2018

Electrical Systems for Transportation

PROJECT

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Index

1 Railway line and selected track

The considered track for this project is a stretch of the main railway line connecting Milan and Genoa. More specifically, the considered section of the line is the part from Pavia to Arquata Scrivia.

This line is used by regional, inter-regional and freight trains since it connects 3 regions: Liguria, Piemonte and Lombardia.

The line is used all year round and it is particularly under stress during winter due to possible ice formation both on track and on the contact line. Thus, for the modelling purpose of this project, the worst adhesion conditions must be considered.

The line consists of 2 tracks each supplied by a 3 kV DC overhead suspension catenary system with 2 messenger and 2 contact wires. A TPSS is located near each one of the main stations (Pavia, Voghera and Tortona) at an average distance of 22 km between each other. Between the main stations, there are a couple of minor stations used by few local trains.

1.1 Line segment description

The considered portion of the line (from here onwards, simply referred to as "line segment") is represented in Figure 1.

Figure 1 Pavia – Arquata Scrivia railway line

The considered train is going to stop at the following 3 stations indicated with a red arrow in Figure 1

- Pavia (starting station).
- Voghera (intermediate station).
- Tortona (intermediate station).
- Arquata Scrivia (arrival station).

The total length of the line segment is 65.90 km divided as follows

- From Pavia to Voghera: 26 km.
- From Voghera to Tortona: 15.30 km.
- From Tortona to Arquata Scrivia: 24.60 km.

1.2 Ground slopes

As far as changes in altitudes are concerned, there is a slight increase in altitude from Pavia to Tortona mostly concentrated from midway onwards, and a slightly higher increase from Tortona to Arquata Scrivia which is, instead, more evenly spread between the two stations.

Observing altitude data from Google Maps, it seems reasonable to assume that the rate of change in altitude is constant along each part of the line segment.

According to this assumption, the line segment can be divided in 4 parts as represented in Figure 2

- From Pavia (km 0) to km 14 (red path), the change in altitude is about +2m (slope of 0.008°).
- From km 14 to Voghera (green path), the change in altitude is about +26m (slope of 0.124°).
- From Voghera to Tortona (blue path), the change in altitude is about +30m (slope of 0.107°).
- From Tortona to Arquata Scrivia (yellow path), the change in altitude is about +116m (slope of 0.270°).

Resistance due to slopes will be modelled as a force appearing right after the train enters the related part of the line segment. This approach will lead to a sudden appearance of the above mentioned force and should be considered only as an approximation since in practice a gradual increase in slope resistance is more likely to be the case.

Figure 2 Track slopes

1.3 Curves

Data on curves was the most difficult to estimate and, probably, the least accurate. Curvature radius has been obtained from Google Maps, by superimposing on each curve a circle in order to encompass the whole curve and roughly estimate the radius.

In general, there are no curves with radius lower than 1 km. The resistance provided by such curves is low compared to aerodynamic and grade resistance, nevertheless, it was included in the model.

Table 1 shows the data on the curves (km 0 is where Pavia station is located):

Curve number	Starting [km]	Length [km]	Radius [km]
1	1.45	2.77	3.50
2	5.90	2.02	4.50
3	10.20	2.70	2.40
4	23.20	1.99	1.20
5	26.12	0.75	2.00
6	31.15	2.19	2.50
7	42.00	1.00	1.00
8	49.00	2.00	1.80
9	53.00	1.00	2.40
10	54.40	2.00	1.20
11	57.00	1.50	1.00
12	59.50	1.25	1.20
13	62.50	2.20	1.75

Table 1 Data on curves

1.4 Commercial speed and maximum speed: GPS data

The train considered in this project is a fast-regional train ("Regionale Veloce"). According to Trenitalia SPA website, the expected travel time, on this kind of trains, from Pavia to Arquata Scrivia is 41 minutes. This leads to an expected theoretical commercial speed of about 96.4 km/h.

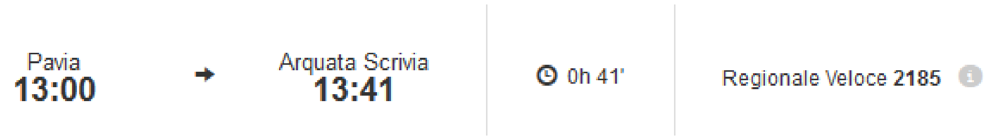


Figure 3 Expected travel time from Trenitalia SPA website

This has been verified by GPS measurements on board of the train shown in Figure 4, which report an average speed of about 94 km/h.

