A methodological approach for managing rail disruptions with different perspectives

Luca D'Acierno, Antonio Placido, Marilisa Botte, and Bruno Montella

Abstract**—**Public transport systems represent a potentially effective tool for managing mobility in urban and metropolitan areas. In particular, especially in high density contexts, rail systems can be adopted as the backbone of transportation services. However, rail systems are also somewhat vulnerable to system failure since, for instance, a faulty train cannot be easily removed or overtaken. Hence, our proposal is to develop an off-line procedure based on a microsimulation approach for analysing the most frequent breakdown conditions and suggesting the adoption of optimal intervention strategies. Finally, different perspectives (i.e. requirements of passengers and rail operators) are proposed and applied in the case of a real metro line in the south of Italy.

Keywords**—**Failure mitigation, microscopic railway simulation, public transport management, travel demand analysis.

I. INTRODUCTION

IN urban contexts, efficient management of travel demand is one of the key elements to ensure high levels in quality of life (see, for instance, [1] and [2]). Hence, it is necessary to plan, design, construct and operate a large number of transportation systems so as to direct users, who tend to maximise their own utility, towards sustainable transport modes. Indeed, especially in areas with high population densities, the limited availability of spaces for travelling (roads) and stopping (parking areas) makes the promotion of public transport the main tool for ensuring the reduction in negative externalities such as congestion, accidents, energy consumption, and air and noise pollution ([3]–[5]). Hence, a rail or a metro system with its high performance in terms of reduced travel times and high passenger capacity (mainly due to exclusive lanes, constrained drive and signalling systems) ensures strong competition with the road system. However, such strengths can also become weaknesses since, in the event of a failure (such as a breakdown of a convoy or a reduction in maximum speed of a line/track section), re-establishing ordinary operative conditions could require a very long time with substantial delays for passengers. *Decision Support Systems* (DSSs) should therefore be developed and implemented so as to enable dispatchers to identify optimal intervention strategies with a view to minimising user discomfort.

However, due to the complexity of interactions among the various components of a rail/metro system (i.e. infrastructure, rolling stock, signalling system, timetable and travel demand), it is worth adopting a micro-simulation approach to identify the optimal corrective actions to be implemented (see, for instance, [6]).

In terms of methodology, as widely shown by [7]–[9], the main focus in managing rail systems, especially in the past, was the analysis of performance and related capacities whilst neglecting the main effects on travel demand. However, as pointed out by several recent contributions, such as [10] and [11], one of the main aims of a rail system is to satisfy passenger requirements. In this context, [12] and [13] proposed a new method to determine train schedules, taking into account rail travel demand and possible service disruptions; [14] and [15] introduced innovative optimisation frameworks for rescheduling rail services in the case of perturbations. Moreover, the deviation of real timetables from planned schedules has been extensively analysed: [16] proposed an off-line procedure for calibrating a predictive model, [17] provided an estimation method of delay propagations, and [18] proposed a tool for resolving conflict in real-time conditions. Finally, optimisation of maintenance planning was analysed by [19].

In this paper we propose an extension of the authors' research in managing rail system breakdowns (see [6], [20] and [21]) by analysing the same failure context from two different perspectives and comparing results in terms of optimal intervention strategies to be applied.

The paper is organised as follows: Section 2 provides the analytical formulation of the problem and describes the two viewpoints adopted; Section 3 applies the proposed approach in the case of a real metro line; finally, conclusions and research prospects are summarised in Section 4.

