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Road and Rail Infrastructure II

Stjepan Lakušić – EDITOR



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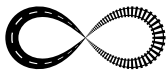
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A MODEL FOR ASSESSING COLLISION RISK ON AUTOMATIC LEVEL CROSSINGS

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Abstract

Railway engineers always point out Level Crossings (LC) as a one of the most critical points in railway networks from the safety point of view. Statistics show that more than 300 people are killed every year in Europe in more than 1200 accidents occurring at LCs. In this article, we carry out a comparative study involving two main types of Automatic Protection Systems (APS), the first using a pair of half-barriers and the second with four half-barriers. Each of these two automatic protection systems has some relative advantages and some drawbacks. In the literature and in railway and road guidance documents, some recommendations are given in order to make the choice between these systems. However, these recommendations are mainly based on a qualitative analysis.

Here, we suggest some behavioural models that can be used as a basis to assess the collision risk quantitatively on both LC configurations. These Stochastic Petri net (SPN) models describe the global dynamics within the LC area while taking into account both technical aspects and human behaviour. Our models are parameterizable and allow a realistic representation of the dynamics through the LC. Moreover, their simulation gives us a clear idea about the risk level according to various features of the dynamics within the level crossing area.

Keywords: Railway safety, level crossings, train-car collision, risk-assessment, stochastic Petri net, Simulation

1 Context and Motivations

The number of fatal accidents at Level Crossings (LC) has been significantly increasing over the years. Accidents at level crossings are the result of complex interactions between factors arising from the design and operations of level crossings. Statistics on railway accidents/incidents show how level-crossings are safety-critical. In many European countries, accidents at LCs cause up to 50% of total casualties in railway accidents.

Several types of level crossing protection systems can be used to manage the traffic operation in LC areas. In most LCs with high traffic moment, two main Automatic Protection Systems (APS) are used: 2-half-barrier APS and 4-half-barrier APS. Even though they are very similar, both of them have relative advantages and drawbacks according to the traffic circumstances within the LC area. The choice between them has always been based on a qualitative expertise of LC stakeholders, which may sometimes be quite subjective.

In this paper, we conduct a quantitative risk-analysis study to compare the two automatic protection systems. We aim to appraise which of the two APSs would be more efficient from the safety point of view according to several features of the LC area dynamics that we consider. For the purpose of developing an exploitable description basis of the dynamics in the LC area, Stochastic Petri Nets (SPN) have been used so that the aleatory fluctuations of the various pa-

rameters involved in the dynamics within the LC area, can be depicted precisely. Then, Monte Carlo simulation is carried out in order to appraise the LC collision risk with both investigated APSs and under different circumstances.

The paper is organized as follows: in section 2, we first show the general topology of the LC area. Then, the models depicting the dynamics within the LC area are elaborated and the main relative potential hazards for both APSs studied are examined. The quantitative risk assessment step is detailed in section 3. Finally, in section 4, we review the main contributions and we list the future tasks to be carried out.

2 Developing Models of the dynamics through the LC

2.1 Topology of the studied LC area

In our study we consider a junction between a unidirectional single track railway line and a bidirectional road. Two kinds of Automatic LC will be studied: Automatic 4-Half-Barrier Level Crossings (4HBLC) – composed of 4 half barriers (2 on each side)- and Automatic 2-Half-Barrier Level Crossings (2HBLC). Together, they formed about two-thirds of the total number of LCs in France in 2006 (vs. 46% in Germany³) and are the location of more than 75% of the collisions occurring at French LCs⁴ (38% in Germany). Besides the barriers, both LCs are equipped with train sensors, road lights and sound alarms (cf. Figure 1).

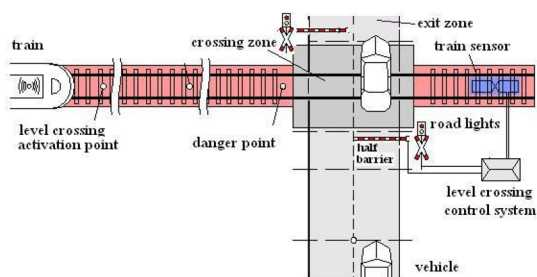


Figure 1 LC Topography.

When a train approaching the LC is detected by the train sensors, the closure cycle is initiated. The LC is reopened to road traffic as soon as the train is detected in the departure direction (also by train sensors).

