

Petri Nets Approach in Assessing the Safety at Level Crossing—The Effect of Traffic and Train Characteristics on Safety Measurement

Siti Zaharah, I.¹, Yue, W.L.² and Somenahalli, S.V.C³

¹ PhD Candidate, ISST- Transport Systems, University of South Australia, Australia

² Program Director, Senior Lecturer, School of Natural & Build Environment, University of South Australia, Australia.

³ Lecturer, School of Natural & Build Environment, University of South Australia, Australia.

ABSTRACT

Level crossing safety is a complicated subject, which is determined by numerous aspects including engineering factors, human errors and combination environments surrounding level crossings. This paper introduces a holistic approach in level crossing safety modelling by using Petri nets. The main aim of this paper is to study the effect of the traffic and train characteristics on safety measurement at level crossings. The result indicates that Level of Service (LOS) and the level crossing distance from the nearest intersection are the sensitive parameters in the Petri nets model.

Key words: Level crossing safety; Safety modelling; Petri nets

1.0 INTRODUCTION

Railways play an important role in providing effective transportation systems to communities. Travelling with railways are safer compared with other modes of transport; however the reported level crossing accidents indicate that more research needs to be directed in this area. The complexity of the railway line at level crossings involves at least two modes of transport intersecting at one point in time and space can result in catastrophic consequences. The level of severity in this type of accidents has drawn extreme attention from public, professionals and transport authorities (Davey et al., 2008b).

This paper attempts to discuss the holistic approach using Petri nets—mathematical modeling languages for the description of discrete distributed systems, with the use of data from South Australia as a case. The Petri nets model will use the Australian Level Crossing Assessment Model (ALCAM) database — Level Crossing Management system (LXM) forming a basic guideline in identifying the most dominating parameters. The flexibility of the Stochastic Petri nets (SPN) and Petri nets tool Π -tools in dealing with qualitative and quantitative data makes it possible to use this approach in the real application of level crossing safety systems for South Australia.

2.0 BACKGROUND

Strategies for improving level crossing safety through comprehensive level crossing safety modelling have been developed by many countries during the past few decades. In Australia, models such as Risk Base Scoring Systems (RBSS), Australian Level Crossing

Assessment Model (ALCAM) and Risk Assessment of Accident and Incident at Level crossings (RAAILc) were developed. The ALCAM model supplants the RBSS and is essentially an improved and extended version of the same model. The ALCAM model is designed to apply on both active and passive level crossings; whereas the RAAILc model can be used to predict accidents at passive level crossings only. The Rail Safety and Standard Board (2007) in the UK has categorised ALCAM under a simple weighted factor—provide some indications of the relative risk contributions of each parameter under a simple defined weighting and a RAAILc as statistically driven approach—based on statistical techniques to determine the weightings. Currently, ALCAM model has been adopted nationally and implemented across Australia. However, the model is still undergoing further development (Spicer, 2007).

Recently, the Coordination Action for the Sixth Framework Program has formed a Safer European Level Crossing Appraisal Technology (SELCAT) consortium. The aims of SELCAT are for knowledge collection, exchange and the identification of the best practices for future design of European level crossings. SELCAT has endorsed a study by Slovak and Schneider (2007) as a work example in modelling the functionality and dependability aspect of the level crossing systems by using a Petri nets approach in real application for their future design of European level crossings.

The work conducted by Slovak et al. (2007) has provided a great motivation in this study. A Petri nets approach used in real application of level crossing safety systems offers several advantages than conventional methods—statistical analysis, fault tree analysis. Girault and Valk (2003) emphasized on the advantages of Petri nets in offering a graphical and mathematical founded modelling formalism as a great comparison. The conventional methods mostly concentrate on one property. A complex system such as level crossing involves large scale design of several parameters. Therefore an abstraction and hierarchical design is crucial. Petri nets allow abstraction and refinement that well integrated into basic models. Several limitations using conventional methods are encountered by Haile and Hess (2006). Conventional methods commonly deal with quantitative analysis and require past accident data at which lack of accident data is faced by many countries. Meanwhile, fault tree analysis used in many studies has created uncontrolled number of accident path. Therefore, Markov Chain and Petri nets approaches are suitable to overcome this problem.

