The Influence of Driver Actions on Fire Risk in Trains

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Abstract

A fire in the cab of a train that resulted in extensive damage initiated a study into the impact of driver decisions on fire outcomes. Interactions between the driver and the fire were investigated for different fire growth rates. Scenarios analysed included the driver opening and closing doors and windows. Controls and design methods used in conventional fire engineering and risk assessment address only a small part of the picture of risk from fire in trains. A comprehensive range of controls and interacting factors should be considered if catastrophic consequences are to be avoided. Using interactive fire modelling, the study illustrates the importance of one element of control, that of the decisions made by the driver, which can change the outcome from a well controlled situation to an uncontrolled and catastrophic one.

1. Introduction

An increase in risk awareness and possible repercussions of corporate responsibility for passenger safety [1] has lead to a number of studies to investigate fire safety in passenger trains [2, 3]. Studies generally seek to show that the risks associated with fire are acceptable while minimising the cost of rolling stock construction, employing principles of fire engineering [4] to demonstrate that there is adequate time for passengers to escape before conditions become untenable. A train fire differs from a building fire since external exit doors cannot be used until the train has been brought to a stop, and so occupants must remain in the relatively small confines of the carriage, or adjacent carriages, until they can safely alight. Most studies have concentrated on the materials of construction, aiming to set limits on fire properties that will inhibit rapid fire growth and spread and allow the atmosphere to remain tenable, maybe with the help of fire suppression and smoke exhaust systems [2, 3, 5]. They have tended to overlook the operational aspects of a train in a fire emergency, especially the activities of the driver and fuel brought onboard by passengers [1].

The ability of the passengers to escape is in fact dependent on the actions of the driver, the time the driver takes to detect the fire, respond and stop the train at a spot suitable for passengers to alight and on systems other than fire safety systems such as the hydraulic systems that operate doors. The problem of qualifying and quantifying risk is thus larger and more complex than that addressed by current fire engineering and risk assessment practice. To highlight some of the deficiencies of current methods and the complexity of interactions that can occur, a study has been conducted to examine the response of train drivers in fire emergencies under existing procedures. The aim of the study is, ultimately, to improve driver response.

2. Existing Driver Procedures

Typically, procedures for fire emergencies relating to passenger train fires are a subset of emergency procedures for a wide range of fires that might occur in trains, stations, depots or next to the track. Advice to personnel concentrates on safety first, encouraging them not to put themselves in danger or at risk of injury while trying to help others. Those at the scene are advised to first assess the situation, and then tell the train controller or fire services before taking action. The train driver should take charge, and if it is considered safe the crew should try to put out the fire. Advice on response to the fire includes recommendations to avoid entering a smoke filled carriage and to avoid opening electrical boxes if they are on fire. If it is not considered safe to put the fire out, the train should be stopped at a place where people can evacuate the carriages and fire services can attend to the fire. The crew should then report to the controller, attempt to control the fire by using basic fire control and move the passengers to other carriages. The burning vehicles should be isolated if this is considered safe. There are a number of other actions that need to be taken that relate to securing the train and detraining the passengers.

Overall, the responsibility of the train driver is to assess the situation and make decisions that will put the crew and passengers in a position of least risk of harm. Since train drivers are not fire scientists, and, we hope, have not been exposed to too many uncontrolled fires during their lives, they are unlikely to be able to predict the severity of the situation and the way in which fire will respond to their actions. Appropriate training and assistance in the decision-making process could potentially prevent disastrous loss of life and property. Advice on decision-making needs to take into account risks associated with alternative actions.

3. The Risk Environment

There are two essential elements to the assessment of risk. One is the extent of the consequences of the event in question. The consequences of train fires can be measured in terms of life safety, property loss, damage to the environment, business interruption and loss of reputation. For this study, we consider only property loss and life safety. The second element is the likelihood of a particular consequence occurring. In this case, since we are addressing driver decisions, we can assume that a fire has occurred, and that the likelihood of damage to any given extent will depend upon the controls that are put in place to prevent or limit the spread of fire and to protect the crew, passengers and assets from its ravages. The extent of property loss can therefore be measured in terms of the ability of the controls to prevent fire spread. Similarly, life safety can be measured in terms of the ability of the controls to avoid any threat to life or threat of injury while there are people present. If there are no people present, there is no threat to life. Controls include engineered systems, routine procedural activities and emergency procedures. Systems that assist people in avoiding the fire are as much a part of the control system as systems that prevent the spread of fire. The driver can interact with some controls but not with others. For example, the driver cannot change the construction materials in the cab, but can use a fire extinguisher.