II. ANALYTICAL FORMULATION

The problem of identifying the optimal intervention strategy in the case of rail/metro system breakdown can be formulated as a multidimensional constrained bi-level optimisation model,

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that is ([21] and [22]):

$$\hat{\boldsymbol{y}} = \arg\min_{\boldsymbol{y} \in \boldsymbol{S}_y} Z\left(\boldsymbol{y}, \boldsymbol{utt}, \boldsymbol{uf}, \boldsymbol{rtm}, \boldsymbol{in}, \boldsymbol{rs}, \boldsymbol{rc}\right) \text{ .} \tag{1}$$

subject to:

$$\left[\boldsymbol{utt}, \boldsymbol{uf}, \boldsymbol{rtm}, \boldsymbol{rc}\right] = \boldsymbol{\Lambda}\left(\boldsymbol{y}, \boldsymbol{in}, \boldsymbol{rs}, \boldsymbol{ss}, \boldsymbol{ptm}, \boldsymbol{td}\right). \tag{2}$$

with:

$$\left[\boldsymbol{in}, \boldsymbol{rs}, \boldsymbol{ss}\right] = \boldsymbol{FM}\left(\boldsymbol{fc}, \boldsymbol{in}^0, \boldsymbol{rs}^0, \boldsymbol{ss}^0\right). \tag{3}$$

where $\boldsymbol{y}$ is the vector describing the intervention strategy to be implemented, $\hat{\boldsymbol{y}}$ is the optimal value of $\boldsymbol{y}$; $\boldsymbol{S}_y$ is the feasibility set of $\boldsymbol{y}$; Z is the objective function to be minimised; $\boldsymbol{utt}$ is the vector describing user travel and waiting times; $\boldsymbol{uf}$ is the vector describing user flows; $\boldsymbol{rtm}$ is the vector describing the real timetable of the rail service; $\boldsymbol{in}$, $\boldsymbol{rs}$ and $\boldsymbol{ss}$ are the vectors describing respectively the infrastructure, rolling stock and signalling system conditions in the failure context analysed; $\boldsymbol{rc}$ is the vector of residual capacities of rail convoys; $\boldsymbol{\Lambda}$ is the simulation function which provides inputs for the calculation of objective function Z; $\boldsymbol{fc}$ is the vector describing the failure context analysed; $\boldsymbol{ptm}$ is the vector describing the planned timetable; $\boldsymbol{td}$ is the vector describing the travel demand; $\boldsymbol{in}^0$, $\boldsymbol{rs}^0$ and $\boldsymbol{ss}^0$ are vectors describing respectively the infrastructure, rolling stock and signalling system conditions in the unperturbed context; $\boldsymbol{FM}$ is the failure model function which provides infrastructure, rolling stock and signalling system conditions depending on the failure context analysed and their performance in the unperturbed condition.

Equation (2) represents a consistency constraint between transportation system performance and travel demand flows, which can be formulated by means of the interaction of different kinds of models. However, as shown by [6] and [21], the aim of these models is to determine the input data of the objective function since:

- the number of passengers arriving on the platform depends on performance of the whole transportation system including the rail system. Details on methodologies for estimating these flows can be found in [23]–[27];
- the number of passengers boarding arriving trains depends on the number of users waiting on the platform (which depends on the passenger arrival rate and service headways of trains) and residual capacities of rail convoys. However, details on formulation and simulation of user behaviours can be found in [20], [28]–[34];
- headways, travel times and residual capacities of rail convoys depend on the intervention strategy implemented and rail system performance. This task can be implemented via microsimulation software (such as OPENTRACK®, [35]), which is based on the solution of a system of differential equations (equation details can be found in [36]).

Equation (3) represents the analytical formulation of a failure model which provides, for each feasible breakdown context, the related reductions in infrastructure, rolling stock and signalling system performance. Outputs in this case may consist, for instance, in maximum speed reduction or the unavailability of a train or a track section. This model is based on the cause-effect relation between the faulty element and the operations of all systems. Details on the management of breakdowns are analysed by RAMS (*Reliability*, *Availability*, *Maintainability and Safety*) procedures as shown by [37] and [38].

In this paper, the solution of problem (1) was performed by adopting two different perspectives for comparison in terms of optimal intervention strategies. The first approach consists in minimising user discomfort expressed in terms of user generalised cost. Hence the related objective function is formulated as follows:

$$Z_1(\cdot) = vot \cdot \left(UWT + UTT\right). \tag{4}$$

with:

$$UWT = \sum_s \sum_p \sum_r \beta_w \cdot tw_{s,p}^r\left(\boldsymbol{utt}\right) \cdot ufw_{s,p}^r\left(\boldsymbol{uf}\right). \tag{5}$$

$$UTT = \sum_l \sum_r \beta_{ob}\left(\boldsymbol{uf}, \boldsymbol{rc}\right) \cdot tb_l^r\left(\boldsymbol{utt}\right) \cdot ufb_l^r\left(\boldsymbol{uf}\right). \tag{6}$$

where vot is a parameter which expresses the monetary value of time in terms of *€/h*; UWT is the total user waiting time whose formulation is provided by Eq. (5); UTT is the total user travel time whose formulation is provided by Eq. (6); β_w is a parameter which describes user perception of the time spent waiting for trains; $tw_{s,p}^r(\cdot)$ is the average waiting time between run $(r-1)$ and run *r* at station *s* and on platform *p*; $ufw_{s,p}^r(\cdot)$ is the number of passengers waiting for run *r* at station *s* and on platform *p*; $\beta_{ob}(\cdot)$ is a parameter which describes user perception of the time spent on board the train which depends on the crowding level (as shown by [39]); $tb_l^r(\cdot)$ is the average travel time of run *r* on link *l*; $ufb_l^r(\cdot)$ is the number of passengers who are on board run *r* and on link *l*.

The second approach considers, in addition to user generalised costs, also two other terms: penalty PEN for passengers who decide to leave the rail system and service operational costs OC. Therefore, the second formulation of the objective function is:

$$Z_2(\cdot) = \beta_{UGC} \cdot UGC + \beta_{PEN} \cdot PEN + \beta_{OC} \cdot OC \text{ .} \tag{7}$$

with:

$$UGC = vot \cdot \left(UWT + UTT\right). \tag{8}$$

$$PEN = vot \cdot \left(\sum_{s} \sum_{p} \sum_{r} twbl^{r}_{s,p}(\boldsymbol{utt}) \cdot ufl^{r}_{s,p}(\boldsymbol{uf}) + \right. \qquad (9)$$

$$\left. + \sum_{s} \sum_{p} \sum_{r} tls^{r}_{s,p}(\boldsymbol{utt}) \cdot ufl^{r}_{s,p}(\boldsymbol{uf}) \right).$$

$$OC = \sum_{r} L_r(\boldsymbol{in},\boldsymbol{rtm}) \cdot c_r(\boldsymbol{rs}) \cdot ntu_r(\boldsymbol{rs}) \qquad (10)$$

where β_{UGC}, β_{PEN} and β_{OC} are parameters which express the relative weight of the objective function terms; UGC is the user generalised cost; $twbl^{r}_{s,p}(\cdot)$ is the time spent waiting by passengers prior to leaving the rail system between run $(r-1)$ and run *r* at station *s* and on platform *p*; $ufl^{r}_{s,p}(\cdot)$ is the number of passengers leaving the rail system between run $(r-1)$ and run *r* at station *s* and on platform *p*; $tls^{r}_{s,p}(\cdot)$ is the time spent leaving the rail system between run $(r-1)$ and run *r* at station *s* and on platform *p*; $L_r(\cdot)$ is the length of run *r*; $c_r(\cdot)$ is the cost per kilometre and per traction unit associated to run *r*; $ntu_r(\cdot)$ is the number of traction units used for run *r*.

In particular, the term PEN considers that, in the case of extremely crowded conditions or disruption events, the waiting time could increase so as to induce passengers to reconsider their mode choice (or path choice) and hence leave the rail system to reach their final destinations on different transport modes (such as alternative public transport systems). Obviously in the case of non-integrated fare schemes, it is necessary to allow for additional monetary costs for travelling by a different mass-transit system.

