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Level crossings ranking by integrated risk analysis for typical hazards

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Abstract

The paper starts from the introduction of the safety management systems, as tools for the continuous improvement of rail safety performances and for the processes to identify the most effective measures to prevent accidents. The focus is on the level crossings, largely representing the most dangerous elements of the railway networks. The scope is the setup of an effective methodology for ranking the level crossings in view of the prioritization of actions to reduce the risks on intersections between rail and road. The methodology will act as a strategic tool for the maximization of effectiveness of safety-related investments. The proposed approach is basing on risk analysis methods, focused on significant variables for typical hazards, customized for the level crossings' operation. The proposed method allows determining an up-gradable ranking process, which qualifies and sorts single level crossings according to typical hazards, addressing viable times and modes for their mitigation.

Keywords: Railway, Safety, Level Crossing, Risk Analysis, Hazards.

1. Problem position and general objectives

The paper is focusing the Level Crossings (LC) operation, which, according to all systematic surveys, largely represent the most dangerous elements of the railway networks all over the world.
The scope is the setup of an effective methodology for the ranking of level crossings in view of the prioritization of actions finalised to reduce the risks related to the intersections between rail and road. On this basis, the presented methodology acts as a strategic tool for the maximisation of effectiveness of safety-related investments.
Indeed the methodology combines:

- The effectiveness and the robustness, necessary to be widely recognized and accepted, only achievable by a rigorous and systematic approach;
- The openness and the flexibility, necessary to be fed by various databases and to tackle an as large as possible set of operational contexts and preventive measures.

The tests of the methodology were on the Italian railway network, thanks to the strict collaboration with Italian Infrastructure Manager (IM) *Rete Ferroviaria Italiana* (RFI), who supported the study by providing data and the support of their expertise.

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2. Literature review

In the field of risk analysis applied to railway systems, the literature is rich of relevant contributions. The present study took into account particularly the key results on data collection and statistical analysis provided by European Union Agency for Railways (2016), Agenzia Nazionale per la Sicurezza Ferroviaria (2017), Rail Safety and Standards Board (2017).
Basing on this consolidated data, the study proceeds considering the large set of measures to reduce the risk at level crossing. The main references in this context are the studies by Hughes B.P. (2003), Ukai M. (2004), Ishak S.Z., Yue W.L., Somenahalli S.V.C. (2008), Schöne E.J., Buder J. (2011), Rybalka R., Honcharov K. (2015), Günther F., Schemmel A., Schöne E.J. (2016), Koistinen J. (2016), Koschutnig L., Dinhobl G. (2017).
As a guidance for the methodological development, an analysis and review work was oriented specifically to the risk analysis methodologies applied or applicable to level crossing accidents.
The main references in this field are milestone papers by Braband J. (2001), Rail Safety and Standards Board (2005), Ben Aoun R., El Koursi E.M., Lemaire E. (2010), Berrado A., El-Koursi E.M., Cherkaoui A., Khaddour M. (2010), El Koursi E.M., Tordai L. (2010), Mariken H.C., Henk A.P. (2010).
More recent and methodologically concerned for the present study are the studies provided by Ritter N. (2011), Mahboob Q., Schöne E.J., Maschek U., Kunze M., Trinckauf J. (2012), Matsika E., Ricci S., Mortimer P., Georgiev N., O'Neill C. (2013), Bosse G. (2014), Chadwick S., Saat R., Dick T., Barkan C. (2014).

3. Methodological requirements and approach

The proposed methodology moves far beyond the state of the art because of the integration of the existing sectorial studies with the following requirements:

1. To be able to deal with the most innovative technologies and operational measures to reduce/cancel the risk for the following typologies of dangerous events (hazards):
   - Trespassing by vehicles and pedestrians of public and private level crossings,
   - Entrapment of vehicles within the barriers,
   - Protecting Signal Passing At Danger (SPAD),
   - Anticipated re-opening of barriers;
2. To be fed from the database of incidents and accidents systematically collected by Infrastructure Managers (IM), where the events are qualified by the standardised indicator Fatalities and Weighted Serious Injuries (FWSI) according to the recommendations of the European Union Agency for Railways and the geo-localised by *Google Earth*;
3. To provide general or selective rankings of level crossings, qualified in terms of the assessed effectiveness of the implementation of measures to reduce or cancel the risk at the level crossings, representing a key tool for orienting the investment strategies of the IM in the general interest of the Society.