As announced earlier in the paper, both 4-HBLC and 2-HBLC have advantages and drawbacks. Mainly, two major aspects will be pointed out:

- zigzags: 4-HBLC prevents road users from bypassing the barriers when the LC is closed to road traffic, while zigzagging remains possible with 2-HBLCs. Let us denote this situation risk₁.
- Traffic jam [1]: Traffic jams are a common phenomenon affecting road users. In the EU, on average, 7,200 km of traffic jams are formed every day. A problem that has caused several train/vehicle collisions at LCs is when a waiting queue is formed in the exit area of the LC. Indeed, it has been shown that, in general, when the LC is open (barriers in the high position and green road lights showing), and when a traffic jam occurs at the LC exit, road users arriving at the LC do not stop before the protection barrier, but enter the LC crossing zone (cz), thus risking remaining blocked on the rail track. Let us denote this situation risk₂. [4] gives a description of an LC accident due to road traffic queuing in Salisbury-South Australia, which caused 4 deaths and the injury of 26 people in the collision of a train with a bus and a car that were trapped on the track. In France, for instance, on average, this situation is the cause of 10 train-vehicle collisions per year. With 4-HBLC, the vehicle which enters the crossing in the presence of a traffic jam gets

trapped when the barriers come down. However, for 2-HBLC, the vehicle can leave the crossing zone as soon as the one ahead moves.

Both phenomena have been identified as major causes of LC accidents. In the sequel, models which depict the dynamics in the LC area will be elaborated. The situations mentioned above will also be taken into account.

2.2 Developed models

In order to depict the dynamics within the LC area, the progressive modelling approach developed in [1] will be applied. This approach, based on the Descartes principle, consists in splitting the studied system into subsystems. Then, before merging them with each other, elementary models for the obtained subsystems are established, while taking into account the interdependencies between the behaviours of these subsystems. In the same way as in [1], the LC area is divided into three subsystems: the railway side, the road side and the LC control system.

For the sake of precision, Stochastic Petri Nets (SPNs) will be used as a notation [2] in such a way as to act out the various aleatory phenomena characterizing the dynamics in the LC area. Only the global structure is given in this section; the dynamics parameters (time assignment, etc.) will be exposed in section 4.

2.2.1 Railway traffic

The model of the railway traffic dynamics is quite simple since trains dynamics is rather predictable and quite regular. As mentioned earlier, a unidirectional single track line is considered. We also assume that two train types with different speeds (passenger and freight) use the track and that the proportion of each type is a priori known, say p_1 and p_2 . In the model of Figure 2, in order to set these proportions, we use custom probabilities p_1 and p_2 respectively on concurrent instantaneous transitions T_1 and T_2 . Finally, we use truncation on the stochastic distributions assigned to the transitions in such a way as to avoid overlaps between consecutive train traversals.

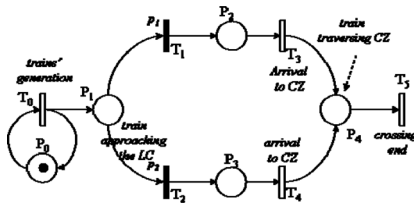


Figure 2 Railway traffic model.

2.2.2 Road traffic

Statistics show that the majority of accidents/incidents occurring at LCs are caused by misbehaviour on the part of road users (more than 95% in Europe according to [5]). Consequently, taking into account the road traffic dynamics becomes essential when carrying out safety studies on LCs. Existing works on LC modelling are often limited to railway traffic and the control system or take into account the road side in a very simplified way (ex. in [3]).

In this section, we will depict the road traffic dynamics. In our model, the traffic jam phenomenon is brought out, but zigzagging will be shown later, since it depends directly on the LC control system. Here, we assume that a traffic jam could arise in one direction of the road in the Exit Zone (Ez) of the LC. In this case, a dangerous behaviour of vehicles consists in entering the LC Crossing Zone (Cz) and incurring the risk of getting trapped in this zone while a train is arriving. The collision risk is clearly bigger with a 4-HB than with a 2-HB. Indeed, with 2-HBs

a risky car waiting on CZ can move as soon as the queue ahead moves on. In contrast, with a 4-HB, if the LC is closed to road traffic when the car with the risky behaviour is still on cz, then the car remains trapped on cz because the half-barrier at the LC exit is lowered. On the other hand, zigzagging is only possible with 2-HBs. Below, the model of the road traffic in the direction where there is a potential traffic jam situation is described independently of the protection system used. The differences in the road traffic dynamics, especially the possibility of zigzagging and the consequences of traffic jam formation, according to the LC protection system used will appear when the models of the defined subsystems are integrated.

