




Article

Energy Efficiency and Integration of Urban Electrical Transport Systems: EVs and Metro-Trains of Two Real European Lines

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Abstract: Transport is a main source of pollutants in cities, where air quality is a major concern. New transport technologies, such as electric vehicles, and public transport modalities, such as urban railways, have arisen as solutions to this important problem. One of the main difficulties for the adoption of electric vehicles by consumers is the scarcity of a suitable charging infrastructure. The use of the railway power supplies to charge electric vehicle batteries could facilitate the deployment of charging infrastructure in cities. It would reduce the cost because of the use of an existing installation. Furthermore, electric vehicles can use braking energy from trains that was previously wasted in rheostats. This paper presents the results of a collaboration between research teams from University of Rome Sapienza and Comillas Pontifical University. In this work, two real European cases are studied: an Italian metro line and a Spanish metro line. The energy performance of these metro lines and their capacity to charge electric vehicles have been studied by means of detailed simulation tools. Their results have shown that the use of regenerated energy is 98% for short interval of trains in both cases. However, the use of regenerated energy decreases as the train intervals grow. In a daily operation, an important amount of regenerated energy is wasted in the Italian and Spanish case. Using this energy, a significant number of electric vehicles could be charged every day.

Keywords: urban railways; electric vehicles; regenerated energy; energy efficiency

1. Introduction

Air pollution is one of the main problems in urban areas because of its impact on public health and the environment [1]. Transport has been identified as the main source of pollutants in cities. Therefore, many cities, not only in Europe [2], but also around the world [3], are developing air quality plans to deal with this problem.

Air quality plans typically implement short term and medium to long-term actions. Short term actions deal with the problem of reducing air pollution when it reaches peak levels and include measures such as road traffic limitations [4]. On the other hand, medium to long term actions deal with the problem of reducing the average air pollution and include measures such as public traffic promotion and new transport technologies support [5]. This concern for air quality has raised the interest on urban railways, to improve the public transport service, and for electric vehicles (EVs), to reduce the impact of road traffic.

In large cities, urban railways are needed to move efficiently a great number of people around the city. This transport mode, apart from being energy efficient [6], does not contribute to air pollution because, as it is an electrified transport mode, pollutants emissions are moved to generation centres away from cities. Furthermore, it could allow using cleaner energy if renewable energies are present in the generation mix.

These advantages have made possible the expansion of urban railways. For instance, the Chinese urban railway system has grown by 150% between 2005 and 2015 [7]. With the growth of cities, it is expected that the expansion of urban railway networks will continue. Furthermore, the promotion of the public sector will increase the rail activity in the cities. Therefore, energy saving measures will be needed to retain the energy consumption increase due to train activity.

Many works investigate how to reduce the energy consumption of train operation. These works are usually classified into three groups: those involving infrastructure, those dealing with rolling stock or those related to traffic operation [8–10]. Despite the classification, many works are related to the exploitation of the regenerated energy from braking because it leads to a relevant reduction of the energy consumption.

Infrastructure measures tackle the problem of DC lines receptivity to regenerated energy from train braking. Typically, regenerated energy is used to feed the auxiliary systems of the train and the surplus is returned to the power supply grid. However, the power supply grid in urban railways is a DC network, which is not always receptive to regenerated energy. To be receptive, other trains have to consume the regenerated energy in the moment of generation, because it cannot be sent to the utility grid. Therefore, it is usual the situation that this energy must be wasted in on-board resistors (rheostats). Two main solutions have been proposed in the literature, to increase the receptivity of the power supply grid and to maximise the use of regenerative energy: reversible substations [11–14] and wayside energy storage systems [15–20]. Reversible substations improve the receptivity by means of returning regenerated energy to the utility grid. On the other hand, wayside energy storages are used to stock exceeding regenerated energy and to supply that energy, when trains need it. Measures related to electrical operation have been also studied to improve the receptivity of the electrical network without including new devices [21] such as no-load voltage schemes.

Other authors developed traffic operation measures such as speed profile optimisation and timetable optimisation to maximise the exchange of regenerated energy between trains [22–25]. On the other hand, improvements in rolling stock, by means of on board energy storage system, have been assessed in literature [26–28], although its implementation in the specific case of urban railways is constrained because of problems related to space and weight.

Regarding EVs, they appear as the keystone to the near term improvement of the road traffic sustainability. The use of EVs allows improving cities air quality and reducing the noise pollution due to cars as well. Furthermore, the operating cost of driving a car is drastically reduced with the introduction of EVs. According to [29] an EV spends \$0.02 per mile while internal combustion engine vehicles spends \$0.12. However, nowadays there are barriers that limit the adoption of EVs by consumers.

Some of these barriers are social, such as consumers' belief that EVs are a new and unproved technology [30]. Other barriers are related to technological issues. Battery technology limitations and its high cost are highlighted in the literature as a major limitation for the spread of EVs [31]. However, the prices of batteries have been reduced during the last years and it is expected that they will continue declining in the future, making EVs more affordable [32]. Another important barrier for EV adoption is the scarcity of a public charging infrastructure. An EV should always have available a charging station within its displacement range. Therefore, there is a need for a wide charging infrastructure in cities to promote electrical mobility [33].

Charging infrastructure could be developed for assuming the EV demand or could be shared with other existing installations. Some authors have proposed the use of the railway power supply grid to

feed EV charging points. The use of the railway electrical system for charging EVs would reduce the cost and would facilitate the deployment of EV charging stations in cities [34].

In [35] the connection of charging stations to the high-speed power supply is proposed. High-speed railway lines allow powering high loads and, typically, they are located near motorways. Therefore, this connection allows the built of charging stations in service areas addressing the problem of finding suitable power sources. Apart from this study, real projects can be found that deal with the problem of connecting charging stations to mainline railway lines. The Spanish railway infrastructure manager (ADIF) led a project called Ferrolinera [36]. In this project, EV charging points were located at railway stations. These charging points are fed by photovoltaic sources and regenerated energy either from trains directly or from a wayside energy storage devices.

Similar approaches can be found in literature for urban railways. In [37] the use of regenerated energy for urban trains to charge EVs batteries is proposed. Vehicle to grid (V2G) functions, to support the railway line, and grid to vehicle (G2V) functions, to charge EVs battery, are identified to maximise the benefits of the EV railway integration. Besides, real projects have been developed in urban railway context. The Train2Car project was undertaken by Metro de Madrid to develop an EV charging point connected to the power supply grid of an urban railway [38,39]. In this project, a surface EVs charging point was installed connected to a railway wayside energy storage devices and to the railway power supply system. Furthermore, strategies for the energy management of this system were proposed.

The synergy between railways and EV could not only facilitate EV charging system deployment in cities, but also improve the energy efficiency of railway lines. EV batteries connected to a railway power supply system can capture regenerated energy from train braking. Thus, the receptivity of the line is increased what could reduce the amount of energy wasted in rheostats. However, it is necessary to analyse the amount of regenerated energy used by trains and wasted in rheostats to determine if this connection improves energy efficiency.

In recent years, research groups at the Comillas Pontifical University in Madrid and University of Rome Sapienza have been performing collaborative research on the use of regenerative energy from urban railways. Furthermore, both groups have made proposals to connect EVs and urban trains. As a result of this collaboration, a simulation study was developed to analyse and compare the potential braking energy that can be used to charge EVs batteries in different urban railway lines. The results of an Italian metro line and a Spanish metro line are presented in this paper where the increase of energy efficiency is assessed. The novelty of the paper lies in the evaluation, in two European real cases, of the service that can be given to EVs using the regenerated energy from trains that is not being used.