After observing a few GPS measurements, as reported in Figure 4, it is worth noticing that

1. The maximum speed recorded is 152 km/h, in accordance with the rated speed of the considered rolling stock.
2. The maximum speed is not always reached immediately nor kept constant after being reached up until braking before the station. Sometimes, on some parts of the line segment, a lower speed is maintained but there seems to be no clear pattern. In the simulation performed in this document, coasting is implemented also to try to take into account this fact.
3. Indeed, the train usually reaches maximum speed "faster" and keeps it for most of the time on the track when it needs to make up for some delay.

4. The measured commercial speed matches the expected one (94 versus the expected 96.4 km/h).
5. The scheduled time for stops is 2 minutes per stop.
6. Coasting, in the case of Fast Regional trains, seems to be applied only when in the proximity of the arrival station. This is due to the fact that the air resistance is very strong and will inevitably slow down too much the convoy.

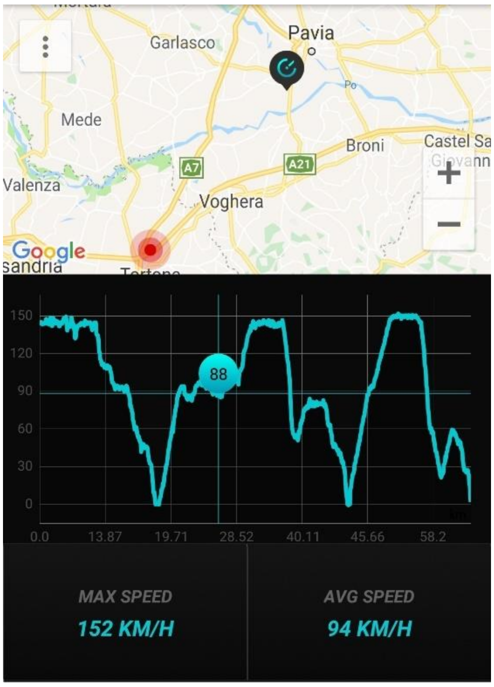


Figure 4 GPS data: speed vs time, maximum and average speed on a portion of the track

2 Electric vehicle

The vehicle considered in this project is a passenger carrying train fast-regional ("Regionale Veloce"). The convoy is composed by a locomotive and a variable number of hauled passenger carriages. In this project, the number of passenger carriages has been fixed to 5.

2.1 Locomotive

The locomotive which usually pulls or pushes the rolling stock on this track (as far as regional and inter-regional trains are concerned) is the model E464 produced by Bombardier Transportation Italy.

Figure 5 Locomotive E464

The locomotive has the following characteristics:

Description	Value	Unit
Rated speed	160	km/h
Mass	72	t
Adhesion mass	72	t
Wheel arrangement	B_0B_0	
Hourly power ("Potenza oraria")	3.5	MW
Continuous rated power	3	MW
Number of motors	4	
Rated supply voltage	3 or 1.5 (reduced power)	kV (DC)
Maximum tractive effort at start-up	200	kN
Rated continuous tractive effort	180	kN

Table 2 Technical characteristics of E464 locomotive

2.2 Carriages

The considered passenger carriages are the following

- Model: MVDE all with only 2nd class service.
- Number of passenger carriages: 5.

Figure 6 Passenger carriage MVDE

The characteristics of each carriage are as follow

Description	Value	Unit
Number of passenger seats	84	
Number of wheelsets	4	
Mass (with no passengers on board)	38	t
Rated speed	160	km/h
Estimated power consumption	30	kW

Table 3 Technical characteristics of MVDE carriage

3 Simulation

3.1 Model hypothesis

The main hypothesis behind the model used in both simulations are reported below

3.1.1 Passenger carriages

- There are 5 hauled passenger carriages.
- Each passenger carriage is travelling at full load (84 passengers per carriage) with a conventional mass of 70 kg per passenger and luggage.
- The auxiliary power required by each carriage is constant and equal to 30 kW.
- During the braking phase, all the carriages brake using mechanical brakes.

3.1.2 Locomotive

- The locomotive works at the power of 2.2 MW during the constant power part of the characteristic. This reduction in power is necessary if one wants the locomotive to work with the ideal characteristic as showed in Figure 7, i.e. with a constant force/torque region up to base speed and a constant power region up to maximum speed.
  Since due to bad adhesion conditions the starting applied tractive effort will be about 80 kN, the base speed at 3 MW would be about 135 km/h while the adhesion limit, at that speed, would impose a maximum tractive effort of about 71 kN. Therefore, lowering the applied force is not an option since the base speed would increase further, so the only option left to obtain the desired characteristic is to reduce the locomotive power.
  It is worth noticing that adhesion conditions deteriorate quickly as the train speeds up due to the model assumed for adhesion modelling as explained in section 3.1.3.

