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HIGH SPEED RAIL

PREDICTION OF SERVICE DEPENDABILITY FOR TRANSIT SYSTEMS: A CASE STUDY OF THE ITALIAN HIGH SPEED RAILWAY

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Abstract

From the conception phase of the life cycle of transit systems, reliability and quality analysis play an important role in defining the structural and operative characteristics of the system and in setting reliability and maintainability specifications which could assure that service quality requirements will be met. To measure service quality of transit systems, dependability has been recognised in the transportation reliability literature as an effective measure.

INTRODUCTION

This paper illustrates a methodology for the prediction of service quality of a high speed railway system. This methodology allows overall measures of service quality to be evaluated as a function of *a*) reliability and maintainability of subsystems forming transit system, *b*) failure recovery policy of failed subsystems, *c*) degraded conditions traffic management policy.

System Service Dependability (SSD) resulted to be the most effective among many measures proposed in the literature (Prashker 1979, and Roesler et al. 1979). SSD is defined as the probability that a passenger experiences a total delay d in a trip not greater than a prefixed tolerated quantity δ:

$$\mathrm{SSD} = \Pr\{d \leq \delta\} \tag{1}$$

This measure reflects the fact that most passengers are ready to accept a delay during their trip only if this delay is short and happens rarely in the continuous usage of the transit system.

The well known structure and operation complexity of transit systems, obliges to develop a specific model to evaluate SSD for each transit system, not being possible the simple identification of models developed for similar systems and presented in the literature. Thus a specific and detailed probabilistic analysis is necessary to model failure occurrence, repair performing, train delay generation and diffusion mechanisms.

The methodology presented in this paper has been developed to analyse the Rome-Naples line of Italian High Speed Railway System, as it is actually defined in the new railway project. Preliminary analyses and evaluation have been recently carried out on other lines of the Italian high speed system, and results are given in Capasso et al. (1993, 1994a, 1994b) and Calabria et al. (1994). In those papers, the analysis level was restricted by the large uncertainty on the design choices of the analysed lines and by the small number of available data. On the contrary, on the Rome-Naples line (which will be the first line to be built) the specification level of design is more detailed, thus allowing exhaustive analyses and evaluations to be performed.

In order to verify whether reliability specifications defined in the statement of work permit to obtain high levels for SSD, reliability requirements and technical specifications are used in SSD evaluations. Results presented in the following mainly refer to the impact that potential failures of technological equipments have on SSD. Technological Installations have been divided into Electric Traction and Signalling subsystems.

Only failure events which may produce train delay have been considered, since system performance has been considered from passenger's viewpoint. Results of statistical surveys on railway equipments in operation on the national territory have been considered for the evaluation of impact of failures on trains traffic (Palmieri 1991, 1993). In particular, information relative to "*Direttissima*" Rome-Florence have been considered as it represents the Italian line with highest velocity, and the line with closest characteristics to the new high speed line. As far as new technology equipments is concerned, whereas statistical information was not available, engineering analyses were performed in order to determine potential failure modes, their effects and relative recovery actions.

All failures caused by catastrophic events (fire, slide, earth flow), human errors and external to railway system were not considered in the analysis, as well as failures induced by primary failures or incorrect recovery actions.

The methodology uses an analytical approach to evaluate overall SSD. This approach is based on the hypothesis that no more than one single failure can occur in a single trip. This hypothesis is not restrictive in the analysis of high speed systems because in this case elements reliability and availability result to be particularly high.

It is to point out that dependability analysis shall follow the system life cycle, thus when more detailed information will be available regarding system operation, reliability and maintainability characteristics, dependability model shall be updated and improved. Successively, when system will be in the operation phase, statistical data will be available and the hypotheses on which the model is based can be verified.

HIGH SPEED SYSTEM FAILURE BREAKDOWN STRUCTURE

For the present analysis the high speed system has been divided as follows: Signalling, Electric Traction, Others. In Table 1 the relative frequencies of failures are reported, as it resulted from a statistical analysis of failure data relative to Rome-Florence *Direttissima* line.

Table 1 Failure distribution

Signalling	60.9 %
Electric traction	1.2 %
Others (train, track, centralized traffic control ctc)	37.9 %

In the remainder of this section, the main structural and operating characteristics as well as failure modes of Signalling and Electric Traction are reported.

Electric traction

Electric Traction (ET) installations comprise: *a*) train power supply (electric traction substation ESS and high voltage transmission network); *b*) overhead contact line (contact wire, messenger and feeders) and accessories (insulators, grounded components, negative conductor, components at line voltage). Components at line voltage consist of a high number of components like: hangers, terminal connections, overhead switches, guys, inductive resistances.