4. Train properties

In his study we consider, the first carriage of a passenger set. This includes the driver's cab separated from a passenger compartment by a door. The cab has two external doors, which include windows that can be opened, one on each side. The train is constructed of materials typically in use in train construction in Australia [2], and the carriage has no automatic detection or suppression systems.

5. Fire spread modelling

The study involved analysis of fire growth and spread in one or more compartments of simple geometry. The model CFAST [6] was selected to predict fire spread because it has been tried and tested and is in regular use in the fire engineering community. CFAST has the added advantage that input parameter values and results can be compared with an extensive Passenger Safety Train analysis conducted by NIST [3]. Outputs for each scenario were time from ignition, upper layer temperature, lower layer temperature, layer height and main fire size. Optical density calculations were performed using Heskestad's temperature approximation method. A ratio of 0.4 (1/ft ºF) was selected as representative of the materials present in the cab [7].

The way the fire grows, which is represented in CFAST by the input design fire, is critical to the outcome of the driver's decisions, especially in the early stages. Since the purpose of this study is to investigate driver response rather than to derive a fire growth curve for trains, standard t-squared fires were selected, and each scenario was run using slow, medium and fast fires. This approach is supported by the NIST study [3], which recommended limiting the fire growth rate to medium. However, since operational factors such as passenger clothing and baggage can play a significant roll in fire growth, as found in the Kaprun ski tunnel fire [1], it was considered appropriate to study the effects of a range of fire growth rates.

6. Threshold Levels

To assess risk the extent of the consequences of the event must be measured. While some consequences bear a direct relationship to the CFAST output parameters, others require further evaluation. Values associated with identifiable and significant consequence states are used to predict response of controls and set thresholds. As with the fire growth and spread models, the uncertainties and variabilities associated with consequence prediction, control response and threshold levels need to be considered. The parameter values selected for use in the study of the train cab act as proxies for the consequence state and are derived from various sources in the fire literature (see Table 1).

7. Scenario selection

The study focussed on a fire in the cab, which grew in the confined compartment and spread to the adjoining passenger compartment.

The factors that influence the development of a fire in an enclosure are well understood [12]. While the geometry and materials of the cab construction are fixed, fire growth rates will vary with available fuel, type of ignition source, and ventilation conditions that can be changed by the driver's actions. Scenarios with different fire growth rates and ventilation conditions were therefore considered. The cab has 2 doors to the outside, each with an openable window, and a crew door leading to the passenger compartment. As a screening exercise, time to flashover was calculated for combinations of doors (open or closed) and windows (open, half open, closed) for slow, medium and fast fires (32 scenarios, each with three fires). The difference between time to flashover with windows open and half open was found to be insignificant and further analysis considered only fully open or closed states. A list of scenarios selected for analysis is given in Table 2.

