Energy efficiency on train control: design of metro ATO driving and impact of energy accumulation devices

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Abstract

Reduction in energy consumption has become a global concern, and the EU is committed to reducing its overall emissions to at least 20% below 1990 levels by 2020. In the transport sector measures are focused on planning, infrastructure, modal change, the renewal of vehicles and also programmes for efficient driving.

In metro lines equipped with ATO systems, the ATO speed profiles are designed to comply with running times requirements, taking into account comfort and operational restrictions. In the design process, energy consumption can also be considered in order to design the speed profile that minimizes the consumption. A design procedure, based on detailed simulation and on decision theory has been proposed and applied to Metro de Madrid (Madrid Underground). Average energy savings of 13% have been measured. The simulation requires high precision in calculations because the different speed profiles in service differ in a few seconds (around 5s). Given that, all the features of the ATO system, the track, the traction and braking curves and the efficiency of the motor, must be considered.

The objective of that design was the minimization of energy consumption without considering the energy of regenerative braking. In metropolitan railways, the regenerated energy is not used if there is no other train starting up at the same time and it is wasted heating resistors. However, the proposed design based on simulation also allows the analysis of different technologies such as on board energy storage devices to improve the use of regenerative energy and its impact on total energy consumption. ATO speed profiles can be redesigned considering the existence of these devices which can take advantage of the regenerated energy increasing the transported mass instead. As a result, the advantages of investing in an on board storage device can be analysed.

1. Introduction

Energy efficiency in railway systems is nowadays a key topic being studied in order to reduce energy consumption and costs since it has become a global concern. With this end in view, different technologies, developments or strategies are being researched and tested from the point of view of driving optimization, capacity and optimal use of regenerative braking.

Metro lines equipped with Automatic Train Operation systems (ATO) have particular behaviors. They use pre-programmed speed commands to drive the trains corresponding to a set of alternative ATO speed profiles per interstation with different running times. As a result, driving is not influenced by drivers and running times and energy consumptions are quite stable when signaling systems do not affect the circulation of trains. Traffic regulation systems performance and total energy consumption strongly depend on the off-line design of these ATO speed commands.

Depending on the required running time, the regulation system on-line selects the ATO speed profile to be executed between two stations. From the user’s point of view a longer running time is preferred rather than a longer station waiting time when a train must be held up. In addition, this regulation strategy achieves energy saving because longer running times are obtained with slower speed profiles. However, ATO speed profiles are usually designed according to running time and comfort criteria, but not to energy consumption.

In order to find speed profiles which optimise energy use, mathematical models have been applied, principally optimal control techniques. In [1] the optimal speed profile is calculated with the maximum principle. The study in [2] considers the problem of the optimal driving strategy based on a generalized equation of motion that can be used in discrete and continuous control but the result is a theoretical approach. The authors of [3], ,developed a discrete dynamic programming algorithm avoiding the difficulties of resolving the optimal control problem with numerical techniques. They use kinetic energy instead of speed and obtain an analytical solution in real time. In [4] Bellman's dynamic programming has also been used to optimise the running profile of a train. The authors transform the original problem into a multistage decision process accomplished by linearization and time-uniform discretization. The problem is that these approaches include simplifications of the track, trains and driving models and because of this, they are not appropriate for the optimal design of Metro ATO speed profiles. The short interstations and the differences of a few seconds between the ATO profiles to be designed make accurate models needed.

The difficulty involved in the analytical resolution of the problem makes approaches based on simulation an alternative since they do not require simplifications and enable an accurate calculation of running times and energy consumption. To explore the solution space and select alternative driving, different direct search methods are used, for instance heuristic search for ATO speed commands design [5], genetic algorithms and fuzzy logic for manual and automatic driving optimisation [6] or genetics for optimisation of coasting points [7, 8]. Wong and Ho [9] compare different search methods for the on-line control of a train using an accurate simulator, determining the coasting points. This work stresses the importance of an accurate train movement modelling for practical applications. In [10], Chang and Xu include Pareto efficiency in differential evolution to find a trade-off between punctuality, consumption and comfort. However, these models cannot be applied to the ATO system considered. Its features make necessary a different approach which optimises the discrete configuration parameters of the ATO equipment and also takes into account operative and comfort restrictions and the highly irregular track gradients.

Relating to regenerated energy different approaches are also found. In metropolitan railways, energy of regenerative braking is only used if there is another train starting up at the same time in the same electrical section. Otherwise, this energy is wasted on heating resistors banks. A possibility for avoiding that is to equip the system with devices which store energy in the train or at substations [11]. These devices can be supercapacitors, flywheels and SMES (Superconducting magnetic energy storage). Thanks to them, it is not needed another train available to use the regenerated energy unlike regeneration between trains [12]. In addition, these devices can be used for voltage regulation [13] and reducing energy demand without effects in transport efficiency and punctuality. Feeding back the regenerative energy to storage devices at substations requires the use of the lines leading to transmission loses whereas placing the device on-board vehicles it is avoided [14].

