Impact of signalling and automation failure modes on railway operation: assessment by simulation

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Abstract
The dependability or RAM (Reliability, Availability and Maintainability) parameters are the most important elements that allow to estimate the Life Cycle Cost (LCC) of a system and to forecast performances during operating conditions. In the field of railway transportation, conventional measures, such as the mean delay of the train, or the Service Dependability (SD), can be profitably used to estimate the overall system behaviour taking into account the presence of failures.

In this paper the authors present a new methodology, fully implemented in the Excel® environment, for estimating the Service Dependability of a railway system. In particular the authors analyse the failure modes impact of an innovative signalling system (ERTMS level 2) on train operation in a typical lay-out for high speed railway lines, as far as scheduling fulfilment only is concerned. Starting from the reliability characteristic of the single items, the failure mode occurrence times are generated by means of a Monte Carlo procedure, already utilised by the authors in similar applications. The joint use of a general purpose traffic simulator allows then to evaluate the effect of failures on the travelling time, and the results collected during the simulations are statistically post-processed in order to estimate, for the failure modes analysed, the probability behaviour of the delay occurrence.

1. Introduction
In railway systems short and rare train delays are usually acceptable for frequent passengers. For this reason some conventional measures can be defined and utilised to estimate quantitatively the quality of service, strictly related to the schedule fulfilment.

In particular, the mean delay a generic train collects to reach the destination, and the Service Dependability [1, 2], that is the probability that a passenger, during a generic travel, collects a delay \(d\) not greater than an allowable quantity \(\delta\), can be assumed as indicators of the railway service quality.

In this paper a new methodology for the Service Dependability demonstration and estimation will be presented and it will be utilised by the authors for analysing the failure modes impact of an innovative signalling system (ERTMS level 2) on train operation. In particular, the case study refers to a typical lay-out for high speed railway lines and is focused on track circuits failure effects.

The overall evaluation of the ERTMS system failures impact on the train operation can be easily performed starting from the example described in this paper, once the RAM characteristics of the following main subsystems (signalling and automation) are taken into account: the Radio Block
Center (RBC), the Base Transceiver Station (BTS), the Base Station Controller (BSC), the Local Control System (LCS) and the Traffic Management System (TMS).

The kernel of the proposed modelling procedure is based on a simulator developed in the Excel® environment and already utilised by the authors in similar applications. Such simulator, starting from the reliability and maintainability characteristics of the single items, generates the failure mode occurrence times and the relevant times to repair by means of a Monte Carlo procedure. Subsequently, through a general purpose traffic simulator the effects of the components failure on travelling times are estimated. The traffic simulator, developed in the Excel® environment, is integrated with the aforementioned failure events simulator in order to automate completely the procedure. During the simulation time window, it is possible to analyse the behaviour of the railway system, collecting information about the delay associate to each trip as a consequence of the occurrence of one or more failure modes inside the system.

The results collected during the simulations must be statistically post-processed in order to estimate, for the failure modes analysed, the probability behaviour of the delay occurrence and, as a consequence, the Service Dependability of the system. As described by the authors in the last section of the paper, a further analysis can be developed on the mean value and the standard deviation of the delay to estimate the associate statistical confidence limits and, consequently, the influence of the sample size (number of simulations) on the final results.

2. The modelling procedure

To estimate the Service Dependability for a railway system a “deterministic” simulator has been developed using Excel® sheets. The first step of the simulation is represented by the estimate of the failure modes and relevant repair actions occurrence times. To this aim, a modelling procedure based on the Monte Carlo method, previously developed by the authors [3, 4, 5], has been used. With this procedure the occurrence of a failure or the duration of a repair event is simulated off-line, by means of the Monte Carlo method, computing a set of failure and/or repair times for each basic system component.

In this case a set of Times To Failure (TTFs) and a set of Times To Repair (TTRs) can be simulated starting of the RAM characteristic of each basic component. The Time To Failure and the Time To Repair of each item are random variables characterised by a Probability Density Function (PDF) \( f(t) \) and a Cumulative Distribution Function (CDF) \( F(t) \), both supposed to be known.