Because of lack of reliability data relative to high speed electric equipments (to be installed in 2x25 kV AC electrified system), reliability data relative to traditional 3 kV DC electric equipments were used to allocate failure rate requirements of high speed electric subsystems at component level. In fact, though high speed and traditional electric items can have different structures, they perform the same function. In Table 2 relative frequency of technological equipments for electric traction experienced in 1992 in the Italian railway network is reported.

Table 2 Relative frequency of electric equipments failures

Items	Relative Frequency (%)
Power supply (electric substation and high voltage line)	63.8
Overhead contact line (contact wire, messenger and feeders)	14.2
Insulators	6.6
Grounded components	7.2
Components at line voltage	8.2

Electric substation

The failure percentage relative to train power supply (Table 2) comprises both failures of high voltage lines and of conversion Electric Substations (ESS). Analyzing new high speed equipments, while for High Voltage (HV) equipments same failure pattern is expected because changes are irrelevant, as far as ESS is concerned, most equipments for high speed will be completely different. In fact, new electric system is composed of main and secondary ESS's. The typical layout used for HV power supply of a main ESS complies with a need that each ESS can be fed by different busses of the national grid (380 or 220 kV). Thus, in case of failure of HV power supply, it is possible to assure the feeding to each ESS. The ESS structure is a parallel of two single-phase transformers connected to the three-phase network in a V-arrangement; full redundancy at component level is adopted in ESS design. Secondary ESS's are at a distance of about 12 km each other, and essentially comprehend two auto transformers connected to the contact line and to negative feeder and a central tap is grounding to track.

This type of electrification at 2x25 kV AC is totally new for Italy, thus neither reliability data are available, nor it is possible to predict failure pattern with deep details for all components. For this reason the conductor negative at -25 kV could not be considered in this analysis, and corresponding potential failures disregarded.

Failure of ESS is defined as any event which causes the outage of the contact line section fed by the ESS. Thus, for main ESS outage refers to high voltage line and internal ESS failures. For secondary ESS, just internal failures are to be considered. In the technical specification reliability requirements for primary and secondary ESS's are not distinguished, thus same failure rate will be assumed for both, this assumption being conservative for secondary ESS.

The same failure recovery action is assumed for both primary and secondary ESS's. In fact, they both can be recovered after a component failure by a restoring and rearrangement (R&R) action.

Contact line

Potential failures of overhead contact line are due to ageing of material and equipments, structural defective materials or abnormal stress caused by lightning stroke or conductor fusing due to excessive current in relation to particular operating conditions. In the case of breakage or fusion of a conductor of overhead contact line, circuit-breakers located in the main ESS open. After failure the following recovery actions are performed: fault location detection, opening of sectioning points located in secondary ESS's adjacent to fault, electrical system rearrangement (closing the sectioning point located in the middle of section) to minimise unfed section. The same procedure is performed in the case of insulator breakage or negative feeder failure.

Components at line voltage are composed of several different elements, whose failure frequency is comparatively small (8.2 %). Therefore, only the most relevant items were analysed, namely top tie, swing link and terminal connections. The failure of one of these elements does not produce any interruption in the traction circuit, it is detected just when the pantograph of a train breaks the wire while passing because of a deformed shape. In the case of wire breakage same effects of contact line breakage are produced. The probability of occurrence of wire breakage after a failure of components at line voltage is assumed, in absence of well founded data, to be equal to .50. When there is no breakage the first driver detecting the failure communicates its occurrence to central control.

Potential failures modes of ground elements (7.2 %) are of the following two types: mechanical breaking of ground wire and of poles. Ground wire failures have no effect on train run, while pole failures have no statistical relevancy, thus ground elements were not considered in the model.

Signalling

Signalling system is composed of equipments which permit a safe train traffic. In this paper track circuits, switches control circuits and hot-box detector are analysed. Failure distribution for these items is reported in Table 3, which refers to signalling equipment failure data of *Direttissima* railway, observed during 1992 operation.

Table 3 **Signalling failure distribution**

Track circuits	14.2 %
Switch control circuits	12.0 %
Hot-box detectors	25.3 %
Others (control desk, level crossing, signal, ...)	48.5 %

Track circuits

To assure train safety high speed line is divided in track sections formed of a certain number of track circuits (TC), each with a length of about 1500 m. Because a track section defines the minimum possible distance between two consecutive trains, then the number of track circuits forming a track section depends on the train maximum allowable speed on the line. For this high speed railway, length of a track section is about 9 km and it follows a number of six track circuits for each track section.

Track circuits have the function to detect train presence on a track section defined by two consecutive electric separation joints, as well as to verify track continuity. They are made of wayside boxes (each containing a receiver and a transmitter) and of connecting circuits. Only receiver and transmitter elements will be considered in this analysis; connecting elements failure rates should be comparatively neglectable, being these elements protected and insulated from external agents.

Switches

In the Rome-Naples line switches are present in service points (SP), namely: passing points (PM), cross-over (PC) and interconnection points (PJ), for a total of 13 points. They permit train overtaking on the same track, crossing in the case of two-way working on one track. A switch is composed of controlling and actuating elements. In the failure analysis of signalling, controlling elements are considered, as signalling failure rate specification does not include failures of the mechanical elements.

Hot-box detector (HBD)

Hot-box detectors (HBD) are located along the line at cross-over and passing points. As it results from Table 3, failures of hot-box detector are a consistent part of total failures. For this reason hot-box detectors will be considered in the dependability model also if no reliability specification is provided for them in the technical specification. The failure rate obtained from *Direttissima* failure data has been assumed.

IMPACT OF FAILURES ON TRAIN RUN AND RECOVERY POLICY

Degraded performance of railway system in consequence of failures has been evaluated in terms of train delay, assuming passenger's viewpoint.

Delays consequent to failures depend on failure detection, communication and recovery procedures established for each failure mode. On the basis of procedures defined by railway management and of failure modes reported in the previous section, delay probability distributions have been determined.

Failure modes are analysed in the following by considering different levels of the resulting impact on train traffic:

a) immediate traffic recovery

b) moderate effects on traffic

c) degraded traffic

A computer program (SITRAD) (Capasso et al. 1994a) simulating train operation in degraded line conditions has been developed to evaluate the impact of failures affecting train traffic. The implemented methodology permits to consider different failure recovery strategies. The total down time for each potential failure is the sum of several time intervals, like: maintenance crew response delay, maintenance crew travel time, fault detection time, repair time. Thus the time required for each recovery strategy is composed of two components, the inherent recovery time covering that part of the recovering time which is a function of the specific recovery mode (and as a consequence of the failure mode), and the location dependent time covering travel time to effect the repair. It is therefore worthwhile to optimise global recovery policy in terms of location and typology of maintenance crews, travel vehicle etc.

Immediate traffic recovery

Failures of high voltage power supply system and of ESS produces blockage of the train which is in the section fed by failed unit just when the failure occurs and delay of the next train. Both the situations are assumed to produce the same train delay.

Failures of high voltage power supply system and of main ESS permit immediate traffic recovery. In fact, it is always possible to restore the power supply to contact line through protection and switching equipments, because of full redundancy realised.

Also in the case of secondary ESS, failure recovery is immediate. For secondary ESS with two active auto transformers it is possible to rearrange the system switching electric power supply from failed unit to the adjacent ESS and using just the unfailed unit. In the case of ESS with one operating unit and one stand-by unit, it is sufficient to switch power supply form failed to stand-by unit.

A time duration of few minutes to perform any of these recovery actions can be assumed, because a supervisor centre is able to perform recovery actions by remote control. Therefore a few minutes train delay is expected as a consequence of these failures.

Moderate effects on traffic

Failures of track circuits and hot-box detectors have a moderate effect on traffic.

Failures of track circuit is detected through signalling system. The first train receiving a failed track circuit warning signal slows down to 15 km/h, runs at sight on failed track circuit, then accelerates up to commercial speed. Considering an average track circuit length of 1500 m and assuming a commercial speed of 250 km/h and a run at sight speed of 15 km/h, a train delay of about 13 minutes is expected for the first train, taking into account that a telephone communication between train driver and central traffic control is provided. In the case that the failure occurs at a short time before train passing and its location is very close to train at that time, it may happen that the train braking run goes over the failed track circuit. In this case, the train driver just communicates with central control and re accelerates up to standard speed. A delay of about 7 minutes is expected in this case. The trains following the first train act a light reduction of speed just on the failed track circuit.

In the case of hot-box failure, only the first train detecting a wrong signal from hot-box should experience a delay. The first train slows down and stops, failure occurrence is communicated to central control and on-board system is checked. Total delay is the sum of braking time (≅ 1'), of communication (≅ 3') and on board system check (≅ 13'); summing up, a total delay of 17' is expected. If the basic headway of 15 minutes is assuming, then the second train has to slow down and will experience a delay of about 7 minutes. The successive trains do not experience delay.

In both cases repair of failed elements is performed during the next operation interruption.

Degraded traffic

Failures which imply immediate repair by maintenance crew and stoppage of traffic in the failed part cause a relevant degradation of traffic. In this case, two-way working on unfailed track is generally actuated for the repair time duration.

Failures modes of contact line and accessories and of switch control system belong to this failure class.

Contact line and accessories

Distribution of train delay consequent to the failure of electric installations primarily depends on the train location at the time of occurrence of failure.

