Impacts of innovative running gear for trains: focus on energy consumption and wheel set maintenance.

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Abstract

Several past and on-going research projects have explored the possible technical developments for future running gear, considering ways to design trains that are more reliable, lighter, less damaging to the track, more comfortable and less noisy. This thesis intends to show how two possible innovations in running gear – with a focus on a metro application— impact on wheel-set maintenance and energy consumption. Now-a-days metros are mostly using two axle bogies made of steel and the efforts required to meet the demands on the reduction of negative economic, social and environmental impacts of rail system operations, to make it an even safer and greener transport mode are increasing day by day. So, if it were possible to replace the conventional bogie frame with a lighter frame or more radically, to do away with the bogie itself and return to simple single-axle configurations thanks to the progress in mechatronics, it should be possible to reduce weight considerably and thus consume less energy.

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Summary

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Chapter 1. **Introduction**

1.1 State of the art

The use of single axle configurations (Figure 2) is increasing for the new generation of rail vehicles in these days [1] . In Europe there are many commercial uses of the single axle configurations for LRT, commuter trains and high-speed applications.

[*Figure 1Figure 2*]

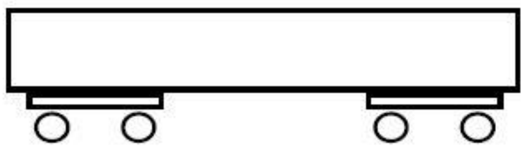


Figure 1 Conventional 2-bogie vehicle

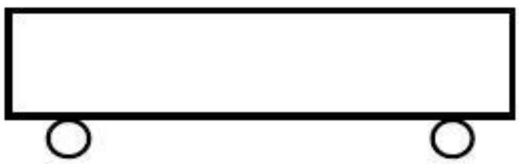


Figure 2 Single axle vehicle

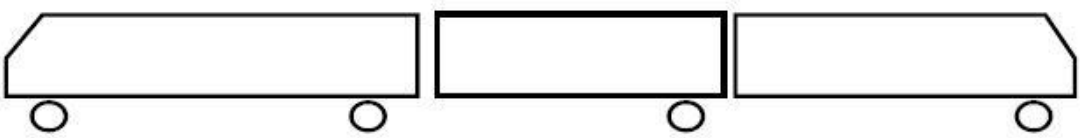


Figure 3 Another example of single-axle configuration

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 [1]. The short body enables a wider body because the amount

[Figure 5 Copenhagen S train] of over-hang. 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.[1]

As for any railway vehicle, historically the problems with single-axle configurations occur mainly in sharp curve negotiation such as lateral force. squeal noise and excessive wear of wheel flange and rail gauge corner.

Metro lines have many sharp and transition curves of small cant because of restrictions on the route plan, and as a result, problems occur at curves.

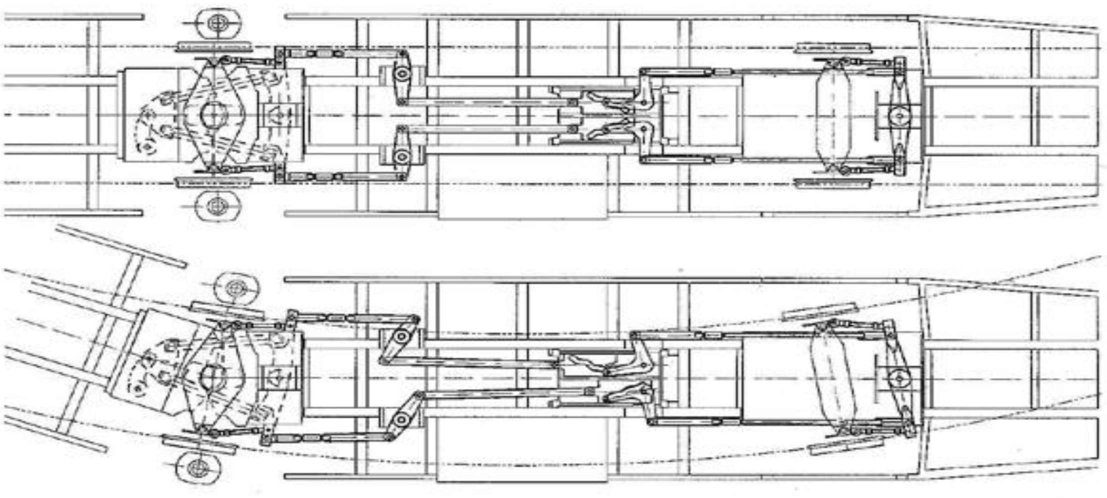


Figure 4 Top view of ULF tram's end-car

To solve these problems, improvement in axle box primary suspension and pneumatic spring systems, friction modifiers, and other measures have been studied, developed and put into practice. One possibility is the optimization of wheel set orientation to reduce wear and noise. In the 1990s this problem was addressed by means of curve-steered bogies with self-steering wheel set

[*Figure 5*]

Another application of Ultra-Low-Floor tram is in [***Figure 4***]. The mechanical complexity of the linkages in such solutions is easy to observe.

Figure 5 Copenhagen S train

Figure 6 High-speed train with bogie type locomotives and single-axle coaches

1.2 Foreseeable innovations in running gear

The running-gear of most railway vehicles, and particularly the metro-type vehicles addressed in this thesis, is made up of rigid wheel-sets that are coupled by means of a frame to make up a bogie, allowing two stages of suspension for the car body.

Bogie systems deliver a balance between reliability, comfort and performance, whilst ensuring safety. The scope for improvements in performance and reduction in wear and damage to the vehicle/ track interface using conventional systems is providing to be small without compromising safety and comfort. The next generation of bogie solution needs to deliver reduced infrastructure / wheel wear and damage, whilst providing higher reliability and availability, with lower maintenance costs.

More dramatic improvements may be obtained through single-axle configurations, if most is made from the advanced state of the art in mechatronics. [ANNEX 2. The mechatronic train]

The research Programme Shift2Rail [2] testifies the importance of the above two possibilities by funding research on innovative running gear. The main expected developments are

1. new sensor and health monitoring architectures and functionality to monitor both bogie and track;
2. light weight and LCC-optimized materials validated and certified for the bogie environment;
3. improved use of the actuator technology to control bogies and wheel sets or wheels according to the running gear configuration.

In this thesis, point 1 is described, whereas points 2 and 3, are addressed, more in detail, in consideration of the possibility of solution, revisiting in a modern context the concept of a single-axle, single stage suspension configuration thanks to the progress in mechatronics.

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. A non-exhaustive list of past projects is given in the following table emerging from an analysis of reference [2] is given in the following table,

Project	Input
MECHATRONIC (1998 – 2001)	Mechatronic technologies for running gear (steering, suspension)
REFRESCO (2013-2016)	Regulatory framework for the use of new structural materials in railway car bodies
EURAXLES (2010-2014)	New design approach for railway wheelsets
DYNOTRAIN (2009-2013)	Virtual certification methods of dynamic performance of railway vehicles
ACOUTRAIN (2011-2014)	Virtual certification methods of acoustic performance of railway vehicles
MODTRAIN (2004-2008)	high speed market with a set of specifications that allow for better inter-changeability of key components for maintenance
INNOTRACK (2010-2013)	innovative methodology for Life Cycle Cost calculation and Reliability Availability Maintainability Safety (RAMS)
ROLL2RAIL (2015-2017)	guidance for selection of technologies with strongest contribution to the S2R overall targets

Table 1 Funded projects which have contributed to the development of running gear

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, considering ways to design trains that are more reliable, lighter, less damaging to the track, more comfortable and less noisy. Moreover, the project is looking at other sectors to gain expertise and to be able to transfer innovative solutions for the running gears of the future. In its workplan, both conventional and single-axle configurations are considered.

1.3 Objectives of this thesis

With due consideration of the RUN2Rail project, this thesis examines a case study with:

a single-axle vehicle with lightweight material, active suspension/ steering, and considering the possibilities of benefiting the condition monitoring advancements (active suspension sensors used for condition monitoring, structural integrity monitoring of light-weight materials used).

In practical terms, as a case study, single-axle train-set is hypothesized for operation on line 9B of metro Madrid. 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 possible;

2) to quantify the corresponding energy consumption reduction on a hypothetical line, with the same length as line 9B, but distance between stops constant and equal to the average distance on line 9B;

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, like that running on that line 9B as a benchmark.

1.4 Methodology

The steps followed in this study were the following

1. Analysis of existing relevant commercial solutions, the technical literature (introduction in Chapter 1) and the relevant standards (Chapter 2);

2. Quantifications of key impacts for the case study (Chapter 3).

The current solutions analyzed for reducing the mass is using light-weight materials such as Carbon-Fibre Reinforced Polymers/Plastics(CFRP) 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.

Chapter 2. **Relevant regulation and standardization documents**

2.1 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**.

Standards are everywhere and play a key role in the economy, by:[9]

- 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.

2.2 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 (ANNEX 3. Maintenance Approaches).

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.[21]

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 7].

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[3].

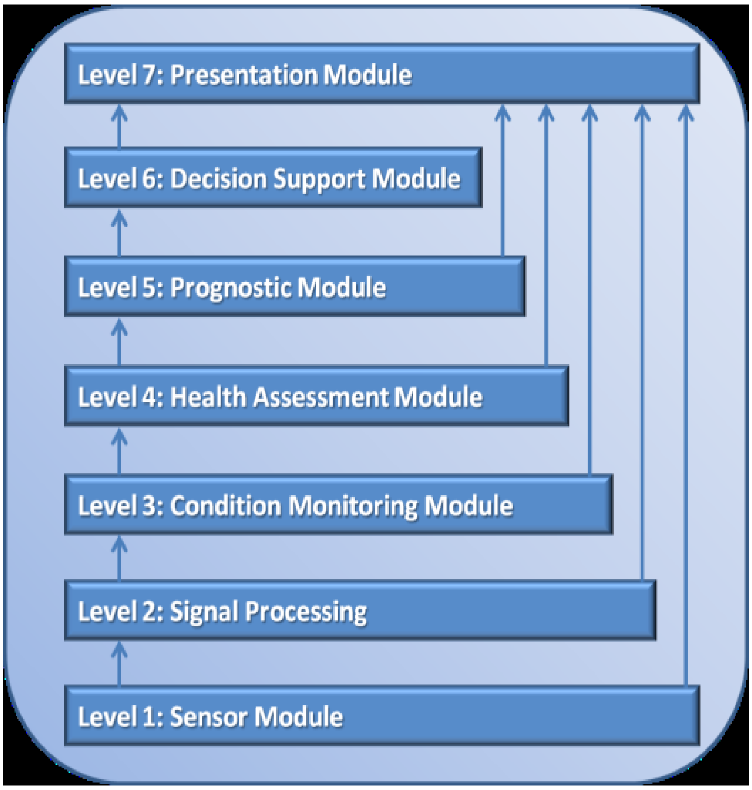


Figure 7 OSA-CBM Architecture

2.3 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.[10]
- **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.[11]
- **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.[12]

- **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.[13]
- **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.[14]
- **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.[15]
- **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.[16]

- **EN 15827:2011: T**his European Standard consolidates all the separate requirements specified in rolling stock TSIs and European Standards relating to bogies and running gear together into an overall requirement and process that ensures a functional and safe design is achieved for a defined operating envelope. The objective of this standard is to bring all these separate design criteria together.[15]
- **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 [17].

- **EN 13749:2011:** This European Standard specifies the method to be followed to achieve a satisfactory design of bogie frames and includes design procedures, assessment methods, verification and manufacturing quality requirements. It is limited to the structural requirements of bogie frames including bolsters and axle box housings. For this European Standard, these terms are taken to include all functional attachments, e.g. damper brackets.[31]

- **EN 14200:2004:** This European Standard applies to parabolic springs as spring elements for rail vehicles. This European Standard is a guide to the following subjects: - design; - specification of technical and qualitative requirements; - approval procedures and quality assurance of production methods; - tests and inspections to be carried out; delivery conditions.[32]
- **prEN 16910-1:** This European Standard provides the specific requirements for NDT of wheelsets for: - in-service maintenance; - off-vehicle maintenance; - NDT personnel; - NDT documentation (Procedure and Instruction); - traceability of the maintenance NDT results. It gives guidance for the introduction of new NDT techniques. For this standard, the following NDT methods are considered: - Ultrasonic testing (UT); - Magnetic particle testing (MT); - Eddy Current testing (ET). Examples of common NDT indications are given in an informative annex. Other methods considered in EN ISO 9712:2012 are outside the scope of this standard. For this purpose, a catalogue of the common defects is given as guidance. Specific NDT requirements relating to the quality of new products delivered by manufacturers are not within the scope of this European Standard.[33]
- **EN 14363:2016:** This European Standard defines the process for assessment of the running characteristics of railway vehicles for the European network of standard gauge tracks (nominally 1 435 mm). In addition to the assessment of

the running characteristics of vehicles for acceptance processes, the standard also defines quantities and dependencies that are not directly used for acceptance purposes.

