frame and the carbody or a bogie frame allow a limited rotational movement around the vertical axis. The directly steered wheels have a coupled rotational degree of freedom. The wheels can be steered by applying differential traction / braking torques on both wheels or by an actuator.

The novel NGT concept is a combination of both (Fig.2.2): we think that both wheels need a tough connection with a beam without any joints except for the wheel rotation. The beam can have a U-shape with respect to the low floor. The aim of the concept is to ensure the same running quality compared to wheelsets and also to improve the running behavior in operation conditions, in which a conventional wheelset reaches its limits – in particular:

- At (very) high speed large yaw dampers are necessary for the stability of the hunting mode.
- In curves with (very) small radius large creeps occur and produce the related problems: wear, corrugation, noise and higher traction effort.

The traction motors of the independently rotating wheels are also used as actuator for the track guidance of the wheel pairs and a radial steering in curves. Therefore, each wheel pair can rotate around the vertical axis. Given that the rotation velocity of each wheel is controlled and that the wheel pair is held in a radial position, the creep can be minimized by force controlling.

The general idea is to assemble a comprehensive simple mechanical system and use an intelligent but robust control system. In principle, the control scheme for the mechatronic guidance is quite simple (Figure.2.3): A sensor detects the lateral displacement between the center of the wheel pair and the track centerline. The controller calculates the necessary differential torque for both wheels, which is passed to an actuator - for example a motor – that applies the torque on the wheel, this system combines perfectly the demands for curving (radial steering) and running stability [4].

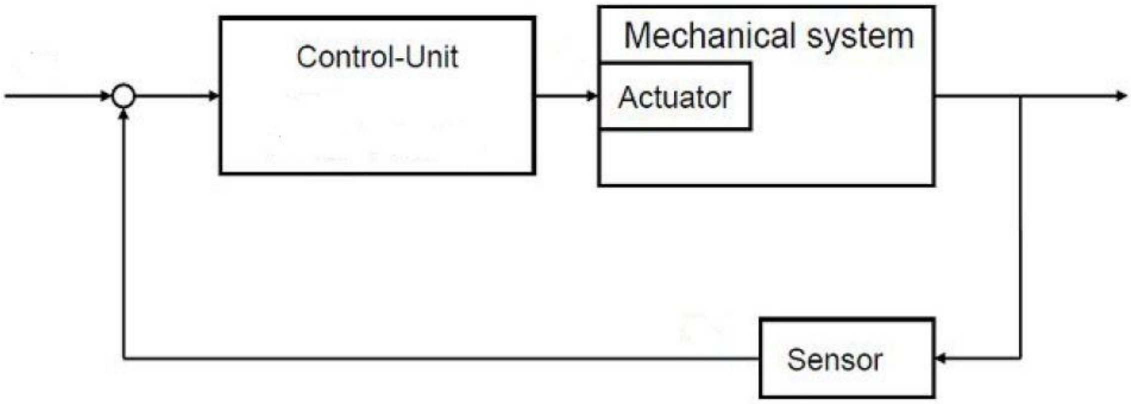


Fig.2.3: control for mechatronic guidance

Unfortunately, in railway practice, the conditions are more complex than ideal models, the following reasons are responsible for this situation [4]:

1. The measurement of the lateral displacement is difficult.

2. The various operation condition of a vehicle – especially of a high-speed train – (nearly straight high-speed lines, conventional lines with lower speed and many curves, and the situation at entering stations with many small S-curves partial without transition curves) require different control algorithms.

3. Each wheel has one traction converter and one motor. This is a quite expensive solution. But the authors expect that the costs for electronic components will further decrease in the next decade. Some light rail concepts already include single driven wheels. Therefore, it is assumed, that the costs of the converters and motors will be less important for the realization.

4. And last but not least, the system must meet all safety requirements.

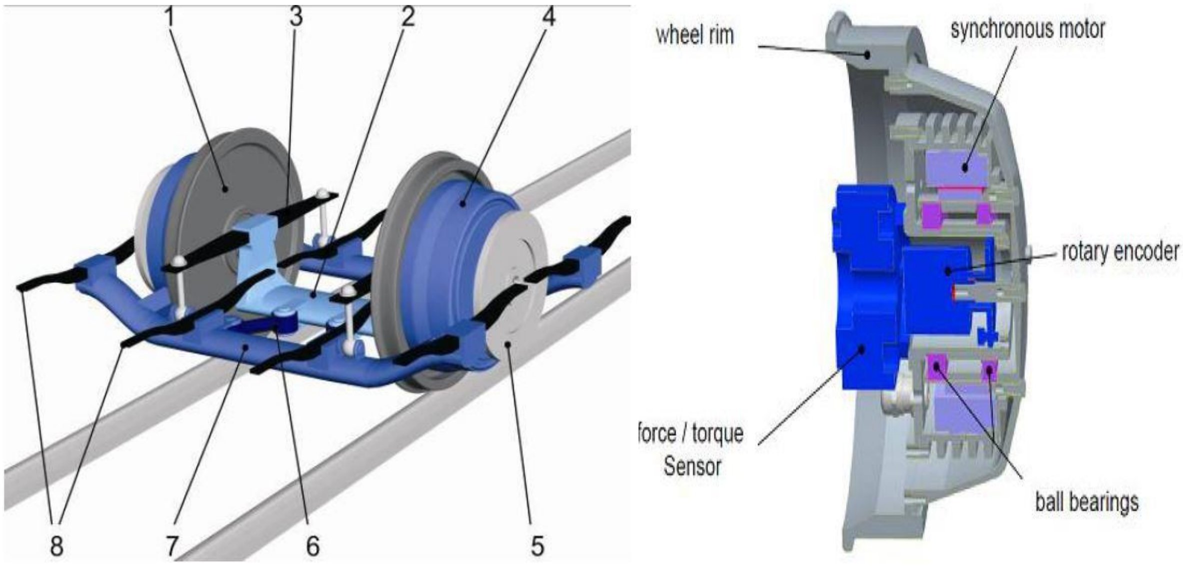


Fig.2.4: single axe running gear & Wheel module

Both wheels (1) in (Figure.2.4) of the running gear are connected by the cranked beam (2). The primary springs (3) are stiff in vertical direction and softer in horizontal direction. At present, the primary springs are only defined by their stiffness. The traction motor (4) and the brake discs (5) are arranged outside the wheels. Two levers (6) transfer the horizontal forces between the cranked beam and the running gear frame (7) and define the center for rotation around the vertical axis. Also actuated fiber-reinforced composite leaf springs are used for the secondary suspension (8) [4].

2.2 REFERENCE CASE: ROME–CIVITACASTELLANA–VITERBO RAILWAY

Here we are analyzing a reference case with a conventional bogie-based vehicle compared with a single-axel configuration using distinctive design material for weight and energy consumption reduction and assuming advanced mechatronic.

