Chongqing PIARC – TESC seminar
October 2006

Ventilation of very long tunnels in Europe

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reminder of ventilation system concepts

longitudinal ventilation
transverse and semi-transverse
mix ventilation system

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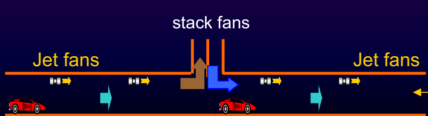
longitudinal ventilation

- principles
  - ⌘ the all air volume is pushed inside the tunnel
    - by jet fans and their thrust
    - or by powerful air injection with Saccardo effect
    - and also use vehicles piston effect

pure longitudinal ventilation system



longitudinal ventilation system with intermediate shaft

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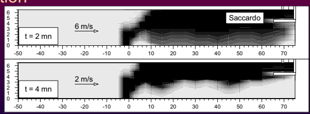
longitudinal ventilation

- Principles (continuation)
  - ⌘ the air is circulating from one portal to the other (or from one stack to the next one)
    - fresh air at portal entrance
    - air get more and more polluted along the tunnel
    - polluted air exits at the other portal
  - ⌘ air velocity is more or less constant inside the tunnel

pollution diagram from entrance portal to exit portal

longitudinal ventilation

- In case of fire
  - ⌘ the smoke is carried by the air flow
    - from the fire place to the exit portal
    - with a smoke-filling of the cross section



  - ⌘ with consequences
    - bi-directional tunnel
      - vehicles downstream are exposed to smoke and toxic gas
    - unidirectional tunnel
      - no safety problem in case of low traffic: vehicles downstream are leaving the tunnel
      - vehicles downstream blocked inside the tunnel by traffic jam are exposed to smoke and toxic gas

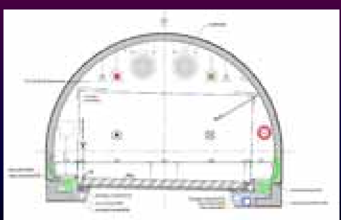
longitudinal ventilation

- In case of fire (continuation)
  - ⌘ bi-directional tunnels and unidirectional tunnel with a recurrent probability of traffic jam
    - smoke exhaust system is required to assure user's safety
    - two solutions
      - construction of smoke exhaust duct all along the tunnel
      - construction of localised and at regular intervals smoke exhaust shaft with massive smoke extraction performance
        - requirement for urban tunnels in France: 500 m spacing

longitudinal ventilation

- Typical cross sections

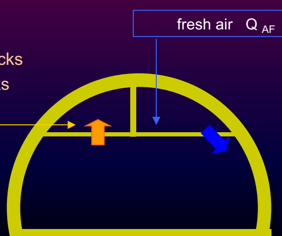
Regular cross profile for longitudinal ventilation system



Cross profile with
- smoke exhaust duct
- emergency escape

transverse and semi-transverse

- principles
  - ⌘ provision of fresh air inside the tunnel
    - by a fresh air duct
    - from portals and eventual stacks
    - local ventilation plants at portals and stacks
  - ⌘ extraction of polluted air and smoke
    - by extraction duct
    - and discharge at portals or through stacks
    - local ventilation plants at portals / stacks



transverse and semi-transverse

- Principles (continuation)
  - ⌘ full transverse ventilation system
    - $Q_{AF} = Q_{AV}$
      - fresh air provision flow = polluted air exhaust flow
  - ⌘ semi-transverse ventilation system
    - $Q_{AF} > Q_{AV}$
      - fresh air provision flow > polluted air exhaust flow
      - a part of polluted air is carried to portals (or stacks) along the tunnel using the traffic section

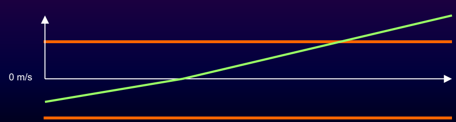
transverse and semi-transverse

- Principles (continuation)
  - ⌘ full transverse ventilation system is not common due to
    - expansive costs of construction
      - bigger cross section for all the larger ducts
      - powerful ventilation plants
    - high operating costs because of ventilation
  - ⌘ the air flow inside the traffic space, the distribution of pressure and air velocity depend on (for semi-transverse ventilation system)
    - fresh air and polluted air flow volumes
    - natural pressure at the portals
    - piston effect of vehicles