The standard also enables the demonstration of compliance against the target test conditions for the case that their combination is not achievable during tests. [20]

2.4 Active suspension and steering

The main relevant standard for this aspect is EN-14363-2016.

Its objective is to quantify the vehicle's performance under known representative conditions of operation and infrastructure.

The vehicle performance is assessed in two stages. Usually in the first stage the basic characteristics and low speed behavior are investigated before first runs on the line under controlled operating conditions. In the second stage the running behavior is assessed. The assessment of a vehicle according to the elements listed above can be performed either by physical testing, simulation resp. calculation or comparison with a known solution (dispensation).

The standard describes methods to assess the vehicle performance in the following areas:

- safety against derailment on twisted track
- running safety under longitudinal comprehensive forces in s-shaped curves
- evaluation of the torsional coefficient
- assessment evaluation of the flexibility coefficient
- loading of the diverging branch of a switch
- running safety in curved crossings
- running safety, track loading and ride characteristics

The longitudinal forces within trains have the potential to increase the risk of derailment when negotiating S-shaped curves. For conventional trains (except for freight) this risk is regarded as low. However, this risk should be considered when non-conventional configurations are developed.

If the standards are approved early then there will be no chance or innovation for the technology or creativity.

If the standard is approved late then the train companies make their own trains which effects interoperability.

So, the standard must be approved or executed at a right time which will allow innovation and business for the companies, manufacturers.

The following aspects regarding fault modes are relevant for active suspensions they are taken directly from the standard

The criticality of the fault modes (the combination of probability and consequence) must be analyzed. If the criticality of a fault mode, considering mitigation measures (e. g. monitoring, inspection, etc.), constitutes a risk higher than broadly acceptable, running safety shall be demonstrated by tests, simulation or a combination of both. The extent of the test procedure and/or the simulation cases shall be defined by reference to the analysis.[20]

Possible fault modes to be considered include but are not limited to active suspension systems, tilt systems, air suspension, yaw dampers.

Unless the analysis indicates a need for it (e. g. physical coupling), no superposition of different fault modes needs to be considered.

For the fault modes it is sufficient to assess the criteria of running safety up to maximum speed (V_{adm}) and maximum cant deficiency (I_{adm}).

If there is a low probability of occurrence of the considered fault mode based on the results of the analysis, the safety margin included in the limit values of the assessment quantities may be reduced supported by justification. It can use specific limit values depending on the type of the fault mode characteristics

And their effects. The limit values shall be agreed prior to testing.

If safe behavior cannot be demonstrated for a relevant fault mode, control measures to reduce the criticality of the fault mode must be defined to allow safe operation.
It shall also be determined whether the partially occupied or partially loaded vehicle with unsymmetrical load distribution is the most unfavorable condition. If a partial load condition is found to be unfavorable, this condition shall be included in the assessment.
The on-track tests must be completed by tests in fault modes where appropriate.
The extent of these tests must be defined after an analysis of the critical conditions.
Vehicles that are tested on high-speed lines with $V_{adm} \geq 250$ km/h must be tested additionally in test zone 1 and test zone 2 for a V_{adm} chosen in the range from 160 km/h to 230 km/h.

Chapter 3. Impacts of innovative single-axle running gear for a metro application

3.1 Reference case: Metro Madrid series 8400 running on line 9B

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

Line 9 of the Metro Madrid opened on 31 January 1980 between Sainz de Baranda and Pavones. Later it was extended from Avenida de América to Herrera Oria on 3 June 1983, however this section was separate from the original part until the missing fragment from Avenida de América to Sainz de Baranda was opened on 24 February 1986. On 1 December 1998, the line was extended from Pavones to Puerta de Arganda.

Figure 8 Metro Madrid Line 9B route

At Puerta de Arganda, an island platform was built, so passengers who required to use line 9B could do so by just crossing to the other side. Line 9B runs through mostly unpopulated areas connecting the three towns of Rivas, La Poveda and Arganda. The line runs with only two or three car trains at long intervals through very scenic landscape of Spanish desert [Figure 9]Rivas Urbanizaciones and Arganda del Rey are underground stations with large island platforms, and Rivas Futura, Rivas Vaciamadrid and La Poveda are surface stations with side platforms. There are many plans of Line 9. Between Puerta de Arganda and Rivas Urbanizaciones, there are three stations currently planned but without date stated.

Figure 9 Satellite Image of Metro Line 9B

The total length of the Metro is about 20 km and one of the depots is shared with line 9a. There are 6 stops for line 9B and it takes about 40 minutes approximately for the round trip.

Currently the rolling stock used is of S6000 (Figure 10) and it almost has same features of Series 8400.

Figure 10 Metro Madrid S6000 train-set

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

Table 2 Parameters Considered

Number of stops	6
Total Length	20 Km
Total round-trip time	41 Minutes
Waiting time at each stop	30 Seconds
Acceleration (assumption)	1 m/s^2
Deceleration (assumption)	0.6 m/s^2
Maximum Speed	110 Km/h
"Representative distance" between each stop	3.33 Km

3.2 Mass reduction

As mentioned in the introduction of this thesis, a reduction of train mass is expected if a single-axle configuration 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. From the literature (e.g. UIC) possible values of around 30% in metro/suburban cases are reported.

3.3 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.

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 of metro Madrid Series 8400, I have listed out the useful input parameters for calculation of cost for wheel maintenance.

Table 3 Line Input Parameters

Length on Line 9B	20 kilometers
Number of Services/hour	4
Number of working hours for the line/day	18 hours/day
Number of working hours for the line/year	365 days
Total Number of Kilometers/year	450000 km

Table 4 Machinery and other Input Parameters

Cost of Machinery(Lathe)	5000000€
Equipment depreciation	20 years
Number of re-profiling /hour	1
Cost of lathe operators/hour	100€
Indirect costs (in percentage of direct costs)	0.5
Number of lathe working days	90.14 days
Working hours/day	8 hours/day
Number of wheel-sets	16

The formula used for calculating the costs in [Table 5]

- 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
- Indirect costs = (Cost of machinery/day + Cost of operators/day) *Direct costs (1.5)
- Total costs = Cost of machinery/day + Cost of operators/day+ Indirect costs
- Costs per re-profiling = Total costs / working hours per day.

Table 5 Costs related to reprofiling

Cost of machinery/day	346.68 €
Cost of operators/day	800 €
Indirect costs	1720.02 €
Total costs	2866.77 €

Table 6 Cost of each reprofile

Cost for Re-profiling	358.33 €

[Table 7][Table 8] shows the costs of reprofiling and renewal of the wheelsets and the total kilometers between reprofiles.

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

Table 7 Cost analysis of renewals and reprofiles for wheel-sets

	Wheel-set		
	Dry	Lubricated	
Kilometres between reprofiling	175000	317143	
Total number of reprofiles	2.57	1.42	
Total renewals per mission profile	0.161	0.089	
Total cost of renewals/wheelset/year (€)	964.3	532.1	€/year
Total cost of reprofiles/wheelset/year (€)	921.4	508.5	€/year
TOTAL COST /VEHICLE/YEAR (€)	30171.6	16648.8	€/year

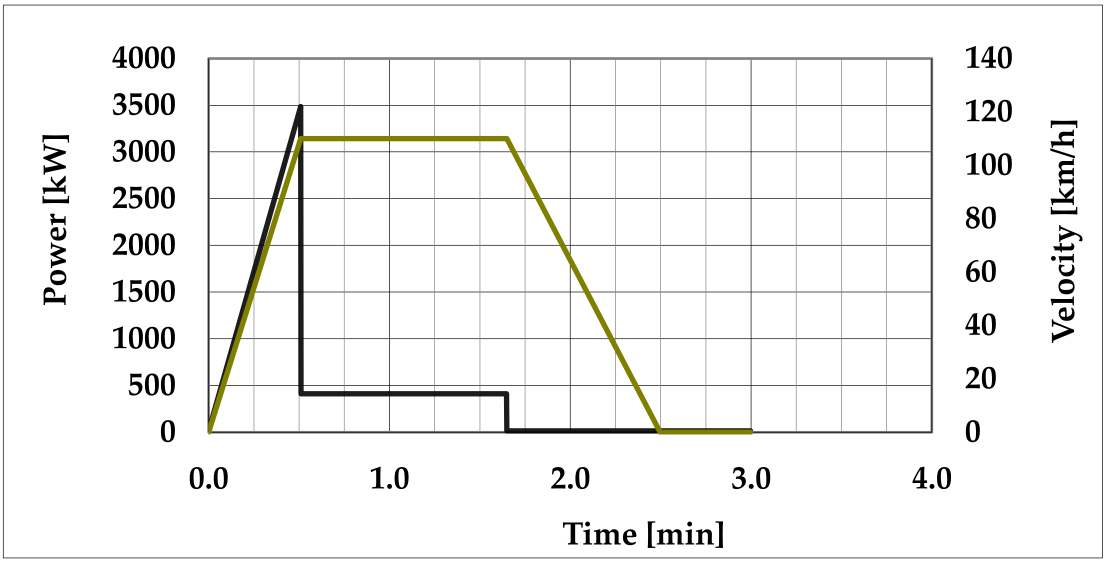
Table 8 Cost analysis of renewals and reprofiles for Independently rotating wheels (IRW)

	Independently rotating wheels		
	Dry	Lubricated	
Kilometres between reprofiling	46667	330000	
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 7 Table 8] [27], if we use independently rotating wheels (lubricated) we can reduce 3.9% of total cost /vehicle/year (€) as compared to the wheelsets (lubricated). This is the order of magnitude (at the very least) that we could expect from a modern mechatronic single-axle running gear.

3.4 Energy consumption

Graph 1 below indicates calculated power consumption and trainset speed for the nominal case (distance 3.3 km, acceleration 1 m/s^2 and deceleration 0.6 m/s^2). The maximum speed considered [27] is 110 km/h.



Graph 1 Power consumption and Velocity in relation to time for 1 stop at full load

The energy calculation considers the three phases of motion

- **Phase 1- Acceleration phase:**

  In this phase the distance travelled is calculated using

  $=(V_{max}/3.6)^2/(2*acceleration)$

  Acceleration Time is calculated using = $(V_{max}/3.6)/acceleration$

- **Phase 2- Constant Velocity:**

  Constant distance = (total length of the line – acceleration distance- braking distance)

  Constant Time = $(Constant\ distance/(V_{max}/3.6))$

- **Phase 3- Braking Phase:**

  Braking time = $(V_{max}/3.6)/deceleration$

  Braking distance=$(V_{max}/3.6)^2/(2*deceleration)$

- **Traction Force calculation:**

  Mass of the car/Tare mass + mass of the passengers (P) = 9.81*(Mcar +Mpax) [kN]

  Equivalent mass (me) = Tare mass*(1+β) + M_{pax} [t]

  Specific Resistance = a+bV^2

  Resistance at Vmax [RV_{max}] = P * r_0 [kN]

  Resistance at V_0 (R_{00}) = P * a [kN]

Average resistance in starting (R_{avg}) = average (R_0, V_{max}, R_{00})

Traction force (T) = [(Equivalent mass (me) * average acceleration) + Average resistance in starting (R_{avg})] [kN]

- **Power/Energy calculation at starting:**

  Average mechanical power(Pmech1) = T * (Vmax /3.6)/2 [kW]

  Power absorbed(P1) = Pmech1/performance efficiency + Pauxiliary [kW]

  Energy absorbed by the number of stops(E1) = (P1* acceleration time (phase 1)/3600) * number of stops [kWh]

- **Power/Energy calculation at constant speed:**

  Average mechanical power(Pmech2) = (Resistance at Vmax [RVmax]) * (Vmax /3.6) [kW]

  Power absorbed(P2) = Pmech2/performance efficiency + Pauxiliary [kW]

  Energy absorbed by the number of stops(E2) = (P2* acceleration time (phase 2)/3600) * number of stops [kWh]

- **Power/Energy calculation at braking:**

  Energy absorbed at phase 3 by the number of stops (E3) = (Pauxiliary * Braking time/ 3600) * number of stops (kWh)

- **Power/Energy calculation at resting phase:**

  Energy absorbed at resting phase by total number of stops(E4) = ($P_{auxiliary}$ * stop time in the station/3600)

- Energy absorbed for the complete journey (E) = E1+E2+E3+E4
- Energy absorbed per km = E/length of the line

To compare the hypothetical effect of energy scenarios by varying the mass of the train against the current running line 9B metro Madrid.

Here we have taken the metro Madrid line 9B, which has 3 conventional cars, only a stop with 3.33 km (Representative distance).

The weight of the train is 123.6 t and the maximum weight of the passengers (100% occupancy rate) is 63.6 t (each car can be loaded 21.2 t).

In [Table 10], the energy is calculated for one stop with a representative distance of 3.33 km by assuming that train is 100% occupied and how the energy varies hypothetically when the tare mass of the trainset is reduced whilst keeping the payload constant.