The Rome–Civitacastellana–Viterbo railway is a light rail way line connecting Rome, Italy, with Viterbo,[1] capital city of the Province of Viterbo. The 102 km long line, also known in Rome as the Roma Nord line, after its former concessionaire, is part of Rome's metropolitan and regional railway network (Figure.2.5).

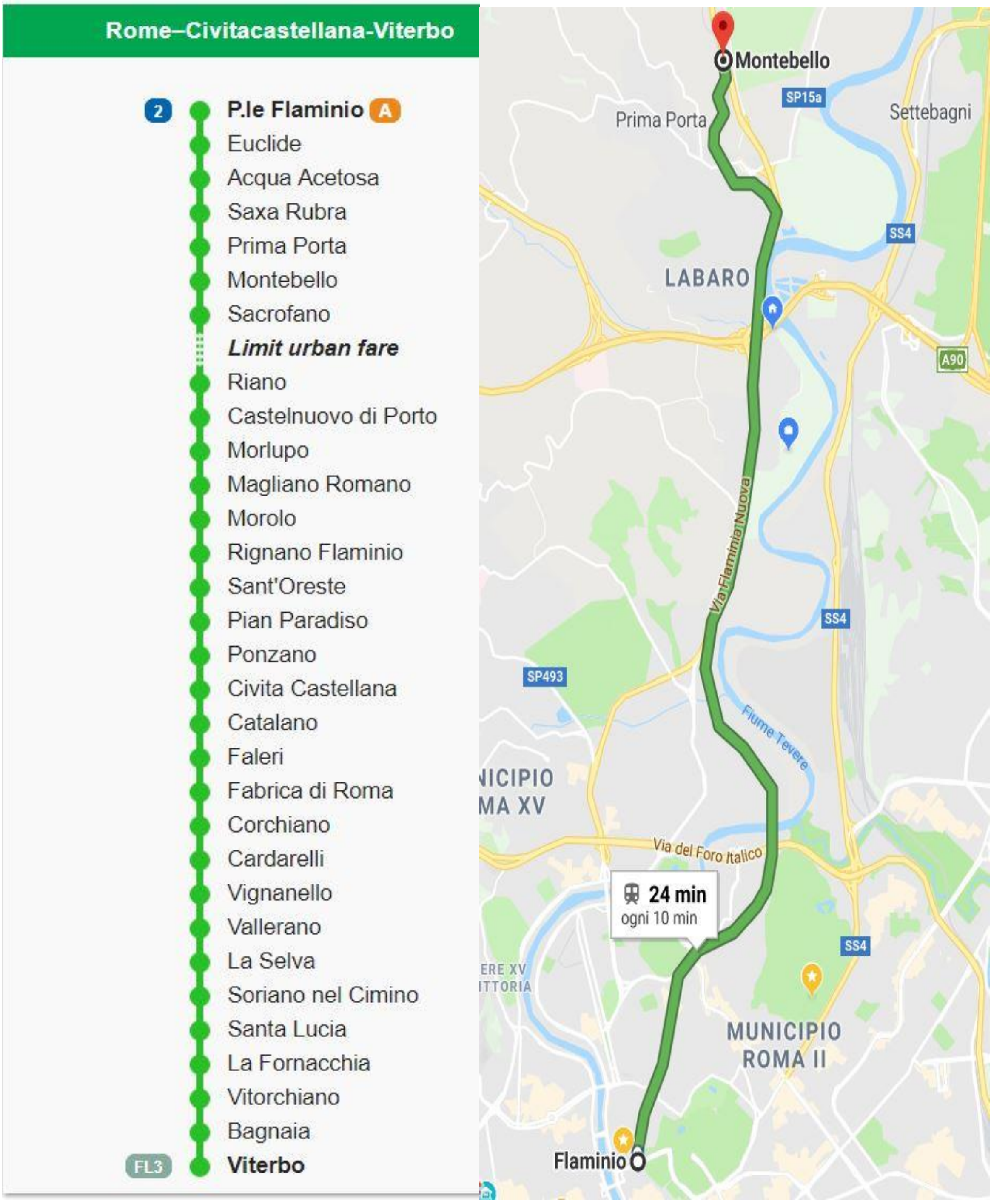


Fig.2.5: Map of the line

The total length of the metro is about 102 km but we consdire only the urban line which has total length of 18.4 km.

There are 31 stops which 7 are urban and 24 extra urban and it takes about 24 minutes approximately for the round trip. Currently the rolling stock used is Elettromotrice 310, terza generazione (Figure.2.6) by CostaRail and Alstom, the rolling stock is consisting of three car body with conventional running gear.

Fig.2.6: Elettromotrice 310, terza generazione

The following table (table1) shows the main characteristics relevant for the two subsequent applications.

Table 1-line input parameters

Number of stops	7
Total Length	18.4
Total round-trip time	24 min
Waiting time at each stop	30 s
Acceleration (assumption)	1 m/s^2
Deceleration (assumption)	1 m/s^2
Maximum Speed	90 km/h
"Representative distance" between each stop	1.5 km

2.4 MASS REDUCTION

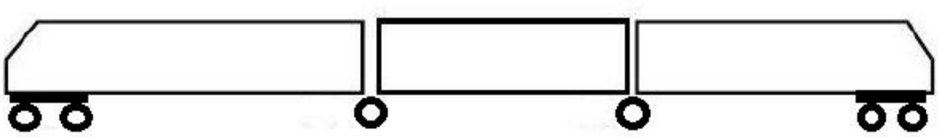


Fig.2.7: configuration of the train

As mentioned in the introduction of this thesis, a reduction of train mass is expected if a single-axle composite material configuration (Figure.2.7) and Three-piece frame (Figure.1.30) is adopted. A preliminary analysis has led to the identification of the following reasons:

1. lightweight materials;

2. wheel configuration requiring different frame;

3. lower bending moments due to vertical static loads in single-axle configuration;

4. lower curving forces in single axle-configuration.

In turn the mass reduction can lead to benefits in terms of wheel maintenance costs and energy consumption (see subsequent sections). In this section, a preliminary assessment is performed of the possible mass reduction due to the above causes.

For the calculation we assume a configuration of Three-piece frame (Figure.1.30) and the mass of single axel the half of the conventional one.