Basing on these requirements, the methodological steps include:

A. Analysis and selection of the most promising technologies and operational measures implementable for reducing the risk consequent to each typology of hazard;
B. Detailed analysis of accidents and near missing databases collected by the IM, by selecting the most relevant parameters per each typology of hazard;
C. Cross correlation of these parameters with the frequency and the consequences of the hazards aiming at the selection of:
   - Significant correlations basing on data availability and their representativeness measured by stochastic tests;
   - Best correlations capable to create the link between the identified potential causal parameters and the corresponding hazard generation effect, in terms of both frequency and magnitude of consequences.

D. Combination of correlated parameters into global and partial indicators to produce priority rankings of the level crossings, where the effectiveness of the implemented measures would be maximum.

4. Relevance of LC accidents

The Level Crossing is a plane intersection among one or more roads and one or more railway lines equipped with devices able to temporary suspend the road traffic on it. The suspension of road traffic is by signals only or by physical barriers, managed by the IM or by private subjects, anyway operated under the assumption that road users

are acting according to the road safety rules.
Nevertheless, the level of risk and the probability of accidents at LC are normally high in comparison with those normally experienced in rail operation. This is a strong push to the progressive elimination of such intersections by all the IM: e.g. in Italy the rate of suppression is over 100 LC/year, though there are still in operation about 4500 LC on a network of approximatively 17.000 km.
However, the elimination of LC is naturally slow, due both to the resource needs and the not negligible time for the design and the construction of alternative infrastructures. Reason why it is recommendable to combine the suppression plans with the implementation of technological equipment or operational measures able to reduce, in the short-medium term, the probability of the accidents and their consequences.
On this basis, it is laying the potential benefit for the Society achievable by maximization the effectiveness of the investments dedicated to reduce the risks due to this typology of accidents.

5. Technological and operational measures for risk reduction

The majority of IM are working to analyse and select the most promising technologies and operational measures implementable for reducing the risk consequent to the typologies of hazards identified in section 3.
As an example, in Italy the solutions identified for the mitigation of the risk are those listed in Table 1, selected basing on a technical analysis of their mitigating performances and technical-economic assessment to quantify their effectiveness versus implantation costs and times.

Table 1: relationships between hazards and mitigation technologies

Hazard	**Mitigation solution**
Trespassing by vehicles and pedestrians	Not avoidable barriers (*Overall*)
Entrapment of vehicles within the barriers	Integrative automatic protection for obstacles detection (*PAI-PL*)
Protecting Signal Passing At Danger (SPAD)	Restrictive ATP functions (*VRIL10*)
Anticipated re-opening of barriers	Electronic pedals (*PE-PL*)
Trespassing of private LC	Remote authorisation systems (*Pr-PLp*)

6. Accidents and near missings databases

The next step is the detailed analysis of the databases collected by the IM, by selecting the most relevant parameters per each typology of the potentially dangerous events, including accidents and near missing (hazards) and correlating them with the frequency and the consequences of the hazards themselves.
The database used for the initial setup of the methodology was that issued by the Italian IM RFI basing on the requirements of the National rail safety agency (ANSF).
The used database is by Rete Ferroviaria Italiana (2009-2016) and each LC is identified by line, section, progressive km, typology, railway traffic, maximum allowed speed, closure time, road traffic intensity, number of tracks, rails-barriers distances, railway-road intersection angle, presence of road intersections in surrounding area, residential density in surrounding area derived by *Google Earth* geo-referenced maps.
To each LC is associated the database of hazards characterized by a value of the Fatalities and Weighted Serious Injuries (*FWSI*) according to European Union Agency for Railways (2016). Therefore, it is possible to calculate the total number of hazards and the total FWSI for each LC in the reference period.
The global volume of hazards was approximatively 1500 affecting about 600 Level Crossings. Figure 1 shows the territorial distribution of LC affected by hazards of the following four typologies:

- Undue opening of barriers (code SA32);
- Trespassing by vehicles (code SA43.1);
- Crash of vehicles against barriers (code SA43.2);
- Trespassing by pedestrians or cycles (code SA44).