The rest of the paper is organised as follows: Section 2 reviews the possibilities of EV connection to the railway power supply grid. Section 3 presents the simulation tools used in this study. Section 4 includes a description of the two lines object of the study and a comparison as well as details related to the trains involved in the two systems. Section 5 summarizes the main results, after a brief reminder on the energy indicators used for evaluating the performance of the two systems. Section 6 deals with conclusions.

2. EV Connection to Railway Power Supply Grid

EV charging stations must be connected to the catenary circuit to take advantage of regenerated energy. Thus, the excess of braking energy that cannot be absorbed by other trains can flow to the EVs' batteries.

One of the main challenges of feeding EV charging stations with regenerated energy is the discontinuity of the braking power generated by trains. During the train operation, the braking process appears mainly at the station arrivals. Therefore, the braking power appears at discrete instants and at different locations in the railway line depending on which trains are arriving at stations. If EV charging stations are fed only by braking energy, solutions will be needed to guarantee the continuity of the service.

On the other hand, there is a mismatch between the order of magnitude of the energy generated by trains during the braking and the power demanded by an EV charging station. Thus, each EV charging station could demand between 3 kW and 20 kW (if slow or fast charging is considered) while a train can generate more than 1 MW of regenerated power. Therefore, there is a need of locating several charging stations spread along the railway line to absorb all the excess of regenerated energy produced by trains.

To handle the discontinuity of braking energy, different solutions have been proposed. In [38], the authors proposed the use of wayside energy storage systems to serve not only the trains but also the EV charging stations. This way, at those moments when there is no production of regenerated energy, EV charging stations can be fed from the storage. This method allows the continuity of the EV charging station service. Moreover, it allows to maximize the capture of regenerated energy with less number of EV charging stations. In the Ferrolinera project [36], photovoltaic sources are used in combination with energy storage systems. This way, EV charging stations can be fed from renewable sources when regenerated energy is not available.

Figure 1 shows the electrical scheme of the EV connection to the railway power supply with all the possibilities commented before. Depending of the needs of the particular application, energy storage systems or renewable energy can be neglected. It can be observed that an energy management system will be needed to control all the energy flows with the objective of maximizing the energy savings of the whole system and to ensure the good quality of EV charging station service.

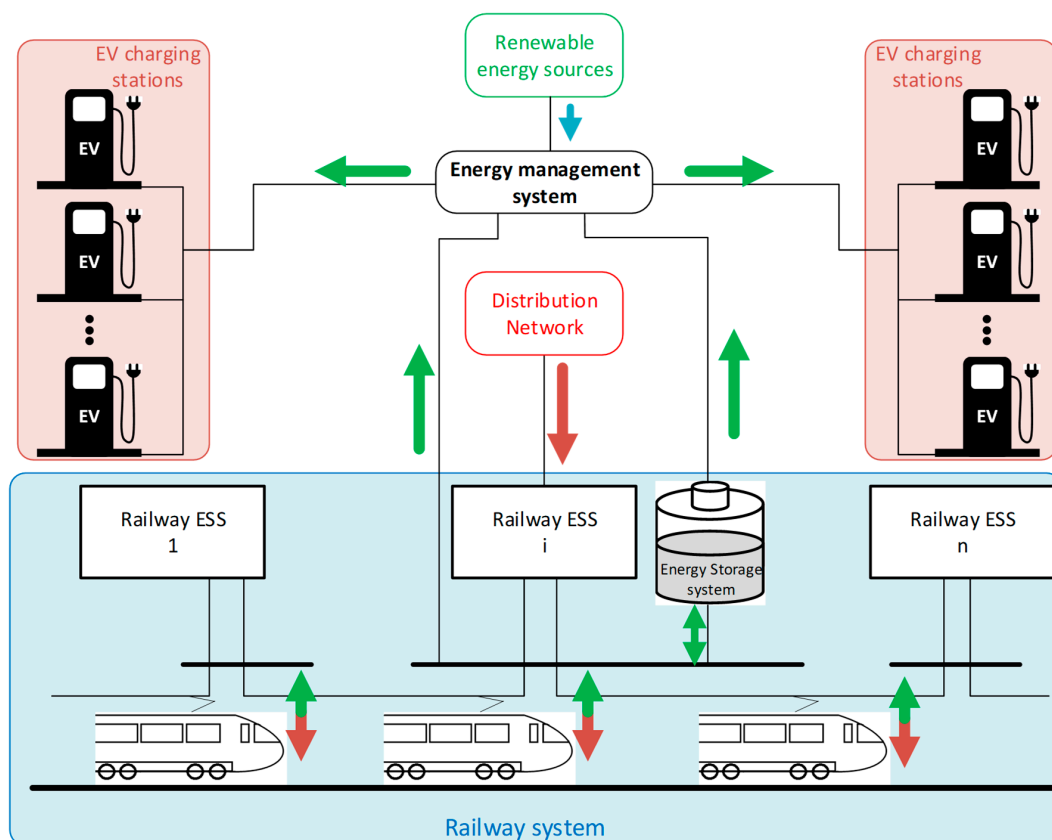


Figure 1. Layout of the EV connection to the urban railway power supply grid.

3. Simulation Tools

Simulation tools are needed to develop the regenerative energy analysis of urban railway systems. Typically, these multi-stage programs simulate not only the electro-mechanical performance of each train, but also the electrical behaviour of the supplying traction system. The research teams of University of Rome Sapienza and Comillas Pontifical University have developed their own simulation

tools to carry out studies on the energy performance of urban railway systems. The simulation models have been validated comparing their results with the real performance of metro systems.

There are many similarities between the approaches of both research teams because the tools are created with the same purpose, the analysis of the energy performance of urban railway systems. However, some differences can be found as these tools are specialized to develop studies in Italian and Spanish metro systems, respectively. For instance, one of the main difference between the approaches is the driving style of trains. The Italian simulation tool models the manual driving of the train. On the contrary, the Spanish simulation tool considers an automated driving and, therefore, a specific module is included to simulate the behaviour of the automatic train operation (ATO) equipment. In the following subsections both simulation tools are described in more detail.

3.1. University of Rome Sapienza Simulation Tool

The simulation tool includes an electro-mechanical train simulator, an electric system simulator and a calculation tool to provide figures to assess energy consumption and electrical performance [37].

In the first stage, the electro-mechanical train simulator receives as input the data about the characteristics of the train and the track. Track data is composed by the position of the stations, the grades, the curves and the speed limitations. Regarding the train data, it includes the train mass, the rotational inertia coefficient, drive-rate power and efficiency, power demanded by auxiliary systems, traction/braking motor curves as a function of the speed and maximum current demanded. The simulator uses a dynamic model to calculate the position, speed, acceleration of trains at each simulation step. A constant speed acceleration is considered at each simulation step.

The manual driving of the train is simulated implementing the balance of forces equation and solving it in function of the limits of speed and the train features. Furthermore, operational parameters are also taken into account as the acceleration rate and the deceleration values when reducing the speed or when braking to the arrival station.

The train simulator calculates at each simulation step the power consumed and regenerated by train during the traction and braking phases. The final output of this simulator is the train-path of the line for a traffic scenario and the position-time curves of the trains in a simulated hour. The traffic scenario is defined by the sequence of trains, departure times, dwell times and the offset time between departures in both directions. The block diagram of this first stage of the Italian simulation tool is shown in Figure 2.