Table 1: Critical values used in train fire study

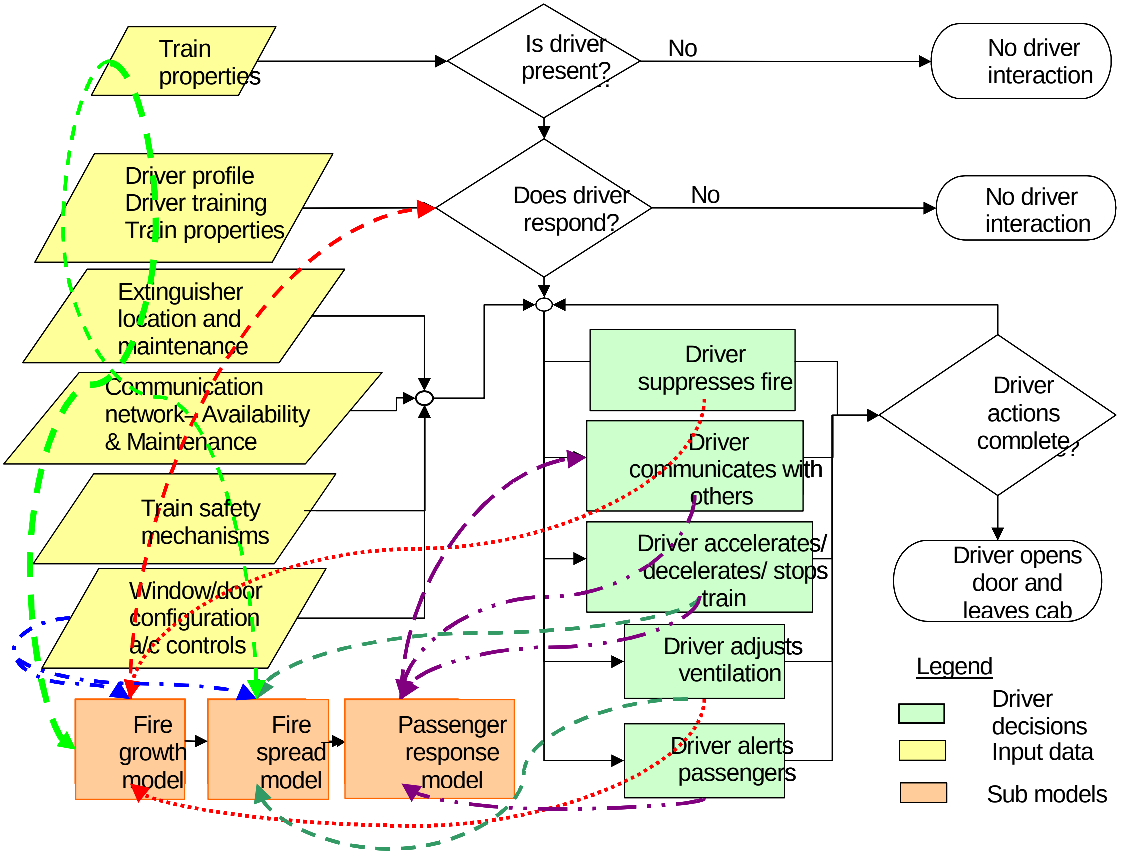
Symbol	Parameter	Threshold Value	Consequence Description	References
Du	Optical density of upper layer	0.05/m	Manual fire detection	[8] See also "Response Times" below
Du	Optical density of upper layer	0.2/m	Limit for normal function in irritant smoke / incapacitation	[8]
C@1.5m	Temperature 1.5m above floor level	65ºC	Incapacitation / death - Single death in cab - Multiple deaths in carriage	[3, 9, 10]
HRR	Heat release rate	25 kW	Replacement of damaged material	Based on [11]
HRR	Heat release rate	50 kW	Refurbishment of whole cab	Based on [11]
FO	Hot layer temperature	600ºC	Replacement of whole carriage	CFAST Flashover criterion [6]

Table 2 Scenarios for detailed analysis

Scenario No	CFAST run	Design fire	LHS door	RHS door	Crew door	LHS window	RHS window	Change ventilation
1	BS1	slow	closed	closed	closed	closed	closed	No change
1	BM1	medium	closed	closed	closed	closed	closed	No change
1	BF1	fast	closed	closed	closed	closed	closed	No change
1	BS1-3	slow	closed	closed	closed	closed	closed	Open 2 windows
1	BM1-3	medium	closed	closed	closed	closed	closed	Open 2 windows
1	BF1-3	fast	closed	closed	closed	closed	closed	Open 2 windows
1	BS1-4	slow	closed	closed	closed	closed	closed	Open 2 windows and door
1	BM1-4	medium	closed	closed	closed	closed	closed	Open 2 windows and door
1	BF1-4	fast	closed	closed	closed	closed	closed	Open 2 windows and door
2	BS7	slow	closed	closed	closed	open	open	No change
2	BM7	medium	closed	closed	closed	open	open	No change
2	BF7	fast	closed	closed	closed	open	open	No change
2	BS7-3	slow	closed	closed	closed	open	open	Close 2 windows
2	BM7-3	medium	closed	closed	closed	open	open	Close 2 windows
2	BF7-3	fast	closed	closed	closed	open	open	Close 2 windows
3	BS23	slow	closed	closed	open	closed	closed	No change
3	BM23	medium	closed	closed	open	closed	closed	No change
3	BF23	fast	closed	closed	open	closed	closed	No change
3	BS23-3	slow	closed	closed	open	closed	closed	Open 2 windows
3	BM23-3	medium	closed	closed	open	closed	closed	Open 2 windows
3	BF23-3	fast	closed	closed	open	closed	closed	Open 2 windows
3	BS23-4	slow	closed	closed	open	closed	closed	Close door
3	BM23-4	medium	closed	closed	open	closed	closed	Close door