III. APPLICATION TO A REAL METRO NETWORK

The proposed methodology was applied to Line 1 of the Naples metro system in Italy (Fig. 1). The line, which is about 17 km long, consists of 17 stations, four of which (PI-Piscinola, CA-Colli Aminei, MO-Medaglie d'Oro and GA-Garibaldi, represented in the figure as white circles) are equipped with points and recovery tracks, and two (VA-Vanvitelli and DA-Dante, represented in the figure as grey circles) only with points.

This line has a somewhat directional travel demand since it connects the suburbs (PI-Piscinola) with the city centre (DA-Dante and GA-Garibaldi). Hence morning flows are directed towards the city centre, and afternoon/evening flows towards the suburbs. Moreover, there is only one depot located near PI-Piscinola and additional (i.e. spare) trains are not always available in the case of breakdowns due to a lack of rolling stock.

The proposed application consists in considering that a breakdown occurs to a train during the morning peak-hour. In detail, a run after leaving Chiaiano (i.e. the station just after PI-Piscinola) at 7.05 breaks down and is forced to travel at a maximum speed of 45 km/h. Obviously, this performance reduction represents a bottleneck for the whole service since the faulty train cannot be easily removed or overtaken.

In this case, in addition to the '*do nothing*' strategy (i.e. the faulty train continues its service all day), it is possible to implement 20 intervention strategies based on:

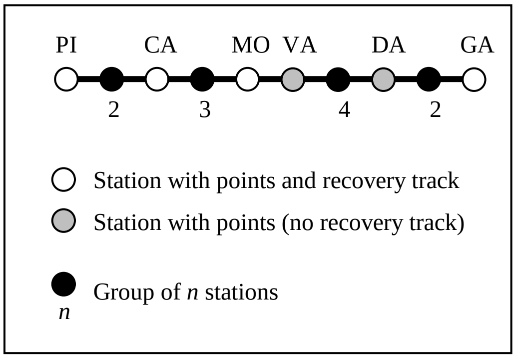

Fig. 1 Line 1 framework

- continuing the service as far as a station equipped with a recovery track, unloading passengers on the platform, driving the faulty train onto the maintenance track;
- continuing the service as far as a station equipped with points, unloading passengers on the platform, driving the faulty train to the depot by changing train direction;
- the faulty train is recovered on a maintenance track or at the depot with or without the use of a spare train for completing the service for the rest of the daily operations.

Detailed descriptions of analysed intervention strategies are reported in Table 1.

Obviously, when passengers are forced to get off the train, they have to wait for a following train, thereby increasing their waiting times.

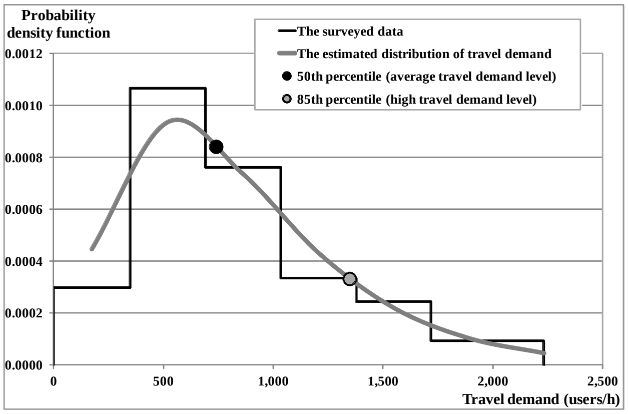

Fig. 2 Different travel demand levels

However, in order to verify the robustness of optimal solutions with respect to travel demand levels, we considered two different demand levels corresponding to average travel demand under usual conditions and higher travel demand compatible with particularly crowded days.

