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A Simulation Approach for Optimising Energy-Efficient Driving Speed Profiles in Metro Lines †

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Abstract: We propose a model for optimising driving speed profiles on metro lines to reduce traction energy consumption. The model optimises the cruising speed to be maintained on each section between two stations; the functions that link the cruising speed to the travel time on the section and the corresponding energy consumption are built using microscopic railway simulation software. In addition to formulating an optimisation model and its resolution through a gradient algorithm, the problem is also solved by using a simulation model and the corresponding optimisation module, with which stochastic factors may be included in the problem. The results are promising and show that traction energy savings of over 25% compared to non-optimised operations may be achieved.

Keywords: energy-saving; railway sector; metro lines; driving speed profiles; simulation

1. Introduction

Energy savings, and hence, the reduction in greenhouse gas emissions and air pollutants are major challenges for planners and transport operators. The importance of this theme is underlined in European documents [1,2]. Transport activities contribute significantly to energy consumption and harmful emissions: For example, in Europe, 31% of the total energy consumed is accounted for by the transport sector [3]. From this perspective, the White Paper [4] disseminated by the European Union identifies several actions that need to be implemented to reduce emissions.

Although road transport can be identified as the main culprit, rail systems have also been examined from this angle [5]. Indeed, all components of the transport sector can contribute to the reduction in energy consumption. Besides, the rising costs and the increased demand for electricity (especially in developing countries) make it important to reduce energy consumption in the rail sector as well.

Among the possible strategies that can be used to reduce rail energy consumption (low consumption engines, energy recovery systems, etc.), energy-efficient driving, or eco-driving, is one of the most promising [6–8]. This lies in the following strengths: (1) It can be adopted even with current trains (rolling stock need not be changed); (2) it requires low investments (the cost of the information system needed to implement the strategy is very low compared to the procurement cost of the train); (3) the time needed for its implementation can be low because the system does not require any intervention on the railway infrastructure or rolling stock.

It is necessary to distinguish energy-efficient driving applied to automatic train operation (ATO), where the whole driving speed profile may be designed, from the same strategy applied to human-driven trains, where only some movement parameters can be effectively controlled and optimised. In this document, we focus on energy-efficient driving applied to human-driven trains, which could also be implemented on lines currently in operation, with limited monetary investments.

Energy efficiency has been extensively studied mainly from a technological point of view. Indeed, technology is constantly evolving, and urban rapid transit systems are now managed with a high degree of automation, improving reliability and safety in rail traffic control [9]; such automation can introduce energy-efficient driving strategies [10]. Automatic train operation (ATO) systems have been widely managed, especially in urban and suburban contexts, by determining optimal speed profiles in terms of running time or energy expenditure [11]. Interesting results have been obtained by loading predefined speed profiles into the system so that, based on the departure time and the minimum running time required, the speed profile that best suits the requirements of the strategy is selected [12]. Other significant results on specific rail systems can be found in Reference [13] on the operation of freight trains, in Reference [14] on the planning of mass rapid transit systems and in Reference [15] on the signalling systems of moving blocks. Optimisation procedures for the definition of energy-efficient speed profiles have also been extensively studied. Some papers have addressed the topic by formulating an optimal control problem [16,17]. Other interesting results on the optimisation of speed profiles were obtained in References [18–28].

New information technologies, together with the continuous evolution of optimisation algorithms and the opportunity offered by new ICT, have recently pushed many studies to implement different solutions that lead to very interesting results and prospects [29–33]. Concerning train/driver interaction, in Reference [34] the author proposed energy-optimal train control, based on a two-level algorithm that leads to the energy-optimal regime sequence with the minimum number of regime changes, to be easily followed by the driver.

Timetable reprogramming procedures and algorithms are often used jointly with eco-driving strategies [35,36]; Especially to reallocate train starts or acceleration regimes to coincide with the braking regime of other trains within the same powered section to optimise the use of recovered energy that would otherwise be dissipated in heating resistors [37]. Further, in Reference [38] the authors proposed an optimisation procedure which first optimises the speed profiles of each train and then increases the receptivity of the network to achieve a compromise between efficient speed profiles and regenerated energy maximisation. In Reference [39], the authors proposed several efficient on-board recovery systems that allow train operations to be independent of other train regimes. In References [40,41], the authors adopted a microscopic approach to analyse the effects of different driving strategies in terms of energy consumption.

This paper extends the authors' research into driving speed profile optimisation [42], proposed at the 20th IEEE International Conference on Environment and Electrical Engineering (IEEE EEEIC 2020) and 4th Industrial and Commercial Power Systems Europe (I&CPS 2020). The above work was enhanced by extending the description of the problem and the case study, which were tackled by using a simulation-based methodology. This innovation also allowed stochastic aspects to be considered, neglected with the resolution of the optimisation problem. Use was made, in particular, of the general-purpose simulation software Arena in which the case study was implemented. Therefore, the final results were also extended.

However, in contrast to the existing literature where the problem has been studied almost exclusively for suburban and regional railways, this work focuses on the case of urban metro lines, where the lengths of the sections (i.e., the distances between two successive stations) are usually less than 2 km. In this case, as will be clearer in the next section, the strategies of running management are significantly different from the case of suburban and regional railways.

The paper is organised as follows: Section 2 examines the problem, highlighting the differences with the cases already covered in the literature; the mathematical formulation of the optimisation model is reported in Section 3; Section 4 illustrates the case study; Section 5 summarises the numerical results; finally, Section 6 concludes the work and outlines research prospects.

2. Problem Description

Energy-efficient driving on rail systems aims to save traction energy by optimising the running profile on a section between two stations or along a route. In this case, we operate only on the train speed profiles along the section. As mentioned in Section 1 and shown in the literature, good results can be achieved both by fully automatic train control and by acting on driving behaviour, providing the driver with the necessary information in real-time to get as close as possible to the optimal driving pattern.

For suburban and regional services, where stations are usually more than 2 km apart, it is assumed that the scheduled timetable, and hence, the departure time of each train from each station are known. Scheduled timetables are designed so that the departure time from a station is equal to the departure time from the previous station plus the minimum running time, *mrt*, between stations, plus the dwell time (necessary for passengers to board and alight), *dt*, plus the reserve time, *rt* (see Figure 1). The reserve time is provided to recover a possible delay of a train so that the departure time from the next station is respected (if the delay is less than the scheduled reserve time). Details on the definition of dwell time can be found in Reference [43]; similarly, the reserve time calculation is shown in Reference [44].