3	BF23-4	fast	closed	closed	open	closed	closed	Close door
4	BS15	slow	closed	closed	open	open	open	No change
4	BM15	medium	closed	closed	open	open	open	No change
4	BF15	fast	closed	closed	open	open	open	No change
4	BS15-3	slow	closed	closed	open	open	open	Close 2 windows
4	BM15-3	medium	closed	closed	open	open	open	Close 2 windows
4	BF15-3	fast	closed	closed	open	open	open	Close 2 windows
4	BS15-4	slow	closed	closed	open	open	open	Close 2 windows and door
4	BM15-4	medium	closed	closed	open	open	open	Close 2 windows and door
4	BF15-4	fast	closed	closed	open	open	open	Close 2 windows and door

Figure 1 Driver response flow diagram



8. Driver response

Studies on human response to fire have shown that alarm audibility, occupant training, fire warden actions and occupant activity all have a major influence on pre-evacuation times [13], Gwynne [14] represented response by three time phases involving pre-event factors and occupant attributes in the first phase, perception and response factors in the second phase and actions in the final phase.

Pre-event factors that might affect the driver include location, activity, the shift roster and the elapsed time on shift. Occupant attributes include gender, age, fitness, mobility, training and experience.

9. Response Times

Consider the case where the driver is in the cab when a fire occurs within the cab, and there is no automatic detection. The driver will most likely become aware of the fire by smelling smoke [15]. Withey [16] found that recognition depended on interpretation of a number of ambiguous clues, and interpretation depended on the mental state and predisposition of the subject to recognise the threat. In this case it is probably reasonable to assume that the driver is not sleeping, has some training in safety, has a sense of responsibility for the safety of the passengers and the welfare of the train and is not distracted by the unstructured actions of the general public. He will therefore respond soon after recognising the fire cue. Studies have been conducted to determine time of response of individuals to fire and smell is a common cue [17, 18], but a search for data relating olfactory response to smoke density did not yield useful results. Purser suggests that at an Optical Density of 0.2m^{-1} (for irritant smoke), people behave as though they are in total darkness [8]. He suggests tenability limits based on Equivalent Optical Density of $0.2\ \text{m}^{-1}$ for small rooms and $0.1\ \text{m}^{-1}$ for other rooms and spaces. For the purposes of this study a response time corresponding to an equivalent optical density in the smoke layer of 0.05m^{-1} has been assumed as the time to detect the fire and start to respond. When the Optical Density reaches $0.2\ \text{m}^{-1}$, the driver will become incapacitated unless he wears a mask or holds his breath.

Once the driver has perceived the threat, he might respond in a number of ways. Actions might include

- Suppress the fire – interacts with fire growth
- Communicate with
- Accelerate/decelerate/stop the train
- Adjust the ventilation – interacts with fire growth
- Alert passengers
- Do nothing

Although the Emergency Procedures provide some guidance, there is no recommended order for the activities and the driver must decide and act in the best interests of everyone's safety.

Figure 1 illustrates the choices the driver must make, showing their impact upon the fire and the passengers. Fire growth and passenger response are represented by fire growth and spread models and the passenger response model.

The relationships are complex, with many interactions between the fire, the driver and the passengers. Further, the input data is greatly simplified in the diagram, and each element can be represented by a number of fixed values or distribution curves. Initial model development required simplification.

10. A simple model

A simplified model taking into account only the driver decisions to adjust the ventilation and suppress the fire was developed. For this less complex case, the growth of fire in the cab and the driver's activities can be represented by an event tree, where each path represents a different choice of action. The time to complete each activity is shown preceding each node. Times of critical events are shown on a time line, which specifies different values for different choice paths through the tree. This duplication is necessary since times can depend on preceding events, which vary with the occurrence of events. The times that the driver will take to perform various functions are described below.

10.1 Time to suppress fire

The type of fuel and fire size indicate that a class 1A extinguisher will be present [19, 20]. Assume it takes 5 seconds to release the extinguisher and 2 seconds to suppress the valve. The standard specifies that there must be not more than 3 seconds between opening the control valve and starting discharge, and effective discharge must occur for a minimum of 10s [21]. Times will vary with pre-event factors and driver attributes. We assume that suppression is successful, and conditions improve from the start of suppression.

