EMERGENCY RESPONSE POSSIBILITIES AT TUNNEL ACCIDENTS

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Abstract

Recent tunnel disasters in several Western European countries such as Austria (Goddharttunnel, 2001 and Tauerntunnel, 1999), France/Italy (Mont Blanc tunnel, 1999) and Great Britain/France (Channel Tunnel, 1996) have made tunnel safety an area for special attention. In-depth investigations into these accidents focused on aspects of tunnel design and emergency response activities. As regards the latter, a major issue was the effectiveness of emergency response activities to reduce the number of victims. For rail tunnels for freight, a three-way research plan was developed to reveal the emergency response opportunities for tunnel accidents. Case studies, expert interviews and physical modeling of fires and firefighting revealed that emergency response possibilities for rescue operations in tunnels are extremely limited. This result is important for both tunnel designers and emergency responders: tunnel designers should reconsider their tunnel design principles and emergency responders should reconsider their tunnel accident strategies.

1. Introduction

As a result of recent and future economic growth, the need for high-capacity transportation facilities in the Netherlands has been increasing. In order to meet this need, additional infrastructure projects are being planned and built, which on land include roads, railways, pipelines and canals. To an increasing extent tunnels are part of these infrastructure projects. The reason for developing and building tunnels is twofold. Firstly, tunnels are built for crossing topographical barriers like rivers and mountains. Secondly, tunnels are built to preserve the built-up areas and natural environment aboveground.

A potential disadvantage of tunnels is the issue of safety. Tunnel developers and emergency response organizations negotiate on technical systems that will support emergency response, such as smoke and heat detection systems, ventilation systems and the required distances between emergency exits. It is not certain, however, whether emergency response organizations will respond to any tunnel accident. The emergency response possibilities and the extent to which technical systems enhance these possibilities are not clear. So far, little research has been done into the possibilities available to emergency response organizations for rescue operations in threatened tunnel tubes. Any research on this topic should include the main characteristics of transport mode and tunnel layout. Different transport modes and tunnel layouts result in different accident and emergency response scenarios.

In the Netherlands, a new railway called Betuweline is being built. The Betuweline connects the seaport of Rotterdam eastwards to a multimodal transfer facility at Valburg and the German industrial Ruhr area. This high-speed railway includes six tunnels of various lengths and is intended for freight transportation only.

In 2000, the organizational unit of the Dutch Ministry of Transportation and Public Works, responsible for the planning and building of the Betuweline, needed insight into the possible emergency response activities in the Betuweline tunnels. This subject for study was formulated as follows: what are the emergency response possibilities for rail tunnels intended for cargo transportation?

This paper contains the established and stated possibilities as well as the modeling of emergency response possibilities for accidents in rail tunnels for freight. First, several tunnel incidents[1] and emergency response activities are described (paragraph 2). Paragraph 3 discusses the results of the interviews with fire officers: possibilities with regard to stated emergency response activities in rail tunnels for freight. Paragraph 4 explains the physical phenomena like smoke and temperature development as time progresses as well as the emergency response activities in time. Gearing emergency response activities with the physical situation in the threatened tunnel tube will determine the possibilities for offensive tactics and entering the tunnel tube at issue. Paragraph 5 mentions the emergency response possibilities as found in this study.

2. Tunnel incidents

The Dutch Ministry of the Interior and Kingdom Relations, responsible for national fire service policies, together with Dutch Rail (NS) and regional fire chiefs, has defined plausible scenarios for tunnel incidents. These scenarios are (BZK, 1997):

1. Derailment. It is generally not expected that a train will derail on a straight section of the railway. Derailment may be a consequence of technical failure, such as broken axles. It may also occur when a train hits an object on the railway, a possible act of sabotage. Fires and leaks may be subsequent scenarios following a derailment. Derailment may lead to a collision in a two-way rail tunnel.
2. Collision. In theory, a train may collide with another train, an object, an animal or a person. The chance of collision with another train is considered negligible because modern technologies prevent trains from riding on the same track. Collisions with people include trespassers, unauthorized or maintenance personnel.
3. Fire. Fire may be a consequence of electrical failure, blocked axles and breaks, or attacks. When hazardous materials are involved, a high-energy fire may occur, like a (leaking) fuel fire. Fires involving trains or cargo are considered to be more serious than fires in tunnel cables or maintenance rooms or during maintenance operations.
4. Leaks of hazardous materials. Minor leaks will probably not be detected during the journey. When a train comes to a stop in a tunnel, the potential effects of a leak of hazardous materials is more serious. Different scenarios exist that involve flammable and/or explosive substances or toxic or radioactive chemicals. Leaks may occur as a result of derailment or collision.
5. Explosion. If an explosion occurs in a tunnel built in wet soil, infrastructure may be lost. Explosions may be caused by deliberate attacks or fire (Boiling Liquid Expanding Vapor Explosion).
6. Miscellaneous. In the Netherlands, floods constitute a specific risk that may affect tunnels. Tunnel system failure and regular transport interruptions are not considered relevant for emergency response organizations.