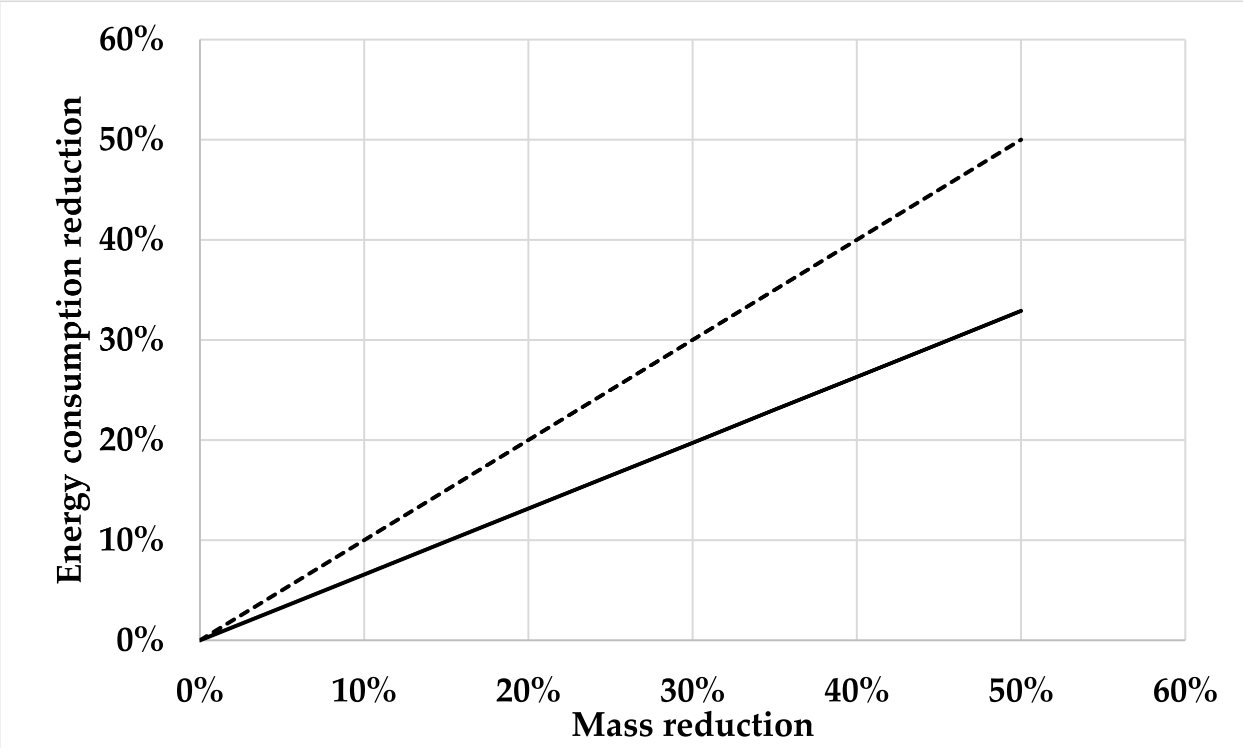
Table 9 Input data for the energy calculation

	Symbol	Unit	Value
LINE CHARECTERISTICS			
Length of the line	L	km	3.33
Total Number of stops	Ns	-	1
Maximum velocity	Vmax	km/h	110
PARAMETERS			
Coefficient a (Specific Resistance)	a	-	0.003
Coefficient b	b	1/(km/h) ^2	0.00000028
Tare mass	m	t	123.6
Coefficient of rotating masses	beta	-	0.07
Mass of passengers	mpax	t	63.6
Auxiliary power	Paux	kW	15
Performance efficiency	eta	-	0.9
Acceleration	aavg	m/s^2	1
Deceleration	davg	m/s^2	0.6

From the above [Table 9], we can calculate the energy with hypothetical reduction of the tare mass. The indications in §3.2 on the achievable mass reduction suggested the exploration in the interval of 0% mass reduction to 50% mass reduction.

Table 10 Single stop calculation

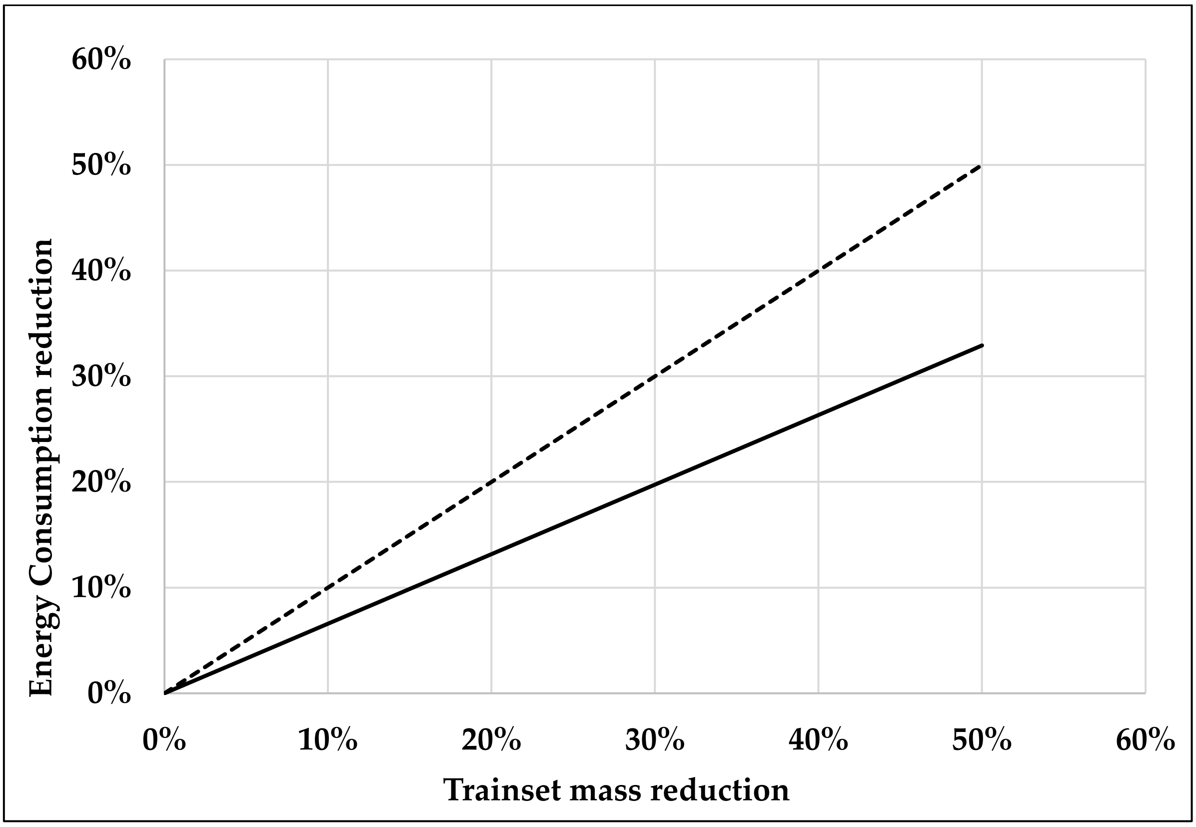
Percentage of Mass reduction	Total weight of the train with the same payload (t)	Energy (kWh)	Relative energy reduction (%)
0%	187.2	38	0%
5%	181.02	37	3%
10%	174.84	35	7%
15%	168.66	34	10%
20%	162.4	33	13%
25%	156.3	32	16%
30%	150.12	30	20%
35%	143.94	29	23%
40%	137.76	28	26%
45%	131.58	27	30%
50%	125.4	25	33%



Graph 2 Energy consumption reduction for one stop (3.3 km) with mass reduction

Table 11: 6 stops calculation

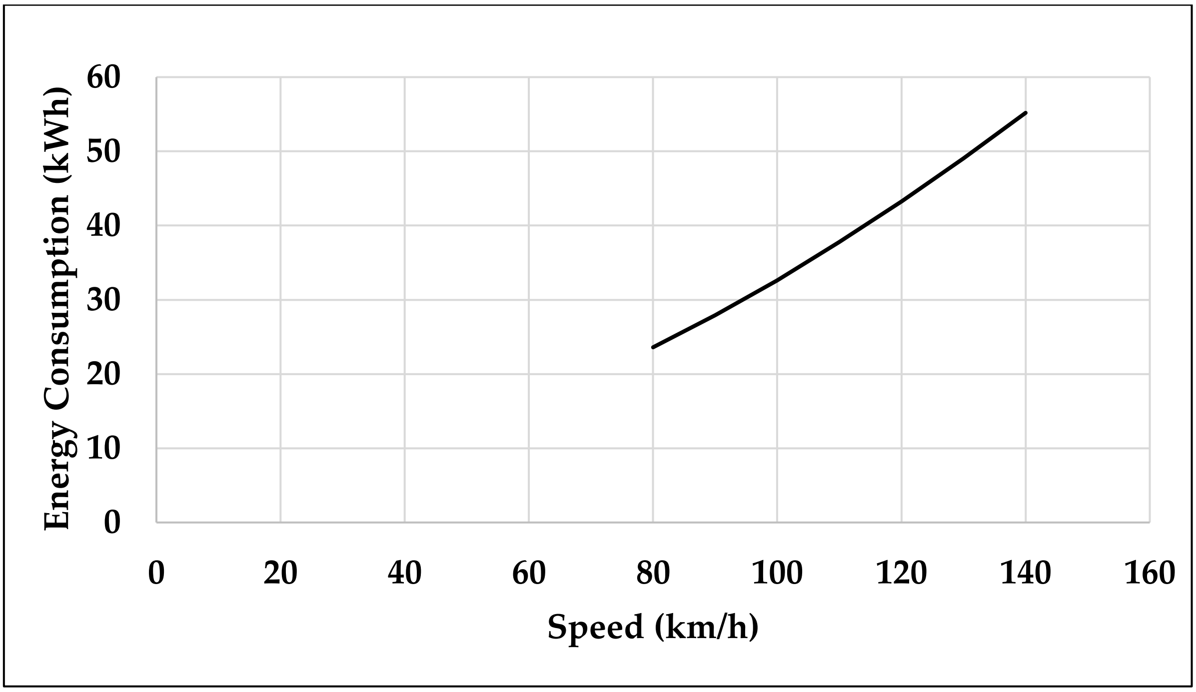
Percentage of Mass reduction	Total weight of the train with the same payload (t)	Energy (kWh)	Relative energy reduction (%)
0%	187.2	226	0%
5%	181.0	219	3.29%
10%	174.8	212	6.58%
15%	168.7	204	9.88%
20%	162.4	197	13.17%
25%	156.3	189	16.46%
30%	150.1	182	19.75%
35%	143.9	174	23.04%
40%	137.8	167	26.33%
45%	131.6	159	29.63%
50%	125.4	152	32.92%



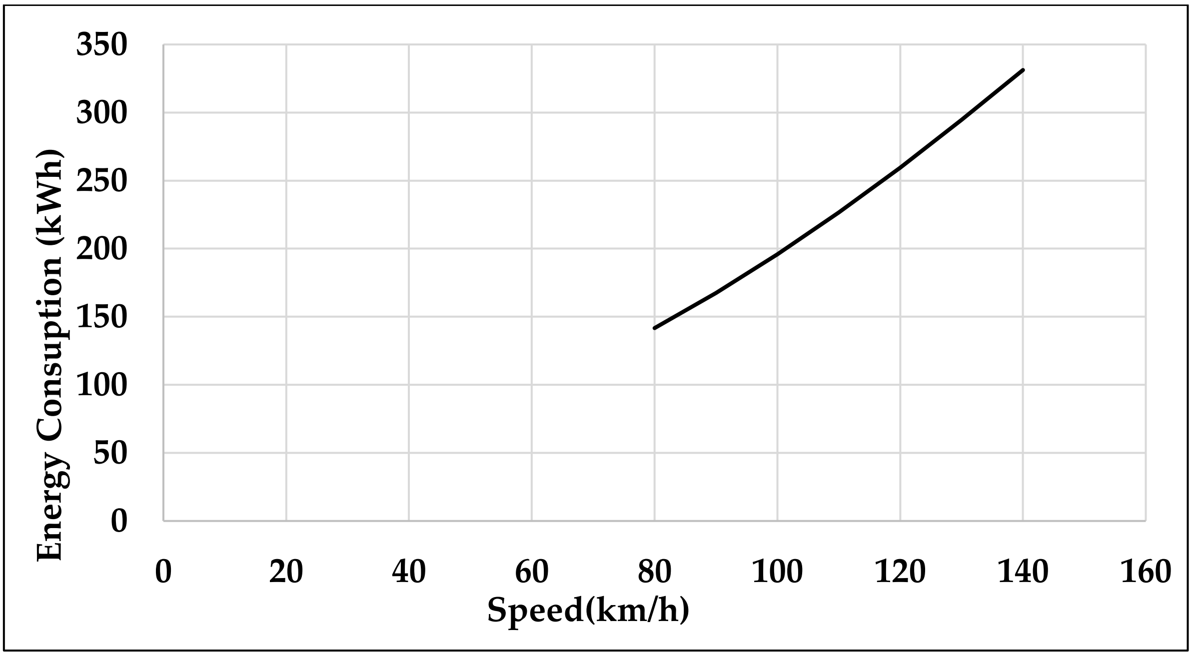
Graph 3 Energy consumption reduction with mass reduction for 6 stops

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.