10.2 Time to open and close windows

It is assumed that the driver takes 5 seconds to complete the action of opening or closing each window or door.

11. Results

Results were found to be dominated by the tenability level for smoke, which for many scenarios rendered the driver unable to operate the fire extinguisher before being overcome. By adding 10, 20 or 30 seconds to the time to untenability, it was found that in many cases the driver would have time to attempt suppression. This additional time could well be achieved by a trained, fit individual holding their breath while releasing and setting off the extinguisher, and is influenced by the driver profile. For this study, values of 0, 10 and 30 seconds were investigated.

Consider a medium fire in the cab. The driver is present and all windows and doors are closed. There is leakage below the doors and an air conditioning vent in the ceiling. (Scenario 1, CFAST run BM1). In this case, smoke makes conditions untenable at the moment the driver starts to suppress the fire. Without suppression, the temperature will become untenable 40 seconds after detection. Even if the fire is not suppressed, there is insufficient oxygen for a flashover situation to develop and so damage will be limited to refurbishment of the cab (see Figure 2).

Now consider the same scenario, but this time the tenability threshold for smoke is increased by 10 seconds and the driver opens both windows to clear the smoke. Conditions become untenable just as suppression starts, but opening the windows means that if suppression fails the fire could develop to flashover (see Figure 3).

For a fast fire in Scenario 3 (windows closed, crew door open, CTAST runs BF23), conditions remain tenable until after suppression starts if the ventilation conditions are not changed, but the fire grows to flashover if suppression is unsuccessful. However, if the crew door is closed, flashover will not occur. Further, the driver will be able to start suppression before the tenability threshold for smoke is reached, if the limit is increased by 30 seconds. It is apparent that the driver's decision and ability to perform will have a substantial effect on the outcome of the fire.

Table 3 shows a summary of the outcomes of three different scenarios. Even for this simplified decision process, an orderly way of presenting the options and their possible outcomes is needed.

Figure 2 Driver action / fire growth event tree and time line medium fire, doors and windows closed

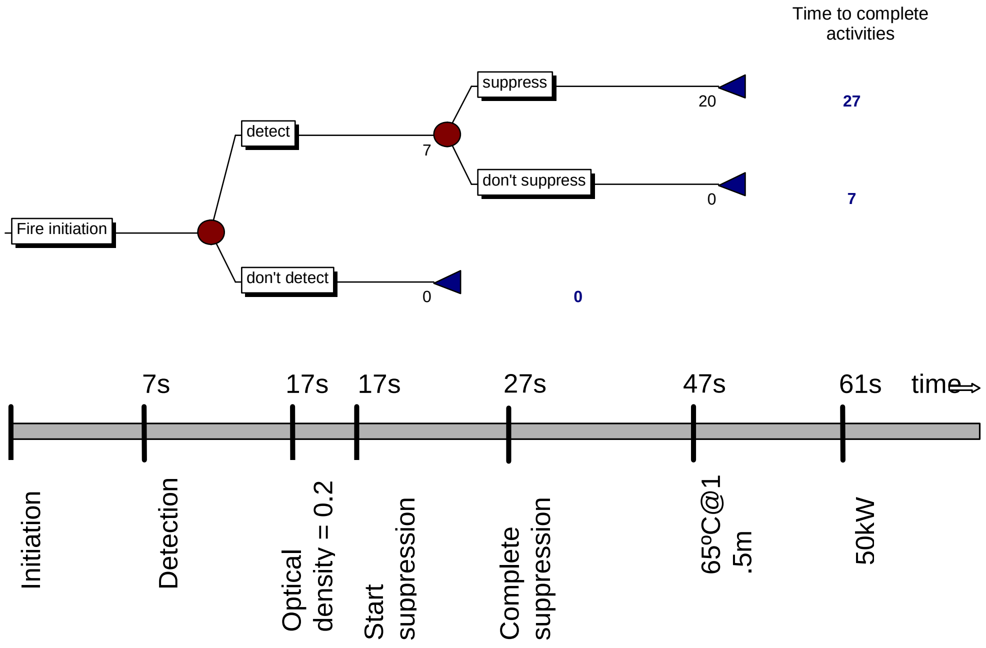


Figure 3 Driver action / fire growth event tree and time line medium fire, doors and windows closed initially, driver opens windows