transverse and semi-transverse

- Principles (continuation for semi-transverse ventilation system)
  - ⌘ air velocity diagram
    - zone with air velocity = 0 m/s
      - this zone is moving according to pressure, and volume flow for fresh air inlet and polluted air extraction
    - airflow current in direction of each portal
  - ⌘ pollution distribution
    - growing in direction of each portal
    - usual accumulation near air velocity null point

air current velocity diagram inside the tunnel

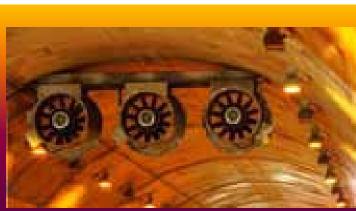


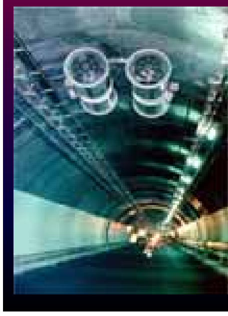
transverse and semi-transverse

- In case of fire
  - ⌘ smoke is extracted through ventilation exhaust duct
  - ⌘ exception for tunnels under particular conditions (as high pressure difference between portals)
    - natural air current velocity may exceed 8 m / s
      - semi-transverse ventilation system is not able to manage, reduce and control this air current
      - smoke is partially extracted through vent. exhaust duct
    - smoke is partially carried by air current from fire place to portals
      - especially before exhaust ventilation starting up
      - but also, even with exhaust under operation, in case of a strong natural air velocity current between both portals
    - with a risk of smoke-filling of the cross section
    - and the same consequences as mentioned for longitudinal

mix ventilation system

- Mix ventilation systems have been developed
  - for very long tunnels
    - under geographic conditions making the construction of shafts impossible
    - for optimisation of construction and operating costs
  - for tunnels under particular atmospheric conditions
    - high pressure difference between portals
    - to manage and control the strong natural air current
      - especially in case of fire
      - in order to avoid smoke to be carried by the current
      - to comply with safety legal requirements
  - systems have diversified principles
- Examples will be presented later





at are the limits for longitudinal ventilation systems ?

sizing factors
boundaries of longitudinal ventilation
some examples of tunnels > 3 km

sizing factors

- Paper is focused on tunnels with unidirectional traffic
- Main considerations
  - main considerations are the same for any country, but
    - criteria or thresholds may be slightly different
    - ditto for vehicles fleet age, and average of emissions
    - as result, limits of a longitudinal ventilation system are changing with national standards and conditions
  - main considerations are
    - health and safety conditions
    - comfort
    - fire conditions
    - economical conditions

sizing factors

- Base for the dimensioning
  - pollution concentration is linearly growing along the tunnel
    - maximum of concentration near the exit portal
  - air flow volume for dilution of the pollution
    - is directly proportional to air flow velocity
- Comfort and safety factor
  - limitation of air flow velocity
    - PIARC recommendations 10 m/s
    - limitation of 8 to 10 m/s in Europe (motor bikes safety)
  - with as consequence
    - limitation of the air volume for dilution

- Fire conditions factor
  - in a pure longitudinal ventilation system
    - smoke is carried by the air flow in the portal direction
    - vehicles blocked downstream are trapped in toxic gas
      - users placed in very dangerous conditions
  - addition of smoke exhaust system
    - needed in tunnel with a risk of traffic jam or dense traffic
    - requirement for urban conditions in Europe
      - smoke exhaust duct
      - or regularly localized massive smoke exhaust plant (spacing 500 m in France)
  - particular conditions and system to establish in case of
    - very important HGV (trucks) traffic
    - hazardous goods transport

- Health and safety factor
  - emission of pollution
    - particular technical conditions according to the tunnel
      - altitude – gradients
      - traffic volume in peak hour - % of HGV
    - legal conditions according to each country
      - vehicles fleet
        - average life time – maintenance – emission control by authorities
      - standard requirements for the emission and evolution of this policy during the 15 last years
        - example European standard with Euro 4 is very strict
        - standards in many countries are today always less demanding than Euro 2 (1998)
  - limits of acceptable pollution level
    - according to each country - environmental policy – standard
    - PIARC international recommendations