Table 1 Description of intervention strategies

No.	Strategy description
0	The faulty train continues to perform its service all day
1	The train stops at CA-Colli Aminei during its outward trip and is then driven onto the recovery track. No spare trains are considered
2	The train stops its run at CA-Colli Aminei and, after changing direction, is driven empty to the depot. No spare trains are considered
3	The train completes the outward trip and starts the return trip up to CA-Colli Aminei where it is driven onto the maintenance track. No spare trains are considered
4	The train stops at MO-Medaglie d'Oro during its outward trip and is then driven onto the recovery track. No spare trains are considered
5	The train stops its run at MO-Medaglie d'Oro and, after changing direction, is driven empty to the depot. No spare trains are considered
6	The train completes the outward trip and starts the return trip up to MO-Medaglie d'Oro where it is driven onto the maintenance track. No spare trains are considered
7	The train stops its run at VA-Vanvitelli and, after changing direction, is driven empty to the depot. No spare trains are considered
8	The train stops its run at DA-Dante and, after changing direction, is driven empty to the depot. No spare trains are considered
9	The train stops at GA-Garibaldi at the end of its outward trip and is then driven onto the recovery track. No spare trains are considered
10	The train completes the outward trip and starts the return trip up to PI-Piscinola where it is driven to the depot. No spare trains are considered
11	The train stops at CA-Colli Aminei during its outward trip and is then driven onto the recovery track. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
12	The train stops its run at CA-Colli Aminei and, after changing direction, is driven empty to the depot. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
13	The train completes the outward trip and starts the return trip up to CA-Colli Aminei where it is driven onto the maintenance track. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
14	The train stops at MO-Medaglie d'Oro during its outward trip and is then driven onto the recovery track. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
15	The train stops its run at MO-Medaglie d'Oro and, after changing direction, is driven empty to the depot. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
16	The train completes the outward trip and starts the return trip up to MO-Medaglie d'Oro where it is driven onto the maintenance track. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
17	The train stops its run at VA-Vanvitelli and, after changing direction, is driven empty to the depot. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
18	The train stops its run at DA-Dante and, after changing direction, is driven empty to the depot. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
19	The train stops at GA-Garibaldi at the end of its outward trip and is then driven onto the recovery track. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation
20	The train completes the outward trip and starts the return trip up to PI-Piscinola where it is driven to the depot. A spare train starts from PI-Piscinola to replace the faulty rolling stock for the rest of the daily operation

Table 2 Parameter values

Parameter	Value	Parameter	Value
vot	5.0 €/h	β_{UGC}	1.00
β_w	2.50	β_{PEN}	2.50
β_{ob}	see Table 3	β_{OC}	1.00
$tls^r_{s,p}$	15 minutes	c_r	18.17 €/train-km

Table 3 Parameter β_{ob} values [39]

Pax / m^2	Sitting	Standing
0	1.00	1.77
1	1.11	1.81
2	1.23	1.85
3	1.34	1.89
4	1.46	1.92
5	1.57	1.96
6	1.69	2.00

The parameter values adopted for calculating the objective functions are indicated in Table 2, while β_{ob} values are shown in Table 3. The extra cost perceived by passengers (i.e. term PEN) was calculated by assuming that passengers decide to leave the rail system if they are forced to wait more than 20 minutes or skip two runs.

Table 4 Objective function values for different travel demand levels

No.	Objective function no.1		Objective function no.2	
	Average demand level	High demand level	Average demand level	High demand level
0	627,102	869,830	785,012	1,124,155
1	691,625	923,061	868,216	1,218,814
2	691,096	922,863	868,098	1,219,027
3	685,735	920,690	859,645	1,210,158
4	690,440	922,786	866,822	1,217,608
5	690,294	922,588	867,087	1,217,821
6	686,196	921,341	859,994	1,210,697
7	690,264	922,926	866,850	1,217,947
8	688,666	923,915	863,914	1,215,859
9	686,340	921,747	859,814	1,210,779
10	685,019	919,663	859,092	1,209,294
11	629,468	865,990	790,874	1,127,110
12	629,322	865,792	790,098	1,126,282
13	**623,961**	**863,056**	**781,643**	**1,116,935**
14	628,666	865,468	789,862	1,125,741
15	628,520	865,270	789,086	1,124,913
16	**624,422**	**863,708**	781,992	**1,117,475**
17	628,490	865,805	788,849	1,125,223
18	626,892	866,281	785,914	1,122,637
19	624,544	864,056	**781,791**	1,117,500
20	**623,245**	**862,029**	**781,090**	**1,116,071**

