Fire Dynamics During the Channel Tunnel Fires

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ABSTRACT

Three major fire incidents have occurred in the Channel Tunnel since it opened in the early 90s. The fires on the 18th of November 1996 and the 11th of September 2008 grew to involve many heavy goods vehicles (HGV) on carrier wagons and caused major damage to the tunnel structure. The fire on the 21st of August 2006 involved only a single HGV and did not spread, although the adjacent HGV was damaged by heat. Each of these incidents is described and the incidents are compared. The official inquiry into the 2008 fire has not yet been published, so information has been collected from press reports. It is clear that the fire development in 1996 and 2008 was broadly similar, while the fire in 2006 was very different. These differences may be due to the cargo and construction of the vehicles involved, but also may be due to the differences in ventilation during the incidents. The conventional model of fire dynamics in multiple vehicle fires is discussed with reference to the Channel Tunnel fires. It is observed that the primary difference between the 2006 fire and the other two was that in the 1996 and 2008 fires, the initial fire would have experienced a reversal in airflow direction and an increase in ventilation flow after the fire was established. In the 2006 fire there was no reversal or increase in flow. It is proposed that these ventilation changes may be able to explain the differences in fire dynamics. Recommendations based on these proposals are made.

KEYWORDS: fire dynamics, channel tunnel, ventilation

INTRODUCTION

The Channel Tunnel forms the rail link between the UK and France. It consists of three parallel tunnels; two running tunnels, each with a single rail track, on either side of a service tunnel, see Figure 1. The tunnels are approximately 50 km long (37 km of which is under the English Channel). The tunnel runs north-west to south-east, the northernmost tunnel is referred to as 'Running Tunnel North' (RTN) and generally handles traffic from the UK to France, with the traffic coming from France generally using 'Running Tunnel South' (RTS). The service tunnel has three main safety functions: to provide normal ventilation for the running tunnels, to provide a safe haven for passengers and crew in the event of an evacuation and to facilitate the speedy arrival of the emergency services.

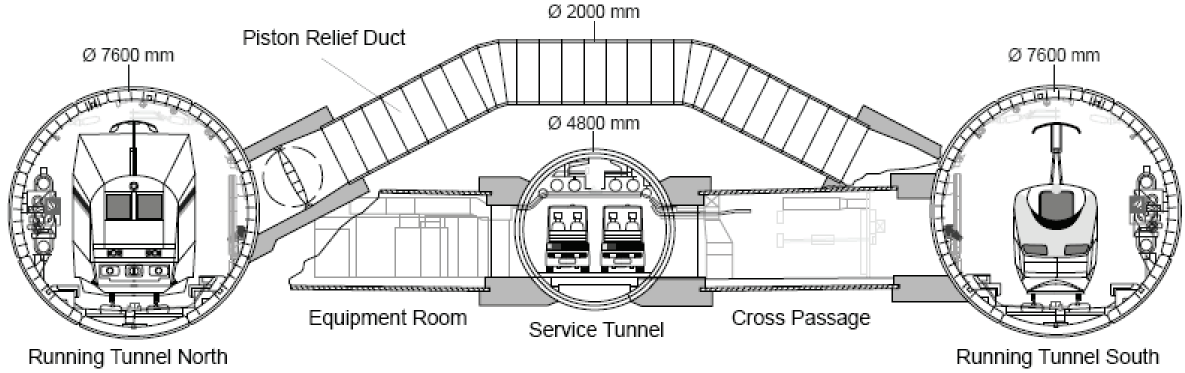

Figure 1 Layout of the Channel Tunnel

Four types of trains use the tunnel:
1. Tourist shuttles, consisting of single and double-decker wagons, carrying coaches and cars
2. Heavy Goods Vehicle (HGV) shuttles carrying lorries and trucks on semi-open wagons
3. Passenger trains (Eurostar)
4. Freight trains

There have been three significant fire incidents in the Channel Tunnel to date: on the 18th of November 1996, the 21st of August 2006 and the 11th of September 2008. Each of these incidents has occurred on a HGV shuttle. In the 1996 fire the train was travelling from France to the UK in RTS, in the other two incidents, the train was travelling from the UK to France in RTN.

