Safety Improvements in the Maurice Lemaire Tunnel (France) with a Safety Gallery and Implementation of a Specific Evacuation Vehicle.

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1. INTRODUCTION

The Maurice Lemaire Tunnel is located in the North of France on the National Road 59 between the departments of Alsace and Vosges (Figure 1). It is the longest road tunnel situated entirely on the French territory and constitutes an important communication route allowing to cross the Vosges massif rapidly. Therefore this tunnel represents a major economic asset for the region.

Initially the tunnel was drilled for the railway. It opened in August 1937 and was exploited by the French rail services (SNCF) until 1967 when the railway line St Die - Sélestat was closed.

Under the impulsion of senator Maurice Lemaire, this tunnel was transformed in 1973 into a bidirectional road tunnel and opened to traffic in February 1976.

Since 1981, the Maurice Lemaire tunnel is operated by the Autoroutes Paris-Rhin-Rhône (APRR).

After the tragic accident of the Mont Blanc tunnel in 1999, a safety analysis of the Maurice Lemaire tunnel was conducted, which led to ban the tunnel to heavy goods vehicle traffic in the year 2000. To satisfy the new French road tunnel regulations of August 2000, the tunnel operator, APRR, has engaged in an ambitious renovation program to improve the tunnel’s safety. The renovation works took place from 2004 until 2008, period during which the tunnel was closed. The tunnel reopened in October 2008.

The follow up to the renovation works was attributed by APRR to the joint venture BG Consulting Engineers - Egis tunnels.
2. **THE EXISTING TUNNEL**

The Maurice Lemaire tunnel is 6'950 m long, including the passage under the ventilation areas located at each portal. In the horizontal plane (as seen from above), the tunnel describes a curve with 500 m radius from St-Marie-aux-Mines to Lusse, followed by a straight section of approximately 6'450 m. The tunnel's profile resembles a rooftop, having a slope of 1.4 % for 5'970 m from St-Marie-aux-Mines towards Lusse and then a very weak 0.1 % slope for 980 m.

The road is 6.80 m wide, composed of two traffic lanes of 3.40 m each, and is bounded by two sidewalks with a width varying from 30 to 50 cm. The narrow width of this tunnel constitutes a critical point contributing to increase the risk of accidents.

3. **SAFETY IMPROVEMENT**

The main achievement of the undertaken improvement works to secure the tunnel was the drilling of a 7 km long safety gallery parallel to the tunnel. This safety gallery has a double function, it is used for the tunnel ventilation as well as for evacuation in case of emergency. The reduced gauge of the main tunnel and the new possibilities offered by this safety gallery led to a transfer of all technical equipments into it. The safety gallery has an internal diameter of 5.20 m and contains an upper part dedicated to smoke extraction and a lower part used for the fresh air supply, evacuation route, electrical network and water mains.

This required a lot of connections to be built between the main tunnel and the gallery. For example: 68 smoke extraction ducts were added between the tunnel ceiling and upper part of the gallery as well as 268 channels supplying fresh air into the tunnel. There are more connections between the tubes for electrical cables and water supply.

However the safety gallery is also connected to the tunnel through 16 shelters placed every 400 m. They offer a safe place for tunnel users, before their evacuation via the safety gallery. These pressured shelters have a surface of 50 m$^2$ and are supplied with fresh air. They are fitted with cameras and communication devices connected to the Operation Control Centre (OCC).

The safety gallery is straight along all of its length except for the last 400 m on the Alsace side where it describes a curve of 250 m radius. It has an average slope of 1.4 % except at the two junctions between the TBM profile and the traditional profile where there is a 20 m long 4 % ramp. Airlocks located at each extremity assure the airtightness of the safety gallery which is kept in overpressure as compared to the tunnel.

Furthermore 9 turn back areas were excavated in the tunnel and the intermediate slab was removed thus freeing space to install jet fans, display panels, cameras and light systems. In fact only the structure of the tunnel was kept, all electro-mechanical equipments were removed and replaced.

Additionally, a primary intervention team of firemen is permanently posted at both portals of the tunnel (24 h / 24 h) and fitted with firetrucks specially designed for fire interventions in tunnels.
4. **EVACUATION VEHICLE**

4.1 **Preliminary Requirements**

The French regulations [1] impose bidirectional road tunnels of length greater than 5 km to have at least one motorised vehicle designed for emergency evacuation at each side of the tube. In order to satisfy this guideline one special vehicle dedicated for evacuation was placed at each extremity of the safety gallery of the Maurice Lemaire tunnel. Their purpose is to evacuate people from the 16 shelters in less than 2 hours, which is the fire resistance of the major structural elements. The strategy is to evacuate the shelters located near the accident location first and the other ones afterwards.

