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2) Tunnel Safety Design Criteria
3) Tunnel Ventilation
4) Operational Safety and intervention
5) Monitoring, Training and Inspections
6) Case study - MCRP IV

1) Lombardi Engineering
Company Presentation
Lombardi Engineering Group

Group employees 2022
Total 785

Company Presentation Services

Hydraulic Works
- Dam (arch, gravity, embankment)
- Water diversion and headrace tunnels
- Underground and external powerhouses
- Pumped plants
- Upgrading and rehabilitation of powerplants
- Hydro-/electromechanical equipment
- River works

Company Presentation Services

Underground Works
- Road tunnel
- Railway tunnel
- Hydraulic and service tunnel
- Large caverns
- Shafts
- Safety and surveillance
- Ventilation and electromechanical facilities

Company Presentation Services

Civil Works
- Bridges and viaducts
- Special foundations and deep excavations
- Rock treatments and soil consolidations
- Housing and industrial building
- General and special structures
- Metal carpentry
- Rehabilitations

Company Presentation Services

Ventilation and Electromechanics
- Design of Various Plants
- Ventilation Systems for Road Tunnels
- Industrial and Safety Systems
- Fireproof Systems for Road Tunnels and Buildings
- Heating, Ventilation, Air Conditioning and Sanitary Systems (HVAC)
- Risk Analysis
- Fire-Resistance Proofing and Expertise
- Customer Support
- Management and Direction of Work

Company Presentation Services

Special Studies
- Rock mechanics
- Soil mechanics
- Dam and tunnel monitoring
- Software development
- Thermal simulations
- Structural static and dynamic analyses

Cerro del Aguila dam (Peru)
Petacón dam (Honduras)
Arenal dam, Honduras
Underground station of Metro Paris, France
Company Presentation

AlpTransit Gotthard railway base tunnel

Longest railway tunnel in the world with 57.09km

TBM refurbishment / assembling in cavern

The first final breakthrough of the Gotthard (15.10.2010)

Company Presentation

Snowy 2.0 Project, New South Wales, Australia

• Nation-building renewable energy project
• 2000 MW
• Lombardi is the consultant for the preliminary design, detailed design for the entire underground work (in JV with Tractebel)

Company Presentation

Second Gotthard Tube, Switzerland

The second Tube allows a complete structural overhaul of the first Tube in 2032 after 52 years of service – the first Tube was inaugurated in September 1980

• 17 km: fourth longest road tunnel in the world and the longest in Central Europe.
• TBM-S single shield drilling machine (diameter of 12.26 metres).
• Lombardi is project leader and in charge of all project phases in a JV

Company Presentation

Brenner Base Tunnel BBT, Austria - Italy

The Brenner Base Tunnel BBT is the key element along the North-South rail corridor for European economy and mobility, to meet the transportation needs of the 21st century.

• BBT, totalling 64 kilometres, will become the longest underground railway link in the world.
• Tunnel system:
  two 8.8 m wide single track railway tubes in 70 m horizontal distance connected by cross passages every 333 m plus 7.5 m wide service tunnel in between.
• Lombardi is - within a JV - in charge of all project phases from tender design to as-built documentation

Company Presentation

Experience in India

Civil Works

2012 – Design and Design Support of USBRL Tunnel T-48 (~10km)
2016 – Design Support of Tunnel USBRL Tunnels T-49 & T-50 (~12km)
2018 – Design of 2 stations, slope stability, 4 bridges and portals at the area between of T-47 and T-49 Tunnels

Company Presentation

Civil Works

2019 – Mumbai Coastal Road Package IV
Tunnel Safety Design Criteria

Safety concept is developed together with other parts of the safety system. This includes the ventilation system, fire detection, the tunnel control system, fire services and operating /intervention plans.

Safety Standards

- NFPA 502 – Standard for Road Tunnels
- NFPA 72 – National Fire Alarm code
- IRC – SP 91 (2019) – Guidelines for Road Tunnels

Evacuation & Rescue operation – Cross Passage and Safety/Escape Tunnel Planning

- Maximum spacing of Cross Passages shall be 500 m as per IRC – SP 91 & 300 m as per NFPA 502.
- Single tube bi-directional tunnels are not applicable for tunnels of length more than 1500 m as per IRC – SP 91. In such a case, an escape tunnel shall be planned for safety aspect.
Tunnel Safety Design Criteria

Emergency walkways

- Protected Walkways should be considered for evacuation.
- Walkway shall have minimum width of 1.5m (IRC SP 91) and 1.12m (NFPA 502).

