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Banana Jet®

The modern way of tunnel ventilation

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- Introduction of Jet fan and ***Banana Jet®***
- Effects
- Tests in Tunnels - Results
- CFD-Simulation
- Benefits
- Conclusions

- Principle of jet fan:
  - shock impulse is generated by the fan inside the tunnel
  - Main task is to maintain a desired air velocity inside the tunnel in order to prevent backlayering of smoke in fire case
- Field of application:
  - longitudinal ventilation of tunnels

    (sometimes also in combination with axial fans)
- What is a ***Banana Jet®*** :
  - ***Banana Jet®*** is a jet fan with unique design. It achieves significantly increased air velocity inside the tunnel. Thus, the efficiency of the tunnel ventilation system is improved dramatically.

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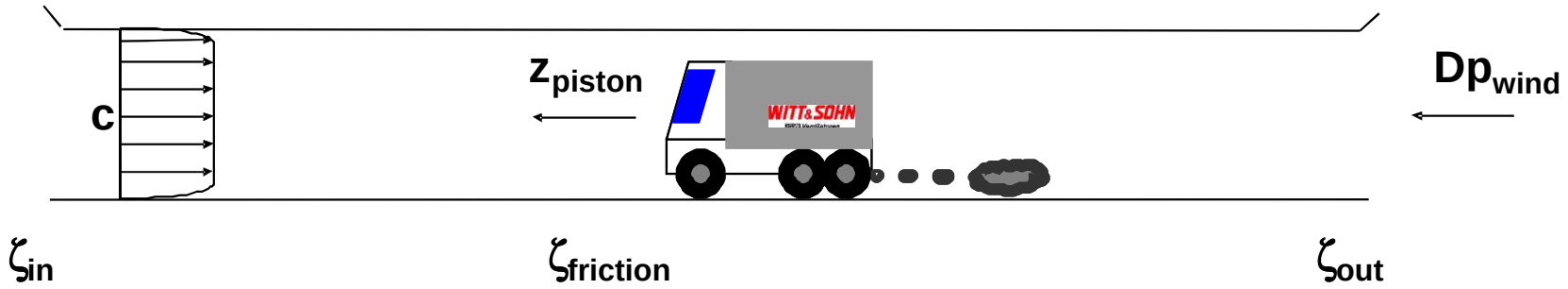
- Thrust calculation of a tunnel:



$$\Delta p_{total} = (\zeta_{in} + \zeta_{friction} + \zeta_{piston} + \zeta_{out}) \cdot \Delta p_{dyn} + \Delta p_{wind}$$

$$\text{with} \quad \Delta p_{dyn} = \frac{\rho}{2} \cdot c^2 = \frac{\rho}{2} \cdot \left(\frac{Q}{A}\right)^2$$

$$T_{total,required,gros} = \Delta p_{total} \cdot A_{tunnel}$$

ζ = Loss coefficient

Q = Volume flow

ρ = Air density

p = Pressure

A = Cross section tunnel

c = Outlet velocity

i.e. Gross Thrust = Total pressure losses x Tunnel cross section

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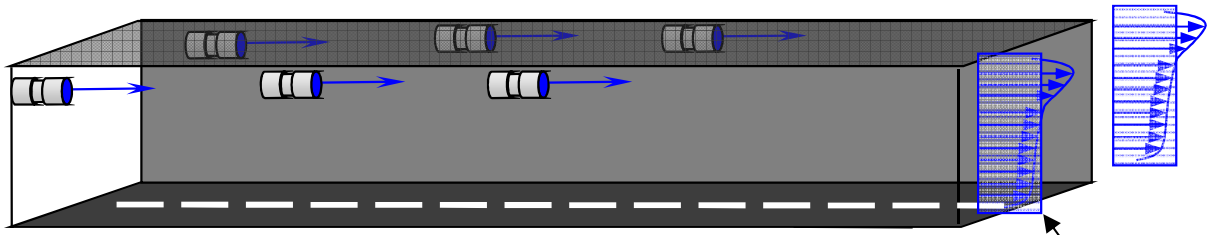
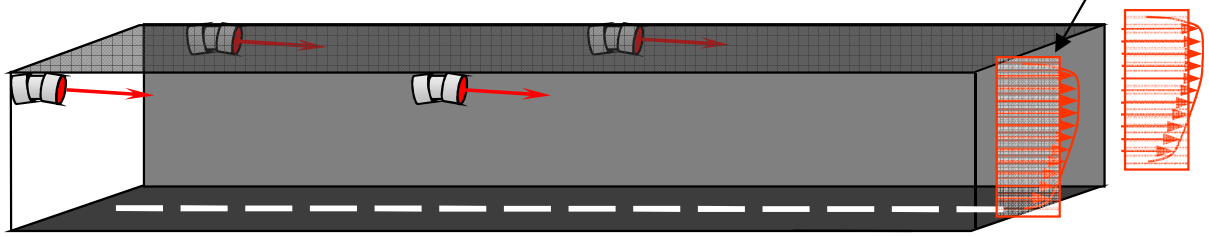
Traditional Jet



