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Comparative study between an alternating current (AC) and a direct current (DC) electrification of an urban railway

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1 Object of the Study

The object of this study is to analyze, regarding technic, energetic and economic factors, the suitability of a traction electrification network in AC in front of an existing one electrified in DC for a metropolitan railway.

2 Justification

Historically, urban and metropolitan railways have been electrified under direct current (DC). This phenomenon can be explained due to the technical limitations in alternating current (AC) power systems existing at the end of the XIX century, when urban railways began to shape. From that time on, the philosophy has been to continue electrifying in direct current and limiting alternating current electrifications for interurban and high speed trains, where the power demand is greater and high voltage transmission lines play a significant role.

But what would happen if an urban or metropolitan line previously electrified under DC or newly projected was to be redesigned with AC electrification? Would it be suitable regarding technical or economic reasons?

To answer this question, it is proposed a study of a DC railway that belongs to this group of configurations that can generate doubts regarding electrification: The Barcelona – Vallès line operated by *Ferrocarrils de la Generalitat de Catalunya* (*FGC*) and currently electrified under 1.500 Vdc.

This comparative study is the result of a cooperation agreement between *Ferrocarrils de la Generalitat de Catalunya* and *Sener Ingeniería y Sistemas*. The first collaborator has provided all the necessary data of real operation conditions and line characteristics to perform an accurate analysis and give consistency to the results obtained, whereas the second collaborator has provided the traction simulation software used to perform the simulations. All the technical support needed has come from both enterprises when needed.

This study could be extrapolated and be used as a reference document for designers when deciding which voltage system could best fit in railways with similar characteristics as the line here studied.

3 Scope

This study will evaluate technically, energetic and economically the traction electrification network of the line Barcelona – Vallès operated by *Ferrocarrils de la Generalitat de Catalunya* (*FGC*) in the existing voltage system (1500 Vdc) and a new electrification under alternative current (25 kVac) will be proposed to be as well studied. The results obtained will be compared in order to obtain decision factors on which system best fits.

This comparative study comprises the following structure:

1. Existing operational conditions of the line are set to be the design criteria for the two traction networks studied (1500 Vdc and 25 kVac).
2. Selection of the validation criteria to analyze the technical viability of the two configurations.
3. Proposal of a 25 kVac traction network that can satisfy the first and second point of this list.
4. The two traction networks are simulated using *STElec* in the most demanding scenarios: peak hour during working days, in default and contingency operation.
5. Technic and energetic study of the two selected configurations, comparing the results obtained in the traction simulations.
6. Economic analysis of the two configurations.

This comparative study does not include:

1. Economic viability and charge-off period.
2. Ticket demand study.

As an introduction to this comparative study, a review of the main electrification systems used in railway technologies is made, providing to the lector the necessary background to comprehend the basic differences existing between them.

4 Basic specifications of the study:

- The period to carry out this study is intended for the June-January period.
- The line characteristics are real data provided by *Ferrocarrils de la Generalitat de Catalunya*.
- The simulation process is performed by a proved traction simulator (*STElec*).

5 Railway Electrification Systems

5.1 Introduction

In this chapter an overview of the different configurations used in railway electrifications is given, explaining their main characteristics and background, their advantages, disadvantages and traction technologies of the rolling stock suitable for each of them. The feeding systems and electrical requirements for each of them are exposed, as well.

After the railway electrifications review is done, there is a scheme where the different train typologies are distributed regarding their voltage system. Is in this part of the chapter where the region of use considered for the coming comparative study is shown. This region studied comprises a shared fringe of use between DC and AC voltage systems.

To finish this chapter and once the region of study is delimited; the factors that are considered as relevant in the voltage system selection are presented and compared for the two different electrifications, becoming the first step to delimit the conditions under which the comparative study will be performed.

5.2 Direct current electrification

The first electrified railway in the world was constructed in Lichterfelde (Berlin) in 1881 [1], using a voltage system of 180 Vdc. These early low voltage feeding systems allowed connecting directly the DC electric motors of the rolling stock with the traction supply and they were controlled using a combination of resistors and relays that connected the motors in parallel or series [2].

However, the main disadvantage these feeding systems had was their low voltage: it meant that high currents were demanded and therefore high section conductors were needed and low power performance was achieved. The necessity to implement alternating current feeding systems in railways was settled.

Nowadays these problems are mostly overcome and direct current railway electrifications are fed from three-phase power lines, ranging between 6 to 45 kV, which are connected with the traction power substations, transforming the voltage to lower values and rectifying it to be suitable for the dc traction system.

The power injected goes through the contact line to the motors of the trains and the current returns to the traction-substations usually through the running rails.

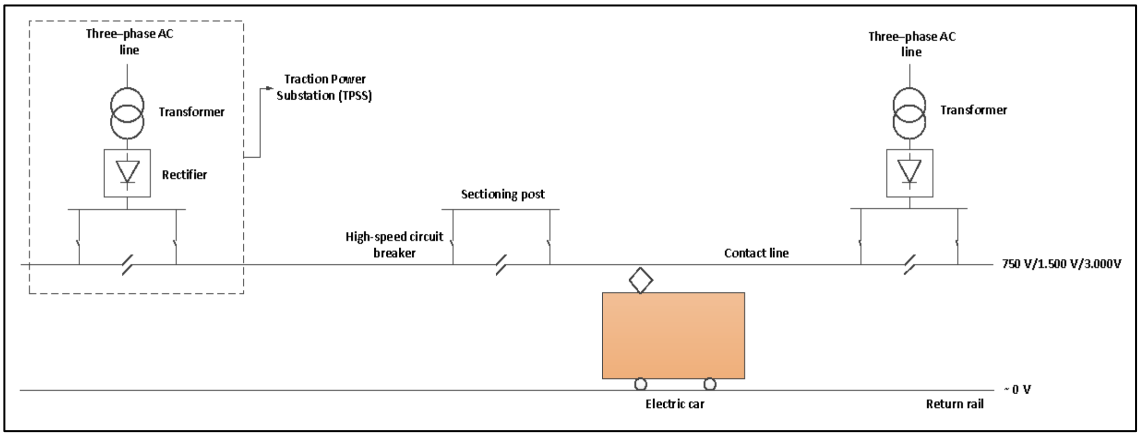


Figure 1 Typical DC electrification system

In this schematic configuration of a typical DC railway system the main components are shown: the transformer-rectifier group inside the traction power substations, the contact line (overhead or conductor rail) and the return rail. The sectioning post has the purpose to isolate the sections in case of failure or when works of maintenance are being made.

The substations receive the power from the utility system at medium voltage. Each substation includes one or more transformers, each of those feeding its own rectifier. The rectifier output is then connected to the overhead catenary system or conductor rail, and the running rails. In typical DC electrification systems, the traction-substations are rated in the 1 MVA to 6 MVA range, depending on the voltage and train loading [3].

DC electrification systems are usually electrified at 750 Vdc, 1500 Vdc or 3000 Vdc. For the same power requirement, the higher the voltage, the lower the currents and the lower the power loss. Furthermore, the spacing between traction-substations is longer for higher voltage electrifications, making them more energetically economic. The typical spacing between traction-substations is approximately 1,5-2 km for 750 Vdc systems, 3-5 km for 1500 Vdc and 6-8 km for 3000 Vdc systems.

There are two kinds of rectifiers, the 6-pulse and 12-pulse system rectifiers. The second features two sets of 6-pulse rectifiers connected in series or in parallel, which causes less harmonic interferences and is capable of providing higher voltage and current, respectively. In those cases with 12-pulse rectifiers, the transformer needs to have two secondary windings (star-triangle connection) or simply a connection of two two-winding independent transformers [4].

Most DC electrification systems use overhead wires but conductor rail or third rail is an option up to about 1000 V, as for higher voltages the security standards will not allow it. Third rail configurations are more compact than overhead configurations and can be used in smaller-diameter tunnels, an important factor for subway systems. All in all, third rail is considered an option only for low speed and small trains in urban usage. London Underground uses this configuration (electrified under 600 Vdc).

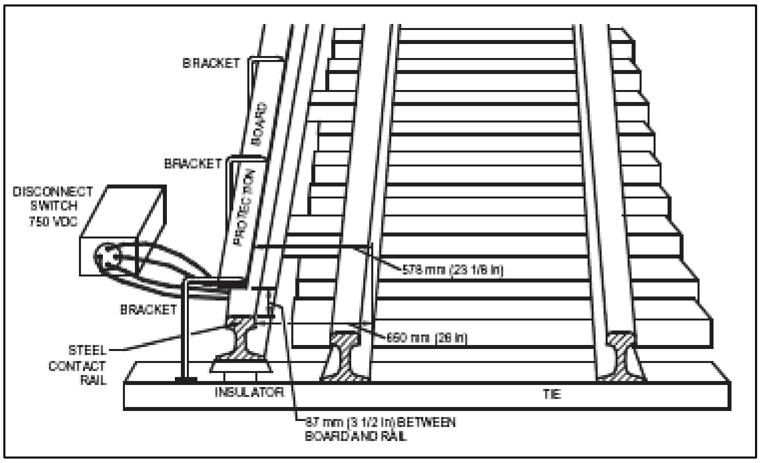


Figure 2 Third rail scheme in a DC railway. *Source: Federal Highway Administration (U.S.)*

As stated before, the returning of the current goes through the running rails but in some configurations there is also a fourth rail to provide an easier path to return the current to the traction-substation. This scheme was introduced to avoid the so called stray currents: returning currents that flow through tunnel linings or through nearby iron pipes due to the voltage potential between earth and running rails. Stray currents and rail potential are a sensible parameter, as they are directly bond to the contact voltage and therefore, prevention measures are always implemented regarding health and security issues [5].

To improve the energy efficiency, rolling stocks with regenerative breaking have been introduced in the last few decades: they are capable of transforming the kinetic energy during the breaking into electric energy that is released to the contact line or used to feed the auxiliary services of the train. However, this energy injected into the contact line is lost if there are no other trains nearby that need it at the same moment. For this reason reversible traction-substations are being introduced, inverting the DC current into AC and providing a path to inject it to the grid.

5.3 Alternating current electrification

The first attempts to electrify a railway in AC current where performed between the end of the XIX century and the beginning of the XX century. The advantages of using high-voltage AC for the power supply from generating stations to the railway feeder points were recognized, and therefore the first traction transformers and converters were firstly developed [6]. One problem that they faced was that AC induces Eddy currents, particularly in non-laminated field pole pieces, which causes overheating and loss of efficiency. To try to alleviate these problems, some countries[1] standardized on 15 kV the frequency of 16.7 Hz (one third of the commercial frequency of 50 Hz) [7].

Another big problem that the AC electrification faced was how to feed a triphasic motor with AC monophasic current (from the traction-substation), and at the same time be able to perform a total speed control.

[1] In Europe: Austria, Switzerland, Germany, Sweden and Norway.

It was not until the 40's when the first railway was electrified in Germany[2] using the nominal frequency of 50 Hz. In the 70's, with the development of the current source inverter (CSI) and semiconductor technologies, the triphasic motor became almost universally used [8].

Nowadays, there are three main kinds of AC railway electrifications: direct feed system (1x25 kV), autotransformer-fed system (2x25 kV) and Booster-Transformer system.

5.3.1 Direct-fed system (1x25 kV)

This is the simplest system. At traction-substations the electrical power is transformed from the high voltage power lines to 25 kV. Then, it is supplied to the overhead catenary system.

These systems can operate at 12.5 kV, 25 kV or 50 kV. However, the 25 kV configuration (1x25 kV) is considered the world standard for this system. The typical spacing between substations is 25-40 km and, with traction-substations located at such wide spacing, a strong and reliable utility net is required, typically between 60 kV and 230 kV. The rated power of the substation tends to be between 30 MVA and 60 MVA.

In addition to the technical advantage of wide spacing between traction substations (lower number of them needed); the lower currents required due to the higher voltage system makes it possible to design a smaller cross section catenary, becoming more economically efficient.

Regarding energy efficiency, less current flowing in the catenary conductors imply lower Joule Effect losses and therefore, the voltage drop in the overhead line has less magnitude. All in all, these conditions make the 1x25 kV voltage systems suitable for medium-high speed trains with large power loads but for interurban railways as well, as the headways of the different train lines can be increased and the power demand of the trains can be higher.

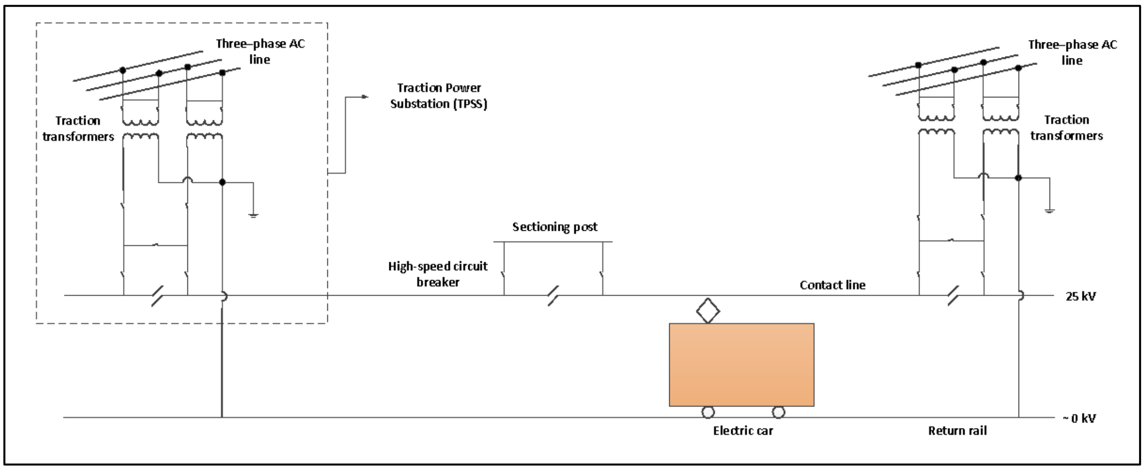


Figure 3 Typical 1x25 AC electrification system

At substations and at approximate mid-point between substations, phase breaks (or neutral sections) are installed in the catenary system to separate sections operating at different phases. Adjacent to the mid-point catenary phase-breaks, wayside switching stations are

[2] In Friburg, the line is called *Höllentalbahn*.

installed to enable switching operations of the catenary system in the event of substation failure. This aspect does not apply to DC voltage systems, as in those there exists a continuous electrification though all the line (in normal operation). Nevertheless, there are 1x25 kV configurations were these neutral sections do not exist in the feeding points at the substations. In these cases, there can only be one transformer connected with the power line of the grid.

Another typical aspect of 25 kV voltage systems is the paralleling between existing catenaries. These paralleling stations are located throughout the line and their function is to improve voltage profile along the system for better current sharing between conductors of the adjacent tracks.

Nevertheless, one handicap that these systems imply is the so called *Electromagnetic interference* (EMI) existing between the catenary conductors and the adjacent equipment of the railway system. To avoid or mitigate this effect, Booster Transformers were formerly used. Their purpose was to cause the catenary and return currents flow as closely as possible to each other so that they cancel their external effects and reduce EMI with wayside equipment. The higher number of booster transformers yields higher levels of mitigation, but impedance of the distribution system correspondingly increases, which is a disadvantage of this system. [9] Nowadays other techniques are implemented, such as a strategic location of the return feeder that results in greater mitigation effects. The concern about this phenomenon is becoming more and more important regarding health issues more than equipment compatibility.

5.3.2 Autotransformer - fed system (2x25 kV)

This voltage system has two main differences compared with the 1x25 kV electrification; the traction substations transform the grid voltage to 50 kV instead of 25 kV and that autotransformers are located along the line.

The power injection to the overhead catenary system is performed through a transformer with two secondary windings capable to transform the grid output to 25 kV for each one. The return is connected to the neutral point of the secondary (between the two windings) and the catenary to one of the windings. Consequently, a catenary – rail voltage of 25 kV is achieved. The other winding connects the feeder (negative feeder) to the rail so 25 kV is as well obtained. Since the catenary to rail and the negative to rail voltages are both of 25 kV, the system gained the name 2x25 kV.

Typical substation spacing is approximately 50 – 60 km. Similarly to the 1x25 kV electrification system, with the traction power substations located at wide spacing a strong and highly reliable grid connection is required, typically between at 115 kV or 230 kV. The rated power of the substations is about 40 to 80 MVA. These highly powered substations answer for the large spacing existing between them and due to the high power demand of the trains, usually high speed trains.

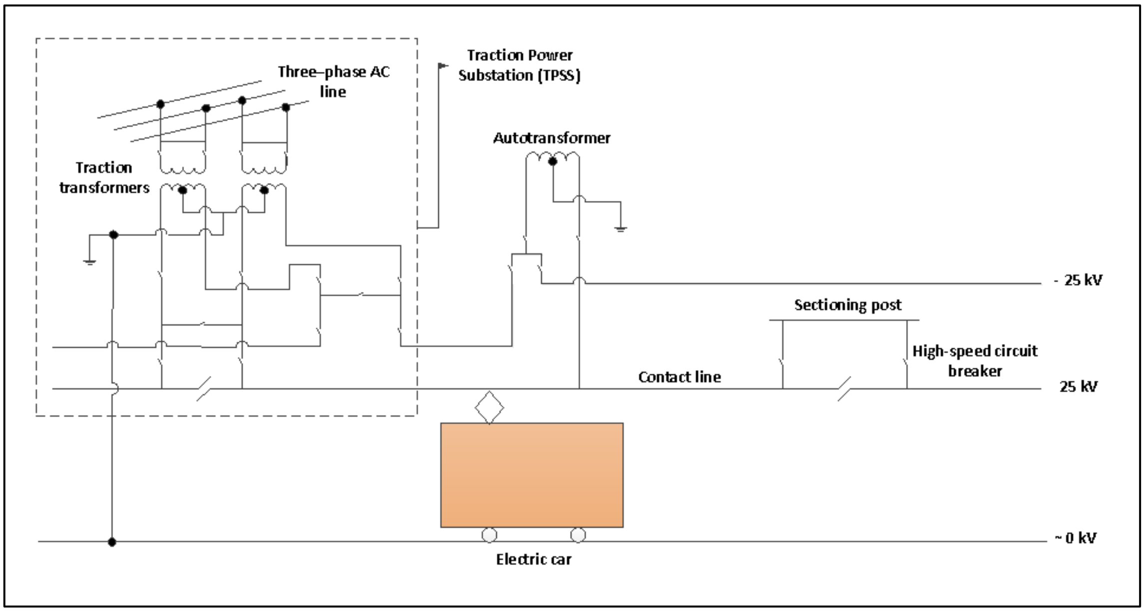


Figure 4 Typical 2x25 AC electrification system

At regular intervals (8 – 12 km), autotransformers stations are installed. The purpose of the autotransformers is to transform the 50 kV feeder to catenary voltage to 25 kV catenary to ground (rail) voltage. With this installation, the power is distributed along the system under 50 kV and the power is used by the trains at 25 kV. Current conduction at 50 kV implies even lower Joule Effect losses than 1x25 kV and therefore, the voltage profile can overcome large power loads demanded by the high speed trains. Moreover, as the train utilization voltage is of 25 kV, electric clearances for 50 kV are not necessary. They are the same needed for 1x25 kV electrification.

5.4 Typology of rolling stock regarding voltage system

Once the railway main electrification systems are reviewed, there can be a theoretical classification regarding train typology and voltage system:

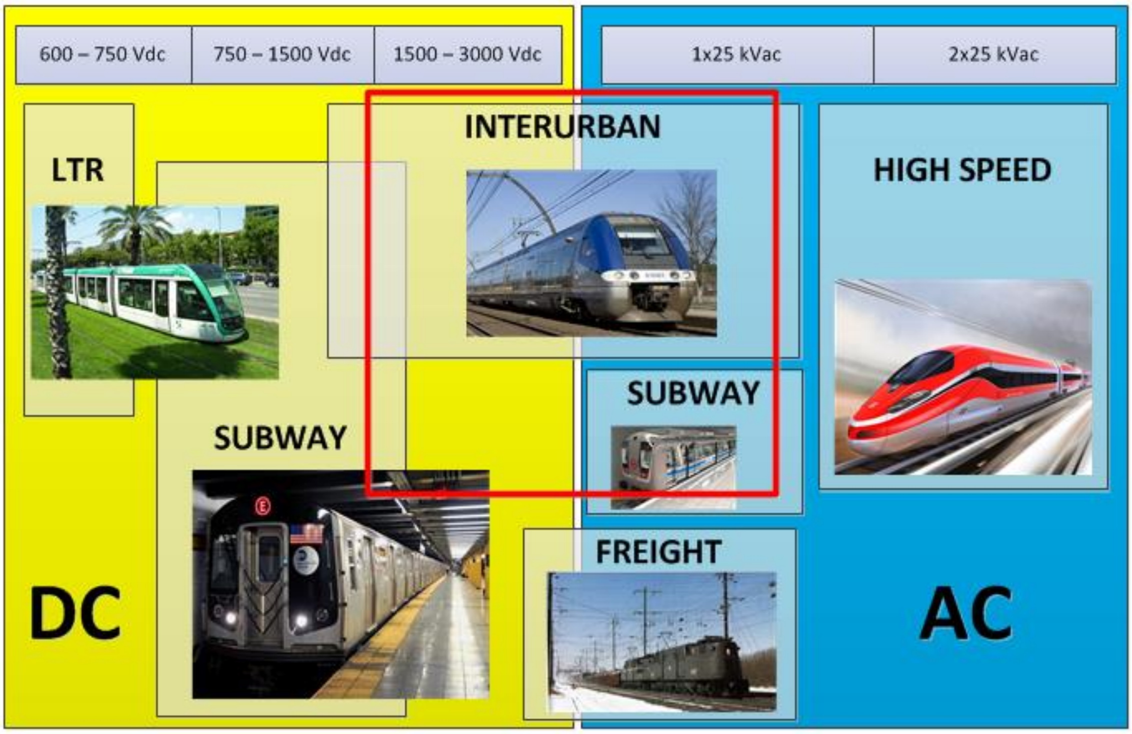


Figure 5 Rolling stock typology scheme with shared fringe of use

The red square represents the shared fringe of use that this study will cover. It is conformed basically by passenger trains that cover distances within metropolitan areas sharing sectors with subway systems (tunneled sectors). As shown in the picture above, the voltage systems comprised in the shared fringe of use are the DC electrification systems of medium voltage (1500 Vdc) and the 1x25 kVac.

As a remark, it should be noticed that subway systems are as well included in this shared area of study. The vast majority of this railway typology are electrified at the range of 600 – 1500 Vdc, but the fact that *Delhi Metro* is electrified at 25 kVac and said to be the 7th largest Metro service in the world by 2016 (phase III finished), makes it suitable for this study to include it as a reference in the use of 25 kV voltage system. Nowadays, Delhi Metro is the thirteenth largest metro in the world in terms of length and number of stations [10].

When speaking about freight trains, notice that even though many work under electric power, a vast majority are driven by combustion motor locomotives, not covered in this scheme.

6 Voltage System Selection Criteria

6.1 Introduction

Railway voltage system selection is a major design element that will affect every other aspect comprised within the whole railway system: from rolling stock to power supply facilities and distribution scheme (overhead line, conductor rail, etc). The traditional factors that determine the selected voltage system, approached in the previous chapter of this study, are the following:

- Previous experience
- Aesthetics
- Sustainability
- Longevity of technology
- Maintenance free content
- Marketing of the technology company

Regarding more technical reasons, there are other factors as well to be considered:

- Maximum power demand of load
- Level of redundancy desired
- Land cost (to consider the number of power supply facilities needed)
- Availability of technology and equipment

These factors will usually be studied and as a result, an electrification scheme with a defined voltage system will be selected. However, there are cases where more than one system is feasible; they have a shared fringe of use.

That is the case of the line studied. The Barcelona – Vallès line operated by *Ferrocarrils de la Generalitat de Catalunya* (FGC) is currently electrified in 1500 Vdc and a possible implementation of 25 kVac will be evaluated.

This study will start analyzing and listing the operational conditions and constrains the current DC Barcelona - Vallès line has. This information will be used as Input data for the following comparative analysis and the same conditions will have to be achieved or improved by the studied AC proposal.

The focus of this chapter will be on cost factors and restrictions imposed by International Standards that differentiate an electrification scheme of 1500 Vdc with an analogue of 25 kVac with both options being technically possible. Some cost factors will be presented and compared in this section and lately a budget will be presented for both systems. The restrictions imposed by International Standards will be tested in the load flow analyzer simulations.

6.2 Key assumptions and operational constraints

As mentioned before, to perform the study that has to conclude if a voltage system of 25 kVac is suitable to be applied in the intended line, the existing operational constraints need to be fulfilled.

6.2.1 Rolling Stock

- Maximum operational speed : 90 [kph]
- Minimum nº of passengers per train ≥ 724
- Passenger occupation of the train: 85 [%]
- Regenerative braking : Available

6.2.2 Traction Power Substations

- Number of TPSS ≤ 7
- Contingency criteria : N-1 (one TPSS not in use)

6.2.3 Train Fleet

- Time of journey : The same for each electrification system ± 3 minutes
- Headways : The same for each electrification system

6.2.4 Catenary

- Cooper equivalent cross section per track ≤ 592 [mm^2]

6.3 Infrastructure cost factors in 1500 Vdc and 25 kVac

6.3.1 Comparison of cost factors

In the following table there are different technical factors that affect the cost of the 1500 Vdc and 25 kVac electrification systems [11]. A comment for each factor is added in order to give an idea of which voltage system induces less cost or less technical difficulties when implemented.

Table 1 Comparison of on cost factors between a 1500 Vdc and 25 kVac voltaje system

Factor	1500 V dc	25 kV ac	Comments
Overhead line	1 MW load is equivalent to 666 Amps (unity power factor)	1 MW load is equivalent to 40 Amps (unity power factor)	Less cooper cross-section required for a 25 kV system. Fewer Amps imply lower Joule Effect losses.
Traction Power Substations	Close feeder station spacing (4 – 6 km) requires more TPSS and electric supply connections.	Typical spacing between TPSS is around 20-50 km. Less electric supply connections.	25 kV system is cheaper for long routes. Less civil works and land affordability required.
Support Insulators	Simplified insulation arrangements and greater design choice.	Substantially larger and heavier insulators required.	Simpler and cheaper insulators for a 1500 V system, though modern polymeric materials enable lighter and more compact

			25 kV designs
Support Structures	Simple Support arrangements at over bridges and tunnels.	More complex support arrangements at over bridges and tunnels.	Simpler and cheaper support arrangements for 1500 V system.
Electrical clearance	Small electrical clearance more easily accommodated by existing infrastructure.	Larger electrical clearance can require civil works to bridges and tunnels	25 kV systems may incur in substantial additional costs where tight clearance structures feature on the route.
Power supply imbalance	Rectifiers operate from three phase supply for equal loading in all phases.	25 kV transformers operate from a single phase with potential to cause supply imbalance. Higher connection costs.	25 kV feed would require additional consultation with the Distribution Network Operator to establish most economical means of supply provision.
Power supply harmonics	Substation harmonics may affect supply.	Problems with harmonics less likely.	Need for harmonic filters and may affect connection costs for 1500 Vdc configuration.
Electromagnetic compatibility	Low affectation to adjacent track circuits or signaling systems. Some mitigation measures may be needed.	Higher affectation. Mitigation measures must be implemented.	Potential higher cost for the 25kV system. Booster transformer may be required to comply with mandated EMC emission limits.
Traction return	Running rails required to have a good isolation from earth to reduce DC leakage current.	AC leakage current less of an issue and standard of rail – earth insulation not as high.	Cathodic protection of buried services may be required for 1500 V system.

The fields in green mean the advantageous electrification for the topic.

Some of these factors will be evaluated with the traction simulations, and others would need further analysis. However, some considerations regarding these factors not studied and for the particular conditions of the FGC line are listed below.

6.3.1.1 Electrical clearance

High voltage systems require increased electrical clearances which can entail costly civil works to existing infrastructure, as well as requiring the installation of physically bigger, and therefore more costly insulating components. Public safety issues may increase costs as well. [12]

Table 2 Electrical clearances for 1500 Vdc and 25 kVac voltage systems

	Electrical clearances	
	1500 Vdc	**25 kVac**
Static clearance (mm)	150	200
Passing clearance (mm)	100	150

Regarding the track alignment of the Barcelona – Vallès line, this electric clearance should not be a major handicap for the 25 kV voltage system, as it is mainly an underground line in the urban sectors and in the interurban sectors there are not street crossings or places where the electrical clearance could become an issue.

Isolating measures regarding health issues for railway workers in passenger stations may be needed, however.

Regarding gauge clearances, a 25kV voltage system would cause problems in the tunnel sectors, as the tunnel clearances were implemented following the historic gauge, insufficient for high voltage electrifications. A further study accounting on mesures to adapt the tunnels to a new higher voltage system would be needed. However, there are technologies and procedures available for these kinds of cases, such as the lowering of the trackbed or raising the soffit heights [13].

6.3.1.2 Support insulators

One of the main reasons to electrify tramways and light trains in low voltage systems, which usually share track sectors with streets and pedestrians, is due to their low electric clearance and for the low insulating measures required. In the study case, the line does not share spaces with pedestrians or roads and therefore particularly demanding measures regarding these aspects would not be required. Nevertheless, insulation procedures and measures should be taken into account in passenger stations and when signaling immunization could be compromised.

6.3.1.3 Support structures

The particular topographic conditions of the line under study are tunnel sectors, basically. There are no bridge crossings and only one short sector on viaduct. Special measures regarding support structures would not be an issue for an electrification system of 25 kVac.