This paper takes and combines two of those strategies. First of all, a procedure for the redesign of the ATO speed profiles of a line of the Madrid Underground is developed. It is focused on the computer-aided design of the ATO speed commands between two metro stations to be pre-programmed in the ATO equipment. The equations and algorithms that define the train motion and ATO control have been modelled and implemented in a very detailed simulator. This simulator includes an automatic generator of every possible profile and a graphical assistant for the selection of speed commands. It has been developed and validated with measurements in the Madrid Underground. Since the considered ATO system provides only certain discrete values for each configuration parameter (coasting, re-motoring and regulation velocities, and braking deceleration rate), it allows the exhaustive and accurate simulation of the whole feasible solution space. Instead of search techniques, decision theory techniques can be directly applied to select the set of solutions per interstations including operational and energy consumption criteria. This way, the obtained driving solutions will be fully adjusted to real features and capabilities of the ATO equipment in service. The solutions obtained are compared with driving profiles in service in order to value the expected energy savings.

Afterwards, the implementation of an on board energy storage device is evaluated. Some authors have suggested to optimize the charge/discharge of the energy storage devices and speed profiles together [15]. With the aim of developing a realistic study, in this paper it is the train and the speed profile he follows what leads the operation of the storage device. Firstly, a realistic initial charge of the on board storage of every interstation is obtained. Then, advantages of a new design in which the regenerated energy can be stored and fed back to the train, are analyzed. Speed profiles even more efficient are obtained. Considerations about the additional mass of this device can be also found.

2. Simulator

The proposed design method is based on the accurate simulation of all the possible combinations of ATO speed commands for each interstation in order to obtain precise results of the decision variables: running times and energy consumption always meeting comfort criteria. To achieve this accuracy, the simulation model has been modularized. Each module represents one of the different subsystems of a real train (Figure 1): ATO equipment simulator, motor, train dynamics model and train consumption model as well as the model of an on board energy storage device. This modular architecture allows validating each module separately and an easy adjustment for specific features of a particular ATO equipment. To this end, the simulator input interfaces are designed to enable the definition of track layout, train characteristics, and ATO system configuration.

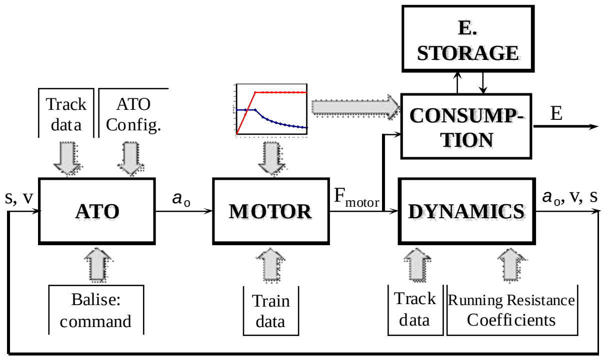


Figure 1: Block diagram of the modularized model simulator

Train velocity, acceleration, traction or brake force and energy consumption are computed at each simulation step and inputted as data for the next simulation step.

After simulating every ATO speed profile the fulfillment of the operational and comfort restrictions specified is checked. In the study case of the Madrid Underground restrictions are minimum speed throughout the journey, maximum number of re-motorings, maximum slope in which coasting is comfortable and a list of minimum speed limits along curves.

2.1 ATO equipment simulator

The ATO model represents the control logic of the driving. It is configured with the real fixed parameters needed for an accurate simulation like the safety distance to be observed when the train has to brake due to a maximum speed reduction, the ATP safety offset to be observed under the maximum speed, deceleration of braking curves, etc.

The variable parameters of the ATO system are the speed commands to be designed:

- Braking command: deceleration rate during the braking process.
- Speed holding. The target speed of the train is the minimum between the maximum velocity and the speed holding.
- Coasting speed: When reached, traction is turned off up to re-motoring speed.
- Re-motoring speed: When reached, traction is turned on up to coasting speed.

At each simulation step, the position and speed of the train is inputted there. Then, a set value is calculated depending on the state of the train: motoring, braking to target speed, braking to stop etc. This value is sent to the motor module.

2.2 Motor equipment simulator

The motor module treats the ATO set value as the ratio between required force and maximum traction force corresponding to the speed at each simulation step. Then, it is checked that the calculated required force is under the limits of maximum force depending on the speed, voltage and mass. Finally, a jerk limitation smoothes abrupt changes of force in transitions like traction-braking or braking-traction in order to assure the comfort of the passengers.

2.3 Train dynamic model

This module recalculates train speed and position at each simulation step. For that purpose the resistance to train movement is needed and it is made up of the rolling and aerodynamic resistance and the track gradient resistance. The first one is modeled as a quadratic function of the velocity with nonnegative parameters depending on each particular train. The latter is the track gradient resistance force due to gravity which is positive for ramps and negative for slopes. The simulator calculates it from a list with the initial and final points of downhill and uphill sections, their values, and the slope transition curves. Track curves are treated as equivalent slopes added to the actual ones. At each simulation step, an average of the gradient where the train is situated is calculated considering it as a distributed mass on a track with continuously varying gradient. Thus, the train acceleration is the result of the traction force minus the total resistance to train movement. After, speed and position are easily calculable.

2.4 Consumption model

The energy consumption of the profile is recalculated at each simulation step according to the time increment and the current. A constant line voltage is assumed. Usually, data of current is only the corresponding to the maximum force. The current consumed could be calculated assuming a constant efficiency, however this is not a realistic assumption. Therefore, a model of efficiency depending on the speed and the ratio between the required and the maximum force has been developed [16].

3. Measurements

Real data have been recorded in trains of the Madrid Underground. Measurements taken have been used to adjust the simulator and validate some data. For example, in one line, differences between the theoretical motor curves and the real ones (measured) have been found (Figure 2).

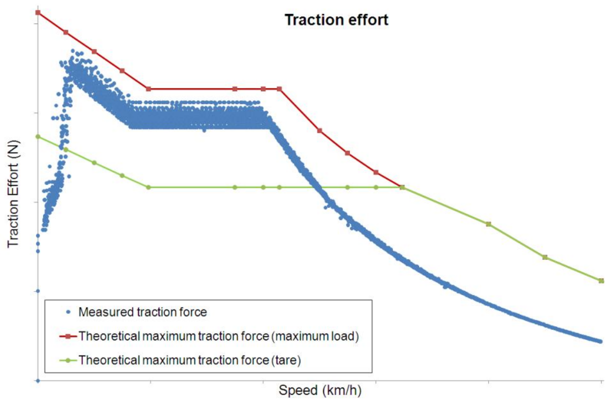


Figure 2: Experimental and theoretical motor curves

A comparison of complete simulations and measured data of running times and energy consumption has been carried out in order to validate the simulator. The results of the comparison of complete simulations and measured data are shown in Table 1 for several interstations. Consumption and running times are compared. An average difference of 4.2% in energy usage and 1.0% in running times is obtained.

	MEASUREMENTS		SIMULATIONS		ERROR			
Stations	R. Time (s)	E (kWh)	R. Time (s)	E (kWh)	R. Time (s)	E (kWh)	R. Time (%)	E (%)
PE2	65.78	15.68	66.55	15.92	0.77	0.24	1.17	1.51
C2	54.46	2.81	55.05	2.79	0.59	-0.02	1.09	-0.73
S2	93.81	2.86	94.70	2.85	0.89	0.00	0.95	-0.01
LV2	58.81	2.55	60.45	2.50	1.64	-0.06	2.79	-2.25
EM2	76.98	7.56	75.40	7.52	-1.58	-0.03	-2.05	-0.42
PF2	62.71	2.46	63.05	2.44	0.34	-0.02	0.54	-0.82

Table 1: Results of energy consumption and running times in complete simulations in comparison with measurements in some interstations.

4. Design procedure

As mentioned before, the simulator combines all the possible commands that the ATO system provides obtaining all the possible speed profiles per interstation. Solution space is plotted in a time-consumption graph with every profile characterized by its running time and energy consumption as well as a color indicating its comfort observance (Figure 3). This is an important point of the simulator since allows verifying the comfort of the selected profiles.

In the Madrid Underground four alternative speed profiles per interstation are needed to be programmed in the Traffic Regulation System. This set of profiles has increasing running times from the first (flat out, the fastest) to the fourth (slowest). If the optimal profiles are chosen, they will also have decreasing energy consumption according to the shape of the Pareto curve which represents the minimum consumption for each running time. An example is given in Figure 3. The longer the running time is, the lower the energy consumption. Consequently, this is a multicriteria problem where the aim is to find an appropriate trade-off between energy consumption and running times. Decision theory techniques have been used to solve it.