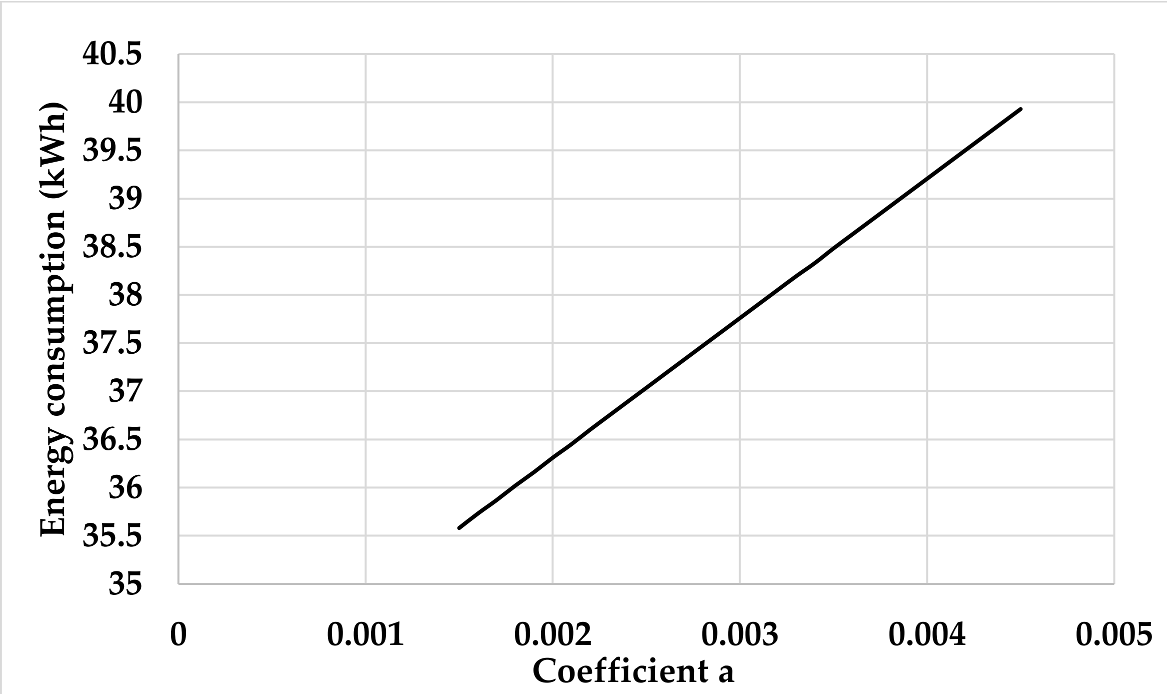
Graph 4 Speed versus Energy for 1 stop with full load



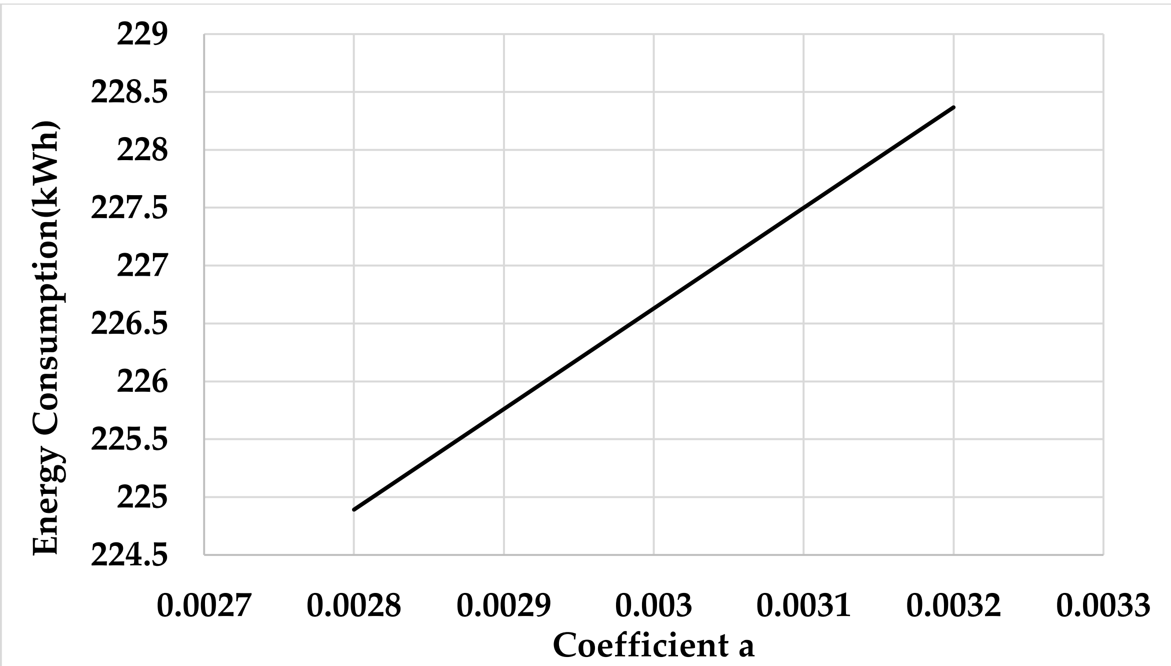
Graph 5 Speed versus Energy for 6 stops with full load

Case 2a: Energy consumption with varying coefficient a

In this case we are trying to see how the energy consumption varies as we vary speed. Here the energy is calculated with full load for one stop.



Graph 6 Energy Consumption with coefficient a for 1 stop

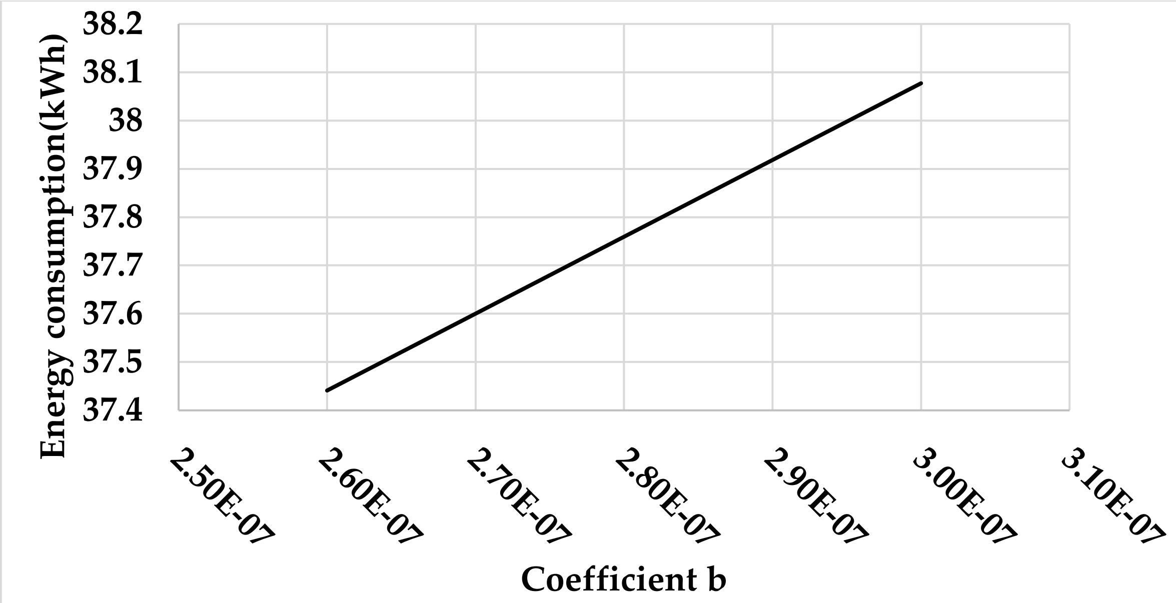


Graph 7 Energy Consumption with coefficient a for 6 stops at full load

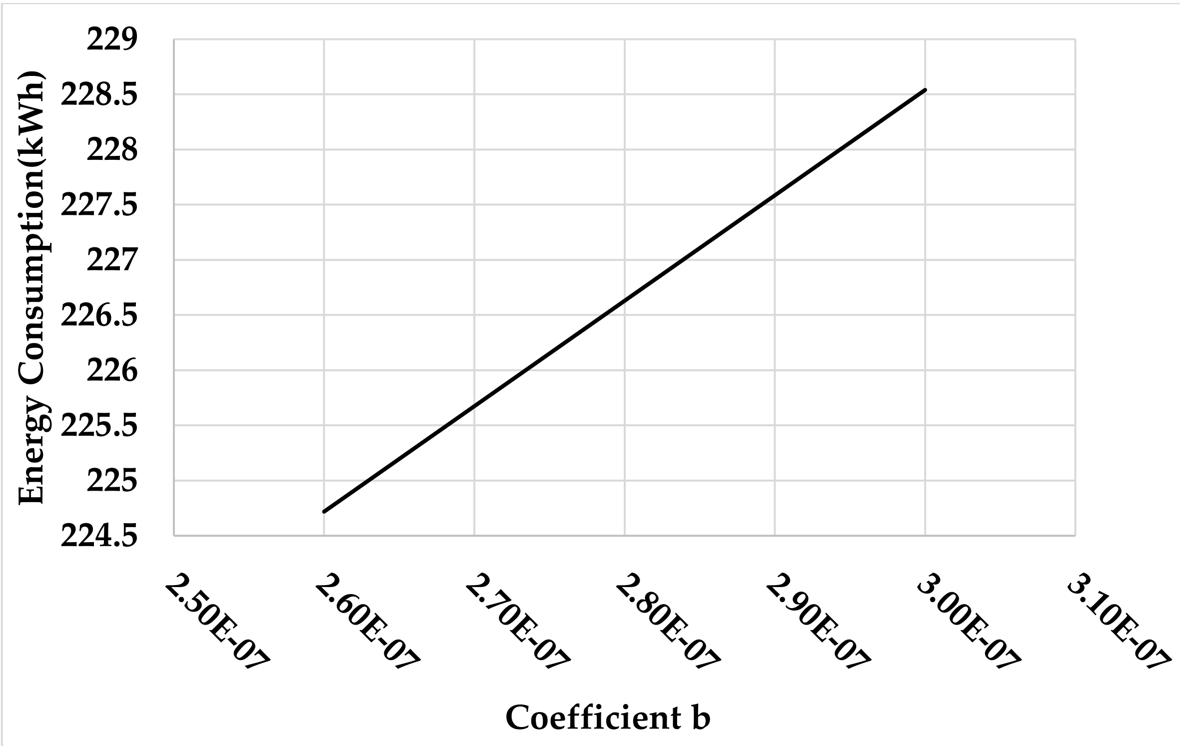
Case 2b: Energy consumption with varying coefficient b

In here, as the coefficient b increases, the energy consumption increases rapidly even for one stop.

The energy here is calculated for one stop at full load of 183.2 t.