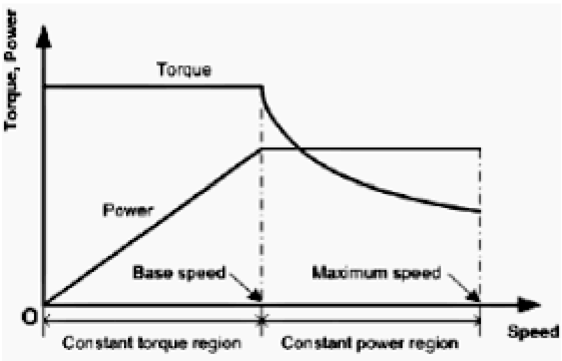


Figure 7 Ideal characteristic

- A maximum speed of 150 km/h has been assumed since this is the maximum speed recorded on the train. This hypothesis might not be fully realistic in case of very bad weather and adhesion conditions.
- For auxiliary services, it has been estimated that the locomotive requires constantly 40 kW.
- The locomotive applies the maximum tractive effort allowed by the adhesion and comfort tests minus a margin that allows to obtain the characteristic represented in Figure 7.
- After the maximum speed has been reached, a proportional (P) regulator simulates tractive effort regulation performed by the train operator due to changes in slope and curvature along the track. The k_p parameter of the regulator has been set to 0.003 by trial and error.
- Coasting is applied only for about 4 km in the proximity of each arrival station. When transitioning in the coasting phase, gradual tractive force reduction by the driver is simulated by decreasing the tractive force by 10 % each second.

- Electrical braking is assumed to be equal to 30 % while the remaining part is covered by mechanical brakes. In the case of a single locomotive hauling carriages equipped with mechanical brakes, this assumption seems reasonable since only a small part of the braking is performed by the locomotive. Furthermore, to avoid stress on the mechanical connections between the rolling stock when the train starts moving from the station, during the braking phase the locomotive should brake a little bit less than the carriages (assuming that the locomotive is pulling the hauled carriages) so as not to lose the mechanical tension on the connections between locomotive and carriages and between carriages.
- The efficiency during traction and braking (electrical) phases is assumed to be equal to 80 %. No official data has been found on this parameter, so this value was simply assumed as true.

3.1.3 Line segment

- Voltage drop across the line is negligible and the supply voltage is assumed to be constant at 3 kV DC.
- It is assumed that the TPSSs allow bi-directional power flow.
- Worst adhesion conditions (icy track) with adhesion coefficient (at zero speed) of 0.25 have been considered, assuming the following model for the adhesion coefficient as a function of speed: $f_{ad}(v) = \frac{0.25}{1+0.011v}$ where the speed is expressed in km/h. It is assumed that this model can be used also for modelling the adhesion conditions of the carriages during braking. This model was obtained from (Brenna, Foiadelli, & Zaninelli, 2018).

It can be noted that, at least in theory and in software, a control system that applies the maximum traction force allowed (minus a margin) by the adhesion conditions represented by $f_{ad}(v)$ could have been used, however, it is not known to the author of this project if such control systems exist in practice. Even if they existed, this would not necessarily allow to obtain the desired characteristic of Figure 9 which was sought after in this project.

3.1.4 Additional hypothesis and settings for the simulation

- Time step for the simulation is 1 s.
- Stopping time at each station has been assumed to be equal to 2 minutes. This value comes from the stopping time indicated by Trenitalia SPA on its mobile application. In practice stopping time seems to be variable from 1.5 to 2.5 minutes, depending on the number of people travelling on this kind of trains.

3.1.5 Quantities of interest

The calculations of quantities of interest are reported in the following table for reference

