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# FEASIBILITY STUDY INTO THE IMPLEMENTATION OF ZERO FLOW TUNNEL VENTILATION IN THE SCHIPHOL KAAGBAAN TUNNEL

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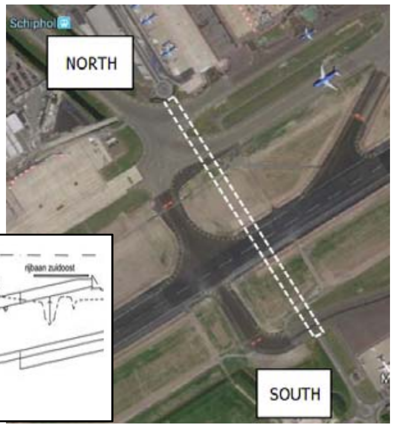
## ABSTRACT

The Schiphol Kaagbaan tunnel had to be refurbished to meet the European Standards. Due to secondary requirements from stake holders, an investigation was started to determine whether removing the evacuation corridor and using a Zero Flow Ventilation strategy was a viable option. Three steps were taken to reach a final design choice. In the final step, the Feasibility Study, the two most decisive requirements of the authorities were 1) to prove the concept through a CFD-simulation and 2) to prove the equivalence of the Zero Flow Ventilation compared to a traditional evacuation approach. Due to remaining risks it was eventually decided to adapt stake holder requirements and implement an adapted evacuation corridor for egress.

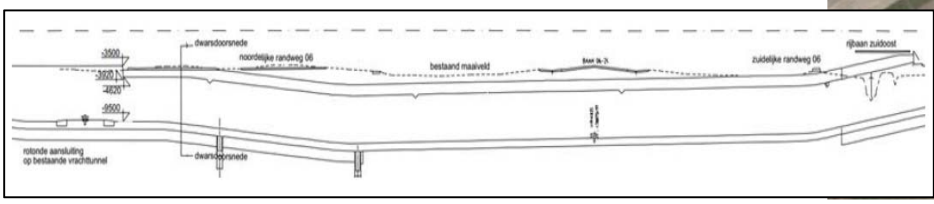
*Keywords: Zero Flow Tunnel Ventilation, conceptual ventilation design, CFD simulation.*

## 1. INTRODUCTION

At Schiphol Amsterdam Airport in the Netherlands renovation of the existing Kaagbaan tunnel (airside) was required. This was needed because following the new Building Permit requirements the European directive 2004/54/EC had to be implemented. The Kaagbaan tunnel is located under the Kaagbaan runway and is designed for bi-directional traffic. The tunnel was built in 1997. Before refurbishment, the tunnel had no escape doors and no ventilation system, but it had several CCTV cameras and a horizontal dry riser system with fire hydrants placed every 50 meters. It is partly built as an immersed tunnel and partly as a cut and cover tunnel. It is predominantly used for the transport of personnel, luggage and fuel.