Delay time distribution for trains entering the line after failure occurrence is the same for insulators and for any failed element of the overhead contact line. This distribution is a function of failed line length where two-way working is performed.

For a train using the section at the instant of failure, delay time distribution is very different in relation to the failed element, because train delay essentially coincides in this case with repair time failed item or with towing time to the next station. In the case of a contact wire failure, train recovery is performed by a diesel tow-vehicle, the delay is a function of relative distance between tow-vehicle location and failure site. If a tow-vehicle is not available, delay time coincides with contact line repair time, which can be evaluated in several hours. Delay relative to an insulator failure depends on the repair time of failed element: the expected time for an insulator replacement is 15'.

As far as elements at line voltage are concerned, train delay depends on the effects of failure on contact line. If the failure causes the contact line breakage, train delay distribution is the same of contact line failure. If the failure does not effect the contact line, no train delay will occur because failure repair will be performed during headways or at operation's end.

Switches

Switch failure is detected by signalling system. Failure management procedure implies the train stop and successive run at sight up to failed switch. First train driver detecting the failure has to perform some manual recovery procedures to try to restore switch control. Delay time of this train has been evaluated, and it is equal to 9 or 19 minutes, depending on the switch position at the failure instant, if correct or not respectively. Missing precise data a 50%-50% probability distribution has been assumed for the two cases. The successive trains, passing when the system is still down, act a reduction of speed and experience a shorter delay.

The same analysis made for track circuit has to be applied to switch failure. In fact, there is a possibility that the train stopping run exceeds the failed switch location because of a too short warning time. In this case delay time is the sum of slowdown and stopping, telephone communication with central traffic control, restarting and accelerating up to the standard speed.

A .85 probability of success for manual switch reset can be evaluated. If manual reset is successful the trains following the first train experiences no delay. If reset is not successful, all trains passing over the failed switch have to stop, ask for authorisation to proceed and run at run at sight. A 11 minutes global delay can be evaluated.

DEPENDABILITY MODELING

A large number of approaches exists in the development of dependability models. Such approaches evaluate SSD starting from *a)* the identification of all possible failure modes of subsystems which constitute the transit system, *b)* the probability of occurrence of each failure mode, and *c)* the probability distribution of elementary delay caused by each failure. Such approaches can be classified into analytical and numerical ones.

Analytical approaches are based on the hypotheses that *a)* the passenger cannot experience more than one elementary delay in his trip, and *b)* all elementary delays are stochastically independent variables. The main advantage in using an analytical approach is short run time required by the numerical code which can run on personal computers, too. However, analytical approaches provide well approximated results only if the probability of occurrence of more than one failure in a single trip is negligible (Roesler et al. 1979, Capasso et al. 1993).

The numerical approach, on the contrary, does not assume any restrictive hypothesis on the number of delays and/or on the stochastic independence among the elementary delays (Rapone et al. 1989, and Calabria et al. 1993). However, such an approach requires longer run times and produces more accurate results, with respect to the analytical approach, only if input data are very accurate. Note that the analytical approach tends to overestimate the SSD if the hypothesis on the number of elementary delays is not satisfied.

In developing the proposed dependability model, the analytical approach has been chosen mainly due to two peculiarities of high speed systems: the high reliability values of subsystems and the short travel distance and time. This choice is strengthened by the fact that in the conception phase of a transit system the defined level of reliability and maintainability characteristics does not allow failure modes and recovery policy from failure to be defined in details.

In the analytical models the SSD (1) is given by:

$$\mathrm{SSD} = \Pr\{d \le \delta\} = \prod_{i=1}^{N} \Pr\{d_i \le \delta\} \qquad (2)$$

where d_i is the elementary delay caused by the i-th failure mode, and N is the total number of failure modes which can delay the train.

By using the Bayes theorem on the conditional probabilities, the probability that each elementary delay is not greater than the acceptable quantity is given by:

$$\Pr\{d_i \le \delta\} = 1 - \Pr\{E_i\} \cdot \Pr\{d_i > \delta \mid E_i\} \qquad (3)$$

where $\Pr\{E_i\}$ denotes the occurrence probability of the i-th failure mode E_i, and $\Pr\{d_i > \delta \mid E_i\}$ is the probability that the elementary delay d_i is greater than δ, given the occurrence of the event E_i. This formulation allows to separate what depends on the reliability and maintainability characteristics of subsystems (ie the failure probability) from what depends on the structural and operative characteristics of the whole system.