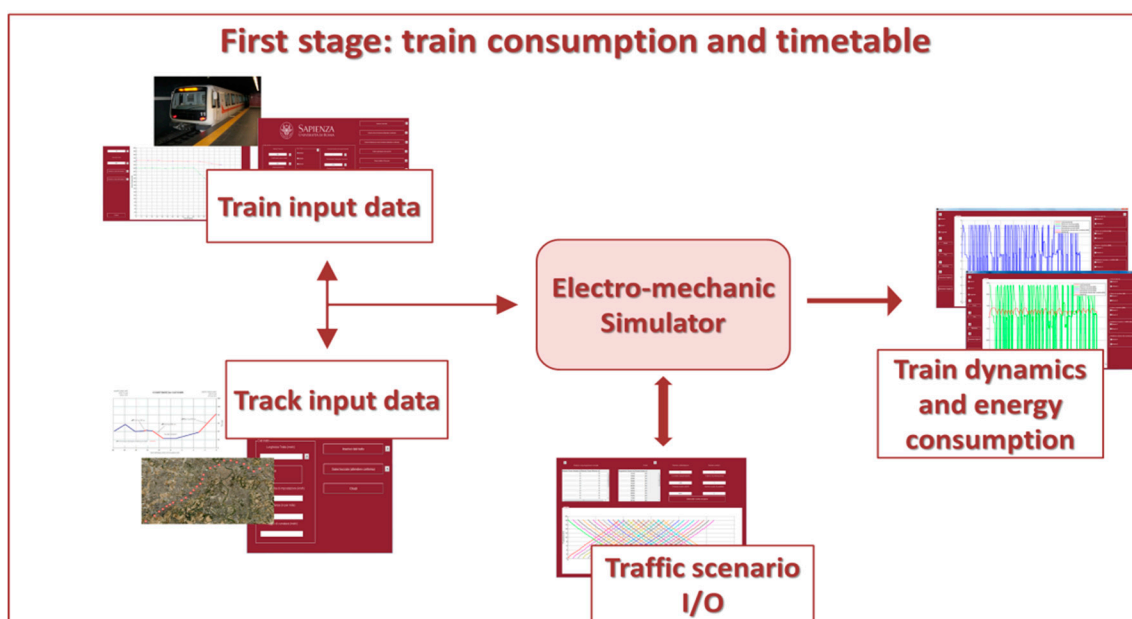


Figure 2. Electro-mechanic simulator of the University of Rome Sapienza simulation tool.

In the second stage, the electric system simulator uses a power-flow solver. It receives the results of the electro-mechanical train simulator. Furthermore, it uses data of the electrical infrastructure, such as number and position of electrical substations (ESSs), power supply line configuration, resistance of lines and rails, etc. The value of the electrical resistance is calculated as a function of the line configuration and can be different in different sections of the track.

This simulator performs a DC power flow calculation, using the data of energy consumed/demanded by the trains, the traffic scenario information and the information about the topology of the electrical traction system. The Newton-Raphson algorithm is applied to solve the problem, because an iterative method is needed. Figure 3 shows the block diagram of this second stage.

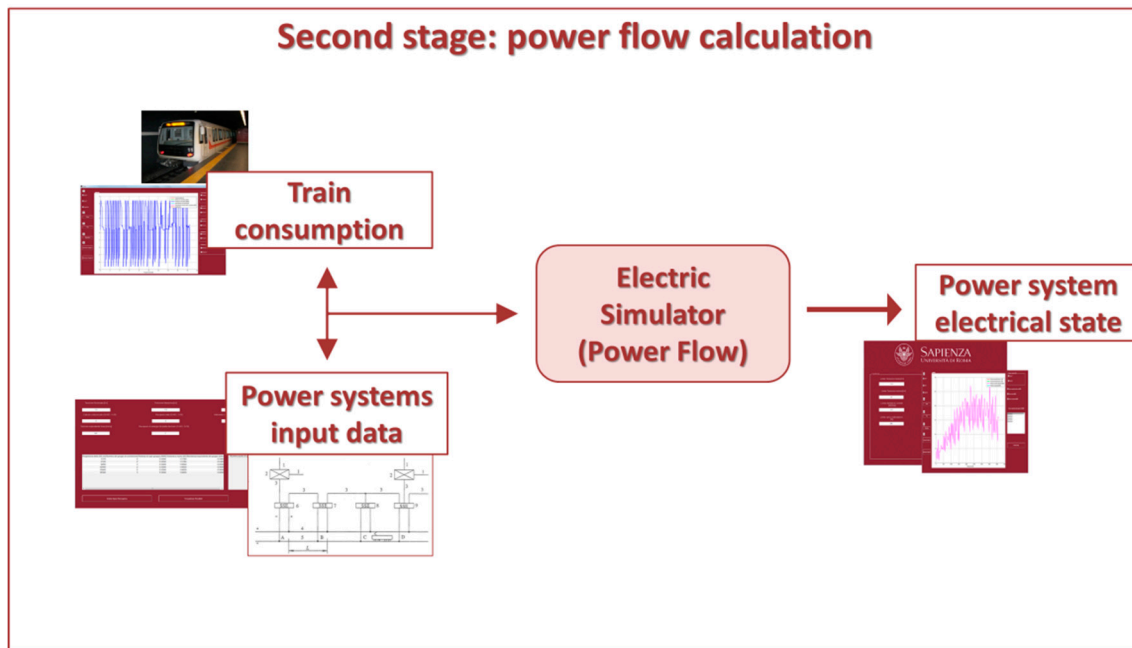


Figure 3. Electric simulator of the University of Rome Sapienza simulation tool.

Finally, a calculation tool is applied to obtain the results of the energy performance of the system. This software can calculate the results of the variables of interest in the evaluation of the energy performance in the railway system, such as the total power consumed by trains, the regenerated energy produced and the regenerated energy used by trains, the power supplied by each ESS and the voltage level of the line at the pantograph of each train. The results obtained are presented in an output graphical interface to facilitate the analysis.

3.2. Comillas Pontifical University Simulation Tool

The simulation model is composed by two main systems: The simulator of the train motion and the simulator of the electrical traction network [13]. The simulator of the train motion consists in four modules that represent the different subsystems of the train as can be seen in Figure 4. These modules are ATO, motor, dynamics and consumption.

The ATO module represents the logic of the driving action performed by the ATO equipment. Urban railways in Spain are typically driven by an ATO equipment that produce the traction or braking demand according to the driving commands. This module represents the logic of these systems. It calculates the traction/braking demand at each simulation step to perform a specific speed profile. This speed profile takes into account not only the driving commands but also the maximum speed limits and the stopping position at stations. It uses as input the position and the speed of the train in the simulation step. The ATO module takes into account the maximum available traction and braking effort according to the motors specification.

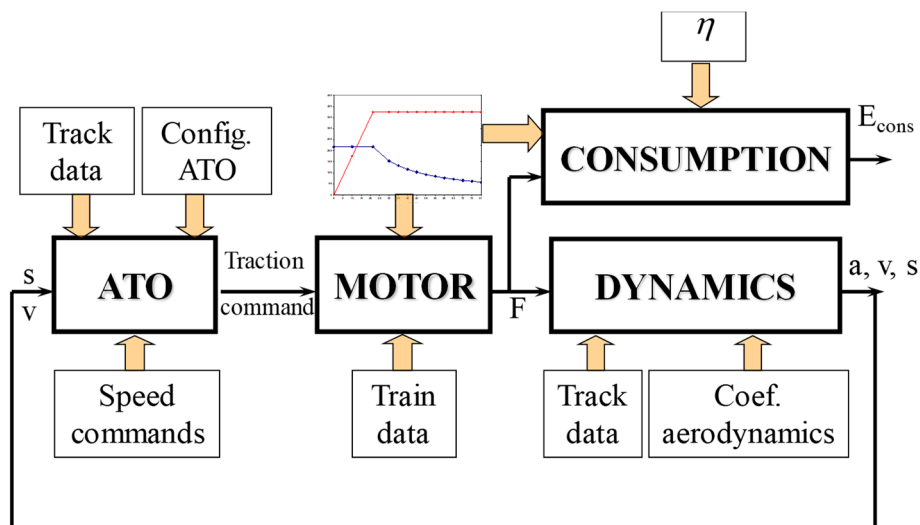


Figure 4. Block diagram of Comillas Pontifical University train motion simulator.