A preliminary safety analysis of these requirements has led to the solution of having vehicles able to transport at least 25 people at 25 km/h. The reduced gauge of the safety gallery, which is only 3 m wide between the sidewalks and 2.30 m high, imposed the construction of two custom vehicles in order to satisfy the required transport capacity. This led to a long and narrow vehicle design fitted with a driving cab at each extremity allowing for travel in both directions due to the impossibility of turning around inside the safety gallery.

The bid for this very specific contract was conducted according to the French public market procedure known as "competitive dialog". This specific procedure, elaborated for complex markets, allows for discussion with each potential contractor in order to define or develop one or several solutions meeting the client's needs. The writing of specifications is done afterwards. The advantage of this procedure is to provide a more complete and comparative vision of the technical, financial or legal solutions which the market can bring, because the offers at the beginning are not restricted by too precise technical specifications.

4.2 **General Specifications of the Evacuation Vehicle**

Since the beginning of the project, the objective was to have an easy to drive vehicle which would be simple to operate by a single person. In fact, people operating these evacuation vehicles are volunteer firemen of St-Die and St-Marie-aux-Mines. After only a short training, they should be able to start it rapidly and drive it without any problems. In order to facilitate the task of the driver the ergonomics of the driving cab should be intuitive and all relevant information for the driver should be centralised.

Two identical vehicles were constructed. A vehicle is composed of a self-supporting central passenger module and two half frames where the driving cabs are mounted. They are installed on both sides of the passenger module which allows to move in both directions inside the gallery (Figure 3).

The vehicle is 14 m long, 2 m wide and 2 m high and can carry 30 people or 2500 kg at 25 km/h with an empty mass of 8000 kg.

One vehicle is parked on each side of the safety gallery, in a waiting zone (Figure 4) located inside the gallery just after the airlocks (coming from outside). In order to save time during an intervention people are dropped...
off just in front of the airlocks, so the vehicle can start again quickly to fetch other passengers waiting into the shelters.

In the waiting zone the vehicle is supplied in electricity to maintain the engine temperature as well as to allow the monitoring of the essential parameters, which are permanently broadcasted to the OCC. On the Alsace side of the gallery after the airlock a workshop is installed to do the maintenance work.

The room inside the passenger module can be modulated depending on the situation so as to transport wounded. For this purpose the benches are pulled up to lay the stretchers on the floor (Figure 5). Access to the passenger area is provided by two 1.8 m wide sliding doors. The passenger module is equipped with lighting, heating and an intercom allowing communication with the driver.

4.3 Motorisation and Transmission

The vehicle is equipped with a four cylinder diesel engine, generating 85 kW at 2000 rpm. The exhaust system is fitted with a catalyst and a particle filter to reduce emissions inside the gallery. The system is certified TIER III. The engine compartment is located between one of the driving cabs and the passenger module and equipped with an automatic extinguishing system to minimise the risk of engine fire.

The diesel engine drives a hydraulic pump which supplies four hydraulic engines inserted into the hub of each wheel. The transmission as well as the steering is taken care of by the hydraulic system allowing to turn the front wheels independently from the rear ones. Short turns and crab movements can be performed which is very useful to move the vehicles in the maintenance area.

For safety reasons the hydraulic system is designed in such way that hydraulic pressure is needed to release the brakes. In case of engine or pump failure, a small auxiliary hydraulic pump can be plugged on the batteries to release the brakes. Thus a damaged vehicle can be pushed or towed by the other one into the maintenance area.
4.4 Driving Mode

Due to the narrow gauge of the gallery and the dimensions of the vehicle it rapidly became apparent that a guidance system controlling the course of the vehicle would greatly help the task of the driver. Therefore the vehicle was equipped with an automatic guidance system which controls its course. The driver acts principally on the potentiometric gas pedal which controls the speed of the diesel engine and the hydraulic pump. The maximum speed is limited to 27 km/h.

The driver can choose between three different driving modes acting on the hydraulic direction: automatic, manual and maneuver.

- **Automatic driving mode**: This is the usual mode used to drive the vehicle. The driver acts only on the gas pedal, the vehicle is automatically directed inside the gallery. The automatic steering system controls the steering angle of the front and rear wheels. In case failure of the automatic guidance system the driver should switch to manual driving mode.

- **Manual driving mode**: The operator himself controls the steering of the vehicle using the steering wheel, which acts only on the front wheels (in the way of motion).

- **Maneuver driving mode**: The operator himself drives the vehicle with the steering wheel acting on the front wheels and steers the rear wheels with a joystick. Therefore all maneuvers are possible, crab motion as well as long and short turns. The speed is limited to 5 km/h in this mode.