7. Data analysis methodology

The statistical analysis of the databases aims to select:

- The significant correlations basing on the data availability and their representativeness measured by stochastic tests;

- The best correlations capable to create the link between the identified potential causal parameters and the corresponding effects, the hazard generation, both in terms of frequency and magnitude of consequences.

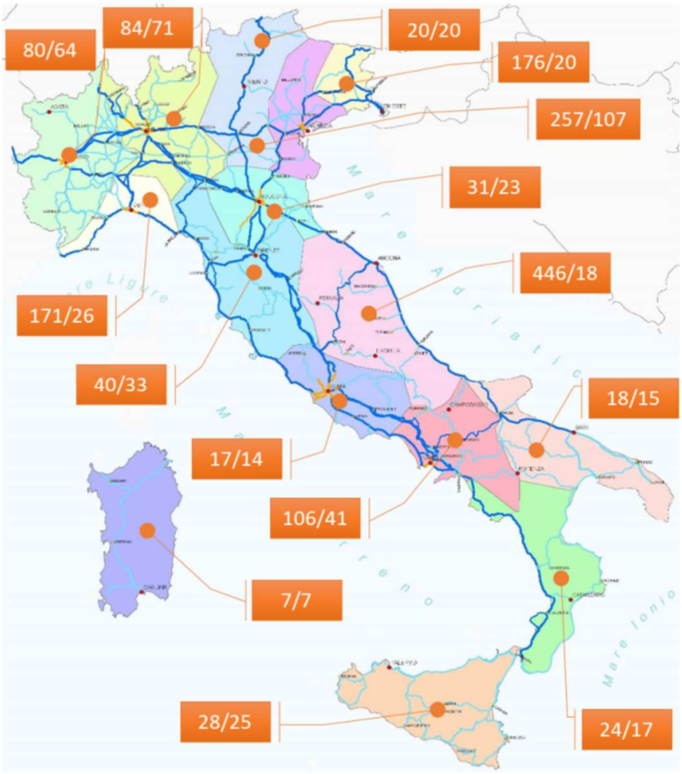

Figure 1: geographical distribution of LC affected by hazards in Italian network (amount of hazards / amount of affected LC)

The first step was to identify the most representative quantitative (numerical) and qualitative (descriptive) parameters and to associate them to a defined set of classes (variable from 2 to 6). The selected parameters, the related number of classes and their units as in Galli A., Genovesi P., Guerrucci L., Franco A., Marinacci C., Ricci S. (2017) are in Table 2.

Table 2: parameters selected for LC analysis

Selected parameters	**Classes**	**Units**
Typology	6	Descriptive
Maximum line speed	4	km/h
Daily traffic	4	Trains/day
Closure time	4	Min
Speed on LC	3	km/h
Traffic moment	4	Descriptive
Number of tracks	3	Number
Minimum rail-barrier distance	3	m
Distance between barriers	3	m
Worst railway-road angle	2	Descriptive
Road intersection in the surrounding area (<30 m)	2	Descriptive
Amplitude of railway-road angle	4	°
Density of residences in the surrounding area	4	Inhabitants/km^2

The correlation among these parameters and the hazards are looking for potential significant links in three different scenarios modulated by the gravity of the consequences expressed by FWSI:

- All hazards ($FWSI \geq 0$);
- Hazards causing injuries ($0 < FWSI < 1$);
- Hazards causing fatalities ($FWSI \geq 1$).

The investigated correlations (Figure 2) are among these parameters and the frequency of the hazards in each class of the concerned parameters:

$$f = \text{number of hazards / millions of trains circulated in the reference period} \quad (1)$$