If the i-th failure mode produces different delay distributions as a function, for example, of the position of the train with respect to the failed subsystem, or of different recovery policies, then different failure dynamics are defined. Thus, equation (3) is rewritten:

$$\Pr\{d_i \le \delta\} = 1 - \sum_{j=1}^{m_i} \Pr\{E_{i,j}\} \cdot \Pr\{d_{i,j} > \delta \mid E_{i,j}\} \qquad (4)$$

where m_i denotes the number of failure dynamics of the i-th failure mode and $d_{i,j}$ is the elementary delay caused by the j-th failure dynamic. Note that the m_i events $E_{i,j}$ must be mutually exclusive.

The explicit expression of $\Pr\{d_i \le \delta\}$ relative to each subsystem is given in this paper. Note that, in evaluating the failure probability $\Pr\{E_i\}$, it has been assumed that times between two successive failures are independent and identically distributed random variables, according to the exponential distribution. Under this hypothesis, the mean time between failures (MTBF) is equal to the inverse of the (constant) failure rate. In Table 4, the MTBF used in the SSD evaluation are shown.

Table 4 Subsystem MTBF

Subsystem	Electric substation	Contact line	Track circuit	Switch	Hot-box detector
Mtbf (h)	333,330	5860	13,390	35,710	3450

Electric substation

When an electric substation (ESS) fails, then a restoring and rearrangement (R&R) action is tried. If this action fails, then the section of overhead contact line fed by the failed ESS is fed, through appropriate switching operations, by contiguous ESS. Let us hypothesise that the switching operations, if required, always succeed (ie the contiguous ESS is always functioning). Thus, two different failure dynamics have been recognised for each ESS:

1. ESS fails and the R&R action succeeds,
2. ESS fails and the R&R action fails.

A different delay distribution is associated to each failure dynamic. Then, equation (3) can be written:

$$\Pr\{d_{\mathrm{ESS}} \le \delta\} = 1 - \left\{ \begin{matrix} [1 - AR(t_u)] \cdot \overline{R} \cdot \Pr\{d_{\mathrm{ESS},1} > \delta \mid E_{\mathrm{ESS},1}\} + \\ [1 - AR(t_u)] \cdot (1 - \overline{R}) \cdot \Pr\{d_{\mathrm{ESS},2} > \delta \mid E_{\mathrm{ESS},2}\} \end{matrix} \right\} \quad (5)$$

where $R(t_u)$ is the probability that no failure occurs during the 'use' time of each ESS, say t_u (such time is equal to the 'use' time of the segment of overhead contact line fed by that ESS), A denotes the probability that the ESS is functioning when the train is going to use it, and $\overline{R}$ is the success probability of R&R action.

For evaluating A, the mean time of no feed (MTNF) is used as down time. MTNF is given by:

$$\text{MTNF} = RRT \cdot \overline{R} + FT \cdot (1 - \overline{R}) \quad (6)$$

where $RRT = 5$ minutes is the time required by the R&R action and $FT = 7.5$ minutes is the time needed to feed the overhead contact line through the ESS contiguous to that failed. Then, since $\overline{R} = 0.93$ (Capasso et al. 1993), MTNF = 5.17 minutes.

Overhead contact line

Three different failure modes of the overhead contact line (CL) have been analysed, which produce train delays:

1. contact wire, messenger, and feeder (CL1)
2. insulators (CL2)
3. components at line voltage (CL3).

The fourth failure mode shown in Table 2 (grounded components) does not produce delays. For each failure mode, two dynamics have been recognised:

1. The failure occurs before the train uses CL,
2. The subsystem is up when the train is going to use it and the failure occurs during the use.

Thus, for example, in case of failure mode CL1, the probability (3) is:

$$\Pr\{d_{\mathrm{CL1}} \le \delta\} = 1 - \left\{(1-A)\cdot \Pr\{d_{\mathrm{CL1,1}} > \delta \mid E_{\mathrm{CL1,1}}\} + A\cdot\left[1-R(t_u)\right]\cdot \Pr\{d_{\mathrm{CL1,2}} > \delta \mid E_{\mathrm{CL1,2}}\}\right\} \quad (7)$$

The mean time between failures relative to each failure mode is to be computed in order to evaluate the reliability $R(t_u)$ and the availability A. For example: $\mathrm{MTBF}_1 = \mathrm{MTBF}/g_1$, where MTBF is the total mean time between failures relative to all failures modes of CL, and g_1 is the occurrence frequency of failure mode #1. Hence by using data in Table 4:

$$\mathrm{MTBF}_1 = 5860/0.39 = 14950\ \mathrm{h} \qquad \mathrm{MTBF}_2 = 32166\ \mathrm{h} \qquad \mathrm{MTBF}_3 = 25890\ \mathrm{h}$$

The availability A has been evaluated by setting the mean time to repair equal to 3 hours for each failure mode.