For each value of the random variable \( t \) in \((0, +\infty)\) \( F(t) \) assumes values uniformly distributed in \((0, 1)\). For this reason, samples of the random variable \( t \), distributed according to \( F(t) \), can be easily obtained generating a random number in \((0, 1)\) and consequently inverting \( F(t) \).

A set of TTFs and TTRs for each item of the analysed system can be so obtained; for instance, if the random variable \( t \) is exponentially distributed, the relevant PDF \( f(t) \) can be expressed as:

\[
f(t) = \begin{cases} 
\lambda e^{-\lambda t} & \text{for } t \geq 0 \\
0 & \text{for } t < 0 
\end{cases}
\]  

(1)

where \( \lambda \) is a constant, and the Cumulative Distribution Function \( F(t) \) is:

\[
F(t) = 1 - e^{-\lambda t}
\]

(2)

If the component TTF is characterised by such distribution, a sample is obtained by solving the following equation:
\[ TTF = \frac{\ln(1 - F)}{-\lambda} \]  

(3)

where \( \lambda \) is the reciprocal of the component Mean Time To Failure MTTF and \( F \) is, for any sample to be generated, a random number in (0, 1) get by Monte Carlo method.

The aforementioned procedure has been successively implemented in the Excel\textsuperscript{®} environment using the Excel\textsuperscript{®} function Random() that generates a random number in (0,1) following a uniform distribution function.

The failure modes occurrence times and the repair times are the input of a general purpose traffic simulator, developed by the authors in the Excel\textsuperscript{®} environment, that allows to analyse the traffic behaviour taking into account the logical relationships that drive the train operation when a particular failure mode occurs.

The traffic simulator has been integrated with the failure/repair times generation procedure, so that the analysis of the system behaviour can be developed in an automatic way, once the simulation time window has been defined. Such procedure allows to compute the travelling time for each train running along the track during the simulated time horizon, and the results can be suitably post-processed, as described in the next chapters, to estimate the probabilistic behaviour of the delay associate with the failure modes taken into account.

3. The real case study: ERTMS system level 2

Within a railway system, signalling and automation play a key role for safety and service quality aspects. Different signalling and Automatic Train Control (ATC) systems operate today in Europe and this fact represents a technical and operational barrier against railway interoperability. Until today, to allow trains crossing the borders of the European countries, it was necessary to equip the rolling stocks with different on-board signalling and ATC systems and to have driving personnel specifically trained to properly use them. For this reason, in order to come to an international standardisation of the European signalling systems, with particular reference to ATC systems, allowing the European railways to pursue technical and operational interoperability, the European Rail Traffic Management System (ERTMS) was born in 1995.

The ERTMS system [6, 7] is composed of two fundamental subsystems (the on-board system and the track-side system) and three different application levels have been foreseen. In particular, the application level identifies both the operating relationships between track and train and the functional/physical structure of each subsystem.

The ERTMS level 1 is a train control system based on spot transmission by means of balises and is used as an overlay to an underlying signalling system. In this case the train detection and integrity supervision, as well as the train separation and protection functions, are performed by the existing signalling system (interlocking, track circuits, etc.) and the relevant information is sent to the trains by means of the information points displaced along the track.

The ERTMS level 2 is a train control system based on radio transmission that can be used as an overlay to an underlying signalling system. The information needed by the on-board system to properly drive the train in safe conditions, is generated track-side by a Radio Block Center (RBC) and is transmitted to the train via the GSM-R media. The Radio Block Center can perform by itself all the signalling functions, including train spacing and protection. Spot transmissions are necessary only to send fixed information to the trains as location references, entry/exit points marking, power supply changes and so on. Train integrity information is safely provided to the RBC by means of track-side systems external to ERTMS, as track circuits and axle counters. In this case the track-side signals can be suppressed, but only fixed block signalling logic can be implemented due to the discontinuity of the track-side train integrity detection systems.
The ERTMS level 3 is a radio based train control system. This case is fundamentally equal to level 2 except the train integrity information, that is evaluated by the RBC based on the continuous information directly provided by the trains thanks to specific on-board devices. Also in this case the track-side signals can be suppressed, and moving block signalling logic can be implemented thanks to the availability of a continuous train integrity information.

In this paper the authors have analysed a typical lay-out for high-speed railway applications equipped with the ERTMS level 2 where the train detection and integrity supervision is performed by the track circuits. The analysed track is about 200 km long with 8 special operation stations and is equipped with more than 120 track circuits.

From the functional point of view, within the architecture taken into account, a Traffic Management System (TMS) is interfaced with the Radio Block Center (RBC) providing this latter with traffic control and regulation information to be translated into orders dispatched to the trains. By means of the GSM-R system, structured in a Base Station Controller (BSC) and several Base Transceiver Stations (BTS), each one covering a given track length, the RBC communicates with the trains. Several Local Control Systems (LCS), connected to the RBC and to the TMS by means of a fibre-optics communication network, safely control, each one, a portion of the track and operate locally performing interlocking functions and collecting, from the field, the track occupancy information to be used by RBC in order to properly carry out the vital signalling functions. In Figure 1 the block diagram of the analysed signalling and automation system is shown.

Being to date not yet available the RAM characteristics of all the subsystems, the authors have studied the impacts on train operations due to track circuits failure modes only. Despite this apparent simplification, all the different scenarios (each defined as a particular operating situation when a failure mode occurs) have been analysed and the associate rules to restore the system to normal operating conditions implemented in the general purpose traffic simulator using the Excel® Macro.

![Figure 1- Signalling and automation system block diagram](image-url)
4. Simulation results

For the simulation purposes, each special operation station has been modelled with a single track circuit and constant acceleration and deceleration rates have been considered. Moreover, the maximum train speed has been assumed equal to 300 km/h.

As mentioned in the previous chapters, the simulations have been carried out taking into account the possible failure of each track circuit. If a failure occurs, the train must stop at the beginning of the failed track circuit and must run along the failed section with a maximum speed of 30 km/h. At the end of the track circuit the train must stop again and then it can follow hereinafter the scheduled running profile.

A time window of 300 operating years (to obtain a large number of samples) has been taken into account for each simulation, and three different headways (600, 300 and 150 seconds) considered. In this time window the track circuits failure occurrence times have been simulated using the methodology based on Monte Carlo method and previously described. To this aim an exponential distribution of the Times to Failure has been supposed and the Mean Time To Failure equal to 122500 hours have been assumed for the line track circuits. For the track circuits modelling the eight passenger stations, the MTTF has been considered equal to 61250 hours. The Times To Repair for all the failure modes have been assumed constant and equal to 4 hours.

![Figure 2](attachment:figure2.png)

**Figure 2 - Histogram of the train delay (600 s)**

In Figure 2 the histogram of the train delay is shown for an headway equal to 600 s. On the abscissa axle the delay classes are represented, while the ordinate axle depicts the number of trips characterised by a specific delay class.

In Figure 3 and Figure 4 analogous histograms are shown, for an headway equal to 300 and 150 seconds respectively.
The travelling times recorded during the simulated time window have been post-processed to estimate the mean value and the standard deviation of the delay, for the three different headways. In the following Table 1 the aforementioned quantities are shown together with the associate 95% statistical confidence interval (in this case only the delayed trips have been considered). To this aim a normal distribution has been supposed for the mean values (Central limit theorem) and the chi-square distribution, with n-1 degrees of freedom, for the variable $n s^2/\sigma^2$ where n is the number of classes, $s^2$ the estimated variance computed using the simulation results and $\sigma^2$ the real variance of the population [8, 9].
Table 1 - Delay mean value and standard deviation (95% confidence interval)

<table>
<thead>
<tr>
<th>Headway [s]</th>
<th>Mean value [s]</th>
<th>Standard deviation [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>401 ± 2.5</td>
<td>64 ± 1.8</td>
</tr>
<tr>
<td>300</td>
<td>544 ± 3.1</td>
<td>559 ± 1.1</td>
</tr>
<tr>
<td>150</td>
<td>2741 ± 10.8</td>
<td>2935 ± 7.5</td>
</tr>
</tbody>
</table>

Table 2 shows all the quantities needed to estimate the probability that a passenger, during a generic travel, collects a delay \( d \) greater than 600 seconds \( \Pr\{d>600\} \), for the three different headways. Such probability, which allows the direct measure of the Service Dependability as \( 1-\Pr\{d>600\} \), has been computed multiplying the probability that a delayed trip has a delay greater than 600 sec \( \Pr\{d>600|E1\} \) and the probability that a generic travel is delayed \( \Pr\{E1\} \).

Table 2 - Probability to collect a delay greater than 600 s

| Headway [s] | \( \Pr\{E1\} \) | \( \Pr\{d>600|E1\} \) | \( \Pr\{d>600\} \) |
|-------------|-----------------|-----------------------|-------------------|
| 600         | 0.00016         | 0.00935               | 1.5 e-6           |
| 300         | 0.00373         | 0.06455               | 2.4 e-4           |
| 150         | 0.00473         | 0.76707               | 3.6 e-3           |

Table 3 shows the results of the last analysis carried out by the authors to estimate the influence of the sample size (number of simulations) on the final results. This table presents the mean value and the standard deviation of the delay (headway equal to 150 s), together with the associate 90% and 95% statistical confidence interval, for three different time windows (100, 200 and 300 years of simulated operating conditions). It is worth noting that in this case too delayed trips only have been considered.

Table 3 - Delay mean value and standard deviation (90% and 95% confidence interval)

<table>
<thead>
<tr>
<th>Estimate (headway = 150 s)</th>
<th>100 years</th>
<th></th>
<th>200 years</th>
<th></th>
<th>300 years</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
<td>95%</td>
<td>90%</td>
<td>95%</td>
<td>90%</td>
<td>95%</td>
</tr>
<tr>
<td>Mean value [s]</td>
<td>2754</td>
<td>2754</td>
<td>2723</td>
<td>2723</td>
<td>2741</td>
<td>2741</td>
</tr>
<tr>
<td></td>
<td>±15.7</td>
<td>±18.8</td>
<td>±11.2</td>
<td>±13.3</td>
<td>±9.0</td>
<td>±10.8</td>
</tr>
<tr>
<td>Standard deviation [s]</td>
<td>2945</td>
<td>2945</td>
<td>2941</td>
<td>2941</td>
<td>2935</td>
<td>2935</td>
</tr>
<tr>
<td></td>
<td>±11.5</td>
<td>±25.9</td>
<td>±6.4</td>
<td>±9.4</td>
<td>±6.4</td>
<td>±7.5</td>
</tr>
</tbody>
</table>

5. Conclusions

When industrial systems are commissioned, dependability requirements are usually set and the customer acceptance must be based on the assessment of their fulfilment too. For this reason suitable dependability models, to be implemented and solved by means of appropriate software tools, have to be used in order to predict and assess the system performances from a probabilistic point of view. For instance, when new railway signalling systems have to be adopted, the demonstration of the fulfilment of the Service Dependability, that is a conventional measure used to
estimate the quality of service, can be a very critical task and often unfeasible with conventional procedures. For this reason, the authors have proposed in this paper a modelling procedure, based on Monte Carlo method, which allows to estimate the behaviour of the railway system taking into account the occurrence of failure events. The whole model is implemented on a simple Excel® sheet: it does not need any specific software engine, it allows to model systems characterised by arbitrarily distributed failure events of the basic components, thanks to the Monte Carlo simulation, and it does not set constraints on the redundancy configurations and maintenance policies. The modelling procedure has been utilised for estimating the impact of railway signalling and automation failure modes on travelling times, taking into account, as case study, a typical lay-out for high speed applications equipped with the signalling system ERTMS level 2. In the paper the simulation results have been shown and through a statistical post-processing the estimate of the Service Dependability provided. The mean value and standard deviation of the delay, together with the statistical confidence intervals, have been computed and the results of a further analysis, carried out by the authors to evaluate the influence of the sample size (number of simulations) on the estimate have been presented.

6. References