- Health and safety factor
  - emission of pollution – complementary considerations
    - in the past only CO and particles (opacity) ware considered
    - NOx is a new criteria since 5 / 10 years (depending of country)
    - other new criteria are raising
      - particles less than 2 µ (PM 2)
      - other pollutants as aldehydes
    - in the past acceptable pollution levels
      - ware fixed considering a maximum concentration
    - today acceptable pollution levels are more and more fixed
      - by a medium concentration average level
      - associated to a duration of exposure to the pollution
      - with, as consequence, a huge decreasing of acceptable pollution level for long tunnels

- Health and safety factor
  - emission of pollution – European situation
    - huge reducing of the vehicles pollution (divided by 15 / 20 on a period of 30 years)
      - due to the average age of the fleet (< 8 years)
      - introduction of challenging Euro standards 15 years ago
      - technical progress : engine performance - oil industry
      - severe control of the vehicles emissions
    - CO is no more determining factor
    - important progress for reducing particles emission (special filters are required for diesel engine vehicles)
    - Euro 5 requires 25% reducing NOx emission
    - with as consequence more opportunities to optimise ventilation systems

sizing factors

- Economical factor
  - for long tunnels with high probability of traffic jam
    - smoke exhaust duct is required
    - need of numerous jet fans
    - increasing of spread power supply along the tunnel with electrical intermediate sub-stations
    - increasing of the maintenance inside the tunnel
      - traffic constraints
      - higher risk for maintenance
  - longitudinal ventilation is in competition with semi-transverse ventilation when considering
      - construction plus maintenance costs
      - heavy repairs and replacement of equipments
      - power consumption
      - impact on traffic and consequences for intervention staff
  - economical conditions are variable according to countries

boundaries of longitudinal ventilation

- General assessments
  - very large international diversity as result of
    - environmental policy according to each country
    - date of introduction of this policy
    - average age and composition of the vehicles fleet
    - technical or financial incentive conditions to make the fleet younger
    - safety requirements
    - economical conditions
  - impossible to propose an international range based on tunnel length as boundary of longitudinal ventilation

boundaries of longitudinal ventilation

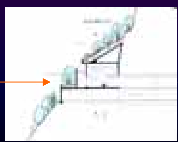
- An approach for French conditions
  - assumptions
    - unidirectional traffic – two tubes each two traffic lanes
    - particularity of high percentage of diesel engine vehicles – technical characteristic of French vehicles fleet – French pollution standards
      - PC gas (30%) – PC Diesel (50%) – HGV (20%)
    - traffic density of non urban tunnel : 50.000 / 60.000 veh/day
  - results for years 2010 / 2015 : maximum tunnel length for longitudinal ventilation system
    - CO is not a determining factor
    - limitation of air velocity — 8.500 m
    - opacity years 2010 / 2015 — 12.000 m / 18.000 m
    - NOx (vehicles under circulation) — 7.800 / 9.300 m
    - NOx (vehicles stopped inside tunnel) — 6.600 / 7.700 m
  - Boundary of about 7 to 8 km for French conditions
    - Result are changing according: traffic – fleet – age of vehicles – country – altitude - gradients

some examples of tunnels longer than 3 km

- France
  - no existing tunnel > 1.600 m with longitudinal ventilation
    - exception of 2 bi-directional tunnels with very low traffic
    - one tunnel 2,8 km : longitudinal + smoke extraction duct
    - reasons
      - at the time of construction (< 1990), pure longitudinal impossible according to pollution emission and pollution level standards
  - evolution today
    - one existing tunnel 3,2 km transformed with longitudinal ventilation during upgrading works
    - one tunnel 3,1 km under construction with longitudinal
    - one tunnel 4,1 km under design with longitudinal
  - evolution made possible
      - by huge decreasing of pollution emissions
      - despite lowering acceptable pollution level
      - despite raising of new pollutants

some examples of tunnels longer than 3 km

- Italy
  - ⌘ very few existing tunnels > 3km with longitudinal ventilation
    - 4,5 km and 4,2 km with traffic 13.000 veh/day
  - ⌘ today under design with longitudinal ventilation
    - 5,6 km with localized smoke extraction plant in middle
    - 8,6 km with extension of pure longitudinal ventilation system with 3 intermediate galleries to outside for
      - fresh air supply
      - polluted air discharge
      - smoke extraction