3.0 PETRI NETS IN RAILWAY MODELLING

Petri Nets is a mathematical modeling tool which was invented by Carl Adam Petri in 1962. Petri Nets is a capable tool for specification and analysis of concurrent, asynchronous, distributed, parallel, nondeterministic and stochastic processes. Through graphical representations, Petri Nets can be used as a visual communication aid similar to flow charts, block diagrams and networks. The Petri Nets is allowed to set up state equations, algebraic equations and other mathematical models leading to an understanding of the system behavior. From the basic Petri nets, extensions such as Coloured Petri Nets (CPN), Timed Petri Nets (TPNs), Stochastic Petri Nets (SPN), Generalised Stochastic Petri Nets (GSPN) have been developed.

Petri Nets have been designed to model the behaviour of dynamic systems. Recently, the

application of basic Petri Nets and other Petri Nets extension (high level Petri Net) such as Hierarchical nets, Stochastic Petri Nets (SPN) or Coloured Petri Nets (CPN) are broadly used in the field of railway networks, operation and safety. Due to its versatility with large calculation capabilities and abilities, Petri Nets are popular in railway engineering and widely studied.

Numerous studies using Petri Nets approach in railway safety have been conducted to examine various factors. For example, several studies had looked into the application of CPN to investigate the functional correctness and performance of the railway networks systems (Janczura, 1998, Jansen et al., 1998, Fanti et al., 2006), consistency and safety of operational and technical devices at level crossings (Einer et al., 2000) and in communication based train control (CBTC) system to increase track utilisation and safety (Xu and Tang, 2007). Petri Nets and their stochastic timed extensions have proven to be a useful formalism for real-time systems. They are considered to be a concise and appropriate way in describing the event systems (Zimmermann and Hommel, 2003). SPN and stochastic timed extension methods is used by Slovak et al. (2003) to describe the railway control process, the function of the railway control systems and the system's function dependability. Human behaviour at level crossings also has been explored using Extended Deterministic and Stochastic Petri Nets (EDSPN) (Slovak et al., 2007).

The aforementioned studies have looked into the main events (top level event) or scenarios that lead to accidents at level crossings and the findings are seen as limiting the understanding of the causes of incidents and precursors. Therefore an improved methodological approach is proposed to provide a deeper understanding not only at the top level event but also at the contributing events which then leads to the main event. All events and sub events will be further categorized into various factors which include engineering infrastructure, level crossing surrounding environment and human factors.

4.0 PETRI NETS MODELLING FOR LEVEL CROSSING SAFETY

4.1 Methodological framework

The methodological framework in assessing the level of risk at level crossing locations is described in Figure 1.

The modelling process involved four different stages. The first stage required an understanding on the level crossing operation, current practices and tools available for analysis. The operation of active level crossings in Australia is based on the Australian Standard: *Manual of Uniform Traffic Control Devices, Part 7: Railway Crossing (AS 1742.7-2007)*. Further categorization is made from the existing ALCAM database—LXM. The suitable Petri nets tool is identified in order to archive the desired research outcome. The suitable Stochastic Petri nets tools— Π -tools are selected. The Π -tools allow creation of complex models with proper classification of states and transitions.

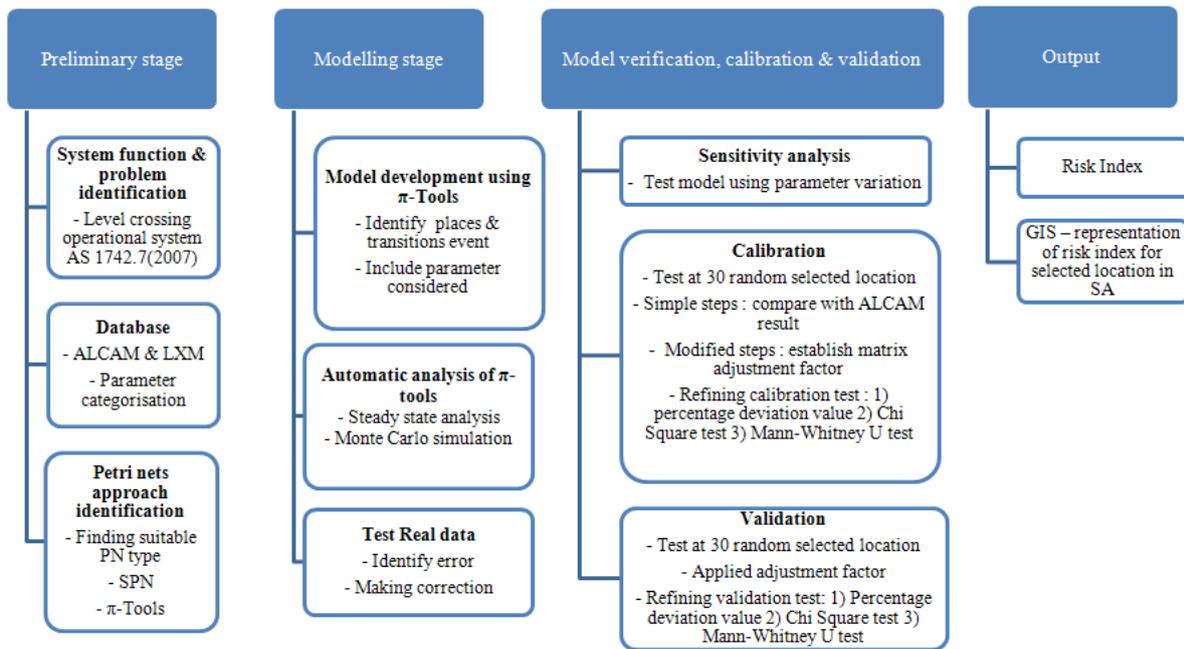


Figure 1 Methodological framework

The second stage is a modelling stage. The entire operation and the best parameter estimates are obtained from the existing ALCAM database are built into the Petri nets model structure and translated into Petri nets language containing place and transitions. Then the completed model is tested and the system is measured through simulation and automatic model checking using Π -tools. This tool allowed automatic verification for steady state and Monte Carlo simulation. If the expected measure is not achieved, the input parameters need to be modified. If the output is equivalent to the real operation then the system is complies.

Model verification, calibration and validation are the third stage in this methodological framework. The process involved the process of proving in the model specified. The verification process involved checking if all parts of the model are reflecting the real operation and the technical behaviour of a level crossing system. In this process, the sensitivity analysis is applied to measure the parameters effecting to the model. The purpose of the calibration process is to make necessary adjustment to the model. Lastly, model is validated in order to prove the model's outputs against reality. The output will be the basis for the development of the level crossing risk indices for the South Australia cases. This development will be supported with the application of Geographic Information System (GIS) at later stage.

4.2 Petri nets concept and terminologies

In order to support the modelling requirement, suitable formal modelling language were applied. The structure of Petri nets is visualized as a bipartial graph. The two disjunctive types of nodes are places and transitions. The places are represents by circles and transitions represents by rectangles. The transition is an active component of a Petri nets and represents activity. Place can be considered as a passive component and represents conditions for events or local states. A token in Petri nets is the volatile component and is

used to model objects. The causal structure of the systems is determined by oriented arcs. An arc will allow the change of state by transferring a token from one place to another by firing the transition. An arc, which is an input as well as an output arc, is called a test arc. A test arc reveals the causal relationship between conditions and events, but will not lead to deleting the condition after the occurrence of the events. For example, the token will still remain at the place after the transition fires. Another special arc is an inhibitor arc which inverses this condition. This means, a transition occurrence is allowed only if the place connected by an inhibitor arc is free from the token.

To meet the requirements of the method, extended stochastic and deterministic Petri nets (EDSPN) were used. The EDSPN allows four types of transitions. There are immediate, deterministic, exponential and general stochastic transitions which reflect temporal behaviour depending on the time parameter as illustrated in Figure 2.

The EDSPN allows qualitative and also quantitative analysis for proving performance and safety properties of the systems described by the net. Using the steady state analysis, the system state probabilities at the infinite time can be obtained.

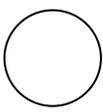
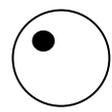
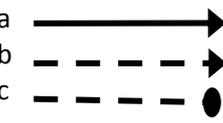
Symbol			 a b c d	 a b c
Type	Places	Places with token	Transition a) Immediate transition b) Deterministic transition c) Exponential transition d) General stochastic transition	Arc a) Normal arc b) Test arc c) Inhibitor arc

Figure 2 Basic symbols of Petri nets

5.0 MODEL DEVELOPMENT

5.1 Parameter estimation

Table 1 Input parameter and criteria

Traffic volume	Traffic parameter	Criteria	Train parameter	Criteria
Traffic / hr Train / hr	Approaching speeds	≤ 60 kph > 60 kph to 80 kph > 80 kph	Approaching speed	≤ 60 kph > 60 kph to 80 kph > 80 kph to 100 kph > 100 kph to 120 kph > 120 kph
	Heavy vehicle percentage	5%, 10%, 25% & 50%	Length of train	< 60 m 60 to 300 m
	Level of Service (LOS)	LOS A, B, C, D, E & F		> 300 to 1000 m > 1000 m

A complete database obtained from LXM established by ALCAM. ALCAM will be the basis of model comparison and as a guideline in this study. The input parameter and criteria used in the model is shown in Table 1. The parameters considered the basic operation at level crossing are train, traffic and signal control. The main input parameter is the traffic and train volume per hour. Traffic parameters considered factors such as approaching speeds, heavy vehicle percentage, Level of Service (LOS) and approximate level crossing distance from the nearest intersection. An approaching train speed and the length of the train are factors considered for train.

5.2 Model Hierarchy

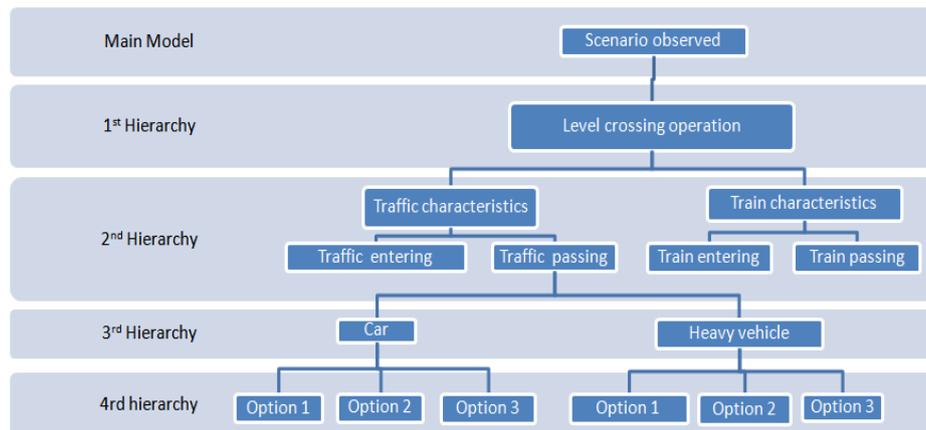


Figure 3: Model structure

The model is developed including various sub-models, known as hierarchy shown in Figure 3. The highest hierarchy represents the main model. It shows the events or scenarios in the operation.

- The first hierarchy of the model represents the basic level crossing operational systems—integrating elements such as train operation, traffic operation and signal control operation.
- The second hierarchy incorporates two sub models and categorised as traffic and train characteristics. Under traffic characteristics, two potential events observed is traffic entering interaction area and traffic passing interaction area. The same event is observed under train characteristics.
- The third hierarchy is basically the sub model of traffic type passing the interaction area. The choice of either car or heavy vehicle passing will depend on the heavy vehicle percentages given in the traffic entering parameter.
- The fourth hierarchy involves the option of traffic type chosen to pass the interaction area by considering the level crossing distances from or to the nearest intersection. It is an important parameter since the distance will affect the driver judgement when passing the interaction area.

An example, Figure 4 illustrates a level crossing operation in Petri nets. All symbols and terminologies used in this figure are based on the definitions listed in section 4.2. This operation represents the first hierarchy in the model.

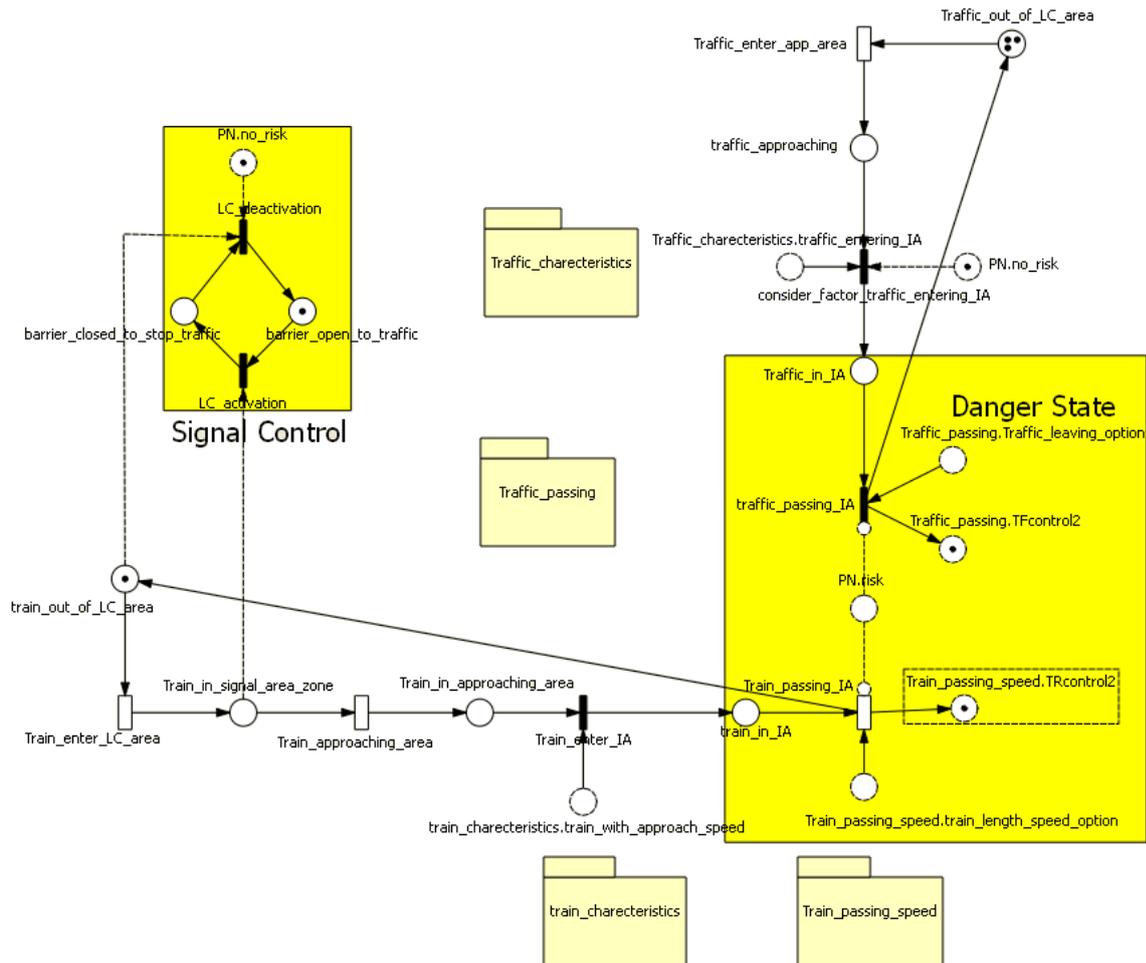


Figure 4 Level crossing operations in Petri nets structure

At level crossings, there are three main operations involved— traffic, train and signal control. The traffic operation starts with token in place represents *traffic_out_of_LC_area*. All activities presented by transitions allow token transferred from one place (condition) to another. The first activity is *traffic_enter_approaching_area* and allows one token (traffic) removes from the initial place to *traffic_approaching* place. Traffic need to consider other traffic parameter as demonstrated in the sub model of traffic characteristics before entering the interaction area (IA)—the area of traffic and train could meet. If there is no indication of oncoming train from the signal control, therefore traffic will be in *traffic_in_IA*. Otherwise traffic needs to stop at *traffic_approaching* place and permits train to pass the level crossing. At this stage, the traffic needs to consider traffic passing factors as demonstrated in the next sub model. Then the traffic can continue journey as *traffic_passing_IA*. The entire operation will start again when the token back in *traffic_out_of_LC_area* place.

The train operation starts with token in place represents *train_out_of_LC_area*. The activity takes place when the *train_enter_LC_area* and the token transfer to *train_in_signal_area_zone*. In this zone, the track circuit detects the oncoming train and activates the signal control. Signal is given to stop traffic and barrier is closed. Then, the train approaches the level crossing area. Train needs to consider train characteristics as indicated in the sub model and enter the IA as *train_in_IA*. Train needs to consider train

passing speed factors as designated in the next sub model. Then the train can continue the journey and *train_passing_IA* safely. The signal control detects the leaving train and signal given to deactivate the signal by open the barrier to traffic and permit traffic to pass the level crossing safely.