6.3.1.4 Electromagnetic compatibility (EMC)

There is a big concern about the effects that this phenomenon can cause regarding health issues, so mitigation measures need always to be accounted. Regarding effects on wayside equipment, more and more communications circuits are being replaced by digital and optic fiber systems immune to EMI and signaling system manufacturers are capable of providing equipment specially designed and built for electrified railroads and resistant to the effects of EMI [15]. In the FGC line, the EMC mitigation measures should be the standard for these kind of voltage systems, as there are no particular conditions such as the train running at high speed near residential areas; the train speed is limited to 60 kph inside urban areas.

7 Comparative Study: Input data

7.1 Introduction

The purpose of the comparative study is to validate if there is a 25 kVac traction system suitable for the existing 1500 Vddc electrification (accomplishing the same operational contraints). To do so, scenarios of operation have been selected and a traction simulator *STElec* has been used. This simulator is entirely developed by SENER and currently used in many projects that this consultant engineering has under contract. Suitable for DC and AC electrifications systems, STElec provides all the results needed to design and size the electrification system of railway lines.

It consists of three modules; each of them depending on the one ran previously in the following order: train simulation (running), fleet simulation and electric simulation.

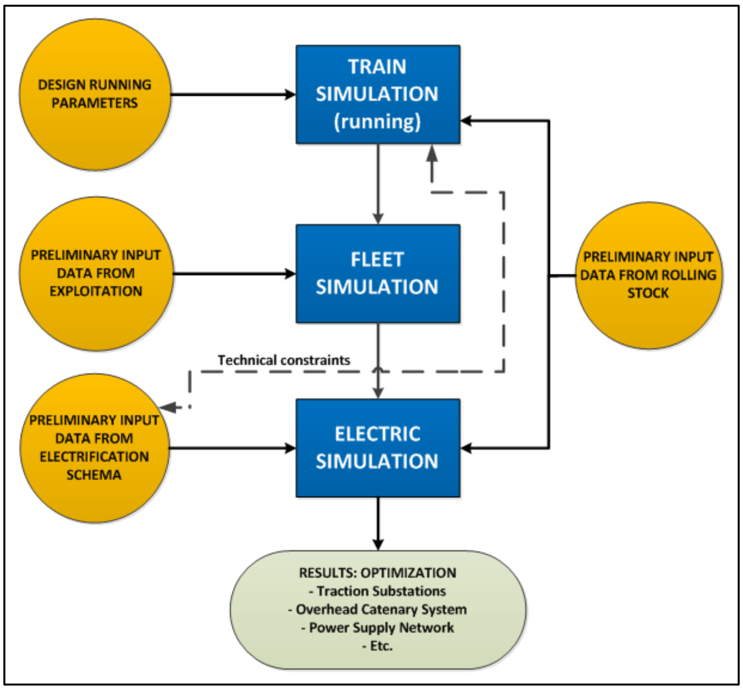


Figure 6 Simulation modules of the STElec simulator and their relations

The three modules will be explained making use of the input data available for the targeted study.

7.2 Train simulation

This simulation analyses the vehicle's parameters when moving along the line with defined conditions of operation. As a result of this stage of simulation, the following data is generated: time of journey, average speed of the train, acceleration, braking force, power consumption (mechanics of rim and electric effects in pantograph), and power to be recharged.

Speed and acceleration profiles are created thanks to the kinematic analysis and then a dynamic analysis is performed to adjust the kinematics' results with the real constraints of the rolling stock.

7.2.1 Input data

7.2.1.1 Track data

- Total line length

Table 3 Line sectors of the Barcelona-Vallès line

Line Sector	Length [m]
Plaça Catalunya – Terrassa Rambla	29.639
Sant Cugat – Sabadell Rambla	12.200
Gràcia – Avda. Tibidabo	1.859
Sarrià – Reina Elisenda	548

- Station/Stop locations[3]

Table 4 Passenger stations existing for each sector of the Barcelona-Vallès line

Plaça Catalunya – Terrassa Rambla		Sant Cugat – Sabadell Rambla		Gràcia - Avda. Tibidabo		Sarrià - Reina Elisenda	
Name	**KP (m)**	**Name**	**KP (m)**	**Name**	**KP (m)**	**Name**	**KP (m)**
Pl. Catalunya	0	**Sant Cugat**	0	**Gràcia**	0	**Sarrià**	0
Provença	1.226	**Volpelleres**	1.532	**Plaça Molina**	635	**Reina Elisenda**	101,72
Gràcia	1.978	**Sant Joan**	2.728	**Pàdua**	955		
Sant Gervasi	2.607	**Bellaterra**	4.402	**El Putxet**	1.379		
Muntaner	2.959	**Universitat Autònoma**	5.679	**Avda. Tibidabo**	1.859		
La Bonanova	3.534	**Sant Quirze**	9.572				
Les Tres Torres	4.010	**Sabadell Estació**	11.320				
Sarrià	4.614	**Sabadell Rambla**	12.200				
Peu Funicular	6.716						
Vallvidriera	8.392						
Les Planes	9.235						
La Floresta	12.165						
Valldoreix	13.855						
Sant Cugat	15.298						
Mira-Sol	16.822						
Hospital General	18.360						
Rubí	20.107						
Les Fonts	25.119						
Terrassa	29.496						

[3] This division of line sectors may not coincide with the division considered by the operator *FGC*.

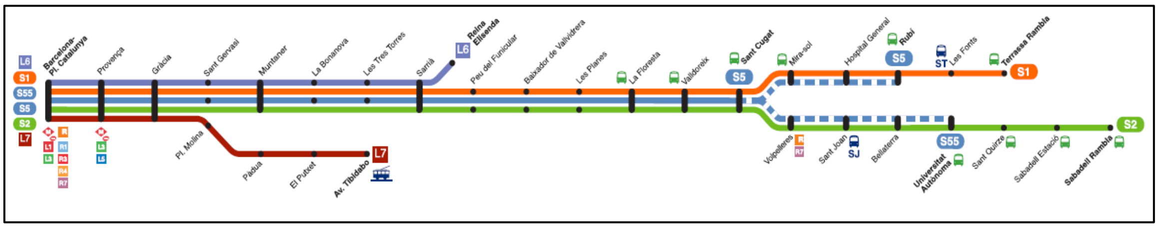
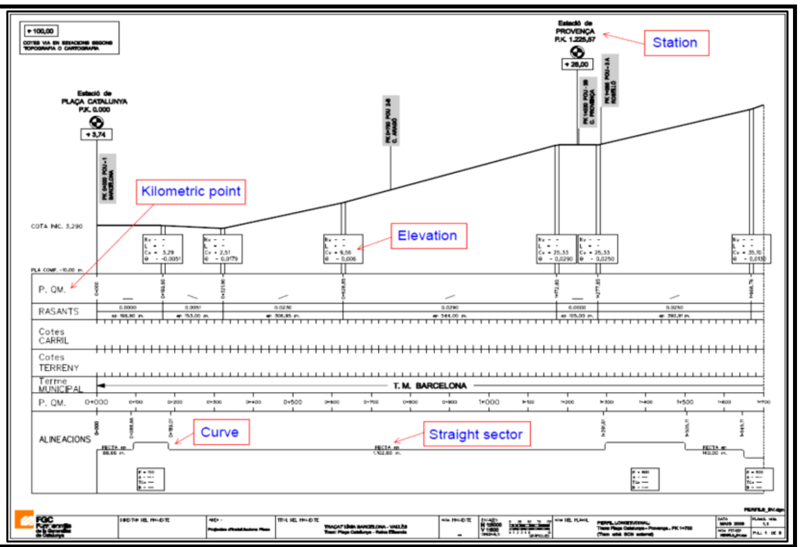
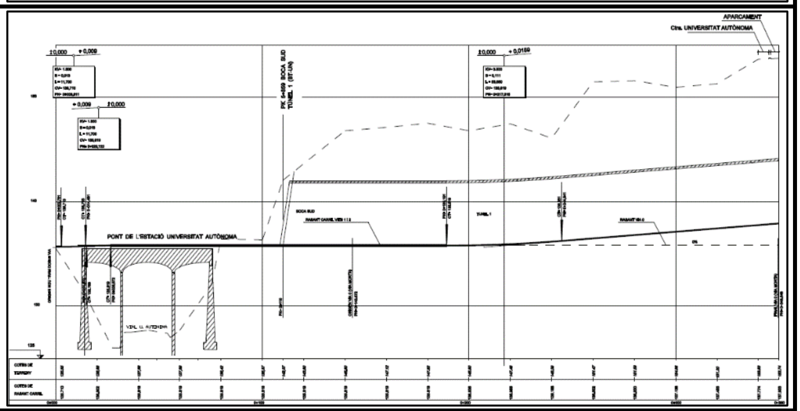


Figure 7 Scheme of the train lines operating in the Barcelona-Vallès line. *Source: Ferrocarrils de la Generalitat de Catalunya (FGC)*

- Scheme of route

These magnitudes are track restrictions used as parameters in the formulas comprised within the kinematic and dynamic analysis.

Table 5 Track longitudinal profiles of the Barcelona –Vallès line. *Source: Ferrocarrils de la Generalitat de Catalunya (FGC)*

Straight sectors and curves (curvature radius)	
Longitudinal profiles: • ramps • cambers	
Transversal profiles: • slopes • superelevations	
Cross sections of railway tunnels	

7.2.1.2 Rolling Stock data

7.2.1.2.1 Direct current configuration

The UT111 and UT112 are the rolling stock currently used along the FGC line. Though new models of rolling stock are being introduced, the two UT considered are the ones with major representation in the lines of the studied railway. The majority of the rolling stock data was provided by *FGC*, and the data required not provided was assumed with typical values for this kind of rolling stock.

Table 6 UT 111 and UT 112 main characteristics

UT 111

Configuration	M-T-M
Voltage supply	1.500 Vdc
Total weight (T)	105.05
Maximum passengers	587
Traction power (kW)	1.104
Auxiliary services power (kW)	33,75
Inertia momentum of rotating masses	1.07
Wheelbase (mm)	1.435
Driving axles	16
Non driving axles	8
Mass of the train on a drive wheel	4.887,5
Electromechanical performance	0,95
Regeneration performance	0
Power factor	0,88
Max speed (km/h)	90
Max acceleration (m/s^2)	1,1
Max braking acceleration (m/s^2)	1,1
Transversal acceleration without compensation (m/s^2)	0,65
Max longitudinal Jerk (m/s^3)	0,25

UT 112

Configuration	M-M-T-M
Voltage supply	1.500 Vdc
Total weight (T)	195
Maximum passengers	724
Traction power (kW)	2.160
Auxiliary services power (kW)	45
Inertia momentum of rotating masses	1,07
Wheelbase (mm)	1.435
Driving axles	12
Non driving axles	4
Mass of the train on a drive wheel	6.375
Electromechanical performance	0,93
Regeneration performance	0,95
Power factor	0,88
Max speed (km/h)	90
Max acceleration (m/s^2)	1
Max braking acceleration (m/s^2)	1
Transversal acceleration without compensation (m/s^2)	0.65
Max longitudinal Jerk (m/s^3)	0,25

7.2.1.2.2 Alternative current configuration

In order to perform the comparative study between a DC and an AC configuration, the characteristics of the rolling stock working under 25 kVac need to be of similar magnitude as the ones currently in use in the *FGC* line. Moreover, to give a more realistic approach to the study, it was selected a commercial model currently in use in other lines of the world. With these considerations, the MOVIA train of Bombardier was selected. The MOVIA of Bombardier is currently used in the RS2 Delhi Metro line [16]. As a remark, notice that as well as the proposed rolling stock is suitable for the line of study, it does not have exactly the same characteristics as the existing ones and therefore, the results obtained with them should not be presented as equivalent and for pure comparison.

Table 7 MOVIA main characteristics

MOVIA	
	
Configuration	T-M-T-M
Voltage supply	25 kVac
Total weight (T)	168
Maximum passengers	1.156
Traction power (kW)	2.000
Auxiliary services power (kW)	50
Inertia momentum of rotating masses	1,07
Wheelbase (mm)	1.435
Driving axles	8
Non driving axles	8
Mass of the train on a drive wheel	5.250
Electromechanical performance	0,85
Regeneration performance	0,85
Power factor	0,9
Max speed (km/h)	90
Max acceleration (m/s^2)	0,82
Max braking acceleration (m/s^2)	1
Transversal acceleration without compensation (m/s^2)	0,65
Max longitudinal Jerk (m/s^3)	0,2

The distribution of the rolling stock, along the two different electrifications:

Table 8 Rolling Stock operating for each line in the 1500 Vdc configuration

	DC	AC
L7 Avinguda Tibidabo	UT111	MOVIA
S1 Terrassa	UT112	MOVIA
S5 Rubí	UT111	MOVIA
S2 Sabadell	UT112	MOVIA
S55 Unviersitat autònoma	UT111	MOVIA

7.2.1.2.3 Davis' coefficients

Particularly important parameters of the rolling stock are the Davis' coefficients, as they provide the formula to calculate the effort needed to overcome the propulsion resistance for every instantaneous velocity during the journey. To compute them, it becomes necessary the interpretation and use of the curve of speed – maximum effort in rim/braking and the advance effort in straight sector. Once obtained the coefficients, the formula can be applied to the train simulation:

$$R_{advance} = A + B \cdot v + C \cdot v^2 \quad [kN]$$

Where *v* is expressed in [km/h].

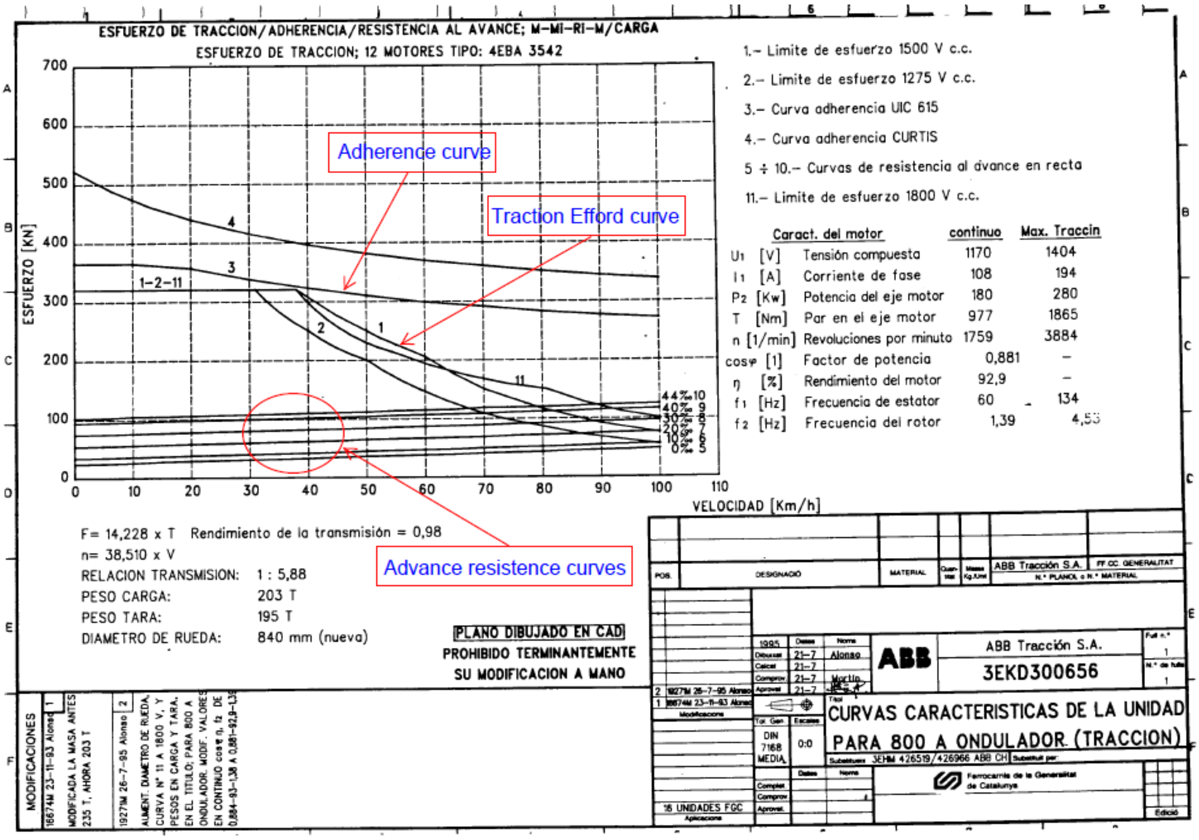


Figure 8 Effort curves of the UT 112 rolling Stock. *Source: Ferrocarrils de la Generalitat de Catalunya (FGC)*

7.2.1.3 Train performance constraints

Once modelled the track and rolling stock, some operational constraints, usually regarding passenger comfort or operation criteria are added:

- Maximum values of[4]:
  - Longitudinal acceleration (m/s^2)
  - Longitudinal Jerk (m/s^3)
  - Change of slope lack (mm/s)
  - Acceptable change of slope (mm/s)
  - Acceptable excess of slope (mm)
  - Vertical acceleration (m/s^2)

Moreover, other parameters such as train stopping time at stations, or external conditions reducing running-train-parameters are taken into account (e.g. when crossing bridges or stations without stop).

7.3 Traffic simulation

Once the running train's simulation within the line is performed and saved, it can be linked with the fleet simulation, which implements the real conditions that stress a railway system.
Its main parameters are:

- Headway for each profile of vehicle (including peak hours and off-peak hours)
- Total time of simulation (s);

The global map of vehicles is generated by means of the superposition of vehicle's profiles considering the defined operation criteria.

Results of fleet simulation are available as a graphic application, the so called "traffic grid", which represents a position(x) at time (y) of each train running inner the line.

7.3.1 Baseline scenario. Hypothesis and assumptions

7.3.1.1 Simulation period

The traffic considered for this study is the one most able to stress the line referring to power demand. Therefore, the train traffic compressed within the rush hour during the morning in working days (Monday to Friday) is selected: from 7.30h to 8.30h.

7.3.1.2 Traffic grid starting constraint

It is as well considered that the starting point of all trains is Plaça Catalunya, at the absolute zero kilometric point. This hypothesis makes the traffic simulation much easier and, as the simulated scenario does not compress the first services of the day and all the trains are already in circulation in the selected period, this assumption is absolutely acceptable and does not affect the results. The reality is that the trains are located in the train garages throughout the line and from there they are distributed.

---

[4] Usually depending on the different rolling stock models and the track morphology

7.3.1.3 Headway

Another assumption for this study is the existence of a fixed headway for each line throughout the simulation time. Due to operational constraints such as minimum time for railway switches in Plaça Catalunya, a fixed service headway is not always achieved. The procedure to assume it as fixed for each line consisted in finding an average headway throughout the simulation time (7:30 to 8:30).

Checking the timetables and applying the average headway for each line, the following headways are considered:

Table 9 Headways considered for each line during peak hour

	First service (h:min)	Headway (min)	turning time at last station (s)
L7 Avinguda Tibidabo	7:33	6	300
S1 Terrassa	7:35	11	300
S5 Rubí	7:31	14	360
S2 Sabadell	7:30	11	300
S55 Unviersitat autònoma	7:37	9	600

The same procedure was applied to find an average turning time at last station for each line.

Notice that the headway of the L6 trains is not included. This fact comes from FGC operational constraints, as they cover the L6 sector with the other lines during the studied period. Taking advantage of this fact, the short inter-station sector at the end of the L6 line between Sarrià and Reina Elisenda is not considered for this study. It is believed that this simplification will not have an impact in the results, as the sector comprises only about 500 m without a change of slopes or curves.

7.4 Electric simulation

7.4.1 Input Data

To perform an electric railway line simulation, it's necessary to model all the elements of the so called electric traction network: Traction Substations, Overhead Contact Lines (catenary) and track circuit.

7.4.1.1 Traction Power Substations:

- Number and location of tractions substations.
- Type of substations: rectifier (DC) substation or transformer (AC) substation.
- Line-High Voltage connections: total length (km), specific impedance (Ω/km), etc.
- Amount of rectifier groups (DC) or transformers (AC).
- Characteristics of each rectifier group/transformer: nominal power, transformation ratio, type of rectifier (6- / 12-phase), voltage during short-circuit breakdown, no-load voltage, etc.
- Characteristics of rechargeable batteries or inverters (if existance).
- Location (m).

7.4.1.1.1 DC electrification

Table 10 TPSS data for the DC voltaje system

TPSS	Kp [m][5]	HV connection [kV]	Pcc AC Network [MVA][6]	Rectifier Power [kVA]	Transformer Power [kVA]	Transformer ratio	Ɛcc transformer [%][7]
Pl. Catalunya	0	25	1.000	1x2.000	1x2.250	25.000/1.180	6
Gràcia	1.978	25	1.000	2x2.700	2x3.000	25.000/1.180	3,5
Sarrià	4.614	11	500	4x2.000	4x2.250	11.000/1.180	1,5
Les Planes	9.235	25	1.000	1x2.700	1x3.000	25.000/1.180	7
St. Cugat	15.298	25	1.000	3x1.800	3x2.250	25.000/1.180	2
St. Quirze	24.870	25	1.000	2x2.000	2x2.250	25.000/1.180	3
Les Fonts	25.119	25	1.000	2x2.000	2x2.250	25.000/1.180	3

The distribution of the TPSS along the line is shown in the following scheme (big blue circles):

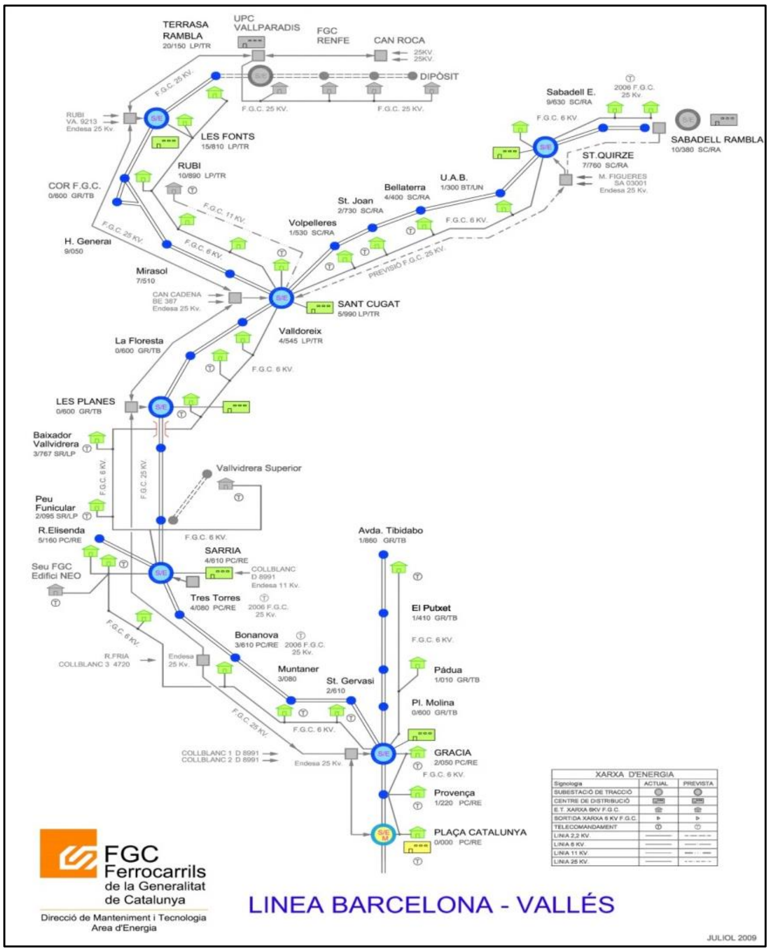


Figure 9 Distribution of the TPSS in the DC voltage system. *Source: Ferrocarrils de la Generalitat de Catalunya (FGC)*

[5] Reference in Plaça Catalunya
[6] Values from IEC 60076-5
[7] Values from IEC 60076-5

7.4.1.1.2 AC electrification

Table 11 TPSS data for the AC voltage system

TPSS	Kp [m][8]	HV connection [kV]	Pcc AC Network [kVA][9]	Transformer Power [MVA]	Transformer ratio	Ɛcc transformer [%][10]
Gràcia	1.978	60	1.000	1x30	60.000/27.500	10
St. Cugat	15.298	60	1.000	1x30	60.000/27.500	10

The proposed distribution of the TPSS along the line is shown in the following scheme:

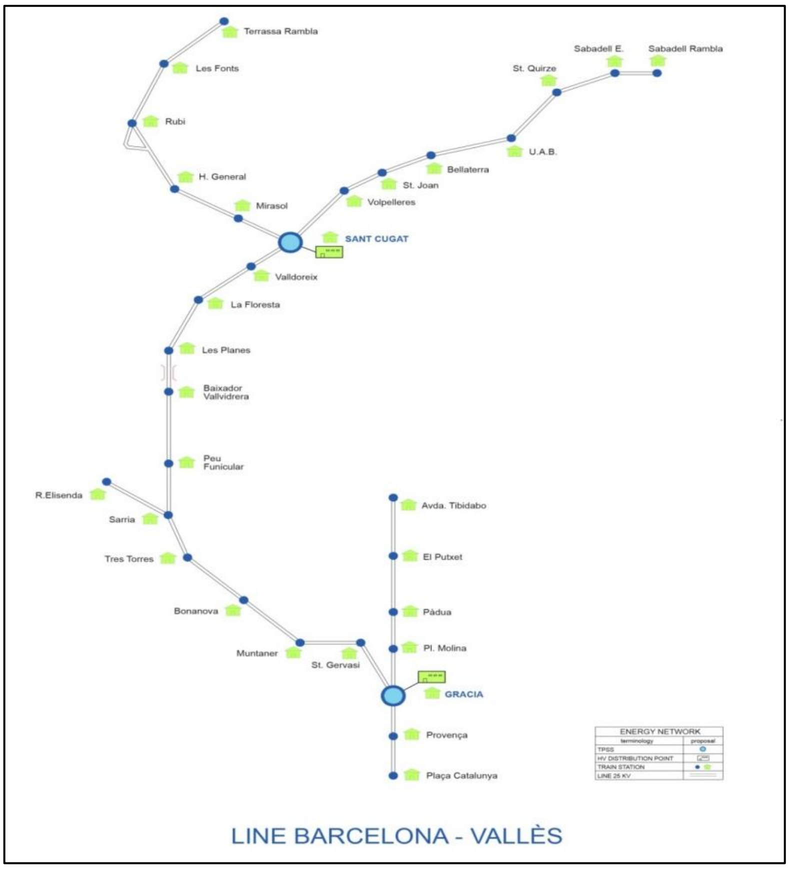


Figure 10 Distribution of the TPSS in the AC voltage system

The proposed distribution of the TPSS was selected regarding the following factors:

- Appropriate spacing between the substations to locate them.
- Power demanded by the trains in the present configuration of the line to size them.
- Future upgrading of the Barcelona – Vallès line in Terrassa and Sabadell make a TPSS in Sant Cugat a most suitable option.

[8] Reference in Plaça Catalunya
[9] Values from IEC 60076-5
[10] Values from IEC 60076-5

- Future upgrading connecting the Barcelona – Valles line and Llobregat – Anoia line (also operated by *FGC*). This connection would unite the passenger stations of Plaça Espanya and Gràcia, making the TPSS location in Gràcia a good choice to foresee the greater power demand needed [17].
- Availability of HV feeding lines. The line goes through a metropolitan area with many options of connection to a HV grid:

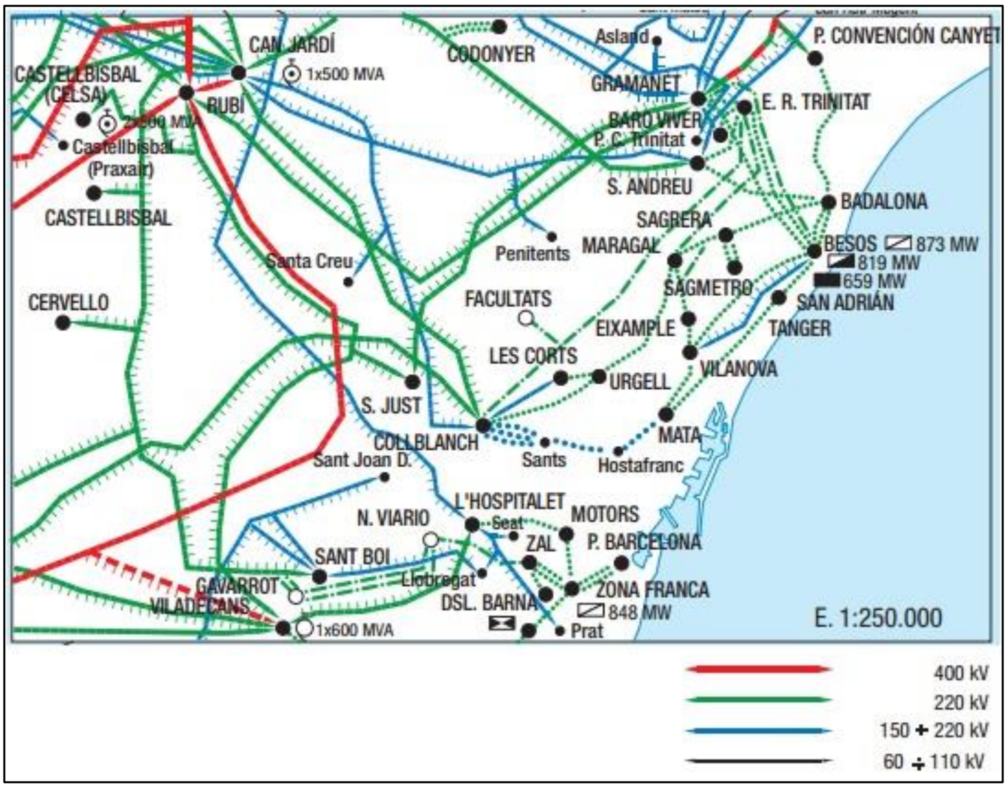


Figure 11 Distribution of the HV lines across Barcelona Metropolitan area. *Source: Red Eléctrica Espanyola (REE)*

Another important comment to make regarding the design of the traction network for the 25 kVac configuration is the use of a single transformer for each TPSS. As explained in the *Electrification systems* chapter, in the cases where only one group of transformation is installed in the traction substation, a neutral section in the feeding point is not needed.

7.4.1.2 Neutral Section

As explained in the *Electrification Systems* chapter, an electrification system under AC needs a neutral zone where it exists an electrical discontinuity. Due to this discontinuity, the train cannot traction in the neutral section as there is the danger that when crossing it, two pantographs of the same train are in the different sides of the neutral section and as a consequence, a short circuit takes place. It is fundamental therefore that the train goes in drift speed when passing a neutral section.

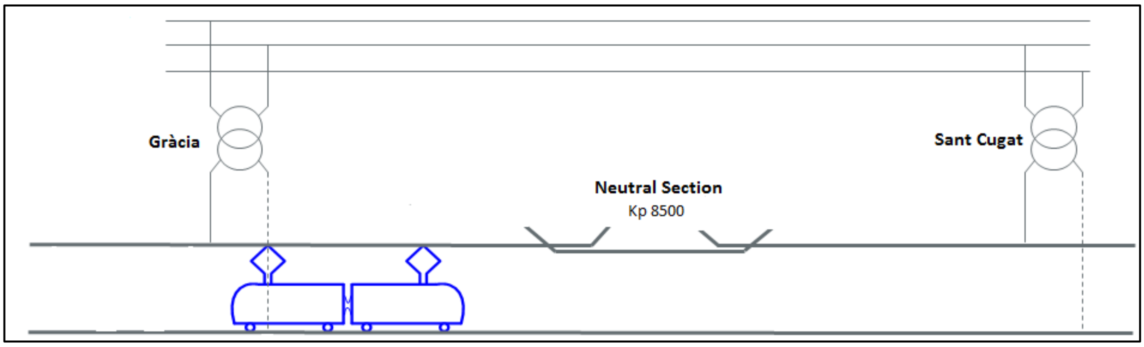


Figure 12 Scheme of the neutral section

The fact that there is the need to run in drift speed makes it important to locate neutral sections in line sectors where the elevation gradient is nearly flat and where the train has enough inertia to overcome the sector in drift speed.

There are different lengths of the neutral zone, depending on the type of rolling stock (high speed, regional, etc.) and on the particular configuration of the train. In the train model proposed for this study, the MOVIA has two independent pantographs located in the first and last car:

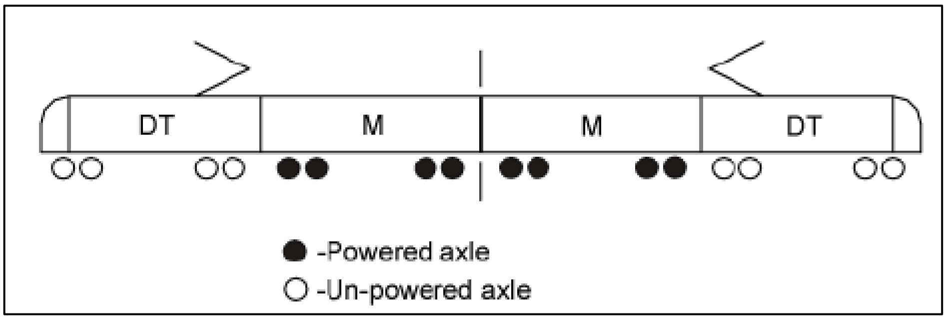


Figure 13 Scheme of the MOVIA train cars and pantographs. *Source: Propulsion System Delhi Metro RS2 (Bombardier)*

The fact that they are independent is an important advantage because it makes it possible for the train unit to be with the two pantographs in different sides of the neutral section (no connection between them, no short circuit) and consequently the neutral section can be shorter.

As stated when speaking about the TPSS characteristics, a neutral section in their feeding points is not considered. This configuration responds to different motivations:

1. Proximity with the nearby passenger stations

The fact that the passenger stations are located in such a short distance within each other makes it difficult to operate a neutral section as the trains need to traction to achieve commercial speeds and a neutral section located in the accelerating sector of the train would handicap the commercial times of the train line or even make the train stop before it reaches the other side of the neutral section again.

2. High elevation gradients in the TPSS' locations

Especially in Gràcia, there are big changes of slopes that would not appear suitable for a neutral section to be installed.

In this study is proposed a 50 m long neutral section located at the kp of 8500m (reference in Plaça Catalunya). This location is in a nearly flat section between Baixador de Vallvidrera and Les Planes.

7.4.1.3 Overhead Contact Line (Catenary):

- Single or double track
- Electric scheme of the catenary: separate (independent) or interconnected catenary
- Composition of catenary for line section (different for every section if necessary) and its conductors

The internal resistance of the conductors is calculated under restrictive conditions, supposing they have a temperature of 80 °C:

$$R_{cond} = R_o \cdot (1 + \alpha \cdot \Delta T)$$

Where:

- R_{cond} is the internal resistance of the conductor at 80 °C [Ω/m]
- $R_o = \rho \cdot \frac{l}{S}$ [Ω/m]
- ρ is the resistivity of the material at 20 °C [Ω·m]
- l is the length of the conductor [m]
- S is the cross section of the conductor [m^2]
- α is the temperature coefficient at 20 °C [1/°C]
- ΔT is the gradient of temperature existing between the reference temperature (20 °C) and the cable temperature (80 °C) [°C]

7.4.1.3.1 DC electrification

Table 12 Catenary characteristics for the DC configuration

		Material	Section (mm^2)	Radius (m)	Resistance (ohm/m)
TRACK 1	**messenger**	Cu	153	8,05E-03	1,17E-04
	contact	Cu	107	5,84E-03	1,71E-04
	contact	Cu	107	5,84E-03	1,71E-04
	feeder	Cu	225	9,73E-03	8,00E-05
	UIC 54	Cu			1,60E-05
	UIC 54	Cu			1,60E-05
TRACK 2	**messenger**	Cu	153	8,05E-03	1,17E-04
	contact	Cu	107	5,84E-03	1,71E-04
	contact	Cu	107	5,84E-03	1,71E-04
	feeder	Cu	225	9,73E-03	8,00E-05

	UIC 54	Cu		1,60E-05
	UIC 54	Cu		1,60E-05

No paralleling points between the catenaries of both tracks are considered along the line.

7.4.1.3.2 AC electrification

Table 13 Catenary characteristics for the AC configuration

		Material	Section (mm^2)	Radius (m)	Resistance (ohm/m)	Reactance (ohm/m)
TRACK 1	**messenger**	BZII70	70	4,72E-03	4,11E-04	4,11E-05
	contact	Cu	107	5,84E-03	1,71E-04	1,71E-05
	return feeder	LA	110	5,20E-03	3,07E-04	3,07E-05
	UIC 54	Cu			1,60E-05	1,60E-06
	UIC 54	Cu			1,60E-05	1,60E-06
TRACK 2	**messenger**	BZII70	70	8,05E-03	1,17E-04	1,17E-05
	contact	Cu	107	5,84E-03	1,71E-04	1,71E-05
	return feeder	LA	110	5,20E-03	3,07E-04	3,07E-05
	UIC 54	Cu			1,60E-05	1,60E-06
	UIC 54	Cu			1,60E-05	1,60E-06

No paralleling points between the catenaries of both tracks are considered along the line.

This is the catenary proposed in the first approach, which corresponds with the typical configuration for 25 kVac voltage systems. Considering the results obtained in the simulations with this configuration, reinforcement feeders would be added thereafter. The criteria to add feeders come from voltage drop and maximum current admissible in the catenaries.

The cross section per track of the proposed catenary is 287 [mm^2], fulfilling the constraint imposed in the *Key assumptions and operational constraints* chapter.

7.4.1.4 Grounding installations

- Distance between grounding points
- Equivalent resistance of the grounding points

7.4.1.4.1 DC electrification

In DC configurations grounding installations in the rail are not usually implemented. This responds to the need to have the high values of return currents under control, so it is common to isolate the rail and provide points where safe paths for the currents make them flow without interfering with nearby installations such as pipes.

However, the traction substations are always grounded with an equivalent impedance not higher than 2 Ω.

7.4.1.4.2 AC electrification

Grounding installations are always considered for the rail in order to maintain the rail voltage under the standardized limits. As a first approximation it was proposed a single ground rod every 400m, but in some contingency simulated scenarios (included in the simulation report) the voltage levels of the rail were too high. As a consequence, a single ground rod is located every 200m, connecting the rails of both tracks with the pole and earth.

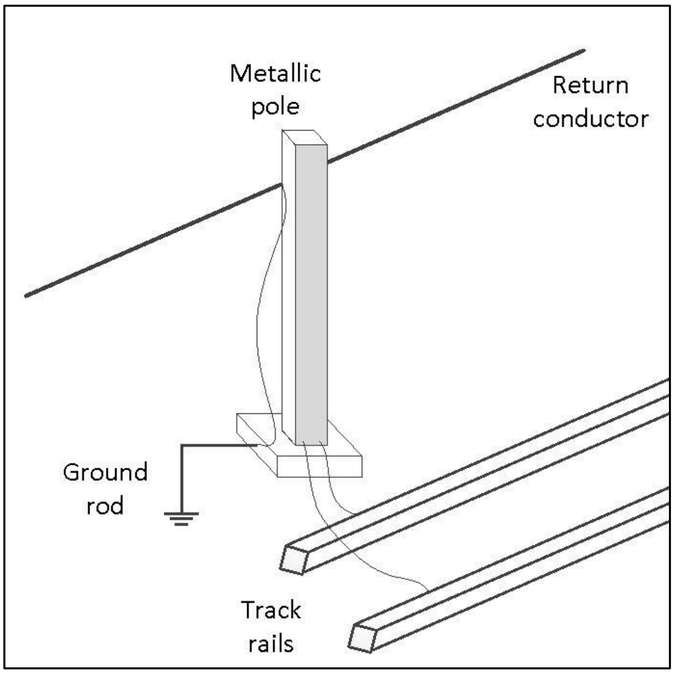


Figure 14 Scheme of a grounding point in AC electrification

To calculate the equivalent impedance of the ground rod, the following formula is used:

$$R_{rod} = \frac{\rho}{N \cdot L}$$

Where:

- ρ is the soil resistivity [Ω·m]
- N is the number of grounding rods
- L is the length of the rod

As said before, there will be grounding points every 200m and they will be comprised by a single grounding rod of 2 meters of length. The soil resistivity depends on the kind of soil and atmospheric factors such as rain, humidity, etc. In this study is supposed a constant soil resistivity of 100 Ω·m.

$$R_{rod} = \frac{100}{1 \cdot 2} = 50\ \Omega$$

Like in the 1500 Vdc voltage system, the traction substations are grounded always with an equivalent impedance not higher that 1,5 Ω.

7.4.2 Load flow analyzer

The load flow analyzer essentially analyses load, level of voltage and power regenerated and consumed in the electric traction system. The analyzer collects information obtained during the fleet simulation, data of the electric traction elements (substations, catenary and track circuit) and performs a load flow across the network using an iterative mathematical method for each sample of time, solving mathematic equations representing the different elements of the network.

These results can be obtained for both normal operation and contingency operation. Obtained results of electric simulation are available for further analysis in the form of numerical values and as graphics, shown in the *Simulation results* chapter in this document.

8 Comparative Study: Simulation Report

8.1 Introduction

This part of the study represents the core to validate the proposed electrification scheme for the studied railway line. The results obtained in the simulations will provide an answer to the question of the technical viability of the 1x25 kV electrification system in front of the DC system that is currently in use.

The steps followed to perform the electric simulation are as follows: once the train and fleet simulations are performed, the electrification systems (DC and AC) are simulated in their default (normal) conditions (traction network in full use) and then in their contingency operation (one or more traction substations not in use). The railway under contingency operation needs to overcome the constraint settled at the beginning of this study: N-1 (one TPSS not in use).

8.2 Contingency operation scenarios

8.2.1 1500 Vdc

The contingency operation scenarios for the current voltage system of the line were decided consulting the operator of the line (*FGC*). Due to their experience, the worst situations to operate the line, regarding a TPSS failure, occurred when either the traction substation of Les Fonts or the one in Sant Quirze were not in service. It makes sense that their failure is worse than the failure of the rest of the TPSS, as both of them are the last ones of the line and the distance between them and the previous one (Sant Cugat) is the highest of the line.

8.2.2 25 kVac

The proposed configuration of the 25 kVac voltage system has two traction substations, in Gràcia and in Sant Cugat. To fulfill the requirement of the N-1, each of them needs to be able to operate the entire line within the limit conditions imposed by the International Standards if the other is under failure. In the Electric Simulation results chapter there is a table showing the limits imposed.

When operating under contingency conditions, the neutral zone located between Les Planes and Baixador de Vallvidrera switches the two sections so there is electric continuity along all the line. Once all the line has electric continuity, the line sectors most critical to stand the electric magnitudes (voltage drop in catenary, rail touch voltage, etc.) within the operational limits are the following:

- Gràcia – Terrassa (contingency in Sant Cugat)
- Gràcia – Sabadell (contingency in Sant Cugat)
- Sant Cugat – Plaça Catalunya (contingency in Gràcia)

They are therefore the line sectors included in this report to check their viability under contingency working scenarios. All the rest of the line has been simulated as well, and the global results of TPSS demands and energy consumption are included in the chapter of Energy balance comparison.

Table 14 Line contingency scenarios for 1500 Vdc electrification system

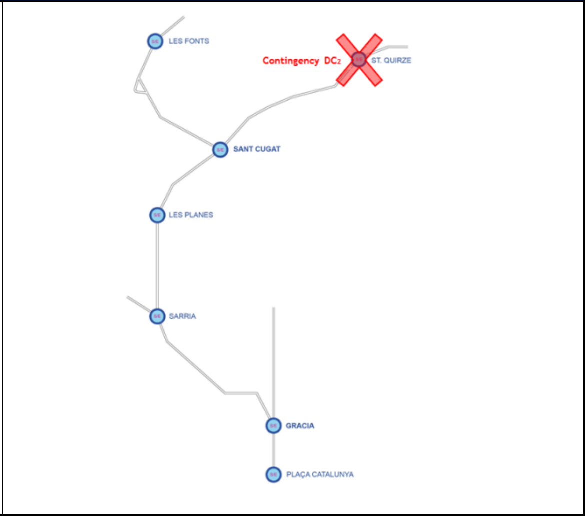
Contingency DC_1	Contingency DC_2
	

Table 15 Line contingency scenarios for 25 kVac electrification system

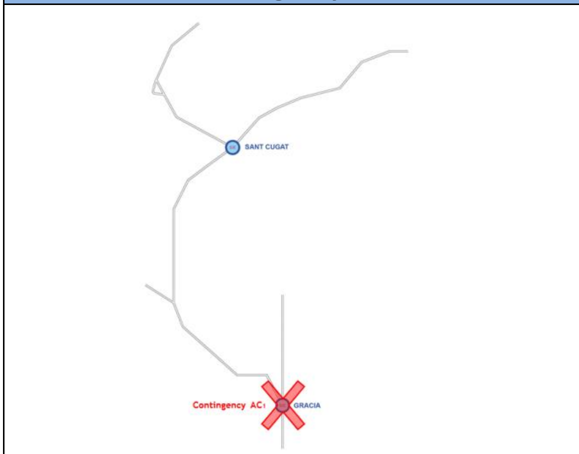
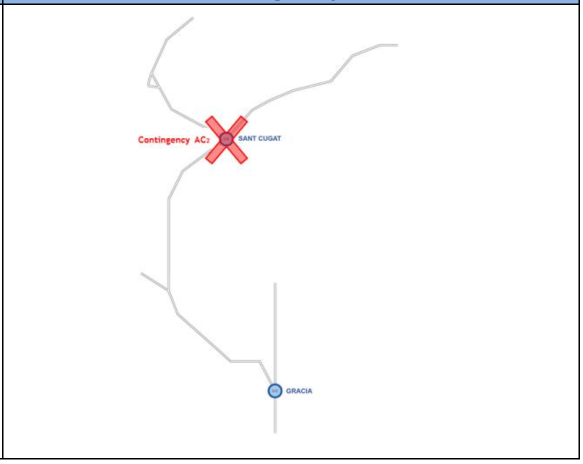
Contingency AC_1	Contingency AC_2
	

Table 16 Scenarios simulated for 1500 Vdc and 25 kVac electrification systems

Default DC							**Default AC**	
Plaça Catalunya	**Gràcia**	**Sarrià**	**Les Planes**	**Sant Cugat**	**Les Fonts**	**Sant Quirze**	**Gràcia**	**Sant Cugat**
✓	✓	✓	✓	✓	✓	✓	✓	✓
Contingency DC_1							**Contingency AC_1**	
Plaça Catalunya	Gràcia	Sarrià	Les Planes	Sant Cugat	Les Fonts	Sant Quirze	Gràcia	Sant Cugat
✓	✓	✓	✓	✓	X	✓	X	✓
Contingency DC_2							**Contingency AC_2**	
Plaça Catalunya	Gràcia	Sarrià	Les Planes	Sant Cugat	Les Fonts	Sant Quirze	Gràcia	Sant Cugat
✓	✓	✓	✓	✓	✓	X	✓	X

8.3 Simulation Results

8.3.1 Results classification

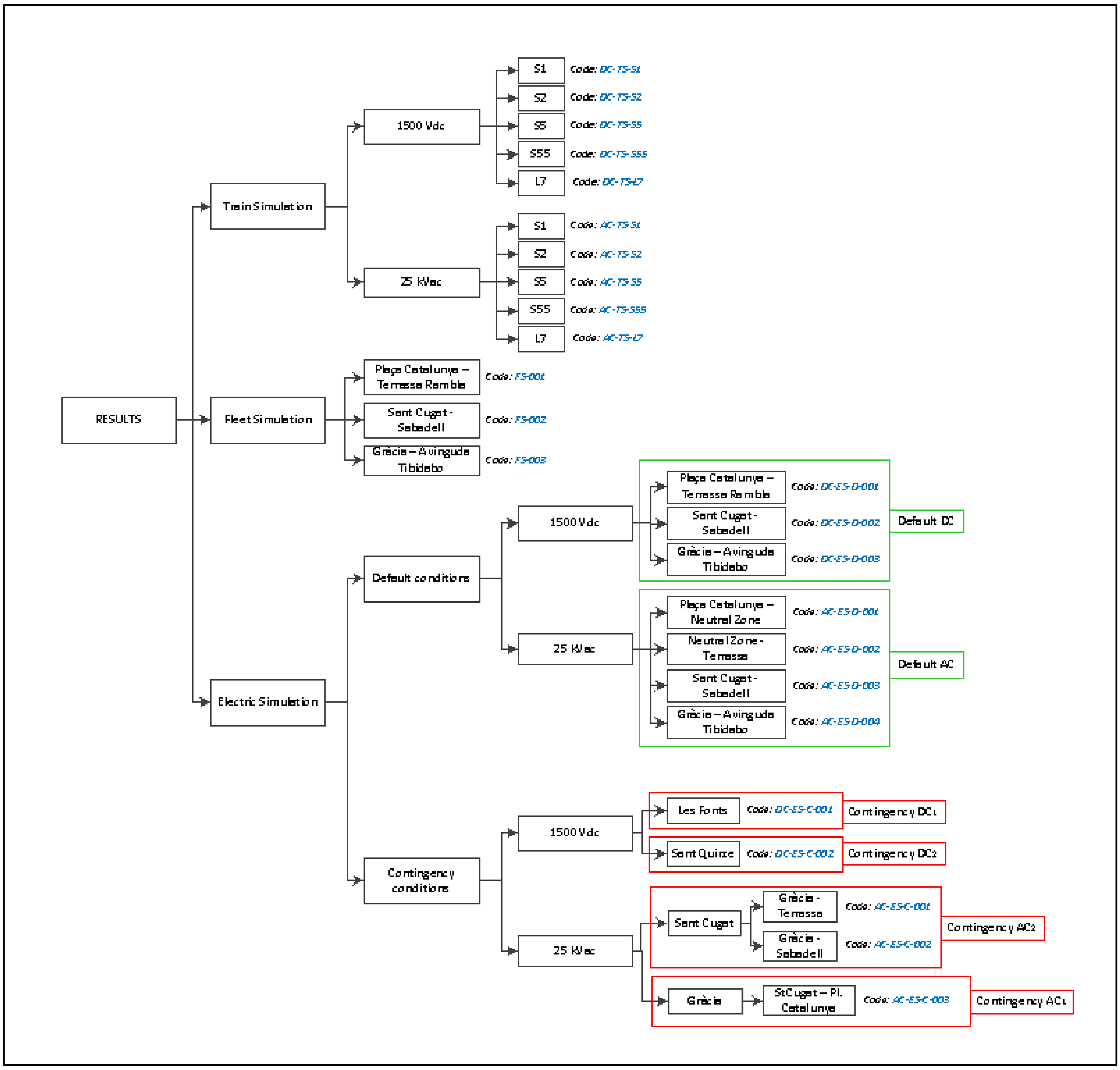


Figure 15 Simulation results scheme

8.3.2 Train Simulation

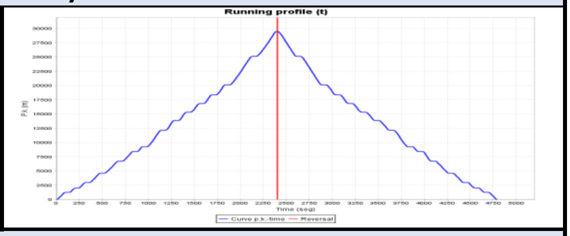
The results obtained are the following for each rolling stock and line sector:

- Real speed profile, for departure and return [km/h].
- Traction effort [kN]
- Elevation of the line sector [m].

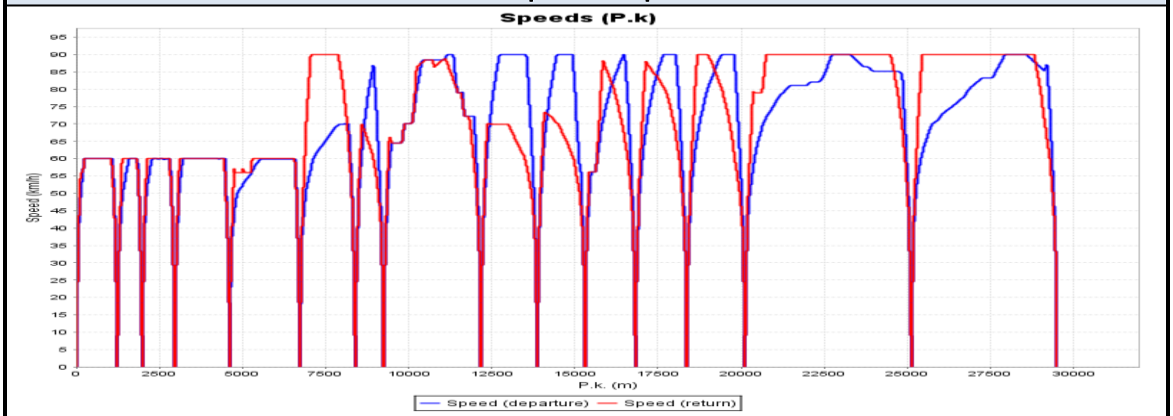
8.3.2.1 1500 Vdc

8.3.2.1.1 Line S1

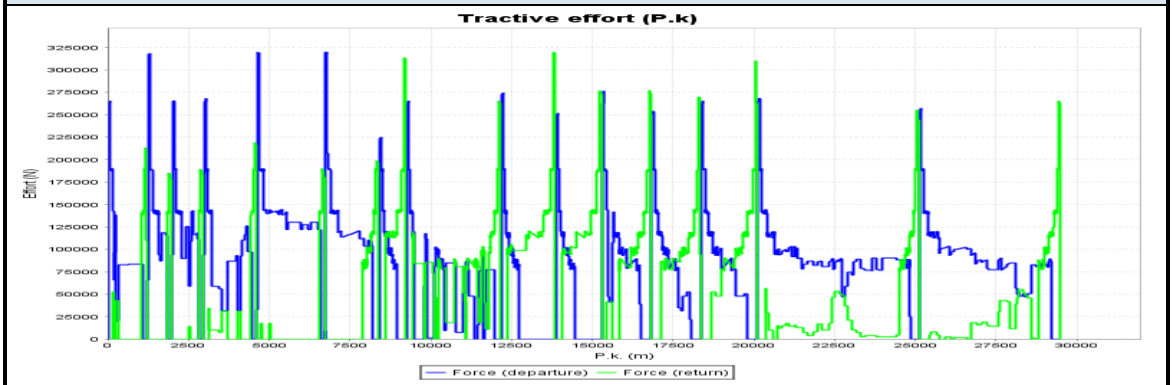
Table 17 Train Simulation results DC. Line S1

TRAIN SIMULATION - RESULTS			
Simulation Code:	DC-TS-S1	**Rolling Stock:**	UT-112
Line sector:	Pl.Catalunya - Terrassa	**Electrification:**	1.500 Vdc
Time of journey			
Pl. Catalunya - Terrassa	00:40:02		
Terrassa – Pl. Catalunya	00:39:56		
Total	01:19:58		

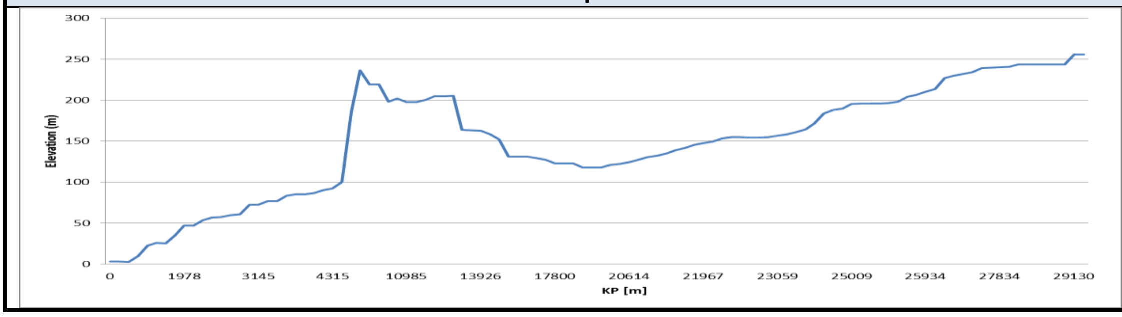
Speed vs Kp



Traction Effort

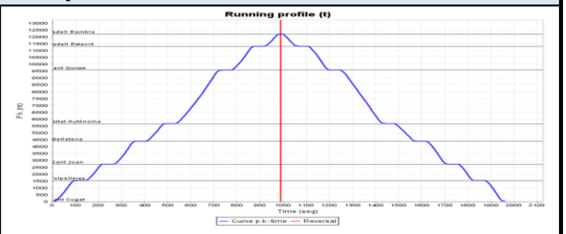
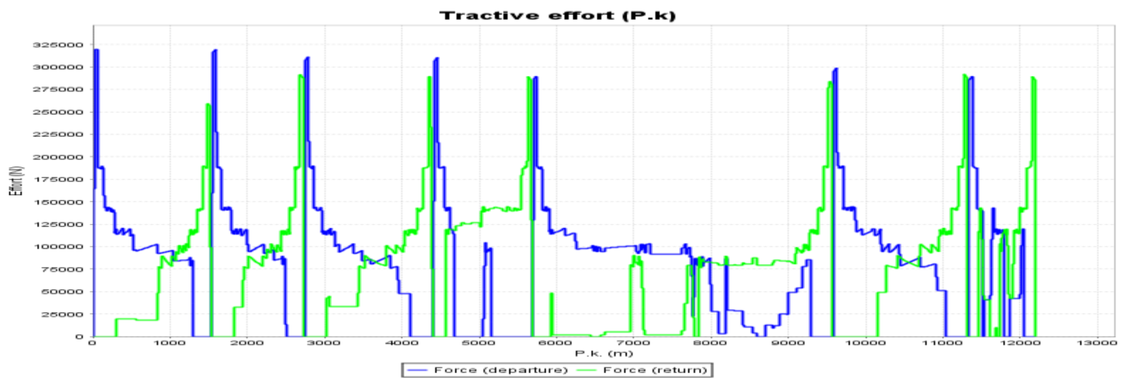
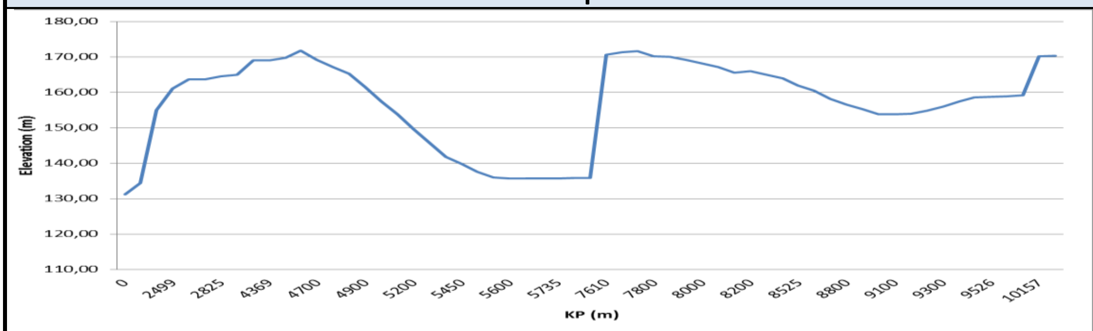