The HGV shuttle trains (see schematic in Figure 2) are generally composed of:
1. A locomotive at the front of the train, staffed by a driver
2. An amenity coach, carrying all passengers (vehicle drivers), staffed by the 'Chef de Train' and a steward. (This is generally at the front of the train; occasionally it is between the rear loader and rear locomotive. In all three fire incidents to date, the amenity coach was at the front.)
3. Front loader wagon
4. Front rake of fifteen 'semi-open' HGV carrier wagons (each 20m long)
5. Middle loader wagon
6. Rear rake of fifteen 'semi-open' HGV carrier wagons
7. Rear loader wagon
8. Rear locomotive, no crew.

In total, the train is about 740 m long.

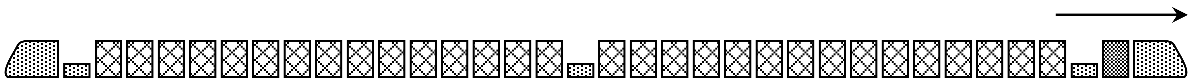

Figure 2 Schematic of the HGV shuttle trains (direction of travel indicated)

During normal operation of the tunnel, there is a minimal supply of fresh air into the tunnel, this is designated the 'Normal Ventilation System' (NVS). Under NVS conditions, the prevailing airflow is due to the piston effect of the trains, thus runs in the same direction as the trains themselves. The speed of the airflow relative to the train is approximately half the speed of the train relative to the tunnel. Thus, before any emergency ventilation conditions are implemented, any fire on the train (travelling at 140 km/h) will experience the relative airflow as having a velocity of about 20 ms^{-1} towards the rear of the train.

Once a fire incident is declared, the 'Supplementary Ventilation System' (SVS) is activated. This generates a flow of about 2.9 ms^{-1} (relative to the tunnel) in the opposite direction to the direction of train travel.

THE INCIDENTS

18th November 1996

The 1996 fire occurred on HGV Shuttle Mission 7539, which departed the French terminal at 21:42 hrs on the 18th of November. The main events relating to ventilation conditions and fire behaviour are summarised in Table 1. The fire ultimately involved the rearmost ten HGV carriers and destructively damaged the rear loader wagon and locomotive. The distribution of cargoes and damage on the rear rake is given in Table 2.

Time	Event	Comment
21:42	Train departs station	Fire visible on 2nd rake. On wagon 7 or 10 (witnesses)
21:48	Train enters tunnel	
21:51	Onboard fire alarm	On rear locomotive
21:58	Train stopped	Driver initially tried to keep going. Decision to stop on basis of a faulty system warning light. Once stopped, driver unable to see tunnel walls to identify location.
22:13	SVS activated	Fan blades set incorrectly. No longitudinal flow
22:22	SVS fully established Evacuation carried out	Ventilation flow now about 2.9 ms^{-1}
22:53	Fire brigade assess fire	~ 5 wagons on fire at the rear
23:39	Fire fighting begins	Takes about 6 hours.

Table 1 Timeline of the 1996 fire.

Loader wagon	Plastic bags	Reels of paper	Plastic racks	Catalogues	Pineapples	Pineapples	Cornflakes	Frozen fat	Frozen chips	Reels of paper	Clothes	Machinery	Cheese	Titanium scraps	Loader wagon	Rear locomotive
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
Salvageable		Serious damage			Irreparable damage to all carrier wagons. All vehicles destroyed.											
								Serious damage to tunnel lining								

Table 2 Distribution of cargo and damage in the 1996 fire.

Time	Event	Comment
13:25	Train departs station	Fire not in evidence
13:26	Train enters tunnel	Smoke emanating from incident vehicle. (Caught on CCTV)
13:30:31	1st smoke detector triggered	Train had passed three earlier smoke detectors which did not activate
13:30:45	Onboard fire detection triggered	Detector on rear loader wagon
13:31	All trains ordered to reduce to 100 km/h	Driver acted on this instruction
13:32:39	2nd smoke detector triggered	
13:34	Train instructed to stop	Train had to clear the 'go zone' before stopping
13:37	SVS started but dampers closed	No SVS in running tunnel
13:39	SVS now operational in both running tunnels	Ventilation assumed to be about 2.5 ms^{-1}
13:40	Train stops	SVS already established, fire never experiences an inversion of flow
13:49	Evacuation complete	Smoke / visibility not an issue
15:45	Fire fighting begins	2 hours after train stopped
16:05	Fire extinguished	One HGV destroyed. Carrier wagon damaged. Downstream HGV suffered significant heat damage, but did not ignite. Upstream HGV suffered minor heat damage.