Passive

- **Option 1**: Design of non-spalling concrete
  - At high temperatures, PP fibres soften and melt → Relieves the pressure due to the restriction on the movement of moisture steam in the concrete

- **Option 2**: Use of fire passive protection
  - Thermal isolation → Limits the increase of temperature in the concrete and reinforcement

Fire protection of Tunnel

**Active**

- Fixed Fire Fighting Systems (FFFS): Activated (either automatically or by the tunnel operator) in the early stages of a fire to minimize fire growth
  - 2 main types of FFFS:
    - Deluge systems (Japan, Australia...)
    - Water Mist systems (France)
  - Commonly used in buildings
  - Large water droplets
  - Smaller droplet sizes => use significantly less water than DS
  - Ex: SAFE stations of the Channel tunnel, A86 tunnel (France), M30 tunnel (Spain), Tyne and Dartfor tunnels (UK)

Their use is not widespread for various political, economic, technical and social reasons. They are not considered in the fire resistance design of the structure. But they can be used as risk reduction measure.

Fixed fire fighting systems in road tunnels: Current practices and recommendations – PIARC 2016

**Passive**

- Use of fire passive protection
  - Thermal isolation → Limits the increase of temperature in the concrete and reinforcement

Fixed fire fighting systems in road tunnels: Current practices and recommendations – PIARC 2016
Road tunnel ventilation

Why ventilation?
- Two main goals: pollution and fire safety

What kind of ventilation system?
- 3 main concepts for tunnel ventilation: choice and requirements
- Ventilation of the escapeways

What kind of equipment?
- Review of required equipment for each ventilation system
- Design and dimensioning criteria and objectives

Why ventilation in normal operation?

Goal: maintain suitable air quality for the tunnel users
- Requirements: defined thresholds for opacity (visibility) and CO
- The ventilation system must dilute and evacuate the pollution
  - Supply of fresh air
  - Evacuation of polluted air
- Emissions depend on type/age/state of vehicles, traffic composition, slope,...
- Reference: FEDRO 13001, PIARC

Evolution of ventilation in normal operation

- Historical perspective:
  - Strong reduction of emissions over the last decades.
  - A minimal requirement for opacity will always remain.
  - Source of opacity non engine related: brakes & tires erosion, dust raise.

Example: Pfändertunnel (Austria, 6.6 km), existing tube 1982 vs new tube 2012.

- Open questions: CO still relevant? Impact of VW dieselgate? Impact of electrical mobility?

Why emergency ventilation?

Goal: in case of fire, protect users from smoke and make a safe evacuation possible
- Smoke control: keep smoke contained, don’t allow the smoke to reach the users.
  - Blow the smoke away
  - Let the smoke stratify
  - Remove the smoke (aspiration)
- Requirements in terms of:
  - Air velocity at the position of the fire
  - Extracted volume flow rate
Why emergency ventilation?

Simplon Pass National Road, Switzerland
Flaming bus – estimated 20-30 MW fire intensity

Why emergency ventilation?

What kind of ventilation system?
The choice mainly depends on tunnel length and traffic conditions

- **Natural ventilation**
  - No equipment at all
  - Relies on piston effect (vehicles push)

- **Longitudinal ventilation**
  - Jet fans
  - Generation and control of a flow along the tunnel

- **Smoke extraction**
  - False ceiling with dampers, smoke duct, axial fans in technical buildings
  - Volume flow out of the tunnel section.

Ventilation of the escapeways
Depending on the tunnel ventilation and escapeway concept (bypass, safety tunnel,...)

Choice of the ventilation system

- **Unidirectional traffic with low risk of queue**
  - Users on one side of the fire
- **Unidirectional traffic with high risk of queue**
  - Users on both sides of the fire
- **Bidirectional traffic**
  - Users on both sides of the fire

Choice of the ventilation system – FEDRO 13001

- **Natural ventilation**
  - Very short tunnels
- **Longitudinal ventilation**
  - Short tunnels
  - Medium tunnels, if users are expected on one side of the fire only
    - Unidirectional traffic with low risk of queue
- **Smoke extraction**
  - Medium tunnels, if users are expected on both sides of the fire
    - Unidirectional traffic with high risk of queue
    - Bidirectional traffic
  - Long tunnels
Natural ventilation

- No equipment at all, passive system
- Normal operation: natural airflow in tunnel, balance between:
  - Piston effect = f(vehicles number, speed and drag)
  - Tunnel resistance = friction + $\Delta p$ at portals + wind pressure + ...
- In case of fire: let smoke stratify
  - Smoke accumulates toward the ceiling
  - Lower portion of tunnel section smoke free (evacuation)
  - Sensitive! $v < \sim 1.5$ m/s

Longitudinal ventilation

- Jet fans generate a longitudinal flow
- Velocity can be controlled
- Airflow in tunnel depends on balance between:
  - Thrust of the jet fans
  - Piston effect: $f(\text{vehicles number, speed and drag})$
  - Tunnel resistance: friction + $\Delta p$ at portals + wind + ...