These scenarios are theoretic scenarios used. In order to assess emergency response possibilities, information about actual incidents and emergency response activities is additionally required. For this purpose, a selection of tunnel accidents was made. A Dutch inventory study (COB, 1997) of

[1] In this paper, the terms 'accident' and 'incident' are used as synonyms.

tunnel incidents showed that in Western Europe incidents in rail tunnels for freight have been limited to only two incidents and do not cover a wide range of scenarios (Channel Tunnel, 1996; Summit Tunnel, 1984). Therefore, the scope was broadened to incidents in road tunnels and rail tunnels for passenger trains. It was assumed that an insight into the physical mechanisms that influence emergency response possibilities could be gained from these types of tunnel incidents. Criteria used in the selection of the cases included (Nibra, 2001):

1. The incident required evident involvement of public emergency response organizations in terms of the duration of operations (over 15 hours) and the number of personnel deployed (over 100 firefighters). Major operations may reveal the possibilities as well as the limitations of emergency response.
2. The incident occurred between 1995 and 2000 (the year in which the study was carried out). The topicality of the incident is important because the state-of-the-art technical and organizational possibilities of emergency response organizations should be taken into account.
3. The incident and the emergency response activities are sufficiently documented.

These criteria led to the selection of the following cases:

1. Channel Tunnel, Great Britain-France, 18 November 1996: Fire on a Heavy Goods Vehicle shuttle (HVG).
2. Leinebusch Tunnel, Germany, 2 March 1999: Derailment of, and fire on a freight train.
3. Mont Blanc Tunnel, France-Italy, 24 March 1999: Fire in a road tunnel involving a considerable number of vehicles.
4. Tauern Tunnel, Austria, 29 May 1999: Collision and fire in a road tunnel involving a considerable number of vehicles.

The accidents and emergency response activities are described in short. The lessons learned from the incidents are summed up.

2.1 Channel Tunnel

The Channel Tunnel (rail tunnel, 50 kilometers) consists of two one-way running tunnels and a service tunnel in between. The running tunnels are connected to the service tunnel by closed cross sections at 375 meters intervals.

The start of the incident was a Heavy Goods Vehicle, consisting of 29 carriages, entering running tunnel south with a burning truck on it. Maintenance personnel detected the fire outside the tunnel but the shuttle was not stopped. Ten minutes later the driver halted the train in the tunnel because of a derailment signal on his control panel caused by burnt cables. The (natural) ventilation in the tunnel spread thick smoke over the train, including the passenger carriages. People were unable to leave the train due to the smoke.

Twenty-three minutes after the stop an emergency exit was opened by the Rail Control Center creating a ‘bubble effect’. Smoke was driven out from the tunnel section making it possible to evacuate the passengers. Subsequently the fire-fighting operation began. Firefighters had trouble estimating the exact location and extent of the fire. Smoke, rubble and explosions were serious obstacles while approaching the fire. In addition, the fire damaged the tunnel water supply system.

Lessons learned from the Channel Tunnel incident, as formulated in this study:

- Smoke prevented passengers from active evacuation.
- Adequate information from the train did not reach emergency response organizations because of extremely limited visibility.
- Tunnel entrance security measures delayed the emergency response units.
- Smoke and heat limited both the approach of the fire site and the working time of firefighters.

2.2 Leinebusch Tunnel

The Leinebusch Tunnel (rail tunnel, 1740 meters) is a single-tube tunnel with separate rail tracks for both directions.

The start of the incident was the derailment of the 14^{th} of 24 carriages of a freight train. The derailment took place 6 kilometers outside the tunnel. Because of the speed reduction the driver halted the train in the tunnel, decoupled the front carriages and drove them out of the tunnel. The cargo (paper) on the derailed carriage had started to burn.

One hour and forty-four minutes after the first alert, a special rescue train arrived at the tunnel entrance. Lacking water supply facilities hindered firefighting. The train could not be taken in tow due to the damaged rail track. For the same reason, an additional rescue train could not reach the site. Eventually, the carriage had to be cut open to extinguish the fire, resulting in heavy smoke development.

Lessons learned from the Leinebusch Tunnel incident, as formulated in this study:

- Inadequate procedures delayed the arrival of the rescue train.
- Heavy smoke filled the tunnel tube despite a relatively large tunnel diameter and an enclosed fire.
- Working conditions were harsh despite relatively large working space and a limited temperature.

2.3 Mont Blanc Tunnel

The Mont Blanc Tunnel (road tunnel, 11,6 kilometers) is a single-tube tunnel allowing two-way traffic. There are parking exits every 300 meters. Every second parking exit has an evacuation room.

The start of the incident was a truck entering the tunnel with a leaking diesel fuel tank. The tank caught fire, making oncoming traffic to alert the truck driver. The driver stopped and left the vehicle. Vehicles kept entering the tunnel on both sides while alerted drivers in the tunnel attempted to turn their vehicles.

The tunnel entrances were closed 10 minutes after the truck had entered the tunnel. At this point, when the first emergency response units entered the tunnel, it was filled with smoke over a 1500-meter distance. Four minutes later, they managed to approach the burning vehicle up to 6 meters distance and lead the way to people at the site. After this, multiple emergency response units saw themselves forced to flee into the evacuation rooms, both downwind and upwind. They were evacuated from the tunnel hours later. The entire emergency response operation took 55 hours and consisted of defensive fire-fighting tactics. Thirty-nine people died in the incident.

Lessons learned from the Mont Blanc Tunnel incident, as formulated in this study:

- Un-coordinated ventilation tactics possibly enhanced the fire.
- Limited visibility made rescue workers fail to recognize evacuation rooms.
- Due to extreme temperatures, firefighting was not possible until after most of the fire load was burnt.

2.4 Tauern Tunnel

The Tauern Tunnel (road tunnel, 6,04 kilometers) is a single-tube tunnel allowing two-way traffic. There are no evacuation rooms inside the tunnel.