All relevant information such as driving mode, distance from the sidewalk, position inside the gallery, engine parameters and warnings is displayed on a 10.4" control screen installed in each driving cab, (Figure 6). The vehicle is also fitted with a dead man pedal which stops the vehicle if it is not periodically pressed by the driver.

4.5 Automatic Guidance System

The automatic guidance system uses the 110 mm high continuous sidewalk on the opposite side of the shelters as a reference. An optical guidance system was chosen so as to compensate for irregularities of the sidewalk which have some imperfections especially at the jointure of the formworks.

A laser sensor is placed on each axle of the vehicle and measures the distance between the vehicle and the sidewalk 100 times per second. Based on this distance and position into the gallery which dictates whether the vehicle is in a straight or in a curved section, the program computes steering lock instructions for the axles. These angular instructions are then used as input for the PID regulator (Proportional Integral Derivative), which limits the sidewalk’s irregularities. In this fashion the system does not take into account local imperfections of the
sidewalk. The measurement of the steering lock angle is done via a sensor integrated into the direction's jack. Both axles of the vehicle are piloted proportionally and independently to one another.

Normally the vehicle moves along the centre of the gallery at a distance of 500 mm from the sidewalk at 25 km/h. If the vehicle deviates from its course, so that the distance to the sidewalk becomes lower than 300 mm or greater than 700 mm, the system proceeds to perform an emergency stop (Figure 7). The operator has to switch to manual driving mode and displace the vehicle outside the emergency stop zone, before continuing his journey in automatic driving mode. The function of these emergency stop zones is to avoid collisions with cables trays and the pressured water mains.

In the curved section at the Alsace portal the speed is voluntarily limited to 7 km/h and the steering locks of the wheels are adapted to negotiate the bend.

The space left for pedestrians to cross is really limited when the vehicle is moving along the centre of the gallery. For this purpose the vehicle can move closer to the sidewalk thus freeing space on the opposite side. To proceed with this operation the driver has to press the "cross" button, first slows down the vehicle to 5 km/h and then moves it closer to the sidewalk, up to a distance of 200 mm. The distance added on the crossing side is approximately 800 mm (Figure 8). When the crossing procedure is finished the driver has to press the "cross" button again, the vehicle will then move back to the centre of the gallery and resume its normal course. Obviously during this procedure the emergency stop zone is deactivated and the speed limited to 5 km/h.

4.6 Geolocalization System

The vehicle is equipped with a geolocalization system allowing it to know its exact position in the gallery. The position is calculated with a tachometer installed on one of the hydraulic engines. This information is processed by the onboard computer, which calculates the distance covered and compares it with the tunnel reference point to determine the vehicle's position. The position is displayed on the control screen in the driving cab and broadcast by radio via the TETRA data channel to the OCC and the other vehicle. In this way each vehicle knows in real time its own position as well as that of the other one.

A geolocalization reflector system is positioned at each extremity of the gallery. Reflectors fixed on the gallery's ceiling close to each waiting zone, reflect a laser beam emitted by the vehicle which recalibrates the geolocalization system. Reflectors are positioned in a different pattern on each side of the gallery, so as to differentiate the Alsace side of the Vosges side. A signal is also sent when a vehicle leaves the gallery indicating that it is not operational any more. Due to the
regular resetting the accuracy of this system is high: on a 7 km long journey the achievable accuracy is 7 m, half length of the vehicle.

The geolocalization system also allows for controlling the speed of the vehicle according to its position. Indeed in both extremities of the gallery the speed is automatically reduced to 7 km/h.

The operator at the OCC has a graphical representation of the gallery with the position of the both vehicles as well as the state of relevant parameters in front of him. With this information and the video installed inside each shelter, the OCC operator can efficiently manage the shelter evacuation and only stopping vehicles at shelters where there are people to be rescued.

5. CONCLUSIONS

This paper has presented the safety improvement works realised in the Maurice Lemaire Tunnel achieved thanks to the drilling of a safety gallery parallel to the tunnel. Making full use of the advantages offered by this new safety gallery, a new ventilation and intervention concept were developed. Also a custom evacuation vehicle specially adapted to the restricted gauge of the safety gallery was designed.

Two identical vehicles were constructed to evacuate people or wounded from the 16 shelters of the tunnel in less than 2 hours. These prototype vehicles have a capacity of 30 people and move at 25 km/h. They are fitted with geolocalization and automatic guidance systems to help the driving.

Various exercises were organised with firemen of both departments and the evacuation vehicles proved their efficiency and their reliability.

REFERENCES: