

# Effects of Rolling Stock Unavailability on the Implementation of Energy-Saving Policies: A Metro System Application

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**Abstract.** The recent world policies have shown the necessity of implementing suitable strategies, especially in urban contexts, in order to promote more sustainable transportation systems. In this context, the rail-based systems allow to achieve sustainable goals according to a threefold effect: reduction in externalities (such as congestion, accidents, air and noise pollution), increase in efficiency (in terms of operational cost per real/potential carried passenger), and delocalization of energy production centres (large industrial plants out of population centres producing with optimal yields). Positive environmental aspects of the rail and metro systems may be further amplified by implementing *Energy-Saving Strategies* (*ESSs*) based on the adoption of suitable driving profiles and/or the installation of onboard/wayside recovery devices. In this context, we investigate the effects of rolling-stock unavailability (for breakdowns, maintenance or under-sized fleet) on the effectiveness of ESSs within a multi-objective framework which combines the reduction in energy consumption with a passenger-oriented perspective. A real metro line in the south of Italy has been analysed as case-study in order to show the feasibility of the proposed approach.

**Keywords:** Rail-based public transport · Energy-Saving Strategies · Passenger-oriented approach

## 1 Introduction

The relevance of promoting the adoption of rail-based systems lies in the advantages they offer, both in terms of sustainability and efficiency. Indeed, besides a low environmental impact, such transport mode offers lower operational costs per real/potential carried passenger with respect to other transport systems. As pointed out by [1], one of the major cost items in rail operations is the power supply required for rolling stock and, for this reason, the implementation of energy saving measures, aimed at reducing energy consumption, is of great importance.

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However, in addition to service providers (i.e. infrastructure operators and/or rail service operators) which aim to minimise operational costs, there are the users which, instead, aim to minimise their total travel times. Therefore, they represent two sides of the same coin, whose needs have to be properly balanced. Moreover, as shown by [2,3], the interaction between rail service and involved passenger flows, occurring at the interface train-platform, needs to be properly modelled for an accurate analysis of rail operations. Hence, travel demand not only represents a perspective to be taken into account but also a factor to be considered in the evaluation of rail systems performance. In light of the above, the strict correlation of rail systems with the energy domain, on one side, and the demand domain, on the other side, appears clear [4].

Nevertheless, also the sub-systems mentioned above (i.e. energy and travel demand) are strictly related to each other. Indeed, as shown by [5,6], the implementation of eco-driving strategies, aimed at reducing energy consumption, implies an increase in user travel times. This happens because, in order to adopt an energy-efficient driving behaviour, speed profiles differ by the so-called *Time Optimal* (*TO*) scenario (in which the convoy operates at maximum performance), with an increase in train running times. Such an increase needs to be properly compensated by exploiting specific reserve times set in the timetable structure, thus minimising passenger inconvenience [7,8]. Also, energy recovery strategies based on the use of regenerative braking can be implemented [9–11]. Different approaches have been proposed in the literature for modelling the implementation of energy-saving measures, namely optimisation [12,13], simulation [14,15] and data-driven [16,17] methods. However, such contributions deal with the adoption of energy-saving strategies in ordinary conditions, without considering failure scenarios.

Given the vulnerability of rail transport to system failure, dispatching and rescheduling issues cover a large part of the rail operational research area. In particular, [18] makes a distinction between online and off-line approaches, and between static and dynamic methods. Online interventions are implemented during rail operations and are characterised by short computational times; while, off-line strategies require greater computational times and are performed in advance (even months before). Moreover, static methods are run only once, without any updates when new information arises; while, adjustments to rescheduling solutions on the basis of further available data can be carried out in the case of dynamic procedures. If the timetabling process is intrinsically a static and off-line procedure [19], the most desirable methodology for addressing a rescheduling problem is characterised by a dynamic structure and an online framework [20–23]. Moreover, further preferable conditions for an accurate evaluation of rescheduling issues are represented by a microscopic modelling of the analysed rail system and the assessment of stochastic factors affecting rail service. Instances of microscopic approaches can be found in [24–26]. While, regarding the type of randomness analysed, it can concern train performance [27,28], running and dwell times [29], arrival and recovery times [30,31], delays [32,33], disruption information [34] and travel demand features [35]. The importance of being able to react to perturbed conditions properly lies in the fact that a certain

level of vulnerability to breakdowns characterises each rail system component, such as infrastructure [36,37], signalling and control devices [38,39], and rolling stock [40,41]. For instance, a complete blockage of some rail sections could bring to the interruption of the whole service; while, a failure to the onboard control system could generate only some delays. Unavailability of traction units, instead, could affect the headway between two successive runs or the carrying capacity offered by the line. However, according to the network analysed and the severity of failure addressed, a different solution turns out to be the one which minimises alterations to ordinary service conditions.

In particular, the paper presents a rescheduling methodology which takes into account all three outlined domains (i.e. rail operation, energy and travel demand). Specifically, the implementation of eco-driving speed profiles under rolling-stock disruption conditions is evaluated and a bi-objective framework, combining the reduction in energy consumption with a passenger-oriented perspective, is proposed.

This paper is structured as follows: Sect. 2 focuses on the rolling stock disruption analysis; Sect. 3 shows an application to a real case study of the proposed approach; finally, Sect. 4 provides concluding remarks and future research.

## 2 Rolling Stock Unavailability Analysis

As widely shown in the literature (see, for instance, [6,8]), in the case of rail or metro systems, there is a strong analytical relationship among the service headway (indicated as $H_{serv}$), the number of utilised rail convoys (indicated as $N_{rc}$) and the service cycle time (indicated as $CT_{serv}$), that is:

$$H_{serv} \cdot N_{rc} = CT_{serv} \tag{1}$$

However, it is worth noting that all terms of Eq. (1) are subject to proper constraints.

For instance, in terms of service headway, although this term may theoretically be equal to any value as long as it is positive (i.e. $H_{serv} \in R^{+}$), it has to satisfy some network constraints. Indeed, the infrastructure and the signalling system impose a time spacing between two successive convoys along the line. Likewise, the inversion and recovery times at the terminuses and the terminus layouts may require a time spacing between a departing train and the subsequent arriving rail convoy. These time spacing values impose the identification of a minimum headway value, indicated as $H_{min}$, which has to constrain the service headway value as follows:

$$H_{min} \leq H_{serv} \tag{2}$$

Likewise, in the case of the number of utilised rail convoys (i.e. term $N_{rc}$), once fixed the cycle time and the service headway, it can be univocally calculated using Eq. (1). However, for physical considerations, it is necessary to impose that $N_{rc}$ has to be a positive integer number (i.e. $N_{rc} \in Z^{+}$).

Finally, the service cycle time may be defined as the total time that a rail convoy spends for the outward trip (including all stops at stations), for all inversion and recovery operations at the outward terminus, for the subsequent return trip (including all stops at stations) and for all inversion and recovery operations at the return terminus. Hence, each train is in the same condition after an interval equal to the cycle time. However, as shown by [6], besides these physical times (i.e. travel times between two successive stations, dwell times at stations and inversion times at terminuses), it is necessary to consider two further time categories: the buffer and the layover times. The former ones are additional times adopted for recovery delays due to the variability of travel, dwell and inversion times. The latter ones express the time spent at the red signal of the initial stations waiting for the departure time according to the planned timetable.

These three constraints mentioned above provide further implications in terms of the feasibility of operational schemes. Indeed, for instance, once fixed service headway $H_{serv}$, since $N_{rc}$ has to belong to $Z^+$, it implies that layover times in the cycle time cannot be arbitrary, but have to be fixed so to satisfy Eq. (1). Likewise, the value of the layover times (conditional to the terminus layouts) may affect the inversion time and, therefore, the minimum headway $H_{min}$ which, in turn, affects value $H_{serv}$ by means of Eq. (2). Finally, the sum of layover times and buffer times cannot exceed term $H_{serv}$, since they represent train stop times.

However, D'Acierno et al. [6] have shown a procedure for determining the feasible operational schemes which satisfy all abovementioned constraints.

In order to increase the sustainability of rail and metro systems, as widely shown in Sect. 1, many authors have proposed the adoption of numerous Energy Saving Strategies (ESSs) where some of them are based on the definition of proper driving speed profiles. As already mentioned, an eco-driving behaviour requires lower energy consumptions but implies higher travel times. In this context, D'Acierno and Botte [8] proposed a bi-level optimisation model for determining the optimal compromise between energy reductions and travel time increases by preserving service headway in a passenger-oriented perspective. In particular, their proposal consisted of adopting layover times as reserve time for compensating travel time increases.

Our contribution represents an advance of the research provided by [6] and [8], since it concerns the analysis of eco-driving strategies within a disruption framework. Specifically, the failure analysed is related to a rolling stock unavailability condition. In order to evaluate breakdown effects, preliminary, it is necessary to identify two kinds of passenger convoy configurations:

- traditional rail convoys consisting of locomotives hauling passenger carriages;
- railcars consisting of self-propelled passenger vehicles which may travel also coupled in multiple units.

Indeed, in the first case, whether the unavailability concerns some passenger carriages, it is possible to preserve the number of rail convoys $N_{rc}$ and, therefore, the service headway $H_{serv}$ according to Eq. (1). Obviously, some (or all) rail

convoys will be shorter with a lower passenger capacity. By an optimisation perspective, shorter rail convoys will require lower energy consumptions but, in some cases, passengers could not be able to board the first arriving train, increasing their waiting time.

On the contrary, whether the unavailability concerns some locomotives, it is not possible to preserve the number of convoys $N_{rc}$ and, therefore, it is necessary to adopt lower service frequencies (i.e. higher service headways according to Eq. 1), which imply a reduction in service carrying capacity, being calculated as:

$$Cap_{serv} = \frac{Cap_{conv}}{H_{serv}} \tag{3}$$

where $Cap_{serv}$ is the service capacity and $Cap_{conv}$ is the convoy capacity. Obviously, the higher the service headway, the higher the waiting time of passengers. Moreover, also in this case, the reduction in carrying capacity may imply the impossibility, for some passengers, to board the first arriving train by further increasing their waiting time. However, this last negative effect could be smoothed by increasing (if possible) the length of working trains by adding to them the passenger cars of the broken convoys. Finally, in terms of energy consumption, the reduced number of rail convoys and the higher value of service headway require a lower amount of energy consumption.

In the second configuration (i.e. when rail convoys consist in railcars), the unavailability of rolling stock may generate three possible rescheduling service schemes:

a. the number of rail convoys $N_{rc}$ is preserved, the service headway $H_{serv}$ is preserved and the length of some (or all) rail convoys is reduced;
b. the number of rail convoys $N_{rc}$ is reduced, the service headway $H_{serv}$ is increased (according to Eq. 1) and the length of all rail convoys is preserved;
c. the number of rail convoys $N_{rc}$ is increased, the service headway $H_{serv}$ is reduced (according to Eq. 1) and the length of some (or all) rail convoys is reduced.

The feasibility of each of the three abovementioned configurations is related to the initial number of railcars, train composition (i.e. the number of railcars for any convoy) and the failure severity (i.e. the number of unavailable railcars). However, in this case, by an optimisation perspective, it is not possible to state a priori which of the three abovementioned functional scheme is the optimal one, since:

– shorter rail convoy provides a lower train capacity and, therefore, some passengers could be not able to board the first arriving train and forced to wait for a subsequent rail convoy;
– the increase in service headway imposes an increase in passenger waiting times and, vice versa, the reduction in service headway implies a reduction in passenger waiting times;

– in a railcar configuration, the amount of required energy depends on the total number of railcars riding jointly on the network and, therefore, unavailability conditions ensure the reduction in energy consumptions with respect to the condition of full availability.

Thus, in this paper, we propose to analyse the rolling stock unavailability in the case of convoys based on the railcar configuration in order to verify the feasibility of the abovementioned service schemes and the related implications in the case of implementation of ESSs.

## 3 Application to a Real Metro Line

In order to show the effects of rolling stock failures in the case of *Energy Saving Strategy* (*ESS*) implementation, we have applied the proposed analysis method in the case of a real metro line: Line 1 of the Naples metro system in Italy. Main details of the line and its service can be found in [6]. However, the service is performed by railcars which may be coupled up to 3 multiple units.

The line was inaugurated in 1993 with an initial length of about 4 km. Over the years, it has been progressively extended up to the current length of 18 km. Obviously, the higher the line length, the higher the cycle time since travel times increase. Hence, according to Eq. (1), to preserve the service headway $H_{serv}$, it is necessary to adopt a higher number of rail convoys $N_{rc}$.

In 1993, the initial fleet consisted of 45 railcars, named as '*Unit of Tractions* (*UoT*)', which allowed to provide 15 triple-header rail convoys. Now, after 23 years, in the absence of fleet renewal, due to maintenance reasons, we may assume that the service is performed by using 8 double-header convoys (i.e. 16 traction units) per day with a service headway equal to 10 min. This condition represents the scenario 1 (i.e. the ordinary condition) in the following application.

Our analysis consists in considering that, during an average working-day, a failure occurs by implying the breakdown of a double-header convoy so that the working number of traction units becomes 14. Hence, assuming that all rail convoys should have the same number of railcars for operational uniformity issues, we can consider two possible operational schemes:

– Scenario 2 with 7 rail convoys consisting in double-header convoys (i.e. service scheme *b*, with a reduced number of rail convoy, an increased service headway and a fixed train length);
– Scenario 3 with 14 rail convoys consisting in single-header convoys (i.e. service scheme *c*, with an increased number of rail convoy, a reduced service headway and a reduced train length).

Hence, having fixed the service cycle time $CT_{serv}$, using the approach proposed by [6], we are able to identify two corresponding service frequencies and related operational parameters as shown in Table 1. In particular, Scenario 2, based on rescheduling service scheme *b*, provides a service headway higher than

**Table 1.** Service parameters in the analysed scenarios.

| Analysed scenario [#] | Total traction units [#] | Number of units per convoy [#] | Total number of convoys [#] | Service headway [min] | Total layover time [min] |
|---|---|---|---|---|---|
| 1 | 16 | 2 | 8 | 10.0 | 3.8 |
| 2 | 14 | 2 | 7 | 11.0 | 0.8 |
| 3 | 14 | 1 | 14 | 5.5 | 0.8 |

Scenario 1 (i.e. 11.0 min); likewise, Scenario 3, based on rescheduling service scheme *c*, provides a service headway lower than Scenario 1 (i.e. 5.5 min).

However, by performing the optimisation procedure proposed by [8] (based on the use of OpenTrack® micro-simulation software [42] and an ad-hoc optimisation tool) for implementing the ESSs, we obtained results described in Tables 2, 3, 4, 5 and 6. Moreover, it is necessary to highlight that, since the reduction in transportation service generally provides a reduction in travel demand, it is necessary to calculate travel times and objective function values in terms of average values per carried passenger and not as a total value. Likewise, variations in train compositions (i.e. double-header vs single-header convoys) require the estimation of service performance indicators such as the daily distance in terms of railcars and not only in terms of rail convoys.

In particular, Table 2 shows that the reduced number of working railcars implies a reduction in the daily round runs (from 95 to 87) in the case of Scenario 2. However, although the adoption of single-header convoys (i.e. Scenario 3) allows increasing the number of daily round runs (from 95 to 173), in terms of daily distance (expressed in terms of railcar-km), as well as in terms of operational costs, both rescheduling scenarios provide similar results.

**Table 2.** Operational parameters in the analysed scenarios.

| Analysed scenario [#] | Daily round runs [#] | Daily distances [convoy-km] | Daily distances [railcar-km] | Daily operational cost [€] |
|---|---|---|---|---|
| 1 | 95 | 3,151 | 6,301 | 114,491 |
| 2 | 87 | 2,885 | 5,771 | 104,850 |
| 3 | 173 | 5,737 | 5,737 | 104,247 |

Table 3 shows that rescheduling scenarios requiring lower layover times (as shown in Table 1) allow to increase the service duration by a total of 12 min (6 min per direction). Hence, although they represent scenarios in disruption conditions (i.e. with a lower availability in railcars), as shown in Table 6, it is possible to attract slightly higher demand values (i.e. +0.18%).

**Table 3.** Daily service duration in the analysed scenarios.

| Analysed scenario [#] | First run/Last run in the outward trip [hh:mm] | First run/Last run in the return trip [hh:mm] |
|---|---|---|
| 1 | 06:00/21:40 | 06:43/22:23 |
| 2 | 06:00/21:46 | 06:39/22:25 |
| 3 | 06:00/21:46 | 06:40/22:26 |

**Table 4.** Speed limit effects in the analysed scenarios.

| Analysed scenario [#] | Speed limit in the outward trip [km/h] | Speed limit in the return trip [km/h] | Travel time increase in the outward trip [min] | Travel time increase in the return trip [min] |
|---|---|---|---|---|
| 1 | 47 | 76 | 3.5 | 0.0 |
| 2 | 77 | 61 | 0.0 | 0.7 |
| 3 | 66 | 65 | 0.4 | 0.3 |

**Table 5.** Energy parameters in the analysed scenarios.

| Analysed scenario [#] | Consumed energy in the outward trip [kWh/convoy] | Consumed energy in the return trip [kWh/convoy] | Daily consumed energy [kWh] | Daily consumption in Time Optimal condition [kWh] |
|---|---|---|---|---|
| 1 | 139.3 | 257.0 | 37,648 | 42,029 |
| 2 | 184.9 | 241.6 | 37,109 | 38,489 |
| 3 | 86.2 | 124.5 | 36,454 | 38,268 |

**Table 6.** Travel demand parameters in the analysed scenarios.

| Analysed scenario [#] | Number of carried passengers [#] | Average passenger travel time [min/pax] | Average passenger waiting time [min/pax] | Average objective function value [€/pax] |
|---|---|---|---|---|
| 1 | 202,062 | 13.7 | 8.9 | 3.03 |
| 2 | 202,431 | 13.2 | 18.5 | 4.99 |
| 3 | 202,431 | 13.2 | 15.9 | 4.44 |

Table 4 shows that both rescheduling scenarios (i.e. Scenario 2 and 3) provide similar reductions in travel time increases (i.e. 0.7 min as the sum of values related to the outward and the return trips), even if distributed differently between the outward and the return trip.

Table 5 provides the required mechanical energies. In particular, in *Time Optimal* condition, a railcar (i.e. a single-header convoy) requires 92.5 kWh and 128.7 kWh, respectively, in the outward and the return trip. Obviously, in the case of double-header convoys, these values become 184.9 kWh and 257.5 kWh. However, the implementation of ESSs provides a reduction in energy consumption equal to 10.4% in the case of Scenario 1 (ordinary condition) which has to decrease to 3.6% and 4.7% in the case of rescheduling scenarios (i.e. Scenario 2 and 3) for compensating waiting time increases (respectively, +157% in the Scenario 2 and +121% in the Scenario 3), as shown by Table 6.

Finally, in terms of optimal intervention strategy, Table 6 highlights that the adoption of shorter trains with a higher service frequency (i.e. Scenario 3) allows reducing the waiting time increase (from 18.5 min to 15.9 min) and the corresponding objective function value (from 4.99 € to 4.44 €).

## 4 Conclusions and Research Prospects

The adoption of *Energy Saving Strategies* (*ESSs*) based on the definition of proper driving speed profiles allows reducing energy consumptions by increasing travel times. Hence, it is necessary to identify an optimal compromise between a reduction in energy consumption and a worsening in transportation system performance, to avoid negative effects on passengers.

In this context, we have investigated the effects of rolling stock unavailability on the definition of ESSs. Indeed, in case of breakdown related to rolling stock, since the ordinary service (in terms of headway, number of convoys and train length) may be unfeasible, it is necessary to reschedule rail operations according to the residual working fleet. Obviously, the new feasible service configurations may have different optimal conditions in terms of ESS implementation.

To confirm these statements, we have analysed a breakdown condition in the case of a metro line whose fleet is based on railcars. In particular, we have simulated a disruption which implies the reduction of available convoys by identifying two possible feasible alternatives: a decrease in service frequency by preserving train lengths and a decrease in train length by increasing service frequencies. Both solutions were able to provide similar performance in terms of service capacities (difference lower than 0.57%), carried passengers (same value), daily consumed energy (difference equal to 1.76%), increase in cycle time (difference equal to 1 second) and average travel time (difference equal to 0.3%). However, due to different convoy capacities, the solution based on single-header convoys was able to provide an increase in the objective function (which represents the total cost of the system per carried passenger) equal to 65.4% with respect to the ordinary condition; while, in the case of double-header convoys, the objective function increase was equal to 85.7% (i.e. a difference in objective function increase equal to 20.3%).

These results show that, although many indicators may assume similar values, slight differences weighted on the passenger flows of a metro system may provide significant global differences. Hence, it is necessary to have suitable analytical tools for estimating these differences in order to identify the optimal scenario in terms of reductions of negative impacts on passengers.

As research perspective, we propose to analyse different breakdown severities by adopting different initial scenarios, both in terms of service performance (i.e. different initial service frequencies) and in terms of network complexity (i.e. different rail networks such as regional or national railways). Finally, we propose to investigate the effects of mitigation strategies based on the adoption of heterogeneous fleet compositions (such as some double-header convoys alternated with single-header convoys).

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