Variable description	Formula	Value	Unit
Train gross mass (empty train)	$m_t = m_{loc} + m_c = 72 + 39 * 5$	267	t
Train equivalent mass	$m_e = 72 * (1 + 0.1) + 39 * (1 + 0.03) * 5$	280.05	t
Passengers mass	$m_p = 0.07 * 84 * 5$	29.40	t
Train gross mass (with passengers)	$m = m_t + m_p$	296.40	t
Total mass to be accelerated	$m_d = m_e + m_p$	309.45	t
Auxiliary services power	$P_{aux} = 40 + 30 * 5$	190	kW
Maximum starting tractive effort (adhesion test in static conditions)	$FT_{max} = 0.25\, m_{\,adhesion\ loc}\, g = 0.25 * 72 * 9.81$	176	kN
Tractive effort applied during constant force part of the characteristic	FT_a	80	kN
Max acceleration (adhesion + comfort + dynamic adhesion test)	$a = \frac{FT_a}{m_d}$	0.26	m/s^2
Base speed	$v_b = 2.2\ MW/FT_a$*3.6	99	km/h
Braking deceleration	$a_{brk} = -a$	-0.26	m/s^2
Maximum speed	$V_{MAX\ km/h}$	150	km/h
Braking time	$t_{brk} = \frac{V_{MAX}}{\lvert a_{brk}\rvert}$	153.65	s
Braking distance (at maximum speed)	$\frac{\frac{1}{2} v_{MAX}{}^{2}}{\lvert a_{brk}\rvert}$	3357	m

Table 4 Quantities of interest

3.2 Formulae used at each iteration

At each iteration k, the following formulae have been used.

3.2.1 Acceleration phase

- Acceleration in [m/s^2] $a_k = \frac{FT_k - R(v_k, s_k)}{m_d}$
- Speed in [m/s] $v_k = a_{k-1}\Delta t + v_{k-1}$
- Position in [m] $s_k = \left(\frac{v_k + v_{k-1}}{2}\right)\Delta t + s_{k-1}$
- Electrical power in [kW] absorbed from the line $P_{el_k} = P_{aux} + FT_k \frac{v_k}{\eta_t}$
- Electrical current in [A] absorbed from the line $I_k = \frac{1000\, P_k}{V_n}$
- Electrical energy in [kWh] $E_k = \frac{(P_{el_k}\Delta t)}{3600} + E_{k-1}$

Note: FT_k and resistance to motion $R(v_k, s_k)$ are expressed in [kN], V_n in [V] and the mass to be accelerated m_d in [t].

3.2.2 Braking phase

During braking the same formulae can be used for speed, position electrical current and energy, however, the acceleration is fixed at a value equal to $a_{brk} < 0$.

The applied braking force is equal (using Newton's 2nd law) to $FT_k = a_{brk} m_d + R(v_k, s_k)$. Of this force, only 30% is applied by the motors, the remaining is applied by mechanical brakes. The electrical power absorbed becomes $P_{el_k} = P_{aux} - |FT_k v_k \xi_e \eta_e|$.

3.2.3 Total resistance to motion

Total resistance to motion at step k is equal to

$$R(v_k, s_k) = R_0(v_k) + Re(s_k)$$

Where $R_0(v_k)$ is a function of the speed expressed in [km/h] and returns a force expressed in kN

$$R_0(v_k) = \left(1.625 + 0.0205\left(\frac{v_k}{10}\right)^2\right) mg$$

While $R_e(s_k)$ is a function of the position of the train on the track and returns a force expressed in kN

$$R_e(s_k) = (\sin[\theta(s_k)] + r_c(s_k))mg$$

Note: s_k is the position on the line segment at step k and m is the gross mass of the train (with passengers) expressed in [t].

3.2.4 Tractive effort

If speed is less than the base speed, then:

$$FT_k = FT_a$$

If speed is less than maximum speed but higher than or equal to base speed, then constant power is applied:

$$FT_k = \frac{P_{max}}{v_k}$$

If the speed is equal to the maximum speed, then a P controller is used to keep the tractive force equal to the total resistance to motion. Speed is not controlled by design in order not to complicate the model further. A different controller to keep constant speed could also have been implemented.

The error term is equal to

$$\varepsilon = R(v_k, s_k) - FT_{k-1}$$

therefore, the tractive force applied at the next step is

$$FT_k = FT_{k-1}(1 + 0.003\varepsilon)$$

During coasting and while $FT_{k-1} > 1$ kN

$$FT_k = FT_{k-1}(0.90)$$

which allows the tractive effort to go rapidly and smoothly below 1 kN and then when $FT_{k-1} < 1$ kN, FT_k is set to 0. This behaviour of the tractive effort during the transition into coasting tries to simulate the behaviour of the train operator when reducing the applied tractive effort.

3.3 Results: traction diagrams

This is the graph of the applied mechanical tractive effort (FT) and its absolute value (|FT|) over the total time interval. Note that "fad" is the maximum tractive effort applicable before the wheels start to slip (and not the adhesion coefficient).