We have

A.1 = Running gear made of steel "conventional"

A.2 = Running gear made of compiste with Glass fibre

A.3 = Running gear made of compiste with Carbone fiber

A.4 = Running gear made of compiste with Kevlar fiber

Table 2

	Mass of conventional running gear				
	volume	A.1 mass [kg]	A.2 mass [kg]	A.3 mass [kg]	A.4 mass [kg]
Composite%	0,54	4.207,60	3.730,56	3.140,96	2.948,00
Steel%	0,10	792,40	792,40	792,40	792,40
Total	0,64	5.000,00	4.522,96	3.933,36	3.740,40
Reduction%		0	10%	21%	25%

Table 3

	Mass of train with 3 cars "conventional running gear"				
	volume	A.1 mass [kg]	A.2 mass [kg]	A.3 mass [kg]	A.4 mass [kg]
Composite%	0,54	4.207,60	3.730,56	3.140,96	2.948,00
Steel%	0,1	792,40	792,40	792,40	792,40
car body		30.000,00	30.000,00	30.000,00	30.000,00
Total		120.000,00	117.137,76	113.600,16	112.442,40
Reduction %		0	2%	5%	6%

Table 4

	Mass of train with 3 cars "single axel running gear"				
	volume	A.1 mass [kg]	A.2 mass [kg]	A.3 mass [kg]	A.4 mass [kg]
Composite%	0,54	4.207,60	3.730,56	3.140,96	2.948,00
Steel%	0,1	792,40	792,40	792,40	792,40
car body		30.000,00	30.000,00	30.000,00	30.000,00
Total		105.000,00	103.568,88	101.800,08	101.221,20
Reduction%		0	1%	3%	4%
Reduction compared to conventional running gear %		13%	14%	15%	16%

We have achieved a reduction of 16% with the configuration above (Figure.2.7) by using single axel with composite material Kevlar fiber, that is the best solution that we can have.

2.5 WHEEL MAINTENANCE COSTS

A significant part of maintenance costs in urban rail systems (metro, tram, light metro) is due to the wheel-rail wear. Wear rates are measured as depth of wear per kilometer run or per train passage depends in a complex manner on several influential factors [5] [6].

Among the most important are the key design factors of the rolling stock. When designing an urban rail system, all these factors must be under control to limit the costs due to wheel/rail re-profiling/grinding and replacement.

The process that determines the lifetime of the wheel is a superposition of running wear and removal of wheel due to re-profiling.

The wheel tread wears down relatively quickly with respect to the flange and so the diameter wear rate dominates

From the data available, I have listed out the useful input parameters for calculation of cost for wheel maintenance.

Table 5-line input parameters

Length of the line	18.4 km
Number of services/hours	4
Number of working hours for the line/day	18 hours/day
Number of working hours for the line/year	365 days

Table 6-Machinery and other input parameters

Cost of Machinery	5.000.000 €
Equipment depreciation	20 years
Number of re-profiling/hours	1
Cost of lathe operators/hour	100 €
Indirect costs (in percentage of direct costs)	0,5
Number of lathes working days	90 days
Working hours/day	8 hours/day

The formula used for calculating the costs in [Table 6]

- Cost of machinery/day = Cost of machinery (lathe)/Equipment depreciation/Number of lathe working days/working hours/day
- Cost of operators/day = Cost of lather operators/hour * working hours/day
- In direct cost = (Cost of machinery/day + Cost of operators/day) *Direct costs
- Total costs = Cost of machinery/day + Cost of operators/day+ Indirect costs
- Costs per re-profiling = Total costs / working hours per day.

Table 7 costs related to reprofiling

Cost of machinery/day	346,68 €
Cost of opertors/day	800 €
Indirect costs	1720,02 €
Total costs	2866,77 €

Table 8 cost of each reprofile

Cost for Re-profiling	358,33 €

[table 9] [table 10] shows the costs of reprofiling and renewal of the wheelset and the totale kilometers between reporofiles.

Here dry means without flange lubrication and lubricated means with flange lubrication.

Table 9-Cost analysis of renewals and reprofiles for wheel-sets

	Wheel-set	
	Dry	Lubricated
Kilometers between reprofiling	175.000	317.143
Total number of reprofiling	2,57	1,42
Total renewals per mission profile	0,161	0,089
Total cost of renewals/wheelset/year (€)	964,3 €/year	532,1 €/year
Total cost of reprofiles/wheelset/year (€)	921,4 €/year	508,5 €/year
TOTAL COST/VEHICLE/YEAR (€)	30171,6 €/year	16648,8 €/year

Table 10-Cost analysis of renewals and reprofiles for single axel (IRW)

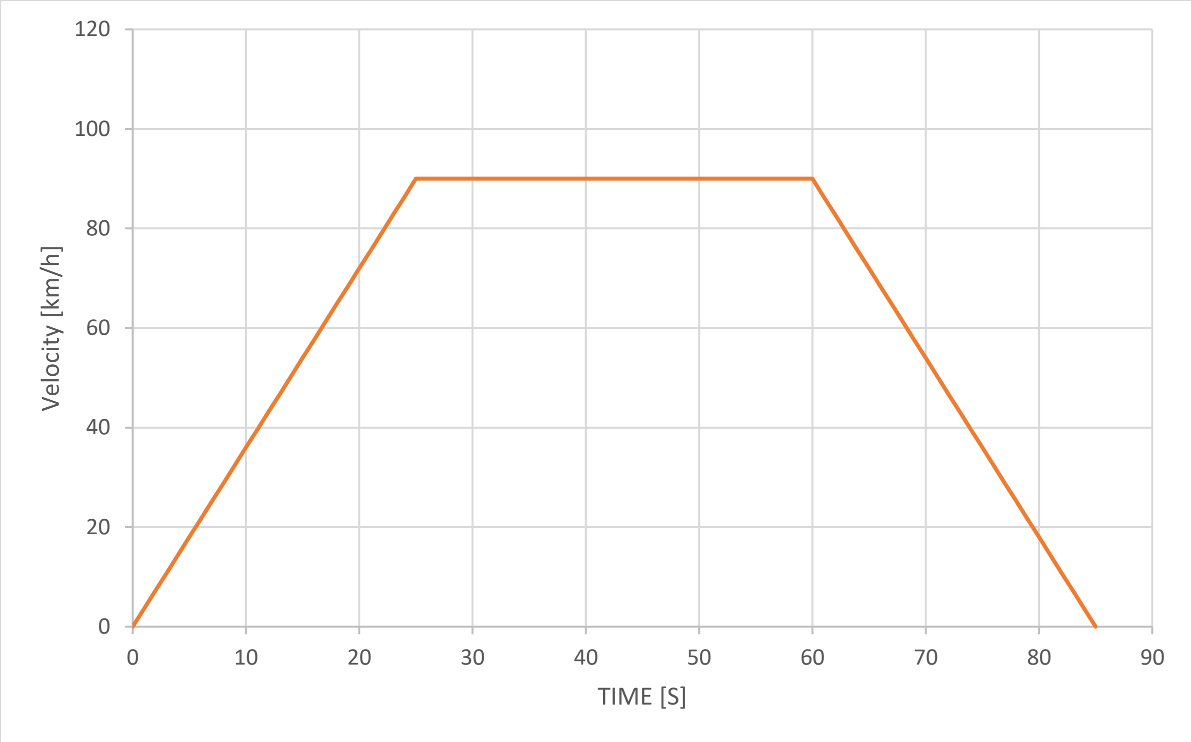
	Independently rotating wheels	
	Dry	Lubricated
Kilometers between reprofiling	46.667	33.000
Total number of reprofiles	9,64	1,36
Total renewals per mission profile	0,592	0,09
Total cost of renewals/wheelset/year (€)	3552,1	511,4 €/year
Total cost of reprofiles/wheelset/year (€)	3455,4	488,6 €/year
TOTAL COST /VEHICLE/YEAR (€)	112119,8	16000,11 €/year

As we can see through the above [Table 9] [Table 10], if we use independently rotating wheels (lubricated) we can reduce 3.9% of total cost /vehicle/year. This is the order of magnitude (at the very least) that we could expect from a modern mechatronic single-axle running gear.

