HGV traffic – Consequences in case of a tunnel fire

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ABSTRACT

A typical design fire for an HGV (Heavy Goods Vehicle) for major urban tunnels carrying a mix of cars and trucks in the past has been set at 30-50MW. However, recent research has shown that fires involving HGV’s and multiple vehicles can reach peak heat release rates of the order of 100-200MW or more. Standards and codes are now taking this “new” data into account and design fire sizes are being updated.

This paper describes part of a risk analysis that was done for a major urban road tunnel to see if there were significant differences in risk level depending of the type of HGV traffic that were allowed into the tunnel. The paper specifically describes the consequence analysis that was performed.

Two different types of HGV fires were used in the analysis (approx. 110 MW and 190MW); these sizes were based on the typical HGV traffic that was foreseen as using the tunnel. The analysis looks into the type of consequences originating from the two fire sizes (damage to systems, damage to structure, etc.).

The paper also investigates the use of CFD modeling (Computational Fluid Dynamics) vs Hand calculations (numerical formulas) for this purpose. It was considered important to see if these two approaches gave different results in terms of consequences (damage to the tunnel).
INTRODUCTION

This paper is based on a risk analysis that was performed for a major urban road tunnel. The objective of the analysis was to investigate the impact of increased HGV design fires (from 30MW of up to 200MW). The paper specifically investigates the potential damage to structure and installations in the tunnel.

Recent research [1], [2], shows that HGV fires can reach sizes of at least 100-200 MW. This is being recognized internationally as standards and codes [3], [4], are now incorporating these values.

It was of interest to see how these fire sizes could affect the tunnel and what type of damage could be expected in case of a fire. Computational Fluid Dynamics was used to determine gas temperatures along the tunnel and these were used to estimate damage to structure and installations.

CFD simulations were used for the analysis, but also hand calculations were done to get a preliminary idea about what type of results that could be expected from large HGV fires. This paper also describes an independent validation exercise that was performed to determine if the two approaches gave similar results or not.

The tunnel studied was a cut and cover tunnel. It has a rectangular cross section shaped by a continuous concrete structure. Its inner dimensions are 18.5m wide by 6m high and allows the transit of road vehicles in the same direction in three different lanes.

RISK ANALYSIS

This section of the paper gives a short description of the risk analysis, and it specifically describes the consequence analysis.

Methodology
The risk analysis was divided into four different steps, these are briefly described below.

1. Hazard Identification
This is the first step in the analysis. Different accident scenarios are identified; these served as a base for the construction of the event trees.

2. Event tree analysis
Event trees were constructed. Probabilities and frequencies were determined for the different end events. The event trees were used to choose the end events that were modeled. The event trees are almost finished at this second step; they still need to be completed with the results from the consequence analysis.

3. Consequence analysis
The different fire scenarios to be modeled were chosen from the event trees. These were simulated and the consequences from each one was determined. The consequence analysis is described in more detail further on in this paper.

4. Evaluation of results
The consequence modeling results are used as input for the event trees. These are now used to determine the risk levels.

This methodology is quite common for different types of risk analysis. A description of a typical risk analysis process for tunnels can be found in “Quantitative Risk Analysis – Urban Road Tunnel” [5].
HGV Fires

During recent years research has shown that HGV fires can reach peak fire sizes of 100-200 MW. The following figure, Figure 1, shows ten different large scale fire tests. It can be seen that the fire sizes are significantly larger than the values, mostly around 30MW, recommended for HGV fires in different standards and guidelines in the past.

![Figure 1](image)

**Figure 1**  
*HRR-Curves (from Lönnermark [6]*)

For the analysis, two typical HGV sizes were used; each one representing a typical vehicle with a weight of 7.5 tones and 12.5 tones respectively. To develop the curves a relationship between the energy content and the maximum HRR development from the Runehamar tests was used, see Figure 2 below, in conjunction with research by Carvel [7].

![Figure 2](image)

**Figure 2**  
*Relationship Energy and HRR (from Lönnermark [6]*)

A detailed description of the development of the relationship shown in Figure 2 can be found in “On the Characteristics of Fires in Tunnels” [6].
The fire curves developed for the two different types of vehicles are shown below in Figure 3. In the analysis these were used as input for the CFD simulations.