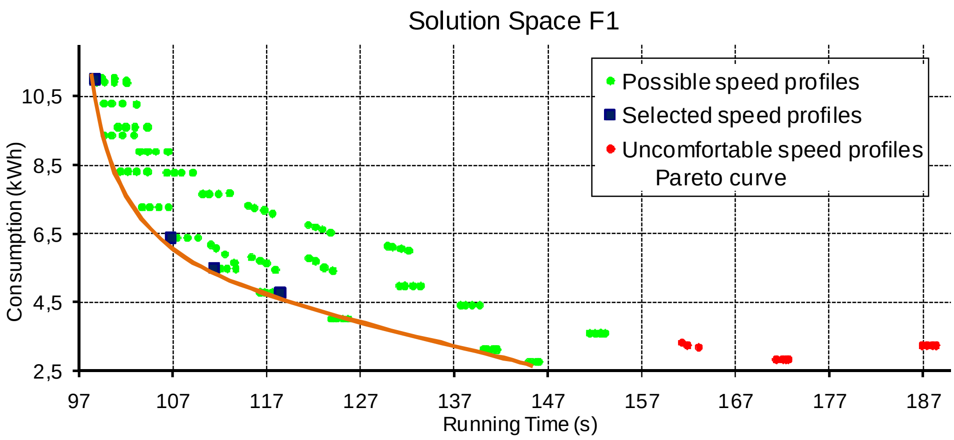


Figure 3: Solution space of F1 with uncomfortable speed profiles.

The proposed procedure follows three criteria: domination, sensitivity and uniform distribution of running times. According to the domination criterion, optimal solutions are over the Pareto curve formed by the solutions with less energy consumption and approximately the same running time of all the possible ones. Solutions not located on the curve are said to be dominated and discarded. Example in Figure 4 shows a dominated profile (in service) which can be replaced achieving a 35% of savings.

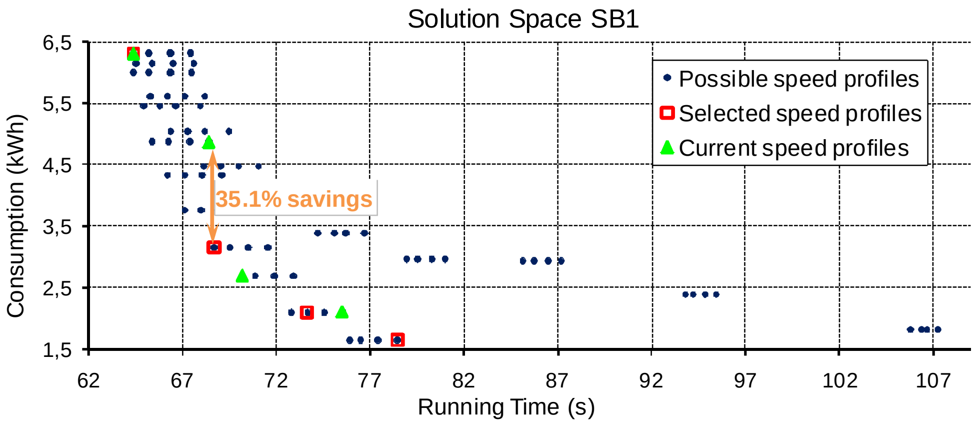


Figure 4: Energy saving achieved applying the domination criterion

The consumption sensitivity criterion is applied for the selection of the slowest speed profile. In the time-consumption graph, the slope of the Pareto curve progressively decreases from the fastest speed profile as the running time increases. In other words, solutions near the flat out have high marginal energetic cost associated per second. These marginal costs decrease reaching almost 0 at the end of the curve. The proposed criterion places the slowest speed profile where the Pareto slope becomes almost flat. However, the maximum running time gap between the fastest and the slowest speed profile is limited in practice, so the slowest profile must be moved and placed before the flat slope of the Pareto curve if it is necessary to observe this restriction. This strategy guarantees energy savings when trains are held up for traffic regulation purposes.

The remaining profiles are designed applying the uniform distribution criterion. The speed commands must be selected in order to obtain a design with a uniform distribution of the running times over the Pareto curve. An example is given in Figure 5 where proposed design and currently one in service are compared. The speed profiles three and four of the current set consume the same energy with different running times. It takes the second and third profile almost the same time to travel the interstation and the flat area of the Pareto curve is hardly well-spent. In contrast the new design proposes profiles over the Pareto curve with a similar gap time between them which favours a proper operation of the traffic regulation system.

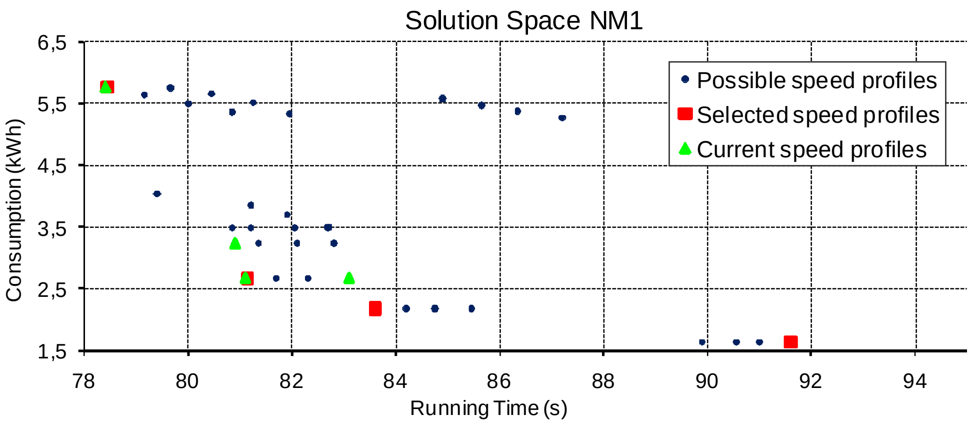


Figure 5: Temporal uniform distribution of the proposed speed profiles.

The design procedure has been applied to redesign the ATO speed commands of some lines of the Madrid Underground in order to value the expected energy savings. An average of 13% energy savings has been measured without affecting commercial speed.

5. Consideration of an on board energy storage device

As shown above, with a proper design of the ATO speed profiles it is possible to achieve significant savings due to the selection of the optimal strategies of speed holding or coasting-motoring which decreases the traction consumption. But too furthermore, taking into account the advantages of the regenerative braking the total energy consumption of the train could decrease considerably. One of the possible technologies for a well spending of this energy is the use of on board energy storage devices and a study of the convenience of the implementation in trains of these devices has been carried out. Trains could store their own regenerated energy while braking and use it during the next start. To assess the convenience of using them, the previous design has been carried out again considering on board storage devices with the result that optimal curves are modified.

With the aim of obtaining realistic results, an on board device with actual features has been look up on the bibliography. The selected technology to be incorporated into the simulator is the “MITRAC Energy Saver” of Bombardier [17, 18]. It has been working from September 2003 in a LRV on Mannheim with a 477kg mass and a maximum power of 300kW. Simulations in a European metropolitan system with an 8 vehicles train of 165t tare and 6 devices of 1.5kWh each have also been carried out [19]. In the present study 4 devices have been assumed with a total mass of M=477x4=1905kg, a maximum power of 300kW and 4x1.5=6kWh storage capacity. Moreover, 85% efficiency has been assumed [19].

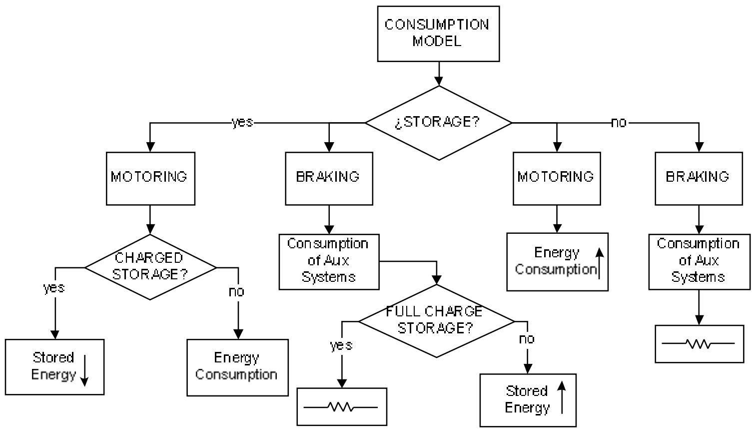


Figure 6: Flowchart of the consumption model with the energy storage device

Taking into account an on board energy storage device modifies the flow of energy. Simulator has been updated according to Figure 6 to calculate new consumptions. Train will be fed from the storage device if it is not discharged when motoring. Otherwise, energy is consumed from catenary. When the train is braking the regenerative energy will supply auxiliary systems and if remaining energy is available, stored energy will increased. If there is not a storage device or it is full charged, braking energy will be wasted on resistors.

Firstly, a study of the consequences of adding an extra mass to the train has been carried out. The charge of the storage device before departing station from which savings are achieved, has been studied from simulations. Then, since this charge depends on the braking in the previous interstation, a simulation of a whole line has been carried out in order to find realistic values for the subsequent designs.

5.1 The additional mass of the storage device

In order to study the trade-off between an additional mass and savings with an on board device, simulations of different scenarios in one line of the Madrid Underground have been carried out. The base case is the simulation of the flat out without any storage system, thus the regenerative energy is wasted heating resistors when it is not spent by the auxiliary systems. Then, an energy storage device is taken into account with the implications of an extra mass. In each scenario the initial charge of energy is increased 10% achieving 100%. Table 2 summarizes the savings obtained by simulation regarding to the base case depending on the initial charge. They are also illustrated in Figure 7 where results of savings depending on the initial charge of the storage device are lineal. So, rejecting the cases of C1 and AR1 stations, a medium slope has been calculated, 0.29 (Table 2) That is to say, that with the flat out 0.29% of more savings can be achieved increasing 1% the initial charge of the storage device. C1 (Figure 8) and AR1 are stations located in a downhill section. Except the first period of traction speeding up the train, the train is driven braking. As a result, the total electricity traction consumption is low and energy savings involve higher percentages than the rest of the stations as it is shown in Figure 7.