2.6 Energy consumption

Graph 1 below indicates time speed for 1 stop using the single axel composite material with Kevlar fiber (solution A.4), also all cases is refer to the best solution A.4 for mass reduction (acceleration 1 m/s^2 and deceleration 1 m/s^2). The maximum speed considered is 90 km/h.

Considering table 11 to compare the hypothetical effect of energy scenarios by varying the mass of the train against the current case study. Here we have taken the trainset, with 3 conventional cars, with only one stop with 1.5 km (Representative distance).



Graph 1: time speed for 1 stop

Table 11-line characteristics & input parameters

line characteristics	symbol	unit	value
Distance between two station	L	km	1.5
Total number of stops	NS		7
Maximum velocity	V_{max}	km/h	90
Parameters			
coefficient a (specific resistance)	a		0,001
coefficient b	b	$1/(km/h)^2$	0,00000028
coefficient of rotating masses	beta		0,07
mass of passengers	m_{pax}	T	21.1
auxiliary power	P_{aux}	KW	15
performance efficiency	eta		0,9
Acceleration	acc	m/s^2	1
deceleration	dec	m/s^2	1

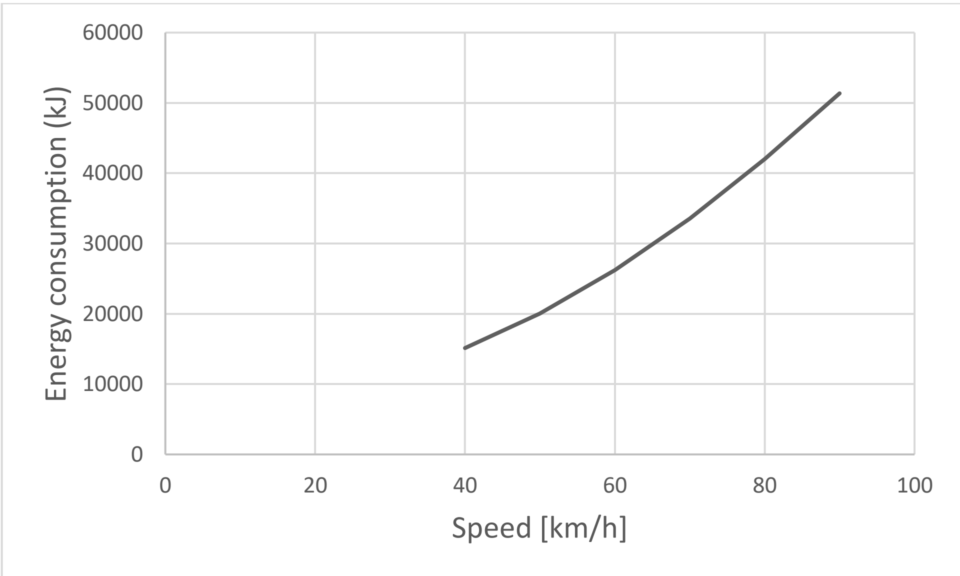
The maximum weight of the passengers (100% occupancy rate) is 63.6 t (each car can be loaded 21.2 t).

Table 12-Energy calculation for single axel trainset with 3 carbody

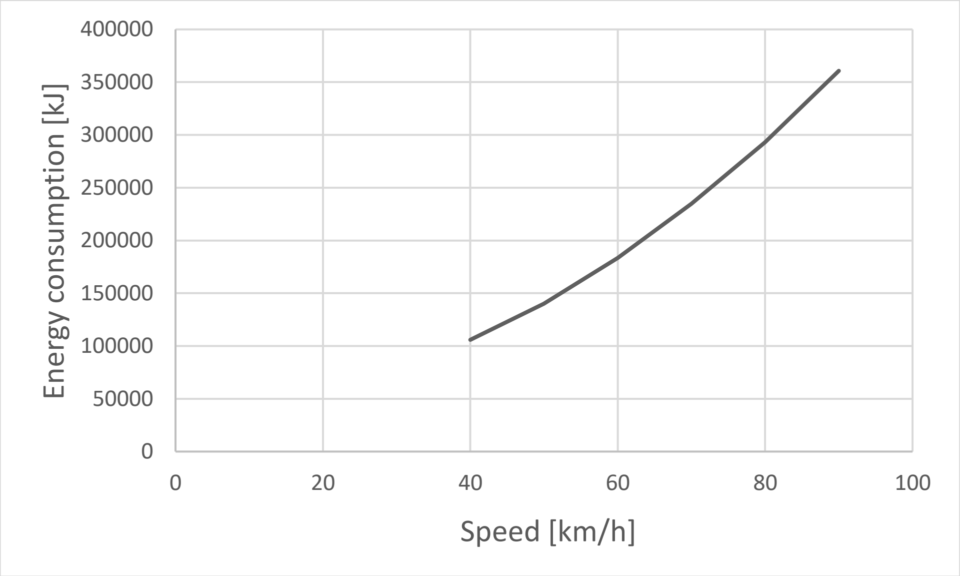
Case	A.1	A.2	A.3	A.4
Energy calculation at starting [kJ]	46.774	46.449	46.048	45.917
Energy calculation at constant speed [kJ]	3.965	3.938	3.905	3.894
Energy for auxiliary [kJ]	1.725	1.725	1.725	1.725
Total energy consumption [kJ]	52.465	52.113	51.678	51.536

CASE 1: ENERGY CONSUMPTION WITH VARYING SPEED

In this case we are analyzing the energy consumption with speed variation. Here the energy is calculated with full load for one stop.