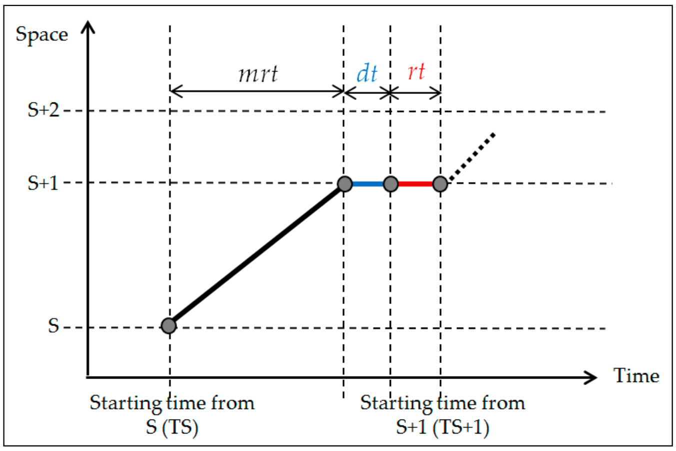

Figure 1. Scheduled timetable scheme. *mrt*, minimum running time; *dt*, dwell time; *rt*, reserve time.

If a train departs late, the driving style must ensure the minimum running time, i.e., maximum acceleration, maximum cruising speed and maximum deceleration (compatible with comfort standards, speed limits and available power). This driving style is also known as time-optimal (or all-out) and is the driving style with the maximum energy consumption; in Figure 2 an all-out driving profile is schematically shown, where t_{acc} is the duration of the acceleration phase, t_{cru} is the duration of the cruising phase, t_{dec} is the duration of the deceleration phase, and sp^{max} is the maximum travel speed.

By contrast, if the train is on time, the reserve time can be used to optimise the driving style to minimise energy consumption. Indeed, reducing the cruising speed and/or introducing a coasting phase (the propulsion system is turned off and the train runs using kinetic energy, reducing its speed) allows energy consumption to be reduced. In Figure 3, two possible energy-saving driving styles are reported: (a) With a coasting phase; (b) without a coasting phase. In Figure 3, besides the already defined terms, t_{coa} is the duration of the coasting phase, and sp^{cru} is the (optimised) cruising speed.

Compared to the case of regional or suburban services, metro lines have two different characteristics that require us to formulate the problem differently. First of all, reserve time is not available at each section because the service is not schedule-based but frequency-based: The operator will try to respect only the departure times from the terminals, to maintain the expected headway, but no departure time is defined at each station. Consequently, the reserve time is provided only at terminals (see Figure 4). The second difference concerns the substantial impossibility of operating an energy-saving driving style with coasting, given the short length of the sections; only with a fully automated train would it be possible. In the next section, an optimisation model based only on speed optimisation is proposed.

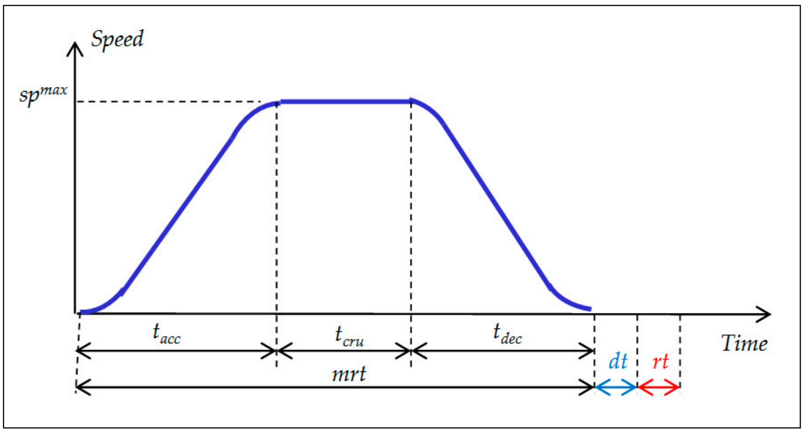

Figure 2. Time-optimal driving style. t_{acc}, the duration of the acceleration phase; t_{cru}, the duration of the cruising phase; t_{dec}, the duration of the deceleration phase; sp^{max}, the maximum travel speed.

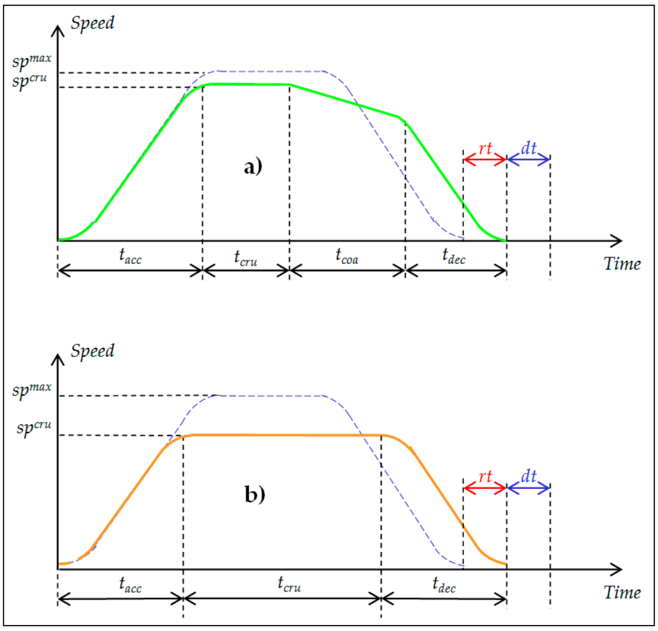

Figure 3. Energy-saving driving styles: (**a**) With a coasting phase; (**b**) without a coasting phase. t_{coa}, the duration of the coasting phase; sp^{cru}, the (optimised) cruising speed.

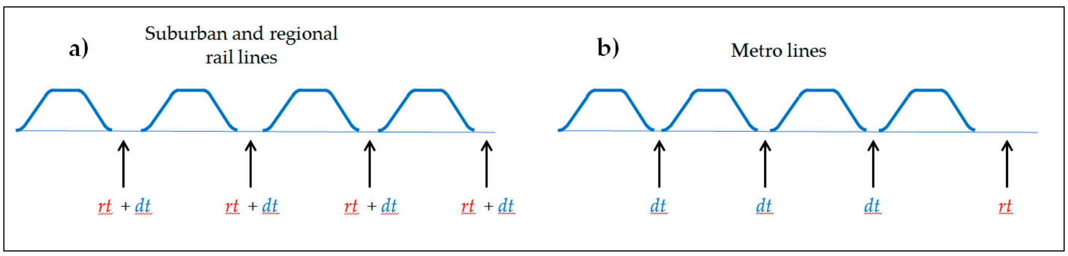

Figure 4. Reserve times for suburban and regional lines (**a**) and metro lines (**b**).

3. Optimisation Model

Although the problem of eco-driving on suburban and regional railway lines has been widely addressed in the literature [22–27], to our best knowledge there has been no specific coverage of metro lines, except for the paper that we are now extending [42].

Herein we assume that, as usually happens, the metro line is frequency-based, reserve time is available only at both terminals, and that the decision variables are only the cruising speeds which the driver must not exceed. The problem, therefore, is to optimise the cruising speeds on the different sections of the line to reduce energy consumption while respecting the departure times from the terminals.

Although not covered in this work, the practical application of the results obtained is possible by training staff and equipping the driver's cab with an intelligent dashboard that communicates with the driver or, if necessary, automatically limits the maximum speed on the section. This speed must, of course, be lower than the maximum technically possible depending on the elevation and curvature characteristics of the track. If the train is late, the dashboard will communicate the maximum possible cruising speed (all-out); if, on the other hand, the train is on time, compared to the expected values, the dashboard will communicate the optimal speed obtained with the procedure.

The problem can be solved by formulating a non-linear constrained optimisation model, where the function to optimise (minimise in this case) is the total traction energy used by the train running on a metro line and the constraints concern the possible speed ranges on each section and the respect of departure times from the terminals. The proposed optimisation model is as follows:

$$\boldsymbol{sp}\hat{} = \text{Arg}_{\,sp} \min E^T(\boldsymbol{sp}) = \text{Arg}_{\,sp} \min \Sigma_i \, E_i{}^T(sp_i) \tag{1}$$

s.t.

$$sp^{min}{}_i \le sp_i \le sp^{max}{}_i \qquad \forall\, i \tag{2}$$

$$\Sigma_{i \in ot}\, t_i(sp_i) \le \Sigma_{i \in ot}\, t_i(sp^{max}{}_i) + RT_{ot} \tag{3}$$

$$\Sigma_{i \in rt}\, t_i(sp_i) \le \Sigma_{i \in rt}\, t_i(sp^{max}{}_i) + RT_{rt} \tag{4}$$

where

$\boldsymbol{sp}$ is the decision variables vector, whose generic element is term sp_i;
sp_i is the cruising speed (m/s) that the train must not exceed when running on section i;
$\boldsymbol{sp}\hat{}$ is the optimal value for $\boldsymbol{sp}$;
$E^T(.)$ is the total traction energy used by a convoy on the metro line for each outward plus return trip;
$E_i{}^T(.)$ is the traction energy used by a metro train on section i;
$sp^{min}{}_i$ is the minimum value of sp_i on section i (m/s);
$sp^{max}{}_i$ is the maximum value of sp_i on section i (m/s), which depends on the features of the railway track and of rolling stock: Such values are those corresponding to a non-optimised (all-out driving style) solution;
$t_i(.)$ is the expected running time (s) of each section i, which depends on sp_i;
ot represents the set of rail sections belonging to a direction of the metro line (for instance, from terminal A to terminal B);
rt represents the set of rail sections belonging to the other direction of the metro line (for instance, from terminal B to terminal A);
RT_{ot} is the reserve time available at terminal B;
RT_{rt} is the reserve time available at terminal A.

Note that $t_i(sp^{max}{}_i)$ is the minimum running time on rail section i (all-out driving style), and in constraints (3) and (4) the dwell times are neglected. Indeed, they are the same in all driving styles and thus, if considered, they cancel each other out in the constraints.

Whatever the resolution method of the model (1–4), we need to know the functions that link traction power consumption and total travel time with the cruising speed value, respectively $E_i^T(sp_i)$ and $t_i(sp_i)$. These functions cannot be generalised, but must be calibrated on each section, taking into account the performance of the rolling stock and the real curvature and elevation track profile. Therefore, we propose that these functions should be calibrated using a microscopic simulation model of railway motion, which can take into account the specific situation of each section and the rolling stock travelling on it. The definition of these functions is thus reported in the next section, where the case study is presented.

4. Case Study

The proposed method was applied to a real case, Line 1 of the Naples Metro. The city of Naples has just under one million inhabitants, is the capital of the region of Campania, and is the third-most populous city in Italy after Rome and Milan. Line 1 is a fundamental infrastructure for urban mobility and connects the northern part of the city with the historic centre and the central station, passing through the densely populated hillside districts. Figure 5 shows the layout of the line, which has 18 stations and 17 sections.

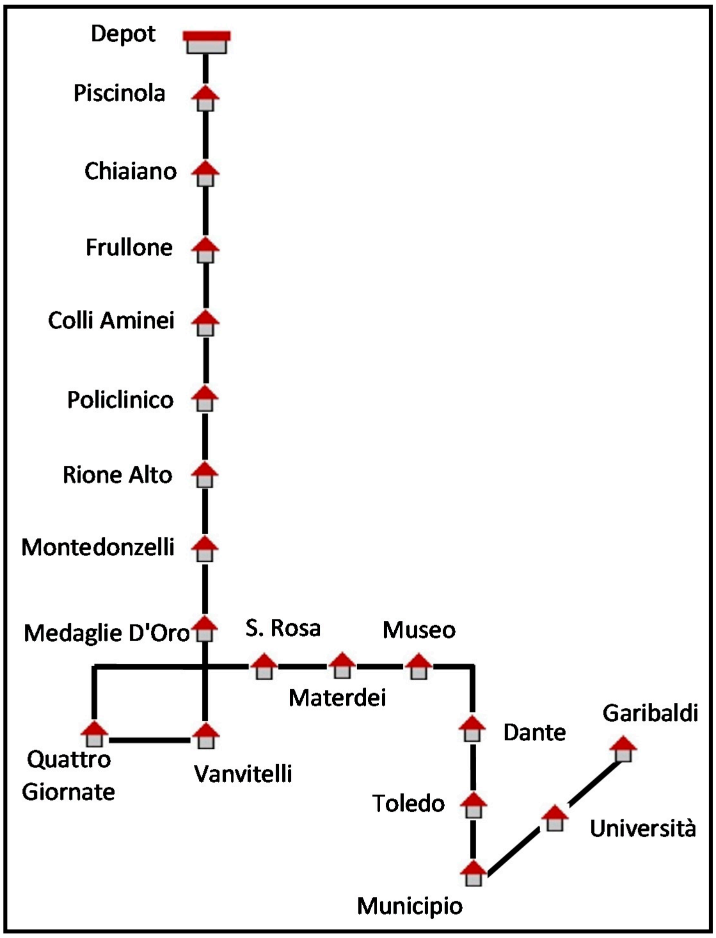

Figure 5. Line 1 of Naples Metro system.

