The use of probabilistic networks in the analysis of risks to the components of the bus power system with hydrogen fuel cells

D Kasperek, G Bartnik, A Marciniak, A Malek*, D Pieniak, L Gil
University of University of Economics and Innovation in Lublin, Department of Transportation and Informatics, Projektwia 4, 20-209 Lublin, Poland;

*arkadiusz.malek@wsei.lublin.pl

Abstract. Probabilistic networks can be a useful tool for reliability modelling and risk analysis in the operation of technical facilities. In the article, the authors present the method of using probabilistic networks in the analysis of threats to the elements of the electric bus power supply system with a hydrogen fuel cell. Both the use of probabilistic networks as a tool supporting decision-making processes and the use of the latest achievements in the field of non-emission propulsion indicate a new area of research. The article presents the construction of a hydrogen bus with particular emphasis on the hydrogen storage and transmission installation. Next one specific case is considered where there is a leak in the hydrogen system with the simultaneous appearance of an ignition initiator in the form of a short circuit in the electrical system. Authors considered Fault Tree-Event Tree method in context of Bayesian networks technology. The conducted research has shown that there is a real risk of hydrogen explosion in a hydrogen fuel cell-powered bus and that it can be accurately calculated.

Key words: alternative drive system, probabilistic networks, automotive safety

1. Introduction
Probabilistic networks can be a useful tool for reliability modeling and risk analysis in the operation of technical facilities [1]. The nodes of the network represent the states of the components of a complex technical object and the arcs of dependence between them. Thus, the entire network represents the state of the object as a whole. Each node of the network is associated with a conditional probability distribution of a given component (part, subassembly) in a given state, determined by the state of the elements functionally related to it.

The knowledge and information representation model in the form of a Bayesian network is a graph that consists of nodes and inter-node relations [2]. The nodes in this case represent events. An event is something that is associated with a change in the state of the process or object under study and takes place at some point in time, where the system changes from one state to another and these variables are set with accuracy to the probability distribution. If such a model is a representation of knowledge and information, questions may be asked of this representation of knowledge and information. The question is a sentence function, i.e. it is a sentence that contains variables and such variables in Polish are interrogative pronouns (e.g. how many, what, where, how, why, etc.).

The use of probabilistic measures results from the fact that changes in state may occur according to more or less unpredictable influence of the environment and the processes of wear and aging of
construction materials. Additionally, network nodes are introduced to represent operational activities, e.g. replacement of a damaged element [3].

In the article, the authors present the method of using probabilistic networks in the analysis of threats to the elements of the electric bus power supply system with a hydrogen fuel cell. Both the use of probabilistic networks as a tool supporting decision-making processes and the use of the latest achievements in the field of non-emission propulsion indicate a new area of research.

The constant striving to improve air quality in cities forces the need to look for new solutions aimed at reducing CO₂ emissions in the urban transport sector [4] [5]. An important activity in this area is the use of alternative fuels and drives [6]. Today they include electricity and hydrogen [7]. Polish and European city bus manufacturers are introducing new generations of ecological city buses [8] [9].

With the first commercial vehicles powered by hydrogen fuel cells entering the market, the first questions related to the safety of their use arose. The differences in operation in relation to traditional internal combustion drives or increasingly popular hybrid drives are also puzzling [10]. On the part of both the users and mechanics, there are questions about potential problems related to the servicing of such vehicles. In 2013, the Korean company Hyundai launched its ix35 Fuel Cell model first, with an ambitious plan to sell 1,000 units in the first two years and 10,000 per year from 2015. In 2014, another strong player appeared on the market - Toyota with its Mirai model. Immediately after the market launch, Toyota decided to popularize the new technology by making available free of charge over 5,000 patents developed by the company in the planning, development and production of the hydrogen Mirai model. This allows other manufacturers to take advantage of patents relating to fuel cell technology, high pressure hydrogen storage tanks, and advanced control systems. According to Toyota, this convenience will increase the interest of car companies and customers in the hydrogen drive. It is considered to be the most ecological type of vehicle propulsion. The first phase of the dissemination of hydrogen vehicles lasted until 2020. Its implementation included technical education at the level of vocational schools, technical universities and Authorized Service Stations. At the beginning, these were the basics of operation, and then the details related to the use, diagnostics and servicing of hydrogen vehicles. The task of scientists in the near future will be to see further development of individual components of hydrogen vehicles in order to reduce weight, cost and increase the range of such vehicles. An important issue significantly affecting the operation, diagnostics and servicing of vehicles powered by hydrogen cells is the type of fuel cells used [11][12]. Another is the method of storing hydrogen on board the vehicle and the related safety of using hydrogen vehicles.