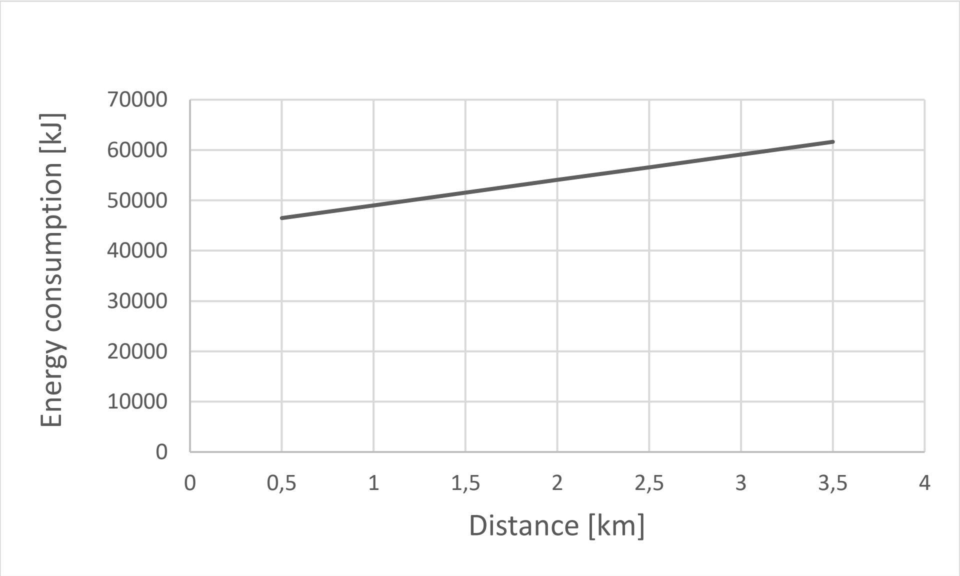
Graph 2: speed versus Energy for 1 stop



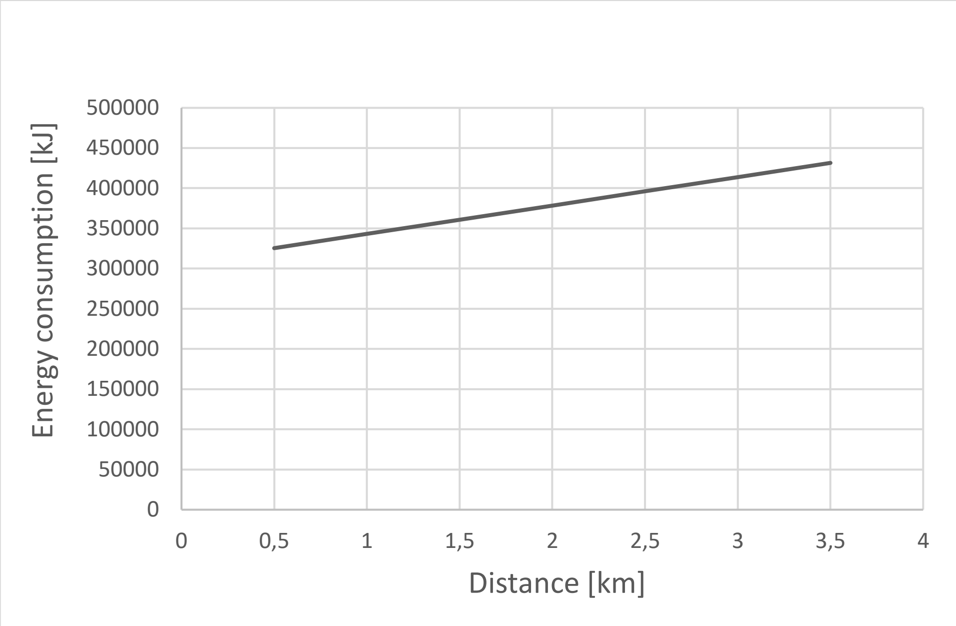
Graph 3: speed versus Energy for 7 stops

CASE 2: ENERGY CONSUMPTION WITH DISTANCE

In the following, the variation of energy consumption with distance is analyzed.



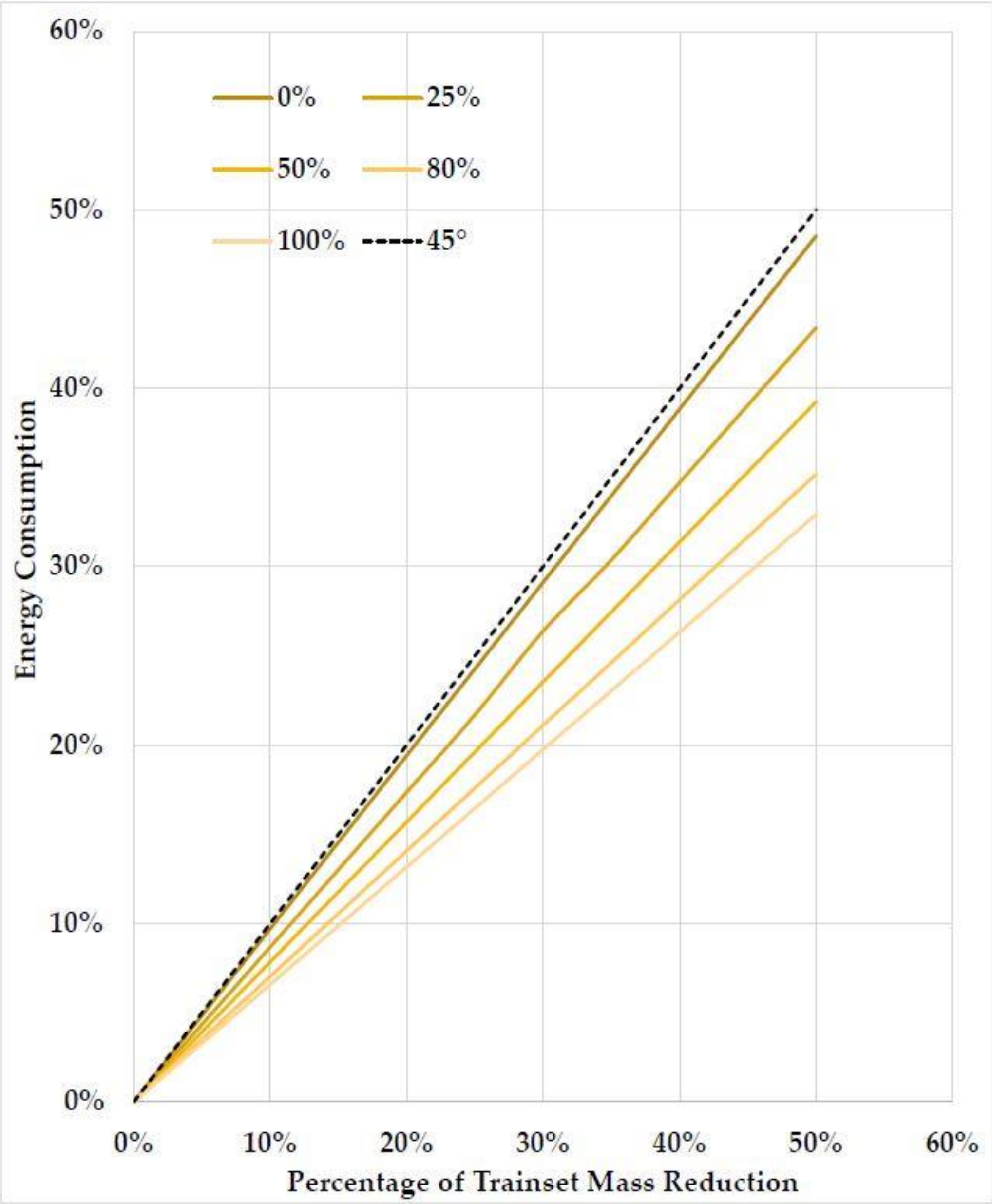
Graph 4: Energy versus distance for 1 stop