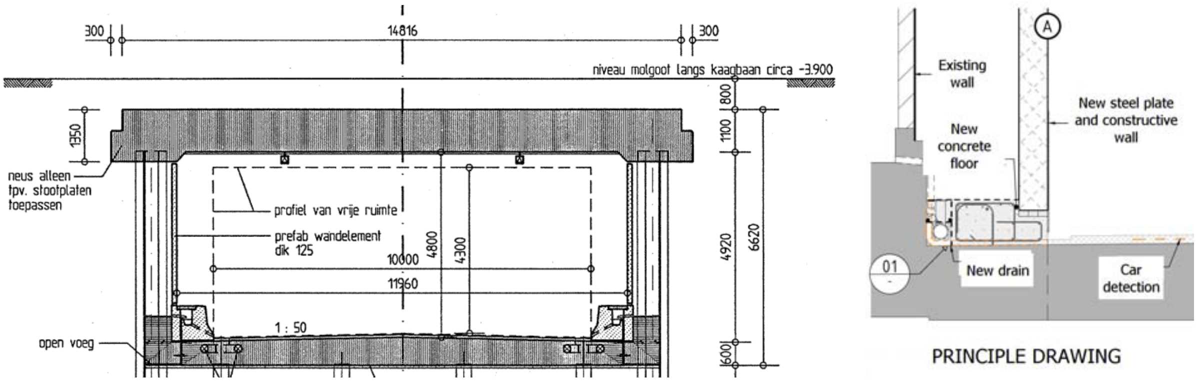

**Fehler! Verweisquelle konnte nicht gefunden werden.**) Location (right) and a longitudinal cross section




of the Kaagbaan tunnel

## 2. ORIGINAL SCOPE OF WORK / DESIGN CHANGE

To achieve the required safety level, one of the main requirements was an evacuation route that was separated from the traffic tube by a wall. The minimum width required for an evacuation route corridor in an existing tunnel in the Netherlands is 0,70 meter. During the construction phase a requirement regarding the maximum collision impact of the dividing wall was updated. A new civil design of the evacuation route wall was necessary and resulted in the implementation of a thicker wall. The minimum evacuation route corridor width and the minimum required road width of 10 meter did not fit in the existing civil tunnel construction anymore. To complicate things further, an additional request from Stakeholder ‘Asset Management’ was to keep the tunnel operational during renovation works. By leaving out the evacuation route corridor and implementing ‘Zero Flow Ventilation’ (ZFV), a solution to these problems could be found. (See paragraph 3.1 for an explanation of ZFV.)




**Fehler! Verweisquelle konnte nicht gefunden werden.**) Original tunnel cross section and (part of) the evacuation route corridor.

## 3. IMPLEMENTING A NEW VENTILATION CONCEPT.

The issue came to light just before the start of actual construction works in 2018. An updated tunnel ventilation design and the design changes would have a large impact on the tunnel safety concept. To implement the new tunnel safety concept during this phase of the project several steps had to be taken in a very short period. According to the license, the tunnel had to be renovated before May 2019. Initially, a high-level management report was necessary to describe the existing design, update the requirements and describe the ensuing construction steps in the project. The background and underlaying reasons for the possible design changes had to be described in relation to current and future safety concepts, including the effect on the tunnel’s technical systems. The management report was accepted and a plan for the implementation of the design changes had to be set up. The first step was to gather more detailed information in order to understand all related consequences. The second step was a Feasibility Study which contained a description of all the relevant consequences. This study had to include the project interfaces, risk assessments, cost assessments, a trade off matrix, etc. The third step, combined with the second step, was an inventory of the consequences related to the stakeholders such as ‘Asset Management’ and ‘Operations’, the Schiphol Tunnel Safety employee, the Fire Department and other authorities. All the consequences of implementing a new safety concept had to be elaborated. Based on this report the Schiphol Board made its final decision. The implications of the new safety concept for the project costs and schedule were large. For the implementation of Zero Flow Ventilation a new detailed design would be necessary. In December 2017 the initial management report was completed, the preliminary study was finished in January 2018 and the Feasibility Study was developed from February up to April 2018.

### 3.1. Zero Flow Ventilation

With Zero Flow Ventilation the air velocity in the tunnel is kept at a low speed so pedestrians can evacuate the tunnel before the heat or smoke reaches dangerous levels at their egress position. It uses variable speed jet-fans to control the impulse, and thus the air velocity, induced by the jet-fans. The direction of the jet-fan air flow is controlled and will be the opposite direction of the existing air velocity in the tunnel. The system can manipulate the maximum air velocity in the tunnel within a short period of time within boundaries of -0,5 to +0,5 m/s.

This air velocity is low enough to allow healthy people to evacuate the tunnel safely at both sides. A swift startup of the Zero Flow Ventilation system is required to reduce the air velocity in the tunnel quickly and allow enough time for accident awareness, including the escape reaction, of the tunnel users to start egress. Several systems are used for this awareness. A swift automatic response or a manual response by the tunnel operator can be achieved by implementing the correct protocols, continuous measurement of wind speed and wind direction and technical facilities like Traffic Low Speed Detection, Linear Heat detection and CCTV-cameras.

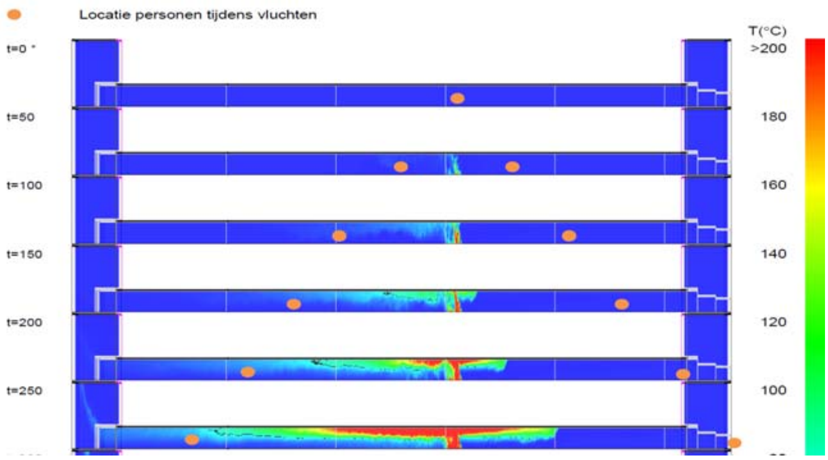



**Figure 3)** Escaping pedestrians (orange dots) able to stay ahead of smoke and toxic gasses.

### *3.2. Preliminary Study*

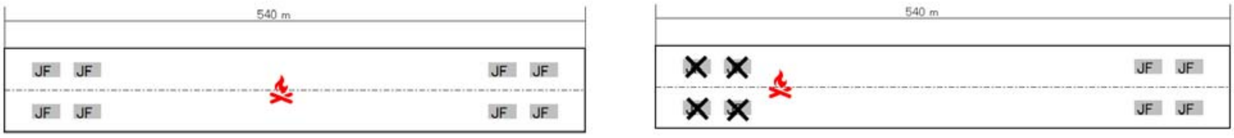
In this study the system uses two clusters of four jet-fans each. The jet-fans are placed 100 meters from the tunnel entrances. This configuration was determined by the 1D-simulation performed by the supplier of ZFV control cabinets, the company Sohatsu (Kobe, Japan). The jet-fans are not located directly at the tunnel entrance to avoid a short circuiting of air (the exact positioning, the number of fan clusters, the number of jet-fans and other parameters are to be validated later with Computational Fluid Dynamics modelling (CFD)). The decrease of air velocity is examined in this phase with the help of 1D-simulations. This was done for different scenario's and with various locations of the fire. If a fire starts in the proximity of a jet-fan cluster the thrust of that jet-fan cluster will be reduced. The thrust can be negligible, depending on the exact exposure of fans to high temperatures and the air temperature.

#### 3.2.1. Starting point fire scenarios for the Preliminary Study.

Taking into account the various scenarios and using past experiences resulted in a design with four jet-fans at each portal. This preliminary study had to prove whether ZFV would be able to reduce the air velocity in a short period of time and in a short and wide tunnel such as the Kaagbaan tunnel.

**Main starting points**

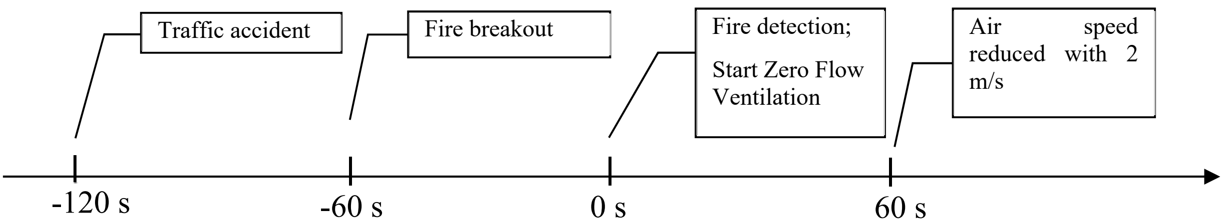
Measurements and calculations have shown a maximum air velocity in the tunnel of 4 m/s due to wind and traffic. It was assumed that healthy tunnel users can walk at 2,2 m/s. To allow the person to evacuate the tunnel safely a longitudinal air velocity reduction of 2 m/s within 60 seconds needs to be achieved. After this period of 60 seconds a further reduction to 0 m/s is intended. In the scenario where a fire is not in the vicinity of the jet-fans, all eight jet-fans can operate to control airflow velocity. In case of a fire close to a cluster of jet-fans, only the other cluster of jet-fans can reduce the air velocity conform the limitations. The impulse created by the cluster close to the fire is unknown because of their exposure to high temperatures. In this study two simulations for the behavior of air in the tunnel have been conducted: one simulation with one active cluster of jet-fans operating and one simulation with both clusters of jet-fans operating. The two scenarios are compared in order to examine the effectiveness of the clusters and to determine if more jet-fan clusters are required.