Slopes



8.3.2.1.2 Line S2

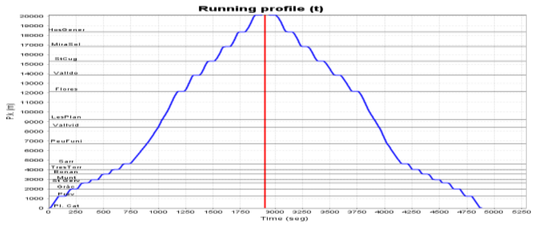
Table 18 Train Simulation results DC. Line S2

TRAIN SIMULATION - RESULTS			
Simulation Code:	DC-TS-S2	**Rolling Stock:**	UT-112
Line sector:	StCugat - Sabadell	**Electrification:**	1.500 Vdc
Time of journey			
Pl. Catalunya - Terrassa	00:16:29		
Terrassa – Pl. Catalunya	00:16:13		
Total	00:32:42		
Speed vs Kp			
			
Traction Effort			
			
Slopes			
			

8.3.2.1.3 Line S5

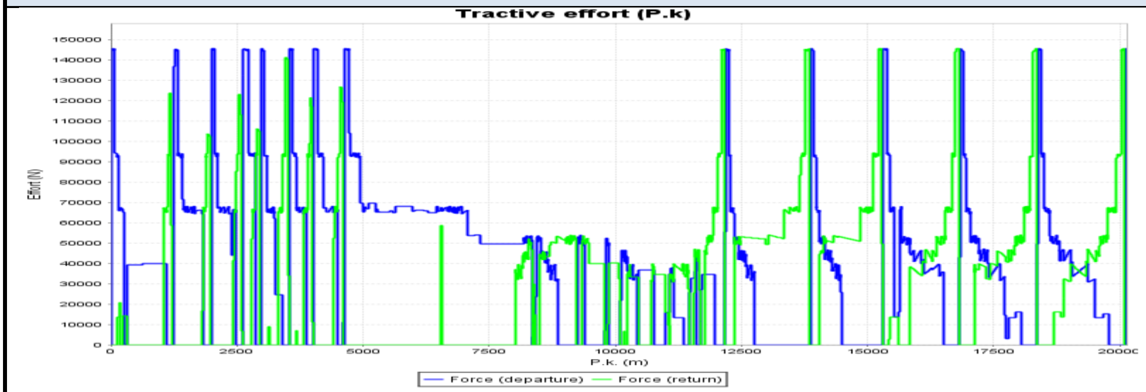
Table 19 Train Simulation results DC. Line S5

TRAIN SIMULATION - RESULTS			
Simulation Code:	DC-TS-S5	**Rolling Stock:**	UT-111
Line sector:	PlCatalunya - Rubí	**Electrification:**	1.500 Vdc
Time of journey			
Pl. Catalunya – Avda. Tibidabo	00:31:36		
Avda. Tibidabo – Pl. Catalunya	00:31:28		
Total	00:63:04		

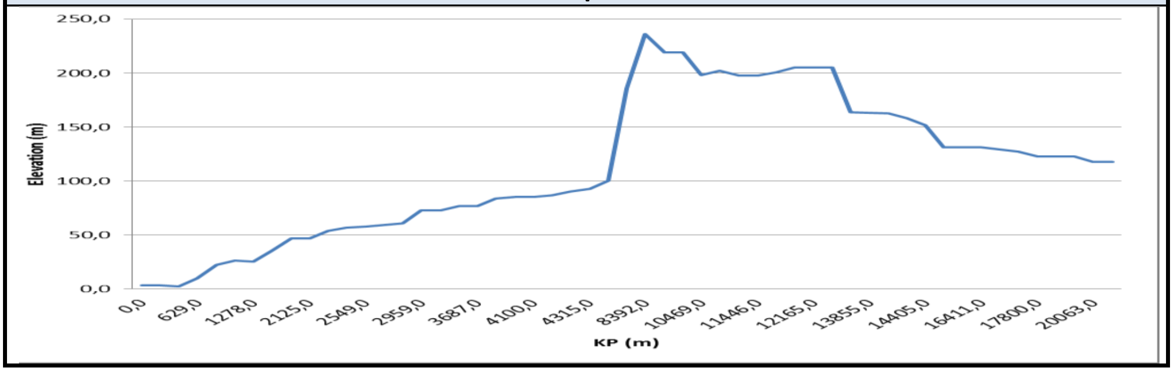


Speed vs Kp

Traction Effort

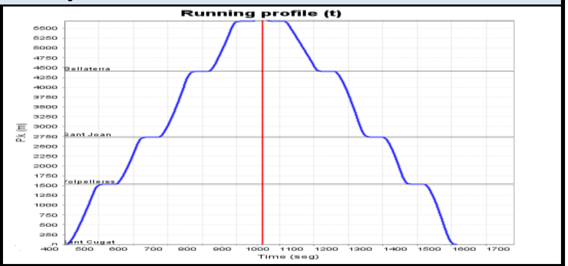


Slopes

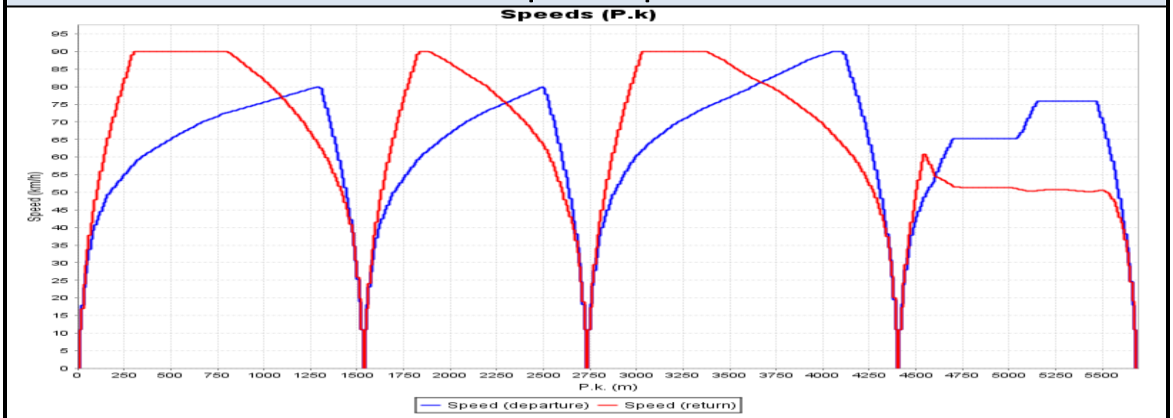


8.3.2.1.4 Line S55

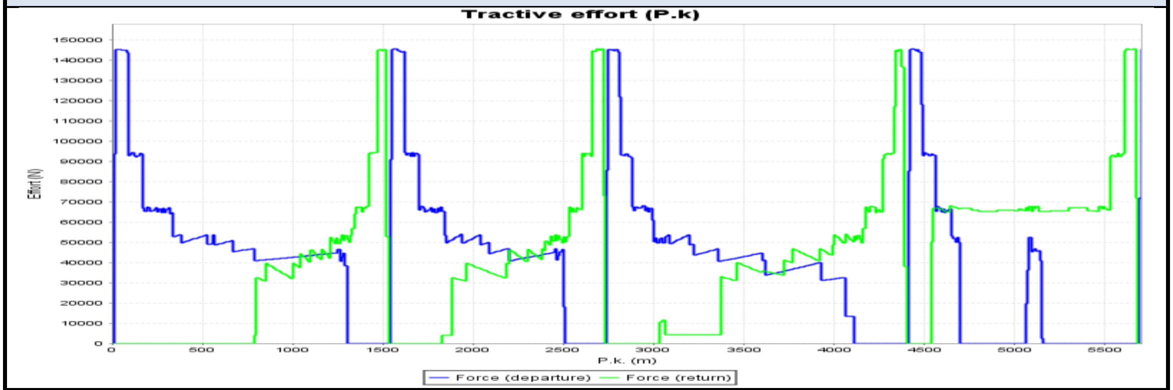
Table 20 Train Simulation results DC. Line S55

TRAIN SIMULATION - RESULTS			
Simulation Code:	DC-TS-S55	**Rolling Stock:**	UT-111
Line sector:	StCugat – Universitat (UAB)	**Electrification:**	1.500 Vdc
Time of journey			
Pl. Catalunya – Avda. Tibidabo	00:08:27		
Avda. Tibidabo – Pl. Catalunya	00:08:23		
Total	00:16:50		

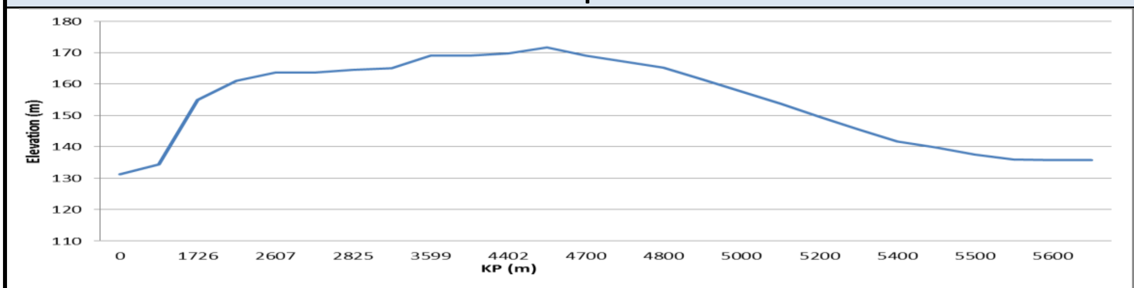
Speed vs Kp



Traction Effort

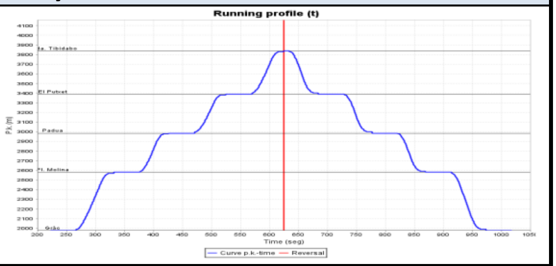


Slopes

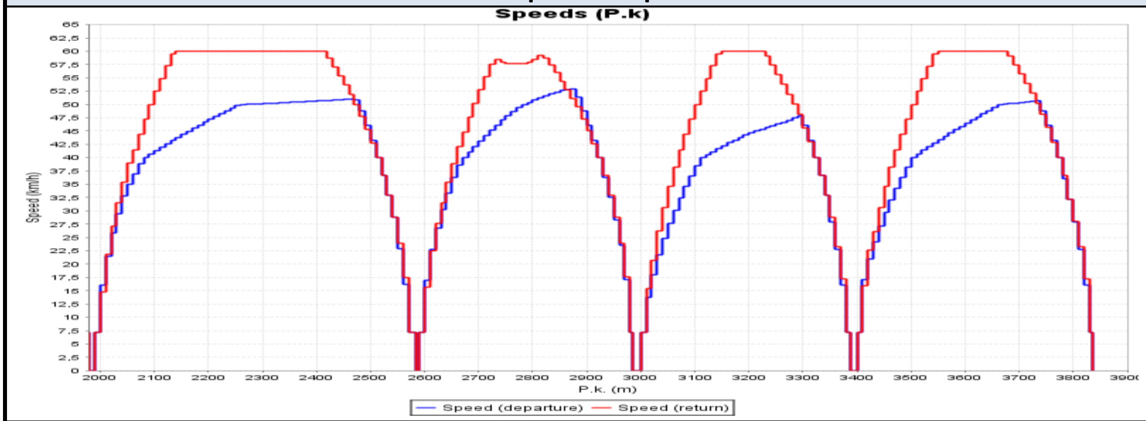


8.3.2.1.5 Line L7

Table 21 Train Simulation results DC. Line L7

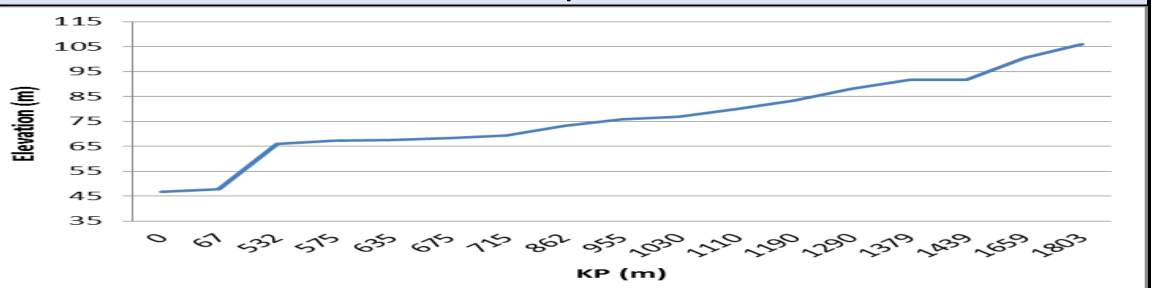
TRAIN SIMULATION - RESULTS			
Simulation Code:	DC-TS-L7	**Rolling Stock:**	UT-111
Line sector:	Gracia – Avda. Tibidabo	**Electrification:**	1.500 Vdc
Time of journey			
Pl. Catalunya – Avda. Tibidabo	00:06:08		
Avda. Tibidabo – Pl. Catalunya	00:05:13		
Total	00:11:21		

Speed vs Kp



Traction Effort

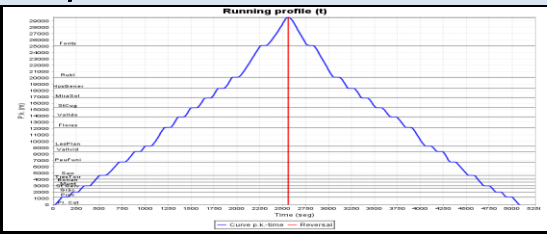
Slopes



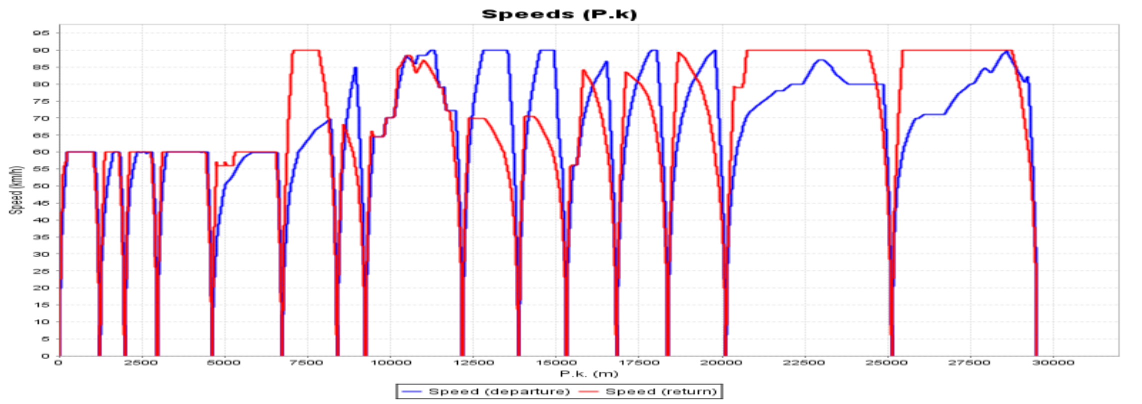
8.3.2.2 25 kVac

8.3.2.2.1 Line S1

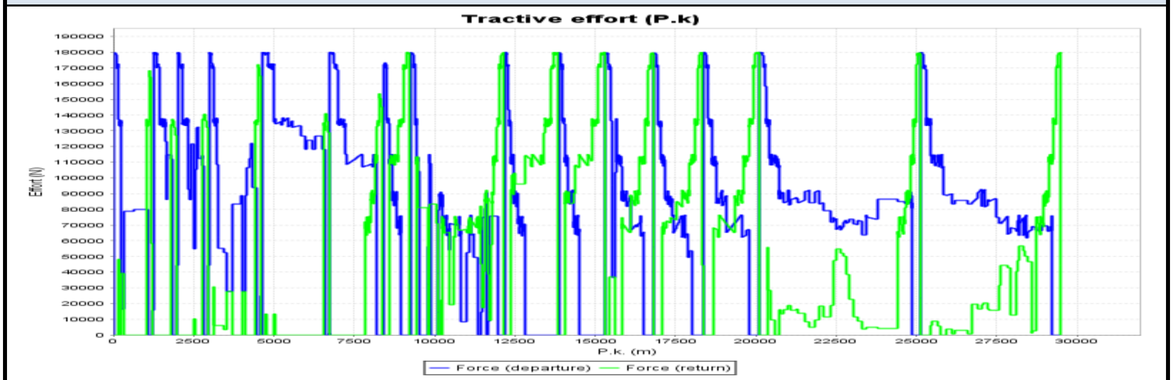
Table 22 Train Simulation results AC. Line S1

TRAIN SIMULATION - RESULTS			
Simulation Code:	AC-TS-S1	**Rolling Stock:**	MOVIA
Line sector:	Pl.Catalunya - Terrassa	**Electrification:**	25 kVac
Time of journey			
Pl. Catalunya - Terrassa	00:42:37		
Terrassa – Pl. Catalunya	00:41:35		
Total	01:24:12		

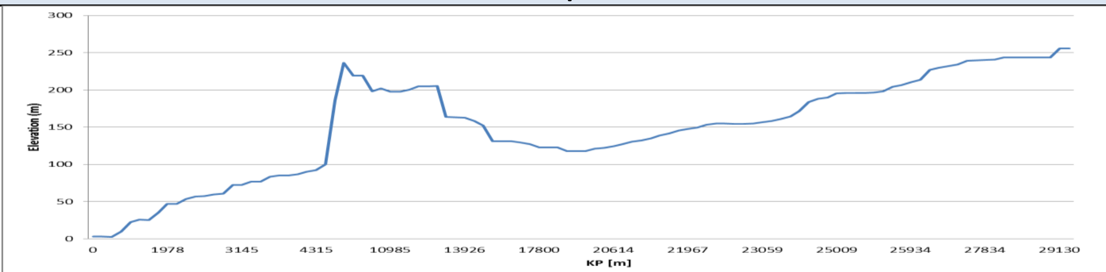
Speed vs Kp



Traction Effort

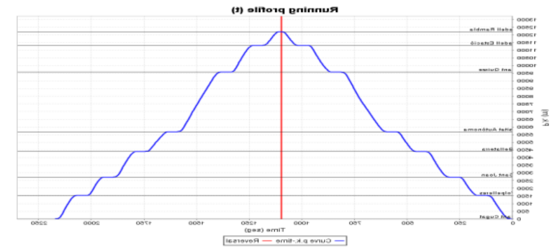


Slopes

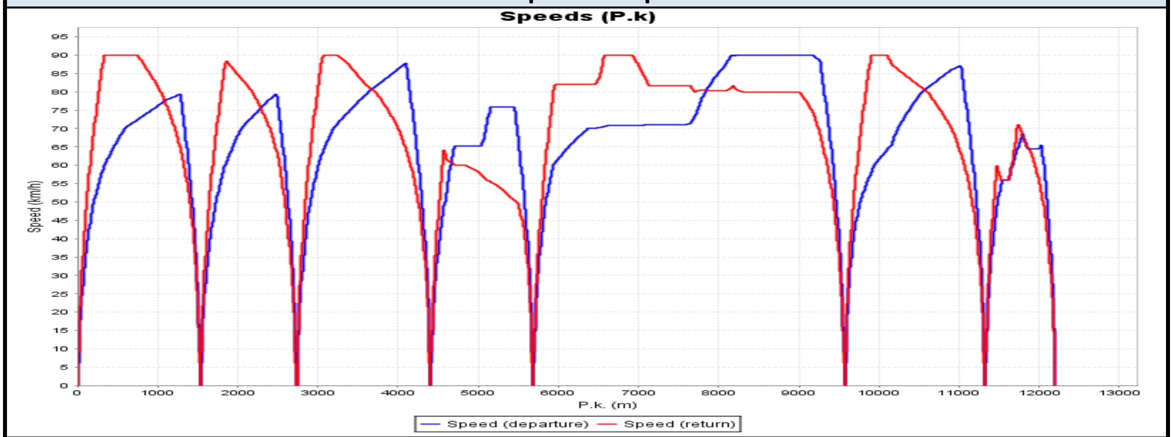


8.3.2.2.2 Line S2

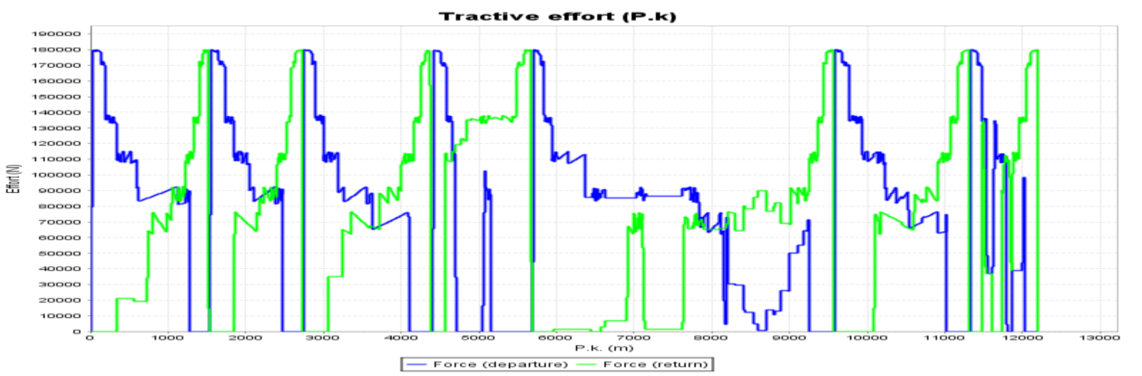
Table 23 Train Simulation results AC. Line S2

TRAIN SIMULATION - RESULTS			
Simulation Code:	AC-TS-S2	**Rolling Stock:**	MOVIA
Line sector:	StCugat - Sabadell	**Electrification:**	25 kVac
Time of journey			
Pl. Catalunya - Terrassa	00:18:17		
Terrassa – Pl. Catalunya	00:17:16		
Total	00:35:33		

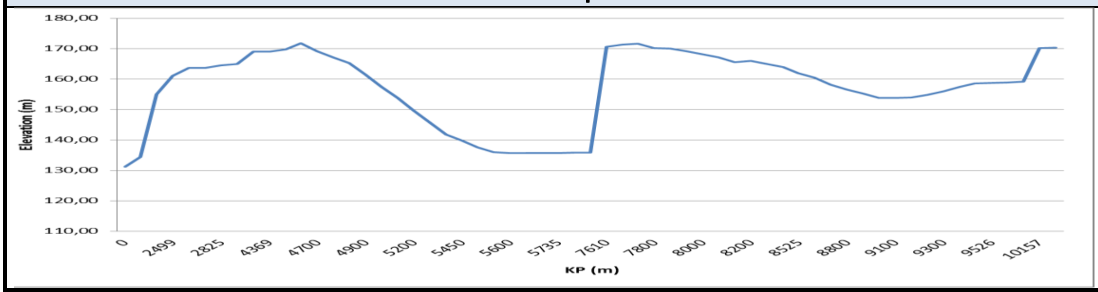
Speed vs Kp



Traction Effort

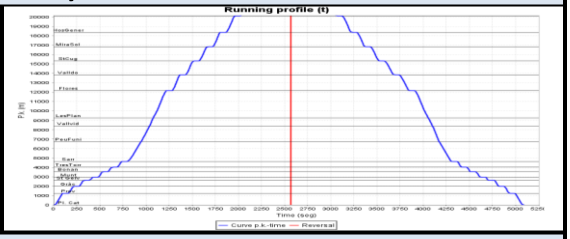
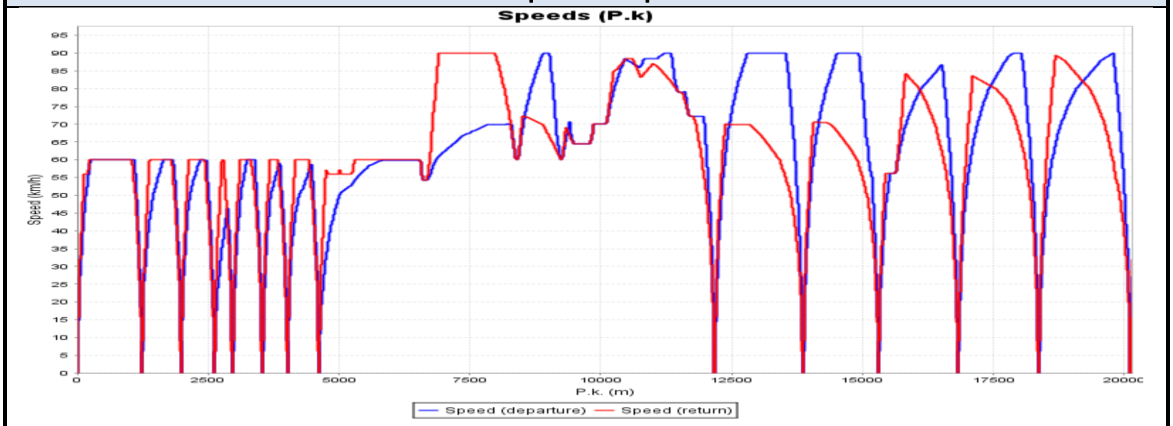


Slopes



8.3.2.2.3 Line S5

Table 24 Train Simulation results AC. Line S5

<table>
<tr><th colspan="4">TRAIN SIMULATION - RESULTS</th></tr>
<tr><td>Simulation Code:</td><td>AC-TS-S5</td><td>Rolling Stock:</td><td>MOVIA</td></tr>
<tr><td>Line sector:</td><td>PlCatalunya - Rubí</td><td>Electrification:</td><td>25 kVac</td></tr>
<tr><td colspan="4">Time of journey</td></tr>
<tr><td>Pl. Catalunya – Avda. Tibidabo</td><td>00:32:52</td><td colspan="2" rowspan="3">
</td></tr>
<tr><td>Avda. Tibidabo – Pl. Catalunya</td><td>00:32:58</td></tr>
<tr><td>Total</td><td>00:65:40</td></tr>
<tr><td colspan="4">Speed vs Kp</td></tr>
<tr><td colspan="4">
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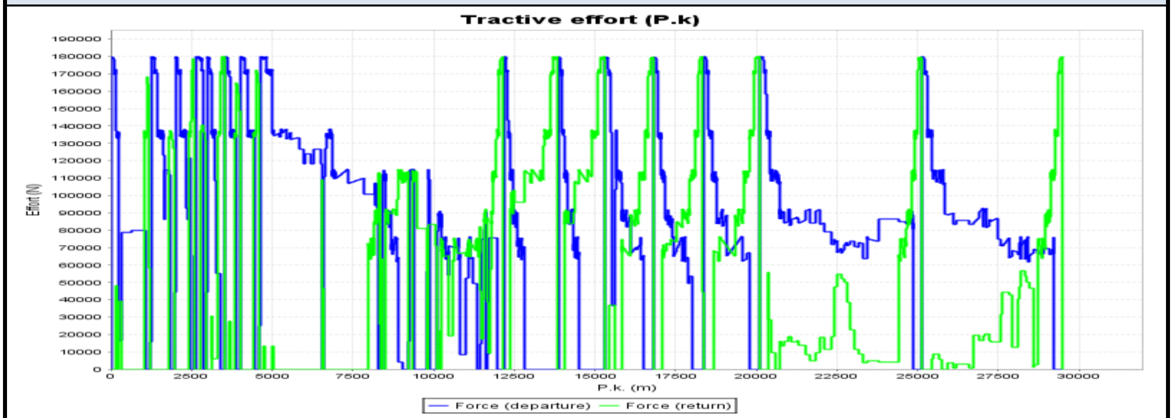
<tr><td colspan="4">Traction Effort</td></tr>
<tr><td colspan="4">
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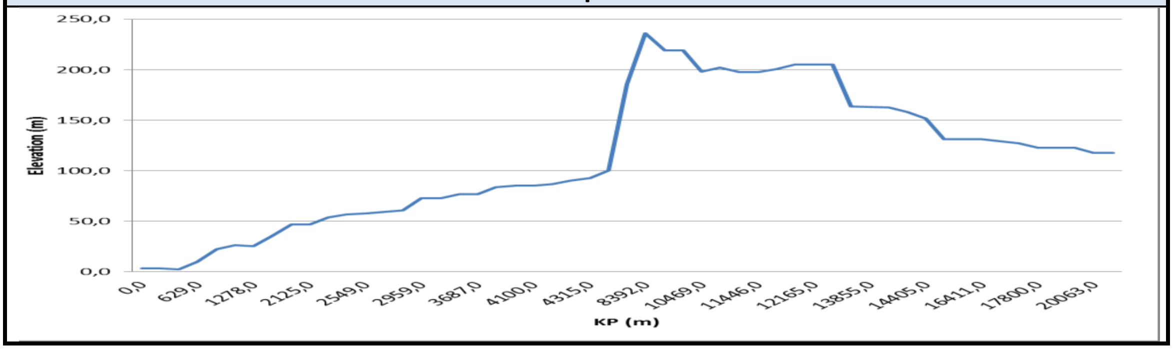
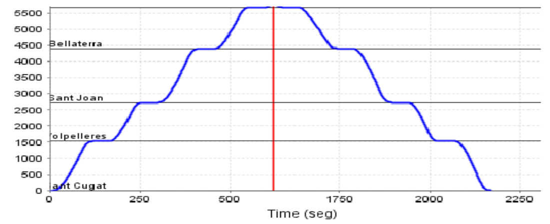
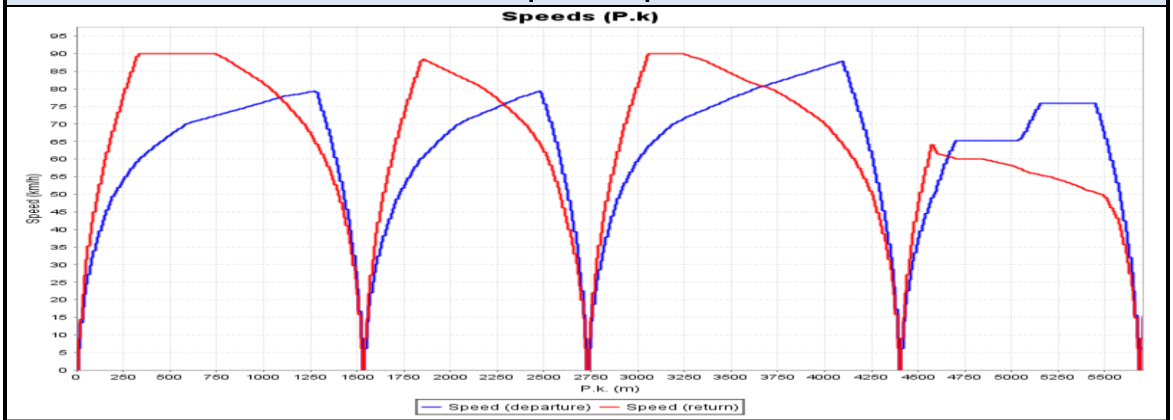
<tr><td colspan="4">Slopes</td></tr>
<tr><td colspan="4">
</td></tr>
</table>