Graph 5: Energy versus distance for 7 stops

CASE 3: ENERGY CONSUMPTION WITH PASSENGER OCCUPANCY RATE

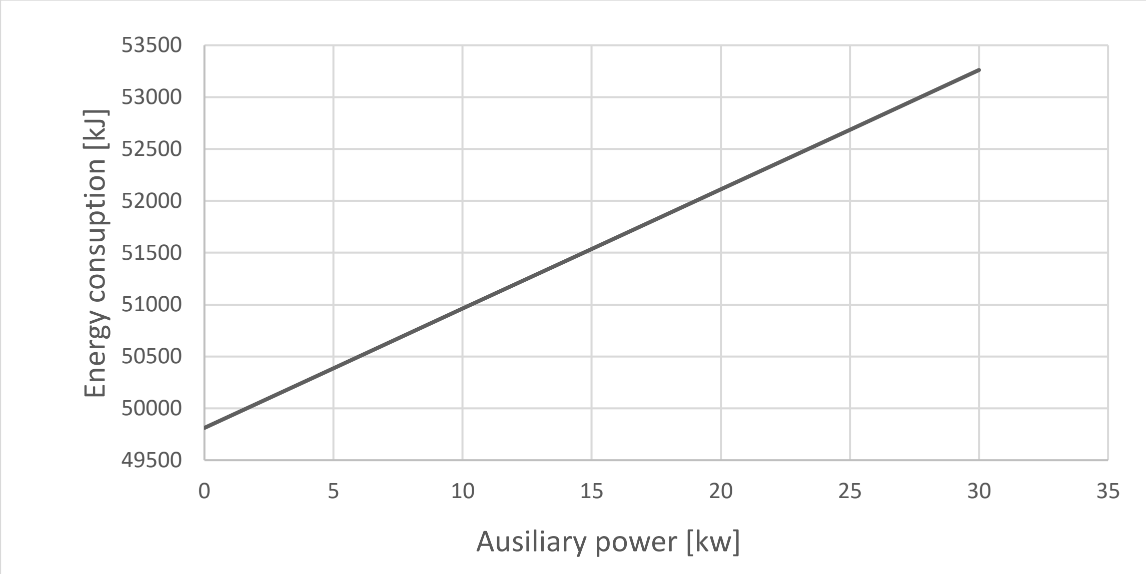
In here we can see how the payload effects the energy consumption and, we can see the approximate percentage of mass reduction and energy consumption reduction.



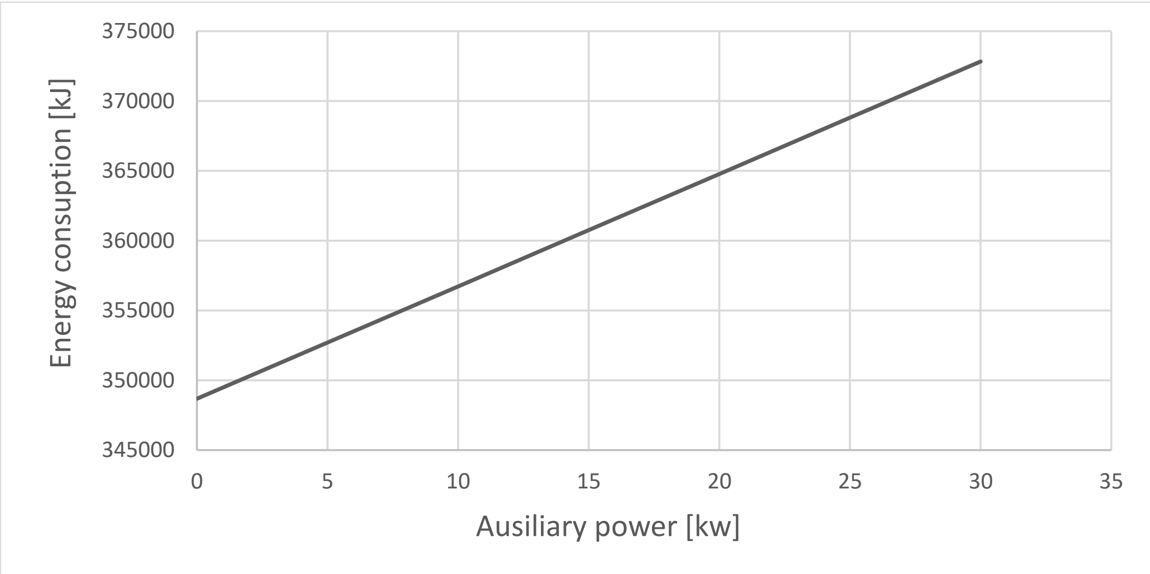
Graph 6: Energy consumption reduction with passenger occupancy rate and mass reduction

CASE 4: ENERGY CONSUMPTION WITH AUXILIARY POWER

In our reference case we assumed the average auxiliary power as 15 kW.



Graph 7: Auxiliary power vs Energy consumption for 1 stop



Graph 8: Auxiliary power vs energy consumption for 7 stops

3 RELEVANT REGULATION AND STANDARDIZATION DOCUMENTS

3.1 IMPORTANCE OF REGULATION AND STANDARDIZATION DOCUMENTS

Standards provide people and organizations with a basis for mutual understanding, and are used as tools to facilitate communication, measurement, commerce and manufacturing [7].

Standards are everywhere and play a key role in the economy, by:

- Facilitating business interaction;
- Enabling companies to comply with relevant laws and regulations;
- Speeding up the introduction of innovative products to market;
- Providing interoperability between new and existing products, services and processes.

Standards form the basis for the introduction of modern technologies and innovations, and ensure that products, components and services supplied by different companies will be mutually compatible. However, they can also introduce barriers to innovation.

In Europe, regulatory documents fall into a broad scope of rail-related legislation, made up of Directives and Regulations, and so-called Technical Specifications for Interoperability.

In the following, an analysis of the most relevant standardization documents is presented, following the order of the topics described in the Shift2Rail Programme.

3.2 CONDITION MONITORING / HEALTH MONITORING

In all industrial fields excessive costs are related to maintenance activities. The excessive costs are related to the loss of productivity due to a poor availability of assets regularly maintained. That is why there are research efforts dedicated to improving condition monitoring/health monitoring as a basis for predictive maintenance.