Graph 8 Energy consumption for 1 stop with coefficient b at full load

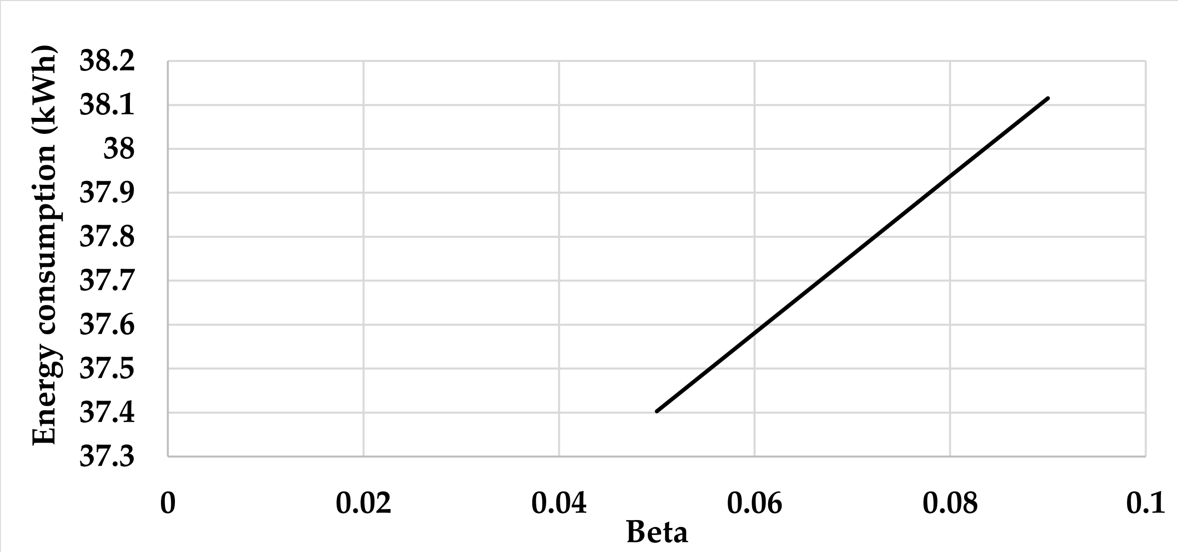


Graph 9 Energy Consumption with coefficient b for 6 stops at full load

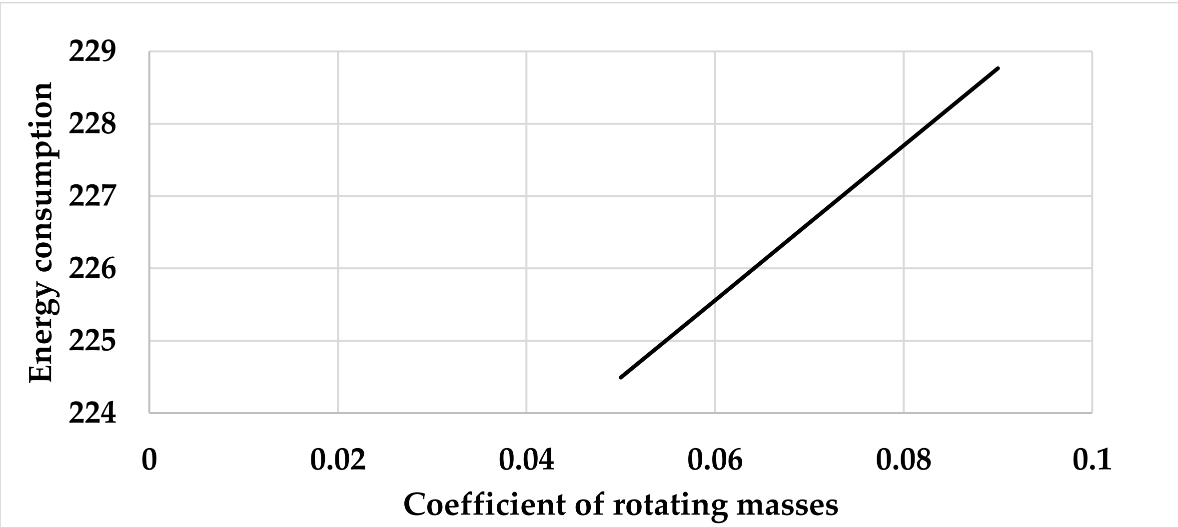
Case 3: Energy consumption with varying coefficient of rotating masses (beta)

In here, as the coefficient of rotating masses (beta) increases, the energy consumption doesn't vary that much for one stop.

The energy here is calculated for one stop at full load of 183.2 t.



Graph 10 Energy consumption for 1 stop with beta



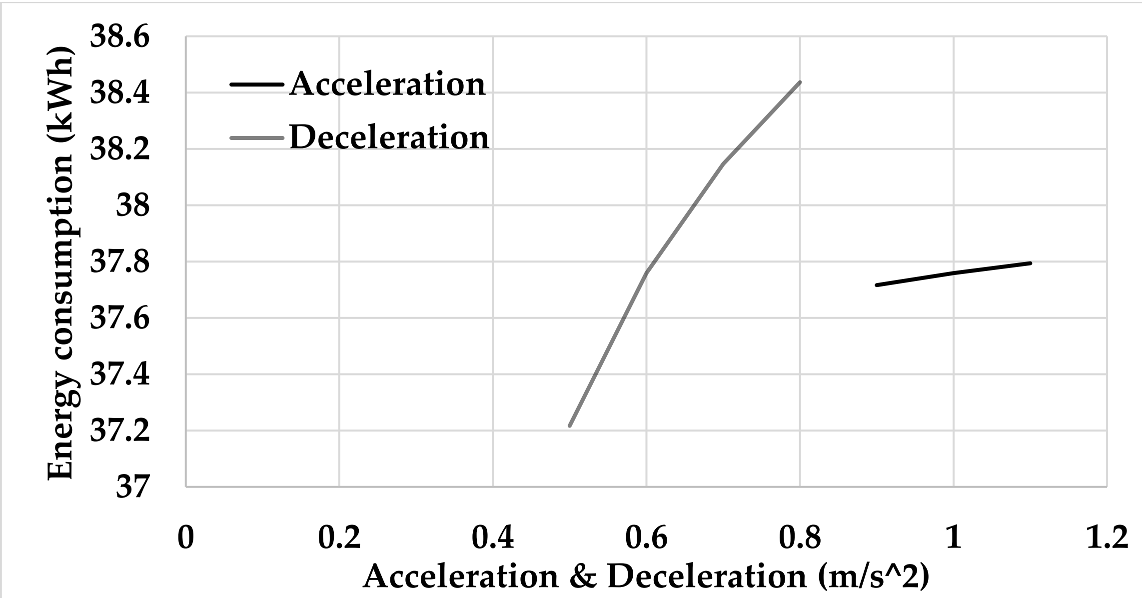
Graph 11 Energy Consumption with coefficient b for 6 stops at full load

Case 4: Energy consumption with Acceleration and Deceleration

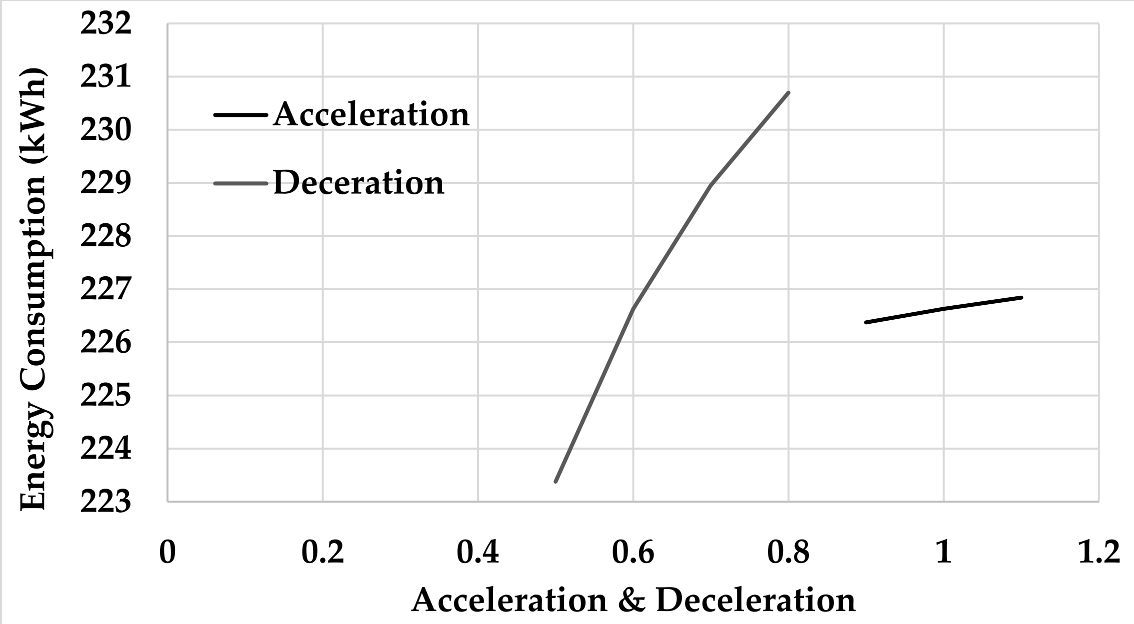
In here the energy calculated is for one stop at maximum payload i.e. 183.2 t.

As we can see that

- When the acceleration is varied, energy consumption doesn't vary that notably;
- But, when deceleration is varied it effects the energy consumption a lot more compared to acceleration.



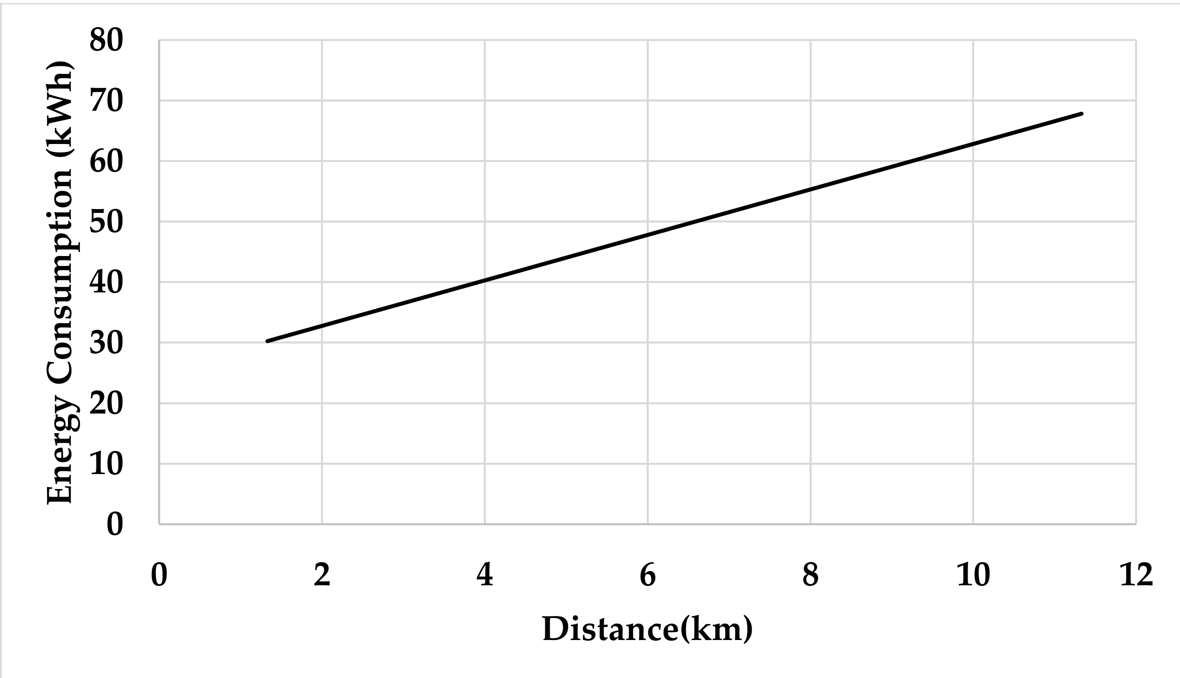
Graph 12 Energy consumption with acceleration and deceleration for 1 stop



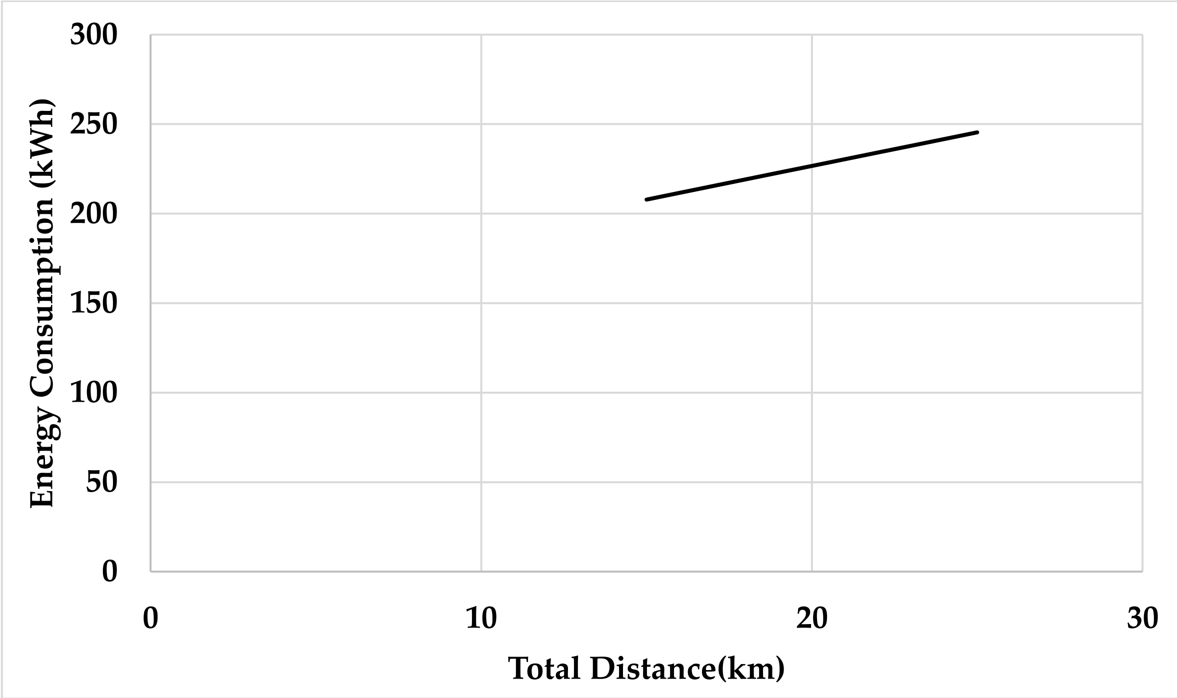
Graph 13 Energy consumption with acceleration and deceleration for 6 stops at full load

Case 5: Energy consumption with Distance

The assumed representative distance in this study is 3.33 km. In the following, the variation of energy consumption with distance is analyzed.