6.0 MODEL ANALYSIS AND DISCUSSION

The sensitivity analysis conducted is to study the effect of the traffic and train characteristics to safety performance at level crossings. The potential risk sensitivity value is based on the range of train and traffic parameters and criteria as set in Table 1.

6.1 Traffic characteristics

a) Heavy vehicle percentage

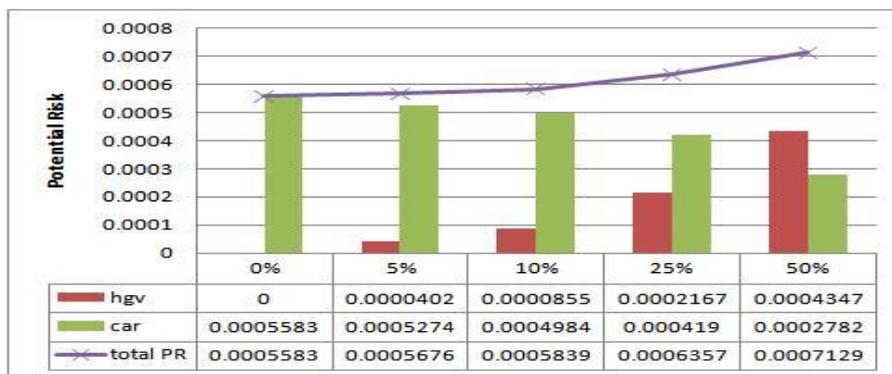


Figure 5 The potential risk according to heavy vehicle percentage and traffic type

According to traffic types, the potential risk measures for heavy and light vehicles are presented in Figure 5. The potential risk value is based on heavy vehicle percentage on the road. The potential risk values obtained from the graph is the combination of the risk posed by light and heavy vehicles when passing the interaction area. With increasing of heavy vehicles, the potential risk measures are also increases. For example, when heavy vehicles are at 50 percentages, the risk posed by them is higher compared with light vehicles even the traffic volume is the same. The risk posed by heavy vehicles is 36 percent higher than light vehicles when the percentages of traffic types on the road are equal as illustrated in Figure 5. Davey (2008a) reported that in recent years the number of heavy vehicles and train accidents at level crossings in Australia has been increasing compared with light vehicle incidents. The factors contributed were due to the size and mass of heavy vehicles.

b) Traffic LOS and approximate level crossing distance from the nearest intersection.

According to traffic parameters, the potential risk—heavy vehicle percentage, traffic LOS and the approximate distance from the nearest intersection is illustrated in Figure 6. Since the analysis contains large amount of information, the distances of more than 200 m and less than 20 m are selected as case analysis. Traffic LOS is a qualitative measure of traffic conditions on the road. The LOS varies from LOS A (free flow), B (stable flow, reasonable freedom to select speed), C (stable flow, restricted freedom), D (flow becoming unstable, all

drivers restricted in free), E (traffic volumes at or close to capacity) and F (forced flow) respectively. In the model, the LOS is categories into three groups such as LOS A and B, LOS C and D and LOS E and F to simplify the model structure.

Overall, the graph shows that the potential risk value increases as the heavy vehicle percentage increases. Higher potential risk obtained at LOS E and F and at less than 20 m distance to the nearest intersections. The differences for the potential risk values at the two distances chosen are significant. The potential risk values are higher when the distances of the level crossing to or from the nearest intersection is less than 20 m. These indicate that the higher risk is posed at level crossing when traffic LOS is at E and F. It was due to the fact that at LOS E and F, the traffic volume is close or at the capacity and caused impeded traffic acceleration. Furthermore, the intersection location which is closer to the level crossing also will significantly increase the risk, especially when it is at a signalised intersection. In reality, the risk of heavy vehicles passing the level crossing is higher due to various reasons such as mass and size of heavy vehicles, and the load carried, etc.

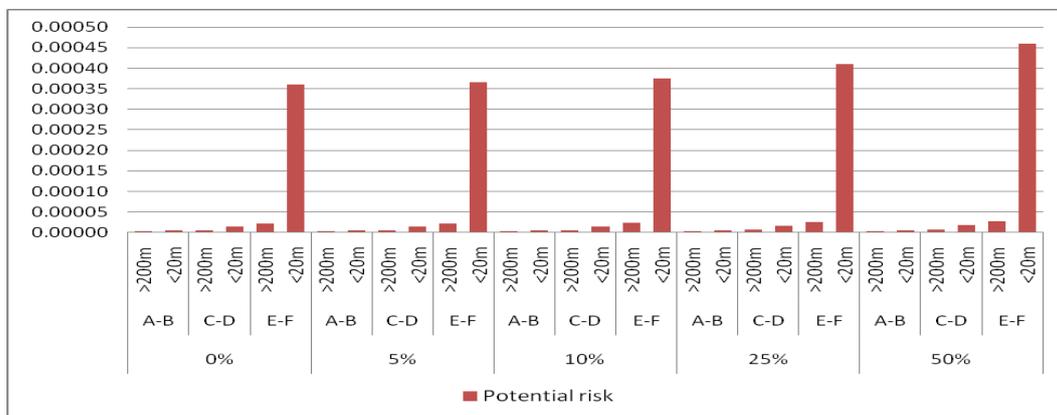


Figure 6 The potential risk according to traffic parameter

6.2 Train characteristics

Key train characteristics considered in the model are approaching speed and the train length. The results are tabulated in Figure 7. The following discussion is referring to Figure 7.

a) Train approaching speed

This factor is important to measure the time in the formation of a risk situation. Different approaching speeds give different time for trains approaching to a level crossing. The approaching speed in this study used 60 kph and greater than 120 kph. The results showed that the potential risk value is higher as the train speed greater than 120 kph and when the traffic LOS is at group E and F. This is due to vehicle drivers may have less time to react on the fast approaching train and take action to clear the interaction area.

b) Train length

The criterion for the train length ranges from less than 60 m to more than 1000 m. In common sense, the potential risk value will be lower when train length is shorter, as the exposure in the interaction area will be less. The potential risk value becomes higher as the

train length is longer. It is due to the fact that the mass of the train will make the train operators have less capacity to react with different scenarios.

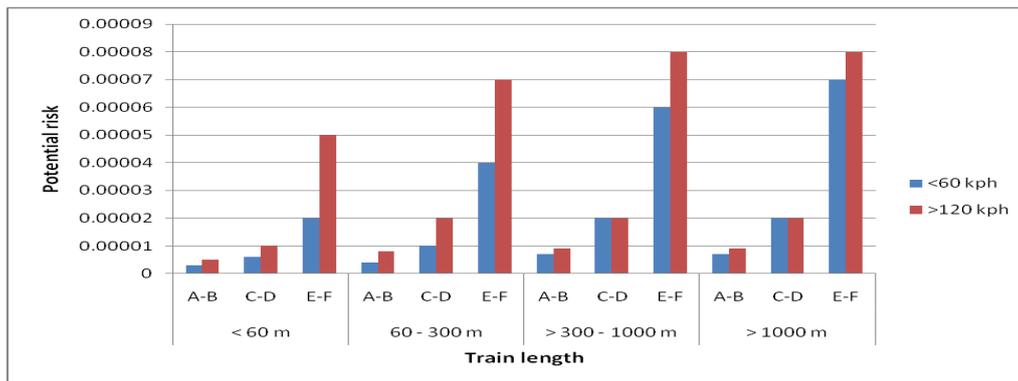


Figure 7 The potential risk according to train parameters

7.0 CONCLUSION AND FUTURE WORK

This paper introduced the concept, model structure and the application of Petri nets as a new approach in dealing with real time studies for level crossing safety. The model is designed to evaluate the likelihood of various scenarios measuring the potential risk at level crossings. The model not only focuses on the basic operations at level crossings but also considers the other factors contributing to the safety performance at level crossings. The sub-nets represented in the paper considered factors that influence the formation of possible risks at level crossings. There are traffic behaviour and train operation characteristics such as the approaching speed, the level of service, heavy vehicle percentage, train length and approximate distance from the nearest intersections; which may heavily affect the safe operations for level crossing locations. The impact magnitude of these factors was calibrated by sensitivity tests. It may be concluded that the important factors contributing to the higher potential risk were the effect of LOS and the distance of the level crossing from the nearest intersection as shown in the simulation processes. It is believed that the model may help engineers in selecting sound alternatives in prioritising locations for improvements or upgrades at level crossing locations. This is an ongoing research project. The next step is to incorporate the application of GIS in spatial representation of level crossing locations which will link model output with visualisations of the surrounding land use environments, and further enhance the understanding of level crossing accident phenomena.