fresh air intake and polluted air discharge

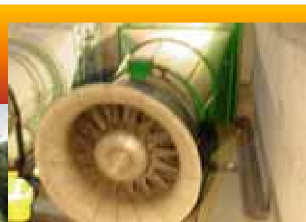
ventilation gallery to the tunnel

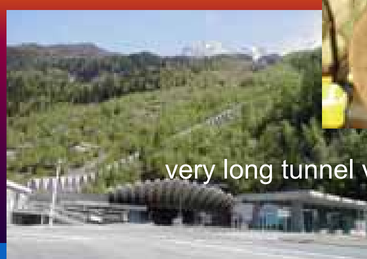
some examples of tunnels longer than 3 km

- Others European countries
  - ⌘ similar situation as in France for tunnels < year 1990
  - ⌘ same evolution today for the same reasons
  - ⌘ some others examples length > 3 km with longitudinal
    - Germany:
      - 3 tunnels 2,4 km to 2,7 km longitudinal with eventually smoke exhaust duct
      - 3,1 km and 3,3 km with exhaust duct
      - 7,9 km with intermediate stacks (fresh air provision – polluted air exhaust)
    - Ireland : urban tunnel 4 km – but very low safety level
    - Norway: numerous tunnels > 3 km but very low traffic – 1 tube
    - UK : no tunnel > 3 km with longitudinal ventilation

some examples of tunnels longer than 3 km

- Others European countries (continuation)
  - ⌘ some others examples length > 3 km with longitudinal
    - Austria – four tunnels
      - Ehrentalerberg 3,3 km
      - Oswaldiberg 4,3 km
      - Semmering 3,4 km
      - Strenger 5,8 km
    - Sweden
      - Urban tunnel in Stockholm 3,6 km 80.000 veh/day
    - Denmark – Sweden Öresund link 3,5 km





very long tunnel ventilation system for European tunnels

particularities
some examples

very long tunnel particularities

- Tunnels longer than 12 km in Europe
  - ⌘ only tunnel with one tube and bi-directional traffic due to
    - geographical conditions
    - medium traffic that today does not require two tubes
  - ⌘ boundary of longitudinal ventilation
    - 7 to 8 km with 50.000 veh/day under French vehicles fleet and pollution standards conditions
    - possible extension if low traffic
    - possible extension with intermediate fresh air intake and polluted air discharge. But not really pure longitudinal system !
  - ⌘ mountainous conditions
    - rare economical possibilities for intermediate shaft
    - very important difference of pressure between portals

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European very long tunnels

- Examples for following tunnels under operation

⌘ Laerdal tunnel in Norway	24,5 km
⌘ Gotthard tunnel in Switzerland	16,3 km
⌘ Arlberg tunnel in Austria	13,98 km
⌘ Fréjus tunnel – France / Italy	12,8 km
⌘ Mont Blanc tunnel – France / Italy	11,6 km

- A project out of norm

⌘ 2nd fix link under the Channel France / UK	47 km

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Laerdal tunnel in Norway

- The longest road tunnel in the world 24,5 km
  - ⌘ one bi-directional tube
  - ⌘ medium traffic ≅ 2.000 veh/day
  - ⌘ gradient 2,1 % to 2,7%
  - ⌘ sea level

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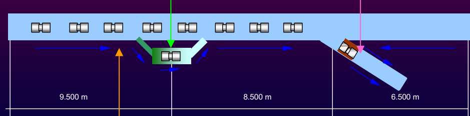
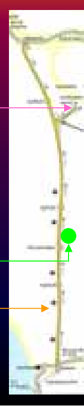
Laerdal tunnel in Norway

- Principles for ventilation system

ventilation gallery Tynjadal
2 fans for polluted air extraction

underground cleaning plant and recycling fresh air





32 jet fans for bringing fresh air from the Aurland portal

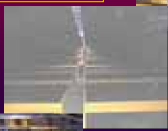
- ⌘ mix system
- ⌘ with air cleaning and recycling

Laerdal tunnel in Norway

3 U – turn stations inside tunnel

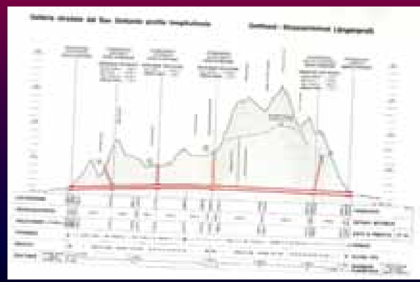
air cleaning plant
dust and NO_2
air recycling





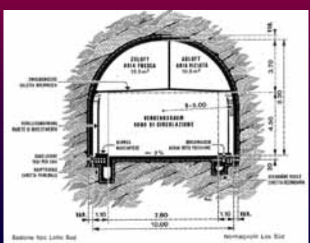
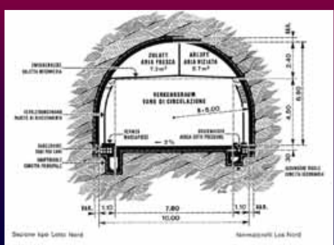
Gotthard tunnel in Switzerland

- Main characteristics
  - one bi-directional tube
  - 16,3 km length
  - 4 ventilation shafts
  - maximum gradient 1,4%
  - 1.100 m altitude



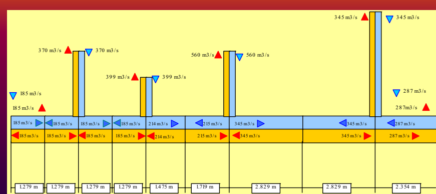
Gotthard tunnel in Switzerland

- North cross section
- South cross section

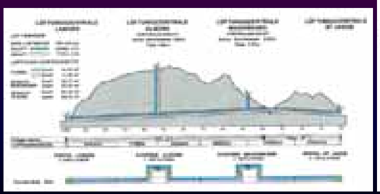
Gotthard tunnel in Switzerland

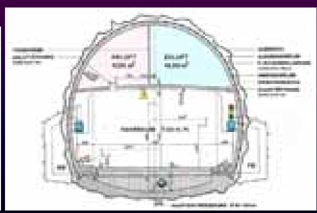
- Ventilation datas
  - ventilation system
    - transverse
    - possibly operation semi-transverse
  - ventilation plants
    - at each portal
    - 4 shafts




Arlberg tunnel in Austria

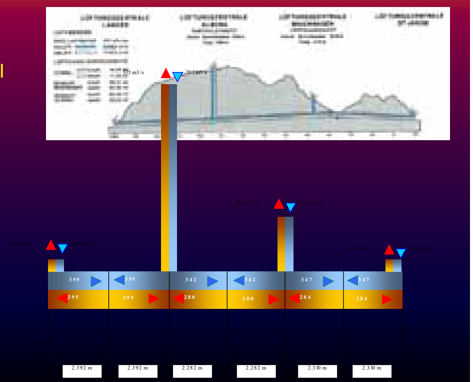
- Main characteristics
  - ⌘ one bi-directional tube
  - ⌘ 13,98 km length
  - ⌘ 2 ventilation shafts
  - ⌘ gradient 1,3 % to 1,67%
  - ⌘ altitude ≅ 1.200 m





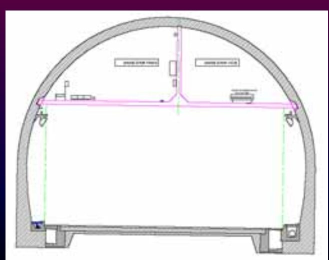
Arlberg tunnel in Austria

- Ventilation system
  - ⌘ semi transverse
  - ⌘ plants at each portal
  - ⌘ 2 shafts



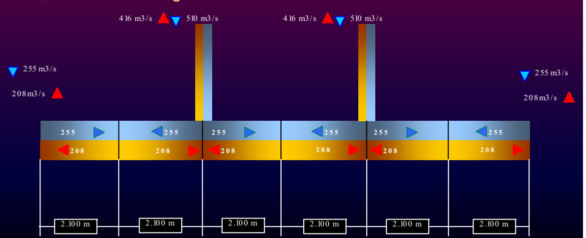
Fréjus tunnel France / Italy

- Main characteristics
  - ⌘ one bi-directional tube
  - ⌘ 12,87 km length
  - ⌘ traffic ≅ 5.000 veh/day with high rate of trucks
  - ⌘ gradient 0,54 %
  - ⌘ altitude ≅ 1.250 m
  - ⌘ two shafts (700m high)



Fréjus tunnel France / Italy

- Semi-transverse ventilation system
  - ⌘ 4 ventilation plants
    - one at each portal
    - one at each stack bottom
    - 2 stacks, one of 700 m high

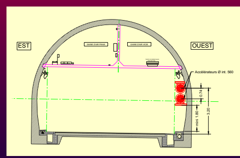


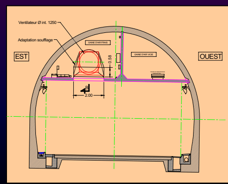
Fréjus tunnel France / Italy

- Transformation of the existing ventilation system
  - ⌘ why this transformation ?
    - important pressure difference between both portals
    - that means natural air current with high velocity, and changing of direction according to pressures at portals
  - ⌘ semi-transverse system is not able to manage air velocity
    - important spreading of smoke during last fire, even with a performing transverse ventilation system
    - air velocity can only be managed by applying a force that requires
      - jet fans
      - or strong air stream injection

Fréjus tunnel France / Italy

- Transformation of the existing ventilation system
  - ⌘ solutions under investigation
    - jet fans on the side walls
      - easy to install
      - closing lane for maintenance
      - inside horizontal clearance
    - jet fans in fresh air duct
      - reversible
      - performance to investigate
    - injectors in fresh air duct
      - no reversible
      - intervention in fresh air duct
      - fresh air duct must be under operation





Mont Blanc tunnel France / Italy

- Main characteristics
  - ⌘ one bi-directional tube
  - ⌘ 11,6 km length
  - ⌘ traffic ≅ 5.000 veh/day with high rate of trucks
  - ⌘ gradient to 2,6%
  - ⌘ altitude ≅ 1.200 m
- Initial ventilation system
  - ⌘ semi-transverse ventilation
    - one plant at each portal
    - fresh air ducts under traffic area
    - exhaust duct (polluted air and smoke) under traffic area

Mont Blanc tunnel France / Italy

- Modification of ventilation system after disaster 1999
  - ⌘ main reasons
    - reinforcement of smoke exhaust capacity
    - very important difference of pressure between French and Italian portals: mountain barrier of 3,2 km high
      - till 800 Pa
      - natural air current may overpass 8 m/s
        - with very important influence for spreading the smoke
        - 300 m of tunnel are filled with smoke in one minute with 5 m/s
        - air current direction is changing according to meteorological conditions
    - semi transverse system is not able to manage such a strong air current
  - ⌘ new concept has been developed
    - mix ventilation system

Mont Blanc tunnel France / Italy

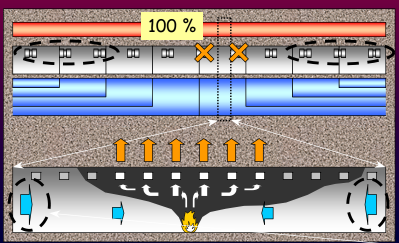
- description of a mix system
  - ⌘ General concept
    - injection of fresh air from air ducts (health condition)
    - extraction of polluted air (health condition) and smoke through remote and motorised dampers (spacing 100m), and an air duct
    - management and control of the air flow (and corollary the smoke) with jet fans installed in vault

Mont Blanc tunnel France / Italy

- description of a mix system
  - ⌘ Fire conditions
    - concept based on R&D since 1990
      - manage the evolution of smoke
      - maintaining the stratification
      - stability of back layering
      - concept of air flow critical velocity
    - principles
      - fire detection with redundant systems
      - reduce air flow velocity to 0 m/s at fire place
      - confine the smoke & establish stratification
      - full automatic regulation of ventilation

Mont Blanc tunnel France / Italy

- control of longitudinal smoke spread



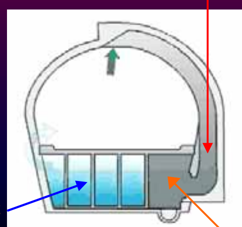
- smoke exhaust makes converge air on fire place (smoke containment)
- jet fan regulate the symmetric convergence

Longitudinal smoke containment

Longitudinal velocity =0 m/s in fire area

Mont Blanc tunnel France / Italy

⌘ New Mont Blanc ventilation system
- 76 jet fans in the vault
  - control the longitudinal draught
  - reduce it to 0 m/s within 2 min (500 Pa)
- smoke extraction dampers spacing 100 m
  - motorised & remote-controlled
- smoke extraction duct
  - 3 axial fans at both portals
  - 4 fans inside the duct to boost the pressure
  - volume: 150 m3/s for a 600 m long section
- captors: opacity and anemometers