Track circuit

The track circuit (TC) is considered a series system from a logical viewpoint composed by N=24 track sections, 9 km long each. When a section fails, the repair action is delayed and is performed during a prefixed maintenance period. Thus, the subsystem remains down from the failure time t_f to the maintenance period, which occurs after τ hours from the beginning of daily service.

Three different failure dynamics have been recognised for each track section:

1. Subsystem is down when the train is 9 km behind and the train is the first one to experience that failure.
2. Subsystem is down when the train is 9 km behind and the train is not the first one to experience that failure.
3. Subsystem is up when the train is 9 km behind and the subsystem fails while the train is covering such a distance.

Then, equation (3) can be written:

$$\Pr\{d_{\mathrm{TC}} \le \delta\} = 1 - \left\{\begin{matrix} \left[1-R(t_c)^N\right]\cdot \Pr\{\mathrm{I}\}\cdot \Pr\{d_{\mathrm{TC,1}} > \delta \mid E_{\mathrm{TC,1}}\} + \\ \left[1-R(t_c)^N\right]\cdot (1-\Pr\{\mathrm{I}\})\cdot \Pr\{d_{\mathrm{TC,2}} > \delta \mid E_{\mathrm{TC,2}}\} + \\ R(t_c)^N\cdot\left[1-(1-F(t_u))^N\right]\cdot \Pr\{d_{\mathrm{TC,3}} > \delta \mid E_{\mathrm{TC,3}}\} \end{matrix}\right\} \quad (8)$$

where $R(t_c)$ is the probability that the subsystem failure occurs after the crossing train time t_c, $F(t_u)$ is the probability that the failure occurs in the time interval $(t_c, t_c + t_u)$ (t_u is the time required to cover 9 km: t_u = 9/250 hours) and Pr{I} is the probability that the train is the first one to experience the failure, given the failure occurrence in (0, t_c).

Since the passenger travels on a generic train, t_c is a random variable that assumes values in the range (0,τ); then a mean value for $R(t_c)$, say $\overline{R}(t_c)$, is required. Assuming a Uniform distribution over the time interval (0,τ) for t_c we have:

$$\overline{R}(t_c) = \frac{1}{\tau}\int_0^{\tau} R(t_c)\,dt_c = \frac{1-\exp(-\tau/\mathrm{MTBF})}{\tau/\mathrm{MTBF}} \quad (9)$$

where MTBF is the mean time between failures of a section of the TC (MTBF=13390 hours)

The probability Pr{I}, given that $t_f < t_c$, is:

$$\Pr\{\mathrm{I}\} = 1/n_t \tag{10}$$

where $n_t = \mathrm{int}\left(\frac{\tau - t_c}{\Delta}\right) + \mathrm{int}\left(\frac{t_c - t_f}{\Delta}\right) + 1$ is the number of train that experience the failure until subsystem repair, t_f is the failure time, and Δ is the headway. Since n_t is a function of the random variables t_f and t_c, then Pr{I} is a random variable, too. Hence, a mean value of Pr{I}, say $\overline{\Pr}\{\mathrm{I}\}$, is required.

However, no analytical tool seems to be available for evaluating neither in an exact manner nor in a well approximated one the mean value of Pr{I}; then a Monte Carlo simulation procedure is used. The crossing train time is drawn from a Uniform distribution over the time interval (0,τ), and the failure time t_f is drawn from a truncated exponential distribution:

$$f(t_f) = \frac{1}{\mathrm{MTBF}} \cdot \frac{\exp(-t_f/\mathrm{MTBF})}{1 - \exp(-t_c/\mathrm{MTBF})} \tag{11}$$

For τ=4 hours and Δ=15 minutes, we have: $\overline{\Pr}\{\mathrm{I}\}=0.1004$.

Switch control circuit

Thirteen sets of switches are located along the Rome-Naples line (see Table 6). The i-th set of switches (i=1,2,...,13) is composed by N_i switches that are supposed to be identical among them from a reliability and maintainability viewpoint. Then, the reliability of the switch control circuit (SCC) of each set depends on N_i, whereas the repair time strongly depends on the distance of the switches from the maintenance station. The mean time to repair (MTTR) of switches in each set has been evaluated and is shown in Table 5.

Table 5 Number of switches and their MTTR in each set

i	1	2	3	4	5	6	7	8	9	10	11	12	13
N$_i$	8	4	8	2	4	8	4	2	8	4	2	8	2
MTTR (min)	86.5	57.0	25.0	47.0	61.0	25.0	55.5	66.0	58.0	33.0	25.0	40.5	34.5

For each set of switches three failure dynamics have been recognised:

1. Subsystem is down when the train is going to use it and the train is the first one to experience that failure.
2. Subsystem is down when the train is going to use it and the train is not the first one to experience that failure.
3. Subsystem is up when the train is 9 km behind and the subsystem fails while the train is covering such a distance.

Then, for the i-th set equation (3) can be written:

$$\Pr\{d_{\mathrm{SCC}} \le \delta\} = 1 - \left\{\begin{array}{l}(1-A_i)\cdot\Pr\{\mathrm{I}\}\cdot\Pr\{d_{\mathrm{SCC},1} > \delta \mid E_{\mathrm{SCC},1}\} + \\ (1-A_i)\cdot(1-\Pr\{\mathrm{I}\})\cdot\Pr\{d_{\mathrm{SCC},2} > \delta \mid E_{\mathrm{SCC},2}\} + \\ A_i\cdot(1-R(t_u))^{N_i}\cdot\Pr\{d_{\mathrm{SCC},3} > \delta \mid E_{\mathrm{SCC},3}\}\end{array}\right\} \tag{12}$$

where t_u is the time required to cover 9 km, and A_i is the availability of that set, given by:

$$A_i = \left(\frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}_i} \right)^{N_i} \tag{13}$$

where MTTR_i is the mean time to repair of each switch in that set.

The probability that the passenger's train is the first one to experience the failure is given by:

$$\Pr\{\mathrm{I}\} = \frac{1}{n_t} \tag{14}$$

where n_t is the number of trains that experience the failure until repair. Since failure is detected when a train uses the switch, then

$$\Pr\{\mathrm{I}\} = \frac{1}{\mathrm{int}(RT/\Delta)+1} \tag{15}$$

where the repair time RT is a random variable. Then, $\Pr\{\mathrm{I}\}$ is a random variable too. Since no assumption can be made on the probability distribution of the repair time, then the only way of obtaining an approximated mean value of $\Pr\{\mathrm{I}\}$, say $\overline{\Pr}\{\mathrm{I}\}$, seems to be:

$$\overline{\Pr}\{\mathrm{I}\} = \frac{1}{\mathrm{int}(\mathrm{MTTR}/\Delta)+1} \tag{16}$$

Hot-box detector

This system is composed by N=9 hot-box detectors (HBD) located at every service point. It is a series system from a logical viewpoint because the failure of a single HBD can cause train delay.

Like the track circuits, repair of a failed detector is performed during the prefixed maintenance period, which occurs after τ hours from the beginning of the service. Two failure dynamics have been analysed:

1. One detector is down when the train uses it and the train is the first one to experience the failure.
2. One detector is down when the train uses it and the train is the second one to experience the failure.

Thus, equation (3) can be written:

$$\Pr\{d_{\mathrm{TBD}} \le \delta\} = 1 - \left\{ \begin{array}{l} \left[1 - R(t_c)^N\right] \cdot \Pr\{\mathrm{I}\} \cdot \Pr\{d_{\mathrm{TBD,1}} > \delta \mid E_{\mathrm{TBD,1}}\} + \\ \left[1 - R(t_c)^N\right] \cdot \Pr\{\mathrm{II}\} \cdot \Pr\{d_{\mathrm{TBD,2}} > \delta \mid E_{\mathrm{TBD,2}}\} \end{array} \right\} \tag{17}$$

where $R(t_c)$ is the probability that the failure of each HBD occurs after the train crossing time t_c, and $\Pr\{\mathrm{I}\}$ ($\Pr\{\mathrm{II}\}$) is the probability that the passenger's train is the first (the second) one to experience the failure of a detector. Like the TC, the mean value of $R(t_c)$ is given by:

$$\overline{R}(t_c) = \frac{1 - \exp(-\tau/\mathrm{MTBF})}{\tau/\mathrm{MTBF}} \tag{18}$$

and the mean value of $\Pr\{\mathrm{I}\}$ can be evaluated by Monte Carlo simulation. A simulation procedure is also used for obtaining the mean value of $\Pr\{\mathrm{II}\}$, say $\overline{\Pr}\{\mathrm{II}\}$, since $\Pr\{\mathrm{II}\} = \Pr\{\mathrm{I}\}$ if $n_t > 1$, and $\Pr\{\mathrm{II}\}=0$ if $n_t = 1$. Of course, MTBF is now the mean time between failures of each detector.

For τ=4 hours and Δ=15 minutes: $\overline{\Pr}\{I\} = 0.1004$ and $\overline{\Pr}\{II\} = 0.0957$.

DELAY DISTRIBUTION

Delay analysis performed in this paper makes reference to Rome-Naples high speed line, as it is actually defined by design, not considering line sections internal to the Rome and Naples urban areas, where DC electrification is adopted.