The start of the incident was a truck crashing into a queue of vehicles waiting at a red traffic light inside the tunnel. Immediately after the crash, in which eight people were killed, the truck - carrying paint products and spray cans - caught fire. During the first 10 minutes after the crash, people at the site tried to extinguish the fire, without effect. People managed to evacuate, walking several hundreds of meters towards the tunnel exit. Others fled into a telephone booth.

Twenty-seven minutes after the crash the first emergency response vehicle entered the tunnel but was forced to withdraw because of heavy smoke up to two kilometers downwind. Forty-five minutes later three people were rescued from the telephone booth. After this, emergency response activities aimed at extinguishing the fire. The operation was seriously hampered by parts of the ceiling collapsing.

Lessons learned from the Tauern Tunnel Incident, as formulated in this study:

- Heat and explosions forced emergency response units to withdraw, despite effective efforts to drive out smoke by active ventilation tactics.
- Failing construction integrity resulted in immediate danger for emergency response units.

2.5 Threats for emergency response

Despite the differences between the cases regarding tunnel layout and incident scenario, the same mechanisms seem to be accountable for possible life-threatening situations for emergency response units. These mechanisms may constitute both direct and indirect threats. Direct threats result in immediate danger independent of subsequent events. Indirect threats may result in danger dependent on subsequent events (like tactical decisions). Indirect threats may be posed by inadequate situation information; inadequate communications between control centers, emergency rooms and response units; inadequate procedures; persons failing to comply with adequate procedures; and failing maintenance of technical systems. Direct physical threats are more compelling and are posed by:

1. Smoke. Smoke spreads faster and fills larger parts of the tunnel than is expected by both people inside the tunnel and emergency response organizations outside the tunnel. Several kilometers of the tube can be filled with smoke within 10 to 15 minutes. Even small fires can cause large amounts of smoke and harsh conditions. Self-rescue and external rescue are seriously hindered by limited visibility.
2. Heat. Temperatures at tunnel fires may rise to over a 1000 degrees Celsius within 10 to 15 minutes. Heat can result in extreme damage to technical systems (communications, water supply) and in lesser construction integrity.
3. Collapsing structure. Falling debris may pile up to 50 centimeters at the center of the accident site. This seriously hampers emergency response activities, even more so in conditions of limited visibility. Moreover, a constant threat of falling debris constitutes a great danger for emergency response units.

The cases reveal that offensive emergency response tactics are not to be expected in case of a tunnel fire when emergency response organizations arrive at the tunnel exit within 10 to 15 minutes. The main impediments for self-rescue and offensive tactics are smoke and heat, in that particular order. This means that rescue opportunities are extremely limited.

3. Interviews with fire officers

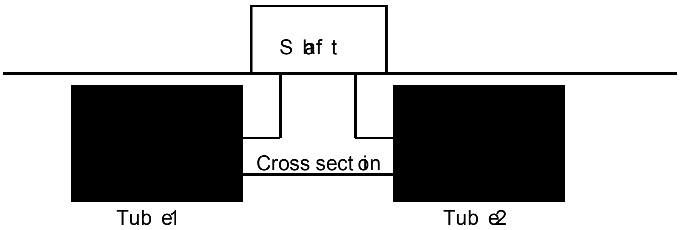
The aim of the second part of the study was to disclose emergency response possibilities in specified tunnel accidents, as perceived by Dutch fire officers. For this purpose, a method was devised for presenting accident scenarios to fire officers in a series of expert interviews. This method included a standard tunnel design, a set of accident scenarios and a selection method for the fire officers to be interviewed.

3.1 Interview structure

In order to gain reliable results it was considered necessary to use a standard tunnel layout in the interviews. Fire officers were shown the same main tunnel layout (TUDelft, 1999) that applies to the six Betuweline tunnels.

The general layout of these tunnels (figure 1) is a double-tube tunnel. Each tube contains one rail track that allows one-way traffic only. The two running tunnels are connected by cross sections at regular, and for the purpose of the interview, variable intervals up to 600 meters maximum. Shafts leading to ground level are included except where the tunnel passes under a canal.

Figure 1: General tunnel layout as used in interviews



Other features of the system are:

- Exit doors are operated by control room personnel and are fire resistant for 60 minutes.
- A permanently available water supply system (deluge system) is installed. The system is designed for extinguishing 300 MegaWatt fires. Its supply capacity is 3000 liters of water per minute for four hours. A distant operator controls it.
- An active ventilation system designed for driving out smoke in either direction is installed. The system is designed for 300 MegaWatt fires. Control room personnel operate the ventilation system.
- Emergency response organizations can use monitoring equipment (camera's, radar) and communication systems.

The second part of the interview method consisted of the set accident scenarios. Fire, leakage of hazardous materials and explosion scenarios were considered relevant because they have potential severe consequences.

Taking the identified direct threats into account (paragraph 2.5), six scenarios for the expert interviews were defined, in order of seriousness. It was assumed that the direct mechanisms strongly cohere with the seriousness of accident scenarios in tunnels. Indirect threats were not considered specific for tunnel accidents. No more scenario information was presented to the fire officers than would have been presented by the emergency room in case of a real alert.