Longitudinal ventilation equipment

- Jet fans deliver thrust, momentum, not flow! $\rightarrow$ High speed jet ($\sim 40$ m/s)
- The jet mixes out (momentum transfer) and generates a pressure rise (F/A)
  - It takes a long path: uniform flow $\sim 8D$, downstream the jet fan
  - FEDRO 13001: 1st group of jet fans: 80m inside portal, 100m between groups
  - The pressure rise drives the flow in the tunnel

Longitudinal ventilation equipment

- Installation efficiency $\eta = \text{transferred thrust} / \text{delivered thrust}$
- Strongly dependent on jet fan installation conditions: spacing and distance from walls (FEDRO: $>30$cm), size and geometry of niche, bladed deflectors, ...
- $\eta$ increases with wall distance

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Alternative: Saccardo injectors

- Like jet fans: high speed/momentum jet, shallow angle
- Unlike jet fans: separate technical building, generally fresh air injected
Smoke extraction

- Axial fans in technical buildings, false ceiling with dampers.
- Normal operation
  - longitudinal ventilation
  - point-extraction if needed (tunnel length, traffic,...)

Smoke extraction in case of fire

- Extraction of smoke through 3 dampers (200 m)
- Axial fans with fire resistance in technical building
  - Extracted flow (FEDRO) up to 4 ∙ A_{vent} (+leakage!)
  - Jet fans: velocity control at fire location
  - Users on one side: 3 m/s upstream
  - Users on both sides: 0 m/s on fire position
  - Exhaust from chimney with high momentum (FEDRO: 15 m/s) → plume dispersion

Smoke extraction equipment – dampers

- False ceiling & damper

Smoke extraction equipment – fans

- Exhaust from chimney with high momentum

Smoke extraction equipment – technical buildings

- San Bernardino, underground technical building (1967)
- Very good example: smooth section changes, low aerodynamic losses

Smoke extraction equipment – technical buildings

- San Bernardino, underground technical building (1967)
- Very good example: smooth section changes, low aerodynamic losses
Smoke extraction equipment – technical buildings

- A2-A13, recent preliminary projects.
- Less room available, sharper corners and contractions needed.
- Maximize curvatures, keep distance upstream and downstream fans (plenums), use deflectors.
- Avoid wide diffusers!
- Uniform inlet condition of fans is crucial!

Ventilation of the escapeways

- Two bores: use jet fans in safe bore to generate overpressure.
- Escape door opens → smoke cannot enter safe tube

Ventilation of the escapeways

- Goal: keep escapeways free of smoke.
- Single bores with safety tunnel: axial fans in technical building to generate overpressure
- Axial fan on each side of the escape tunnel

Ideal Scenario
Double Door Concept and ET Pressurization

Double Door Concept and ET Pressurization

Ideal Scenario
Ventilation of the escapeways

Double Door Concept and ET Pressurization

Realistic Scenario

"Over-Design" of the Cross Passage fan

Double Door Concept and ET Pressurization

Ventilation of the escapeways

3D CFD flow simulations

Gotthard road tunnel:
jet fans efficiency and optimization of underground ventilation buildings

3D CFD simulations of fire scenarios and evacuation

Simulation of a fire scenario and evacuation in a railway tunnel

Simulation of a fire scenario and evacuation in a road tunnel

Operational safety and Intervention

Simulation of a fire scenario and evacuation in a railway tunnel
Goal & needs

Goal
- Conceive the operation and intervention manual for the tunnel based on our knowledge and experience, tailored upon Indian reality implementing the working mode of the stakeholders (tunnel operator, firefighting brigade, rescue teams, etc.).

Needs
- Identify the single points of contact within various organizations involved in intervention and operation;
- Identify how does the "intervention machine" work / can work in the expected conditions;
- Help to identify needs of operation and intervention to be formulated in the manual under the condition of the designed tunnel & equipment.