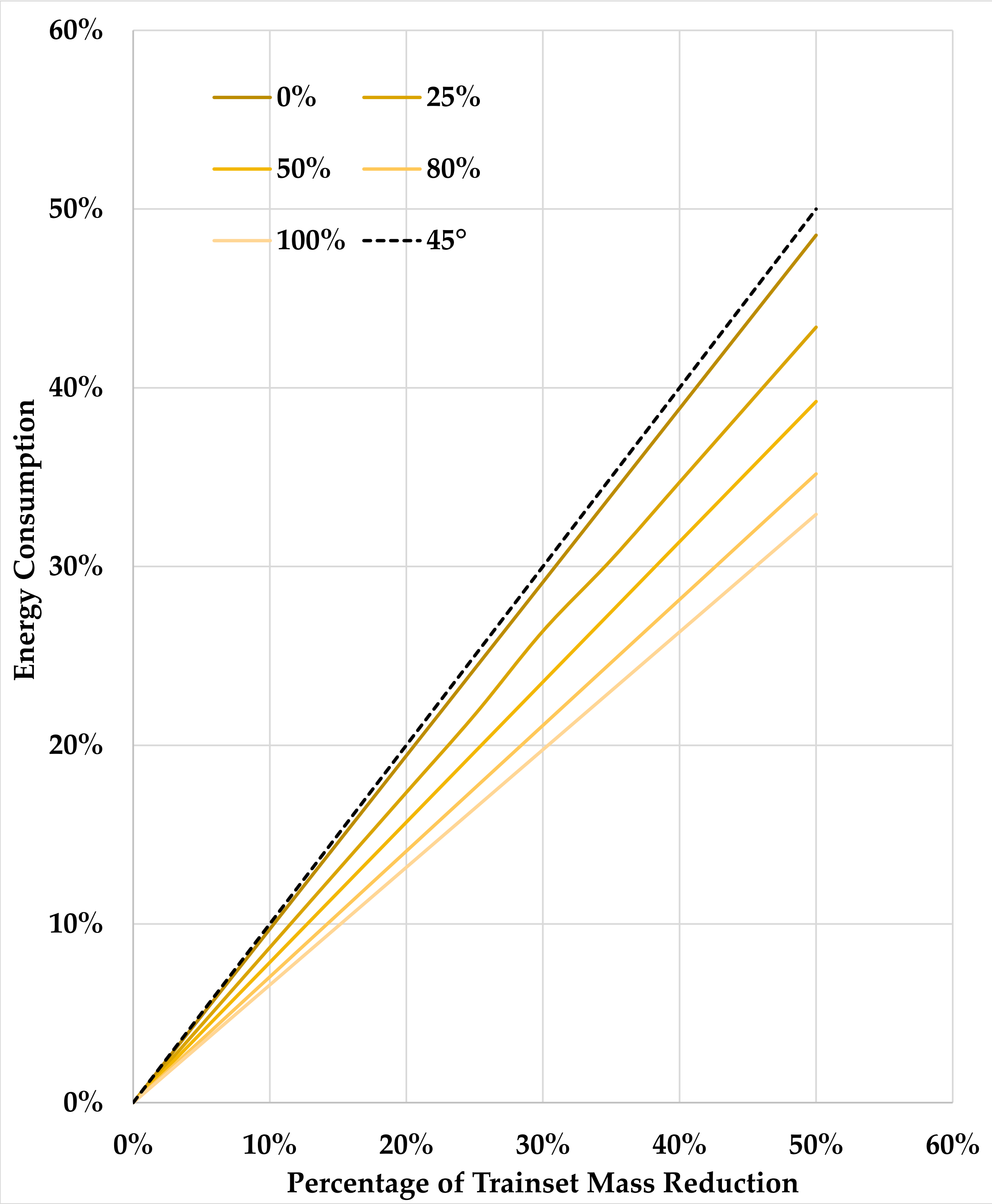
Graph 14 Energy versus distance for 1 stop



Graph 15 Energy with distance for 6 stops at full load

Case 6: Energy consumption with Passenger occupancy rate

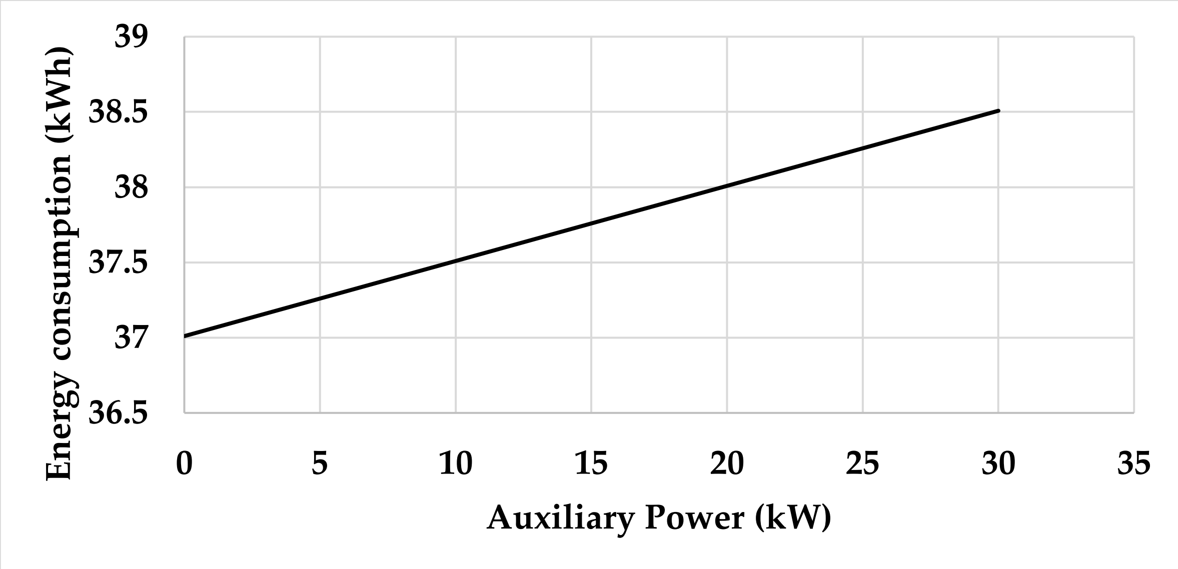
In here we can see how the payload effects the energy consumption and, we can see the approximate percentage of mass reduction and energy consumption reduction.



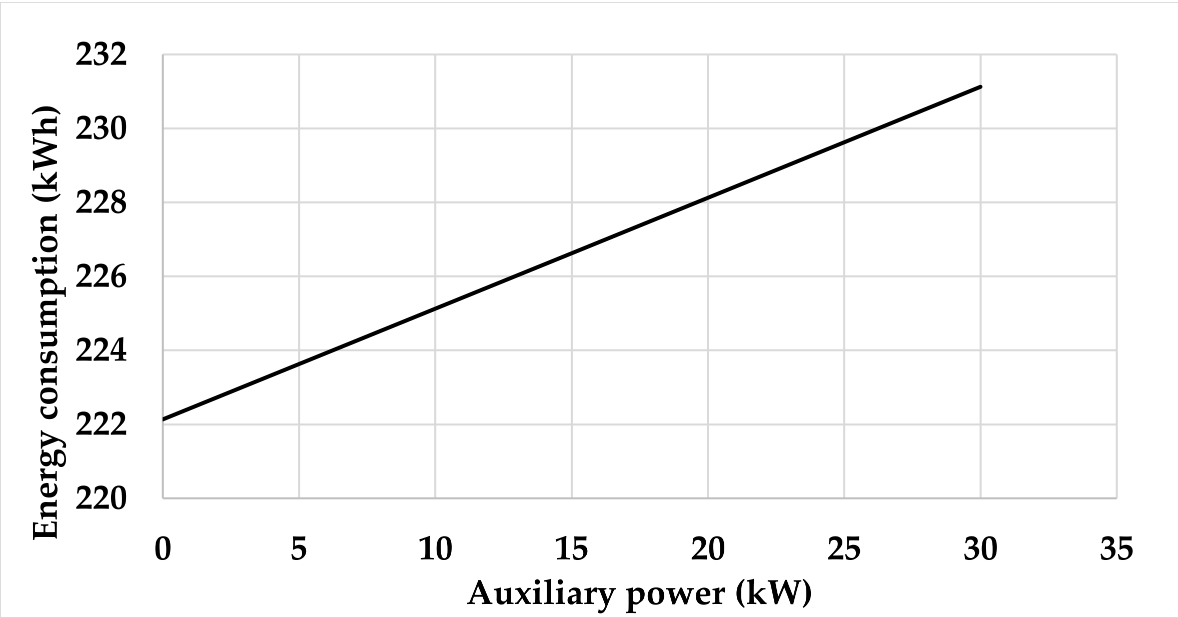
Graph 16 Energy consumption reduction with passenger occupancy rate and mass reduction

Case 7: Energy consumption with auxiliary power

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



Graph 17 Auxiliary power vs Energy consumption for 1 stop



Graph 18 Auxiliary power vs energy consumption for 6 stops

Chapter 4. **Main conclusions**

This thesis has focused on the potential of reducing mass and energy consumption with light-weight materials 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 30% as assumed, then almost 30% energy consumption reduction could theoretically be obtained. This is possible in the empty condition because, for the application under analysis, 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 20%. 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 the Metro Madrid case analyzed, the most influential variables on energy consumption, apart from mass, proved to be maximum speed and braking deceleration. An increase of the former increases the required power both for the traction and constant velocity phases, whereas an increase of the latter increases the required power due to the lengthening of the constant velocity phase. 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

Acronyms	Description
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

ANNEXES

ANNEX 1. Integrated Maintenance:

[SOURCE: DR. ENG. ROBERTO NAPPI. INTEGRATED MAINTENANCE: ANALYSIS AND PERSPECTIVE OF INNOVATION IN RAILWAY SECTOR]

Many complex systems, in different engineering application fields (e.g. aerospace, aeronautic, naval, railway, etc.), work in specific environmental conditions for which it is required to be compliant with specific requirements of usability, reliability, safety, and maintainability. Regarding these requirements, the target of the maintainability is to maximize the lifetime of the systems produced with the minimum global cost (Life Cost Cycle).
Based on this consideration, the maintenance of a system becomes a strategic element for the economic competitiveness of the infrastructure operators.
Indeed, to have a system of high complexity that properly operates, without interruptions, it is necessary to sustain its usage by a constant maintenance activity.
The "traditional" approach to the maintenance is typically intended as repair.
However, it is possible to evolve this approach through actions such as the prevention and the continuous improvement of the maintenance process focused on the system life-cycle.
To deal with big data analysis, innovative algorithms and data mining tools are needed to extract information and discover knowledge from the continuous and increasing data volume. In most of data mining methods the data volume and variety directly impact the computational load.

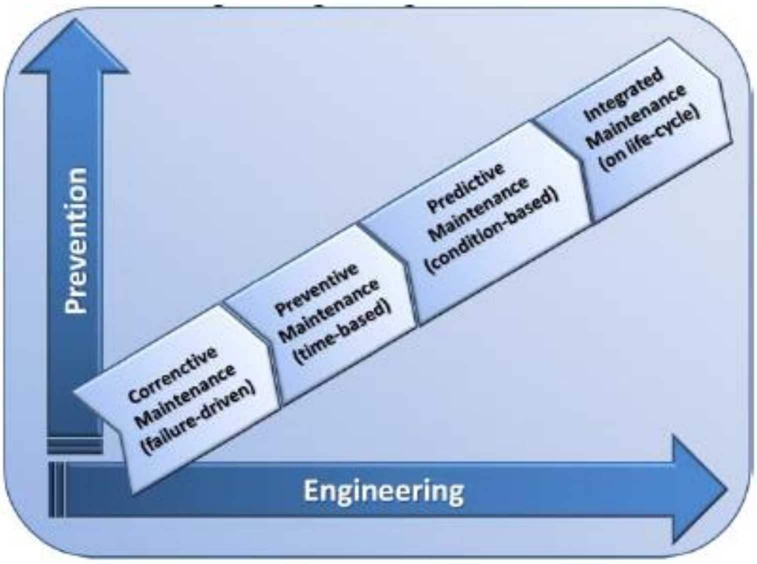

Figure 11 Maintenance processes

ANNEX 2. The mechatronic train project:

[SOURCE: EUROPEAN UNION MECHATRONIC TRAIN]
Railway vehicle suspensions have been essentially mechanical in nature since railways were born in the early 1800s, but the use of advanced control technology and a "Mechatronic" approach to vehicle design now offer great opportunities for the design of future rail vehicles. Mechatronics is the "synergetic combination of precision mechanical engineering, electronic control and systems thinking", and when applied to rail vehicles the approach can lead to lower weight, increased energy efficiency and enhanced commercial viability, whilst maintaining the normal ambitious standards of performance, comfort and safety.