The motor module calculates the result of the traction or braking effort as well as the current of train motors taking into account the ATO demand. Maximum traction and braking effort and maximum traction and braking curves are included in the model. Moreover, a jerk limitation is applied in the model to prevent abrupt changes in acceleration.

The dynamics module calculates the acceleration, the speed and the position of the train at each simulation step. Running resistance and the average gradient affecting the train are used for these calculations.

The consumption model calculates the power consumed or regenerated in pantograph during the train movement. The traction chain efficiency is used to obtain the power result. This efficiency is modelled as a function of the ratio between the required and the maximum traction forces. Furthermore, the energy consumption of auxiliary systems is included in the energy consumption results.

Once the power and speed profile of a train is obtained at each section between stations, it is necessary to simulate the electrical interactions between all the trains in the line to obtain the energy consumption result at substation. A three-step simulator has been developed to obtain these results as shown in Figure 5.

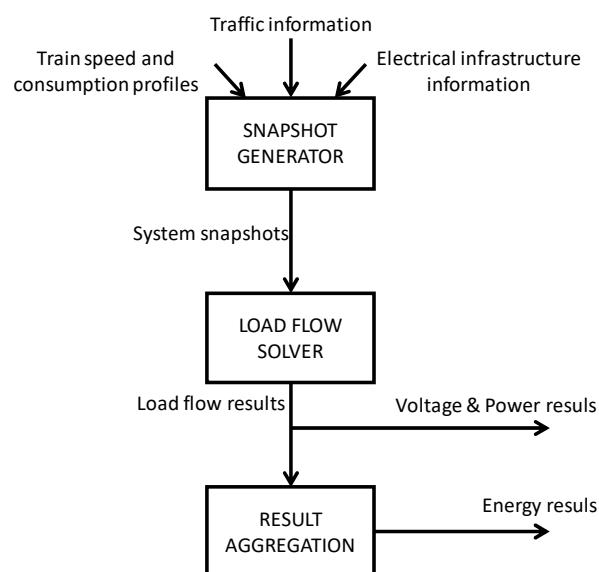


Figure 5. Block diagram of Comillas Pontifical University electrical traction network simulator.

The snapshot generator module of the electrical traction network is in charge of combining the speed and power profile of trains given a timetable. Electrical infrastructure is also included to calculate the resistance and inductance along the line depending on train positions. This module calculates using this information a set of snapshot that represents the system state at a constant sample time. As trains move, the electrical circuit to be solved changes because the position and the amount of power demands changes and because the impedance in front and behind of each train change as well. Therefore, each snapshot contains a circuit to be solved representing an instant of the system behaviour.

Thereafter, each snapshot circuit is solved by means of the load flow solver module. ESSs and losses in the line are taken into account in this stage by means of sub-station models and line impedance. Furthermore, rectifiers are also considered by means of a model included in the simulator. The equations of the electric circuit are non-linear and, therefore, an iterative method is applied to calculate the load flow of each snapshot. The unified Newton-Raphson method is applied in this simulator due to its convergence performance when solving DC electrified network problems.

Finally, the results of the load flow are treated in the result aggregation module to obtain the energy results of the system.

4. Urban Railway Systems Studied

4.1. Lines Description

Two real metro-lines have been used in this analysis to be compared. An Italian metro line and a Spanish metro line. The Italian line is, on two tracks, 18.76 km long, with 27 stations and a layout including many slopes and curves. The distance between stations is about 694 m and trains circulate at maximum speed of 80 km/h.

The power system is composed by six ESSs. Each ESS includes conversion groups, whose voltage output is 1500 V DC for the traction line supplying, and equipped with AC/DC full diode bridge converters with nominal power rating of 3.5 MW. In Table 1 the main features of the ESSs of Italian line are represented.

Table 1. Italian metro electrical substations (ESS) main features.

ESS	Progressive (km)	Number of Transformation/ Conversion Groups	Nominal Power Ratings (MVA)
ESS1	1.37	2	3.86
ESS2	5.16	2	3.86
ESS3	9.26	3	4.00
ESS4	12.46	3	4.00
ESS5	15.06	3	4.00
ESS6	18.36	3	4.00

Regarding the traction line, it is composed by two 100 mm² contact wires, two 120 mm² carrying cables and one 120 mm² feeder. This results in a total resistance for the traction and the rail of 0.0537 Ω /km.

On the other hand, the Spanish line is, on two tracks, 19 km long with 23 stations and a layout that also includes many slopes and curves. The distance between stations is 826 m and trains circulate at maximum speed of 70 km/h.

The power system is composed by 11 ESSs that include conversion groups, whose voltage output is 600 V DC for the traction line, and equipped with AC/DC full diode bridge converters with nominal power rating of 2 MVA. Table 2 includes the main features of ESSs of Spanish line. There are two types of catenary systems:

- Starting at the beginning of the line, between ESS1 and ESS2, there is a 1.3 km rigid-catenary stretch. The supply and return circuits are parallelised every 500 m.

- Then, from that point until the end of the line, the catenary system is made up of a 150 mm² copper catenary wire plus two 107 mm² copper contact wires.

Due to low pantograph voltage problems in the line, the latter stretch is reinforced by means of an auxiliary aluminium feeder. This feeder, which is laid in parallel with both tracks, consists of four 645 mm² wires. A parallelisation point between the feeder and both-track catenary systems takes place every 100 m. Due to this high parallelisation frequency, in practical terms, trains make use of the catenary systems of both tracks. This improves dramatically the train voltage profiles with respect to the habitual approach where tracks are only parallelised at ESSs. This results in a total resistance for the traction and the rail of 0.026 Ω /km for the stretch with rigid catenary, while 0.022 Ω /km resistance is obtained for the rest of the line.

Table 2. Spanish metro electrical substations (ESS) main features.

ESS	Progressive (km)	Number of Transformation/ Conversion Groups	Nominal Power Ratings (MVA)
ESS1	0.3	1	2.4
ESS2	2.4	2	2.4
ESS3	4.9	2	2.4
ESS4	6.4	2	2.4
ESS5	7.8	2	2.4
ESS6	9.3	2	2.4
ESS7	10.1	2	2.4
ESS8	12.6	2	2.4
ESS9	14.4	2	2.4
ESS10	16.7	2	2.4
ESS11	19.3	2	2.4

The main differences between the two systems are:

- The length of the systems is practically the same. However, in the Italian case there are more stations resulting in a smaller distance between stations.
- Trains circulate at higher speed on the Italian line.
- The Italian system feeds the train at higher voltage (1500 V) than the Spanish one (600 V).
- The number of ESS in the Spanish line is greater than in the Italian line. However, the rated power of each transformation and conversion group is greater in the Italian case. The total power of all installed transformation and conversion groups is also greater for the Italian case.
- The total equivalent resistance of the Italian traction circuit is more than two times the Spanish one.