The scenarios of which fire officers were to assess the emergency response possibilities are:

1. Small fire. In case of a small fire on a freight train in a tunnel, the temperature rises moderately, the spread of smoke is limited and the risk of collapse is negligible.
2. Major fire. In case of a major fire on a freight train in a tunnel, heat and smoke are intense. The risk of collapsing construction parts is plausible.
3. Minor leak of toxic chemicals (less than 10 liters). Temperature and smoke development are negligible as is the risk of collapse. Depending on the properties of the chemical, a minor leak may constitute a risk for persons in the tunnel.
4. Major leak of toxic chemicals (more than 10 liters). In this case, large amounts of (liquid) chemicals leak from a carriage in the rail tunnel for freight. Again, temperature and smoke development are negligible as is the risk of collapse. Due to evaporation, high concentrations of vapor are to be expected.

5. Explosion. A detonation has taken place inside the tunnel. The risk of (partial) collapse is plausible.
6. The threat of a Boiling Liquid Expanding Vapor Explosion (BLEVE). A carriage containing condensed gas is warmed up by heat radiation coming from a burning carriage nearby. Heat and smoke are intense. The risk of collapse will be realistic after an actual BLEVE.

Fire officers were asked to state what actions (purpose and means) they would take in the given scenarios had they been responsible for the operational tactics of the emergency response. It was emphasized that the perceived emergency response possibilities apply to situations at the tunnel entrance, at the time of arrival of the first emergency response units, and are geared to the specific tunnel properties as described above. The experts were also asked whether their perceived emergency response possibilities would be different if toxic chemicals were involved in the minor and major fire scenarios.

A standardized interview guide was constructed to prepare interviewers for requests for additional information on the exact position of the train, the number of carriages burning, the nature of the chemicals involved, the duration of the fire and the train's composition.

The experts had to be knowledgeable about tunnel emergency response possibilities. Therefore, experts were selected from various cities' fire services in The Netherlands where one or more tunnels already existed or were planned for the near future. In this way, fifteen experts were selected, including two experts from Dutch Rail.

3.2 Results from the interviews

The interviews resulted in consistent views on emergency response possibilities per scenario. It is important to consider some general notions that resulted from the interviews.

First, fire officers have a great need for precise situation information before considering entering the threatened tunnel tube. For information about the train composition, goods involved, exact location, tunnel climate, technical support systems and so on, fire officers heavily depend on Dutch Rail.

Second, fire officers assume that the train driver and a restricted number of co-drivers are able to reach a safe location outside the tunnel without external help. In fact, rail tunnels for freight are designed to meet this principle.

Third, the fire officers' main concern is the safety of firefighters. If their lives may be endangered in any way, firefighters will not be ordered to enter the tunnel. Because of this principle and the expectation that a restricted number of people in the tunnel will be able to get out by themselves, defensive tactics are generally preferred.

Fourth, fire officers consider explorative activities equal to exposing personnel to danger. This strengthens their preference for caution.

As regards the scenarios, fire officers perceive possibilities for offensive emergency response tactics only for operations involving small fires or minor leaks of hazardous materials. These scenarios are not considered life threatening. However, when dealing with a small fire, measures (like ventilation) are to be taken before entering the tunnel to stabilize the spread of smoke and rise of temperature. As for dealing with a minor leak, some fire officers mention the responsibility of the transporter or Dutch Rail for taking appropriate action.

In the other scenarios, experts state that immediately entering the threatened tunnel tube is not considered. Extensive exploration from a great distance is preferred in operations involving major leaks, and with built-in time delay after an explosion.

Fire officers are not consistent in stating the tactics required for handling a major leak of hazardous materials. Perceived emergency response possibilities for this scenario seem to depend on confidence and pre-determined risk perception. In case of a major fire on a freight train, entering the tunnel tube is not considered a realistic option: waiting is the fire officers' motto. In a situation when a BLEVE is expected, all efforts of emergency response will focus on the evacuation of people in the direct vicinity of the tunnel.

4. Modeling of emergency response to tunnel fires

The cases and the expert interviews led to the identification of threats and stated emergency response actions in several scenarios. In order to clarify the critical mechanisms for emergency response at certain moments in time, a third research method was used. Data on the development of tunnel fires were incorporated into an empirical timeline of the primary process of emergency response.

In paragraph 4.1, the physical mechanisms that appear in tunnel fires are described, using data from fire experiments. Paragraph 4.2 sets out the emergency response timeline. In paragraph 4.3, the mechanisms and the response timeline are set side by side in order to assess the situation in the threatened tunnel tube at the time of arrival of emergency responders.

4.1 Physical mechanisms in tunnel fires

The development of the physical mechanisms of smoke, heat and collapse are themselves dependent on other variables. The variables that determine the development of a tunnel fire are:

- The nature of the burning materials (wood, plastics, steel) and the extent to which all material is burnt determine the spread of smoke.
- The amount of the fire load (in MegaWatts) determines the temperature.
- The properties of the hazardous materials (acute danger, manner of intoxication) determine to what extent the tunnel climate is accessible for emergency responders.
- The extent of the fire load, tunnel wall thickness and the nature of the concrete and coatings of the tunnel wall determine the risk of collapse.

Of course, construction characteristics (length, diameter) and the set of technical support systems installed in the tunnel (ventilation, water supply, detection systems) also influence the development of physical mechanisms.

In a project initiated by the European Union, called EUREKA EU 499 FIRETUN (EU, 1999), eight European countries participated in exploring possibilities for the protection of people in tunnels, for maintaining the infrastructure in case of a tunnel fire and for the fire service with regard to rescue and fire extinguishing operations. For this purpose, experiments were carried out in the Norwegian Reppafjord Tunnel. The Reppafjord Tunnel is located 200 kilometers north of the polar circle at an altitude of 200 meters. It is a mineshaft of 2.3 kilometers length horizontally. The tunnel is 5.5 to 7.0 meters wide and 4.8 to 5.5 meters high.

Temperature, light intensity, carbon monoxide concentration, and rubble height were measured during several fires involving various vehicles in this tunnel. The measurements were held at a wind speed of 0.5 meters per second and at a height of 1.5 to 2 meters. Three vehicles were set on fire at a distance of 295 meters from the tunnel entrance. The burning vehicles were:

- A bus: 48000 Mega Joules
- A subway carriage (aluminum): 41000 Mega Joules
- A passenger carriage (steel): 77000 Mega Joules

The results of the measurements, as presented in Blume (1994) and Blume (1996), are shown below.

Figure 2 shows the temperature development in time, as measured at a height of 2 meters, 20 meters downwind from the burning vehicles. It is clear that the maximum temperatures of the bus and subway carriage fires are reached after approximately 15 minutes: 800 and 1150 degrees Celsius. The train fire reaches a maximum temperature of 700 degrees Celsius after 100 minutes.

Figure 2: Temperature in time

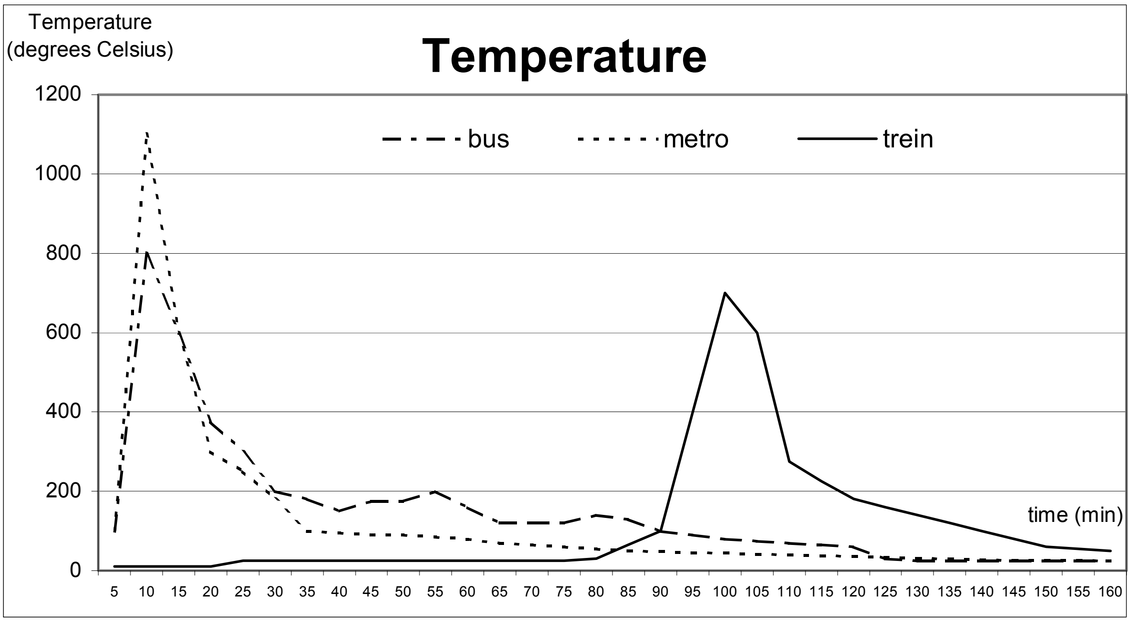
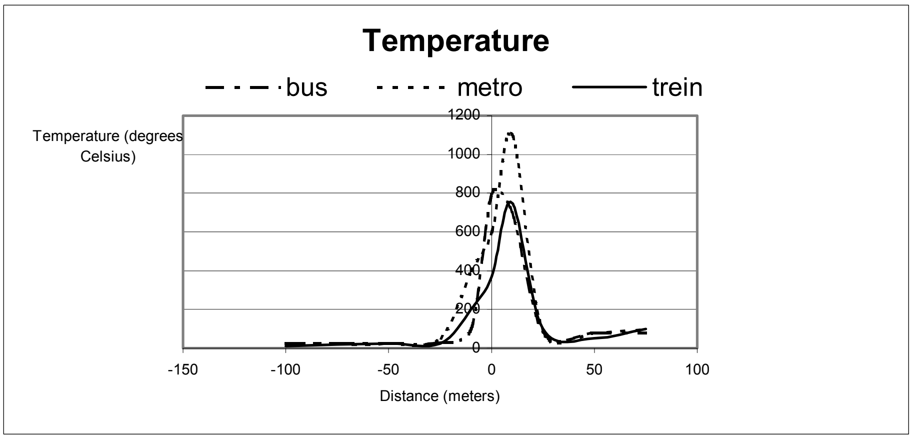