ACKNOWLEDGEMENT

The authors would like to thank Prof.Dr.-Ing.Dr. h.c Echehard Schneider, the director of The Institute for Traffic Safety and Automation Engineering, Technical University of Braunschweig for his support and valuable ideas in this research. Special thanks also to the rest of the members in the Institute especially to Dr. Ing. Roman Slovak, Dr. Ing. Stefan Wegele and Ing. Lisandro Quiroga for their assistance in Petri nets tool Π-tools. Last but not the least, thanks to Mr. Chris Lees from ALCAM Technical Committee for his permission in assessing the ALCAM data & LXM and to personnel from DTEI and rail industries in South Australia.

REFERENCES

- DAVEY, J., WALLACE, A., STENSON, N. & FREEMAN, J. (2008a) The experiences and perceptions of heavy vehicle drivers and train drivers of dangers at railway level crossings. *Accident Analysis & Prevention*, 40, 1217-1222.
- DAVEY, J. D., WALLACE, A. M., MCCUSKER, L. & HIRSCH, L. (2008b) Level Crossings Research Database. Brisbane, QLD, CRC for Rail Innovation and Australian Government's Cooperative Research Centres Program.
- EINER, S., SLOVAK, R. & SCHNIEDER, E. (2000) Modelling Train Control Systems with Petri Nets - An Operational Specification. *IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC'2000)*. Nashville, TN.
- FANTI, M. P., GIUA, A. & SEATZU, C. (2006) Monitor design for colored Petri nets: An application to deadlock prevention in railway networks. *Control Engineering Practice*, Vol.14, 1231-1247.
- GIRAULT, C. & VALK, R. (2003) *Petri Nets for Systems Engineering. A Guide to Modelling, Verification and Applications.*, Springer- Verlag Berlin Heidelberg New York.
- HAILE, J. & HESS, T. (2006) The Event Window - Modelling Risk at Level Crossings. *Conference of Railway Engineering*. Melbourne.
- JANCZURA, C. W. (1998) Modelling and Analysis of Railway Network Control Logic using Coloured Petri-Nets. *The School of Mathematics*. University of South Australia.
- JANSEN, L., MEYER, Z. H. & SCHNIEDER, E. (1998) Technical Issues in Modelling the European Train Control System(ETCS) Using Coloured Petri Nets and the Design/CPN Tools. IN K. JENSEN, E., WORKSHOP ON PRACTICAL USE OF COLOURED PETRI NETS AND DESIGN/CPN (Ed.) *DAIMI PB - 532*. Denmark, Department of Computer Science, University of Aarhus
- RAIL SAFETY AND STANDARD BOARD (2007) Use of Risk Models and Risk Assessments for Level Crossings by Other Railways. *Reference 21138*. United Kingdom, RSSB's Research and Development.
- SLOVAK, R., WEGELE, S. & SCHNIEDER, E. (2003) Process-based safety requirements parameter derivation for a transportation system using stochastic petri nets modelling. *Scientific Conference Transport 2003*. Sofia, Bulgarien,.
- SLOVAK, R., WEGELE, S. & SCHNIEDER, E. (2007) Holistic Modelling And Safety Analysis Of Railway Systems By Example Of A Level Crossing Protection. *Proceedings of the 15th International Symposium Eurnex - Zel 2007 "Towards more competitive European rail system*. Zilina, Slovak Republic.
- SPICER, T. (2007) Implementing the Australian Level Crossing Assesstment Model (ALCAM) in Victoria. *Australasian Transport Research Forum*. Langham Hotel, Melbourne.
- XU, T. & TANG, T. (2007) The Modelling Analysis of Data Communication System (DCS) in Communication Based Train Control (CBTC) with Coloured Petri nets. *Eight International Symposium on Autonomous Decentralized Systems (ISADS'07)*. Arizona, U.S.A.
- ZIMMERMANN, A. & HOMMEL, G. (2003) A train Control Systems Case Study in Model-Based real Time System Design. *International Parallel and Distributed Processing Symposium (IPDPS'03)*. Nice, France.