In terms of the optimisation algorithm, since the number of alternative solutions to be analysed is limited (i.e. only 21) and the average calculation time for each analysis requires about 6 minutes, it was possible to apply an exhaustive approach for solving problem (1). Values of both objective functions for each travel demand level analysed are indicated in Table 4, where bold values show the three strategies which provide lower objective function values.

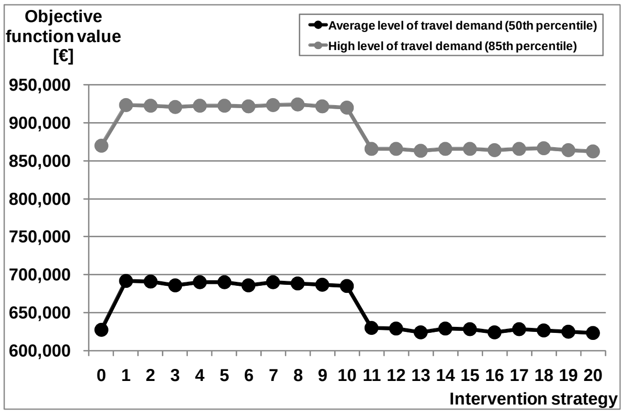

Fig. 3 Comparison of different demand levels in the case of objective function 1

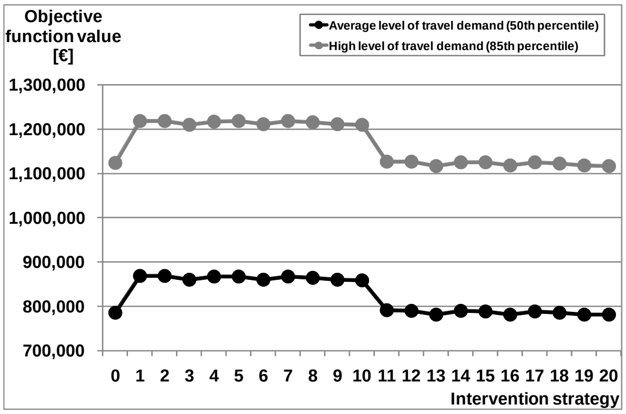

Fig. 4 Comparison of different demand levels in the case of objective function 2

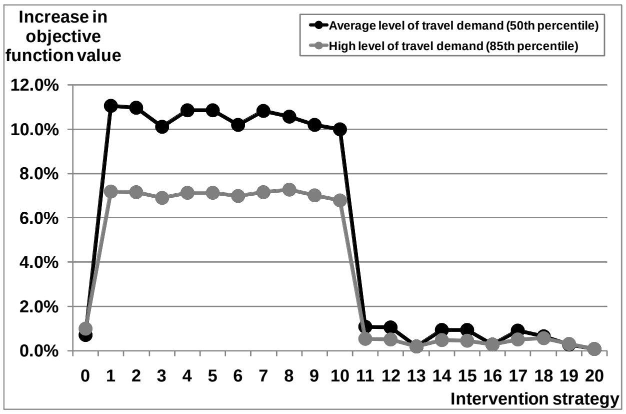

Fig. 5 Increase in objective function value for different demand levels in the case of objective function 1

Comparison among optimal intervention solutions for different travel demand levels are shown in Fig. 3 and Fig. 4 respectively in the case of objective function 1 (i.e. Eq. 4) and objective function 2 (i.e. Eq. 7). Similar results in terms of an increase in objective function values with respect to ordinary conditions have been shown in Fig. 5 and Fig. 6. Indeed, in the case of no faulty conditions, values of objective function 1 are equal to 622,722 and 861,289, respectively, in the case of average and high demand levels. Likewise, ordinary conditions provide values of objective function 2 equal to 780,567 and 1,115,358 in the same two demand level contexts.

Differences in terms of objective function formulations for each travel demand level are indicated in Fig. 7 and Fig. 8 in terms of absolute values and in Fig. 9 and Fig. 10 in terms of an increase in objective function with respect to ordinary conditions.

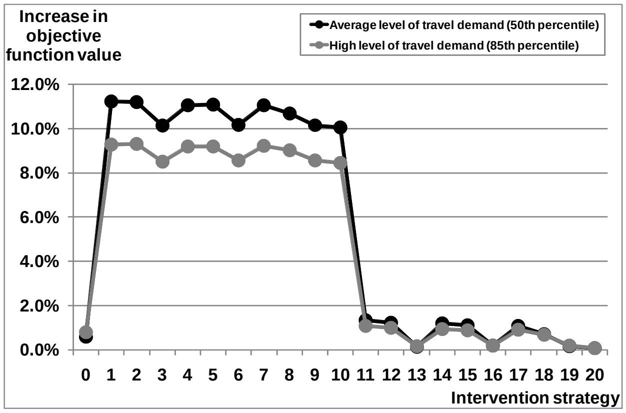

Fig. 6 Increase in objective function value for different demand levels in the case of objective function 2

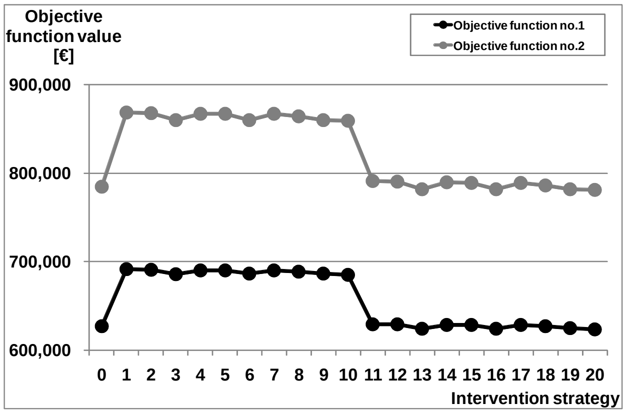

Fig. 7 Objective function comparison in the case of an average travel demand level (i.e. 50th percentile)

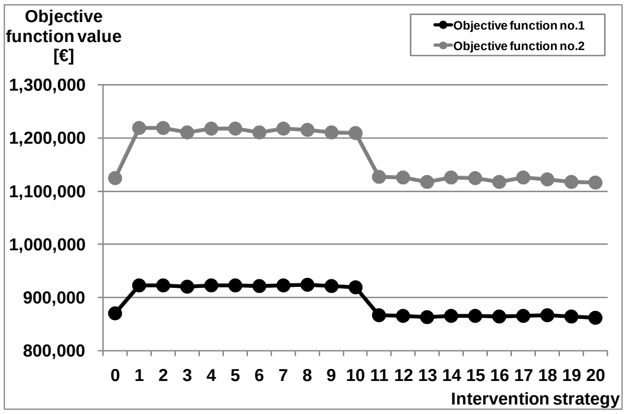

Fig. 8 Objective function comparison in the case of a high travel demand level (i.e. 85th percentile)

Our results indicate that, if it is not possible to provide any spare train, the optimal intervention strategy consists in continuing the service all day with the faulty train (i.e. '*do* *nothing*' strategy). Indeed, in this case, the reduction in maximum speed to 45 km/h provides a better result than implementing a service with fewer convoys (i.e. one train less). Likewise, if a replacement train can be provided, the best intervention strategy for each objective function and for each demand level is to conclude the trip of the faulty train as far as the depot and then insert the spare train (i.e. strategy 20). Indeed, this strategy would avoid the discomfort of passengers having to alight onto the platform from the faulty train (which has to be allocated to the maintenance track or driven on points) and wait for a following train.

