ABSTRACT

The first actions carried out by the users and the operators of a tunnel can have a significant effect on the outcome. Most minor tunnel fires are dealt with by application of a pre-planned response procedure without injury or serious damage. On the rare occasions when a serious fire breaks out the dynamics of the situation are different. This paper sets out some of the technical questions which need to be addressed in understanding emergency response; how quickly smoke moves, the effect of wind and traffic-induced air flows, tunnel slope and the time response of the ventilation system.

A three-dimensional, transient CFD model has been developed and applied to study these effects. Validation has been obtained previously by way of comparison with both laboratory and full-scale fire experiments. The methodologies developed during validation studies have been applied so that the level of confidence in the parametric studies reported in this paper is very high.

The objective of the paper is to stimulate discussion on what advice to give to tunnel operators with regard to how the initial response to a fire emergency should be managed.

1 INTRODUCTION

Tunnel operators handle many minor incidents involving vehicle breakdowns and small fires and these are largely unrecorded. However, contrasting a small vehicle fire with the events of, say the Mt Blanc fire, it is self-evident that the smoke produced in a small fire and the hazards which they represent are of minor significance in comparison with larger magnitude events. The smoke produced by a small fire is quickly diluted by the air movements in a tunnel, be they driven by ventilation or traffic movement. Larger fires can, by virtue of the energy produced, have a greater influence and the higher concentrations of smoke lead to life-threatening situations. It is important, therefore, to understand the dynamics of flow, particularly in the self-rescue phase. During this period, shortly after the beginning of an incident, the traffic in a tunnel will stop, the operator will become aware that there is a problem and will begin a process of evaluation to determine response. The tunnel users, meanwhile, will encounter an unfamiliar set of circumstances and will not know what action to take.
This general problem requires a consideration of information that can, perhaps, be divided into two forms, that which is scientifically quantifiable, such as airflow rates, smoke concentrations and temperature, and that which is uncertain and difficult to predict, namely, the area of human response.

Much work has been done to evaluate the technical aspects of tunnel behaviour with respect to fire. However, the knowledge of the combination of effects is probably not complete. Smoke behaviour in a tunnel fire might be affected by:

- The growth rate and ultimate size of the fire; this would depend on the type of vehicle involved in the fire, its load etc.
- The tunnel air velocity; this would be affected by the initial traffic speed, ventilation design and environmental effects such as wind or buoyancy effects due to differences between tunnel temperature, ambient air temperature and slope of the tunnel.
- The speed with which the operator can identify the fire location and take appropriate action.
- The speed of response of the tunnel ventilation system.

It is probable that the fatalities which occur in a fire do so in the earliest stages of an emergency in most cases. However, note that fatalities themselves are relatively rare and more likely to occur in more severe fires, when the situation in the tunnel can quickly become untenable.

The purpose of this paper is to firstly attempt to define the effect of variable parameters which affect smoke movement. Three-dimensional CFD simulations have been carried out to illustrate the effect of air velocities induced by the various mechanisms mentioned above. The second purpose here is to pose the question ~ what should the tunnel user do? The question needs to be thought about in two parts; what does the tunnel designer/operator want the tunnel user to do, and what will the tunnel user actually do. Human behaviour is unpredictable, and there is ample evidence of motorists ignoring stop-lights and entering tunnels when forbidden to do so. Motorists are inclined to stay in their cars, and if asked to leave them unlocked, are unwilling to do so.

However, consider firstly the conditions which users might experience in fire situation. This is controlled by the dynamics and timescale’s of air behaviour in tunnels.

2  DYNAMICS OF AIR BEHAVIOUR

The air velocities in tunnels will vary in magnitude and direction due to the influence of traffic movement, natural and mechanical ventilation effects and the particular geometry of the tunnel components. Superimposed on these, smoke from a fire will tend to stratify and progress along the tunnel on either side of the fire source. The behaviour of the smoke will be predominantly affected by the longitudinal velocity in the tunnel. Bearing in mind that to control the smoke a longitudinal critical velocity of about 3 m/s has to be achieved, the following values can be considered as potential initial values prior to the implementation of control measures:
• Wind effects: pressure differences between tunnel portals give rise to longitudinal velocities. Day et al, reference 1, quotes measured values of up to 3 m/s in the 19.05 km long Vereina Tunnel in Switzerland, this velocity arising due to pressure differences between portal of 200 to 300 Pa.

• Geothermal: the differences between tunnel wall temperatures and ambient air can give rise to a stack effect in a sloping tunnel. A 15 C temperature difference in a tunnel sloping at 3% would result in a mean velocity of about 1 m/s.