In the model of Figure 3, P6 and T8 allow vehicle generation, T9 corresponds to entering the crossing zone (cz) and P8 and P9 model position in cz. T9 represents entering the exit zone (EZ) and Places P10, in [1,N] positions in EZ. T12 corresponds to the exit from EZ. P11 initially marked with N tokens -N being the vehicles' capacity of EZ- represents the remaining free places in EZ. Conversely, P12 contains the number of vehicles in EZ and stands for a counter. The traffic jam situation is modelled using the set {P15, P16, T17} and T18. The route in the considered direction is blocked when P16 is marked, which is represented by the inhibitor arc linking P16 to T12. We will adjust the durations associated to T17 and T18 in such a way as to set the proportion of time during which there is a traffic jam situation in the exit zone of the LC. Traffic jam may correspond, for instance, to the situation when some vehicles leaving CZ want to turn left. As they do not have priority, they may block the following vehicles. Also, a traffic jam situation may be caused by road-works on a portion of the route exiting the LC. The normal situation (without traffic jams on EZ) is represented by the upper sequence $T_9 \rightarrow T_{10} \rightarrow T_{11} \rightarrow T_{12}$. T9 is enabled only if EZ is not yet saturated. Otherwise, either of the immediate transitions T13 or T15 immediately fires. Conversely, T13 and T15 are enabled only if P11 is empty.

When EZ is saturated [$M(P_{12}) = N$, $M(P_{11}) = 0$], vehicles may behave safely, by waiting until EZ is no longer saturated; this corresponds to sequence $T_{13} \rightarrow T_{14}$. However, the vehicle may also adopt a dangerous behaviour while entering cz and incurring the risk of remaining trapped on the crossing zone until an approaching train arrives; this corresponds to sequence $T_{15} \rightarrow T_{16}$. Finally, when EZ is saturated, if the vehicle in front of cz decides not to proceed, then the following vehicles cannot advance; this is depicted with the inhibitor arcs linking P13 to T13, P13 to T15, P14 to T13, P14 to T15 and P14 to T9.

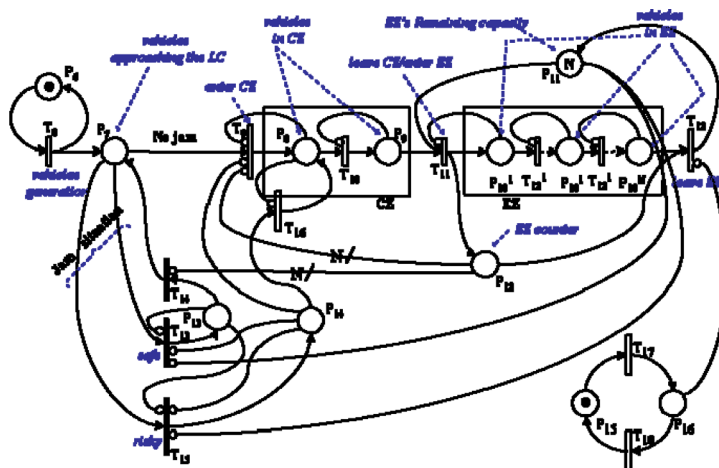


Figure 3 Road traffic model.

2.2.3 The LC control system

Here, we propose a quite simplified model of the LC control system dynamics. Two states of the system are considered: open, when the road lights are switched off and the barriers are raised, and closed, when the road lights show red and the barriers lowered (cf. Fig 4). The protection system is supposed to operate safely.

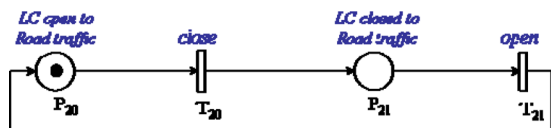


Figure 4 Local control model.

3 Risk-assessment

In this section, first the global model describing the dynamics within the LC area is established. This model is obtained by merging the models of the subsystems previously developed. Model integration is done while taking into account the interdependencies between the individual behaviours. Secondly, numerical simulation is proceeded in order to quantitatively assess the risk according to several setups we make. The results are interpreted in order to point out some features relative to 2-HBLC and 4-HBLC.

3.1 Representation of the global dynamics within the LC area

Since the LC control system is responsible for managing the traffic within the LC area, it stands for an interface between the railway traffic and the road traffic, and there is no direct interaction between them. Basically, the control system gives absolute priority to the railway traffic whenever a train is approaching.

- between the railway traffic and the control system: independently of the type of protection system used (either 2-HBLC or 4-HBLC), whenever a train is detected by the sensor in the arrival direction, the closure cycle is started and the LC is considered to be closed when the road lights show red and the barriers are lowered, namely 8 seconds later. Conversely, as soon as the train is detected in the departure direction, the LC is reopened to road traffic, that is 5 seconds later. All these interactions are depicted in grey in Figure 5. Namely, two new places are added to our model: Pa for train arrivals and Pd for train departures.
- between the control system and the road traffic: the interaction between these subsystems depends on the type of protection system used.