As underlined in the previous section, the functions that link traction energy consumption and travel times to cruising speeds have to be calibrated. To do so, a detailed model of the line was built using OpenTrack railway microsimulation software; Figure 6 shows the graphic representation of the supply model. To build a microscopic simulation model of a rail line, it is generally necessary to reproduce its features in terms of infrastructure, signalling and control systems, rolling stock, timetable and travel demand flows. However, in this specific case, given the fact that the goal is limited to capturing the relationship between speed values on the one hand and related travel times and energy consumption on the other, the modelling of infrastructure features (in terms of slope, curvature radii and tunnel sections) and rolling stock characteristics (in terms of the tractive effort curve) is required. Further, it is worth noting that the simulation model, given its calibration purposes, considers an isolated convoy, and therefore, circulation rules related to the spacing between two successive convoys, dictated by signalling and control systems, are neglected. By contrast, signalling and control issues governing trains entering and leaving stations were accurately modelled.

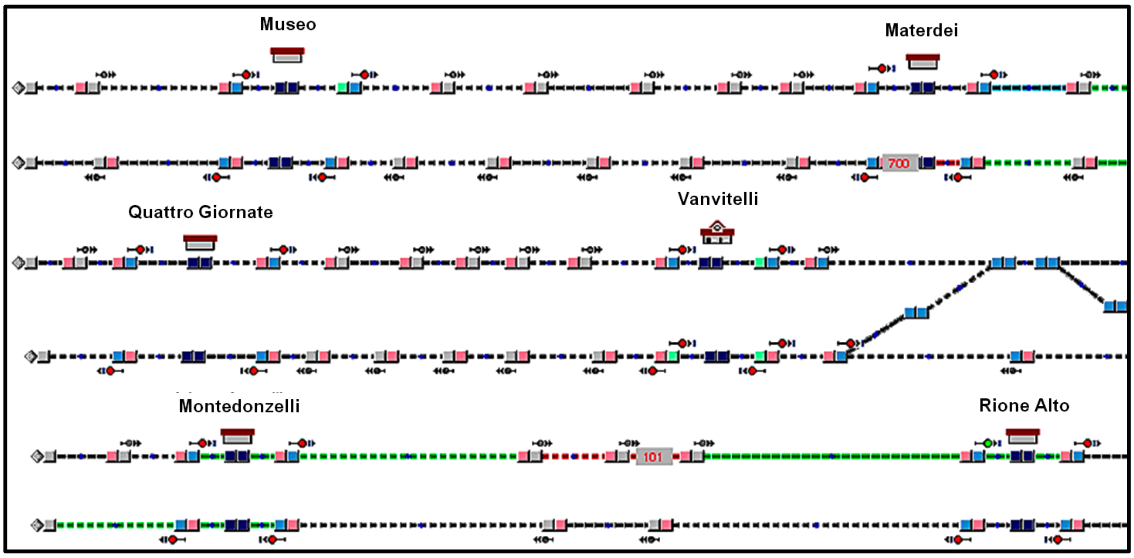

Figure 6. Detail of the supply model implemented in OpenTrack.

Once the model was built, several simulations were performed, considering different maximum cruising speeds, falling within a range between a minimum of 30 km/h and a maximum of 80 km/h, with steps of 2 km/h, for a total of 26 simulated scenarios. The upper limit (80 km/h) takes into account the maximum speed allowed on the fastest section of the line, while the lower limit (30 km/h) is set to avoid excessively long travel times. Clearly, on some sections the maximum value was reduced to take into account the actual maximum speed possible for safety reasons; on other sections, on the other hand, the convoy cannot reach the maximum speed (especially on some uphill sections). For each scenario (cruising speed) and each section, the simulation results were extracted, in terms of travel time and traction energy consumed. These data made it possible to calibrate the functions to be used in the optimisation model.

In Figure 7, some examples of the relationship between travel time and cruising speed are reported; the interpolating functions for each metro section are assumed quadratic:

$$t_i(sp_i) = a_0 + a_1\, sp_i + a_2\, sp_i{}^2 \tag{5}$$

In Figure 8, instead, some examples are reported of the relation between energy consumed and maximum speed resulting from the simulations; the interpolating functions, in this case, are assumed linear:

$$E_i{}^T(sp_i) = b_0 + b_1\, sp_i \tag{6}$$

Tables 1 and 2 report the values assumed by the coefficients for each section. Note that the values of the coefficient of determination are almost always very close to 1, and therefore, the calibrated functions accurately reflect the actual line.

Table 1. Coefficients of Equation (5) for each section.

Section	a_0	a_1	a_2	R^2
Piscinola−Chiaiano	382.58	−7.3153	0.0494	0.995
Chiaiano−Frullone	311.59	−5.9263	0.0412	0.994
Frullone−Colli Aminei	308.64	−5.9925	0.0426	0.995
Colli Aminei−Policlinico	193.63	−3.6940	0.0278	0.993
Policlinico−Rione Alto	137.07	−3.4154	0.0346	0.998
Rione Alto−Montedonzelli	208.99	−4.2972	0.0343	0.993
Montedonzelli−Medaglie d'Oro	277.64	−7.3952	0.0714	0.999
Medaglie d'Oro−Vanvitelli	214.36	−5.4264	0.0522	0.995
Vanvitelli−Quattro Giornate	347.22	−7.659	0.0621	0.994
Quattro Giornate−Salvator Rosa	303.51	−6.3979	0.0490	0.997
Salvator Rosa−Materdei	152.39	−3.0893	0.0258	0.994
Materdei−Museo	319.45	−6.6472	0.0502	0.996
Museo−Dante	129.67	−2.3601	0.0223	0.997
Dante−Toledo	167.81	−3.1315	0.0253	0.993
Toledo−Municipio	155.36	−3.4048	0.0298	0.999
Municipio−Università	165.01	−4.4123	0.0417	0.998
Università−Garibaldi	355.30	−6.8061	0.0470	0.993
Garibaldi−Università	348.93	−6.542	0.0440	0.994
Università−Municipio	165.10	−4.200	0.0417	0.997
Municipio−Toledo	172.21	−4.1688	0.0395	0.998
Toledo−Dante	182.46	−3.7264	0.0322	0.998
Dante−Museo *	73	0	0	−
Museo−Materdei	307.77	−6.5452	0.0507	0.997
Materdei−Salvator Rosa	162.36	−3.5414	0.0312	0.993
Salvator Rosa−Quattro Giornate	296.22	−6.2573	0.0486	0.996
Quattro Giornate−Vanvitelli	308.43	−6.6977	0.0536	0.995
Vanvitelli−Medaglie d'Oro	228.10	−6.2305	0.0631	0.995
Medaglie d'Oro−Montedonzelli	266.19	−7.1081	0.0698	0.998
Montedonzelli−Rione Alto	228.22	−4.9491	0.0409	0.996
Rione Alto−Policlinico	132.20	−3.0712	0.0296	0.994
Policlinico−Colli Aminei	208.79	−4.2971	0.0341	0.994
Colli Aminei−Frullone	324.50	−6.7636	0.0510	0.997
Frullone−Chiaiano	335.00	−6.3842	0.0439	0.994
Chiaiano−Piscinola	367.75	−6.6808	0.0473	0.995