		SAVINGS (%)																	
	STATION	VA	SC	VC	CI	SF	DO	AL	L	DL	PF	E	LV	S	C	PE	VR	AR	
INITIAL CHARGE	0	1.27	6.12	0.96	-0.98	-1.64	17.31	3.22	-1.44	-0.28	3.58	-1.39	-0.26	-1.84	-5.99	-1.70	-1.39	-2.74	
	10%	4.25	9.23	3.96	3.29	2.17	20.62	6.32	0.93	2.74	6.93	2.22	1.88	1.56	3.04	2.41	2.08	6.37	
	20%	7.23	12.34	6.96	7.56	5.98	23.93	9.42	3.29	5.75	10.29	5.83	4.02	4.96	11.98	6.51	5.54	15.49	
	30%	9.87	15.10	9.62	11.35	9.36	26.87	12.16	5.39	8.49	13.31	9.19	5.98	7.98	19.86	10.27	8.67	23.58	
	40%	12.48	17.82	12.24	15.07	12.69	29.75	14.87	7.46	11.13	16.23	12.33	7.85	10.95	27.74	13.85	11.70	31.53	
	50%	15.08	20.53	14.86	18.80	16.02	32.64	17.57	9.52	13.75	19.16	15.48	9.72	13.92	35.62	17.43	14.72	39.49	
	60%	17.68	23.24	17.48	22.52	19.34	35.53	20.36	11.59	16.38	22.07	18.63	11.57	16.90	43.50	21.01	17.73	47.44	
	70%	20.26	25.96	20.10	26.25	22.67	38.42	23.41	13.65	19.01	24.99	21.76	13.44	19.85	51.33	24.57	20.76	55.40	
	80%	23.14	28.66	22.71	29.95	25.98	41.29	26.12	15.71	21.65	27.92	24.90	15.31	22.82	59.38	28.15	23.79	63.31	
	90%	26.12	31.37	25.33	33.68	29.30	44.18	28.82	17.77	24.27	30.84	28.05	17.43	25.79	68.24	31.73	26.81	71.26	
	100%	28.86	34.09	27.95	37.40	32.63	47.25	31.52	19.84	26.90	33.75	31.20	19.52	28.76	76.12	35.31	29.82	79.15	
	SLOPE	0.27	0.28	0.27	0.38	0.34	0.29	0.28	0.21	0.27	0.30	0.32	0.19	0.30	0.81	0.37	0.31	0.81	**0.29**

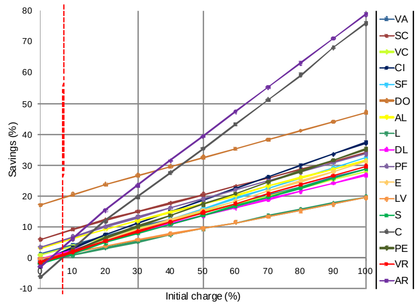


Table 2 and Figure 7
Savings expected depending on the initial charge of the storage device

One of the arguments against the use of storage devices is the increase of the train mass which could be an impediment for obtaining big savings. According to that, under the same conditions and being not possible to feed regenerative energy back to the catenary, a train carrying a device initially discharged would consume more than a train without it. However, this statement is not always true as it can be seen in the first row of Table 2 where positive results mean that less energy was consumed by the train with the initially discharged storage device. Figure 7 shows it graphically.

For example, interstations “C1” and “AR” are in downhill, thus, there is only a traction period for starting up the train (Figure 8). That is the period in which there is no charge in the device. After that, the train only brakes and the storage device is charged up again, but this energy will not be used until next interestation. Consequently and as it was expected, the energy consumption is higher with the storage device due to the additional mass.

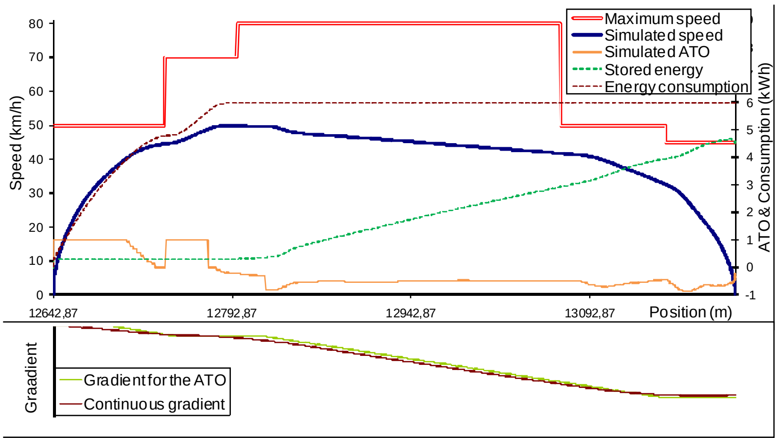


Figure 8: Speed profile, energy consumption and stored energy in interstation “C1” in a downhill

However, in other interstations the train travels along a variable gradient with different periods of motoring and braking. Thus, it can be fed from the on board energy storage device after the first period of braking (Figure 9). In that case, the total energy consumption simulated in the interstation is lower than in the scenario without the device. This highlights the importance of the detailed simulation to verify or reject an a priori judgment.