4.2. Trains Description

The Italian metro train characteristics are 181.6 Tn of empty mass and 108 m of length. On the other hand, the Spanish metro train characteristics are 195 Tn of empty mass and 108 m of length. As it can be seen, both trains are physically very similar. The main traction features of the train motors are compared in Figure 6.

The figure shows how the maximum effort provided by the Spanish train is higher than the maximum effort of the Italian train. However, train of Italy is more powerful. It can be observed in the fact that the Italian train maintains the maximum effort until 50 km/h, while the train of Spain reduces the maximum effort in 22 km/h when starts the constant power phase of the curve. A similar conclusion can be obtained analysing the electrical braking curves shown in Figure 7.

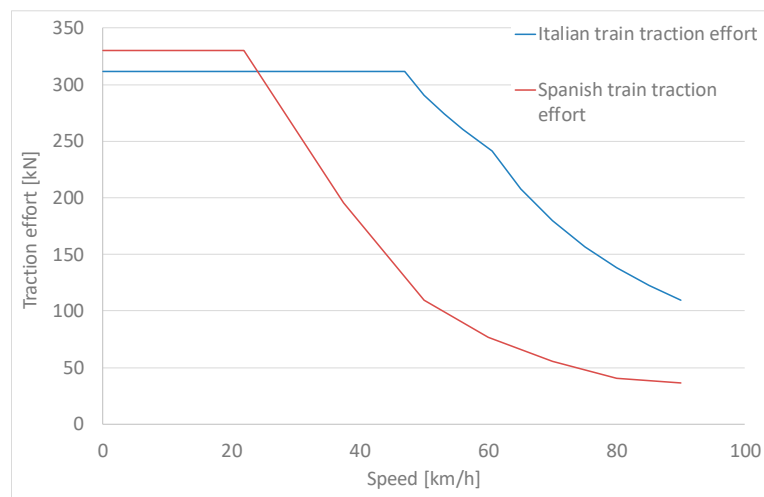


Figure 6. Traction curves.

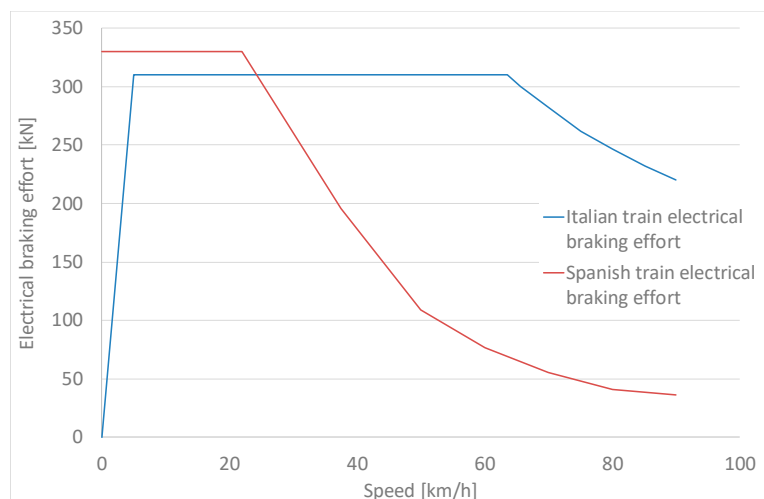


Figure 7. Electrical braking curves.

5. Simulation Results

The energy assessment are based on the following indexes proposed in [40]. These measures make use of figures obtained under different simulation hypothesis.

For some of the measures applied, the calculation of the supplied energy by all ESSs without recovering of the trains braking energy ($E_{ESS}^{W/O REC}$) is needed. Therefore, it is necessary to assess the railway system taking into account that the regenerated energy can be used to feed the auxiliary system of the train but cannot be injected in the catenary.

The supplied energy by all ESSs in case of recovering of the trains braking energy ($E_{ESS}^{W REC}$) is also calculated. In this case, the assessment of the railway system is performed taking into account that the regenerated energy can be used not only to feed auxiliary system but also to feed other trains that can be motoring in that moment. Using this hypothesis the effective recovered braking energy ($E_{TR REC, ED}$) is calculated.

However, other results needed for the energy evaluation are independent of the two previous hypothesis considered. For instance, the requested energy by the trains ($E_{TR REQ}$) or the regenerated energy produced by trains ($E_{TR REC, BLE}$) obtain the same results in the two cases.

The measures used in this paper are the following:

- The energy saving percentage ($ES_{\%}$). It calculates the energy saving obtained thanks to the exchange of regenerated energy among trains. It is defined as:

$$ES_{\%} = \left(1 - \frac{E_{ESS}^{W REC}}{E_{ESS}^{W/O REC}} \right) \cdot 100 \quad (1)$$

where $E_{ESS}^{W REC}$ is the energy supplied by all ESSs in case of recovering of the trains braking energy and $E_{ESS}^{W/O REC}$ is the energy supplied by all ESSs without recovering of the trains braking energy.

- The effective recovered braking energy percentage ($ER'_{\%}$) in respect of the recoverable braking energy. It calculates the fraction of the regenerated energy that is used by trains. It is defined as:

$$ER'_{\%} = \frac{E_{TR REC, ED}}{E_{TR REC, BLE}} \cdot 100 \quad (2)$$

where $E_{TR REC, ED}$ is the effective recovered braking energy and $E_{TR REC, BLE}$ is the potential recoverable braking energy.

- The effective recovered braking energy percentage ($ER''_{\%}$) in respect of the total required energy by the trains. It calculates the fraction of the energy consumed by trains that comes from regenerated energy. It is defined as:

$$ER''_{\%} = \frac{E_{TR REC, ED}}{E_{TR REQ}} \cdot 100 \quad (3)$$

where $E_{TR REC, ED}$ is the effective recovered braking energy and $E_{TR REQ}$ is the requested energy by the trains.

These indicators have been calculated in reference of 7 cases of train frequency: 120 s, 150 s, 180 s, 240 s, 300 s, 360 s, 600 s. A simulation time of 3600 s is performed in all cases. In both the Italian and Spanish cases a 20 s of dwell time at stations is configured.

5.1. Results of Energy Efficiency Assessment

Figures 8 and 9 show some system energy values obtained for the lines in Italy and Spain. As can be seen, in both cases as the number of circulating trains is decreased (i.e., as the interval between them increases), the energy supplied by ESSs and the potential recoverable energy from braking decreases. The energy demanded by the trains and supplied by the ESSs is lower in the Spanish case, mainly because of the lower number of circulating trains. As detailed in Section 4.1, both lines have the same length but the Italian line has more stations. Therefore, as the dwell time at stations is equal in both cases, the line of Italy needs more trains to perform the same time interval between consecutive trains. The same effect can be observed in the braking energy result that decreases as the time interval increases.

The energy performance of both metropolitan systems can be compared in terms of their energy losses. The energy losses percentage is calculated with the objective of obtaining comparable results. Energy losses percentage is the fraction of the energy losses obtained by the system divided by the total traction energy required by the trains. Figure 10 shows the results obtained.

As it can also be seen, the Spanish line obtained lower energy loss results compared with the Italian line. This result is the opposite of what one would think at first sight because the Spanish line works with lower level of catenary voltage (600 V) than the Italian line (1500 V). However, as shown in Section 4, the rigid catenary of the Spanish line leads to lower transmission resistance. The line resistance in the Spanish line is sufficiently low to compensate the increase in losses due to the catenary voltage.