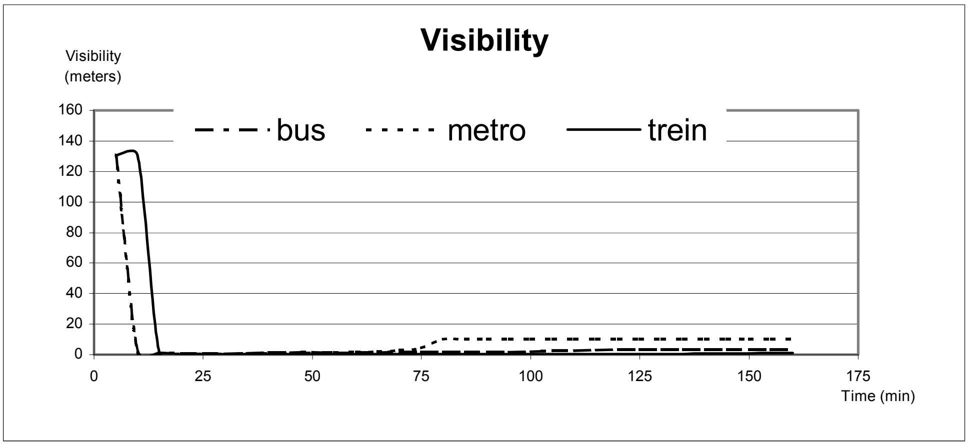
Figure 3 shows the maximum temperatures at a height of 2 meters measured at varying distances from the vehicles. Seen from the vehicles, the wind direction is toward the 2-kilometer part of the tunnel. The figure shows that the maximum temperature in the bus fire is reached at a 0-meter distance (800 degrees Celsius), whereas maximum temperatures in the other vehicle fires are reached at 15 meters (1100 and 750 degrees Celsius), probably due to the wind in the tunnel. Temperatures drop rapidly with increasing distances: at a 20-meter distance temperatures are down to approximately 100 degrees Celsius.

Figure 3: Temperature at varying distances



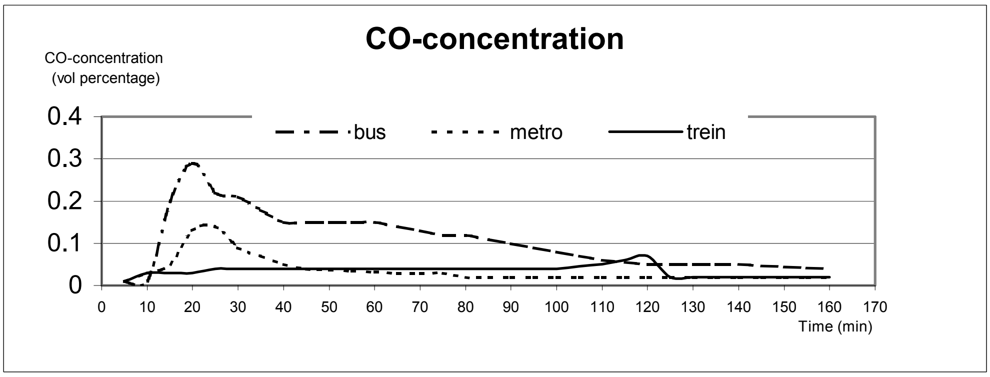
In the experiments, visibility was not measured but calculated on the basis of light intensity (I) measurements, according to Jin (1976). Light intensity was measured at a height of 2 meters at a 100-meter distance from the burning vehicles. Figure 4 shows the visibility development in time. For the first 75 minutes, the bus and subway carriage curves coincide. After 10 minutes, visibility in these fires is reduced to less than 10 meters. At the train fire, visibility becomes less than 10 meters within 15 minutes. It is also evident that visibility – at the current wind speed - hardly improves, even after several hours.

Figure 4: Visibility in time



In the EUREKA 499 FIRETUN project, no specific tests were carried out to measure toxic concentrations. Toxic concentrations heavily depend on the nature of the burning material. In fact, no products were burnt other than the empty vehicles (without their interiors). Of all the chemicals in the emitted smoke, only carbon monoxide (CO) concentrations were measured. Figure 5 shows that in the bus and subway carriage fires the maximum CO-concentrations reach peak levels (0.29 and 0.14 volume percentage[2], respectively) within 20 minutes. The train fire results in a 0.07 CO concentration after 2 hours. Concentrations drop slowly in the bus and subway carriage fires and more rapidly in the train fire.

Figure 5: CO-concentration in time



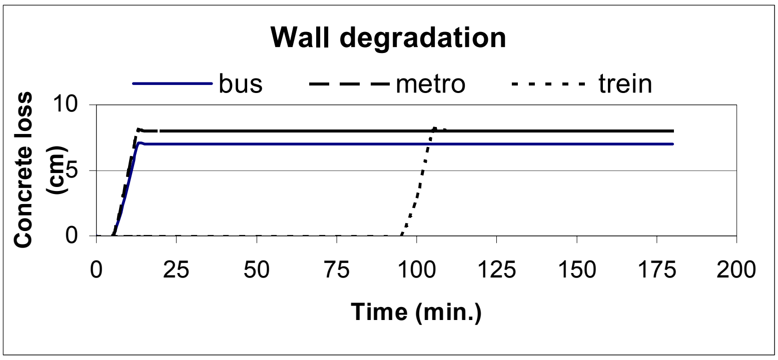
The Reppafjord Tunnel experiments did not include measurements of rubble heights near the fires. Therefore, a hypothetical curve is presented on the basis of a calculation. According to the Dutch

[2] One volume percentage corresponds with 10.000 parts CO per million parts air.

Ministry of Public Works, a realistic threat of collapse is introduced when the tunnel wall thickness is reduced to half its original value. The tunnel wall degrades by 1 centimeter per minute on average – depending on the density of the concrete - when the temperature exceeds 600 degrees Celcius. The remaining tunnel wall thickness (T) can be calculated using the following formula, in which t is the time elapsed (minutes) and D is the tunnel diameter (centimeters): $T_t = 1/25D - (1*t)$. For example, the tunnel wall thickness in a 10-meter wide tunnel after a 15-minute fire and at a temperature exceeding 600 degrees Celsius will be 25 centimeters. Because half of the tunnel wall thickness is 20 centimeters, there is no real risk of collapse.