**Fehler! Verweisquelle konnte nicht gefunden werden.**) Fire locations with four or eight jet-fans in operation.

**Fire Breakout Scenario**

The fire breakout scenario is defined by three events: traffic accident at time t= -120 s, fire breakout at time t= -60 s, and fire detection at time t= 0 s. As the Zero Flow Ventilation control is initiated by fire detection, the system starts operating at t= 0 s. For the Kaagbaan study it was vital to establish the period that the system requires to control the airflow in the tunnel. The target was set at 2 m/s air velocity reduction within the first 60 seconds.

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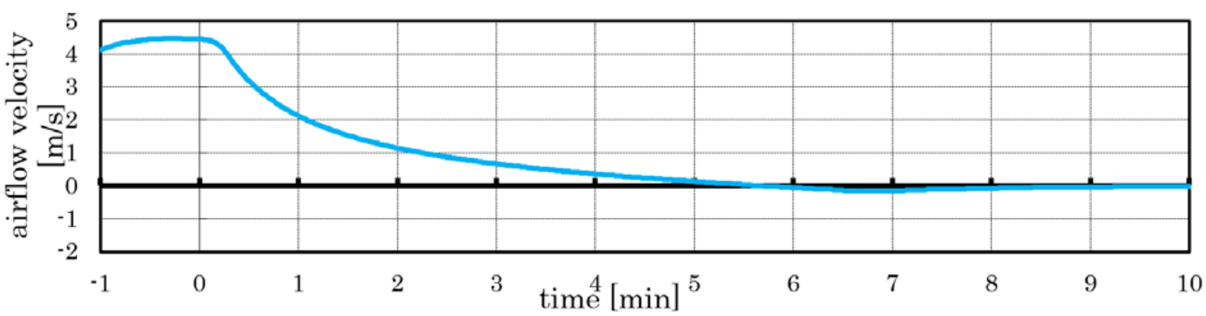
**3.2.2. Results**




**Fehler! Verweisquelle konnte nicht gefunden werden.**) 1D simulation result; scenario with 4 jet-fans operating.

Fig. 6 shows the reduction of airflow velocity where only one active cluster of jet-fans is operating. The airflow velocity is reduced to 2 m/s within 60 seconds. Calculations with two active clusters of jet-fans illustrate that zero-flow ventilation can reduce the airflow velocity to less than 2 m/s within 30 seconds, and a further reduction to 0 m/s within 120 seconds after activation at t= 0 s.

**Conclusion in December 2017**: a Zero Flow Ventilation system is effective in a short and wide tunnel such as the Kaagbaan tunnel. The required thrust and the number and type of jet-fans will be determined at a later stage during the Feasibility Study. Then there will be more clarity about the system requirements, the type of fires that and the various scenarios.

*In January 2018 several stakeholders (including the local Authorities, the tunnel owner, the tunnel safety authority, the Fire Department) came together for a scenario analysis session* *with regards to fire and other calamities in the Kaagbaan tunnel. Consensus was achieved on how all systems and authorities should operate following fire detection and the response to calamities. The scenario analysis gave insight into the procedures in case of fire when a Zero Flow Ventilation System is in operation. It became clear that this safety concept would only be accepted after a proven and agreed safety case. A detailed CFD-model showing the safe evacuation of tunnel users would be accepted as proof. An independent third party was to conduct the CFD-modeling. As required by local regulations, when an alternative system is to be used, the performance of that system should be equal or better than the previously used system. This needs to be proven for the aspects Safety, Environment, Use, Energy and Health. Safety appeared to be the most important subject for implementation of ZFV at this stage. It was also decided that the walking speed of evacuating healthy pedestrians was reduced from 2.2 m/s to 1.6 m/s in the models to meet requirements in other standards. The air velocity in the models as result of the outside wind influences was increased to the conservative value of 5 m/s.*

### 3.3. FEASIBILITY STUDY

The feasibility study was important to prove that the implementation of this new ventilation concept was possible. Three subjects in the feasibility study, shown in bold and underlined below, were the most important aspects that could cause the discontinuation of the implementation of a ZFV-system.