8.3.2.2.4 Line S55

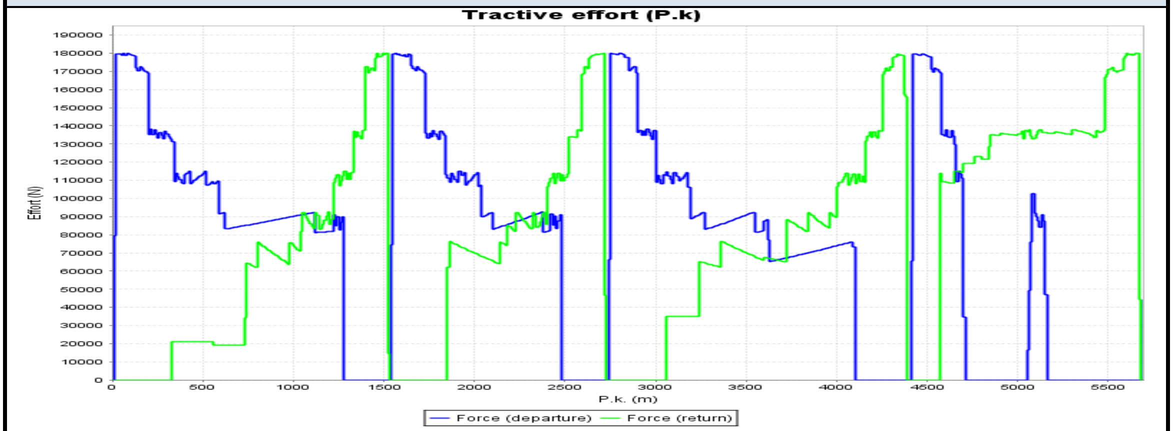
Table 25 Train Simulation results AC. Line S55

TRAIN SIMULATION - RESULTS			
Simulation name:	AC-TS-S55	**Rolling Stock:**	MOVIA
Line sector:	StCugat – Universitat (UAB)	**Electrification:**	25 kVac
Time of journey			
Pl. Catalunya – Avda. Tibidabo	00:09:15		
Avda. Tibidabo – Pl. Catalunya	00:09:03		
Total	00:18:18		

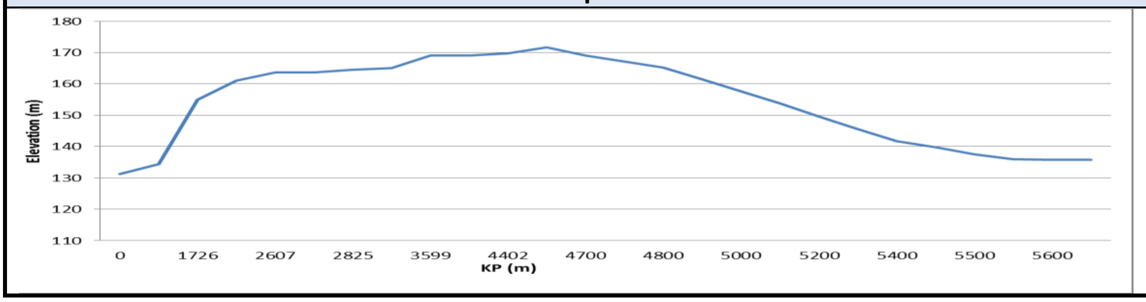
Speed vs Kp



Traction Effort

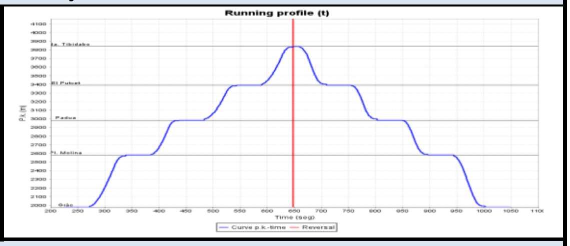
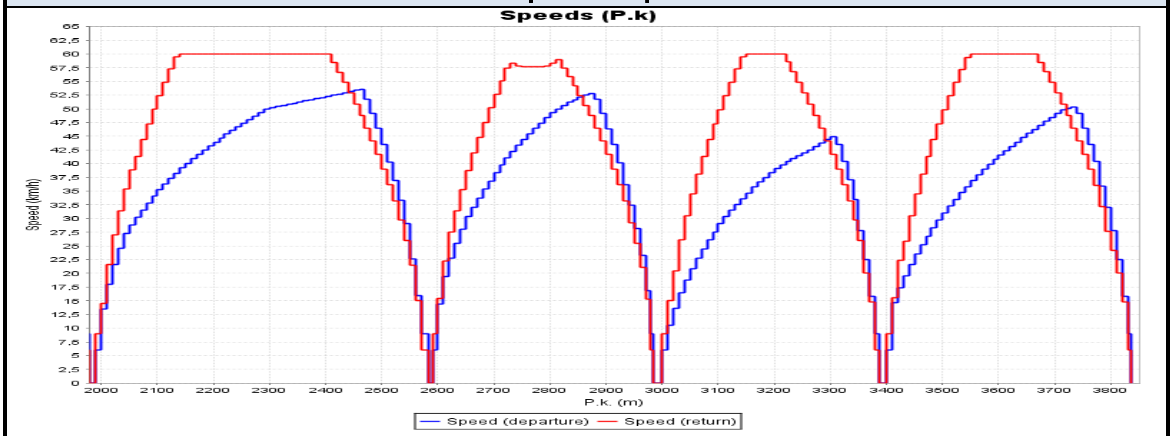


Slopes



8.3.2.2.5 Line L7

Table 26 Train Simulation results AC. Line L7

<table>
<tr><th colspan="4">TRAIN SIMULATION - RESULTS</th></tr>
<tr><td>Simulation Code:</td><td>AC-TS-L7</td><td>Rolling Stock:</td><td>MOVIA</td></tr>
<tr><td>Line sector:</td><td>Gracia – Avda. Tibidabo</td><td>Electrification:</td><td>1x25 kV</td></tr>
<tr><th colspan="4">Time of journey</th></tr>
<tr><td>Pl. Catalunya – Avda. Tibidabo</td><td>00:06:26</td><td colspan="2" rowspan="3">
</td></tr>
<tr><td>Avda. Tibidabo – Pl. Catalunya</td><td>00:05:19</td></tr>
<tr><td>Total</td><td>00:11:45</td></tr>
<tr><th colspan="4">Speed vs Kp</th></tr>
<tr><td colspan="4">
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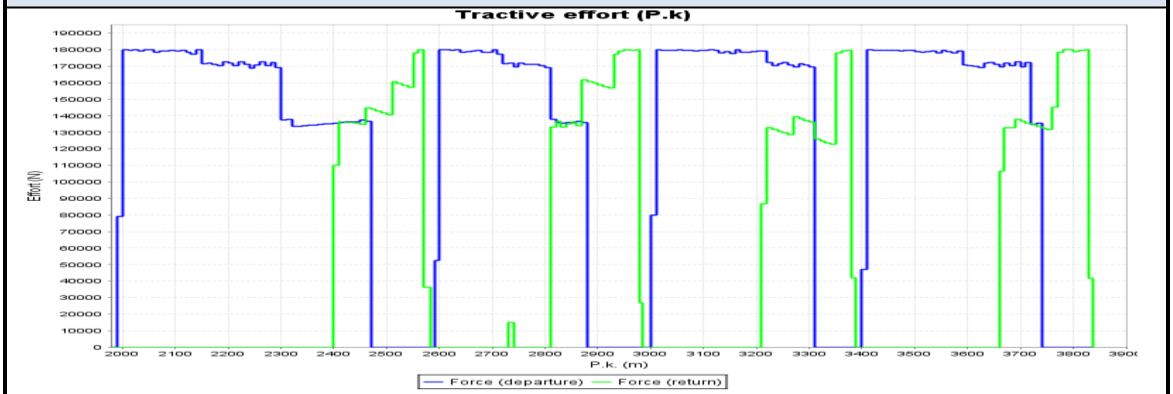
<tr><td colspan="4">
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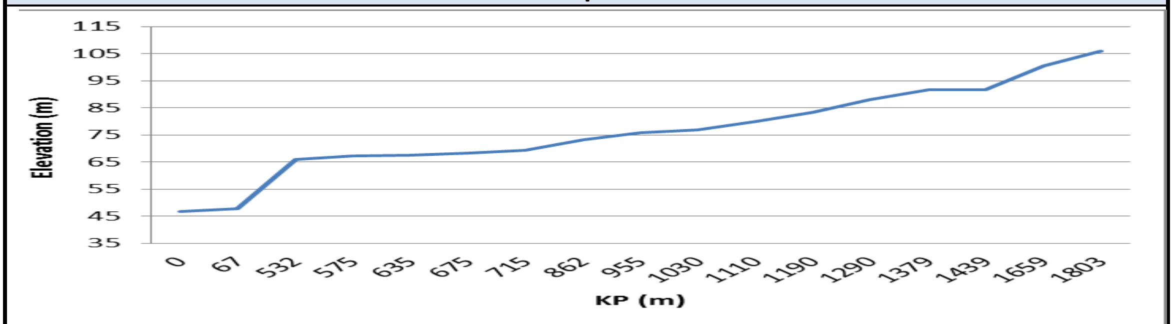
<tr><td colspan="4">
</td></tr>
</table>

Apart from the journey times, there are presented, for each line, the speed profile and the traction effort profile. They are of capital importance in the simulation process, as the power demanded for each time instant by the trains is function of the effort needed and the speed.

8.3.2.3 Comparison between journey times

Table 27 Journey times for each train line and electrification scheme

		1500 Vdc		25 kVac	
Line Sector	**Train line**	**departure time**	**return time**	**departure time**	**return time**
Pl. Catalunya - Terrassa	S1	0:40:02	0:39:56	0:42:37	0:41:35
St. Cugat - Sabadell	S2	0:16:29	0:16:13	0:18:17	0:17:16
Pl. Catalunya - Rubí	S5	0:31:36	0:31:28	0:32:52	0:32:58
St. Cugat - UAB	S55	0:08:27	0:08:23	0:09:15	0:09:03
Gràcia - Avda. Tibidabo	L7	0:06:08	0:05:13	0:06:26	0:05:19

As it can be noticed, the MOVIA train electrified in 25 kVac goes slightly slower in comparison with the the rolling stock of the 1500 Vdc configuration.

This delay in the journey times is a normal consequence of using different train models; the MOVIA train can be loaded with much more people than the *FGC* models. Besides, the motorization of the UT111 and UT112 allow higher accelerations. What in this study becomes necessary to focus on after the train simulation, is that the journey times are in the same order and therefore, all the results obtained (electric results) in the following modules of the simulation process are consistent for the study proposed.

Regarding the *Key assumptions and operational constraints* chapter, all the lines operating under AC would maintain less than three minutes difference compared with the DC configuration. Therefore, from the rolling stock point of view, the 25 kVac voltage system would be suitable for the *FGC* line.

To validate if the 1500 Vdc train simulations are consistent with the commercial Journey times available in the website of *FGC*[11], the following table is attached:

Table 28 Comparison between simulation times and comercial times for the 1500 Vdc configuration

		Simulation Times		Commercial Times	
Line Sector	Train line	departure time [h:min:s]	return time [h:min:s]	departure time [min]	return time [min]
Pl. Catalunya - Terrassa	S1	0:40:02	0:39:56	41	42
St. Cugat - Sabadell	S2	0:16:29	0:16:13	17	19

[11] http://www.fgc.cat/cat/cercador.asp

Pl. Catalunya - Rubí	S5	0:31:36	0:31:28	32	33
St. Cugat - UAB	S55	0:08:27	0:08:23	08	10
Gràcia - Avda. Tibidabo	L7	0:06:08	0:05:13	05	05

The commercial times available in the *FGC* website are rounded to the minutes, but even though, it becomes clear that the simulation results are able to represent with good accuracy the journey times achieved in the real operation.

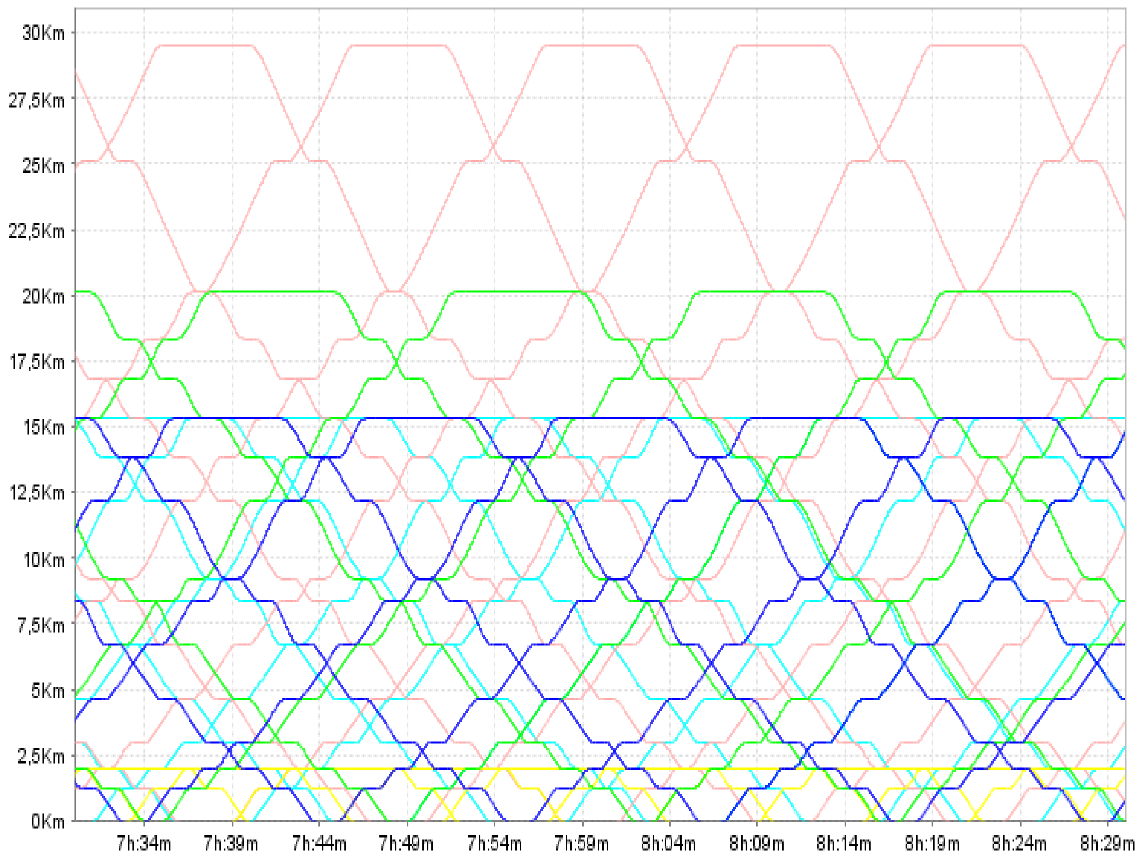
8.3.3 Traffic simulation

In the traffic simulation the traffic grid for each line sector is obtained. The so called traffic grid represents the position(x) at time (y) of each train running inner the line.

8.3.3.1 Plaça Catalunya – Terrassa Sector

Table 29 Traffic grid for Plaça Catalunya – Terrassa sector

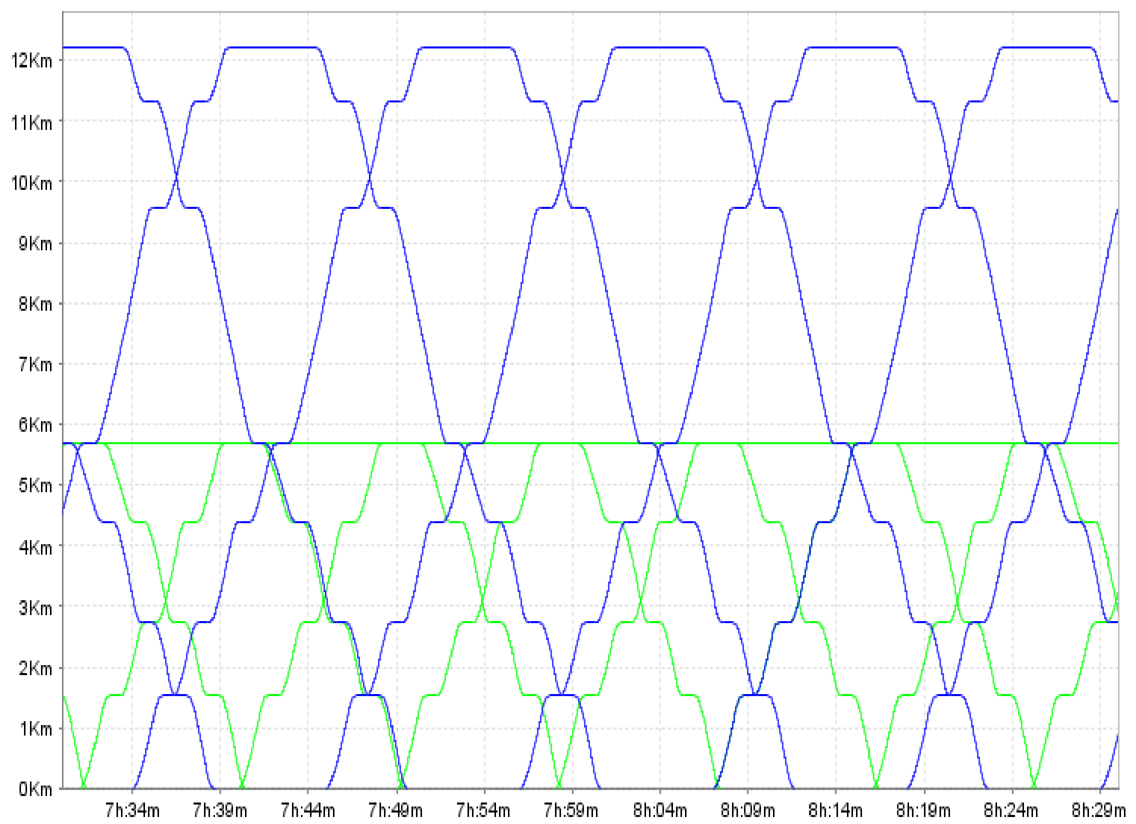
TRAFFIC SIMULATION - RESULTS				
Simulation Code:	FS-001	**Simulation period:**	7.30 – 8.30	
Line sector:	PlCatalunya - Terrassa	**Electrification:**	1.500 Vdc	
Train Lines				
Line Name	**Headway [min]**	**Time at last station [s]**	**Rolling Stock**	**Colour**
L7 Avinguda Tibidabo	6	360	UT 111	
S1 Terrassa	11	300	UT 112	
S5 Rubí	14	300	UT 111	
S2 Sabadell	11	300	UT 112	
S55 Universitat autònoma	9	600	UT 111	
Traffic Grid				



8.3.3.2 Sant Cugat – Sabadell Sector

Table 30 Traffic grid for Sant Cugat – Sabadell sector

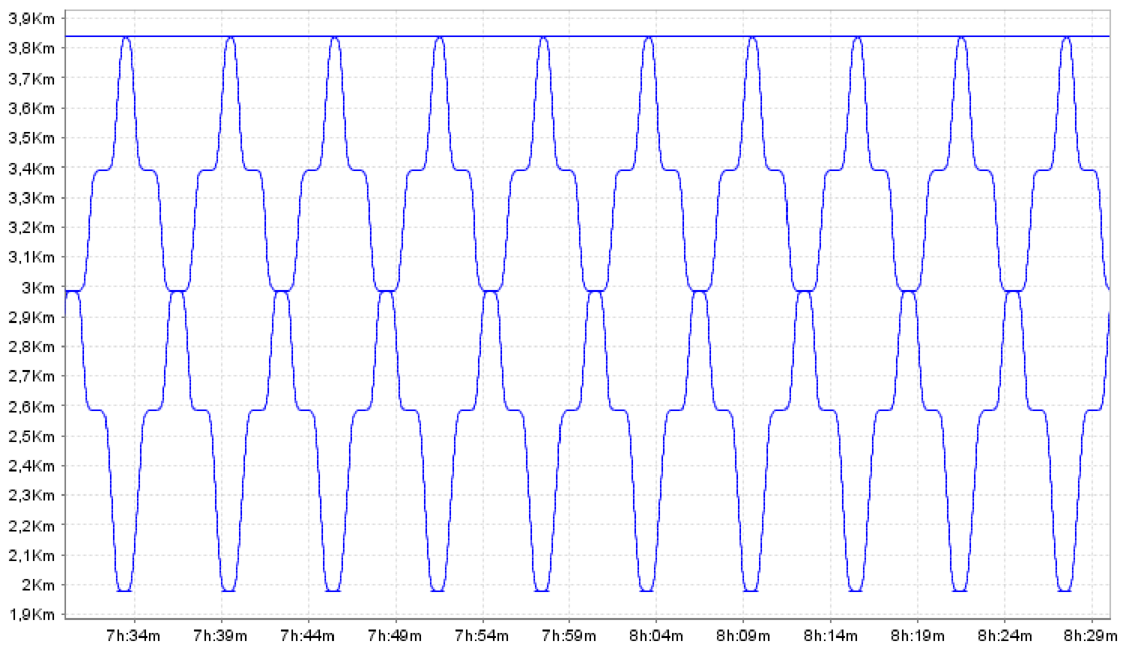
TRAFFIC SIMULATION - RESULTS				
Simulation code:	FS-002	**Simulation period:**	7.30 – 8.30	
Line sector:	Sant Cugat - Sabadell	**Electrification:**	1.500 Vdc	
Train Lines				
Line Name	**Headway [min]**	**Time at last station [s]**	**Rolling Stock**	**Colour**
S2 Sabadell	11	300	UT 112	
S55 Universitat autònoma	9	600	UT 111	
Traffic Grid				



8.3.3.3 Gràcia – Avda. Tibidabo sector

Table 31 Traffic grid for Gràcia – Avda. Tibidabo sector

TRAFFIC SIMULATION - RESULTS				
Simulation code:	FS-003	**Simulation period:**	7.30 – 8.30	
Line sector:	Gracia - AvdaTibidabo	**Electrification:**	1.500 Vdc	
Train Lines				
Line Name	**Headway [min]**	**Time at last station [s]**	**Rolling Stock**	**Colour**
L7 Avda. Tibidabo	11	300	UT 112	
Traffic Grid				



As a remark, notice that these traffic grids correspond to the 1500 Vdc configuration. The traffic grids obtained with the 25 kVac configuration are not presented in the results report of this study because, even though they were used to perform the electric simulation, they are highly similar to the ones here presented because the journey times differ less than 2 minutes in the worst case, as mentioned in the previous chapter.

8.3.4 Electric simulation

The following results are obtained in the electric simulation for each track:

- Catenary's voltage drop profile

Represented instantaneously, each line represents the voltage profile (y) in front of the kilometric point (x) for every second of the simulation period. Besides, there is a red line representing the average line voltage per Kp.

- Return circuit's voltage profile

Represented instantaneously, each line represents the touch voltage profile (y) in the rails in front of the kilometric point (x) for every second of the simulation period. Besides, there is a red line representing the average line voltage per Kp.

- Current flowing through the catenary

Represented instantaneously, each line represents the current profile (y) in the catenary conductors in front of the kilometric point (x) for every second of the simulation period. Besides, there is a red line representing the RMS values per Kp.

- Traction power delivered by the traction substations (TPSS)

There is, for each TPSS in the line sector simulated, the maximum instantaneous , RMS 1' and RMS 15' power demanded during the simulation period.

- Percentage of energy consumed from the TPSS' or from regenerative braking

Shown as a percentage, there is the energy consumed in the line, divided between the amount provided by the TPSS and the regenerative breaking of the rolling stock

- Joule losses

Shown as a percentage, there is the share of the Loule losses between the catenary and rail of the wo tracks.

Every magnitude is presented graphically and for each track.

8.3.4.1 Acceptance criteria for the fixed elements

The results obtained from the electric simulation regarding voltage drop in the overhead line, touch voltage in the rails or the traction substation power demand need to be within the limit values shown in the following international standards:

- EN 50122-1 : Railway applications - Fixed installations - Electrical safety, earthing and the return circuit
- EN 50163 : Railway applications - Supply voltages of traction systems
- EN 50329 : Railway applications - Fixed installations – Traction transformers

These limit values of operation are the following:

Table 32 Limit values of operation for a 1500 Vdc and a 25 kVac electrified railway

		DC	AC
OVERHEAD CATENARY		**[V]**	**[V]**
Nominal Voltage		1.500	25.000
Lowest permanent Voltage		1.000	19.000
Lowest non-permanent Voltage (Instantaneous)		1.000	17.500
Highest permanent Voltage		1.800	27.500
Highest non-permanent Voltage (Instantaneous)		1.950	29.000
RAIL		**[V]**	**[V]**
Highest permanent voltage	**> 300 [s]**	120	60
	300 [s]	150	65
	1 [s]	160	75
	0,9 [s]	165	80
	0,8 [s]	170	85
	0,7 [s]	175	90
POWER TRANSFORMERS			
Maximum load		100% permanent	100% permanent
		150% for 2 hours every 3 hours	131,5% for 2 hours every 3 hours
		300% for 1 minute every 1 minute	193,7% for 4 minutes every 30 minutes

The accomplishment of these limits will determine if the fixed elements are suitable for the electrification design. If they are outside these limits in the AC configuration, new elements need to be taken into account, meaning that a new electric simulation with these new elements is required.

For the DC configuration, if some values are outside of the limits imposed, it means that the current electrification of the *FGC* line has some handicaps that under full conditions of use do not allow it to maintain the operational constraints imposed at the beginning of this study (headways, power of the trains, etc), always under the theoretical simulation.

8.3.4.2 Default operation

8.3.4.2.1 1500 Vdc

8.3.4.2.1.1 Plaça Catalunya – Terrassa sector

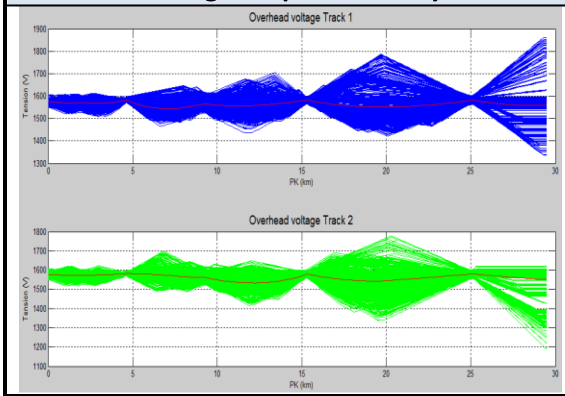
Table 33 Electric results for Plaça Catalunya – Terrassa sector. DC default scenario

ELECTRIC SIMULATION - RESULTS			
Simulation name:	DC-ES-D-001	**Simulation period:**	7:30 – 8.30
Line sector:	PlaçaCat – Terrassa	**Electrification:**	1.500 Vdc

Traction network

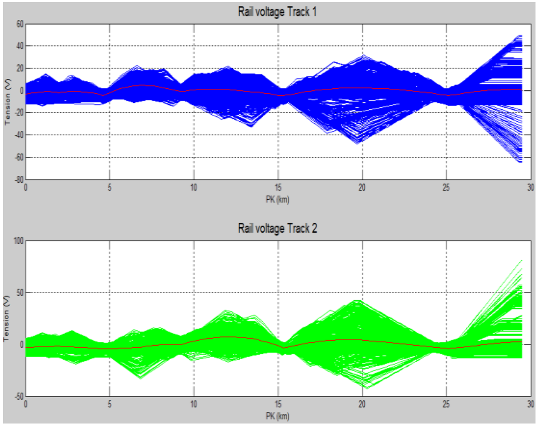
TPSS in service	PlCat	Gracia	Sarria	Planes	StCugat	Fonts
	✓	✓	✓	✓	✓	✓

Voltage drop in Catenary



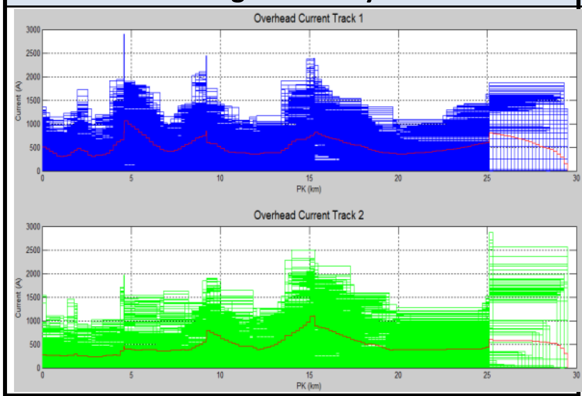
Vmax (V)	1.861,83
Vmin (V)	1.187,96

Voltage drop in Return circuit



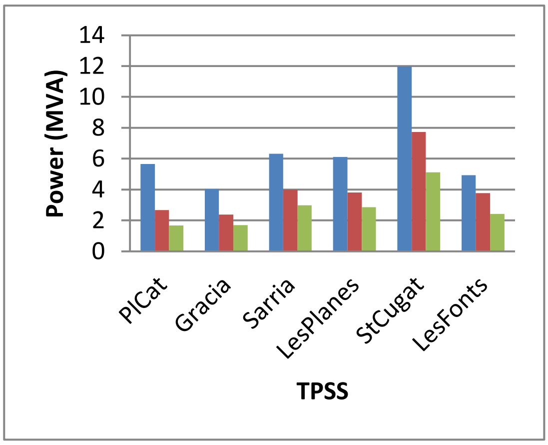
Vmax (V)	81,67

Current through Catenary conductors

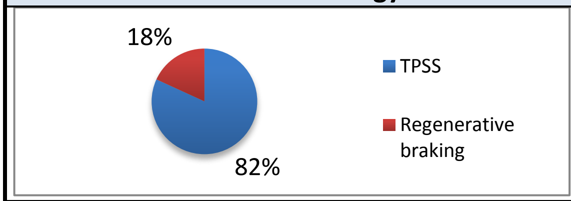


Imax (A)	2.893,42
$Imax_{RMS}$ (A)	1.102,21

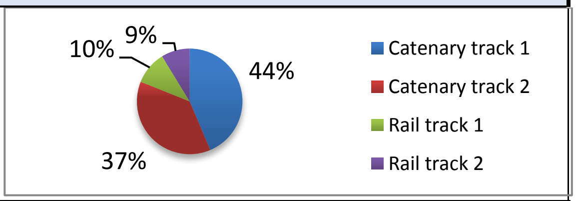
SS Traction Power



Consumed Energy



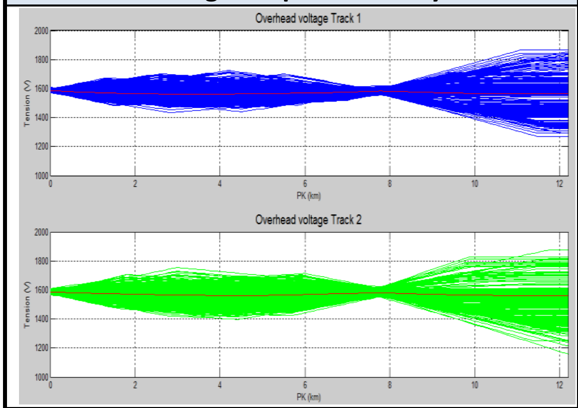
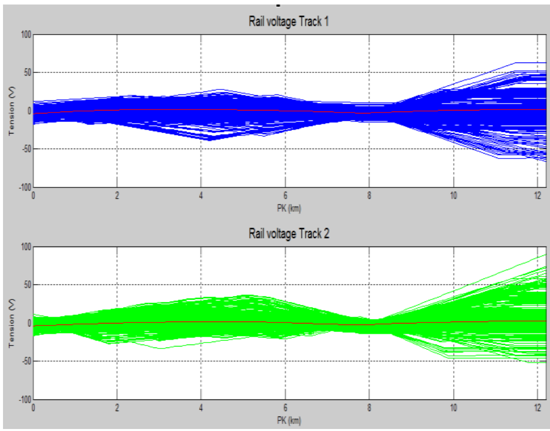
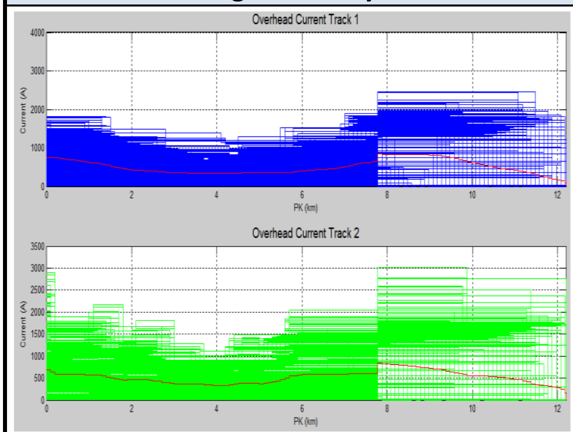
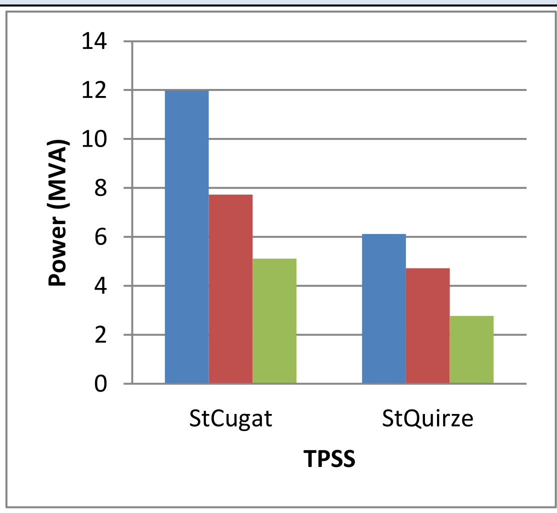
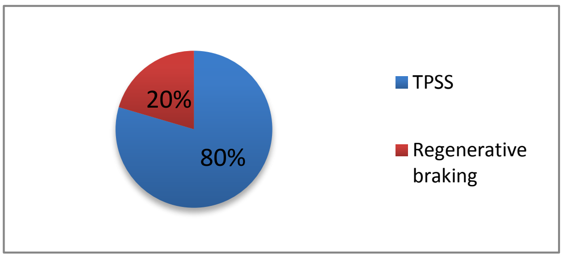
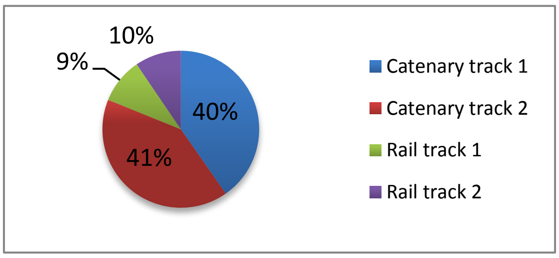
Joule Losses



Consumed Energy from TPSS (MWh)	12,48	**Total Joule Losses (kW)**	680

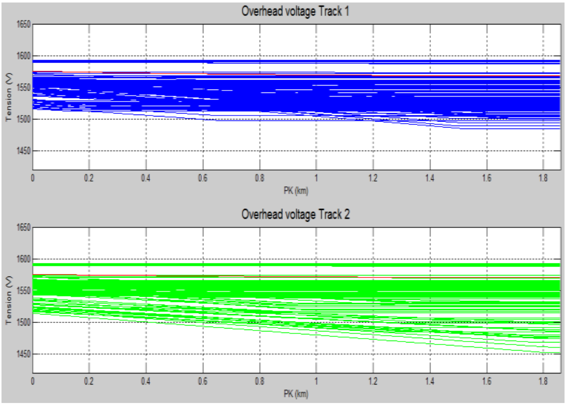
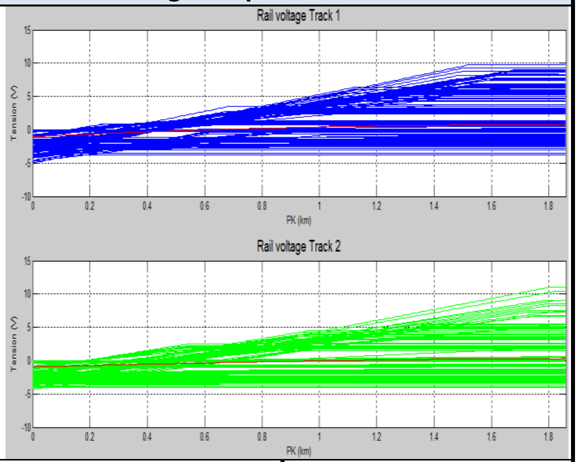
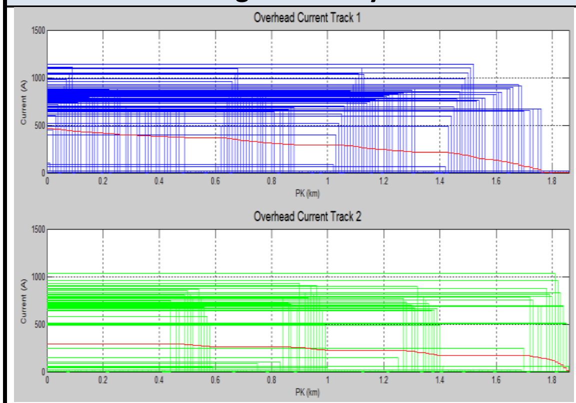
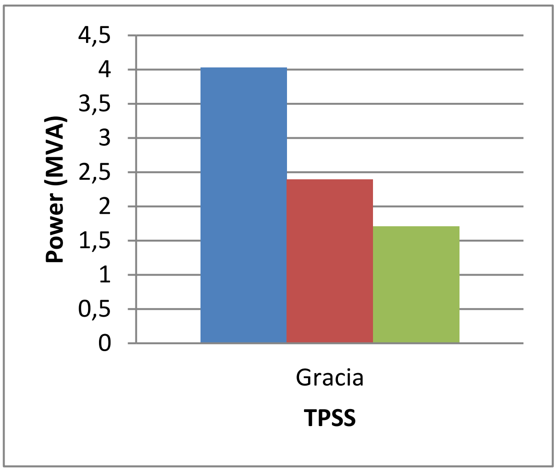
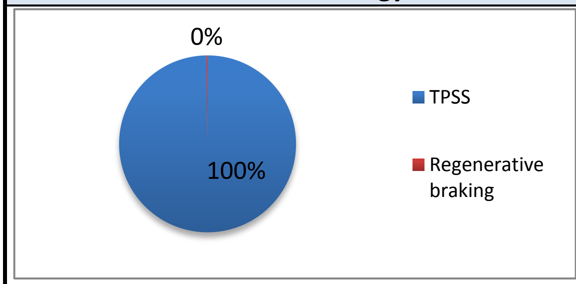
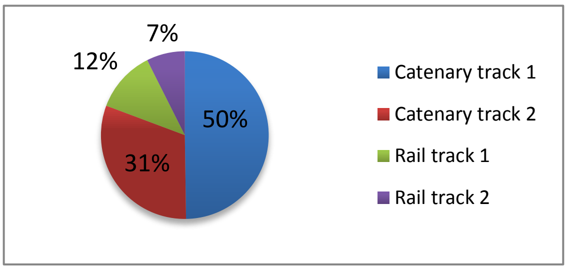
8.3.4.2.1.2 Sant Cugat – Sabadell Centre

Table 34 Electric results for Sant Cugat – Sabadell sector. DC default scenario

ELECTRIC SIMULATION - RESULTS			
Simulation name:	DC-ES-D-002	**Simulation period:**	7:30 – 8.30
Line sector:	Sant Cugat – Sabadell	**Electrification:**	1.500 Vdc
Traction network			
TPSS in service		StCugat	StQuirze
		✓	✓
Voltage drop in Catenary		**Voltage drop in Return circuit**	
			
Vmax (V)	1.878,28		
Vmin (V)	1.158,40	**Vmax (V)**	89,76
Current through Catenary conductors		**SS Traction Power**	
			
Imax (A)	3.023,76		
$Imax_{RMS}$ (A)	843,13		
Consumed Energy		**Joule Losses**	
			
Consumed Power from TPSS (MWh)	4,83	**Total Joule Losses (kW)**	294

8.3.4.2.1.3 Gràcia – Avda. Tibidabo

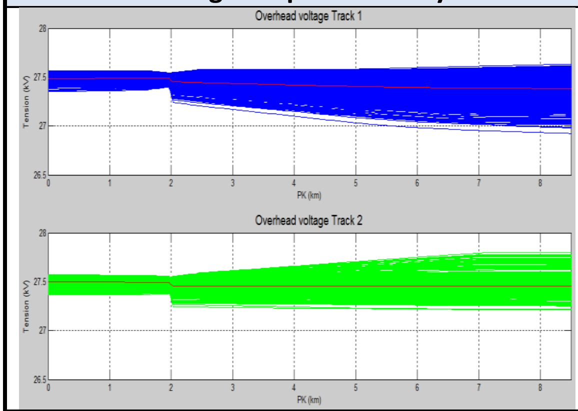
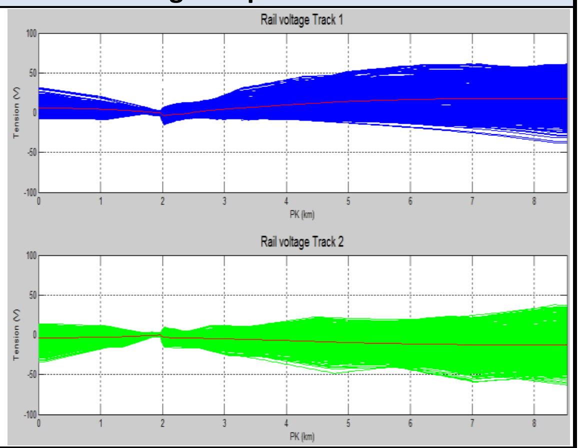
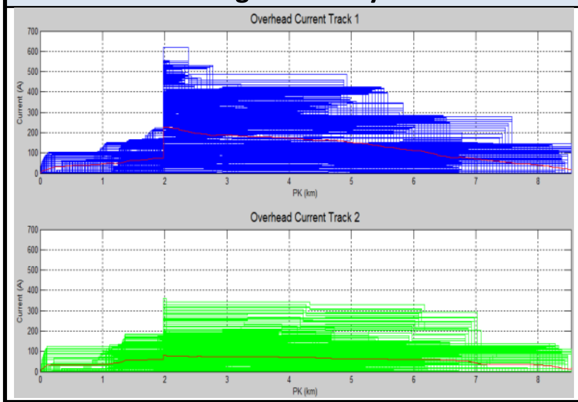
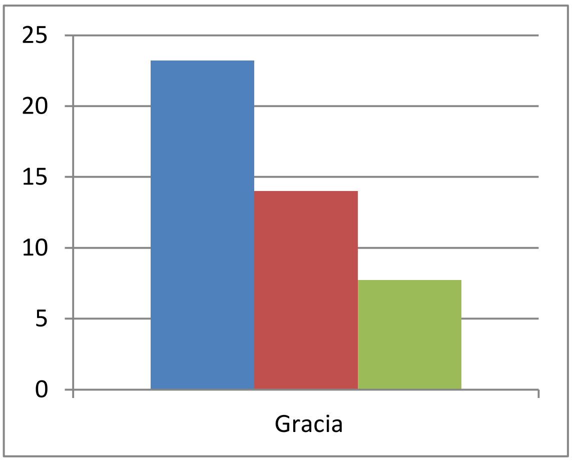
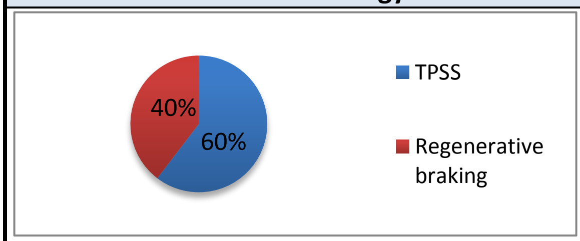
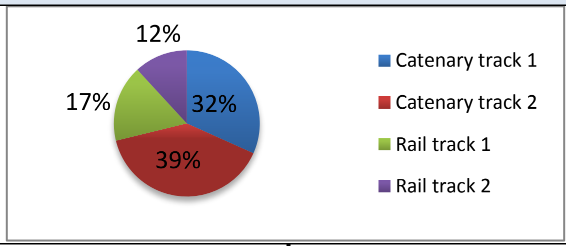
Table 35 Electric results for Gràcia – Avda. Tibidabo sector. DC default scenario

<table>
<tr><th colspan="4">ELECTRIC SIMULATION - RESULTS</th></tr>
<tr><td>Simulation name:</td><td>DC-ES-D-003</td><td>Simulation period:</td><td>7.30 – 8.30</td></tr>
<tr><td>Line sector:</td><td>Gracia – Avda Tibidabo</td><td>Electrification:</td><td>1.500 Vdc</td></tr>
<tr><td colspan="4">Traction network</td></tr>
<tr><td colspan="2" rowspan="2">Traction Substations in service</td><td colspan="2">Gracia</td></tr>
<tr><td colspan="2">✓</td></tr>
<tr><td colspan="2">Voltage drop in Catenary</td><td colspan="2">Voltage drop in Return circuit</td></tr>
<tr><td colspan="2">
</td><td colspan="2" rowspan="2">
</td></tr>
<tr><td>Vmax (V)</td><td>1.593</td></tr>
<tr><td>Vmin (V)</td><td>1.451,94</td><td>Vmax (V)</td><td>11,06</td></tr>
<tr><td colspan="2">Current through Catenary conductors</td><td colspan="2">SS Traction Power</td></tr>
<tr><td colspan="2">
</td><td colspan="2" rowspan="3">
</td></tr>
<tr><td>Imax (A)</td><td>1.142,80</td></tr>
<tr><td>$Imax_{RMS}$ (A)</td><td>463,19</td></tr>
<tr><td colspan="2">Consumed Energy</td><td colspan="2">Joule Losses</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td>Consumed Energy from TPSS (MWh)</td><td>0,640</td><td>Total Joule Losses (kW)</td><td>11,7</td></tr>
</table>

8.3.4.2.2 25 kVac

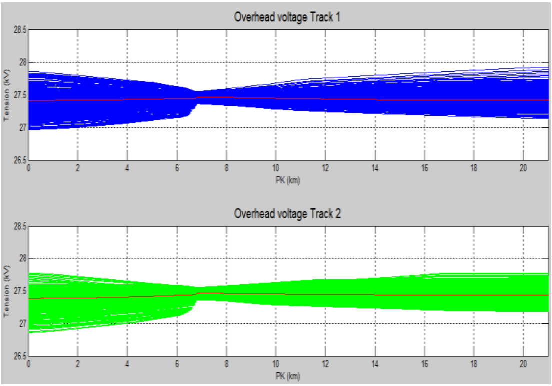
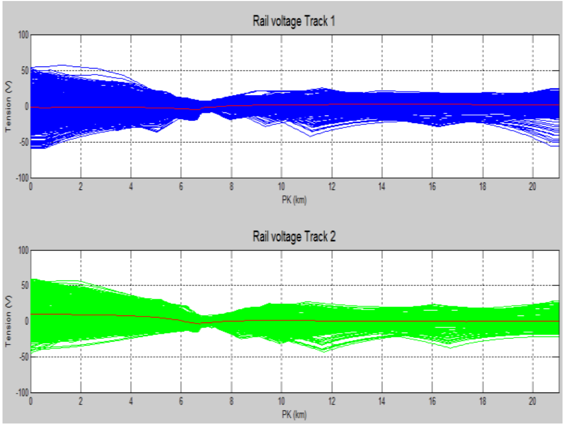
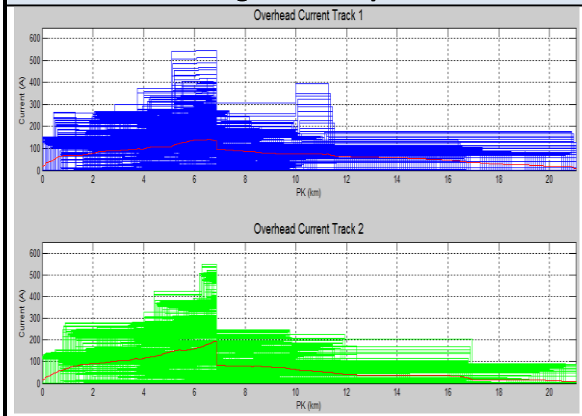
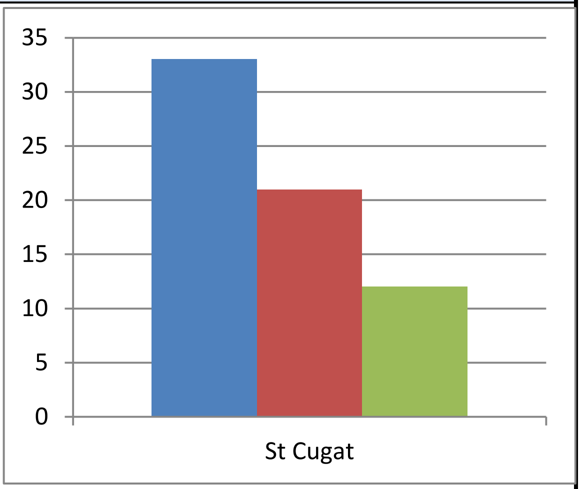
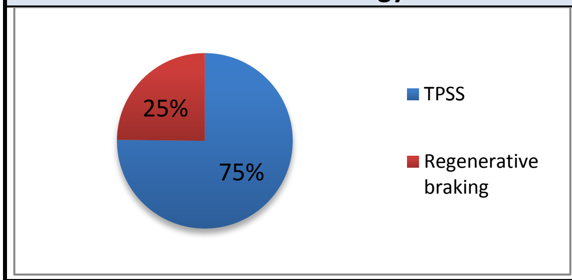
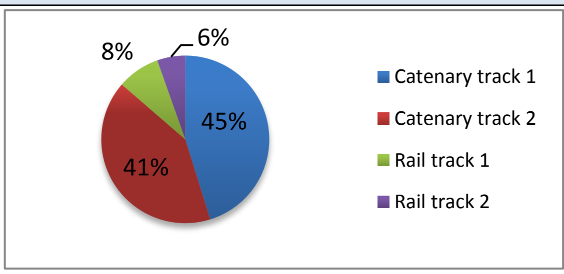
8.3.4.2.2.1 Plaça Catalunya – Neutral Zone sector

Table 36 Electric results for Plaça Catalunya – Zona Neutra sector. AC default scenario

<table>
<tr><th colspan="4">ELECTRIC SIMULATION - RESULTS</th></tr>
<tr><td>Simulation name:</td><td>AC-ES-D-001</td><td>Simulation period:</td><td>7.30 – 8.30</td></tr>
<tr><td>Line sector:</td><td>PlCatalunya - ZonaNeutra</td><td>Electrification:</td><td>25 kVac</td></tr>
<tr><td colspan="4">Traction network</td></tr>
<tr><td colspan="2" rowspan="2">Traction Substations in service</td><td colspan="2">Gràcia</td></tr>
<tr><td colspan="2">✓</td></tr>
<tr><td colspan="2">Voltage drop in Catenary</td><td colspan="2">Voltage drop in Return circuit</td></tr>
<tr><td colspan="2">
</td><td colspan="2" rowspan="2">
</td></tr>
<tr><td>Vmax (V)</td><td>27.812,0</td></tr>
<tr><td>Vmin (V)</td><td>26.923,4</td><td>Vmax (V)</td><td>61,33</td></tr>
<tr><td colspan="2">Current through Catenary conductors</td><td colspan="2">SS Traction Power</td></tr>
<tr><td colspan="2">
</td><td colspan="2" rowspan="3">
</td></tr>
<tr><td>Imax (A)</td><td>620,9</td></tr>
<tr><td>Imax_{RMS} (A)</td><td>228,18</td></tr>
<tr><td colspan="2">Consumed Energy</td><td colspan="2">Joule Losses</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td>Consumed Energy in TPSS (MWh)</td><td>5,375</td><td>Total Joule Losses (kW)</td><td>6,6</td></tr>
</table>

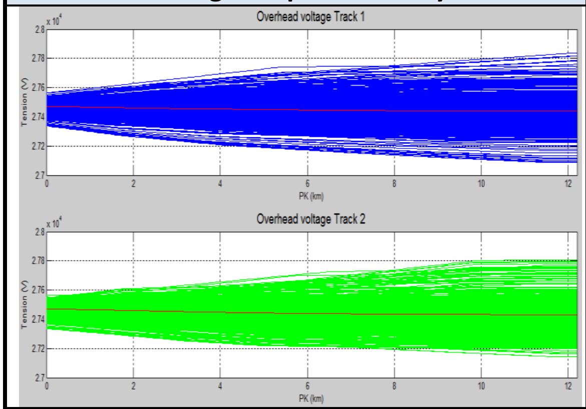
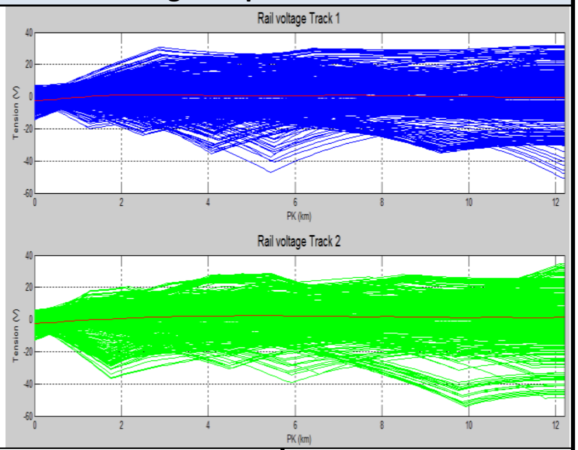
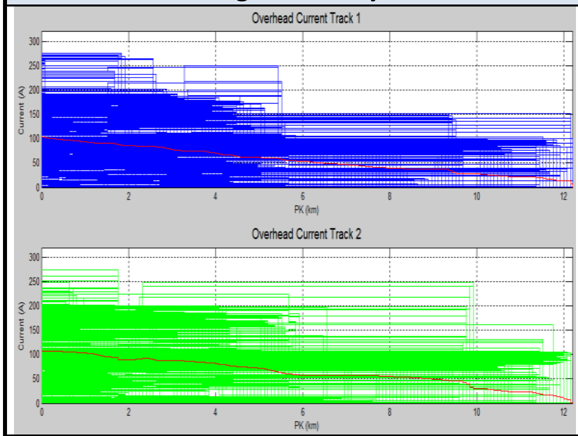
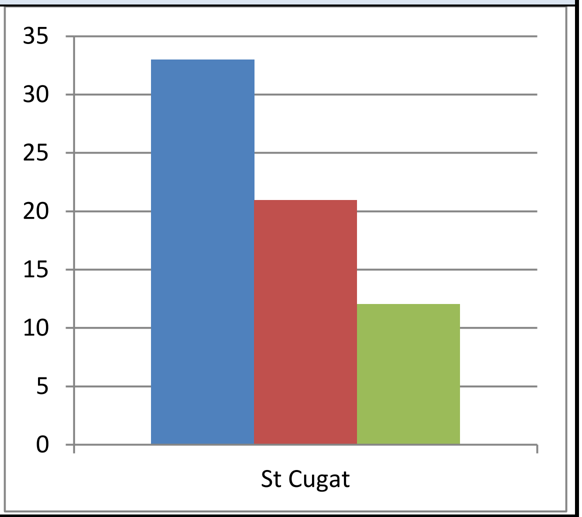
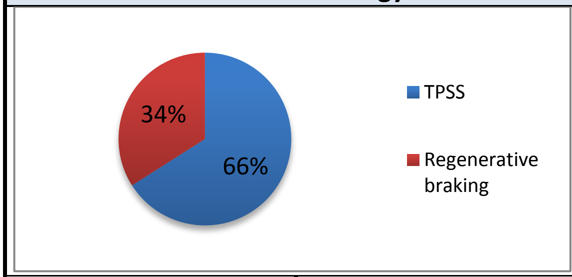
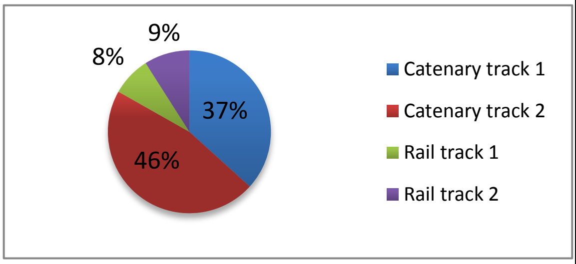
8.3.4.2.2.2 Neutral Zone –Terrassa sector

Table 37 Electric results for Zona Neutra – Terrassa sector. AC default scenario

ELECTRIC SIMULATION - RESULTS			
Simulation name:	AC-ES-D-002	**Simulation period:**	7.30 – 8.30
Line sector:	ZonaNeutra - Terrassa	**Electrification:**	25 kVac
Traction network			
Traction Substations in service		Sant Cugat ✓	
Voltage drop in Catenary		**Voltage drop in Return circuit**	
			
Vmax (V)	27.923,6		
Vmin (V)	26.861,1	**Vmax (V)**	58,99
Current through Catenary conductors		**SS Traction Power**	
			
Imax (A)	550,63		
Imax$_{RMS}$ (A)	193,25		
Consumed Energy		**Joule Losses**	
			
Consumed Energy in TPSS (MWh)	7,526	**Total Joule Losses (kW)**	19

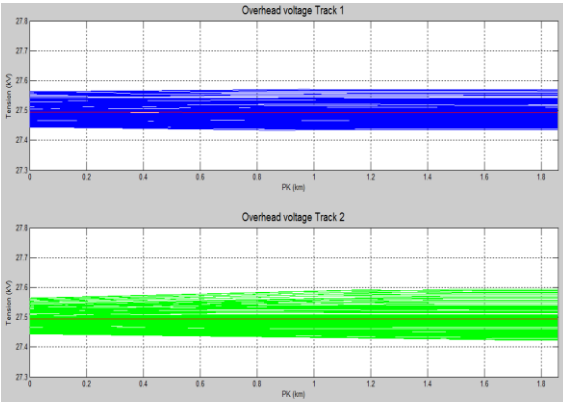
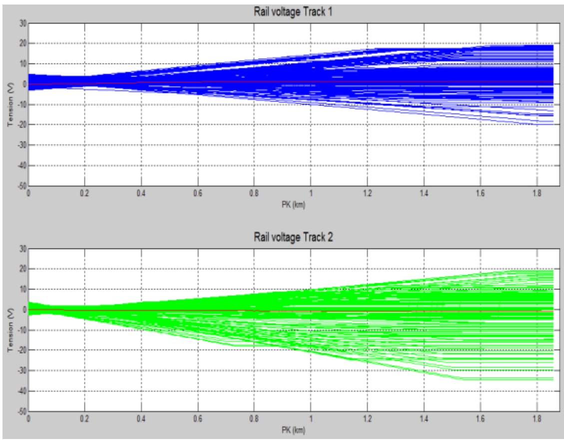
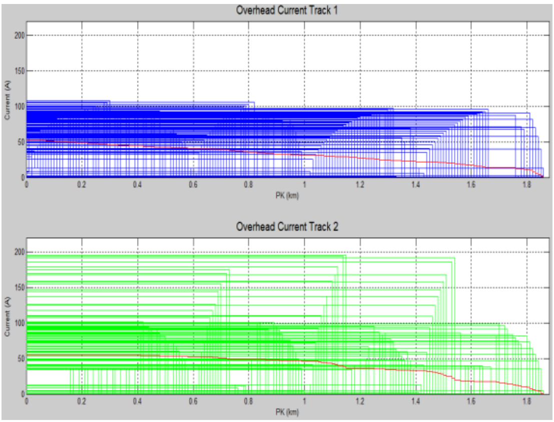
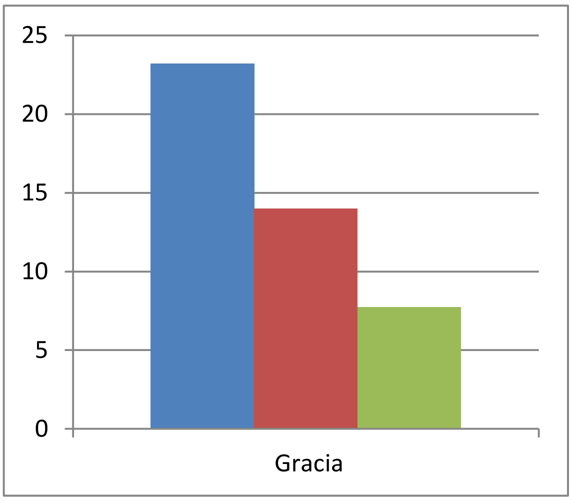
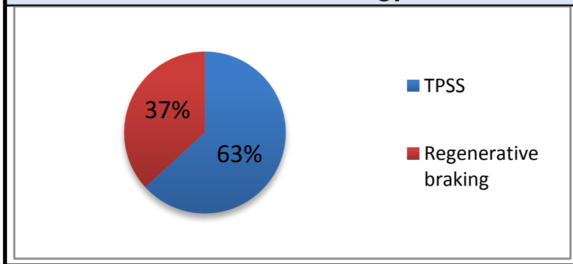
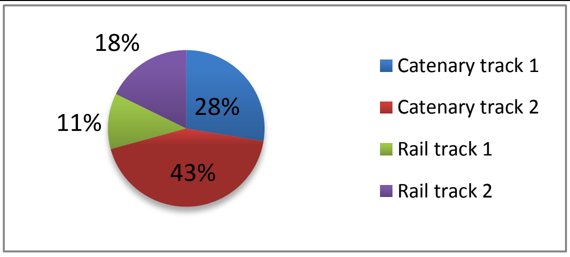
8.3.4.2.2.3 Sant Cugat –Sabadell sector

Table 38 Electric results for Sant Cugat – Sabadell sector. AC default scenario

ELECTRIC SIMULATION - RESULTS			
Simulation name:	AC-ES-D-003	**Simulation period:**	7.30 – 8.30
Line sector:	Sant Cugat - Sabadell	**Electrification:**	25 kVac
Traction network			
Traction Substations in service		Sant Cugat ✓	
Voltage drop in Catenary		**Voltage drop in Return circuit**	
			
Vmax (V)	27.837,55		
Vmin (V)	27.086,02	**Vmax (V)**	54,09
Current through Catenary conductors		**SS Traction Power**	
			
Imax (A)	276,49		
$Imax_{RMS}$ (A)	106,92		
Consumed Energy		**Joule Losses**	
			
Consumed Energy in TPSS (MWh)	2,83	**Total Joule Losses (kW)**	23,9

8.3.4.2.2.4 Gràcia –Avda. Tibidabo sector

Table 39 Electric results for Gràcia –Avda. Tibidabo sector. AC default scenario

ELECTRIC SIMULATION - RESULTS			
Simulation Code:	AC-ES-D-004	**Simulation period:**	7.30 – 8.30
Line sector:	Gràcia – Avda Tibidabo	**Electrification:**	25 kVac
Traction network			
Traction Substations in service		Gràcia ✓	
Voltage drop in Catenary		**Voltage drop in Return circuit**	
			
Vmax (V)	27.590,2		
Vmin (V)	27.422,6	**Vmax(V)**	34,6
Current through Catenary conductors		**SS Traction Power**	
			
Imax (A)	195,51		
$Imax_{RMS}$ (A)	54,98		
Consumed Energy		**Joule Losses**	
			
Consumed Energy in TPSS (MWh)	1,086	**Total Joule Losses (kW)**	1,9

8.3.4.2.3 Results validation and comparison

In order to validate the results, the following procedure is considered:

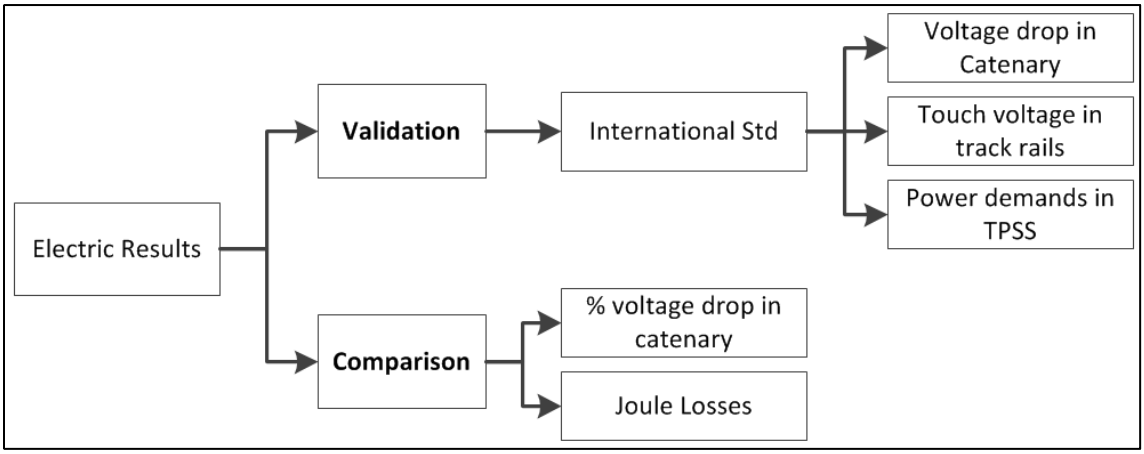


Figure 16 Results validation procedure scheme

In the validation step, the results obtained will be accepted as suitable if they are within the limits that the International Standards mentioned before impose. If both systems are suitable, a comparison between them regarding the percentage of how far the values obtained are from the nominal and therefore ideal values will be carried out.

8.3.4.2.3.1 Validation

In the following tables the results are presented next to a validation tick (✓) or a red cross (X) depending on their validity regarding the International Standards.

Table 40 Validation table for Plaça Catalunya- Terrassa sector electric results

Line Sector		Plaça Catalunya – Terrassa Rambla			
Default operation		**DC**		**AC**	
OVERHEAD CATENARY					
Lowest voltage	**[V]**	1.187,96	✓	26.861,1	✓
Highest voltage	**[V]**	1.861,83	✓	27.923,6	✓
RETURN CIRCUIT					
Highest voltage	**[V]**	81,67	✓	61,33	✓

Table 41 Validation table for Sant Cugat - Sabadell sector electric results

Line Sector		Sant Cugat – Sabadell Rambla			
Default operation		**DC**		**AC**	
OVERHEAD CATENARY					
Lowest voltage	**[V]**	1.158,40	✓	27.086,02	✓
Highest voltage	**[V]**	1.878,28	✓	27.837,55	✓
RETURN CIRCUIT					
Highest voltage	**[V]**	89,76	✓	54,09	✓

Table 42 Validation table for Gràcia – Avda Tibidabo sector electric results

Line Sector		Gràcia – Avinguda Tibidabo			
Default operation		**DC**		**AC**	
OVERHEAD CATENARY					
Lowest voltage	**[V]**	1.451,94	✓	27.422,6	✓
Highest voltage	**[V]**	1.593,00	✓	27.590,2	✓
RETURN CIRCUIT					
Highest voltage	**[V]**	11,06	✓	34,6	✓

Regarding power demands in the TPSS:

Table 43 Power demands in TPSS for 1.500 Vdc and 25 kVac configurations

Default operation							
TPSS		**DC**			**AC**		
		Instant	**RMS 1'**	**RMS 15'**	**Instant**	**RMS 1'**	**RMS 15'**
Plaça Catalunya	**[MVA]**	5,656	2,679	1,670	n/a		
Gràcia	**[MVA]**	4,032	2,391	1,705	23,201	13,986	7,731
Sarrià	**[MVA]**	6,324	4,007	2,975	n/a		
Les Planes	**[MVA]**	6,119	3,813	2,852			
Sant Cugat	**[MVA]**	11,979	7,733	5,109	33,015	20,971	12,032
Les Fonts	**[MVA]**	4,930	3,780	2,388	n/a		
Sant Quirze	**[MVA]**	7,949	5,136	3,759			

And as graphic representation:

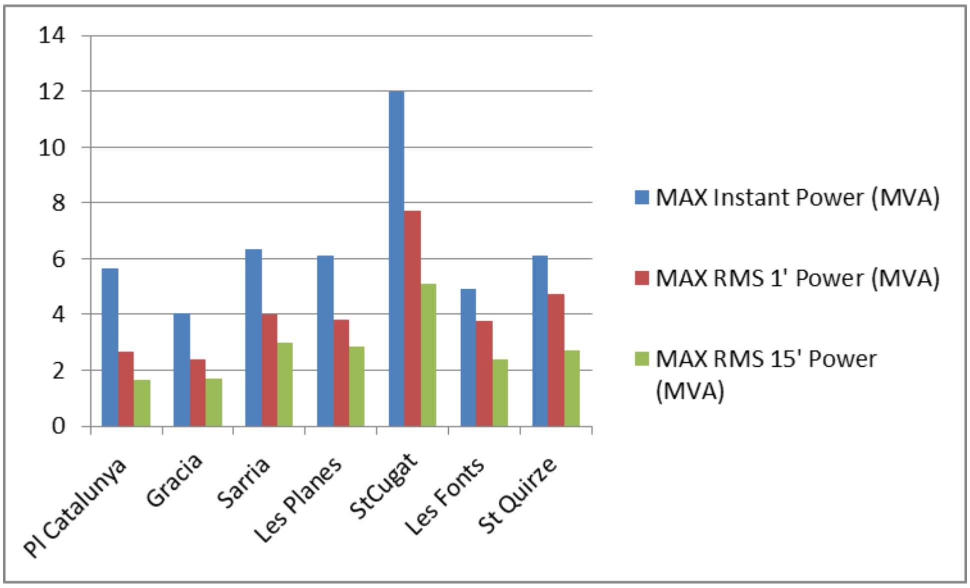


Figure 17 TPSS Power demands in default operation for 1500 Vdc voltage system

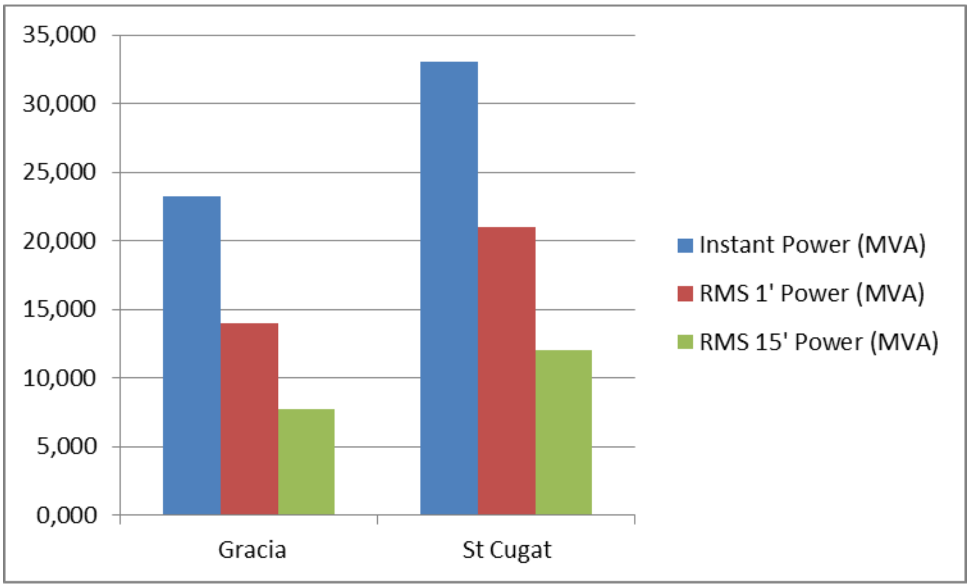


Figure 18 TPSS Power demands in default operation for 25 kVac voltage system

Both systems demand power (in permanent situation RMS 15’) that is within the limits of the nominal power installed for each TPSS.

As a summary, in default operation of the *FGC* line both systems can sustain the scenario in peak hour maintaining their electrical values within the limits of good operation.

As a remark, in the 1500 Vdc configuration the results are in concordance with the reality, as the line functions without any problem when default conditions in normal operation.

8.3.4.2.3.2 Comparison

As both systems are feasible regarding the simulation results, it becomes interesting to see which system could be nearer to the ideal working situation, with simulation values for each voltage system being as near as possible as the nominal values. To do so, a table showing the voltage drop percentage from the nominal values for each configuration is shown.

Table 44 Voltage drop percentage in default operation for the 1500 Vdc and the 25 kVac configuration

	DC		AC	
Line Sector	**Nominal value [V]**	**Drop [%]**	**Nominal value [V]**	**Drop [%]**
Pl Catalunya - Terrassa	1.590	25,29	27.500	2,32
Sant Cugat – Sabadell	1.590	27,14	27.500	1,51
Gràcia – Avda Tibidabo	1.590	8,68	27.500	0,28

There is a big difference in the voltage drop percentage of the two configurations studied. It is easy to recognize that having similar train power demands and the same number of trains simultaneously in the line, the main cause for the big difference of percentages between the two voltage systems lies upon the working currents values. Analyzing these results, a conclusion could be that the train fleets in the AC voltage system can be increased as there is still range of voltage drop in the catenary. Of course, this conclusion would have to be taken in concordance with other aspects concerning the operator of the line such as signaling systems or line capacity.

Comparing the maximum current in permanent conditions ($I_{RMS\ 15'}$) for each line sector and electrification, the Joule losses can be easier to understand:

Table 45 Current comparison between the 1500 Vdc and 25 kVac configurations

	DC	AC	
Line Sector	**IRMS 15' (A)**	**IRMS 15' (A)**	**Current reduction with the AC configuration [%]**
Plaça Catalunya - Terrassa	1.102	421	61,8
Sant Cugat - Sabadell	843	107	87,3
Gràcia - Plaça Catalunya	463	55	88,1

Considering these reduction percentages and considering the length of each sector, there is a global current reduction percentage of 69% with the 25 kVac traction network system.

The Joule losses are directly bond to the amount of current required, as they are proportional to the quadratic value of the current.

In the following table it is shown a comparison between the Joule losses of each configuration, where the decreasing percentage that the 25 kVac configuration losses mean in front of the losses of the 1500 Vdc configuration is calculated.

Table 46 Joule losses in default operation for the 1500 Vdc and the 25 kVac configuration

Line Sector	Line lenght [m]	DC losses [kW]	AC losses [kW]	Decrease of Joule losses with the AC voltage system [%]
Pl Catalunya - Terrassa	29.639	680	25,6	96,24
Sant Cugat – Sabadell	12.200	294	23,9	91,87
Gràcia – Avda Tibidabo	1.859	11,7	1,9	83,76

The Joule losses generated suppose the 5,1 % of the total power consumed for the 1500 Vdc configuration and a 0,26 % of the power consumed for the 25 kVac.

It can be appreciated that the longer the line is, the better performance regarding Joule losses the AC configuration has. That is why railways with high power demands and covering long routes such as High Speed lines are always electrified under alternating current.

8.3.4.3 Contingency operation

8.3.4.3.1 1500 Vdc

8.3.4.3.1.1 Contingency DC_1

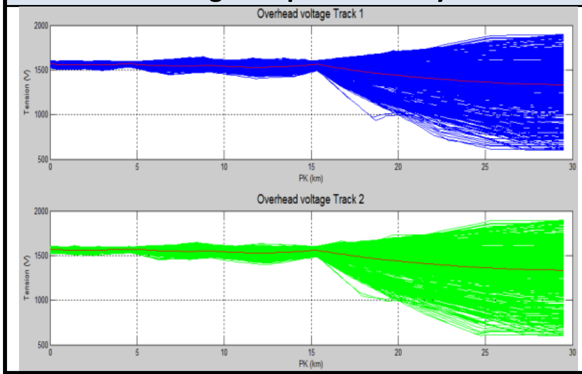
Table 47 Electric results for Plaça Catalunya – Terrassa sector. ContingencyDC_1 scenario

ELECTRIC SIMULATION – RESULTS			
Simulation name:	DC-ES-C-001	**Simulation period:**	7:30 – 8.30
Line sector:	PlaçaCat – Terrassa	**Electrification:**	1.500 Vdc

Traction network

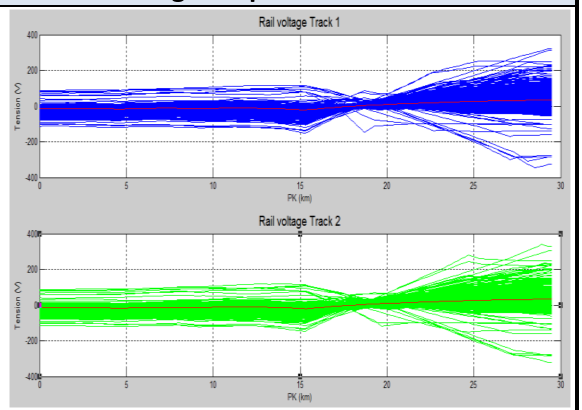
TPSS in service	PlCat	Gracia	Sarria	Planes	StCugat	Fonts
	✓	✓	✓	✓	✓	X

Voltage drop in Catenary



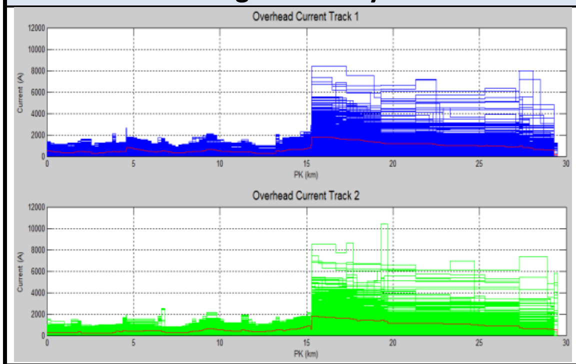
Vmax (V)	1.899,89
Vmin (V)	601,70

Voltage drop in Return circuit



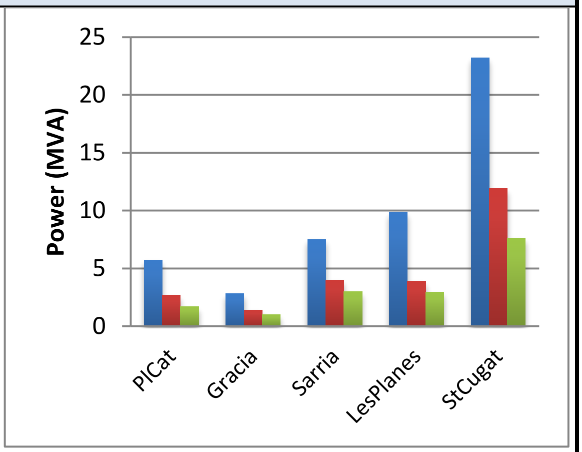
Vmax (V)	349,90

Current through Catenary conductors

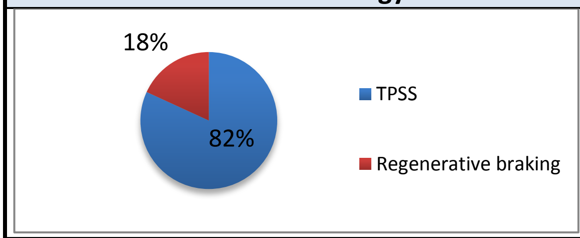


Imax (A)	10.395,11
$Imax_{RMS}$ (A)	1.810,06

SS Traction Power

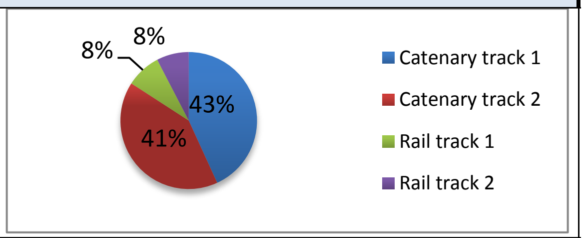


Consumed Energy



Consumed Energy from TPSS (MWh)	14,01

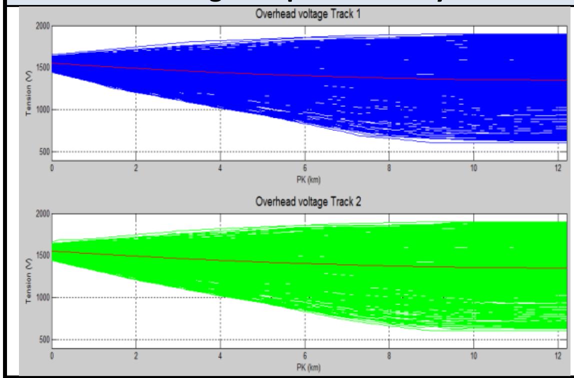
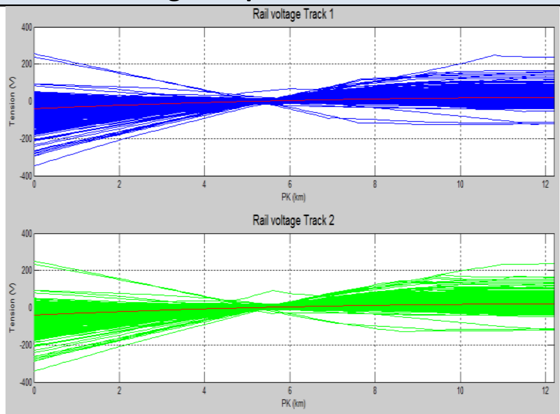
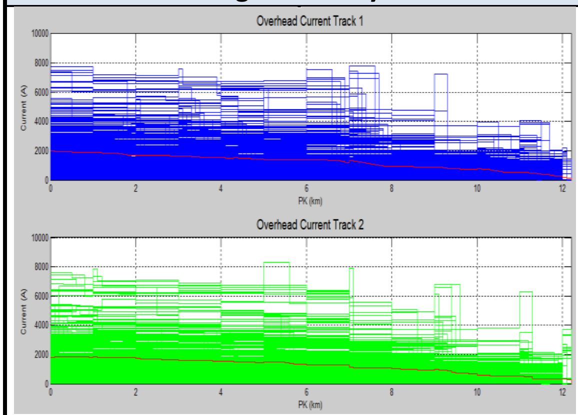
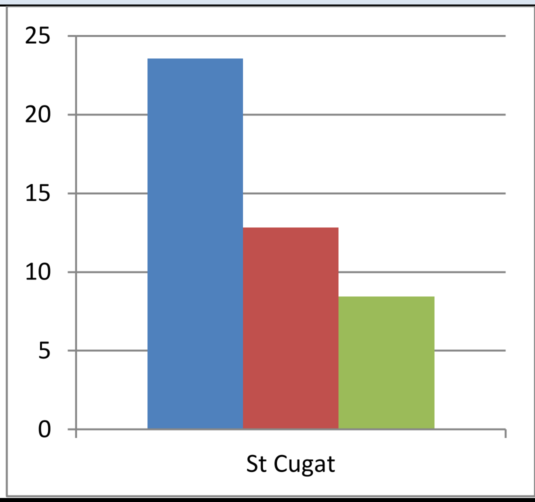
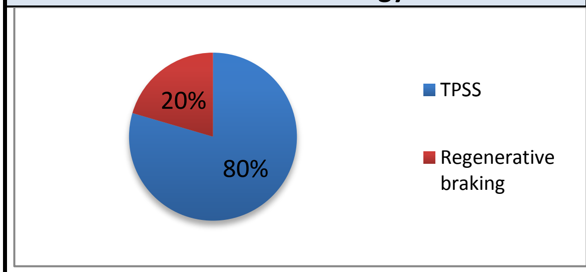
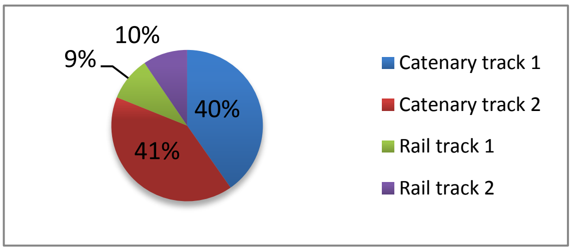
Joule Losses



Total Joule Losses (kW)	2.410

8.3.4.3.1.2 Contingency DC_2

Table 48 Electric results for Sant Cugat – Sabadell sector. ContingencyDC_2 scenario

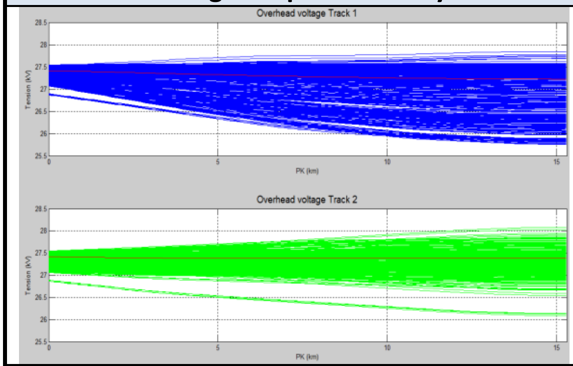
<table>
<tr><th colspan="4">ELECTRIC SIMULATION - RESULTS</th></tr>
<tr><td>Simulation name:</td><td>DC-ES-C-002</td><td>Simulation period:</td><td>7:30 – 8.30</td></tr>
<tr><td>Line sector:</td><td>Sant Cugat – Sabadell Rambla</td><td>Electrification:</td><td>1.500 Vdc</td></tr>
<tr><td colspan="4">Traction network</td></tr>
<tr><td colspan="2" rowspan="2">TPSS in service</td><td>StCugat</td><td>StQuirze</td></tr>
<tr><td>✓</td><td>X</td></tr>
<tr><td colspan="2">Voltage drop in Catenary</td><td colspan="2">Voltage drop in Return circuit</td></tr>
<tr><td colspan="2">
</td><td colspan="2" rowspan="2">
</td></tr>
<tr><td>Vmax (V)</td><td>1.900,90</td></tr>
<tr><td>Vmin (V)</td><td>605,72</td><td>Vmax (V)</td><td>347,70</td></tr>
<tr><td colspan="2">Current through Catenary conductors</td><td colspan="2">SS Traction Power</td></tr>
<tr><td colspan="2">
</td><td colspan="2" rowspan="3">
</td></tr>
<tr><td>Imax (A)</td><td>8.294,33</td></tr>
<tr><td>$Imax_{RMS}$ (A)</td><td>1.970,50</td></tr>
<tr><td colspan="2">Consumed Energy</td><td colspan="2">Joule Losses</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td>Consumed Energy from TPSS (MWh)</td><td>4,02</td><td>Total Joule Losses (kW)</td><td>3.633</td></tr>
</table>

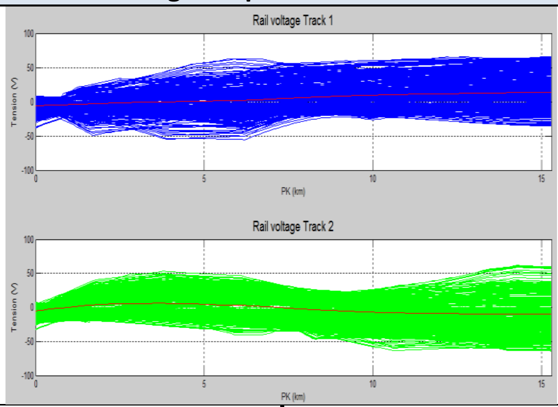
8.3.4.3.2 25 kVac

8.3.4.3.2.1 Contingency AC_1

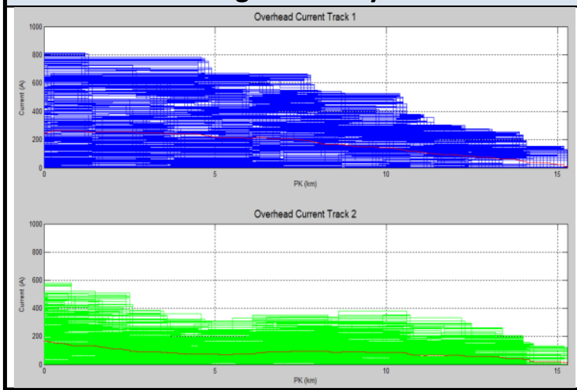
Table 49 Electric results for Sant Cugat – Plaça Catalunya sector. Contingency AC_1 scenario

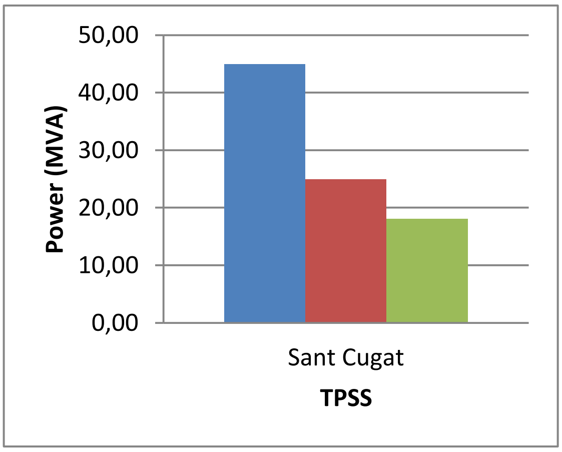
ELECTRIC SIMULATION - RESULTS			
Simulation name:	AC-ES-C-003	**Simulation period:**	7.30 – 8.30
Line sector:	Sant Cugat – Pl.Catalunya	**Electrification:**	25 kVac
Traction network			
Traction Substations in service		Gracia	Sant Cugat
		X	✓
Voltage drop in Catenary		**Voltage drop in Return circuit**	



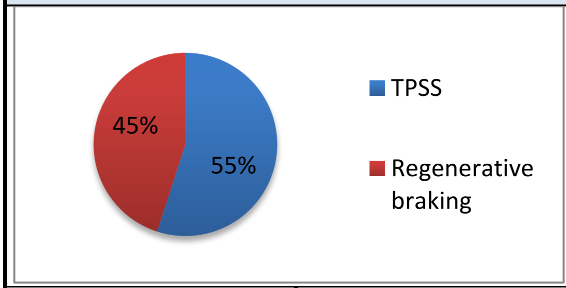


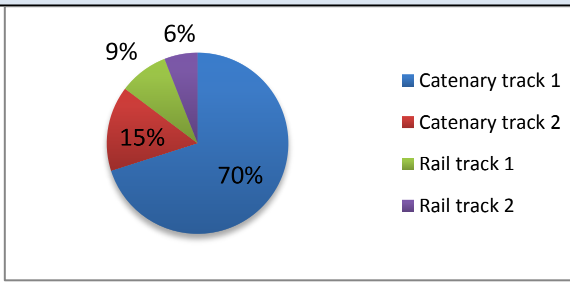
Vmax (V)	28.074,88		
Vmin (V)	25.770,09	**Vmax (V)**	62,16
Current through Catenary conductors		**SS Traction Power**	





Imax (A)	814,70		
$Imax_{RMS}$ (A)	262,67		
Consumed Power		**Joule Losses**	





Consumed Power in TPSS (MWh)	7,56	**Total Joule Losses (kW)**	230

8.3.4.3.2.2 Contingency AC_2

Table 50 Electric results for Gràcia – Terrassa sector. ContingencyAC_2 scenario

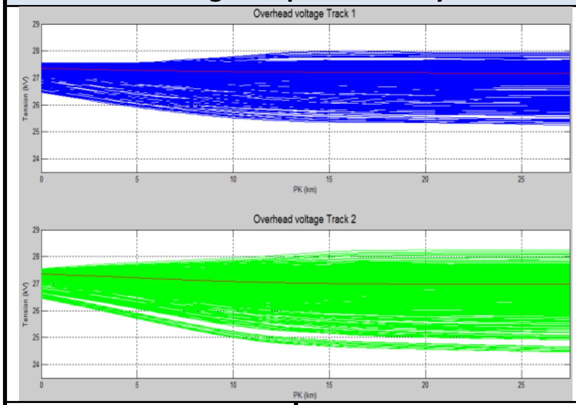
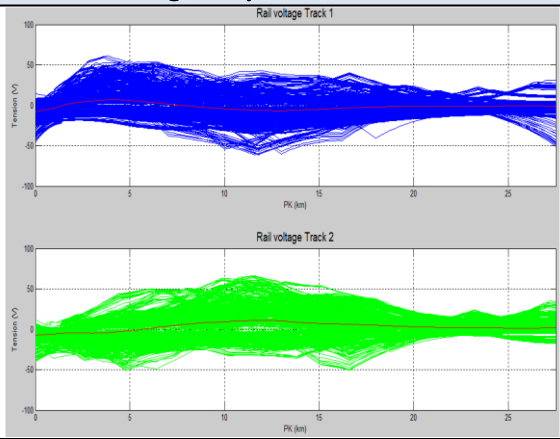
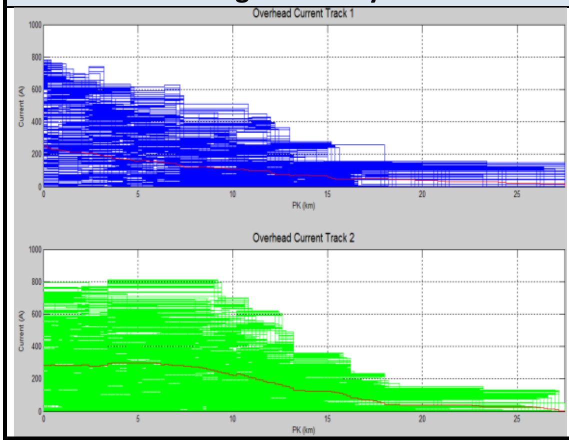
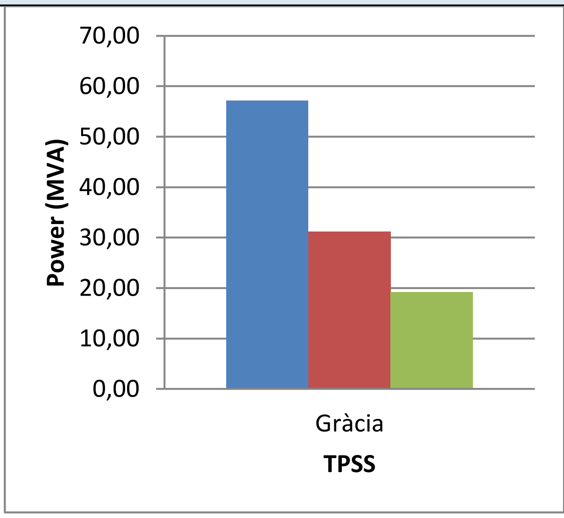
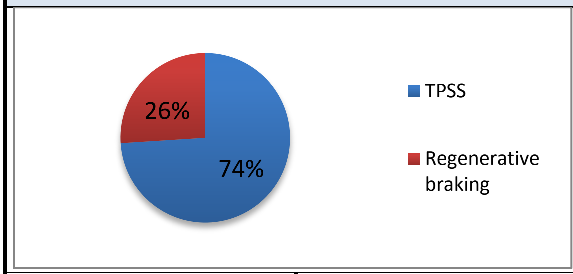
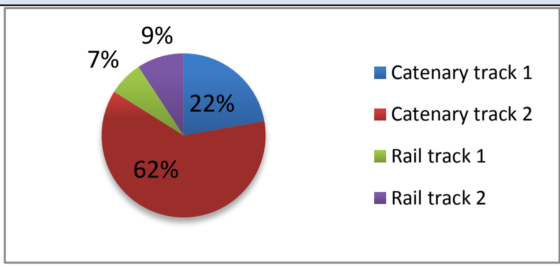
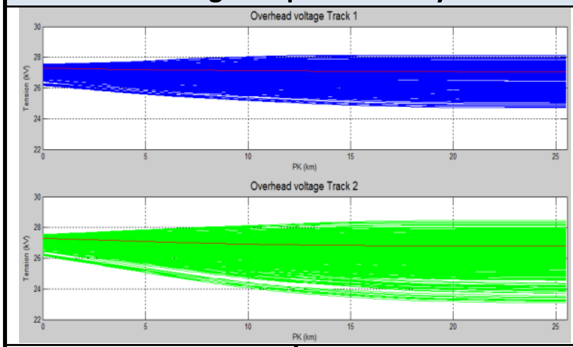
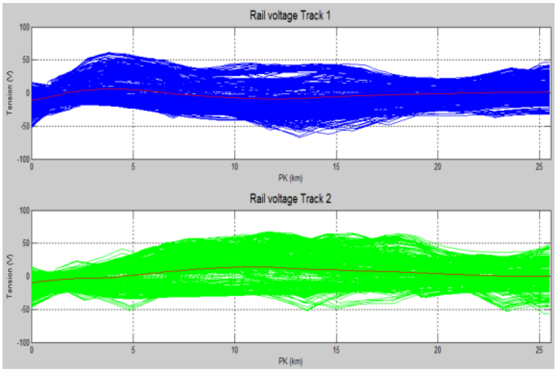
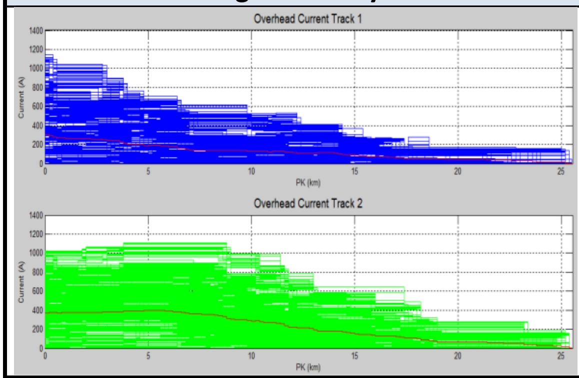
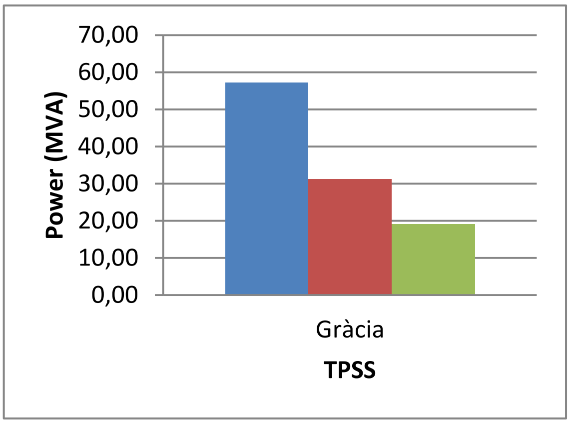
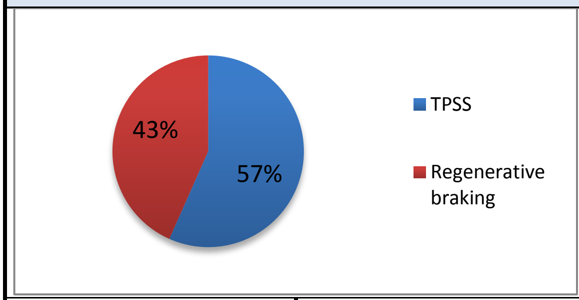
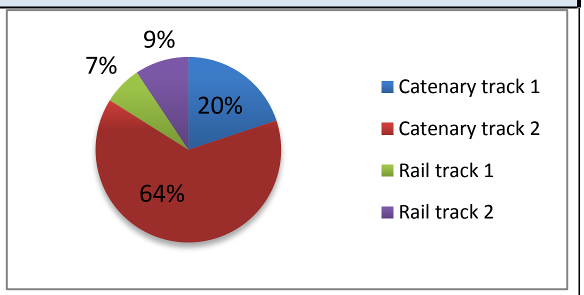
ELECTRIC SIMULATION - RESULTS			
Simulation name:	AC-ES-C-001	**Simulation period:**	7.30 – 8.30
Line sector:	Gràcia - Terrassa	**Electrification:**	AC
Traction network			
Traction Substations in service		Gracia	Sant Cugat
		✓	X
Voltage drop in Catenary		**Voltage drop in Return circuit**	
			
Vmax (V)	28.245,23		
Vmin (V)	24.489,21	**Vmax(V)**	64,72
Current through Catenary conductors		**SS Traction Power**	
			
Imax (A)	811,92		
$Imax_{RMS}$ (A)	298,9		
Consumed Power		**Joule Losses**	
			
Consumed Power in TPSS (MWh)	10,78	**Total Joule Losses (kW)**	340

Table 51 Electric results for Gràcia – Sabadell sector. Contingency AC_2 scenario

ELECTRIC SIMULATION - RESULTS			
Simulation name:	DC-ES-C-002	**Simulation period:**	7.30 – 8.30
Line sector:	Gràcia - Sabadell	**Electrification:**	AC
Traction network			
Traction Substations in service		Gracia	Sant Cugat
		✓	X
Voltage drop in Catenary		**Voltage drop in Return circuit**	
			
Vmax (V)	28.442,78		
Vmin (V)	23.091,08	**Vmax(V)**	67,72
Current through Catenary conductors		**SS Traction Power**	
			
Imax (A)	1.146,0		
$Imax_{RMS}$ (A)	395,2		
Consumed Power		**Joule Losses**	
			
Consumed Power in TPSS (MWh)	13,75	**Total Joule Losses (kW)**	590

8.3.4.3.3 Results validation and comparison

As the contingency situations for the two studied configurations include different line sectors, they will be presented independently and lately a global conclusion will be extracted.

8.3.4.3.3.1 Validation

8.3.4.3.3.1.1 1500 Vdc Contingency scenarios

Table 52 Validation table for Contingency DC1 scenario electric results

Line Sector		Plaça Catalunya – Terrassa Rambla	
Contingency DC_1			
OVERHEAD CATENARY			
Lowest voltage	**[V]**	601,70	X
Highest voltage	**[V]**	1.899,89	✓
RETURN CIRCUIT			
Highest voltage	**[V]**	349,90	X

Table 53 Validation table for Contingency DC2 scenario electric results

Line Sector		Sant Cugat - Sabadell	
Contingency DC_2			
OVERHEAD CATENARY			
Lowest voltage	**[V]**	605,72	X
Highest voltage	**[V]**	1.900,90	✓
RETURN CIRCUIT			
Highest voltage	**[V]**	347,70	X

8.3.4.3.3.1.2 25 kVac Contingency scenarios

Table 54 Validation table for Contingency AC1 scenario electric results

Line Sector		Sant Cugat – Pl.Catalunya	
Contingency AC_1			
OVERHEAD CATENARY			
Lowest voltage	**[V]**	25.770,09	✓
Highest voltage	**[V]**	28.074,88	✓
RETURN CIRCUIT			
Highest voltage	**[V]**	62,16	✓

Table 55 Validation table for Contingency AC2 scenario (Gràcia – Terrassa) electric results

Line Sector		Gràcia - Terrassa	
Contingency AC_2			
OVERHEAD CATENARY			
Lowest voltage	**[V]**	24.489,21	✓
Highest voltage	**[V]**	28.245,23	✓
RETURN CIRCUIT			
Highest voltage	**[V]**	64,72	✓

Table 56 Validation table for Contingency AC2 scenario (Gràcia – Sabadell) electric results

Line Sector		Gràcia - Sabadell	
Contingency AC_2			
OVERHEAD CATENARY			
Lowest voltage	**[V]**	23.091,08	✓
Highest voltage	**[V]**	28.442,78	✓
RETURN CIRCUIT			
Highest voltage	**[V]**	67,72	✓

Regarding power demands in TPSS:

Table 57 Power demands in TPSS for the DC and AC scenarios in contingency operation

Contingency operation							
TPSS		**DC**			**AC**		
		Instant	**RMS 1'**	**RMS 15'**	**Instant**	**RMS 1'**	**RMS 15'**
Plaça Catalunya	**[MVA]**	5,71	2,69	1,68	n/a		
Gràcia	**[MVA]**	4,64	2,33	1,76	57,16	31,18	19,15
Sarrià	**[MVA]**	7,51	4,00	3,00	n/a		
Les Planes	**[MVA]**	9,86	3,88	2,94			
Sant Cugat	**[MVA]**	23,19	11,91	**7,61**	44,89	24,94	18,08
Les Fonts	**[MVA]**	**X**			n/a		
Sant Quirze	**[MVA]**	**X**					

8.3.4.3.3.2 Conclusion

The results for contingency operation (N-1) show the stress that the line works under when the operational conditions are not the ones required to work properly. A good design needs to be able to overcome these contingency conditions and continue working properly until the default conditions are back again.

It is important to remember that the train simulations are performed always considering full load working conditions and not considering efficient conduction. As they are simulations for sizing and designing a railway traction network and therefore the working limit conditions are searched, the simulation conditions need to be always as demanding as possible. In both contingency scenarios for the 1500 Vdc configuration, there were some instants that could not even converge due to the amount of power demanded with the traction system not being able to absorb it.

After the before mentioned considerations, there can be concluded that the 1500 Vdc electrification operated by *FGC* cannot operate in the conditions exposed in the chapter *Key assumptions and operational constraints,* when the TPSS of Les Fonts or the one in Sant Quirze are under failure and consequently not providing power to the line.

Nevertheless, the results of voltage drop in catenary and power demands would not take place in reality, as there are many factors that would prevent it to happen:

1. The train has its logic that makes it stop demanding power if the line voltage drops under a certain limit. This requirement is a result of the current – speed curve of the train, which prevents damage due to abnormal high values of current.
2. The possibility to freeze services of some lines and therefore increasing their headways and decreasing the global output power demanded.
3. In the worst case, if there is more than one line operating in the same line sector, one of the lines could be temporally blocked and a provisional schedule with the new headways and departures of the trains would be released by the operator.
4. Generally, when working under contingency scenarios, the operator gives to the train drivers some references to operate more efficiently:
    a. Smooth accelerations when departing
    b. Not to achieve the maximum speed of the train

Regarding the 25 kVac configuration, the contingency scenarios would not handicap the normal operating conditions of the railway. Lower values of catenary losses become the main advantage for this voltage system when operating under contingency situations. Regarding voltage drop in the catenary, the values obtained are within the limits of safe operation and therefore, no feeders are required (it validates the configuration selected in the chapter *7.4.1.3.2*).

Considering the power demands, the substation of Sant Cugat in the 1500 Vdc voltage system when Les Fonts not in use demands (RMS 15') more power (shown in red color) than its nominal installed output power (3x2250). Consequently, regarding power demands, the 1500

Vdc configuration would be outside of the acceptable working limits imposed by the International Standards.

There is a result that can induce surprise: in contingency operation the power demands of the TPSS in the 25 kVac configuration are lower than in normal operation. The difference is minimum compared to the values obtained in the default operation but, as a first approach, it would seem that due to the joule losses of the line as a result of the higher values of current, the power demanded should be higher than in normal operation. The reality is that this phenomenon is explained because the neutral section does not divide the line in two electrical independent sections when under contingency and consequently, the power regenerated in each section can be consumed by trains located in the other section. In normal operation, the power regenerated in each section was converted in losses if there were not enough trains to consume it.

All in all, working in N-1 contingency situation, the 25 kVac configuration would be the only one that can maintain the operational constraints fixed at the beginning of this study.

8.3.4.3.3.3 Comparison

With the 1500 Vdc not accomplishing the operational constraints in N-1 scenarios, a comparison is not necessary as the 25 kVac configuration would be the only one suitable and able to accomplish the starting *Key assumptions and operational constraints*.

8.4 Traction Energy Balance

8.4.1 Introduction

One of the main aspects to consider when comparing two different railway electric configurations is the energetic cost that it will have for the operator.

In this chapter the energy consumption corresponding to the peak hour (7.30 – 8.30 Monday-Friday) for normal operational conditions will be analyzed for the two configurations proposed in this study.

As the rolling stock is not the same for the two configurations as they have different passenger capacity, power and traction curves, the energy balance comparison will be presented as a ratio per passenger and km of the line [Wh/(km·seat)]. This ratio is common in transportation disciplines and in this way; the results can be easier to extrapolate and to be compared.

8.4.2 Input data

8.4.2.1 Travelled km

The total amount of km travelled in the peak hour for each train line:

Table 58 Total amount of km travelled by the train lines during peak hour

Line	Lenght [km]	Headway [min]	Distance travelled [km/h]
L7	3,84	6	76,7
S1	29,64	11	331
S5	20,11	14	178
S2	27,50	11	335,5
S55	20,98	9	237,3

The total km travelled by the trains during peak hour is 1158,5 km.

8.4.2.2 Number of passengers

There are three types of rolling stock operating in the *FGC* line: two for the 1500 Vdc configuration (UT111 and UT112) and one in the proposed 25 kVac configuration (MOVIA). The passengers that each train carries, regarding the operational constraints exposed at the beginning of this study are the following:

Table 59 Total number of passengers per rolling stock

Rolling stock	Voltage system	Total capacity	Ocupation %	Total pax
UT111	1.500 Vdc	587	85	499
UT112	1.500 Vdc	724	85	615
MOVIA	25 kVac	1156	85	983

To do a single passenger ratio per electrification system and considering that the energy values of the TPSS include the consumption of each line and therefore of each rolling stock, for the DC electrification it becomes necessary to calculate an equivalent number of passengers for the two existing rolling stock:

Table 60 Share of the distance travelled by the DC configuration rolling stock

Rolling stock	Distance travelled [km]	Distance travelled in front of total amount travelled [%]
UT 111	528,78	45,90
UT 112	623,31	54,10

The equivalent number of passengers for the 1500 Vdc rolling stock considered to calculate the energy consumption ratio is 562.

8.4.3 Results

The following table shows the traction energy consumption for the normal operation (default) scenario:

Table 61 Energy consumption ratios for each TPSS and electrification system

	DC			AC		
TPSS	**kWh**	**kWh/km**	**kWh/(km·seat)**	**KWh**	**kWh/km**	**kWh/(km·seat)**
Plaça Catalunya	1.273,73	1,10	0,0020			
Gràcia	1.409,56	1,22	0,0022	6.461,32	5,58	0,0057
Sarrià	2.661,39	2,30	0,0041			
Les Planes	2.490,60	2,15	0,0038			
Sant Cugat	4.640,43	4,01	0,0071	10.355,18	8,94	0,0091
Les Fonts	1.951,90	1,68	0,0030			
Sant Quirze	2.126,52	1,84	0,0033			
TOTAL		14,3	**0,025**		14,5	**0,015**

The global results of the FGC line:

Table 62 Total energy consumption ratios for the 1500 Vdc and 25 kVac systems

	kWh/km	kWh/(km·seat)
1500 Vdc	14,3	0,025
25 kVac	14,5	0,015

Before analyzing the results for the comparison chapter, the validity of the value of energy per km in the 1500 Vdc configuration is accepted regarding public consumption data provided by *FGC.* In the document *Revisión crítica de datos sobre consumo de energía y emisiones de los medios públicos de transporte* [18] there is the consumption ratio for the Rolling stock UT-112 and it can be compared with the ratio here obtained:

Table 63 Energy consumption kWh/(km·seat) for real operation and normal operation simulation for the 1500 Vdc

	Real operation	Simulation
Energy consumption [kWh/(km·seat)]	11,17	14,3

It is important to notice that the real operation value is an average of the annual consumption, which includes the peak hour periods but also the off-peak hours and weekends, where the energy demand is lower than in peak hour and therefore, the ratio needs to be lower. All in all, this comparison with real consumption values gives validity and consistency to the comparative study performed.

8.4.4 Comparison

Even if the energy consumed per km is basically the same (25 kVac electrification consumption is 1,4% higher), it appears a big gap when comparing the magnitudes per seat. The fact that for the same consumption and therefore the same bill of energy, one configuration can transport 43% more people than in the other configuration opens a new horizon for the operator of the line. Per km-seat ratio, the consumption of the proposed configuration of 25kVac sinks 40% compared with the value in the 1500 Vdc configuration.

Furthermore, the increasing of the number of passenger able to be transported would raise the ticket sales and a bigger part of the traction energy consumption bill could be amortized.

8.5 Economic analysis

8.5.1 Introduction

In this chapter the implantation economic cost of the two traction networks proposed in this study will be compared. The total costs here presented can be revised in the *Budget* document of this study.

It is important to remark that this part of the study has considered a new implementation of a railway to perform the comparison between the two systems studied. The motivation to process this way responds to the fact that the 1500 Vdc is already implemented, and evaluating the economic impact that the dismantle of the existing traction network to be substituted by the proposed one is not included in the scope of this study.

The implementation cost is divided in the following elements:

- Catenary
- Traction Power Substation (TPSS)
- Administrative costs

This economic approach does not include:

- Maintenance cost for the traction network systems
- Rolling stock costs
- Tunneling costs
- Energy cost
- No taxes on the final budget are included

8.5.2 Implantation cost

Table 64 Traction implantation costs for the 1500 Vdc and 25 kVac configurations

Item	1500 Vdc	25 kVac
Catenary	12.400.800,00	8.531.136,00
Feeder Stations (TPSS)	25.868.255,00	16.601.925,00
Administrative Costs	137.630,00	301.711,00
TOTAL	**38.406.685,00**	**25.434.772,00**

8.5.3 Cost comparison

The results clearly show that, considering the implantation of a new railway traction network, the 25 kVac configuration would be less expensive (33,7% lower).

These results are linked with the simulation results and can be analyzed from a technical point of view: the catenary of the DC configuration becomes more expensive due to the higher cross section of cables installed. This higher amount of cables respond to the need to sustain the high values of current needed to feed the rolling stock and, consequently, higher Joule losses appear heating the cables and therefore, sinking the quality of the current conduction.

Even if the 25 kV configuration needs to account for the neutral sections and bigger and more expensive insulators, the higher equivalent section of cable becomes the most important cost factor in a catenary system.

Regarding the cost of the feeder stations (TPSS), the implementation of the 25 kVac configuration would be less expensive than the alternative of 1500 Vdc. This aspect shows a clear advantage of the 25 kVac traction system: less TPPS are needed. Even if a traction power substation in the DC configuration is around 55,5% less expensive than the analogue of 25 kVac, the fact that in this line studied there are 7 TPSS in the 1500 Vdc configuration in front of the 2 proposed for the AC alternative, makes the 25 kVac traction network more advantageous from an economic point of view.

9 Conclusions

The consecution of this comparative study between a 1500 Vdc and a 25 kVac traction network electrification has provided an answer to the question formulated at the justification of the present work: It is possible technically, energetic and economically to electrify the Barcelona – Vallès railway with a 25 kVac electrification.

Regarding technical aspects, the simulation results show the inherent property of the 1500 Vdc voltage system: the line has an average of 69% more current demand in normal operation conditions than the 25 kVac configuration. Consequently, the voltage drop in the catenary is higher in the DC voltage system and therefore, the distance between traction substations (TPSS) sinks, increasing their number with all the costs associated. Extrapolating the results of voltage drop in the catenary, a direct consequence could be that a generic line in 25 kVac could be fed with a higher number of trains, increasing the passengers transported and consequently the profitability of the entire line.

The number of TPSS has as well handicapped the DC configuration when working under contingency scenarios, as there are two situations (when TPSS of Les Fonts or Sant Cugat are out of service) where the 1500 Vdc electrification cannot stand the operational constraints imposed at the beginning of the present study. On the other hand, the 25 kVac traction network can operate normally under contingency scenarios.

To finish the conclusions extracted from the technical viability of both configurations, the losses in the line (Joule losses) play an important role regarding efficiency: the Joule losses with the 25 kVac configuration are a 0,26% of the total power demanded in the TPSS and for the 1500 Vdc configuration they suppose a 5,1%.

The energetic analysis shows the same global energy consumption for both configurations. Nevertheless, these results cannot be directly compared because they come from rolling stocks with similar technical characteristics but with different capacities: the MOVIA rolling stock considered for the 25 kVac configuration can be loaded with 43% more people than the DC configurations. As both configurations were simulated with an 85% occupancy and therefore different number of passengers, they need to be compared with an energy ratio including the capacity of the trains (kWh/(km·seat), widely used in railway projects. It is through this ratio when the lower energy demand for the 25 kVac becomes clear: the energy consumption sinks 40% compared with the value in the 1500 Vdc configuration.

The economic analysis has accounted for the main traction network elements: the catenary system and the traction power substations. Once again, the high currents demanded in the DC configuration implies the need for high cross section catenaries and higher number of TPSS. Even if a TPSS in 25 kVac is around 55% more expensive than one in the 1500 Vdc voltage system, the 1500 Vdc system requires more TPSS and the global economic cost for the 1500 Vdc configuration becomes 33% more expensive.

Even if the results regarding a technical, energetic and economical point of view fall into the 25 kVac side, it is important to not forget that there exist other decision factors outside the scope of this study that can influence the selected traction network: regarding traction power substations, the ones needed for the 25 kVac configuration require more space than the ones of the 1500 Vdc configuration (but less location points) and, considering the feeding points to the HV grid, the connection becomes more complicated in the 25 kVac case than in the 1500 Vdc.

Another factor to take into account would be the availability of rolling stock in 25 kVac for the typology of line studied: as historically there has been a major use of the DC technologies for the railways with similar characteristics as the Barcelona – Vallès, there are less rolling stock models for 25 kVac configurations that can fit with the operational constraints required for the line studied.

Once revised the results obtained in this comparative study, it is not of less importance to correlate them with the reality. As pointed out in the *Simulation Report* chapter, the journey times and the ratio of energy consumption per km and seat are consistent with the real operational values; which enables to validate the simulation process and the simulating tool: *STElec*.

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