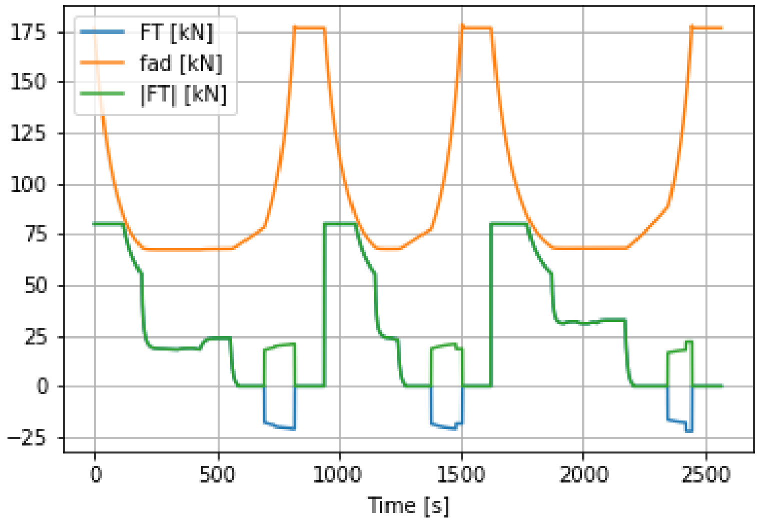


Figure 8 Tractive effort, and adhesion conditions vs time

It can be noted that:

- When the train is not breaking, FT and |FT| coincide.
- The adhesion conditions are particularly bad. No slipping of the wheels occurs but a lower initial tractive effort would allow for more safety on this regard, especially at higher speeds.
- The ideal characteristic (constant force up to base speed and then constant power) can be applied by using a very low initial tractive effort and lower power (2.2 MW instead of the rated 3 MW). The characteristic obtained is represented in Figure 9. It can be noted that base speed is about 99 km/h, as expected.
- If a higher initial tractive effort were to be used, the locomotive would generally incur in adhesion problems before reaching base speed, as can be clearly seen from Figure 8.

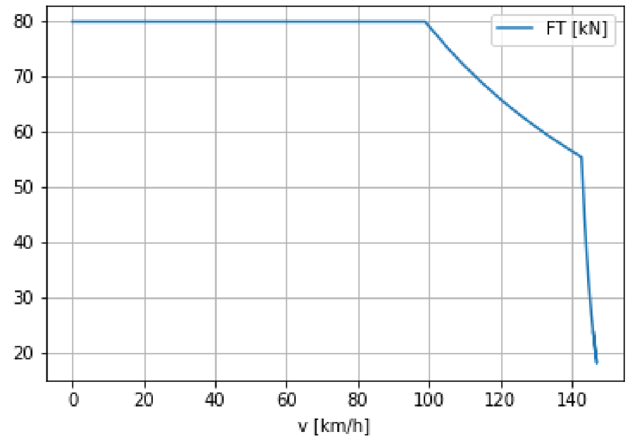


Figure 9 Mechanical characteristic

- During braking adhesion is not a problem since all the carriages are braking using their mechanical brakes and only part of the braking force is applied by the locomotive's motors. As it can be seen in Figure 10, no wheel slipping occurs during braking.

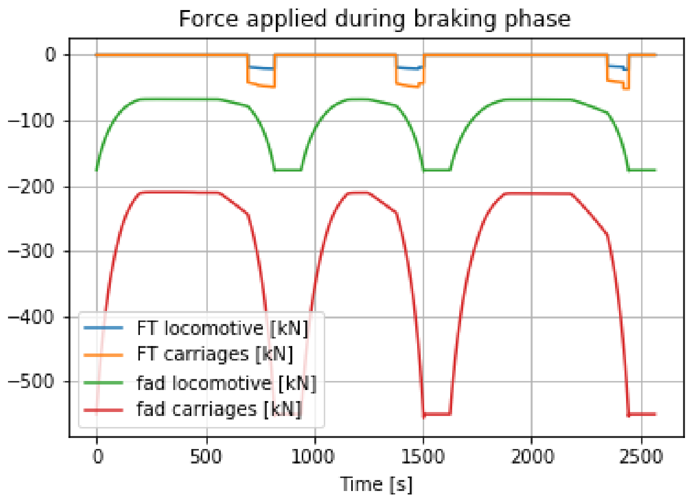


Figure 10 Adhesion conditions in braking phase

- To keep (roughly) constant speed after the maximum speed has been reached, the train operator has to counterbalance the changing slope and curvature resistance which both depend on the position of the train on the line segment, while aerodynamic resistance, depends only on the train speed and is therefore constant when the train's speed is constant. To achieve this adjustment, a proportional regulator P was introduced, which aims to keep the traction force equal to the sum of all resistive forces and simulate the adjustments made by the train operator. In Figure 8, smooth changes in the applied tractive force can be observed (for example right before t = 500 s where there is a change in slope).
  In Figure 11 the total resistance to motion $R = R_e + R_0$ is represented, as well as its components. Of course, Figure 11 is only a rough approximation of the actual resistance to motion.

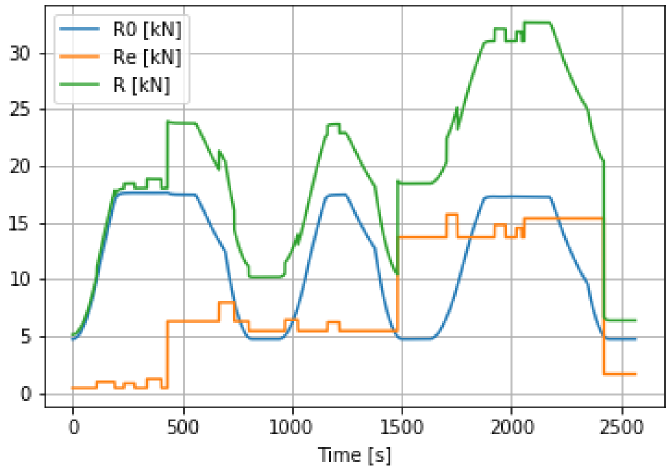


Figure 11 Resistance to motion and its components vs time

- It can be noted that grade resistance is much larger than curvature resistance. This was expected since the curvature radii are very large (larger than 1 km). Air resistance is generally larger than grade resistance except in the last part of the track where the two resistances are comparable.
- During the coasting phase, the tractive force has been gradually decreased by 10% each second to simulate a gradual tractive force decrease by the train operator. This can be seen right after t = 500 s before the braking phase in Figure 8.

Figure 12 shows the electrical power absorbed from the line.

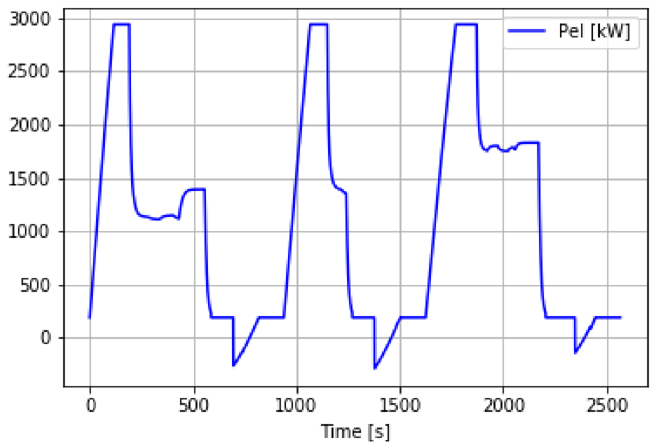


Figure 12 Electrical power absorbed from the line

It can be noted that:

- The power initially rises linearly with time, as expected, since the applied tractive effort is constant and speed rises linearly with time.
- After base speed has been reached, constant power is applied.
- After the maximum speed has been reached, only the power required to maintain maximum speed (plus auxiliary services power) is absorbed.

- It can be noted that around t = 500 s there is an increase in the absorbed power. This is due to a slope change which occurs at around 14 km from Pavia. In this case there is a significant increase in the required power, so the slope is not negligible.
- The power becomes negative during the braking phases meaning that in this case it is injected back into the supply system by using regenerative braking.

The graph of energy absorbed from the line versus time in Figure 13 shows that in this kind of service (Fast Regional trains), regenerative braking is not very advantageous since the energy given back to the supply system is negligible compared to the energy absorbed by the train. This conclusion is consistent with the fact that Fast Regional trains are supposed to cover large spans of track with infrequent braking. Also, the adoption of a prolonged coasting phase greatly reduces the speed of the train therefore it reduces the kinetic energy that remains to be recovered.

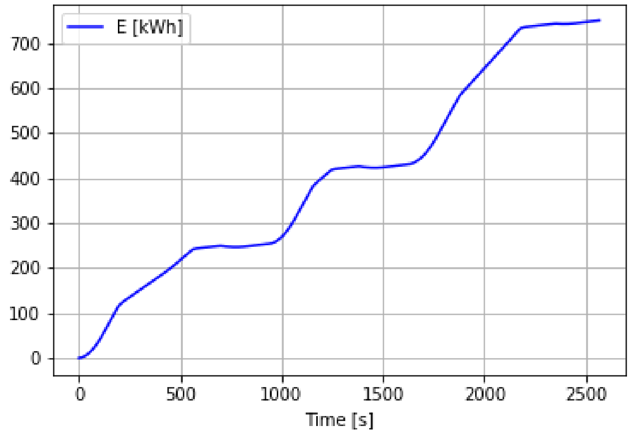


Figure 13 Electrical energy absorbed from the line

The current versus time graph represented in Figure 14 looks the same as the power vs time graph since the supply voltage is assumed to be constant at 3 kV DC.

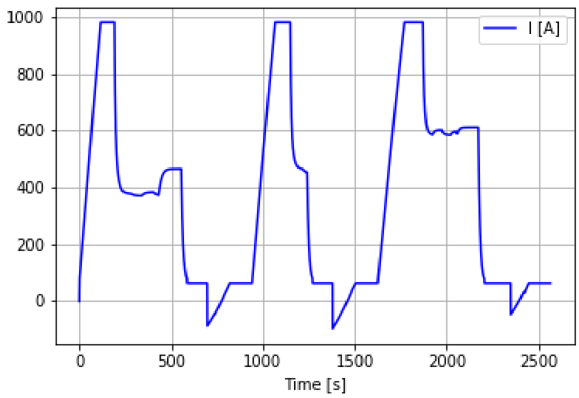


Figure 14 Electrical current absorbed from the line

Below, the graphs of acceleration, speed and distance travelled versus time are shown.

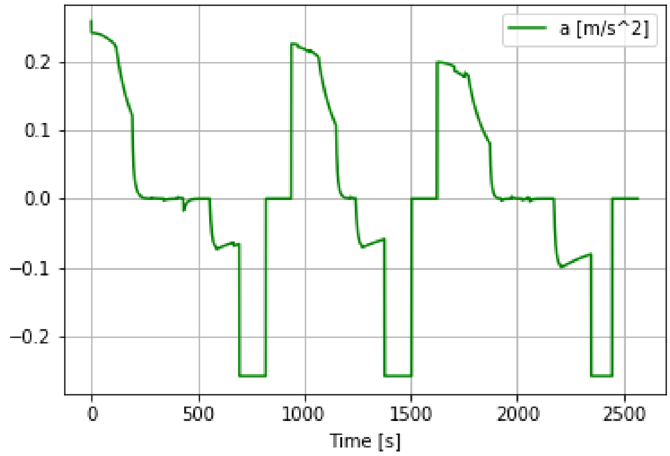


Figure 15 Acceleration over time of the train

The acceleration is only approximately constant during the constant force traction phase. This is due to the fact that resistance to motion increases as the train speeds up. Furthermore, grade and curvature resistance change as the train changes its position on the line segment. During the braking phase instead, a constant deceleration is imposed by design and then the applied force is obtained.

It can also be noted that acceleration is negative during the coasting phase, as expected. More specifically, the resistance to motion in this case is very high so that coasting cannot be applied for a very long period of time otherwise the train slows down too much. Typically, some coasting is applied when in the proximity of the arrival stations. In Figure 16, during the coasting phase, a sharp decrease in speed can be noted.

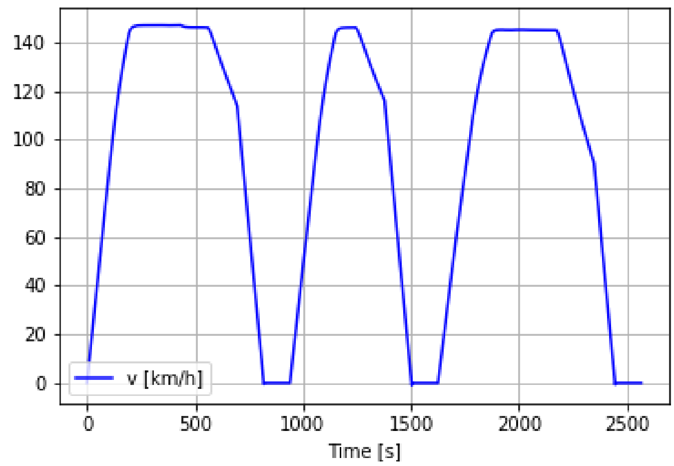


Figure 16 Speed over time of the train

The speed profile obtained seems consistent with the one measured on the GPS and shown in paragraph 1.4. In particular, the commercial speed is 96.95 km/h and the total travel time is equal to 40 minutes and 46 seconds which is quite close to the 41 minutes indicated by Trenitalia SPA.