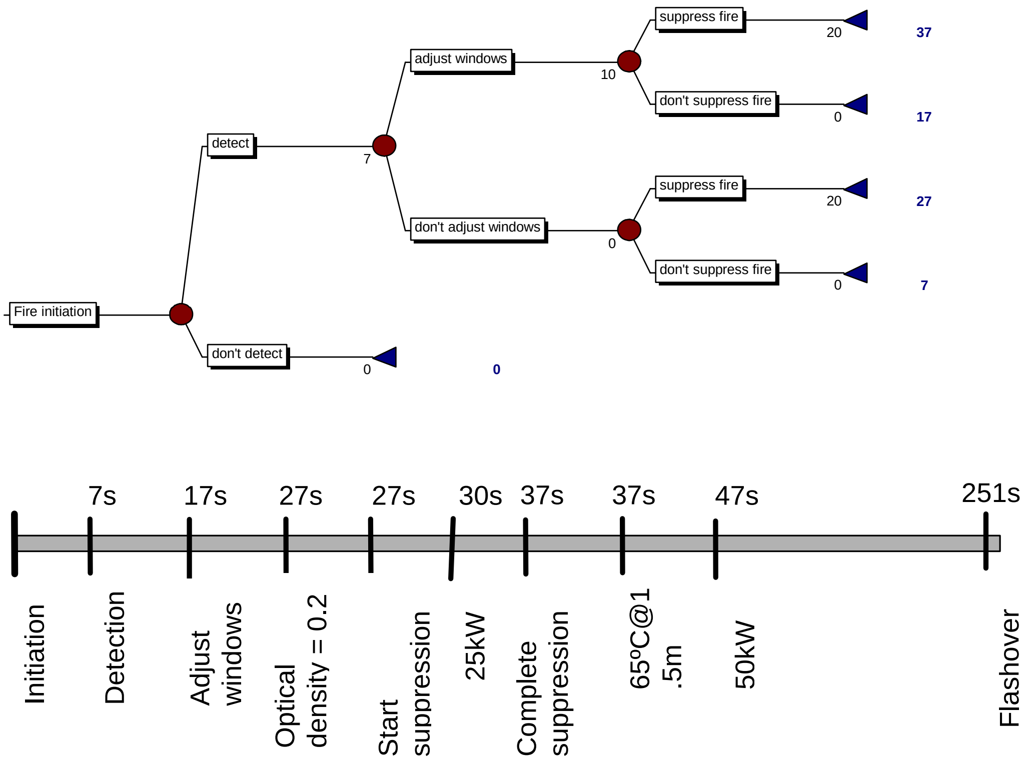
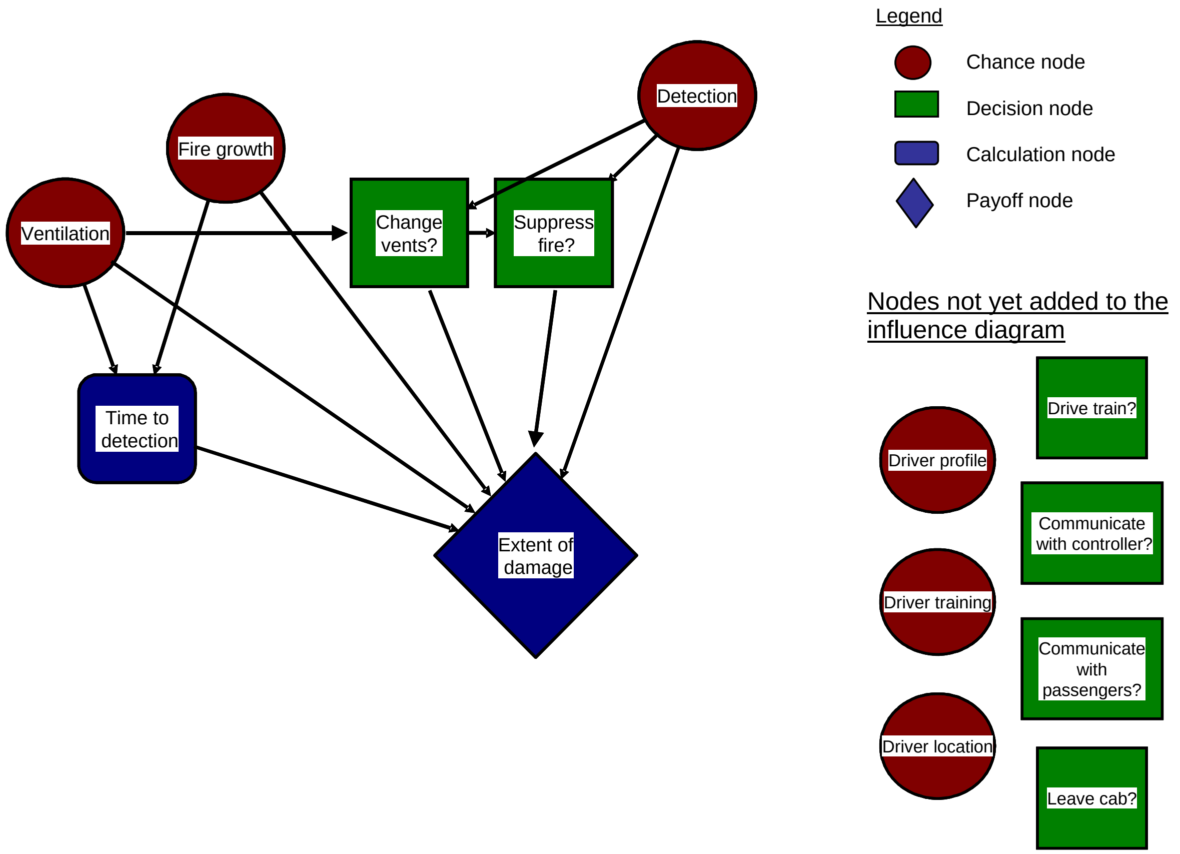