![Figure 3 HGV Fire Curves](image)

The curve developed for the 12.5 tonne vehicle reaches a peak HRR of 192 MW and the curve developed for the 7.5 tonne vehicle reaches a peak HRR of 110 MW.

**Consequence analysis**

The consequence analysis used the results from the CFD simulations to quantitatively determine damage to structure and different engineering systems. The following sections give a description of the analysis and the criteria used.

**Damage to the structure**

Part of the consequence analysis included an estimation of the damage that the concrete structure of the tunnel could suffer after either of the two design fires. The intention was to quantify the extent of damaged concrete surface of the tunnel linings caused by spalling which later would have to be repaired in order to compare the consequences between the two design fires.

A risk based method developed by Lamont, S. *et al* [8] was used to predict the amount of *spalled* surfaces together with a spalling matrix developed for the studied tunnel. This risk-based method is intended to assess the likelihood and extent of spalling for normal-weight ordinary strength concrete structures. This method allows the different factors that can cause spalling such as the material properties, heating condition and member configuration to be considered; for a more detailed description see “A new risk-based approach to predict spalling of ordinary strength concrete walls subjected to fire” [8].

According to this methodology, two main different risk levels could occur for the studied scenarios in the tunnel, Category B-Low Risk and Category D-High Risk. The two characteristic risk levels are based on the following influence factors of the tunnel concrete linings that promote spalling:

- Moisture content in the concrete is higher than 3% by weight.
- Reinforcement cover is larger than 40mm
- Silica aggregates are part of the concrete mixture
- Structural elements are laterally and vertically restrained
- Structural elements are stressed under compression
The following table shows relevant details of the different spalling risk categories as classified by [8].

<table>
<thead>
<tr>
<th>Category</th>
<th>Risk of spalling</th>
<th>Key factors</th>
<th>Spalling level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very low</td>
<td>Ordinary strength, NWC, Unloaded, Unrestrained, Standard fire exposure, Reinforced, moisture &lt;3%, one side exposure</td>
<td>Zero or minimal</td>
</tr>
<tr>
<td>B</td>
<td>Low</td>
<td>Ordinary strength, NWC, restrained, Standard fire exposure Significant number of key variables* likely to promote spalling</td>
<td>Up to the level of the reinforcement</td>
</tr>
<tr>
<td>C</td>
<td>Med</td>
<td>Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure Small number of key variables* likely to promote spalling</td>
<td>3mm/min</td>
</tr>
<tr>
<td>D</td>
<td>High</td>
<td>Ordinary strength, NWC, restrained, Standard hydrocarbon fire exposure Significant number of key variables* likely to promote spalling</td>
<td>7mm/min</td>
</tr>
<tr>
<td>E</td>
<td>Very high</td>
<td>High strength (Design strength &gt;55Mpa), standard hydrocarbon fire exposure.</td>
<td>Unquantifiable</td>
</tr>
</tbody>
</table>

(*key variables = properties of the concrete or the boundary conditions that are known to promote spalling e.g. aggregate type, section thickness, compressive load etc as discussed earlier)

The spalling level from Table 1 was used to consider the occurrence of spalling only, the spalling levels were not quantified but give a good insight whether determined tunnel areas in the fire scenarios can suffer from significant spalling which could compromise the overall integrity of the structure.

**Spalling criteria**

The type of fire exposure is the key factor to classify the spalling risk category for the studied tunnel, depending on whether the temperature development is similar to the standard cellulosic curve or the standard hydrocarbon curve, as can be seen in Table 1. Hence, the spalling criteria used to identify the occurrence of spalling in a determined area in the tunnel are based on the temperature development along the tunnel and on the following literature data:

- Explosive spalling occurs during the first 20-30 minutes of the standard cellulosic and hydrocarbon fire curves [9].
- After the 2nd minute of a typical hydrocarbon exposure, spalling can occur in high strength concretes with polypropylene fibres [10] and in concretes with high moisture content independent of the type of standard curve [11]. Also, concretes with high moisture content can suffer spalling after the 3rd minute of exposure [12].
- External temperature increments between 20-30ºC/min are typical in the occurrence of explosive spalling [9].
- Temperature increments of more than 3ºC/min are enough for the occurrence of explosive spalling [9].
- Concrete external layers can be released from concrete members when these reach temperatures between 250 - 420ºC [10]; 375 - 425ºC [12], [13].
Table 2 below shows a spalling criteria matrix (to assign the occurrence of spalling and/or magnitude of spalling according to the spalling level risks from table 1). This matrix only applies for the first 30 minutes of fire exposure.

<table>
<thead>
<tr>
<th>Development curve</th>
<th>External temp. ≥1000°C</th>
<th>External temp. ≥840°C</th>
<th>External temp. ≥640°C</th>
<th>External temp. ≥440°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature increase ≥20°C/min</td>
<td>High Risk D</td>
<td>High Risk D</td>
<td>Low Risk B</td>
<td>Low Risk B</td>
</tr>
<tr>
<td>Temperature increase ≥3°C/min</td>
<td>High Risk D</td>
<td>Low Risk B</td>
<td>Low Risk B</td>
<td>Minimum Risk</td>
</tr>
<tr>
<td>Temperature decrease ≥0°C/min</td>
<td>Low Risk B</td>
<td>Low Risk B</td>
<td>Minimum Risk</td>
<td>Minimum Risk</td>
</tr>
<tr>
<td>Decreasing temperature</td>
<td>Minimum Risk</td>
<td>Minimum Risk</td>
<td>Minimum Risk</td>
<td>Minimum Risk</td>
</tr>
</tbody>
</table>

It is possible to estimate the total surface of spalled linings for each fire scenario by knowing the temperature exposure along the concrete tunnel inner faces and with the help of tables 1 and 2. When a ‘High Risk D’ and ‘Low Risk B’ case is assigned (see table 2), spalling is assumed to occur; for the ‘Minimum Risk’ cases, no spalling is assumed to occur, as no sufficient information exists to affirm that spalling will occur under cooling exposures. This methodology does not aim to show a very precise approximation of the total amount of affected structure, as the science of calculating spalling still needs relevant improvements; however, it allows us to perform our intended comparison between the two design fires.

**Damage to systems**

As the different engineering systems inside a tunnel can be damaged when exposed to high temperatures and smoke, it has been conservatively assumed for the comparison of scenarios that all systems exposed to temperatures equal or higher than 200ºC would need to be replaced. To determine the amount of damaged systems in the tunnel with respect to each scenario, the following methodology was used:

- Obtain maximum temperature data from the CFD analysis.
- Identify the maximum extension along the tunnel where temperatures reach more than 200ºC.
- Assume that all systems exposed to temperatures higher than 200ºC need to be replaced.

**Results**

For the analysis, the risk was defined as a determined consequence per year and was assigned to each fire scenario for each type of HGV. The total risk is the result of the multiplication of the magnitude of the consequences times the frequency of the events causing the consequences; however, in this paper we only show the magnitude of the consequences in order to compare the impact of two different fire sizes on this specific tunnel.

**Structure**

The following table shows the results of the amount of expected surface area to be damaged due to spalling. This table helps us compare the consequences on the structure from the two different fire scenarios.

<table>
<thead>
<tr>
<th>Inner surface area affected in case of fire (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGV 12 ton (HRRmax = 192MW) 2010 m²</td>
</tr>
<tr>
<td>HGV 7.5 ton (HRRmax = 110MW) 1190 m²</td>
</tr>
</tbody>
</table>

Table 3 shows that the amount of damaged surfaces is larger for the 12 tonne HGV, as expected. The ratio of the affected surface values between each scenario is very close to the ratio between their maximum heat release rates (HRRmax).
The CFD calculations and the previous tests from Figure 1 show that temperature developments that are more severe than the standard hydrocarbon curve can occur close to the source of HGV fires in tunnels. The spalling matrix developed for the study shows that these exposures would cause severe spalling close to the fire source and could potentially compromise the stability of the concrete structure. The risk increases as the fire size is grows, as is to be expected.