* For this segment the maximum and minimum speeds are 30 km/h.

Table 2. Coefficients of Equation (6) for each section.

Section	b_0	b_1	R^2
Piscinola−Chiaiano	32.130	0.1714	0.970
Chiaiano−Frullone	21.017	0.1877	0.979
Frullone−Colli Aminei	22.536	0.2184	0.918
Colli Aminei−Policlinico	0.386	0.2768	0.986
Policlinico−Rione Alto	−4.451	0.2200	0.959
Rione Alto−Montedonzelli	−3.346	0.1890	0.984
Montedonzelli−Medaglie d'Oro	−4.193	0.2142	0.965
Medaglie d'Oro−Vanvitelli	29.933	0.0333	0.246 **
Vanvitelli−Quattro Giornate	−3.886	0.2088	0.987
Quattro Giornate−Salvator Rosa	−3.645	0.1979	0.985
Salvator Rosa−Materdei	−3.346	0.1890	0.984
Materdei−Museo	−3.275	0.1877	0.984
Museo−Dante	−4.766	0.2306	0.958
Dante−Toledo	−3.823	0.1755	0.981
Toledo−Municipio	−5.336	0.2493	0.958
Municipio−Università	−5.366	0.2503	0.958
Università−Garibaldi	−8.0533	0.4045	0.991

Table 2. *Cont.*

Section	b_0	b_1	R^2
Garibaldi–Università	−0.8627	0.2295	0.961
Università–Municipio	0.2106	0.2315	0.963
Municipio–Toledo	28.198	0.0046	0.029
Toledo–Dante	14.332	–	–
Dante–Museo *	43.570	0.0851	0.850
Museo–Materdei	23.618	0.0102	0.067 **
Materdei–Salvator Rosa	41.334	0.1080	0.957
Salvator Rosa–Quattro Giornate	31.098	0.0812	0.814
Quattro Giornate–Vanvitelli	−3.403	0.1901	0.974
Vanvitelli–Medaglie d'Oro	26.093	0.0528	0.499 **
Medaglie d'Oro–Montedonzelli	34.757	0.0437	0.636
Montedonzelli–Rione Alto	17.031	0.0030	0.006 **
Rione Alto–Policlinico	−5.771	0.2574	0.982
Policlinico–Colli Aminei	−5.633	0.2520	0.980
Colli Aminei–Frullone	−5.524	0.2483	0.991
Frullone–Chiaiano	−5.029	0.2363	0.993
Chiaiano–Piscinola	−8.0533	0.4045	0.991

* For this segment the maximum and minimum speeds are 30 km/h. ** These low values of R^2 correspond to a function with a low variation with a maximum speed (b_2 very low); the corresponding MSE is variable from 0.225 and 0.209.

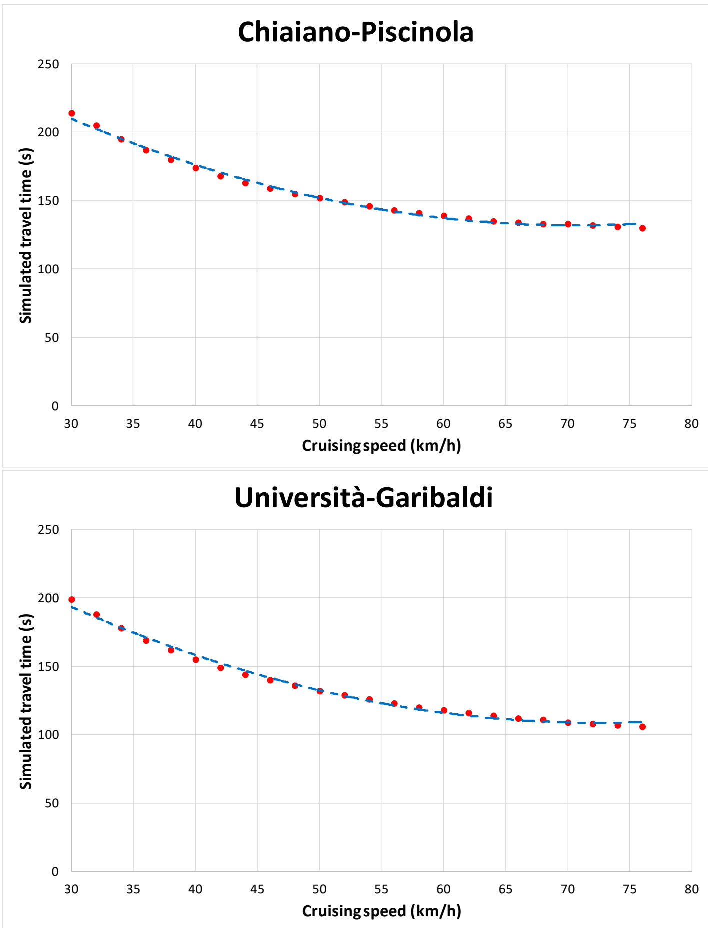

Figure 7. Examples of the relationship between travel time and cruising speed.

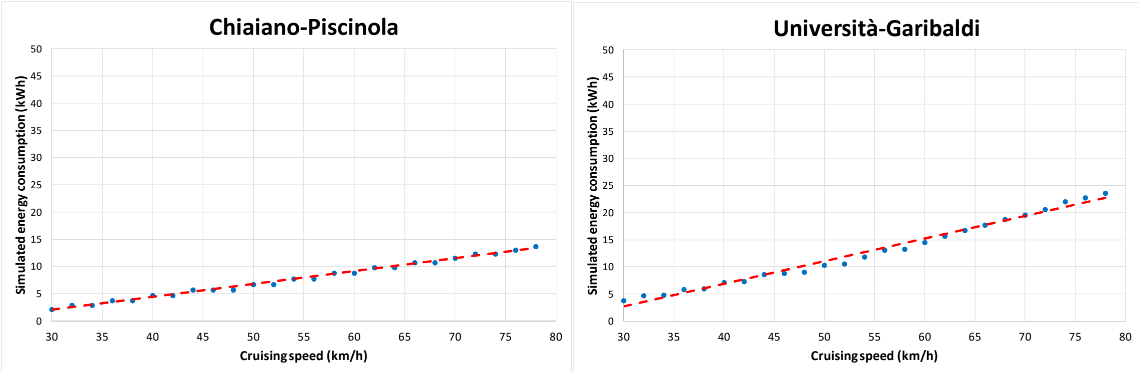

Figure 8. Examples of the relationship between energy consumed and cruising speed.

5. Solution Approaches and Numerical Results

For solving the optimisation model (1–4), we propose two different approaches. The first is based on using a generalised reduced gradient (GRG) algorithm. In this case, the possibility of on-line delays is not considered in any way and the values obtained, thus, represent ideal ones. It is expected that it is not always possible to reach such values because, as stated above, the optimal cruising speed can be used on the section only if the train is not delayed. The second approach consists in implementing the line through a discrete simulation model, built, in our case, with Arena software [45] and Optquest for Arena [46], which is an optimisation module that can be used in Arena. It is thereby possible to include in the model some delay travel time functions on every section and simulate, should the delay of one train be such as to prevent the next train occupying the same section, the propagation of the delay to the following trains. The functions calibrated in Section 4 were used in both cases and the following assumptions, considering the real operation of the metro line, were considered: (i) Dwell times of 20 s at each station; (ii) a reserve time of 240 s at each terminal.

5.1. Results with the GRG Algorithm

The optimisation model (1–4) was implemented in Excel and solved with the GRG algorithm included in the Solver tool. In Table 3, we report the data before optimisation of cruising speeds; in this case, all speed profiles are those corresponding to the minimum running times (all-out). In Table 4, instead, the same data after optimisation are reported; note that the reserve times are entirely used. Indeed, the solution of the problem distributes the reserve time between the rail sections, optimising the maximum speed on each section. Total traction energy consumption decreases from 678.332 kWh to 505.668 kWh, amounting to a reduction of about 25%.

It should be pointed out that this reduction is the most that can be achieved, assuming that there are no delays to be made up along the line. Indeed, when a train has accumulated a delay, the following sections will have to be run assuming the highest value of the maximum speed along the sections until the delay is recovered. The real savings can be assessed based on the regularity of the line. Using the whole reserve time, the number of trains needed for the service is 11, which is the same as the case of all-out driving style. Of course, although the cycle time, which includes the recovery times, is the same, the travel times for users increase up to about 13% (depending on trip length).

Moreover, the optimisation model was also applied to several reserve times to assess how much energy could be saved by increasing the train cycle time, and hence, the time available to implement the energy-saving strategy. The reserve time was, therefore, increased up to 400 s, verifying whether an additional train would need to be put into operation. Table 5 summarises the results obtained.

Table 3. Data before optimisation.

Section	sp^{cru} [km/h]	t_i [s]	dt [s]	rt [s]	$E_i{}^T$ [kWh]
Piscinola-Chiaiano	77	112.19	20		45.328
Chiaiano-Frullone	77	99.54	20		35.470
Frullone-Colli Aminei	77	99.79	20		39.353
Colli Aminei-Policlinico	77	74.02	20		21.700
Policlinico-Rione Alto	45	53.44	20		5.449
Rione Alto-Montedonzelli	65	74.59	20		8.939
Montedonzelli-Medaglie d'Oro	45	89.44	20		5.446
Medaglie d'Oro-Vanvitelli	65	82.19	20		27.769
Vanvitelli-Quattro Giornate	65	111.76	20	240	9.686
Quattro Giornate-Salvator Rosa	65	94.67	20		9.218
Salvator Rosa-Materdei	65	60.59	20		8.939
Materdei-Museo	65	99.48	20		8.926
Museo-Dante	45	68.62	20		5.611
Dante-Toledo	77	76.69	20		9.691
Toledo-Municipio	45	62.49	20		5.882
Municipio-Università	77	87.75	20		13.907
Università-Garibaldi	80	111.61	20		23.722
Garibaldi-Università	77	106.07	20		23.093
Università-Municipio	77	88.94	20		16.809
Municipio-Toledo	45	64.60	20		10.628
Toledo-Dante	77	86.44	20		28.552
Dante-Museo*	30	73.00	20		14.332
Museo-Materdei	65	96.54	20		49.102
Materdei-Salvator Rosa	65	63.99	20		24.281
Salvator Rosa-Quattro Giornate	65	94.83	20		48.354
Quattro Giornate-Vanvitelli	65	99.54	20	240	36.376
Vanvitelli-Medaglie d'Oro	65	89.72	20		8.953
Medaglie d'Oro-Montedonzelli	65	99.07	20		29.525
Montedonzelli-Rione Alto	65	79.33	20		37.598
Rione Alto-Policlinico	65	57.63	20		17.226
Policlinico-Colli Aminei	65	73.55	20		10.960
Colli Aminei-Frullone	65	100.34	20		10.748
Frullone-Chiaiano	77	103.70	20		13.595
Chiaiano-Piscinola	77	133.77	20		13.167
Total			4129.92		678.335

Table 4. Data after optimisation.

Section	sp^{cru} [km/h]	t_i [s]	dt [s]	rt [s]	$E_i{}^T$ [kWh]
Piscinola-Chiaiano	60	121.15	20		42.458
Chiaiano-Frullone	54	111.99	20		31.118
Frullone-Colli Aminei	50	115.59	20		33.447
Colli Aminei-Policlinico	30	107.83	20		8.690
Policlinico-Rione Alto	30	65.75	20		2.149
Rione Alto-Montedonzelli	41	90.84	20		4.354
Montedonzelli-Medaglie d'Oro	40	96.30	20		4.345
Medaglie d'Oro-Vanvitelli	55	73.67	20		28.118
Vanvitelli-Quattro Giornate	48	122.16	20		6.200
Quattro Giornate-Salvator Rosa	49	107.29	20		6.098
Salvator Rosa-Materdei	31	81.82	20		2.462
Materdei-Museo	51	110.49	20		6.363
Museo-Dante	30	78.94	20		2.152
Dante-Toledo	34	90.13	20		2.201
Toledo-Municipio	30	80.04	20		2.143
Municipio-Università	30	76.11	20		2.143
Università-Garibaldi	37	168.76	20		5.457

Table 4. *Cont.*

Section	sp^{cru} [km/h]	t_i [s]	dt [s]	rt [s]	$E_i{}^T$ [kWh]
Garibaldi-Università	30	192.27	20		4.082
Università-Municipio	30	76.63	20		6.022
Municipio-Toledo	30	82.70	20		7.156
Toledo-Dante	57	74.67	20		28.460
Dante-Museo*	30	73.00	20		14.332
Museo-Materdei	55	101.19	20		48.247
Materdei-Salvator Rosa	55	61.97	20		24.178
Salvator Rosa-Quattro Giornate	52	102.65	20		46.915
Quattro Giornate-Vanvitelli	54	103.22	20		35.468
Vanvitelli-Medaglie d'Oro	32	92.99	20		2.710
Medaglie d'Oro-Montedonzelli	47	86.53	20		28.553
Montedonzelli-Rione Alto	54	80.03	20		37.134
Rione Alto-Policlinico	51	52.54	20		17.185
Policlinico-Colli Aminei	30	110.57	20		1.951
Colli Aminei-Frullone	38	140.93	20		3.961
Frullone-Chiaiano	40	148.76	20		4.505
Chiaiano-Piscinola	42	170.41	20		4.912
Total			4129.92		505.669

Table 5. Results with different reserve times (for both terminals).

Reserve Time [s]	Consumption [kWh]	Train Cycle Time [s]	Running Travel Time [s]	Vehicle Number [#]
Non-optimised	678.332	4130	3650	11
240 (480)	505.668	4130	4130	11
260 (520)	501.513	4170	4170	11
280 (560)	497.567	4250	4250	11
300 (600)	493.805	4290	4290	11
320 (640)	490.214	4330	4330	11
340 (680)	486.813	4370	4370	11
360 (720)	483.602	4410	4410	11
380 (760)	480.640	4450	4450	11
400 (800)	477.958	4490	4490	12

These results show that energy consumption may be significantly reduced with appropriate management of metro trains. The energy-saving values, shown in Table 5 (varying from 25% to 30%), are the maximum obtainable (service perfectly regular). However, even if the actual savings were only one-third of the maximum, an 8–10% reduction in energy consumption can be achieved, with a significant benefit in the overall energy balance of a line.

5.2. Results with Arena and Optquest

The outward and return routes of line 1 were modelled with Arena software. A portion of the outward route (sections: Piscinola-Chiaiano, Chiaiano-Frullone) is reported in Figure 9. The modules used to construct the simulation model are as follows:

1. *Create*. This module represents the end of the line; it was set to generate a convoy every 480 s, which is the headway of the line.
2. *Assign*. This module is necessary to record the outward time of the convoy from the terminal to arrive at the other terminal (before arrival there is a *Record* module, not shown in the figure, which is used to record statistics on convoy journey times).

3. *Decide*. This module verifies the occupation of the sections and allows the train to enter the section (module 5) only if the next two sections are empty. Otherwise, the train will have to wait, and in the simulation model, it will be directed to module 4.
4. *Hold*. This module hosts the convoy until the next two sections are empty.
5. *Assign*. This second assign module is used to calculate the traction energy consumption variable on the section. This expression links travel times to consumption and is obtained, on each section, by combining Equation (5) with Equation (6) to obtain a relation between consumption and travel time.
6. *Process*. This module represents the resources, in terms of railway tracks, of the section. The capacity attributed to the module is equal to 1: Only one train can occupy the section at the same time. Moreover, a delay function is included, representing a negative exponential distribution of an average of 7.5% of the total travel time of the section.
7. *Process*. This second process module represents the presence of the train in the station. In this case, the time the train stays in the station is represented by a normal variable of mean 20 s and a standard deviation of 0.2.

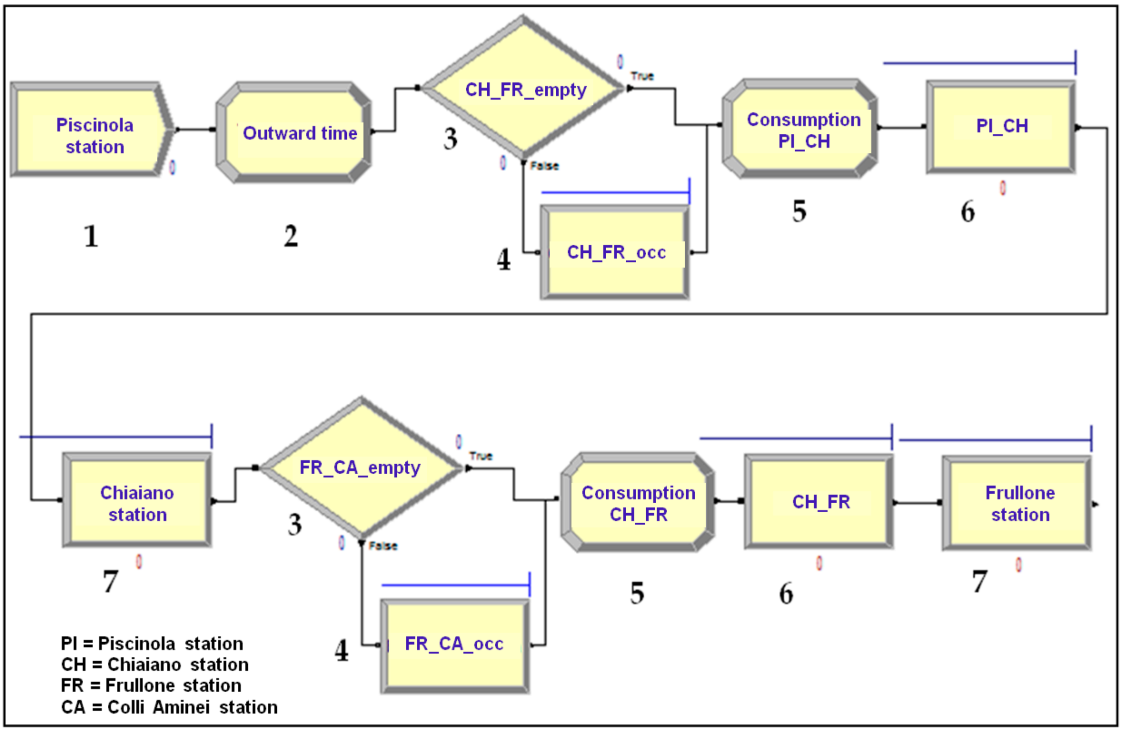

Figure 9. A portion of Line 1 implemented in Arena.