Table 3 Consequences of driver actions

CFAST run	*Scenario description*	*Smoke tenability threshold*	*Driver action - vents*	*Tenable at suppression?*	*Flashover?*
BF23	Fast fire Windows closed Crew door open	Du=0.2s	No change	Yes	Yes
BF23	"	Du=0.2+10s	No change	Yes	Yes
BF23-3	"	Du=0.2+10s	Open 2 windows	No	TTFO Increased >2min
BF23-4	"	Du=0.2+10s	Close door	No	No
BF23	"	Du=0.2+30s	No change	Yes	Yes
BF23-3	"	Du=0.2+30s	Open 2 windows	Yes	TTFO Increased >2min
BF23-4	"	Du=0.2+30s	Close door	Yes	No
BM15	Medium fire Windows and crew door open	Du=0.2s	No change	No	Yes
BM15	"	Du=0.2+10s	No change	Yes	Yes
BM15-3	"	Du=0.2+10s	Close windows	No	TTFO Reduced by 1 min
BM15-4	"	Du=0.2+10s	Close windows and door	No	No
BM15	"	Du=0.2+30s	No change	Yes	Yes
BM15-3	"	Du=0.2+30s	Close windows	Yes	TTFO Reduced by 1 min
BM15-4	"	Du=0.2+30s	Close windows and door	Yes	No
BM1	Medium fire Windows and Crew door closed	Du=0.2s	No change	No	No
BM1	"	Du=0.2+10s	No change	Yes	No
BM1-3	"	Du=0.2+10s	Open 2 windows	No	FO Occurs after 4 mins
BM1-4	"	Du=0.2+10s	Open 2 windows and door	No	FO Occurs after 5 mins
BM1	"	Du=0.2+30s	No change	Yes	No
BM1-3	"	Du=0.2+30s	Open 2 windows	Yes	FO Occurs after 4 mins
BM1-4	"	Du=0.2+30s	Open 2 windows and door	Yes	FO Occurs after 5 mins

Figure 4 Influence diagram for driver decision to change ventilation or suppress fire



12.Influence diagrams

Influence diagrams are made up of chance nodes, decision nodes, calculation nodes and payoff nodes. Relationships are identified by arcs, which have the attributes of value, timing and structure. An influence diagram can be converted to a decision tree, which allows you to clarify options and evaluate the consequences of different decisions. Policy recommendations, or best routes through the tree, can be generated automatically.