2. Hydrogen power supply system for electric city bus - components and functions

In the 21st century, many components are available for building a bus's electric drive system. The most important of them are the electric motor and traction batteries, and in the case of hydrogen propulsion, a stack of fuel cells and hydrogen tanks [12][14]. The appropriate selection of each of them determines the suitability of the bus for a specific application (city, intercity) and its price. In addition to the correct selection of components, their integration is also important, which enables failure-free operation with high efficiency [15][16][17].

One of the problems with hydrogen vehicles is its storage. There are many ways to store hydrogen. It can be collected in a compressed or cryogenic version. The latter method enables large amounts of hydrogen to be stored in a small volume. However, it is very expensive due to the need to maintain very low temperatures at the level of production, distribution and transportation of hydrogen. There are also hybrid tanks with cryogenic and additionally cryo-compressed hydrogen [18]. The hydrogen can also be stored in solid form in metal hydrides. It is very easy to use and efficient method, however, it has one disadvantage - it is relatively heavy. One of the newest methods of collecting hydrogen is the use of carbon nanotubes [19]. However, metal or composite high-pressure tanks are most often used to store hydrogen on board vehicles. At present, composite tanks have almost completely replaced the originally used, very heavy, steel tanks. Lightweight and capable of collecting hydrogen
under high pressure, the composite tanks are manufactured in a cylindrical version with various
diameters and lengths. They have a capacity of several to several hundred liters. Several European and
world producers produce tanks that are approved at the international level.

Alternative drive technologies used in city buses include hybrid electric (HEV), plug-in hybrid
(PHEV), pure electric (EV) and fuel cell buses (FCEB).

These alternative technologies are the basis of the electrification of urban transport. The
electrification strategy enables the improvement of air quality in cities (no local emissions), the
diversification of primary energy sources (electricity / hydrogen can be produced from a wider variety
of sources, not necessarily fossil sources) and the use of technologies that can improve energy
efficiency\(^{[20]}\)[21].

Fuel Cell Electric Bus (FCEB) buses use an electric motor to drive. In a hydrogen vehicle,
electricity to power the engine is generated on an ongoing basis in a hydrogen fuel cell powered by
hydrogen stored in tanks usually located on the roof of the vehicle. A chemical reaction takes place in
a hydrogen fuel cell whereby the hydrogen combined with oxygen in the air produces electricity. The
reaction product is also steam and heat\(^{[22]}\).

Electric buses using hydrogen fuel cells (abbreviated as "hydrogen buses") are the most
technologically advanced solution among zero-emission vehicles (Fig. 1). During the operation of
hydrogen buses, zero emission of pollutants is achieved at the place of use of the vehicle. As a result
of the chemical reaction of hydrogen and oxygen in the fuel cell, electricity is generated and a by-
product is water vapor.

Figure 1. The hydrogen fuel cell bus

Buses powered by pure hydrogen energy differ from classic electric buses in that the source of
electricity is a hydrogen fuel cell, while the batteries act as an energy buffer - they are powered by
both the fuel cell and the energy recuperation system obtained during vehicle braking\(^{[23]}\).

A hydrogen bus uses an average of 9 kg of hydrogen per 100 km. Consumption depends on the
parameters of the built-in components and the number of passengers transported, but also the driver's
driving technique, season, i.e. weather conditions and outside temperature. Greater consumption will
occur in summer due to the need to supply air conditioning equipment in the passenger compartment,
and in winter due to the need to use some of the electricity to heat the vehicle.

Hydrogen tanks placed on the roof of the bus have a capacity of approx. 35 kg of hydrogen, which,
depending on the conditions, is enough for a distance of approx. 350-450 km, without the need to refill
the route (as is the case with battery electric vehicles). Hydrogen is collected in tanks under a pressure
of 35 MPa\(^{[8]}\). PEMFC (Proton Exchange Membrane Fuel Cell) hydrogen cells are successfully used
in electromobility applications.
While the bus is stationary, the traction batteries can be charged with electricity from the power distribution network. In many European countries, a large proportion of electricity comes from renewable energy sources [24].

3. Methodology

The article presents the safety risk during the operation of electric bus power system components with a hydrogen cell, which has been considered the most dangerous. According to the theory of probability, dangerous events are rare and usually result from the fact that certain elements of the structure of a technical object accumulate considerable energy and the sudden release of this energy is the cause of an event defined as dangerous or dangerous.