- 1 2-HBLC: with 2-HBLC, as soon as the LC is closed to road traffic, entering CZ becomes prohibited for the arriving vehicles. In case of traffic jams, if some vehicles remain on CZ after the barriers are lowered, they may move as soon as the queue ahead advances. In order to take into account these elements, some modifications (in grey) are made to our models (cf. Figure 5). On the other hand, some undisciplined drivers may incur the risk of crossing CZ by bypassing (zigzag) the half barriers. This will be depicted in mauve. In particular, sequence $T_{30} \rightarrow T_{31}$ with probability $prisk_1$ assigned to T_{30} stands for entering CZ while the 2 half-barriers are lowered. In contrast, $T_{32} \rightarrow T_{33}$ represents a safe behaviour, which is the one where the arriving vehicle waits until the LC is reopened to road traffic. It should be noted that the model part depicting zigzagging ($P_{30}, P_{31}, T_{30} \rightarrow T_{33}$) is quite similar to the one relative to the vehicles' behaviour in a traffic jam situation ($P_{13}, P_{14}, T_{13} \rightarrow T_{16}$). What is different in the latter is the extra inhibitor arcs emanating from P_{13} . This expresses the fact that, when the heading vehicle arriving at the LC stops before CZ in traffic jam situation, the following vehicles cannot proceed. On the

contrary, concerning zigzagging, the attitude of the leading vehicle does not influence the behaviour of the following vehicles. In other terms, when the LC is closed to road traffic, whether the leading car decides to zigzag or not, the following vehicles may adopt either a risky or a safe behaviour.

- 2 4-HBLC: with 4-HBLC, as soon as the LC is closed to road traffic, arriving vehicles cannot enter CZ. Moreover, in traffic jam situation, if some vehicles remain on CZ after the barriers are lowered, they cannot proceed, even if the way ahead is clear. This fact is depicted (in blue) in the global model (cf. Figure 5). The part composed of P_{21}' , T_{20}' (deterministic(6)), P_{21}'' and their associated arcs has been added in order to model the fact that, 4 seconds after the barrier at the entry of the LC has been lowered, the barrier at the exit side is lowered, thus preventing possible vehicles on CZ from leaving this zone. In contrast to 2-HBLC, zigzagging is not possible when the barriers are lowered. In Figure 5, the mauve part (zigzagging) is specific to the 2-HBLC and the blue inhibitor arc is specific to the 4-HBLC. All the other parts are common for both protection systems. Actually, there are 2 different models, but, for the sake of conciseness, we use one model while pointing out the differences. Here we have chosen temporal parameters relative to an urban LC with a medium traffic moment: one train every 10 minutes and 1 vehicle every 10 seconds, on average. The time characterization has been chosen so as to be quite realistic. For instance, vehicle generation is depicted with a Poisson distribution, whereas train generation is made with a discrete distribution, since the arrival of trains is more regular.

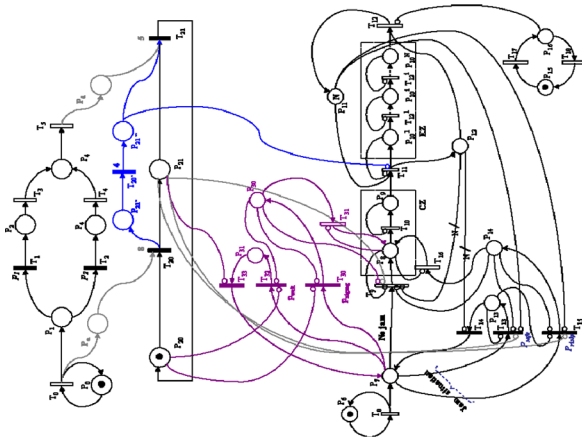


Figure 5 Global model.

3.2 Numerical analysis

The numerical analysis is carried out by a Monte-Carlo simulation on the basis of the global model. The impact of the scrutinized parameters (traffic moment, traffic jam length, arrival vehicle rate, etc.) can be assessed by varying the values of these parameters. Note that what is important from the results obtained is not the risk values themselves, since these directly depend on the considered environment parameters, but their variation according to the investigated parameters and for the two APS comparatively to each other.

Finally, the obtained results may help decision makers from the road and railway sides to take appropriate measures in order to decrease the risk by acting on some controllable parameters (intermitting traversing delay for instance).

4 Discussions and future works

In this paper, first a general overview on the safety of level crossings throughout Europe and on risk analysis methods in railways is given. Then, a risk assessment study is carried out with the aim of scrutinizing potential dangerous situations according to two distinct configurations of LC automatic control systems.

The main contribution of our study consists in developing a parameterizable model which may serve as a template for risk assessment relative to the main potential hazards discussed beforehand. To our knowledge, this is the first work dealing with this issue. Moreover, it is worth noticing that our model takes into account both railway and road dynamics, but it also considers humans error, which is quite new with regard to existing studies on LC model-based risk assessment. Obviously, the results obtained depend directly on the predetermined parameters of the dynamics, and consequently, the established model has to be adapted to the situation under investigation.

Safety analysis of railway systems involves complex interactions between technological devices, rules and directives, and human behaviour [6]. We intend to deepen our safety analysis investigation on level crossings while exploring different factors impacting LC safety.

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