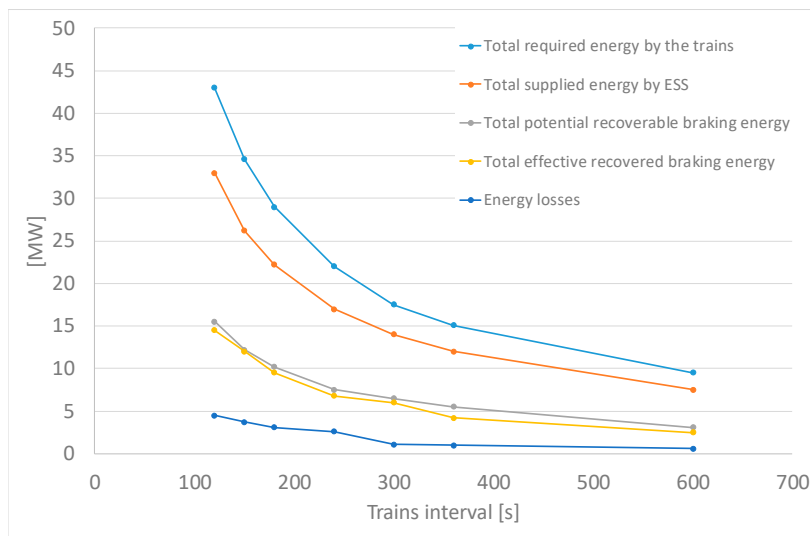


Figure 8. System energy values for the Italian case in the different interval scenarios.

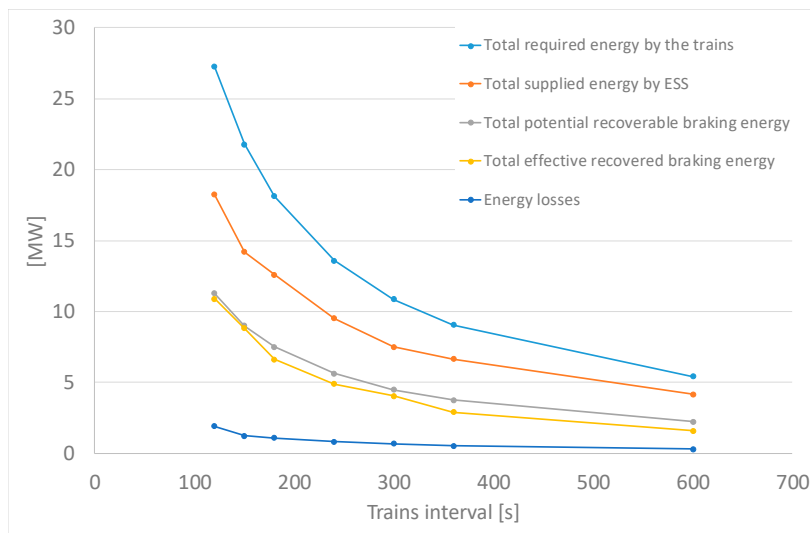


Figure 9. System energy values for the Spanish case in the different interval scenarios.

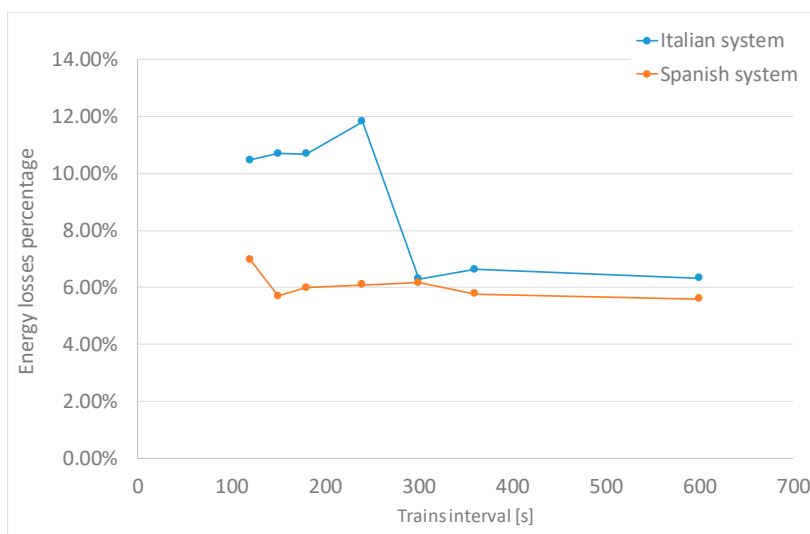


Figure 10. Energy losses results for the Italian and the Spanish railway line.

The energy consumption of a daily operation of the lines can be obtained using previous results in the proportion given by the timetable. The timetable of the Italian line is presented in Table 3. As can be seen there is an interval of 150'' in peak hours while the train interval is 240'' in off-peak hours. Moreover, an interval of 360'' during 4 h of sparse traffic conditions. At night, the service is interrupted for 6 h.

Table 3. Timetable of the line of Italy.

Hours of Service	Trains Interval
4 h	150''
10 h	240''
4 h	360''
6 h	No service

The operation of the Spanish line is slightly different. It can be observed in Table 4. The timetable of the Spanish line presents an interval of 240'' in peak hours while the train interval of 300'' is used during off-peak hours. In sparse traffic conditions the interval of 360'' is used during 4 h of service while 600'' of time interval is performed during one hour at night. As in the Italian case, the service is interrupted for 6 h the rest of the night.

Table 4. Timetable of the line of Spain.

Hours of Service	Trains Interval
2 h	240''
11 h	300''
4 h	360''
1 h	600''
6 h	No service

Matching the data from Figure 8, Table 3, Figure 9 and Table 4 it can be obtained that:

- The daily energy consumption of the Italian line is 322.8 MWh.
- The daily energy produced by the trains braking in the Italian line is 145.8 MWh.
- The daily energy consumption of the Spanish line is 132.12 MWh.
- The daily energy produced by the trains braking in the Spanish line is 77.71 MWh.

As can be seen, the energy consumption of the Italian line is significantly greater than in the Spanish case. The Italian line is a busy line, which collects many travellers of the city. Therefore, the train intervals are smaller during most of the time periods and more trains are circulating on the line. It also explains that the energy produced during the trains braking is greater for the Italian case.

An important amount of energy is generated during the train braking in both railway lines. However, not all of this regenerated energy is consumed by other trains. Regenerated energy is used firstly to feed auxiliary systems and, then, the excess is either sent to other trains or sent to on-board rheostats. Regenerated energy is sent to rheostats when the voltage measured at pantograph is over an upper limit. This voltage level is reached when a train is braking and there is no other train close to it demanding energy. In these cases, the system does not take advantage of the braking energy generated.

The indicators presented before have been calculated to assess the energy performance and the use of regenerated energy. The results of the energy indicators are presented in Figures 11 and 12 for the Italian and Spanish lines, respectively:

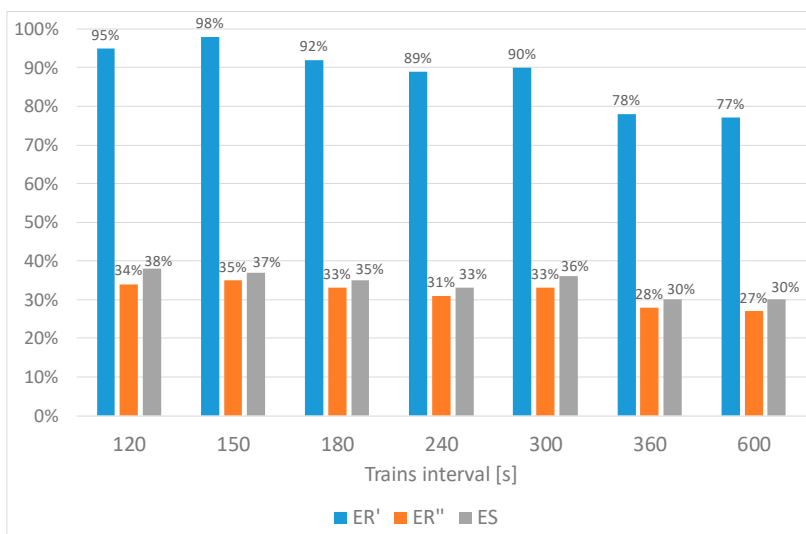


Figure 11. System energy percentage values for the Italian case.