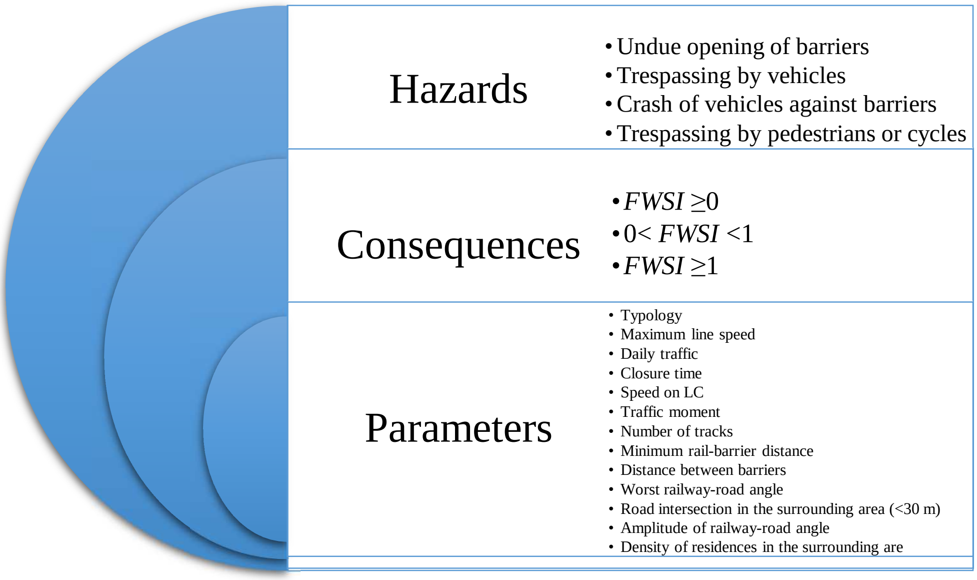

Figure 2: overview of investigated correlations

This hypothesis is valid under the assumption that the number of trains correspond to the number of closures of the concerned LC.
The next step is to assess the significance of the correlations according to filtering requirements.
In the investigated case study, the following minimum thresholds were filtering the significance of the 156 correlations:

- Minimum number of hazards per correlation: 20;
- Minimum number of hazards per class: 10;
- Ratio between extreme values of numerical frequency trend: > 1/3;
- Ratio between isolated frequency values of classes and other values: > 3.

The assessment of the correlations by the filters above allowed identifying the significant parameters, qualified as possible causal factors, both endogenous (typology and closure time) and exogenous (daily traffic, maximum line speed, traffic moment and density of residence) to LC. In Table 3, the resulting possible causal factors, set by frequency and split into the corresponding classes of hazards.

Table 3: Significant correlations useful to identify the Causal Factor Index (*CFI*)

Hazards	**Causal factors**
Undue opening of barriers	I. *FWSI* ≥0 - Daily traffic: 0÷50 trains/day (f = 14.5)
Trespassing by vehicles	I. *FWSI* ≥1 - Density of residence: 200÷600 inhabitants/km^2: (f = 60.8) II. *FWSI* ≥0 - Closure time: 3,5 min (f = 30.5) III. *FWSI* ≥0 - Road traffic: high (f = 30.1) IV. *FWSI* ≥0 - Typology: automatic with full barriers (f = 29.6) V. 0< *FWSI* <1 - Density of residence: 0÷200 inhabitants/km^2 (f = 15.3) VI. *FWSI* ≥0 - Maximum speed line: 121÷180 km/h (f = 7.9)
Crash of vehicles against barriers	I. *FWSI* ≥0 - Maximum speed line: 61÷120 (f = 37.3) II. *FWSI* ≥0 - Daily traffic: 0÷50 trains/day (f = 21.0)
Trespassing by pedestrians or cycles	I. *FWSI* ≥0 - Daily traffic: 0÷50 trains/day (f = 11.7)

The last methodological step is the setup of an indicator to produce priority rankings of the level crossings according to the potential effectiveness of the implemented technological and operational measures.
In the case study, the prioritization of the measures is basing on discriminant parameters applicable to each LC, as follows:

1. Total number of hazards;
2. *FWSI* value;
3. Causal Factor Index (*CFI*) defined as the sum of frequencies of hazards concerning the causal factors

identified by the correlation analysis reported in Table 3;
4. Deviation of the hazards frequency of each class by the highest frequency class.

8. Setup of the priority ranking

The described method is finally setting up a systematic ranking of level crossings in view of the prioritization of actions reducing the risks for the specific hazard.
The positive assessment of the reliability of the method is basing on the following aspects:

- Large (13%) sampling rate (600 LC affected by recorded hazards over a total of 4500 LC);
- Classification of Top LC in terms of number of recorded hazards and consequences (measured by *FWSI*) within the Top 50 of the ranking list;
- Positive review of the results by safety experts of the Italian Infrastructure Manager (RFI) with the consequent translation into an internal procedure, now in operation.