Banana Jet ®



c

INPUT:

$P_{el,\ TJ} > P_{el,\ BJ}$

OUTPUT:

$c_{TJ} = c_{BJ}$

$$\eta = \frac{\text{OUTPUT}}{\text{INPUT}}$$

$$\eta_{TVS} \sim \frac{c_{tunnel}}{P_{el}}$$

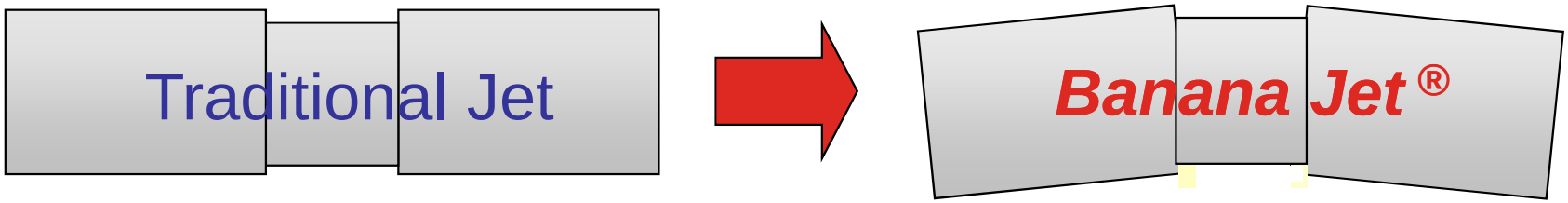
$$\eta_{TVS,\ BJ} > \eta_{TVS,\ TJ}$$

- Commercial aspect:
  - Higher efficiency of the TVS (Tunnel Ventilation System):

$$\eta_{TVS} \sim \frac{c_{tunnel}}{\sum P_{el}}$$

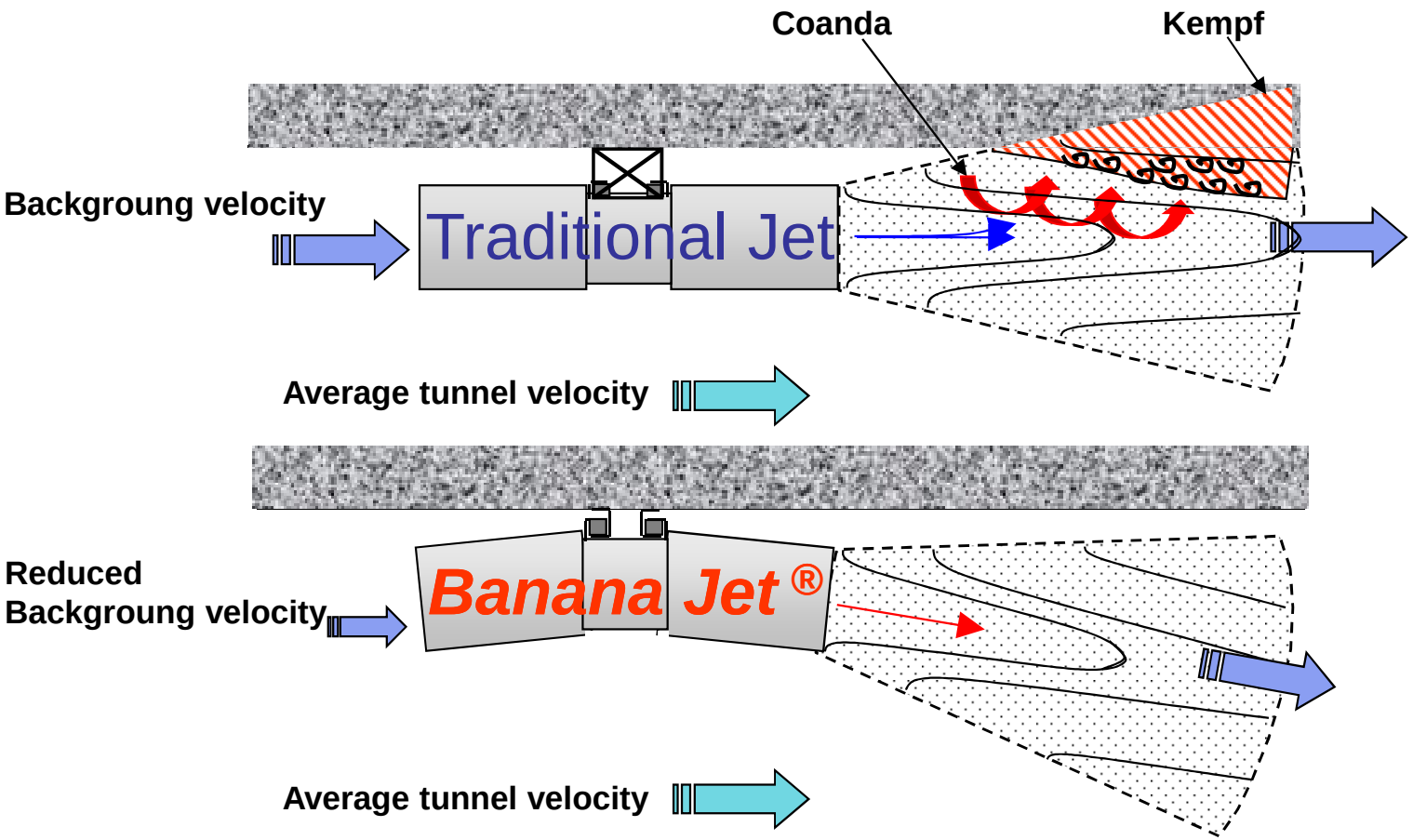
  - Smaller fans or lower number of fans can be used
  - Lower costs of investment, installation, operation and maintenance