A small change in speed can be noted before t = 500 s, that is, where a significant slope change occurs. This is due to the time needed by the controller to adjust the tractive force. Indeed in Figure 15 the acceleration becomes negative for a brief period due to the need of some adjustment period for the controller action to balance the tractive force required.

Finally, in Figure 17, position as a function of time is shown. It can be noted that during the constant force phase, the distance travelled tends to increase like a parabola, while when speed is constant, the distance travelled increases linearly with time.

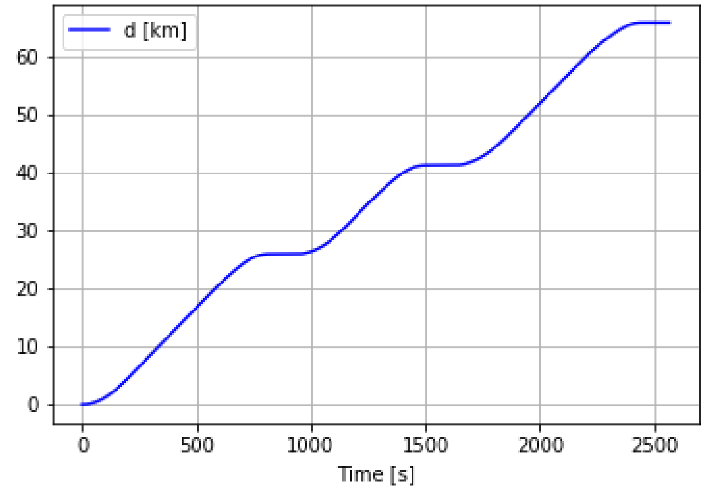


Figure 17 Position over time of the train

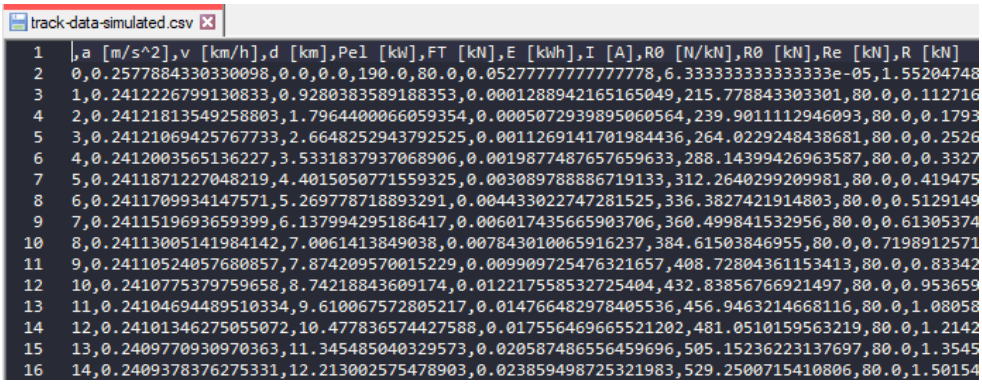
References

Brenna, M., Foiadelli, F., & Zaninelli, D. (2018). *Electrical Railway Transportation Systems.* IEEE Wiley.

Appendix – Project files and simulation results data

The project presented in this report is composed of the following files

1. File “Report-YYYYMMDD.pdf” (which is this report).
2. File “Fast-Regional-Train-simulation-YYYYMMDD.py” which contains the Python script that simulates the model. Although there is no need to run the script, it can be run by installing the “Data Science Platform” [Anaconda](). The output of this script is the file “track-data-simulated.csv” which is described below.
3. File “track-data-simulated.csv” which contains the results of the simulation in a text file with *.csv* formatting as shown in Figure 18. This file can be easily imported in Microsoft Excel for further analysis or checking.

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,a [m/s^2],v [km/h],d [km],Pel [kW],FT [kN],E [kWh],I [A],R0 [N/kN],R0 [kN],Re [kN],R [kN]
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11,0.2410469448951033,9.610067572805217,0.014766482978405536,456.9463214668116,80.0,1.08058
12,0.2410134627505507,10.477836574427588,0.017556469665521202,481.0510159563219,80.0,1.2142
13,0.2409770930970363,11.345485040329573,0.020587486556459696,505.15236223137697,80.0,1.3545
14,0.2409378376275331,12.213002575478903,0.023859498725321983,529.2500715410806,80.0,1.50154
```

Figure 18 Simulation results data in .csv file