Objectives of 'mechatronic train '

By using the application of advanced suspensions and integrated drives will make it possible to simplify and lighten the running gear of trains.

Train mass per unit payload reduces (by 40%)

Energy consumption reduced (by 30%)

Noise emission at medium/high frequency is reduced (by 10 dB(A))

Design, Manufacturing & assembly costs reduced (30%)

Mechanically simpler

Reduced track maintenance

The project has contributed significantly to attaining these targets by providing a scientific basis for the application of advanced mechatronic suspensions and drives. The fundamental problem with vehicle systems is the interaction between structural dynamics, the forces between wheel and rail, and the control systems. Accordingly, the overriding aim of this research project was to research the engineering science needed for an integrated application of electronic and mechanical components to achieve the optimum systems design of railway trains, with the following specific objectives:

To develop a fundamental understanding of the dynamic response of lightweight rail vehicles with active controls.

To develop methods of analysis for advanced vehicles emphasizing configurations which would take full advantage of emerging control technology (leading to reduced weight, lower cost, lower car-body structural vibrations, etc.)

To identify systems architectures (sensors, actuators, processing) which would provide the level of safety, reliability, and maintainability needed for an operational railway.

CONSORTIUM of

- CAF (Spain)
- CEIT (Spain)
- DB (Germany)
- DLR (Germany)
- ERRI (European)
- UIC
- INTEC GmbH (Germany)

One of the most difficult problems is to solve the axle steering. This study contains a brief description of the solutions which are thought to be most interesting. Most non-conventional configurations are based on wheel sets steered using passive kinematic connections. Almost all of them have been designed for low speed (up to 120km/h). Such solutions could pose stability problems at high speeds. To solve this type of problems at high speeds, it seems to be necessary to consider non-passive solutions based on wheel sets or on independent wheels. The solution of this problem will be one of the main objectives of this project.

For the conventional vehicle of bogies, a complete parameter list was produced specifically for this project and the data have not been taken from any actual vehicle, although several vehicle characteristics have been taken from actual high-speed trains information found on public domain publications.

For a non-conventional double-axle vehicle some basic data were defined. In this case it proves more complicated to define a complete parameter list since currently no high-speed motor vehicle exists in line with this configuration. However, some relevant data such as weights and geometrical parameters were included.

The proposed evaluation parameters and design criteria for each one of the above-mentioned aspects are based on the UIC standard regulations. A comprehensive study of these standards has been carried out. Typical operators' requirements have also been considered, and a summary of the limits and objectives requested by the Deutsche Bahn with respect to the safety and running behavior of railway vehicles have been included in the report.

During the study of Single vehicle with 2-axles, a steered wheel set module could be developed and then it could be relatively straight-forward to extent the results to the study of more complex configurations of mixed vehicles of one or two single wheel sets.

Figure 12 Mixed configuration

Another crucial factor in the case of high-speed trains is the maximum vertical load allowed per wheel set. Within Europe the maximum value has been set at 170 kN per axle. In this way vehicles based on independent axles must be shorter than bogie-based vehicles, and this could reduce their capacity since each car must normally include its own minimal services (access areas, WC …). On the other hand, a short vehicle may be wider, since it shall experience less problems with the track's kinematic gauge.

In the case of Single vehicle with 2-axle, one of the most difficult problems to solve is the axle steering. Most non-conventional configurations are based on wheel sets steered using passive kinematic connections. Almost all of them have been designed for low speeds (up to 120 km/h). Such solutions could pose stability problems at high speeds.

ANNEX 3. Maintenance Approaches

[SOURCE: DR. ENG. ROBERTO NAPPI. INTEGRATED MAINTENANCE: ANALYSIS AND PERSPECTIVE OF INNOVATION IN RAILWAY SECTOR]

A. Corrective Maintenance:

The failure-driven approach is a reactive management approach, where the corrective maintenance is often dominated by unplanned events and it is performed only after the occurrence of failures or breakages of the system. Corrective Maintenance actions can recover the malfunctioning part of the system, repairing or replacing the failed component. If the system is not-critical and easily repairable, any potential unplanned crashes will cause a minimum impact related to the availability. In this way, the failure-driven maintenance can be a good maintenance approach. The systematic use of an urgent corrective maintenance often is translated into unpredictable performance of the system.[21]

B. Preventive Maintenance

The time-based maintenance is also known as periodic preventive maintenance. To slow down the process of deterioration that leads to a failure, a primary preventive maintenance is performed periodically inspecting and controlling the system through scheduled regular activities. The time-based maintenance assumes that the estimated malfunctioning of the system, i.e. mean time between two functional failures (Mean Time Between Failure – MTBF), is statistically or experimentally known for system and device degradation during their normal use. The time-based maintenance involves also scheduled shutdown of the system for revisions or predetermined repair activities on the system still operating. [21]

C. Predictive Maintenance:

Another approach is represented by the condition-based maintenance as a method to reduce the uncertainty of maintenance activities. These activities will be performed according to the needs indicated by the results of system status monitoring (condition-monitoring). The predictive condition-based maintenance uses, therefore, the results of condition-monitoring and, according to these, plans the maintenance actions. The goal of condition-monitoring is to delete the failures and extend the preventive maintenance intervals. The condition-based fault diagnosis is triggered by the detection of an evaluated condition of the system, such as the deviation from the expected level, recognizes and analyses symptomatic information, identifies the causes of the malfunction, obtains the development trend of the fault and predicts the remaining useful life of the system (Remaining Useful Life – RUL). A maintenance in advance can be performed to avoid an excessive supply of replacement parts. [21]

D. Integrated Maintenance:

For the most modern and complex industrial systems, the attention of the manager of maintenance shall be focused on the following three aspects:

1. how to re-plan and reschedule the maintenance of sophisticated systems operating in complex environmental conditions;
2. how to reduce the excessive costs of stocks of the replacement parts;
3. how to avoid risks of catastrophic failures and eliminate the forced and unplanned interruption in system availability.

A Decision Support System (Decision Support System – DSS) is a computer-based processing system that contains a specific knowledge of domain and analytic decisional models to assist the decision-maker through the presentation of information and interpretation of possible operational alternatives. The decision support system is aimed to improve the decision-making process of maintainer, providing an easy definition and identification of the problem, an appropriate management of information and statistical tools, with a proper application of the knowledge.

Therefore, an Intelligent Predictive Decision Support System (IPDSS), []for a condition-based maintenance, integrates the following concepts:

- ➔ monitoring of system condition;
- ➔ intelligent faults diagnosis, based on system condition;
- ➔ prediction of deterioration trend of the system.

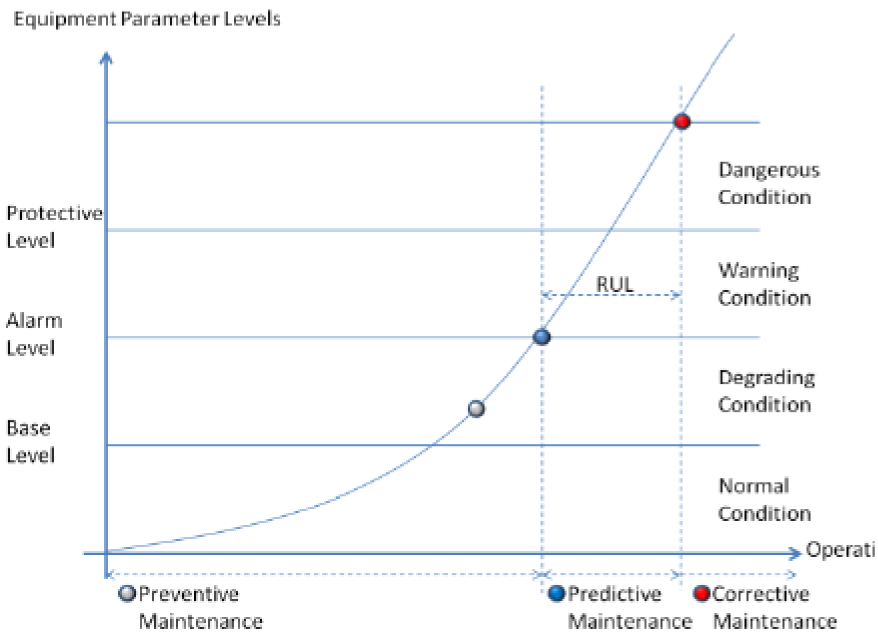

Figure 13 Management of maintenance activities through an Intelligent Predictive Decision Support System

When the system operates in "normal condition", only a generic preventive maintenance activity is required. Instead, when the monitored parameters of the system reach the "base level", the system goes into "degraded condition" and this indicates that failures may be experienced. In this case, the analysis of the development trend of faults should be conducted to indicate the areas of the system affected by potential problems due to new faults or areas where it is probable that faults occur. When a "degraded condition" occurs, no special maintenance action is required; instead, more condition-monitoring actions should be performed to prevent emergency interventions. When the monitored parameters of the system exceed the "alarm level", then appropriate indications alarm will be activated to alert the operators and the maintenance staff [21].

ANNEX 4. Active suspension/ steering

[Source: R. M. Goodall and T. X. Mei – Active suspensions.]

Vehicle dynamists have been aware of active suspensions for some time, with major reviews having been undertaken in 1975, 1983, and 1997, but so far, they have only found substantial application in tilting trains — which can now be thought of an established suspension technology.[22]

However, there are two other major categories:

- active secondary suspensions for improved ride quality, and
- active primary suspensions for improved running stability and curving performance.

ACTIVE AND SEMI ACTIVE SUSPENSION

The greatest benefits can be achieved by using fully-controllable actuators with their own power supply, such that the desired control action (usually a force) can be achieved irrespective of the movement of the actuator. Energy can flow from or to the power supply as required to implement the control law. This is known as a "full-active" suspension (), but it is also possible to use a "semi-active" () approach in which the characteristic of an otherwise passive suspension component can be rapidly varied under electronic control.

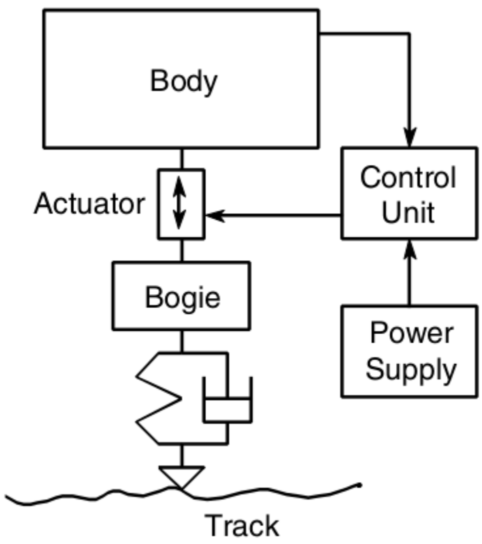

Figure 14 Full active suspension

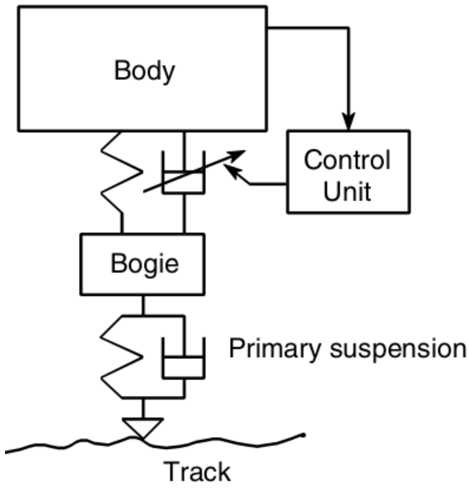

Figure 15 Semi-active suspension

The benefit of the semi-active approach compared with full-active is one of simplicity, because a separate power supply for the actuator is not needed. The disadvantage of a semi-active damper is that the force remains dependent upon the speed of damper movement, which means that large forces cannot be produced when its speed is low, and it cannot develop a positive force when the speed reverses because it is only possible to dissipate energy, not inject it[22].

Tilting Trains

Tilting trains take advantage of the fact that the speed through curves is principally limited by passenger comfort, and not by either the lateral forces on the track or the risk of overturning, although these are constraints that cannot be ignored. Tilting the vehicle bodies on curves reduces the acceleration experienced by the passenger, which permits higher speeds and provides a variety of operational benefits. The principles and basic equations related to tilting are relatively straightforward and are explained here in a manner that focuses upon the operational advantages.