Table 3 Timeline of the 2006 fire

21st August 2006

The 2006 fire occurred on HGV Shuttle Mission 7370, from the UK to France, which departed the Folkestone terminal at 13:23 hrs on the 21st of August. The main events relating to ventilation conditions and fire behaviour are summarised in Table 3.

11th September 2008

At the time of writing (December 2009), the official report on the investigation into this fire has not been published. The French Bureau d'Enquêtes sur les Accidents de Transport Terrestre (BEA-TT) and the UK Rail Accident Investigation Branch (RAIB) are carrying out a joint investigation into the fire. As the official investigation is not yet public, the precise details of the incident cannot be listed here. A few facts can be gleaned from the RAIB web pages [1], press reports on the BBC web pages [2], The Guardian newspaper [3], New Civil Engineer (NCE) magazine [4] and elsewhere, including:

- No fire was visible as the train entered the tunnel
- The train was stopped, beside a cross-passage, ‘immediately’ following identification of the fire
- The train stopped 39km into the tunnel (11.5 km from the French Portal)
- The fire was larger and more destructive than the 1996 fire
- The passengers could see flames from the amenity coach and heard “an explosion”
- The passengers felt the heat from the fire before they evacuated the amenity coach
- 29 passengers and 3 crew were evacuated, 14 required hospital attention
- Graphics on the BBC web pages imply that the initial fire was on the first HGV carrier wagon
- The fire may have started on “a lorry carrying chemicals, which is understood to have overturned” [this is not mentioned in later press articles, so may be spurious]
- The concrete tunnel lining required repairs along 650m of its length
- There was ‘severe damage’ to the concrete (spalling to a depth of 400mm; the full depth of the tunnel lining) over a 20m long section of the tunnel
- The train was not carrying a full complement of HGV; some carrier wagons were empty
- Some of the HGV were not carrying any cargo
- The incident evolved in a similar manner to the 1996 fire, except that the SVS was operated sooner
- The fire was extinguished by mid-morning the following day.

From these facts we can deduce the following:

- The fire started near the front of the train (it was visible by the passengers)
- The fire extended along most of the length of the train (the damage to the tunnel was 170m – i.e. approx 8 wagons – longer than in the 1996 fire, which involved almost half the train)

COMPARISON OF THE INCIDENTS

Obviously, the most striking difference between the three incidents is that in the 1996 and 2008 fires, the fire would appear to have spread very rapidly to involve multiple HGV and carrier wagons by the time the fire brigade arrived at the scene and made their initial assessment, whereas in the 2006 incident, the fire had not spread to either of the adjacent vehicles by the time the fire brigade arrived.

There are a number of possible reasons for this discrepancy, including:

- The construction and cargo of the initial vehicle on fire
- The construction and cargoes of the adjacent vehicles
- The differences in ventilation flow experienced by the fire in its development

In this paper it is proposed that the differences in ventilation conditions experienced by the fires in these instances are the primary factor responsible for the different outcomes of the events.

The 2006 fire differs significantly from the other two incidents in that the fire, while it did experience some changes in the velocity of the airflow, did not experience any reversal of the flow or periods of low flow. This is due to the fact that the fire was detected while the train was in the 'go zone' (a section of the tunnel where Eurotunnel policy states that no trains should be stopped) and, hence, the SVS airflow was established before the train came to a halt. Thus (very approximately) the airflow experienced by the train would have been:

~ 20 ms^{-1} before detection / ~ 15 ms^{-1} after detection / ~ 3 ms^{-1} after train stopped

In the 1996 fire, the sequence would have been more like this:

~ 20 ms^{-1} before / ~15 ms^{-1} after / reversal of flow when stopped / minimal flow for 20 min / ~ 3 ms^{-1}

In the 2008 fire, the pattern is believed to have been much like in 1996, except that the minimal flow period would only have been of the order of a few minutes.