Table of contents of the feasibility study with most relevant subjects highlighted:

1. System architecture
2. Performance of the system
    a. **<u>CFD analysis</u>**
    b. Energy availability
    c. Electromagnetic Compatibility (EMC)
    d. Civil impact
    e. RAMS
    f. Maintenance
3. Total Cost of Ownership
4. **<u>Building Permit / Safety Analysis</u>**
5. Risk Analysis
6. Time Schedule
7. Contractual impact

**<u>Item 2a: CFD analysis</u>**

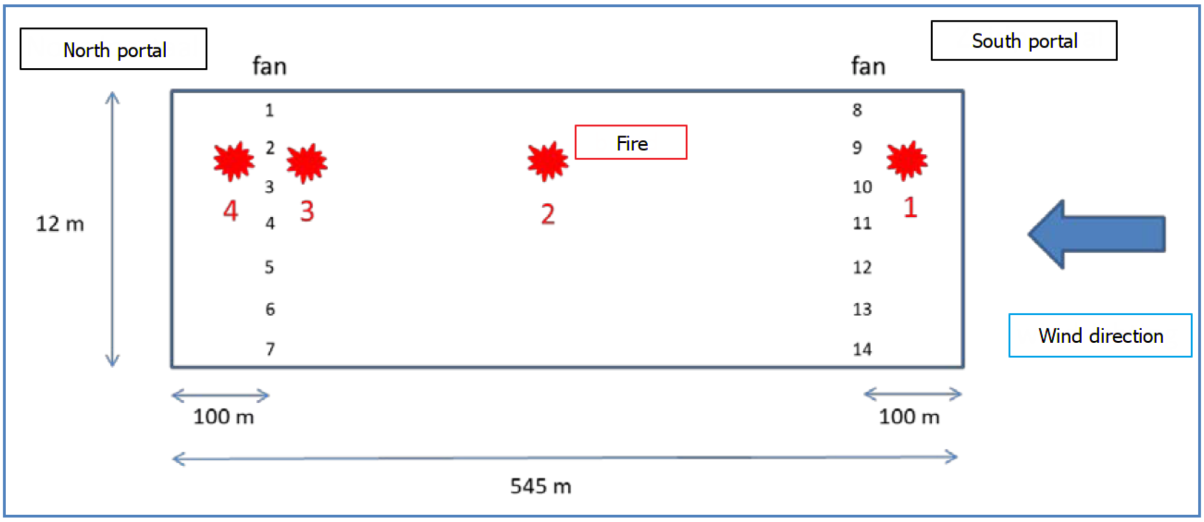
An independent consultant *Efectis NL* created the CFD-simulations in conjunction with *Royal HaskoningDHV*. Stakeholder requirements, the civil, mechanical, electrical parameters, the fire and smoke scenarios and the response scenarios had to be agreed upon with the various stakeholders. The critical parameters to be used in the models had to be agreed upon before the simulations could be started. Critical parameters such as the air temperature, air quality and radiation are shown in figure 7.

| | **Critical Parameter** | **Acceptance Value** |
|---|---|---|
| 1 | **Sight distance** on light emitting subjects in horizontal direction at 2.5 m height: | ≥ 30 meter |
| 2A | **Temperature** over the total height of the smoke layer: | ≤ 200 °C. |

| | | |
|---|---|---|
| 2B | *If* the temperature of the top of the smoke layer is > 200 °C. *and* at the bottom is < 200 °C. *then*: **heat radiation** at 2.1 meter: | ≤ 2.5 kW/m$^2$ |

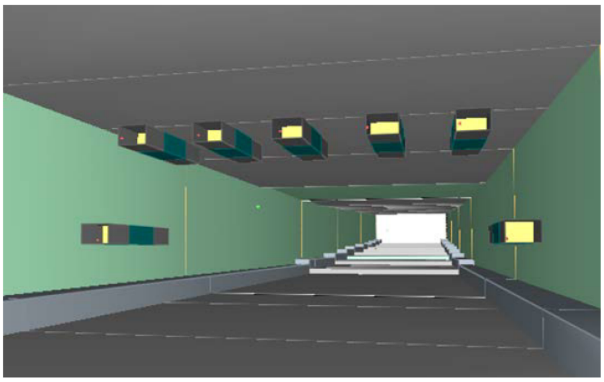
**Figure 7)** Critical values

The 1D simulation was completed to determine the necessary impulse and thus the required number of jet-fans. A scenario analysis led to 4 critical scenarios and several additional starting points such as the maximum wind influences, available electrical power, etc. Four locations of a fire are important (Figure 8).