What is maximum tilt angle being to be provided (θ tilt), a decision based upon mechanical design of the vehicle, especially taking gauging issues into account. The second decision is what cant deficiency the passengers should experience on a steady curve (θ active), which clearly is of primary importance to comfort. Given these two decisions, and the cant deficiency that applies for the passive (non- tilting) case (θ passive), it is possible to derive an equation for the increase in speed offered by tilt.[22]

$$\text{speed increase} = \frac{V_{\text{active}} - V_{\text{passive}}}{V_{\text{passive}}} = \left\{ \sqrt{\frac{\sin(\theta_{\text{cant}} + \theta_{\text{tilt}} + \theta_{\text{active}})}{\sin(\theta_{\text{cant}} + \theta_{\text{passive}})}} - 1 \right\} \times 100\%$$

There are four mechanical arrangements which are possible to provide the tilting action.

The first is passive or pendular tilt, in which the secondary suspension is raised to around roof level in the vehicle: the vehicle Centre of gravity is then substantially below the suspension and the body naturally swings outwards, reducing the lateral curving acceleration experienced by the passengers. (Used by Talgo).

A second approach is to achieve tilt directly by applying active control to the secondary roll suspension.

With the tilting bolster above the secondary suspension, the increased curving forces need to be reacted by the secondary lateral suspension; since a stiffer lateral suspension is not consistent with the higher operating speed of a tilting train, in practice, either an increased lateral suspension movement or some form of active centering method is needed to avoid reaching the limits of travel.

The final arrangement has the tilting bolster below the secondary suspension, thereby avoiding the increased curving forces on the lateral suspension, and this is probably the most common of all schemes, the necessary rotation being achieved using either a pair of inclined swing links, or a circular roller beam.

ACTIVE SECONDARY SUSPENSIONS

For the secondary suspensions, active controls improve the vehicle dynamic response and provide a better isolation of the vehicle body to the track irregularities than the use of only passive springs and dampers. Active control can be applied to any or all the suspension degrees-of-freedom, but, when applied in the lateral direction, will implicitly include the yaw mode, and in the vertical direction will include the pitching mode.[22]

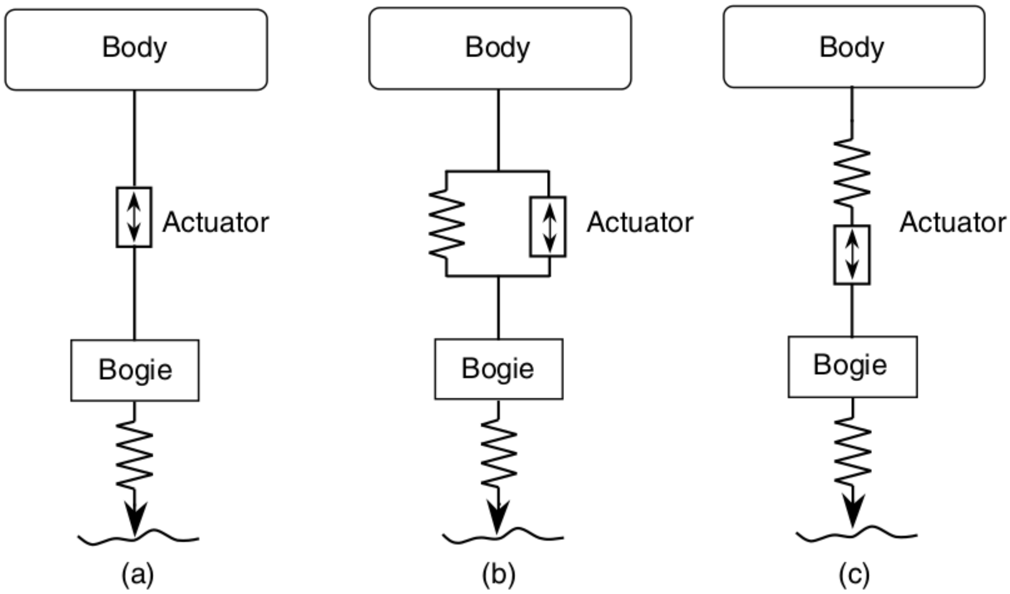

Figure 16 Active secondary suspension actuator configurations

Active control can be applied to any or all the suspension degrees-of-freedom, but, when applied in the lateral direction, will implicitly include the yaw mode, and in the vertical direction will include the pitching mode.

In (*Figure* 16a) the suspension behavior will be completely controlled via active means.

In (*Figure* 16b) when connected in parallel, the size of an actuator can be significantly reduced as the passive component will be largely responsible for providing a constant force to support the body mass of a vehicle in the vertical direction or quasi-static curving forces in the lateral direction.

In (*Figure* 16c) when connected in series, helps with the high frequency problem caused by the lack of response in the actuator movement and control output at high frequencies.

ACTIVE PRIMARY SUSPENSIONS

Although active control could be applied to vertical primary suspensions, in fact, there seems little to be gained from such an application. The main area of interest therefore relates to controlling the wheel set kinematics through the active primary suspensions. The key issue here is the trade-off between running stability (critical speed) and curving performance, which with a passive suspension is difficult. However, the idea of using active control for the wheel set steering is relatively new.

Many actuation schemes are possible for implementing active steering. One of the obvious options is to apply a controlled torque to the wheel set in the yaw direction. This can be achieved via yaw actuators.

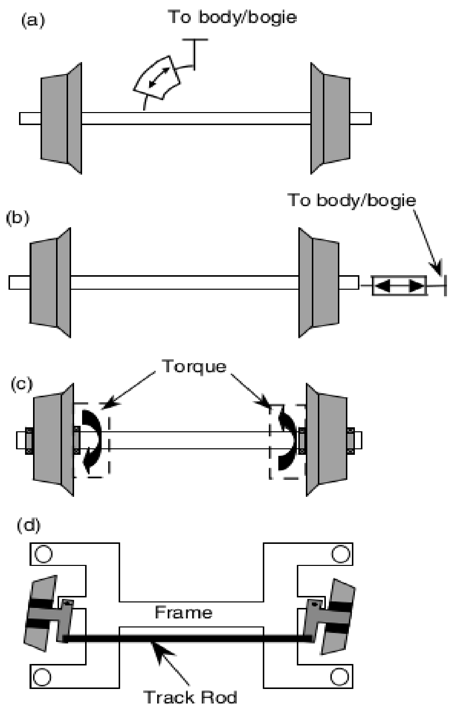

Figure 17 Schemes for active steering

Alternatively, actuators may be installed onto a wheel set in the lateral direction, but a drawback of the configuration is that the stabilization forces also cause the ride quality on the vehicle to deteriorate. For the independently-rotating wheel set, there is a possibility of controlling the wheel set via an active torsional coupling between the two wheels.

ANNEX 5. Steering Mechanisms:

When passing a curve, wheel sets shift to the outer rail side, and because of the taper, the effective diameter of the outer wheel increases and that of the inner wheel decreases. A conventional bogie tends to take an under-steer attitude, or to turn outwards with respect to the tangent of the curve, and as a result, the front axle has an angle of attack to the curve, which gives rise to a lateral creep force pressing the outer wheel to the outer rail. On the other hand, the rear axle stays near the track Centre, and consequently, the differential wheel diameter is insufficient, and there occurs a longitudinal creep force (tangential force) between the rear wheels and the rails. These forces act as anti-steering moments on the bogie, and cause high lateral force of the front wheel set toward the outer rail [28].

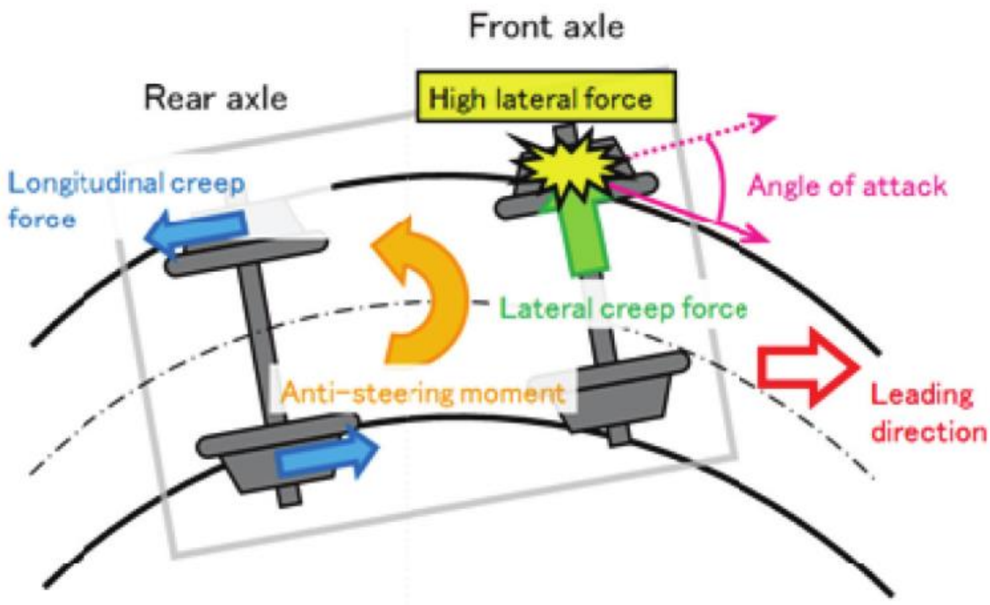

Figure 18 Behavior of non-steering, conventional bogie in sharp curve

As explained above, the problems with railway vehicles at sharp curves are large lateral force and high derailment coefficient, an indicator of running safety defined as the lateral force of a wheel on the rail divided by the vertical load. In addition, because the wheels turn at sharp curves with their flanges contacting the gauge corner of the outer rail, there are other problems arising from the wheel/rail contact such as high-frequency noises and the wear of the wheel flanges and the gauge corner of the rail. In view of the large lateral force and high derailment coefficient, derailment is prevented physically by providing anti-derailment angles or rails along the inner rail. Since the above large lateral force, high-frequency noises, and the wear of the flanges and the rail gauge corner result from wheels contacting the rail, they have been taken care of by providing oiling facilities to the tracks or wheels for lubrication control. Oiling, however, often leads to wheel spinning during power running or slipping during braking, and thus is not adequate for curves.[28]

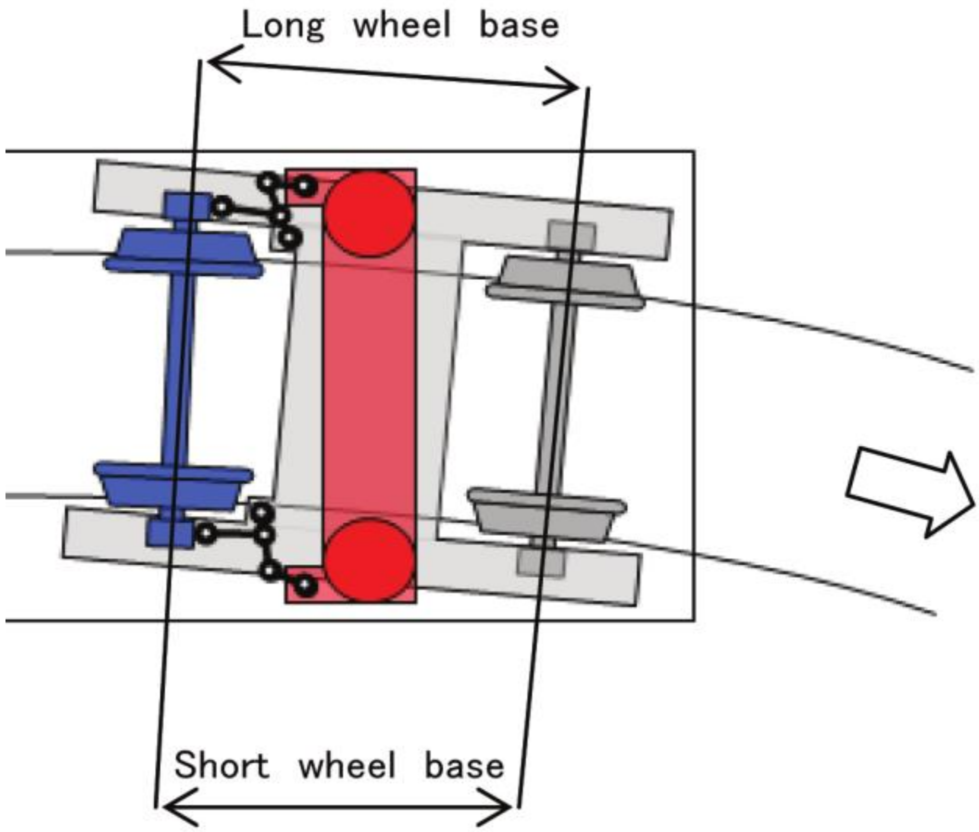

Figure 19 Axle steering

Steering bogies can solve all these problems. As shows, the idea of steering bogies is to steer a wheel set or wheel sets such that the wheelbase on the outer side of a curve becomes longer than that on the inner side, and the wheel axles turn radially in the direction of the curve