**Systems**

The extent of damaged systems has been calculated for each fire scenario. The engineering devices and systems in the tunnel such as CCTV cameras, light fixtures, cables, signs, etc will be damaged in a maximum distance everywhere a 200°C temperature is reached.

The maximum extension of affected systems along the tunnel is 400m and 300m for the 12.5 tonne HGV and 7.5 tonne HGV fire scenarios respectively.

**CFD VS HAND CALCULATIONS**

It was of interest to compare the results obtained from the CFD analysis with numerical formulas, and therefore a validation process was performed. The numerical formulas used were the ones developed by Newman & Tewarson [14]. The correct estimation of gas temperatures is very important to be able to predict conditions in tunnels; it can be related to evacuation, fire fighting access, fire spread, damage assessment, etc.

The formulas developed by Newman & Tewarson have been compared to real full scale tests and it was found that in principle they gave a good approximation of the actual gas temperatures that were measured in the tunnel used for those tests. For a more detailed description see “Fire Spread and Flame Length in Large-Scale Tunnel Fires” [15].

This form of quasi-validation exercise performed for the risk analysis compares results from CFD simulations with results obtained by using the numerical formulas.

**CFD Simulations**

CFD simulations were used to simulate a large HGV fire, 200MW. The CFD programme used to model the fire was Fire Dynamics Simulator (FDS), version 5.1.4. This software has been shown to perform quite well in predicting gas temperatures inside tunnel, research [16], [17] using large scale testing has shown this.

For this validation exercise the model had the following main characteristics / inputs:

- Tunnel geometry: height 5m, width 10m and length 300m.
- Fire location: 75m from the tunnel entrance.
- Measuring locations (gas temperatures): 75m, 125m and 175m downwind the fire location.
- Air velocity: 2.5 m/s
- Steady state fire: 200MW

The simulation was run during 20 minutes. At each one of the three measuring locations nine measuring points were used to determine the average gas temperature at that location. This was necessary as the hand calculations give the average temperature in the cross section at a certain distance in the tunnel.

**Hand calculations**

The model that Newman & Tewarson developed is used to predict an average temperature in a duct; it was specifically developed to analyze flame propagation in ducts.
They used a heat balance to develop their formula, the heat balance equation can be seen below:

$$\dot{Q}_A = \dot{Q}_C + \dot{Q}_L = \dot{Q}_C + \dot{Q}_{LC} + \dot{Q}_{LR}$$  \hspace{1cm} \text{Eqn. 1}

Where $\dot{Q}_A$ is the heat release rate for the fire (kW), $\dot{Q}_C$ is the convective heat flow rate (kW), and $\dot{Q}_L$ is the rate of heat loss through the walls (the heat loss is further divided into a radiation factor and a convective factor).

The different terms are expressed as follows:

$$\dot{Q}_C = \rho_0 c_0 \nu_0 A_f (T_{avg} - T_0)$$  \hspace{1cm} \text{Eqn. 2}

$$\dot{Q}_{LC} = h_{lc} A_w (T_{avg} - T_W)$$  \hspace{1cm} \text{Eqn. 3}

$$\dot{Q}_{LR} = F_{ws} A_w \sigma (\varepsilon_g T_{avg}^4 - \varepsilon_w T_W^4)$$  \hspace{1cm} \text{Eqn. 4}

For the convective loss expression it is necessary to use an average convective heat transfer coefficient which is expressed as follows.

$$h_{lc} = 0.026 [\text{Re}]^{0.2} \left[ 1 + \left( \frac{D_H}{T} \right)^{0.7} \right] \rho_0 c_0 \nu_0$$  \hspace{1cm} \text{Eqn. 5}

By combining and rearranging the equations above (and assuming that $T_W = T_0$, $F_{ws} = 1$ and $\varepsilon_g = \varepsilon_w = 1$) the average temperature can be expressed in the following way:

$$T_{avg} = T_0 + \frac{1}{\rho_0 c_0 \nu_0 A_f + h_{lc} A_w} \left[ \dot{Q}_A - A_w \sigma (T_{avg}^4 - T_0^4) \right]$$  \hspace{1cm} \text{Eqn. 6}

By using an iterative process the average temperature (for a certain fire size, a certain tunnel dimension, a certain air velocity, etc.) at a certain distance downwind the fire can be determined.