**Fehler! Verweisquelle konnte nicht gefunden werden.8**) The four decisive fire locations

The simulation program Fire Dynamic Simulator (FDS v6.6.0) and the visualization program 'SmokeView' were used. The Dutch Ministry of Infrastructure has validated this simulation program since 2003. The following parameters were placed in the model: the geometry of the civil construction, jet-fans with accompanying airflow patterns, the jet-fan maximum operational temperature of 300°C, location based grid sizes including the accompanying time steps were important to receive correct simulation results around the decisive locations. The model contained more than 1.1 billion cells. The largest cells were 0.4x0.5x0.33 and the smallest cells were 0.4x0.25x0.16 (in meters). Later on a 'cold' CFD simulation was carried out for the verification of the 1D calculation and other traffic parameters like the positions of vehicles, fans etc.



**Fehler! Verweisquelle konnte nicht gefunden werden.**) Cross section of the tunnel with one of the two clusters of seven jet-fans

From the models it was determined that 2 jet-fan clusters of 7 jet-fans (thrust 540 N each) were required. During the scenario analysis it became clear that the third scenario (fire at location 3, see figure 8) was the decisive scenario. In this scenario the visibility conditions were poor as soon as the fire started. Additional CFD's were run to show what would happen in the location around the fire in the first two minutes after a fire started. See fig. 10 and 11.

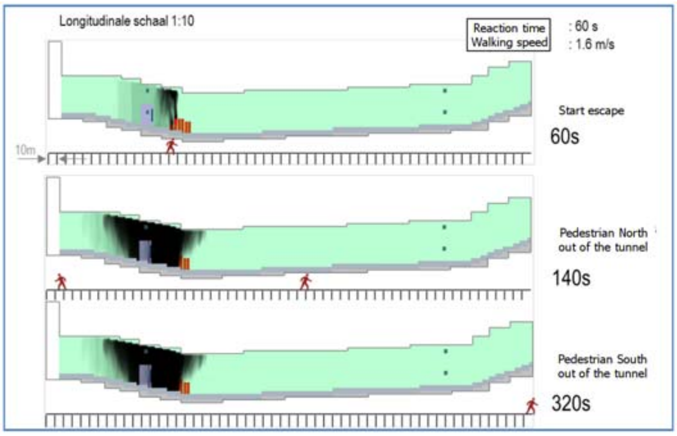



Figure 10:
Smoke dilution and evacuation positions in scenario 3.

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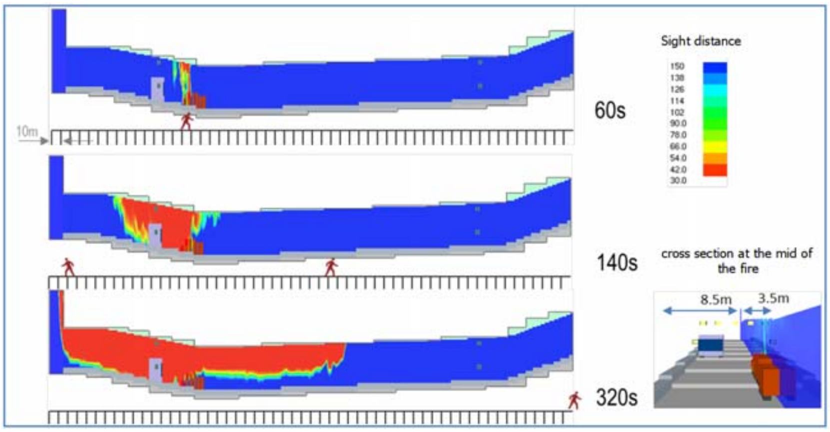
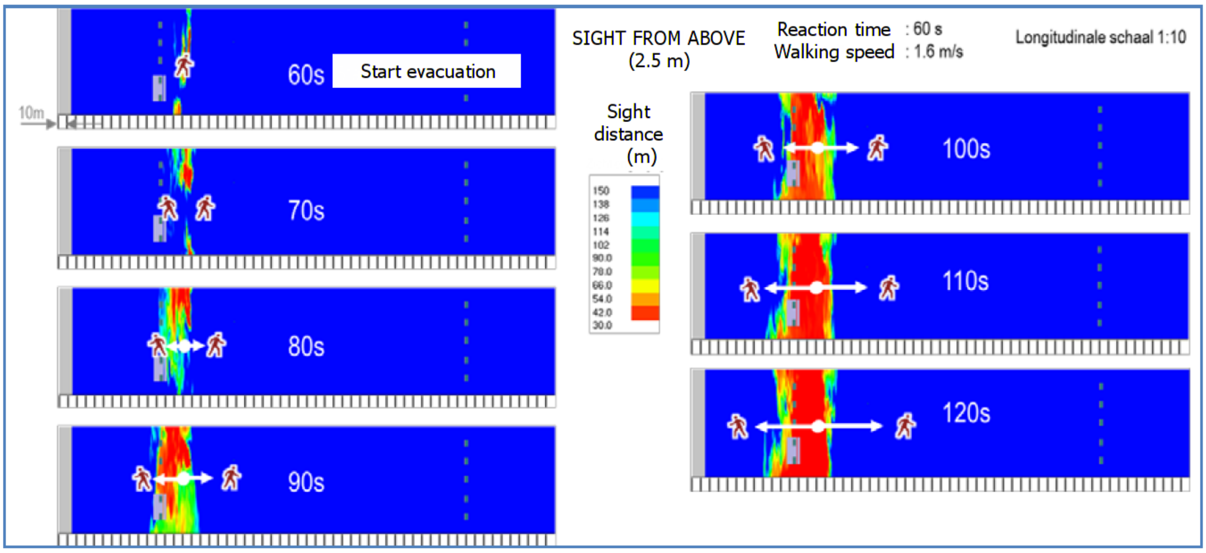