This last point implies the acceptance of the methodology and its expansion to the whole network, as a driver to estimate the latent dangerousness and maximize the effectiveness of the dedicated investments.
Moreover, the method itself and the generated ranking lists will include the natural dynamic update due to the decreasing number of operated LC, the temporary interruptions of lines and stations, as well as the progressive implementation of technological devices.
As an example of results achievable with the application of the method, in Table 4 a sketch of the classification of LC organized as follows:

- Iper-link to the Google Earth layout;
- Line ora station section;
- Technical ID;
- Ranking position concerning undue opening of barriers (code SA32);
- Ranking position concerning trespassing by vehicles (code SA43.1);
- Ranking position concerning crash of vehicles against barriers (code SA43.2);
- Ranking position concerning trespassing by pedestrians or cycles (code SA44).

Table 4: classification of LC with assignment of rankings for each hazard typology

Layout Google Earth link	***Line/Station***	***Technical ID***	***Ranking SA32***	***Ranking SA43.1***	***Ranking SA43.2***	***Ranking SA44***
Not available	Novara	LO1917-PL-SP01-PL1	570	139	517	585
Immagini PL\145- LO2001-PL-SP02-PL1.JPG	Padova Campo Marte	LO2001-PL-SP02-PL1	562	132	590	580
Immagini PL\66-LO2024-PL-SP01-PL1.JPG	Palmanova	LO2024-PL-SP01-PL1	158	48	389	226
Immagini PL\146 - LO3002-PL-SP06-PL1.png	Ve.Marghera Sc. - Venezia Mestre	LO3002-PL-SP06-PL1	598	492	276	600
Not available	Ancona - Ancona Mar. (Varco Lazzaretto)	LO0429-PL-SP01-PL1	574	204	2	587
Immagini PL\6-LO1122-PL-SP01-PL1.JPG	Civitanova Marche-Montegranaro	LO1122-PL-SP01-PL1	517	5	586	87
Not available	Ancona Marittima	LO0429-PL-SP02-PL1	526	254	383	556
Immagini PL\TR3502-PL-SP01-PL1.JPG	Udine - P.M.Vat	TR3502-PL-SP01-PL1	388	578	231	447
Immagini PL\465 - TR2141-PL-SP01-PL1.png	Monza	TR2141-PL-SP01-PL1	596	376	592	3
Not available	Ancona	LO0429-PL-SP02-PL2	561	250	591	579

As an example, very critical emerging situations, highlighted in red, are for LC in:

- Line 5, Top2 for crash of vehicles against barriers (code SA43.2);
- Line 6, Top5 for trespassing by vehicles (code SA43.1);
- Line 9, Top3 for trespassing pedestrian or cycles (code SA44).

9. Conclusions

The methodology setup and described in the present paper allows identifying, for each typology of hazard at LC, a prioritization criteria to rank the measures able to reduce the risk due to them. It includes a sequence of four discriminant parameters basing on an extended case study including almost 600 hazards affecting in 8 years a network of approximatively 17,000 km of lines

Moreover, the method is generalizable and expansible to whole populations of LC to make available an estimation *driver* of the latent dangerousness. On this basis, the presented methodology acts as a strategic tool for the maximisation of effectiveness of safety-related investments.

The nature of the indicators provided the method make the final rankings dynamic, according to the continuous update of consistence, operational, infrastructural and functional features (e.g. typology, layout, traffic, technological devices).

After the completion of the research and the development of a certain amount of validation tests, the reliability of the method allowed its inclusion into internal procedures for the prioritization of the implementation of risk mitigation measures by the Italian IM.

Acknowledgements

The research the paper is basing on was in strict collaboration with the main Italian IM *Rete Ferroviaria Italiana*, which co-founded the research and provided access to the relevant databases for factual calibration and validation tests of the methodological approach, as well as the expertise of their expert.

Finally, they included the setup method into the internal procedures for the ranking of risk mitigating measures at Level Crossings.

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