- Technical aspect:
  - Bent silencers at an angle of 5-10° (Banana Jet design)



- Technical

  Increased thrust efficiency in the tunnel



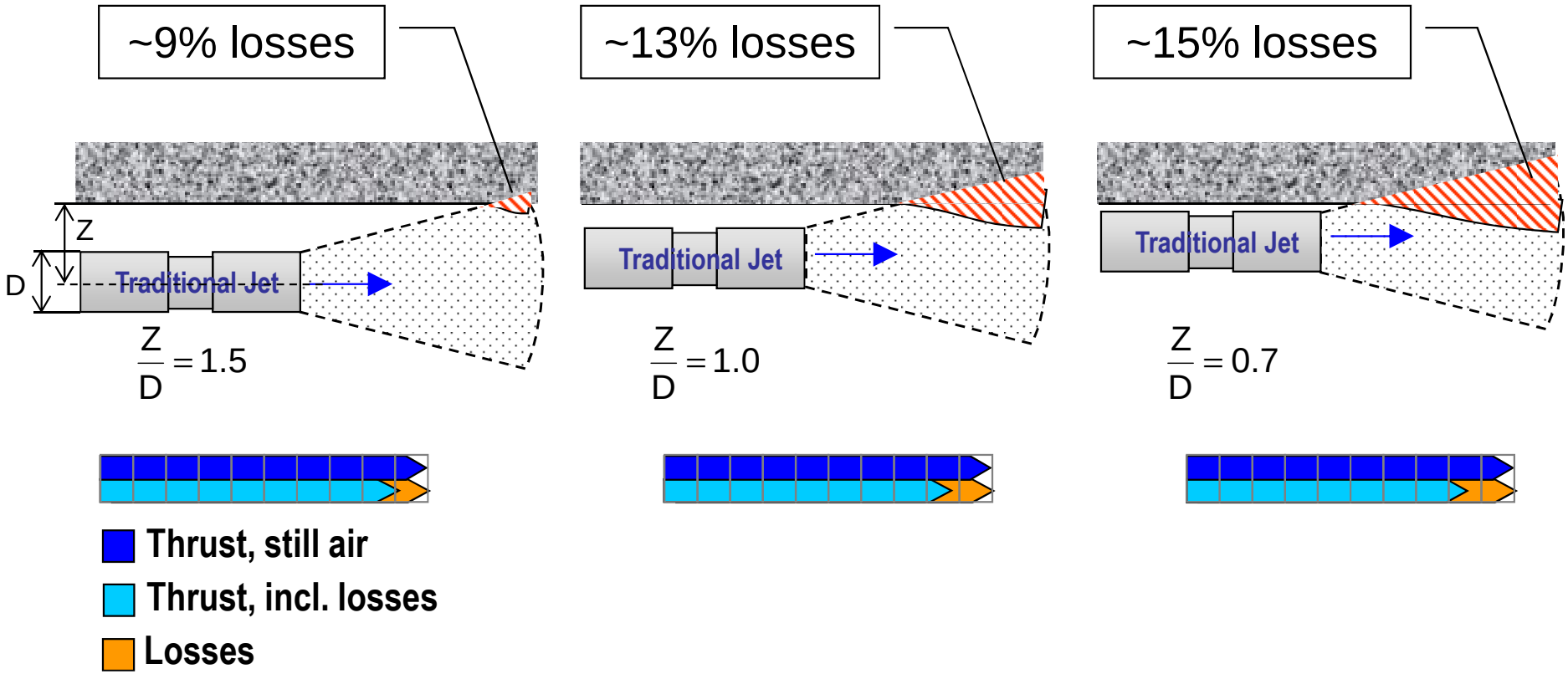
by reduction of losses

- Main effects[1] explaining higher efficiency[2]:
  - No Impulse losses due to
    - Wall effect (Kempf)
    - Background velocity
    - Tunnel discharge profile at portal
  - Influence of tunnel geometry
  - Flow/ friction losses due to
    - Coanda effect

[1] no congestion,
no piston,
no chimney effect

[2] compared to
Traditional Jet Fan

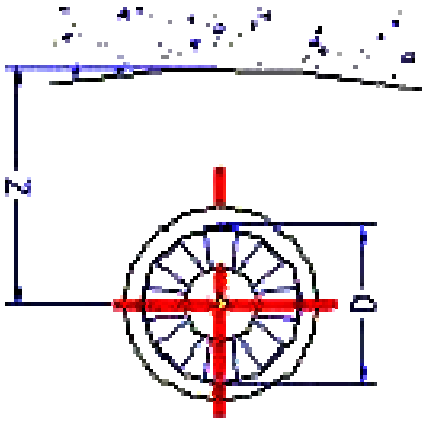
- Impulse loss - “Wall effect” (Kempf)
  - Distance of fan axis to one boundary



- Calculation of wall effect losses (Kempf)

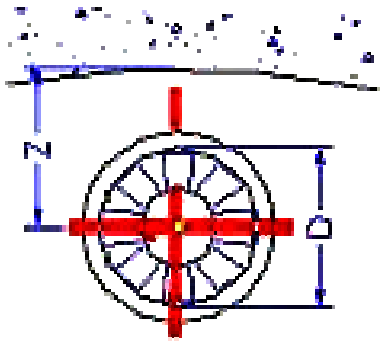
$$T_{net} = T_{jet} \cdot \frac{1}{K}$$