An influence diagram representing the decisions described above is shown in Figure 4. In this diagram the fire growth rate (slow, medium, fast), ventilation conditions (Scenario 1, 2, 3 or 4) and detection (detect/don't detect) are shown as chance nodes. The decision to change vents is influenced by whether detection takes place and the start condition of the vents. The decision to suppress the fire is influenced by detection, and by the values generated by the decision to change vents. Times calculated in CFAST are included in the value tables associated with each node. Chance nodes that have yet to be included include the driver profile, driver training and driver location and properties of the train. Properties of the train are currently assumed in the fire growth options and calculation of time to detection. Decisions yet to be added include whether to drive the train, communicate with the controller, communicate with passengers or leave the cab.

13. Discussion

Table 3 clearly shows that, even with a limited choice of actions, the decisions of the driver can have a critical effect on the outcome of a fire in the driver's cab. For the fast fire in Scenario 3 (runs BF23), the decision to open the windows leads to untenable conditions developing before the driver has had time to operate the fire extinguisher, rendering the development of flashover conditions almost inevitable. If, on the other hand, the driver decides to close the door and holds his breath while he releases the extinguisher, suppression is possible and, even if the extinguisher fails to function, the fire will not reach flashover. The order in which decisions are made is also critical. For the medium fire in Scenario 4 (runs BM15), the act of adjusting the ventilation takes up valuable time so that conditions become untenable before suppression can start. However, adjusting the ventilation prevents flashover developing, a situation that cannot be achieved by controlling the materials of construction and the cab contents to ensure a slow fire growth rate. The driver's actions can alter the situation from a controlled to an uncontrolled state.

In reality, the driver has many more choices, such as whether to continue to drive the train, communicate with train control or the fire brigade or alert the passengers. Each action will delay the start of other actions and could be critical to the outcome. The time taken to respond, make decisions and perform actions, as well as their likelihood of success, will be influenced by the driver profile and training, shift rosters, maintenance of equipment and a whole host of factors, some of which influence the implementation of controls in more than one way. These feedback loops and common causes can lead to catastrophic results that are not recognised by current risk assessment methodologies.

This study also highlighted the need for accurate understanding and specification of threshold levels and values for control response prediction. If our acceptance criterion was that the cab should remain tenable until the driver starts suppression, then acceptance is as sensitive to the threshold level selected as it is to the parameters influencing the design itself. This introduces an increased level of complexity, since suitable threshold levels are also linked to the factors which so heavily influence consequences. For example, the tenability level for smoke for a fit driver at the start of a shift might be much higher than that for a tired asthmatic. Setting inappropriate threshold levels for risk assessment can also result in catastrophe.

The consideration of a wider range of factors in a risk assessment leads to many feedback loops that can result in emergent phenomena, a situation that occurs in real life. As is seen in this study the range of outcomes is considerable, from safely containing and controlling the fire with minimal impact on the cab to full cab involvement and death of the driver. The outcome is highly sensitive to the state of the system at the time of ignition. Current methods of risk assessment fail to capture this sensitivity and in practice catastrophic outcomes are quite frequent, even though such events are considered very rare. The reason is that the controls that have been put in place are unsuitable.

14. Conclusions

It is apparent from this study that the controls and design methods used in conventional fire engineering and risk assessment address only a small part of the picture of risk from fire in trains. Those occasional catastrophic outcomes are the result of the many interactions involved in a complex environment. The magnitude of the consequences is dependent upon the control states that prevail at the time of the fire, and the risks associated with train fires look very different when a comprehensive range of controls and interacting factors are considered. The simple model developed during the course of this study illustrates the importance of one element of control, that of the decisions made by the driver, in train fire safety.

The study used standard t-squared fires as input design fires to CFAST, a well tried and tested combination in use by fire engineers. However, the study highlighted the need for accurate fire growth modelling during the early stages of compartment fires to provide the accuracy necessary to accommodate the multitude of critical interactions necessary for comprehensive risk assessment. Improved fire growth modelling will not only assist in the modelling of consequences of fire. Selection of appropriate threshold levels and control response levels depend upon accurate prediction of early fire growth. These levels are an integral part of the risk assessment process, and can have a profound effect on the perception of risk. They are influenced by many of the same factors as the outcomes which they aim to control.

While existing computer tools offer some assistance in developing models to represent the complex interactions involved in comprehensive risk assessment of fire scenarios, there is need for a suitable IT platform that can accommodate the many calculations required. With an appropriate platform, the study could be extended to accommodate data distributions and probabilities of success of controls, and critical interactions could be accurately modelled. The result would be a truly interactive and useful train driver decision model.

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