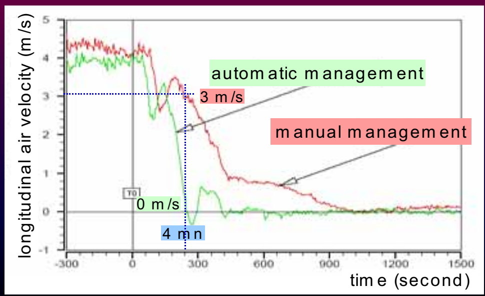


Mont Blanc tunnel France / Italy

- fully automatic management required
  - ⌘ numerous actions to be done when fire appears
  - ⌘ operator is under stress and very busy

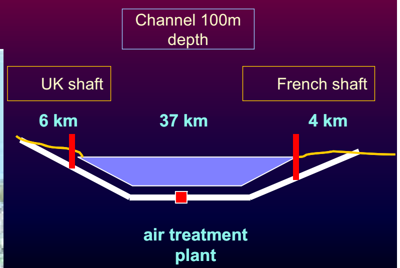
automatic system is much more efficient

0 m/s air velocity after 4mn (automatic) instead 17mn (manual)



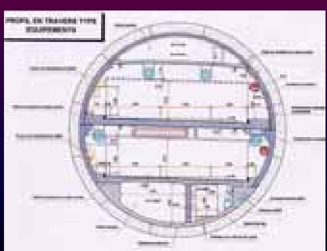
2nd fix link under the Channel France / UK

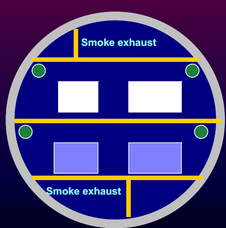
- A huge challenging project out of norms
  - ⌘ general concept
    - investigation for a light cars link
    - by the year 2015 / 2020



2nd fix link under the Channel France / UK

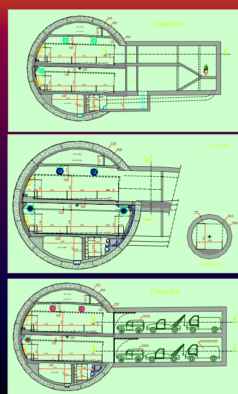
- 2 x 2 lanes on two levels
  - ⌘ clearance 2,75 m under equipments in the ceiling
  - ⌘ mix ventilation system
  - ⌘ 15 m diameter





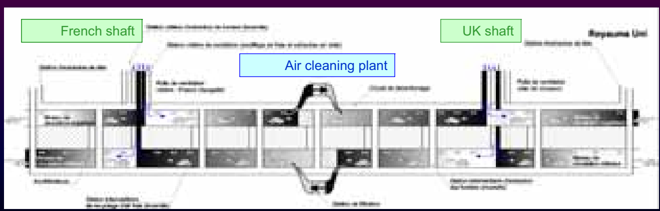
2nd fix link under the Channel France / UK

- Safety concept
  - ⌘ shelters spacing 380 m
    - access from both levels
    - complementary connexion with the technical gallery
    - connexions with the service gallery of the existing rail tunnel (with spacing 3.800 m between connections)
  - ⌘ vehicles connection 3.800 m
    - with ramp between the two levels
  - ⌘ breakdown and safety underground stations
    - 2 or 3 units



2nd fix link under the Channel France / UK

- Ventilation concept
  - ⌘ one ventilation plant at each portal
  - ⌘ 2 shafts at each sea shore
  - ⌘ air cleaning plant and recycling the air
  - ⌘ fresh air distribution with longitudinal ventilation



2nd fix link under the Channel France / UK

- Ventilation in case of fire
  - ⌘ fire place isolation with smoke containment (= Mont Blanc)
  - ⌘ use of cross galleries for fresh air distribution on both levels
  - ⌘ smoke extraction to both stacks through removed dampers and smoke extraction ducts

2nd fix link under the Channel France / UK

- A very challenging project !
- A project to push the limits !
- But not for tomorrow according to the financial situation of Eurotunnel company

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Thank you for your attention