Rome-Naples line is 215 km long, presents 5 passing points (PM), 4 cross-over (PC) and 4 interconnections (PJ) located at distances reported in Table 6.

Table 6 Service points location in Rome-Naples high speed line

	Cumulated distance (km)												
PM	12		62			113			153			210	
PC		36			89		134			174			
PJ				75				143			177		212

The following data have been assumed in the simulation:

- Train average speed: 250 km/h
- Maximum train speed at switch points and in two-way working on one track: 160 km/h

For each failure considered in the analysis, times necessary for the correct application of standard procedures defined by railway regulation have been evaluated.

Electric traction

For electric fixed installations, maintenance service crews are assumed to be stationed in two passing points (at km 62 and km 113) and in an interconnection point with existing railway line at km 178. The crew is assumed to travel by an independent mean to the malfunction site either at 80 km/h on track or at 40 km/h on road.

With reference to failure and recovery modes analysed earlier, delay distribution for train involved in a time duration of one hour have been evaluated, starting from failure detection by a train or from the opening of line protection breakers in ESS.

Resulting distributions are reported in Table 7. In particular, the probability distribution of train delay is given for each failure dynamic and each failure mode.

Table 7 Probability mass distribution of delay time for overhead contact line

Delay time *D*	Failure mode #1 and #2		Failure mode #3	
(minute)	Failure Dynamic #1	Failure Dynamic #2	Failure Dynamic #1	Failure Dynamic #2
$d =$ 0'	.00	.40	.50	.73
0' $< d <$ 2'	00	.00	.00	.00
2' $< d \leq$ 5'	.28	.17	.13	.04
5' $< d \leq$ 10'	.13	.12	.06	.06
10'$< d \leq$ 15'	.11	.11	.06	.02
15'$< d \leq$ 20'	.10	.06	.05	.01
$d >$ 20'	.38	.14	.20	.14

For failure mode #1 (contact wire, ...) and failure mode #2 (insulators) only one distribution is given because, as motivated earlier, the train delay is the same.

Electric power supply

For power supply subsystem delay times have been evaluated as presented in previous sections. Both if the ESS fails when the train is using it and if the ESS is down when the train is going to use it, delay time depends on the restoring and rearrangement action. If the R&R action succeeds, then the train delay is assumed to be equal to the restoring and rearrangement time (5 minutes), whereas, if the R&R action fails, train delay is equal to the time required to feed the contact line through the ESS contiguous to that failed (7.5 minutes).

Signalling

Delay distribution relative to signalling failures are reported in Table 8. In this table, train delay distributions have been distinguished considering all failure dynamics recognised earlier. Single delay value implies one point distribution, otherwise probability mass are specified.

Table 8 Delay time distribution for signalling failures

Subsystem	Failure Dynamic	Delay time (minute)	
Track circuit	#1	13'	
	#2	15"	
	#3	7' (0.50)	13' (0.50)
Switch control	#1	9' (0.50)	19' (0.50)
	#2	7'	
	#3	0' (0.85)	11' (0.15)
Hot-box detector	#1	17'	
	#2	7'	

DEPENDABILITY EVALUATION

The proposed dependability model has been applied to the Naples-Rome line and the effect of the failures of the fixed installation has been evaluated. In particular, 21 subsystems have been considered: 5 electric traction substations, 13 sets of switch control circuit, the overhead contact line, the track circuit, and the hot-box detectors, for a total of 23 failure modes.

The SSD has been evaluated for different values of acceptable delay δ and results are shown in Table 9. These SSD values seem to show that the design choices on the fixed installation allow high dependability values to be achieved.

Table 9 SSD evaluation

delay δ	0	2	5	10	15	20
	0.99296	0.99534	0.99559	0.99645	0.99788	0.99985

A comparative analysis on the effect of each subsystem S on the SSD has been made in terms of the share of subsystem S on the service *un-quality* (1-SSD), defined as:

$$\frac{1-\Pr\{d_S \le \delta\}}{1-\mathrm{SSD}} \tag{19}$$

In Table 10 the share relative to subsystems: *a*) Electric Substations, *b*) Contact Line, *c*) Track Circuits, *d*) Switch Control Circuits, and *e*) Hot-Box Detectors, is shown for δ = 0 and 10 minutes. It appears that the more critical subsystems are the track circuits and the hot-box detectors, whereas the shares relative to the train power supply subsystems are small.

Table 10 Share of subsystems on quality degradation

Subsystem	δ = 0 minute	δ = 10 minutes
Electric subsystem	2.2 %	0.0 %
Contact line	5.8 %	6.7 %
Track circuit	51.7 %	34.5 %
Switch control circuit	8.6 %	9.9 %
Hot-box detectors	31.7 %	48.9 %

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