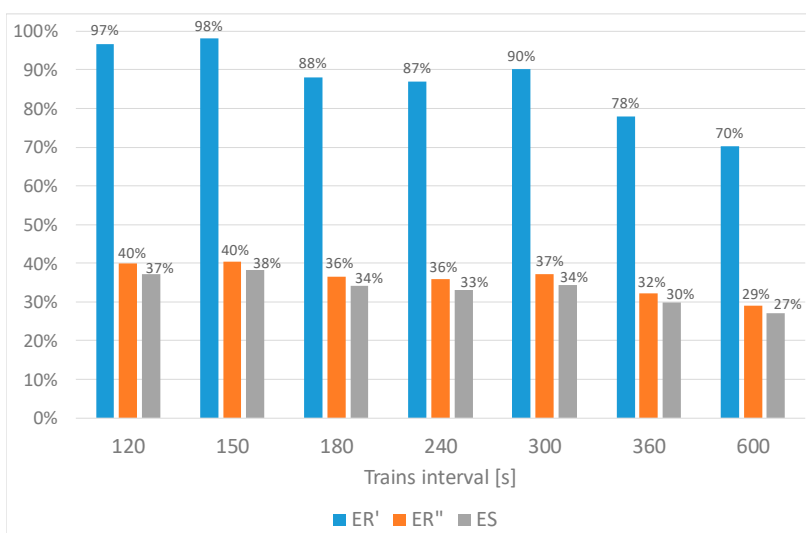


Figure 12. System energy percentage values for the Spanish case.

As it can be seen, in the Italian line the value of ER' % varies from 98% in the smaller intervals to 77% in the greatest. On the other hand, in the Spanish line the value of ER' % varies from 98% in the smaller intervals to 70% in the greatest. There is an important exploitation of braking energy for short train interval. In both cases, the 98% of braking energy produced is used by other trains for an interval of 150 s. However, as the interval increases (i.e., the number of circulating trains is reduced), the exploitations of the regenerated decreases because there are less opportunities to exchange energy among trains.

Regarding the value of ER'' %, it can be observed in the Italian case that it varies from 35% for smaller intervals to 27% for the greatest. Similar results are obtained in the Spanish case, where the value of ER'' % varies from 40% for smaller intervals to 29% for the greatest. That means in both cases that, around one third of the energy demanded by trains is obtained from regenerated energy instead of coming from ESSs. These values of ER'' % obtained demonstrate the importance of the use of braking energy in urban railways to reduce the energy consumption of the system.

The results of ES % are slightly inferior in the case of the Spanish line. In the Italian system, energy saving varies from 38% for smaller intervals to 30% for the greatest. In the Spanish system, it varies from 38% for the smaller train interval to 27% for the greatest. These results confirm the importance of the use of regenerative braking to reduce the energy consumption in urban railways. In both cases,

allowing the exchange of braking energy among trains leads to an important reduction of energy consumption in ESSs which is the measure used in the railway electric bid.

5.2. Regenerated Energy Potential to Charge Electric Vehicles

Despite the great results on energy efficiency that have been shown before, there is an important fraction of regenerated energy that is not being used. Figures 13 and 14 show the potential recoverable energy, the effective recovered braking energy and the difference between them for the Italian and Spanish cases. The difference between the potential recoverable energy and the effective recovered braking energy corresponds to the regenerated energy that is wasted in rheostats.

As it can be seen in both cases, the difference between the potential and the effective recovered braking energy varies with the frequency and there is a tendency of increasing with the interval of trains. In the Italian case, it varies from 0.3 to 1.2 MWh/h, while in the Spanish case, it varies from 0.2 to 0.89 MWh/h.

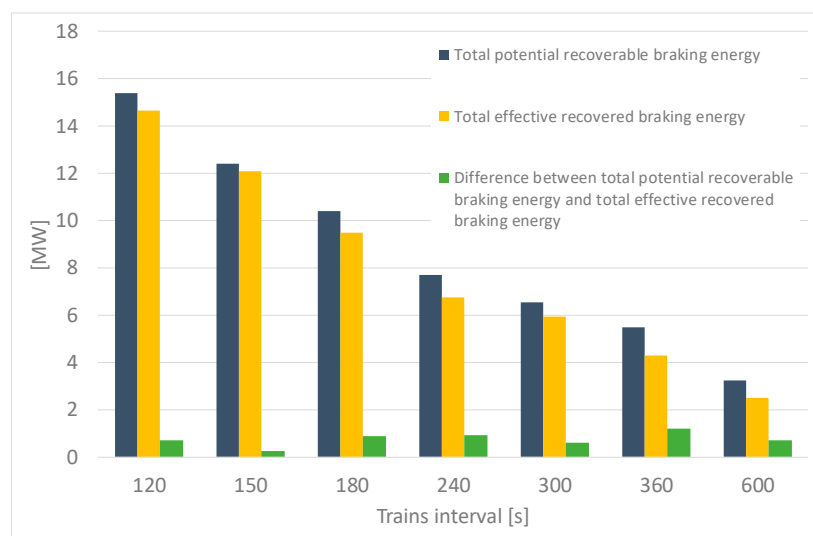


Figure 13. Comparison between potential and effective recovered energy for the Italian case.

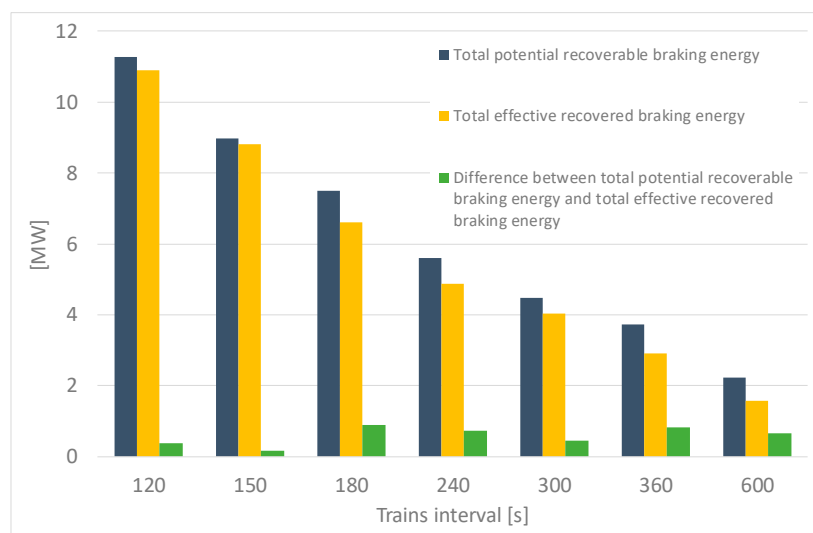


Figure 14. Comparison between potential and effective recovered energy for the Spanish case.