Figure 6 shows tunnel wall degradation as calculated for the Reppafjord Tunnel fires, where the periods of high temperature (exceeding 600 degrees) determine the reduced wall thickness. Seven to eight centimeters of concrete would be lost in all three fires.

Figure 6: Tunnel wall degradation



The figures explained above show the development of the physical situation in tunnel fires. In order to assess the situation that emergency responders face when they reach the tunnel entrance, a timeline for emergency response was constructed.

4.2 Emergency response timeline

The physical situation on arrival at the tunnel entrance determines the decision for explorative or offensive activities inside the tunnel by the fire service. Before arrival, emergency response units go through several stages (McAleer and Naqvi, 1994; Repede and Bernardo, 1994; Rosmuller, 2001):

1. Report time: the time necessary for an emergency report to reach the public emergency room. Action by people in the tunnel and Rail Traffic Control Centre.
2. Alert time: the time necessary for an emergency alert to reach fire service units. Action by the public emergency room.
3. Turn-out time: the time necessary for the fire service to turn out.
4. Driving time: the time necessary for the first fire service vehicle to reach the tunnel entrance.
5. Exploration time: the time between arrival and the decision for an intervention inside the threatened tunnel tube.
6. Walking time: the time it takes to walk from the tunnel entrance to the right cross section where response tactics are to be carried out.
7. Checking time: the time it takes to check whether the overhead wire is dead.

These are successive stages. Parallel actions have to be carried out by other organizations apart from emergency response organizations, like stopping the traffic (by traffic control), self-evacuation (by people inside the train and the tunnel), shutting down power on the overhead wire and opening cross section exit doors (rail control). It is important to recognize that these parallel actions may cause delays in the stages mentioned above.

However, potential delays were ignored in the construction of the timeline. It was assumed that emergency response units will be given full support in obtaining information about train composition and cargo, opening cross section doors and shutting down overhead wire power. Moreover, it was assumed that the physical mechanisms and emergency response timeline share the same starting point (t=0), i.e. the moment when the train comes to a stop in the tunnel. In addition, the actual emergency response activities in the threatened tunnel tube were not considered.

The minimum amount of time needed for fire service units to arrive at the tunnel entrance is the cumulative time necessary for the stages mentioned above. The time per stage is set out below. In the accumulation, the minimum time per stage is used. This means, that the most optimistic scenario for emergency response is considered.

1. Report time. Based on expert judgment in the Dutch High Speed Rail (Amsterdam-Paris) Safety Committee, this time is set at 5 to 15 minutes.
2. Alert time. The emergency rooms of three fire service regions in The Netherlands were consulted. Both acute and non-acute reports can be processed into an adequate alert within 1 minute.
3. Turn-out time. According to national fire statistics, fire service units can turn out within 3 to 4 minutes. This is an average for urban and rural areas.
4. Driving time. Variables, such as road type, weather type, alert type, vehicle type and time of the day determine driving speeds under different conditions. Driving time can be calculated using these driving speeds and a pre-determined distance from a barracks to the tunnel entrance. By day and under normal weather conditions it will take approximately 10 minutes to reach a tunnel that is 10 kilometers away (a plausible situation in the Netherlands), driving through built-up areas and country roads.
5. Exploration time. Once emergency response units have arrived at the tunnel entrance, operation command at the site will have to make a decision about subsequent activities on the basis of emergency room information and own observations. Common practice shows that it takes approximately 5 minutes to reach such a decision.
6. Walking time. Rosmuller (2001) measured various walking times of firemen, taking into account variables such as walking ground, distance, weather conditions, lift load and personal physical characteristics. He deduced some rules of thumb for walking speeds: walking on a rail track (1.5 meters per second); walking up a rail slope (1 meter per second); walking up a ladder (0.5 meters per second) et cetera. These speeds will not (and cannot) exhaust emergency responders. The walking time in an accident situation involving a train standing 600 meters from the tunnel entrance right in front of a cross section door (a plausible situation for a Betuweline tunnel), at a downhill speed of 2 meters per second, would be 5 minutes.
7. Checking time. Empirical data for this aspect are not available. Consulted fire officers estimate checking time (to ensure the overhead wire is dead) at 4 to 5 minutes.

The cumulative timeline for emergency response is summed up in table 7:

Table 7: Cumulative timeline for emergency response

Stage	Time necessary (minutes)	Total time (minutes)
Report time	5-15	5
Alert time	1	6
Turn-out time	3-4	9
Driving time	Depending on distance (10 at 10 kilometers)	19
Exploration time	5	24

Walking time	Depending on distance (5 at 600 meters)	29
Checking time	4-5	33

It can be concluded, that there are roughly 33 minutes between the stopping of the train and the arrival of the first emergency responders at the right cross section inside the tunnel, ready for action in the threatened tunnel tube.

4.3 Confronting the physical mechanisms and the emergency response timeline

Based on the described mechanisms and the timeline above, it is possible to estimate emergency response possibilities. Table 8 shows temperature, visibility, CO-concentration after 33 minutes. The values are deduced from the figures presented in paragraph 4.1. This table reflects the situation, as modeled, in a tunnel tube where a vehicle has been burning for 33 minutes. Now, fire service units would be ready to enter the threatened tunnel tube near the burning vehicle, 600 meters from the tunnel entrance. It is important to recognize that no artificial ventilation techniques are used in this situation.