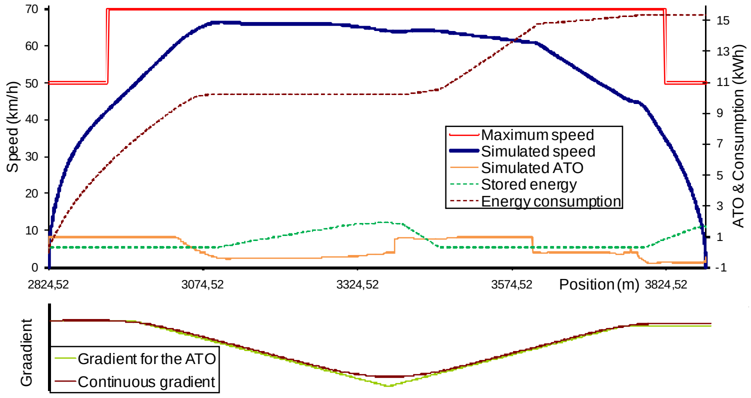


Figure 9: Speed profile, variable gradient, energy consumption and stored energy in interstation "SC1"

Simulating a train traveling through the line without storage device with different passenger loads, a relation between the percentage of load and the increase in energy consumption is obtained. This relation is shown in Figure 10 and is lineal. According to that, an increase of 1% in the load of the train involves an average increase of 0.28% in energy consumption. The device simulated means 1.21% extra mass regarding to the train considered, in other words, 0.34% more consumption. It was shown in Table 2 that increasing 1% the initial charge of the storage an average of 0.29% of savings could be achieved. Therefore, from an average initial charge of 1.16% savings can be achieved with the use of an on board energy storage device. That is an average case and from an initial charge of 6.2% (dotted red line in Figure 7) there are savings in every interstation with the storage device.

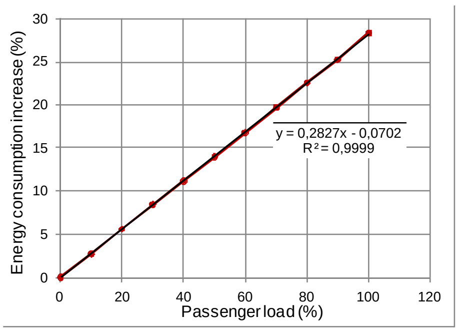


Figure 10: Increase of the energy consumption depending on the passenger load

5.2 Calculation of the initial charge

As it has been shown, scenarios with 10 different initial charges have been simulated obtaining results of savings depending on the charge. However, at the end of each interestation the same charged is stored in the device. In other words, the energy stored traveling the interestation is independent of the initial charge. It is completely consumed starting up the train and later, charge and discharge periods are the same at each interestation. As a result, trains reach next stop with the same charge in the storage device. The example of one interestation is given in Table 3.

Running Time (s)	Traction Energy (kWh)	Braking Energy (kWh)	Energy Consumption (kWh)	Mechanical Work (kWh)	Storage device initial charge	Storage device final charge	Energy Stored (kWh)	Wasted Energy (kWh)
98.5	12.81	3.65	16.47	9.75	-	-	-	1.83
98.7	12.91	3.69	15.94	9.84	0.00%	12.94%	1.58	0.00
98.7	12.91	3.69	15.43	9.84	10.00%	12.94%	1.58	0.00
98.7	12.91	3.69	14.92	9.84	20.00%	12.94%	1.58	0.00
98.7	12.91	3.69	14.46	9.84	30.00%	12.94%	1.58	0.00
98.7	12.91	3.69	14.02	9.84	40.00%	12.94%	1.58	0.00
98.7	12.91	3.69	13.57	9.84	50.00%	12.94%	1.58	0.00
98.7	12.91	3.69	13.11	9.84	60.00%	12.94%	1.58	0.00
98.7	12.91	3.69	12.61	9.84	70.00%	12.94%	1.58	0.00
98.7	12.91	3.69	12.17	9.84	80.00%	12.94%	1.58	0.00
98.7	12.91	3.69	11.72	9.84	90.00%	12.94%	1.58	0.00
98.7	12.91	3.69	11.28	9.84	100.00%	12.94%	1.58	0.00

Table 3: Simulations of one interstation varying the initial charge of the storage device.

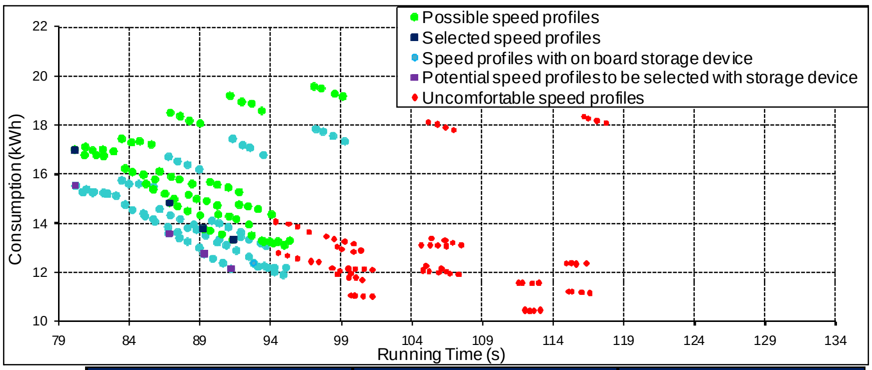
Bearing in mind this result and knowing that depending on the gradient, length, driving and maximum speed, the possible regenerative energy to be stored is different, the objective now is to find out the available initial charge in each interstation since it depends on the braking in previous interstation. A whole line of the Madrid Underground has been simulated assuming a full initial charge in the first interstation. Then, the charge of the on board energy storage varies along the line and a realistic initial charge for each interstation has been obtained. Results are shown in Table 4. With these data it is possible now, to simulate each interstation in order to study the potential savings to achieve with an energy storage device with the particular initial charge.

STATION	VA1	SC1	VC1	CI1	SF1	DO1	AL1	L1	DL1	PF1	E1	LV1	S1	C1	PE1	VR1	AR1	M1
INITIAL CHARGE	100%	42%	26%	25%	77%	23%	13%	13%	20%	11%	9%	8%	21%	20%	75%	19%	20%	53%

Table 4: Charges of the storage before train's departure

5.3 Redesign of speed profiles

In Figure 11, the solution space of VC1 is shown. An on board energy storage device which is 26% (see Table 4) charged before travelling the interstation, has been taken into account. It is possible to see the comparison between the design previously done without storage and the current one. The energy saving expected is shown in Table 5: up to 8.9% with the fourth profile. It is important to notice that it is a saving regarding to the *Selected speed profiles* shown in Figure 11 which is the designed set of profiles in service in this interestation. As it has been mentioned before, with the redesign of the speed profiles of this line, an average 13% of savings was achieved. Therefore, savings expected when taking into account an on board storage device would be supplementary added to the already achieved with the previous design shown.



	Design without on board storage		Design with on board storage		Differences	
	R. Time (s)	E. Consumption (kWh)	R. Time (s)	E. Consumption (kWh)	R. Time (%)	E. Consumption (%)
Profile 1	80.1	16.99	80.2	15.53	-0.06	8.59
Profile 2	86.8	14.83	86.8	13.58	0.06	8.44
Profile 3	89.2	13.77	89.3	12.75	-0.06	7.43
Profile 4	91.3	13.34	91.2	12.15	0.16	8.90

Figure 11 and Table 5

Comparison between designs with and without energy storage device

Table 6 shows average results of savings. With the implementation of an on board storage device, energy consumption measured in the train would decrease up to 12% regarding to the previous design carried out. It would be 24% of savings regarding to old situation before the implementation of the proposed design.

		Design without storage regarding to the old situation		Design with storage regarding to the design without storage		Design with storage regarding to the old situation	
	Use of the profile (%)	Profile E. saving (%)	Savings in the line (%)	Profile E. saving (%)	Savings in the line (%)	Profile E. saving (%)	Savings in the line (%)
Profile 1	40	0	**13.61**	12.04	**12.91**	12.04	**24.67**
Profile 2	60	20.16		12.90		30.46	
Profile 3		22.87		13.38		33.19	
Profile 4		25.005		14.17		35.63	
		17.01		**13.12**		**27.83**	

Table 6: Summary table. Average energy savings with the proposed designs

6. Conclusions

A detailed simulator of the particular ATO system of the Madrid Underground has been developed in order to obtain realistic simulations that allow calculating slight differences between alternative speed profiles. High precision is needed since in the case study of the Madrid Underground these differences can be a few seconds. Thanks to that, it has been possible to carry out a realistic design of the speed profiles of the Madrid Underground with which up to a 13% of savings have been measured.

Advantages of taking into account an on board storage device even discharged in spite of the additional mass involved, have also been discussed. Taking into account the implementation of on board storage devices, up to 12% of savings could be expected regarding to the previously designed speed profiles and 24% regarding to the old situation of the line before applying the design procedure presented. The design has been carried out with a different initial charge of the storage device depending on the interstation. Realistic values have been obtained simulating a train traveling through the line charging and discharging the device.

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