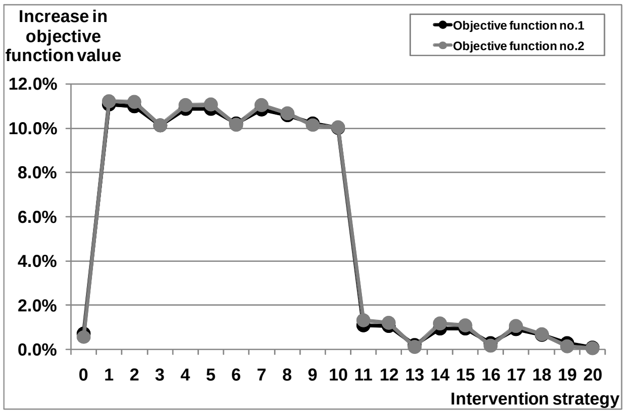

Fig. 9 Increase in objective function value in the case of an average travel demand level (i.e. 50th percentile)

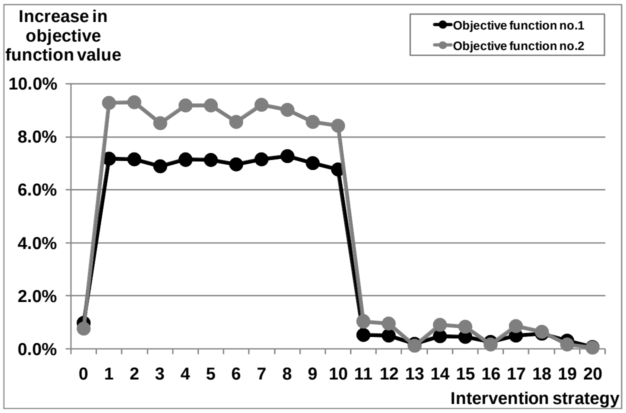

Fig. 10 Increase in objective function value in the case of a high travel demand level (i.e. 85th percentile)

However, differences in terms of sub-optimal strategies can be found by comparing results when switching perspective (i.e. objective function formulation) or demand levels. In particular, the second optimal solution is strategy 13 which consists in completing the outward trip, undertaking the return trip as far as the last recovery track in CA-Colli Aminei (i.e. just before the depot) and replacing the faulty train with a spare convoy. Likewise, the third optimal strategy is 16 (in three cases) and 19 (in only one case) which consist in completing the outward trip and leaving the faulty train in MO-Medaglie d'Oro (i.e. strategy 16) which is the recovery station just before CA-Colli Aminei or in GA-Garibaldi (i.e. strategy 19) which is the terminus of the outward trip.

IV. CONCLUSIONS AND RESEARCH PROSPECTS

In this paper we proposed a methodology for determining the optimal intervention strategy in the case of rail/metro system failure. The results were analysed from different perspectives (i.e. by adopting different formulations for the objective function to be minimised) with different demand levels (corresponding to average and high levels of travel demand).

Our results showed that user discomfort can be reduced by avoiding or minimising the unloading of passengers due to driving faulty trains to recovery positions (i.e. maintenance tracks or depot). Moreover, if there is a lack of additional rolling stock and the reduction in performance is fairly low, the optimal intervention strategy is to continue the service with a faulty train rather than provide a service with fewer working trains.

In terms of research prospects, we suggest applying the proposed methodology in different contexts in terms of failure conditions, travel demand levels and network complexities (i.e. by analysing different rail and/or metro networks). Moreover we propose to investigate possible relations between service quality (expressed, for instance, in terms of frequencies or average waiting times as shown by [40]) in ordinary conditions, as well as thresholds (assumed in this paper equal to 20 minutes or two runs) for passengers who decide to leave the rail system and reach their final destinations with different transportation systems.

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