For the rail sector no standards were found for condition monitoring/ health monitoring. General standardization efforts in the United Stated on the other hand, regards integrated system maintenance and goes along with:

- a standard for an easy transduction interface for sensors and actuators (IEEE 1451);
- a proposal of standardization for the architecture of condition-monitoring systems (OSA-CBM);
- a proposal of standardization for the communication between different condition-monitoring systems (MIMOSA)

A. ISEE (1451)

Due to the problems encountered by users during the activities of products integration (transducer, sensors and actuators) of different vendors and their network connection, it is necessary to adopt a standard for the hardware and software interconnection level, to obtain the interoperability in the exchange and in the use of information.

To develop a standard interface for intelligent sensors, the National Institute of Standards and Technology (NIST), in cooperation with the Institute of Electrical and Electronics Engineers (IEEE), has started to work on this objective since the mid 90's. This purpose is subsequently becoming the standard IEEE 1451, which aims to achieve common interfaces to connect transducers towards systems based on microprocessors and towards tools and field networks, avoiding that the operation related to a network node (insertion/deletion) can influence the behavior of the other nodes.

B. OSA-CBM

OSA-CBM is the acronym of Open System Architecture for Condition Based Maintenance.

The mission of OSA-CBM organization states that the standard proposal should cover the entire range of functions of a condition-based maintenance system, both for hardware and software components. The proposed Condition-Based Maintenance System is divided into seven levels (figure.3.1).

Level 1 Sensor Module: It provides sensors that return digitalized results or transducers that return data. Signal module could be built following the standard IEEE 1451.

Level 2 Signal Processing: The module receives signals and data from the sensor module or other modules of signal processing. The output of signal processing module includes sensor-data digitally filtered, frequency spectrum, signals of virtual sensor. The signal processing module may consist of an AI-ESTATE, as reported in IEEE 1232 standard.

Level 3 Condition Monitor: The condition-monitor level receives data from sensor modules, signal processing modules and other condition-monitor modules. The main goal of this level is to compare data with their expected values. The condition-monitor level shall be also able to generate alerts based on operational limits previously set. This latter can be a very useful function during development of rapid failures.

Level 4 Health Monitoring: The module devoted to the assessment of the “status of health” receives data from different condition-monitor modules or other modules of assessment of the system conditions. The main goal of the condition assessment module is to determine if the condition of the monitored component/subsystem/system is degraded. The evaluation module shall be able to generate diagnostic recordings and propose failure estimation. The diagnosis shall be based on trends of the health status history, on operating status, workload and maintenance history.

Level 5 Prognostics: The prognostic module shall be able to consider data from all the previous levels. The main goal of the prognostic module is to compute the future health status of an asset, considering its future profile of usage. The module will report the future health status at a specified time or, alternatively, the remaining useful lifetime.

Level 6 Decision Support: The decision support module receives data from the module of health status evaluation and the prognostic module. Its main goal is to generate the recommended actions and the alternatives ones. Actions may be of maintenance type but also related to how to run an asset until the current mission is completed without the occurrence of breakage.

Level 7 Presentation: The presentation module must show the data coming from all the previous modules. The most important levels of which present the data are those related to Health Assessment, Prognostic and Decision Support, as well as the alarms generated by the condition-monitor modules. The presentation module can also can look further downwards and can be inserted also into a machine-interface.

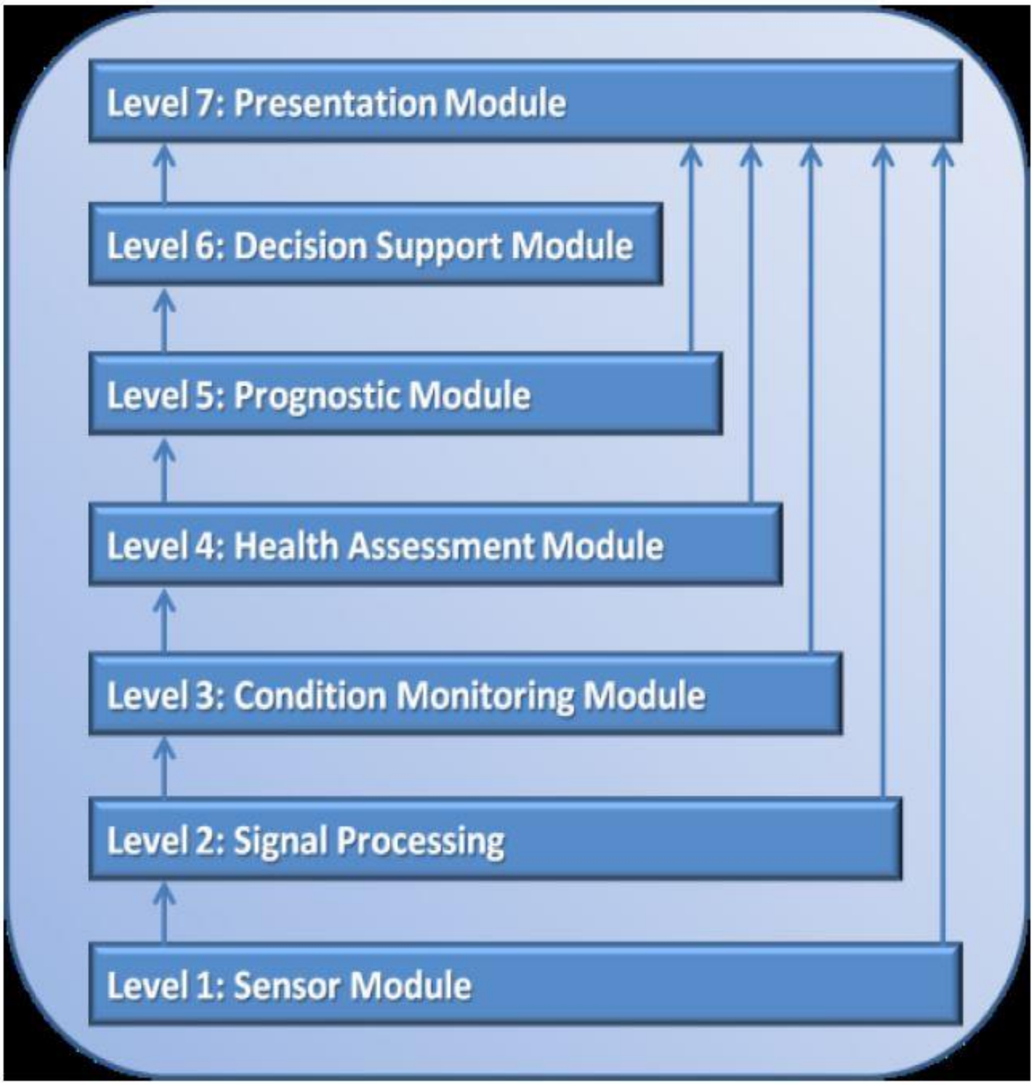


Fig.3.1: OSA-CBM Architecture

3.3 Materials and manufacturing processes

There are several standards for using the varied materials and different manufacturing processes. Here are some of the standards:

- **prEn-17084:** This standard specifies the toxicity test on materials and components of railway vehicles [13].
- **EN 45545:** The protection of passengers and staff is essentially based on measures to: - prevent fires occurring due to technical faults and due to equipment design or vehicle layout [14].
- **EN 50125:** This European Standard intends to define environmental conditions within Europe. The scope of this European Standard covers the definitions and ranges of the following parameters: Altitude, temperature, humidity, air movement, rain, snow and hail, ice, solar radiation, lightning, pollution for rolling stock and on-board equipment (mechanical, electromechanical, electrical, electronic). This European Standard defines interface conditions between the vehicle and its environment. The defined environmental conditions are considered as normal in service [15].
- **EN 16452:2015:** This European Standard gives the requirements for the design, dimensions, performance, and testing of a brake block (otherwise known as brake shoe insert) that acts on the wheel tread as part of a tread brake system. This European Standard contains the requirements for interfacing the brake block with the rail vehicle, the testing procedures to confirm that it satisfies the basic safety and technical interchangeability requirements, the material control procedures to ensure product quality, reliability and conformity and considers health and environmental needs [16].
- **EN 15085-1:2007+A1:2013:** This series of standards applies to welding of metallic materials in the manufacture and maintenance of railway vehicles and their parts. With respect to the railway environment, this series of standards defines the certification and quality requirements for the welding manufacturer to undertake new building and repair work. It then provides

an essential link between performance requirements defined during design, and achieves appropriate quality welds during production and the demonstration of the required quality by inspection. This link is achieved by defining a weld performance class during design, which is based on safety and stress factors relevant to railway operation [17].

- **EN-50155:** This European Standard applies to all electronic equipment for control, regulation, protection, diagnostic, energy supply, etc. installed on rail vehicles. For this European Standard, electronic equipment is defined as equipment mainly composed of semiconductor devices and recognized associated components. These components will mainly be mounted on printed boards. This European Standard covers the conditions of operation, design requirements, documentation, and testing of electronic equipment, as well as basic hardware and software requirements considered necessary for compliant and reliable equipment [18].

- **EN 13261:2009+A1:2010**: This European Standard specifies the characteristics of axles for use on European networks. It defines characteristics of forged or rolled solid and hollow axles, made from vacuum-degassed steel grade EA1N1 that is the most commonly used grade on European networks. For hollow axles, this standard applies only to those that are manufactured by machining of a hole in a forged or rolled solid axle in addition, the characteristics for axles in grade EA1T1 and EA4T1 are given in Annex A. Two categories of axle are defined, category 1 and category 2. Generally, category 1 is chosen when the operational speed is higher than 200 km/h. This standard is applicable to axles that are designed in accordance with the requirements of EN 13103 and EN 13104. NOTE Different values for some characteristics may be agreed if a process of fabrication (e.g. cold rolling, shot peening, shot peening, steel cleanliness, reduction ratio, improved material properties from melting and heat treatment processes, etc.) has an influence on them [19].

- **EN 12663:** This European Standard specifies minimum structural requirements for freight wagon bodies and associated specific equipment such as: roof, side and end walls, door, stanchion, fasteners and attachments. It defines also specific requirements for the freight wagon bodies when the wagon is equipped with crashworthy buffers. It defines the loads sustained by vehicle bodies and specific equipment, gives material data, identifies its use and presents principles and methods to be used for design validation by analysis and testing. For this design validation, two methods are given: - one based on loadings, tests and criteria based upon methods used previously by the UIC rules and applicable only for car bodies made of steel; - one based on the method of design and assessment of vehicles bodies given in EN 12663-1. For this method, the load conditions to be applied to freight wagons are given in this European Standard [20].

The standard also enables the demonstration of compliance against the target test conditions for the case that their combination is not achievable during tests.

4 MAIN CONCLUSIONS

In the past the realization of a single axe fails because of:

1. a lack of practicable sensors
2. an adequate control algorithm
3. the costs for the high number of converts and motors

some study show that the new running gear can offer a better running performance than a conventional running gear under all operation condition in combination with a low maintenance effort. Because of less friction at curves a lower emission level of the ground and the air as well as a lower need for traction is expected.

This thesis has focused also on the potential of reducing mass of the running gear and energy consumption with composite material “light-weight” with single axel and by using those materials there will be reduction in the overall costs of the train, infrastructure, rolling stock and the energy. To justify this, it needs in-depth research. The result of this work is a demonstration of the energy consumption reduction with mass reduction (percentage).

Under the assumptions of this study, energy consumption reduction values can approach the trainset mass reduction values – e.g. if a reasonably achievable mass reduction is 16% as assumed, then almost 10% energy consumption reduction could theoretically be obtained, by far the most significant contribution to energy consumption is the traction phase. However, this is also due to the assumption of no power limitation, which would need to be removed through further analysis.

In real conditions the payload will of course usually be variable and relatively high Therefore the expectable energy reductions lie closer to 15% without payload. In fact, the same trainset mass reduction has a lower overall effect due to the presence of the payload, i.e. the overall mass reduction (trainset + payload) is lower the higher the payload.

In this case study analyzed, the most influential variables on energy consumption, apart from mass, proved to be maximum speed and braking deceleration.

Acceleration during traction did not show much influence, because a lower acceleration means a longer time without an appreciable variation in required traction.

Regarding wheel maintenance the preliminary analysis has shown that reductions of annual wheel maintenance costs could be reduced by at least a few percentage points.

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ACRONYMS AND ABBREVIATIONS

AI-ESTATE	*Artificial Intelligence and Expert System Tie to Automatic Test Equipment*
BAB	*Bogie Acquisition Box*
CAF	*Construcciones y Auxiliar de Ferrocarriles*
CEIT	*Centro de Estudios e Investigaciones Técnicas de Gipuzkoa*
CMS	*Condition Monitoring System*
CRIS	*Common Relation Information Schema*
CS	*Control Station*
DB	*Deutsche Bahn*
DLR	*German Aerospace Centre*
DSS	*Decision Support System*
ERRI	*European Rail Research Institute*
ERTMS	*European Railway Traffic Management System*
IEEE	*Institute of Electrical and Electronics Engineers*
INTEC GmbH	*INTEC Energy Systems*
IPDSS	*Intelligent Predictive Decision Support System*
KERF	*Kurvengesteuerte Einzelradsatz-Fahrwerke*
LCC	*Life Cycle Cost*
LRT	*Light Rail Transit*
MIMOSA	*Machinery Information Management Open System Alliance*
MTBF	*Mean Time Between Failure*

NIST	*National Institute of Standards and Technology*
OSA-CBM	*Open System Architecture for Condition Based Maintenance*
PS	*Power Source*
RUL	*Remaining Useful Life*
SN	*Suspension*
UIC	*International Union of Railways*
ULF	*Ultra-Low Floor*
UPS	*Uninterruptible Power Supply*
VMB	*Vehicle Monitoring Box*