Alarm
- Identify the whole alarm triggering process
- Clearly identify relationships between stakeholders (functional & institutional)

Communication
- Who is able to talk with who and how?
- How to handle coordination (possible scheme, to be finalised before actual operation)

Levels of conduct
- Identify the criteria for raising the conduct level based on different stakeholders and based on escalation of the event;
- Well known procedures.

Accessing the tunnel
- Operation and intervention strategy must be homogeneous all through the entire Project (coordination!)
- The intervention command center is at PDP portal (operation room)
- Define from where first responders will access the tunnel (where are the police, the fire brigade, the ambulances?)
- Operation room will provide first responders information about traffic and access (centralized operation center CLIENT?)
- By suitable signalisation, operation room will provide emergency lane for approaching first responders.
- Well known procedures.

Operation and intervention - roles
- Tunnel manager / Owner
- Surveillance and maintenance
- Safety manager
- Role of DMA
- Best practices for tunnel intervention India / International?
- Police
- Ambulance
- Road assistance
- Other stakeholders
Traffic diversion in case of event

If applicable
- Traffic diversion policy
- Roles and responsibilities
- Well known procedures

Types of Events

- Breakdown
- Accident
- Fire
- Tsunami / monsoons

Intervention tactic

Breakdown
- Road assistance reach the vehicle stopped on the emergency lane, rescue it and leave the tunnel in the direction of the traffic;
- Traffic in both tubes keep driving as usual;
- Police informed.

Intervention tactic

Accident (Yellow zone) 2/2
- If there is no smoke (yellow zone), ambulance joins firefighters in the event helping rescue incarcerated;
- Traffic must create intervention lane in the middle without blocking emergency lane;
- Traffic stopped in both tubes.

Intervention tactic

Fire (red zone) 2/3 in case of traffic blocked
- Reach tunnel from both sides!
- Fighting fire priority 1! Start recognition and rescue ASAP. Nobody else enter the tunnel!
- Self rescue of users leaving tube via cross-passages. Use police for gathering users outside the tunnel;
- Prevent other vehicle from entering the tunnel. Traffic stopped in both tubes.

Intervention tactic

Fire (red zone) 3/3 in case of free access
- Reach tunnel from both sides!
- Fighting fire priority 1! Start recognition and rescue ASAP. Nobody else enter the tunnel!
- Self rescue of users leaving tube via cross-passages. Use police for gathering users outside the tunnel;
- Prevent other vehicle from entering the tunnel. Traffic stopped in both tubes.
### Alternative fuel vehicles – electrical power

- Propagation of toxic gas during battery fire. (harmfulness degree unknown yet);
- Low time of propagation and hard to extinguish.

![Tesla S in Austria. Intervention went on for 5 hours](image)

### Tsunami / severe storms / monsoons

- Weather forecast and early announcement measures prevent catastrophes;
- Evacuate people from coastal road and close the tunnel!

### Monitoring, Training and Inspections

### On site flow measurements

### Fire and smoke testing

### Inspections and supervisions
### Monitoring of Tunnels

Trained personnel in operation rooms

- Gotthard Road Tunnel (CH) - 16.9 km
- Ticino area control system (CH)

### Safety training

**Education and training / auditing**

- Safety training / drill / practice.
  - Definition of scenario, screenplay and infrastructure technical knowledge;
  - Technical support for training and drill (Smoke production, liquid tracing);
  - Goals definition and check;
  - Debriefing and return of experience;
  - Education and information about technical and operational aspects;
  - Audits and education check about technical and operational aspects.

### Case Study

**Mumbai Coastal Road IV**

### General Layout MCRP Package IV

### Typical Cross-section

- Minimum vertical Clearance = 5.0 m
- Minimal width of the lanes = 3.2 m
- Maximum camber slope = 5%
- 2 lanes + 1 emergency lanes till year 2033
- Possibility to extend to 3 lanes from year 2034
- Traffic management according to guideline: limit to 2400 vehicle/Hr/direction with 2 lanes; limit to 3600 vehicle/Hr/direction with 3 lanes
**Technical Buildings**

Technical Buildings are underground structure that sits over both the tunnels, nearly square layout. Equipment parallel to the Saccardo.

**Ventilation concept (MCRP)**

**Concept & equipment**
- Longitudinal ventilation with bidirectional Saccardo injectors.
- Ventilation building in cut & cover section, close to the entry portal, one in each bore.
- Axial fans and injection nozzles in both directions.

**Normal Operation**
- The polluted air is diluted and exhausted through exit portal by the injected flow.

**Emergency operation with unidirectional fluid traffic**
- Injectors blow the smoke in the traffic direction.
- Goal: air velocity upstream the fire > critical velocity → no back layering of the smoke.
- The vehicles stopped upstream the fire location are protected from the smoke, while the vehicles downstream the fire leave the tunnel.

**Emergency operation with contra-flow traffic (maintenance)**
- Injectors control the air velocity at the fire location and foster the smoke stratification.
- Goal: air velocity at fire location is between 1m/s and 1m/s → smoke stratifies.
- The lower portion of the tunnel is kept free from smoke during the evacuation phase.

**Traffic control measures to ensure that traffic congestion is avoided at any time**
- Ventilation of the escapeways
- Cross passages with active ventilation (pressurisation)
- Non-incident tube: flow in same direction than fire tube → avoid recirculation at portal

**Longitudinal ventilation equipment**
- Alternative: Saccardo injectors
- Like jet fans: high speed/momentum jet, shallow angle
- Unlike jet fans: separate technical building, generally fresh air injected

**Ventilation with Saccardo Injection**

- Longitudinal ventilation air injection parallel with the traffic direction
- Ventilation building with fans and Saccardo injectors
**Ventilation with Saccardo Injection**

![Diagram of Tunnel Ventilation](image)

**Ventilation Scenarios (Unidirectional Traffic)**

- Emergency operation with unidirectional fluid traffic:
  - Fire bore: Saccardo blows the smoke in the traffic direction.
  - Air velocity > critical velocity → back layering of the smoke is avoided.
  - The vehicles stopped upstream the fire are protected from the smoke.
  - The vehicles downstream the fire leave the tunnel portal.
  - Safe bore: ventilation in same direction of fire bore to avoid recirculation at Portal.
  - Consistent with NFPA 502 and other European Standards.

**Ventilation of Cross Passages**

- In case of fire, the users must leave the cars and evacuate to the cross passages and from there to the safe tube.
- To avoid that the smoke enters the cross passages, the cross passages must be in overpressure (higher pressure than the tube with the fire).
- With a ventilation based on Saccardo injectors, the safe bore cannot be put in overpressure by the tunnel ventilation alone.
- Therefore, the cross passages must have a dedicated ventilation.
  - Each cross passage has a dedicated fan with dampers. The fan blows air from the safe tube inside the cross passage and generates the needed overpressure.
  - In the safe tube, the Saccardo is used to generate a flow in the same direction as the fire tube → avoid recirculation at portal.

**Means of Escape**

The means of escape will allow the tunnel user to self-escape the tunnel and to head to safe locations where they will be assisted with more ease.

- **EM equipment – Lighting**
  - Entrance lighting or Day time Lighting.
  - Interior lighting or Normal lighting.
  - Emergency lighting for the main tunnel, escape tunnel, cross passages and adits.

- **EM equipment – Signages**
  - Traffic control systems with fully automated reactions in case of danger.
  - Optimized traffic flow management system.
  - Escape routes signages.
Means of Escape

The means of escape will allow the tunnel user to self-escape the tunnel and to head to safe locations where they will be assisted with more ease.

- EM equipment
- Communication system
  - Tunnel radio communication.
  - Public address system

The means of escape will allow the tunnel user to self-escape the tunnel and to head to safe locations where they will be assisted with more ease.

Safety and intervention Rescue and fire suppression

- Smoke flows in the direction of the traffic.
- Firefighters and first responders attack the event from both sides of the tunnel.
- Firefighters try to reach and extinguish the fire from behind (upstream). A squad from the other portal makes recognition through the safe tube and cross-passages.
- The goals are: save lives, extinguish the fire and keep the temperature under control.
- Intervention tactic is fully conditioned by the event.
- Coordination between teams (ex: firefighters 1 and 2) and between first responders (ex: firefighters + police) is crucial.
- Clearly identify an intervention leader possibly located behind the fire and a second person at the other side leading the second team.
- Nobody enters the tunnel without being allowed by firefighters in case of fire.

Intervention concept based on IFA (International Fire Academy)

- Use of fire passive protection (30 mm board)
- Thermal isolation limits the increase of temperature in the concrete and reinforcement

Testing of Fireboards

Fire testing of the Segments along with selected fireboard were done at CBRI, Roorkee

- After test Segments with Fireboard on
- After test Segments with Fireboard removed

Mumbai Coastal Road Project
Thank you