For a more detailed description about the development of the formula see “Flame Propagation in Ducts” [15].

**Analysis and Results**

The results from the two methods were analyzed and compared with each other. The gas temperatures used from the CFD simulations were taken after 20 minutes of simulation time, and an average gas temperature was calculated for each of the measuring locations. To be able to determine the average gas temperature by using the hand calculation formulas it was necessary to perform an iterative process. The table below shows the comparison between the two methods.

<table>
<thead>
<tr>
<th>Measuring location, distance downstream the fire location (m)</th>
<th>Average gas temperature, CFD simulations (°C)</th>
<th>Average gas temperature, Hand calculations (°C)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>613</td>
<td>565</td>
<td>7.8</td>
</tr>
<tr>
<td>125</td>
<td>512</td>
<td>481</td>
<td>6.0</td>
</tr>
<tr>
<td>175</td>
<td>432</td>
<td>429</td>
<td>0.8</td>
</tr>
</tbody>
</table>
As can be seen in Table 4, a good correlation between the results exists. For this specific case it is less than a 10% difference at all three measuring locations.

For the hand calculations one of the assumptions was that the wall temperature (Tw) is the same as the ambient temperature (To), the same assumption was used by Newman & Tewarson. It is very likely that this is not the case, and if taking this into account i.e. performing a heat transfer analysis, it will probably reduce the difference between the CFD results and the hand calculations. However, this was not done for this analysis.

CONCLUSION

It can be seen that for this specific analysis there was a significant difference in damage level between the two fire sizes analyzed. If looking at the spalling damage it was almost a 100% difference between the two cases, almost in direct correlation with the fire size. When looking at the damage to the installations system there was less difference between the two fire sizes but still a significant difference (around 25%). The risk analysis clearly showed that the yearly estimated damage due to HGV fires was heavily underestimated if the design fire size was increased from 30MW to 100MW or 200MW. This suggests that for any type of consequence analysis for tunnels (structural assessment), using HGV fires, it is necessary to determine in detail what is the most likely fire sizes could be, as this can have a significant effect on the damage levels.

The quasi-validation exercise showed that the hand calculations formulas gave similar results as those obtained from the CFD simulations, with the correlation between them quite good. This tends to show that the model developed by Newman & Tewarson can be used to predict average gas temperatures in tunnels, and it can certainly be used to get preliminary and reliable results while a more detailed CFD analysis is performed.

NOMENCLATURE

\[ A_w = \text{Surface area of tunnel walls (m}^2\). \]
\[ A_f = \text{Tunnel cross section area along flow (m}^2\). \]
\[ c_b = \text{Gas specific heat at ambient conditions (kJ/kg-K).} \]
\[ D_H = \text{Hydraulic diameter of the tunnel (m).} \]
\[ h_f = \text{Average convective heat transfer coefficient along the tunnel (kW/m}^2\text{-K).} \]
\[ \dot{Q}_A = \text{Actual heat release rate (kW).} \]
\[ \dot{Q}_{l,c} = \text{Heat loss to the walls by convection (kW).} \]
\[ \dot{Q}_{l,R} = \text{Heat loss to the walls by radiation (kW).} \]
\[ \text{Re} = \text{Reynolds number (-).} \]
\[ T_w = \text{Temperature of tunnel walls (K).} \]
\[ T_0 = \text{Gas temperature at ambient conditions (K).} \]
\[ T_{avg} = \text{Average temperature (K).} \]
\[ v_0 = \text{Gas velocity (m/s).} \]
\[ \varepsilon_g = \text{Gas surface emissivity (-).} \]
\[ \varepsilon_w = \text{Walls surface emissivity (-).} \]
\[ \rho_0 = \text{Gas density at ambient conditions (kg/m}^3\). \]
\[ \sigma = \text{Stefan-Boltzmann constant.} \]
REFERENCES