Table 8: Physical situation after 33 minutes

Vehicle	Temperature (33 mins.)	Visibility (33 mins.)	CO (33 mins.)	Wall degradation
Bus	App. 200 degrees Celsius (decreasing)	Less than 5 meters (constant)	0.20 volume percentage (decreasing)	No danger of collapse
Subway carriage	App. 180 degrees Celsius (decreasing)	Less than 5 meters (constant)	0.08 volume percentage (decreasing)	No danger of collapse
Train carriage	App. 50 degrees Celsius (increasing)	Less than 5 meters (constant)	0.04 volume percentage (constant)	No danger of collapse

Emergency response possibilities depend on both the physical mechanisms and capacities of trained emergency responders, as experienced in common practice or as taught by instructors.

Dutch fire service teaching material sets the maximum temperature for intervention in enclosed spaces at 70 degrees Celsius. Comparing this standard with the temperatures mentioned in table 9 shows that the standard temperature for emergency response activities is exceeded, except in the case of the train fire.

There are no accepted standards for minimal visibility in fire service activities. However, Blume (1994) states that with a visibility of less than 10 meters, victims in a tunnel fire will lose their bearings, which makes it virtually impossible for them to find their way out. Note, that visibility is extremely limited over a great distance (figure 5 depicts visibility at a distance of 100 meters). The same risk of losing direction applies to emergency responders when visibility is less than 5 meters. This means that intervening in the smoke-filled tunnel tube constitutes a serious threat to their safety.

With regard to CO-concentrations, Blume (1994) states that persons not wearing breathing apparatus will be seriously affected by a gas concentration exceeding 0.1 volume percentage. Using breathing apparatus can remove the threat posed by carbon monoxide. This means that active intervention is possible.

Reduction of tunnel wall thickness after 33 minutes does not cause a real danger of collapse. It should be recognized, however, that rubble falling from the tunnel wall that is piled up on the floor is a serious (psychological) impediment for emergency responders. It should also be considered that the use of breathing apparatus is a physical effort in itself. In addition, the physical capacities (and working time) of emergency responders are restricted because of heat absorption and harsh working conditions.

It can be concluded that reduced visibility is the first critical mechanism that limits emergency response possibilities. Heat is the second mechanism that impedes rescue or fire-fighting opportunities. Carbon monoxide does not pose a real threat to emergency response units, whereas the effect of falling rubble is a psychological barrier.

5. Emergency response possibilities

The results of the three research activities - case studies, interviews and modeling - are consistent in pointing out the extreme limitations for emergency response organizations to apply offensive operational tactics in a threatened tunnel tube.

Case studies revealed that offensive action may result in endangering the lives of emergency responders, while the effects in terms of rescue and extinguishing the fire are highly uncertain. Smoke, heat and construction damage are overwhelming.

Interviews revealed that fire officers exercise restraint in ordering personnel to work in the threatened tunnel tube. Especially with a limited number of people present in the tunnel, as is the case in rail tunnels for freight, risk calculations generally work out in favor of emergency response personnel.

Modeling of threatening physical mechanisms and the emergency response timeline revealed that a safe intervention is unlikely due to extremely limited visibility and high temperatures.

On the basis of the results, a guideline was proposed for *Emergency response possibilities in the accident scenarios in rail tunnels for freight* as used in the interviews, which can be summarized as follows:

- Small fire, not involving hazardous materials: no attempt at rapid rescue, extinguishing the fire after extensive exploration.
- Minor fire, involving hazardous materials: no immediate action, response organizations wait until the fire has gone out naturally.
- Major fire, not involving hazardous materials: no immediate action.
- Major fire, involving hazardous materials: no immediate action.
- Minor leaks of hazardous materials: no attempt at rapid rescue, possible co-operation of fire service with Dutch Rail emergency response to take out the source of the leak. Active ventilation tactics should be considered as an alternative.
- Major leak of hazardous materials: no immediate actions inside the tunnel. Active ventilation tactics and measures to lessen the environmental effects are priorities.
- Explosion: after an explosion immediate action is not recommended.
- Threat of a BLEVE: no immediate action, evacuation of the tunnel environment.

Some comments can be made on the research design and methods. First, the emergency response possibilities as perceived and stated by fire officers may be different from the decisions they will take in actual accident situations. Second, empirical data from the Reppafjord tunnel may not apply to all tunnel fires. The research did not include fires involving cargo or a considerable number of vehicles. Both tunnel characteristics and fire loads are crucial for the development of the physical conditions in the tunnel. Remember that results were not specified for situations in which active ventilation tactics were employed.

Despite these comments, there is a strong case for the conclusion, which is endorsed by all three parts of the research. Notwithstanding this conclusion, compelling topics for further research are suggested:

- More specific examples of accidents involving rail tunnels for freight should be studied. Comparative case studies in general should involve cases with standardized tunnel characteristics.

- Realistic simulation of fire officers' decision making under stress in a tunnel accident scenario could reveal the actual behavior of emergency response organizations.
- The influence on physical mechanisms (smoke, heat) of tunnel characteristics and technical systems, such as automatic extinguishing installations and ventilation systems, should be studied in controlled experiments, like the EUREKA project. In addition, fires involving different vehicles, including cargo and a considerable number of vehicles should be studied. Accident scenarios used in the experiments should be as realistic as possible.
- Similar studies should be carried out to explore possible differences in emergency response opportunities in rail tunnels for freight and road tunnels, and rail tunnels for freight and rail tunnels for passenger trains, respectively.

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