This paper proposes that the reversal of flow and the velocity increases following periods of minimal flow are directly linked to periods of rapid fire spread along the train.

FIRE DYNAMICS IN A MULTIPLE VEHICLE FIRE

The generally accepted model of fire development in multiple vehicle tunnel fire incidents was described in 2003 by Ingason [5]. The process, divided into zones, is discussed using a schematic picture similar to the one in Figure 3.

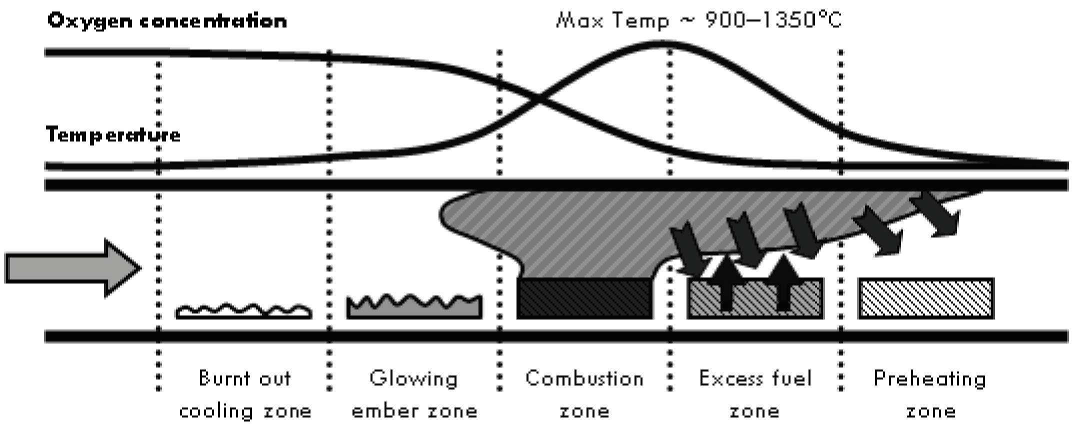

Figure 3 The conventional model of catastrophic tunnel fires, based on Ingason

The basic concept is that there is a fire travelling along a line of vehicles in the direction of ventilation flow. The fire consumes fuel as it progresses, but the extent of the combustion zone is limited by the amount of fresh air supplied by the (forced) ventilation system.

A large fire in a tunnel will consume a large amount of oxygen. It is well established [6,7] that most fuel types release about 13 MJ of energy per kg of oxygen consumed (approximately equivalent to about 3 MJ/m^3 of air 'consumed'; although this value is temperature dependent). Thus, the maximum sustainable heat release rate of a large fire in a tunnel is constrained by the airflow to the fire.

The Channel Tunnel tubes may be taken to be 40 m^2 in cross-section, thus, the volumetric flow of air to the fire is approximately 40*v* m^3s^{-1}, where *v* is the longitudinal airflow velocity (in ms^{-1}). Thus the maximum sustainable heat release rate of a fire in the tunnel is approximately 120*v* MW.

Thus, when the train was moving (and the flow was over 15 ms^{-1}), the theoretical maximum HRR of the fire would have been over 1.8 GW (an unrealistically high number), whereas while the SVS was active and the train stopped, the maximum sustainable HRR would have been about 350 MW – which is equivalent to only two or three HGV fires simultaneously (based on the HGV fire tests from Runehamar; up to 200 MW [8] and Hammerfest; up to 120 MW [9]). When the flow was lower than SVS flow, the maximum HRR would also have been lower.

It is only during the periods of relatively low flow (i.e. after the train had stopped) that the fire behaviour would follow Ingason's pattern. Under these circumstances, a zone of hot, unburned, gaseous fuel would be produced downstream of the fire location. If, after this zone of hot fuel developed, the ventilation conditions in the tunnel were changed – either by reversing or increasing the flow – these hot flammable gases would mix with fresh air and this would lead to very rapid burning, perhaps even an explosive event analogous to backdraught in compartment fires.