Figure 11:
Sight distances to light emitting objects and evacuation positions in scenario 3.

Picture left: side view.
Picture below: top view.




From the illustrations above it can be concluded that the sight distance to illuminating objects in evacuation positions will always be 30 meters or more. From t = 90 s evacuees will escape in both directions in front of the moving smoke blanket. Heat radiation also stays within acceptable limits, the illustration showing this is not included in this paper. Conclusion: with a reaction time of maximum 60 seconds from the start of the fire and with a walking speed of 1.6 m/s, safe egress is possible in all the scenarios.

*(CFD motion pictures will be shown during the presentation at the conference in May 2022.)*

**Item 4: Building Permit / Safety Analysis**

The reason for the whole project was to obtain an updated Building Permit. Approval of the original tunnel design would have been received from the local authorities without any issues. By deviating from the original tunnel design and introducing a different tunnel safety and ventilation concept, such as ZFV, risks were introduced in the Permit Application process. The table below is a comparison between the original and the proposed new variant on important aspects:

| **Building Permit 2012** | ***Variant 'Evacuation route'.*** | ***Variant 'Zero Flow Ventilation'.*** |
|---|---|---|
| ***Decisive aspects*** | | |
| 1) Evacuation route | | |
| - Self-rescue | + | 0 |
| - Rescue assistance | 0 | + |
| 2) Ventilation | | |
| - Health | 0 | + |
| - Self-rescue | 0 | 0 |
| - Rescue assistance | 0 | 0 / + |
| 3) Reliability | | |
| - System reliability | 0 | 0 [1)] |
| - Installation reliability | 0 | 0 / - [2)] |

1) The system reliability had to be proven in a CFD report (as described in chapter 3).
2) The reliability of the technical installations had to be proven by a RAMS report. To meet requirements several additional redundant systems were required.

## 4. PROJECT PROGRESS AFTER THE FEASIBILITY STUDY AND CONCLUSION

During the process from January to April 2018 an additional Impact Analysis as well as a Risk Analysis were carried out. The conclusion from these analyses was that the risks and impact of a non-approval of the Building Permit application as well as some of the technical risks were too large. Schiphol decided that the disadvantages from the 'Evacuation route' variant (narrower road and 6 – 8 months of traffic obstructions due to building activities) were not large enough to revise the project design to a Zero Flow Ventilation design concept and changed these initial requirements.

The renovation project 'Kaagbaantunnel' was finished with an accepted time delay by the Authorities in December 2019 using the original concept of an evacuation route corridor.

With the results of this Feasibility Study, it is concluded that Zero Flow Tunnel ventilation can be part of a safe(r) evacuation strategy in bi-directional tunnels with or without an escape gallery. For implementation in projects additional time and cooperation of authorities is needed when legislation aspects are debated. Certainly for countries where Zero Flow Tunnel Ventilation systems are not common practice.

## 5. REFERENCES

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