The previous results can be compared for both systems calculating the excess of regenerated energy percentage. It can be calculated as the difference between the potential and the effective recovered braking energy divided by the potential of recoverable braking energy. Figure 15 shows the

results obtained. As can be seen, the Spanish line obtained higher values of excess of regenerated energy percentage in most of the scenarios. It can be explained because with lower catenary voltage level, as happens in the Spanish line, the transmission of regenerated energy is more difficult among trains. Thus, the regenerated energy is better used in line with higher catenary voltage as the Italian one.

Matching the results from Figures 13 and 14 with the timetable of the lines presented in Tables 3 and 4, the following results can be obtained:

- The daily braking energy wasted in rheostats on the line in Italy is 15 MWh.
- The daily braking energy wasted in rheostats in the line in Spain is 10.28 MWh.

The previous results highlight the importance of the energy that is not being used and it is wasted every day. The excess of regenerated energy can be used for other purposes given that trains cannot use the total amount of braking energy generated.

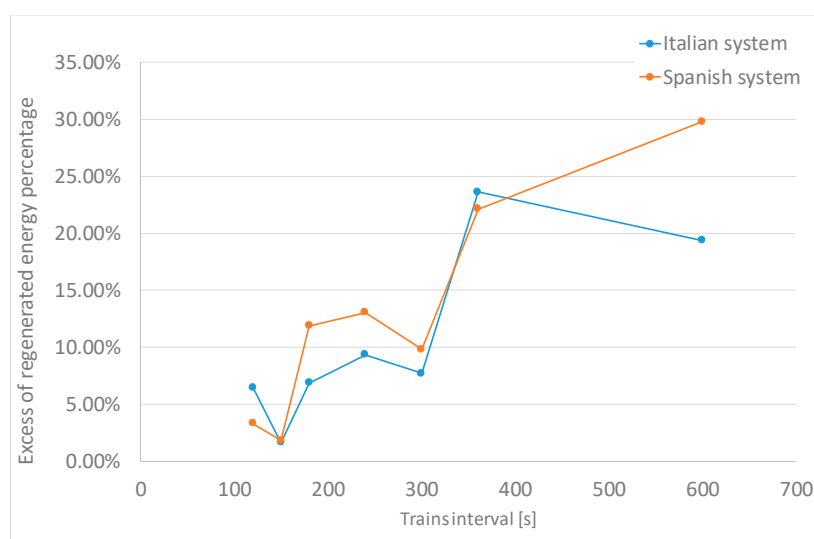


Figure 15. Comparison between potential and effective recovered energy for the Spanish case.

As indicated in Section 1, the regenerated energy that cannot be consumed by trains can be used for feeding EV charging points. This way, two keystones of transport sustainability could be promoted. On one hand, the connection of EV charging points to the urban railway power supply grid would reduce the installation cost, because of the use of an existing infrastructure. Therefore, it would facilitate the deployment of EV charging stations in cities promoting the use of EVs. On the other hand, EVs' batteries could absorb the excess of regenerated energy improving the efficiency of the energy consumed. It would reduce the cost of urban railway operation given that the energy consumption is a major fraction of the total cost of railway companies.

The impact of EV connection to the power supply grid of urban railways can be demonstrated by the following data. The average daily energy consumed by a single EV in a day can be estimated in 15 kWh for guaranteeing an autonomy of 50–60 km on a standard city cycle. Therefore, the theoretical amount of EVs that can be charged using regenerated energy can be calculated matching this data with the results of regenerated energy not used. Thus, it can be obtained that:

- 1.000 EVs can be recharged every day using the braking energy not used on the line of the Italian metro system
- 685 EVs can be recharged every day using the braking energy not used in the line of Spanish metro system

These results correspond to a single metro line. However, typically there is more than one line in big cities. Therefore, these theoretical results should be multiplied by the number of metro lines in

an urban railway system to obtain the total amount EVs that can be charged by trains regenerating energy in a city. Furthermore, the results show that a relevant number of EVs can be recharged from braking energy, not only in a busy metro line such as the Italian one, but also in a line with less train frequency such as the Spanish one.

The results of theoretical EVs that can be charged using regenerated energy from urban trains are especially important if we compare them with the actual fleet of EVs in Rome and Madrid. In these cities, the number of private EVs does not exceed 2.000 units in 2018 [41].

However, as shown in [38], the excess of regenerated energy cannot be used by EVs' batteries just by connecting them to the catenary. There are positions of the line where the use of regenerated energy for EVs is more adequate than others. Besides, the number of EVs that the railway power supply grid can feed depends on the moment of the day and the train frequency.

For these reasons, the future work to be developed will consist in the proposal of design methods that determine the size and the best location of charging stations on a railway line. The objective of these methods will be the maximization of use of regenerated energy respecting the system limits. The application of these methods will permit to bring closer the number of EVs that could be charged in reality by regenerated energy to the theoretical results obtained in this paper.

Moreover, future work will be dedicated to assess the capacity of EVs connected to railway power supply grid not only to capture the excess of regenerated energy, but also to support the trains when needed. In [37] the V2G function was proposed to level the ESS during the day time. This function will provide improvements in power quality and reduction in operational cost. The detailed evaluation of the benefits from the viewpoint of railway power supply grid must be realized.

6. Conclusions

The connection of EVs to the power supply grid of an urban railway system to charge their batteries could provide several benefits for the transport system of a city. On one hand, there is a cost reduction of the charging station deployment in the city because of the use of existing installations. Besides, EVs can capture the excess of energy produced by trains when braking. If there is no other train motoring when a train brakes, the regenerated energy must be wasted in on-board rheostats. Therefore, the presence of EV batteries could provide a path for that energy, minimizing the use of rheostats and improving the efficiency of the system.

This paper collects the results of a collaboration between University of Rome Sapienza and Comillas Pontifical University research teams. In this shared work, two urban railway lines have been compared: an Italian metro line and a Spanish metro line. The study has focused on the energy efficiency of both lines and the use of regenerated energy.

Characteristics of the trains running on those systems have been presented. It has been found that both trains have similar physical characteristics, however, Spanish trains have less powerful motors compared with the Italian ones.

Both systems have been simulated to study and compare their energy performance. Several energy indicators have been applied to obtain the results. The results show that, in both cases, 98% of the regenerated energy produced is used by trains for small train intervals. However, the regenerated energy usage decreases as the train interval grows. Furthermore, it has been observed that the energy savings obtained because of the braking energy exchange among trains is more than 30% in almost all the cases studied in both systems.

However, an important amount of regenerated energy wasted in rheostats is found in a daily operation of the lines studied. On the line in Italy, 15 MWh of regenerated energy is not used, while 10 MWh are wasted in rheostats in the line in Spain.

An important amount of EV batteries could be charged every day using the regenerated energy that it is wasted in rheostats. Every day, 1.000 EVs could charge their batteries using the power supply grid of a busy urban railway line as the line in Italy. On the other hand, 685 EVs could be recharged using the Spanish line.

The results obtained in this paper are theoretical and, therefore, future work will be needed to assess in more detail the capacity of the line. Furthermore, optimization methods will be needed to obtain the most adequate positions of the line where charging stations must be installed to maximize the use of regenerated energy. On the other hand, V2G functions must be studied carefully to evaluate potential benefits from the point of view of the railway power supply grid of the EVs connection.

Author Contributions: For the Spanish line, A.P.C. and A.F.-C. conceived simulation models and the design of the integration of Electrical Vehicles in the urban railway network and designed the experiments. M.C.F. conceived the previous models, designs and performed the experiments for the Italian line; A.F.-R. performed the experiments of the Spanish line and analyzed the comparison between both railway lines; A.F.-R. wrote the paper, and the rest of authors reviewed it.

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