It is proposed that these rapid burning events in the 1996 and 2008 Channel Tunnel fires lead to rapid fire spread between wagons, possibly across several wagons at a time. It may be that the 2006 fire did not spread in the same way because there were no reversals of flow or increases in flow during the incident.

FIRE GROWTH AND SPREAD IN THE 1996 AND 2008 FIRES

In both the very large fire incidents in the Channel Tunnel, the fire was detected by a fixed flame detector while the train was moving at high speed in the tunnel. Given the nature of the detection systems, it is assumed that the fire was at least a few MW in size and external to the initial incident vehicle by the time it was detected.

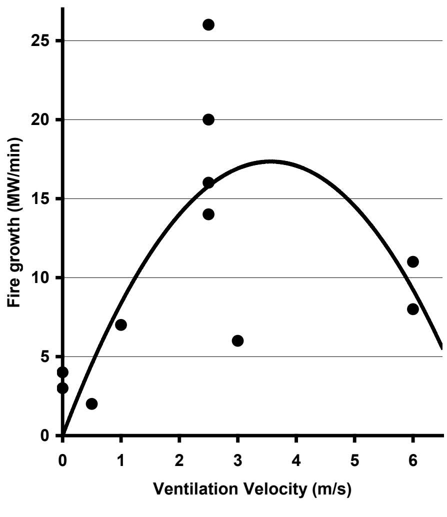

Figure 4 The apparent relationship between fire growth rate and ventilation velocity [11].

It has previously been observed that the rate of growth of a fire in a tunnel is dependent on the ventilation rate [10,11]. While no experimental fire tests have been carried out in tunnels with ventilation flow rates above about 6 ms^{-1}, such information as is available suggests that there is a decline in growth rate with increasing velocity, for ventilation velocities above about 4 ms^{-1}, see

Figure 4. Thus it is likely that the fire would not have grown very large while the train was moving at high velocity.

As the train progressed, the fire may have spread to the vehicle immediately following the initial incident vehicle, or this vehicle could have simply been pre-heated by the initial fire. It is likely that – at the least – some small fires may have been ignited on this vehicle by firebrands. Once the train came to a stop, the resulting reversal of flow would have given these small fires (on a pre-heated fuel load) a plentiful supply of fresh air at a velocity likely to lead to rapid fire growth [10], thus the adjacent vehicle (previously downstream) vehicle would be likely to become fully involved at this time. Concurrently with this, the flames from the initial fire would be directed towards the (previously upstream) other adjacent vehicle, so it is quite likely that the fire would spread in that direction too.

As the flow reduced to 'natural ventilation' conditions, the fires on these vehicles would become established but, due to the lack of available fresh air, may not have burned fully, producing a hot, fuel rich atmosphere. In the 1996 fire this phase may have lasted as much as 20 minutes, in 2008 it was shorter. Despite the lack of oxygen at the initial burning vehicle, the hot flammable gases would burn whenever and wherever they mixed with fresh air. This burning zone could have migrated several vehicle lengths away from the initial fire location, igniting small fires on every vehicle in the zone.

Once the SVS was established (introducing another reversal in flow direction), there would be sufficient fresh air to enflame these small fires, so the fire would grow and spread very rapidly; perhaps even explosively if the conditions were suitable.

This process is able to explain the rapid spread to a very large fire observed by the fire brigade on entrance to the tunnel in both incidents.

RECOMMENDATIONS

At present this analysis is largely speculation. Further research is required and is intended. However, if this scenario is demonstrated to be valid, the following recommendations can be made for train fires in tunnels:

1. If it is necessary to stop the train in the tunnel, the emergency ventilation system should be activated and allowed to become fully established before the train is signalled to stop. This would mean that the fire would never experience a reversal in flow direction or a period of very low flow.
2. If a train on fire is stopped in the tunnel and is subject to a longitudinal airflow, the airflow velocity should not be increased after the fire has become well established.
3. Given that fire growth and spread appears to be slower on a fast moving train, compared to one that is stopped, consideration should be given to drive the train out of the tunnel before stopping.

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