$$K = 0.0192 \cdot \left(\frac{Z}{D}\right)^2 - 0.144 \cdot \frac{Z}{D} + 1.27$$



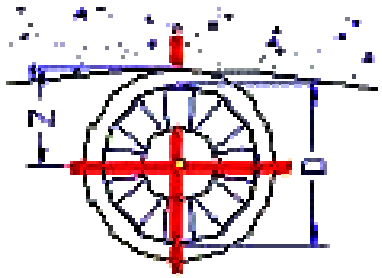
$\frac{Z}{D} = 1.5$

$T_{net} \cong T_{jet} \cdot 0.91$



$\frac{Z}{D} = 1.0$

$T_{net} \cong T_{jet} \cdot 0.87$



$\frac{Z}{D} = 0.7$

$T_{net} \cong T_{jet} \cdot 0.85$

- Reduction due to „No“ wall effect (depending on type of installation)

	 $\approx 1-\frac{1}{K}$	 $\approx 1-\left(\frac{1}{K}\right)^2$	 $\approx 1-\left(\frac{1}{K}\right)^3$
Loss of thrust, **Traditional Jet**	5-15%	15-25%	20-35%
Loss of thrust, ***Banana Jet®***	~0%	~0%	~2-5%
Reduction of required thrust	**- (5 - 15%)**	**- (15 - 25%)**	**- (18-30%)**

- Impulse loss - Background velocity
  - Reduces gross outlet velocity
    (to increase average tunnel speed)