• Traffic: The motion of vehicles through a tunnel will impose forces which push air in the same direction. In a rail tunnel with relatively little clearance, this would dominate other effects, including that of mechanical ventilation, less so in road tunnels. However, velocities in excess of critical value could easily be generated by moderate road traffic.

Consider now the effect of smoke movement, firstly without the above effects.

Figure 1 shows the predictions of a CFD model of a rectangular tunnel having a length of 1000 m, a height of 3.8 m and a width of 10 m. The fire size is 10 MW, developing in a time of 1 minute – a rather fast development time, but considered to be a worst case.

Figure 1: Progress of smoke in a horizontal tunnel 1000 m long – zero slope; 1, 2 and 3 minutes

In this figure, the outer contour represents a 1% smoke concentration, defined simply as the mass concentration of the combustion products. It can be seen that smoke has travelled about 220 m on either side of the fire source within 3 minutes. Contrast this with a tunnel having a 4% slope in Figure 2.

Figure 2: Progress of smoke in a tunnel having a slope of 4%

In this case, it can be seen that after only 3 minutes, smoke has progressed about 350 m from the fire source. This shows how influential the effects of slope might be. This type of behaviour was observed in the Memorial Tunnel tests, reference 2, which had a slope of 3.2% and in the absence of ventilation the uphill section of the tunnel could become smoke logged in 2 or 3 minutes. It is interesting to note that on the down-slope side of the fire, the length of the smoke backlayer diminishes as the buoyancy-induced flow increases.
This type of result can be represented in a more quantitative way. In the following graphs, the edge of the smoke layer is defined as the distance from the fire source to the points on either side where the concentration falls below 1%. Plotting these distances as they vary with time provides a means of comparing the effects of the different variables which affect the longitudinal flow. Figure 3 represents a case where traffic has been assumed to move downhill (positive to negative distance in the figure, and the origin coincides with the fire source), causing a longitudinal velocity in that direction, but is stopped by the incident fire; note that traffic would be backed up behind the fire, i.e. uphill. There is no effect of wind in this case. It can be seen that the residual velocity transports the smoke downhill for about the first 130 seconds, after which the buoyancy effects take over and begin to move smoke back over the stalled traffic. Bear in mind that the region between the curves is smoke-filled.

Figure 3: 1% smoke concentration positions on either side of the fire source – 4% slope

Had the residual velocity been cancelled by wind and stack effects, the smoke behaviour would have been as shown in Figure 4, with smoke progressing over the stalled traffic at a much earlier time.

Figure 4: 1% smoke concentration positions – wind effect cancels residual traffic-induced velocity
Figure 5: As for the case in Figure 3, but with ventilation implemented after 60 seconds

Figure 5 shows a more ideal case where control of the smoke is exercised after 60 seconds, and the smoke continues to move in a downhill direction, away from the stalled traffic.

The above results are presented to indicate possible scenarios which would result in less desirable conditions for tunnel users. They show that a very rapid response might be required in order to bring smoke under control and provide a safe environment. Numerous other scenarios are possible and exercises of the kind outlined above are useful for any particular tunnel geometry and specific conditions. The objective is to provide an initial database for designers and operators to understand the predicament of tunnel users in an incident situation, and then to consider the rescue and evacuation procedures that need to be put in place.

3 THE TUNNEL USERS PERSPECTIVE

The question of response of the user is uncertain. Muir, reference 3, provides a summary of possible behavioural responses under the headings of fear, anxiety, disorientation, depersonalisation, panic, behavioural inaction, affiliative behaviour, focused attention and enhanced physical performance. Her work has researched evacuation from aircraft. However, it is quite probable that similar responses might be expected from tunnel users.

Now imagine that you are in your car, stopped in a traffic queue in a tunnel and you see a blanket of smoke moving steadily towards you. You have no knowledge of tunnel infrastructure or ventilation and have no idea whether anyone “in control” even knows about the accident. This is the situation to be imagined by the designer. Emergency response procedures may be active, but how will the communication be made with the user, how effective will that communication be?

The European research program ‘Fires in Tunnels Thematic Network’, details of which can be found on http://www.etnfit.net, is focussed on bringing together current knowledge of fires and behaviour in tunnels, as well as the techniques and technical information available for the study of this subject. If you can propose an answer any of the questions noted above, then please make contact.
The issues that need to be considered in the future include the education of tunnel users, the interaction between possible behavioural modes and tunnel infrastructure, such as signing. Tunnel evacuation modelling, training exercises and full scale trials would be required to define the complex interface between the user and the operator.

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References


2 Memorial Tunnel Fire Ventilation Test Program. Interactive CD-ROM & Comprehensive Test Report, Massachusetts Highway Department, Federal Highways Administration