This scheme is replicated for all sections. After the last section, two final modules are inserted: (a) a *Record* module to register the total outward time and an *Assign* module to represent the total consumption variable, equal to the sum of the consumption on each section; (b) a *Dispose* module representing the last station, where the convoy ends its run.

The simulation of the overall system was performed considering 18 h of operation and was repeated 100 times, since the problem has several stochastic aspects (delays on sections and dwell times at stations).

After simulating the outward and return operation of line 1, OptQuest software for Arena was used to optimise energy consumption. The decision variables (or control variables), in this case, are the travel times on each section, clearly as a function of cruising speed, while the objective function is overall consumption along the route. The constraints of the problem are the minimum and maximum travel time (depending on the maximum and minimum speed planned on each section) and the total travel time which cannot exceed the time in all-out conditions plus the reserve time. In this case, we assumed a reserve time of 300 s at each terminal.

In Table 6, we report, the values of consumption and cruising speed before and after optimisation for each section. Upon examining the results, a reduction in consumption was noted, from 661.54 kWh to 495.67 kWh (−25.07%). The reduction is lower with respect to the optimisation approach (−27.20% with a reserve time of 300 s), due to the stochastic effects considered in the simulation approach. It is worth noting that there is no significant difference between the results obtained with the two approaches. This may well be due to the duration of the headway: Given that the latter is 8 min, convoy delays are unlikely to be such as to delay access of the next convoy to a section.

Table 6. Data before and after optimisation.

	Before Optimisation		**After Optimisation**	
Section	E_i^T **[kWh]**	sp^{cru} **[km/h]**	E_i^T **[kWh]**	sp^{cru} **[km/h]**
Piscinola-Chiaiano	44.92	77	44.32	69
Chiaiano-Frullone	35.50	77	31.61	53
Frullone-Colli Aminei	38.80	77	30.83	44
Colli Aminei-Policlinico	19.80	77	12.95	45
Policlinico-Rione Alto	5.59	45	2.45	31
Rione Alto-Montedonzelli	7.68	65	4.58	41
Montedonzelli-Medaglie d’Oro	5.60	45	4.72	40
Medaglie d’Oro-Vanvitelli	27.85	65	16.82	34
Vanvitelli-Quattro Giornate	8.89	65	6.46	48
Quattro Giornate-Salvator Rosa	8.23	65	2.92	34
Salvator Rosa-Materdei	8.44	65	1.21	35
Materdei-Museo	7.67	65	5.69	50
Museo-Dante	5.20	45	4.79	40
Dante-Toledo	7.83	77	2.65	40
Toledo-Municipio	5.36	45	3.50	36
Municipio-Università	13.75	77	2.86	33
Università-Garibaldi	20.97	80	3.98	39
Garibaldi-Università	25.44	77	11.78	39
Università-Municipio	16.42	77	5.80	31
Municipio-Toledo	10.93	45	10.83	44
Toledo-Dante	28.08	77	15.94	32
Dante-Museo*	14.22	30	14.19	32
Museo-Materdei	48.17	65	46.71	44
Materdei-Salvator Rosa	24.05	65	20.24	37
Salvator Rosa-Quattro Giornate	48.45	65	48.15	59
Quattro Giornate-Vanvitelli	35.49	65	35.20	47
Vanvitelli-Medaglie d’Oro	8.80	65	2.07	34
Medaglie d’Oro-Montedonzelli	28.20	65	28.09	40
Montedonzelli-Rione Alto	36.55	65	36.53	48
Rione Alto-Policlinico	16.25	65	13.24	36
Policlinico-Colli Aminei	10.52	65	2.89	34
Colli Aminei-Frullone	11.48	65	10.74	48
Frullone-Chiaiano	12.84	77	8.78	53
Chiaiano-Piscinola	13.61	80	2.11	40
Total	661.54		495.67	

6. Conclusions

Our results show that it is possible to obtain significant reductions in energy consumption by working on driving style. The literature has highlighted this opportunity especially on regional or suburban railway lines (with distances between stations of about 3 to 10 km), in which case the coasting phase can be used to reduce consumption, in addition to acting on the cruising speed of the line. For urban metro lines, it is assumed that it is only possible to act on the cruising speed of the section, given the short distances between stations. The tests reported in this paper, referring to the Naples metro case study, have underlined the possibility of obtaining reductions in traction energy consumption of up to 25%, in the current case, and up to about 30%, if the available reserve time, and hence, the total travel time are increased.

The application of the proposed model is limited to frequency-based lines; other models proposed in the literature (see, for instance [8,35]) must be used for schedule-based services. Clearly, the application of the model to other metro lines requires the recalibration of time and consumption functions and the construction of the corresponding simulation models. Moreover, it is worth accompanying these promising results with the following observations. Against a reduction in energy consumption, an increase in train running time occurs. This has a two-fold implication. On the operational-side, a reduction in the capacity of the line may occur; while, on the demand-side, the greater the train running time, the greater the passengers travel time, with a consequent increase in travellers' discomfort. Considering such a trade-off phenomenon when eco-driving is applied turns out to be, therefore, crucial for making the energy-efficient strategy feasible and effective.

Besides a classic optimisation approach, the problem was also solved by using a simulation model with a tool for optimising variables. The latter permitted the inclusion of stochastic elements in the model, such as in-line delays and the duration of dwell times. The results obtained, relative to a reserve time of 5 min, show a reduction in energy that can be saved (about 25% against about 27% of the classic optimisation model). This result is expected, and the difference for this case study is limited because the line has headways of 8 min. Indeed, in this case, the delay on a route is unlikely to be such as to propagate to the following trains.

Future research will focus on extending the proposed method to other cases, especially those with lower headways and higher mean delays. Besides, the model can be improved by distributing the reserve time according to the distance from the arrival terminal, to prevent the available reserve time being over-consumed in the initial sections and not being sufficient to recover possible delays in later sections.

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