In the bus power supply system with a hydrogen cell (Fig. 2), there is an element (there are of course more of them) in which there is a significant amount of energy - it is a hydrogen tank. The energy of the hydrogen tank, or actually the chemical energy stored in this hydrogen, if it is released in the form of an explosion, it will be this dangerous event.

![Diagram of the hydrogen supply system for the bus drive](image)

**Figure 2.** Diagram of the hydrogen supply system for the bus drive

The problem of the reliability of the hydrogen supply to fuel cells is not considered here, but one specific case is considered where there is a leak in the hydrogen system with the simultaneous appearance of an ignition initiator in the form of a short circuit in the electrical system. The occurrence of both events will lead to a hydrogen explosion (explosive combustion of hydrogen) (Fig. 3).
4. Bayesian networks modelling the operational risk of rare catastrophic events

Bayesian networks (BN) are graphs whose relations represent cause-and-effect interactions and nodes are propositional functions whose arguments are known with accuracy to the conditional probability distribution. BN allow you to infer value of unobserved variables and calculate the effect of observing the values of a subset of model variables on the probability distribution of other variables. Bayesian update, also called belief update, or probabilistic inference, is based on determining cumulative probability distributions.

Application of Bayesian networks in systems reliability and safety domain is well known. The aim of presented article is an introductory conceptualization and analysis of modeling methods of rare catastrophic events. We considered well known Fault Tree-Event Tree method in context of Bayesian networks technology. The FTA-ETA_BN is shown below as a modified “bow tie” graph (Fig. 4).

Figure 3. Potential locations of the initiators of the explosion

Figure 4. Fault–Consequences events graph – (modified “bow tie” graph)
In presented article we analysed two methods of risk modelling as Bayesian networks. The first one was invented by N. Fenton & M. Neil in “Risk Assessment and Decision Analysis with Bayesian Networks” [25]. Risk conceptualization as an risk event that can have negative or positive impact, involving the risk event, one at least consequence event which characterizes the impact, and additionally one or more trigger events, one or more control events, and one or more mitigating or inhibiting events (Fig. 5). "Control event" represents the prevention of the occurrence of danger and "Mitigant" represents the occurrence of interventions mitigating the effects of the "Risk event".

![Bayesian network conceptualization of risk (Fenton, Neil 2013)](image)

**Figure 5. Bayesian network conceptualization of risk (Fenton, Neil 2013)**

A risk characterized in Fig.5 has five categories of events. Each of them may have deeper specification as a sub network of detailed events of a given type. Events have a number of possible outcomes (in the simplest case it can be just two outcomes true and false). Every event and hence every object associated with risk has uncertainty that is characterized by the probabilities of the event’s outcomes.

It is possible to build arbitrarily large risk-based BNs using the above approach. This involves the following steps:

1. Consider the set of risk events from a given subject domain
2. For each risk event identify any triggers and/or controls
3. For each risk event identify any consequences and mitigants

By chaining together different risks we can model multiple risks, risks from different perspectives, and common causes, consequences and mitigants, all within the same model. So, we can get the BN to generate quantified risk predictions and other useful functions like simulation, backward reasoning and what-if-analysis.

Another method of risk representation in Bayesian Networks is possible with Bayes Fusion product Genie [26]. Especially interested is its qualitative variant Queenie. It explicitly distinguishes four categories of causal relationships, Fig.6.
Figure 6. Representation of risk event in QGenie BN

The QGeNiE qualitative modeling environment has many applications, for example:

- Rapid prototyping – even if the goal is to build a fully quantified Bayesian network, models developed at QGeNiE can be exported to GeNiE for further refinement and learning of parameters.
- Modeling the reliability and safety of processes in which significant threats are very rare events and we have almost no hard data about them, only expert qualitative knowledge.

5. Conclusions

In the article, the authors present the method of using probabilistic networks in the analysis of threats to the elements of the electric bus power supply system with a hydrogen fuel cell. Both the use of probabilistic networks as a tool supporting decision-making processes and the use of the latest achievements in the field of non-emission propulsion indicate a new area of research. The article presents the construction of a hydrogen bus with particular emphasis on the hydrogen storage and transmission installation. Next one specific case is considered where there is a leak in the hydrogen system with the simultaneous appearance of an ignition initiator in the form of a short circuit in the electrical system. Authors considered Fault Tree-Event Tree method in context of Bayesian networks technology. The conducted research has shown that there is a real risk of hydrogen explosion in a hydrogen fuel cell-powered bus and that it can be accurately calculated.

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