Gross outlet vel. $\vec{c}_{out, g}$

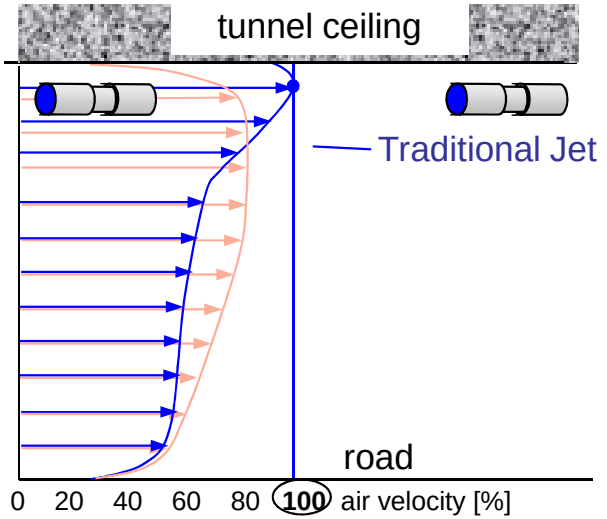
=

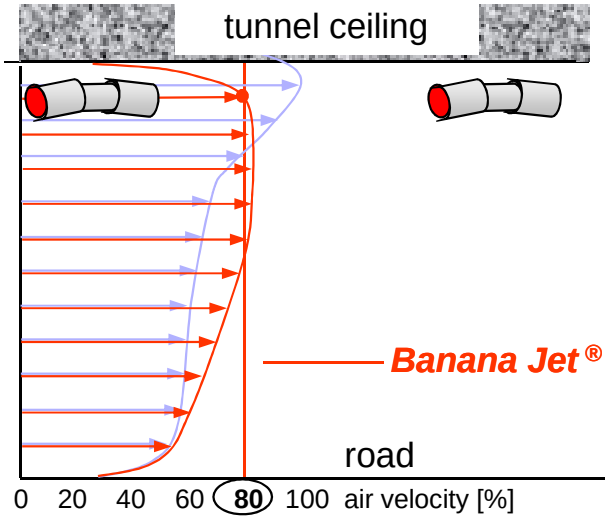
Net outlet vel. $\vec{c}_{out, n}$

-

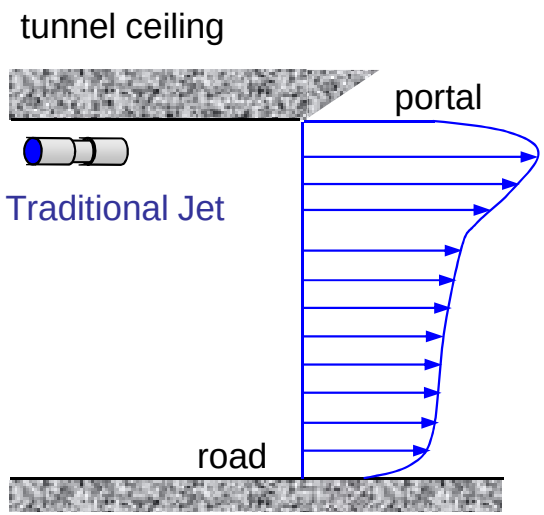
Background vel. $\vec{c}_{BG}$

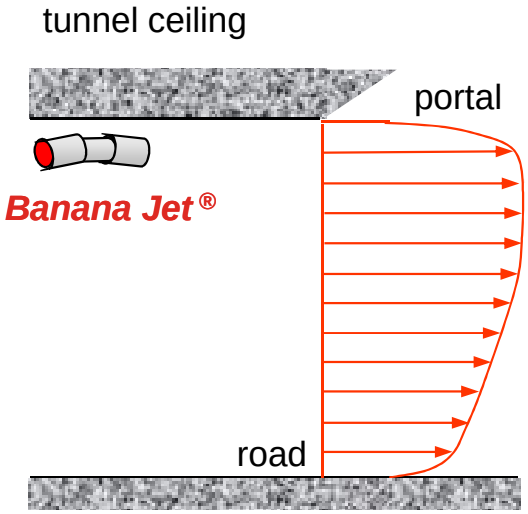
- Different profiles:
  - Traditional Jet Fan
    - Inhomogeneous air profile
    - High velocity at wall/ ceiling
  - ***Banana Jet*** ® Fan
    - Homogeneous air profile
    - Reduced velocity at wall/ ceiling (~80%)





- Impulse loss - Profile at portal:
  - Short distance of last jet fan battery to exit portal (< 100m) due to cost savings for cables



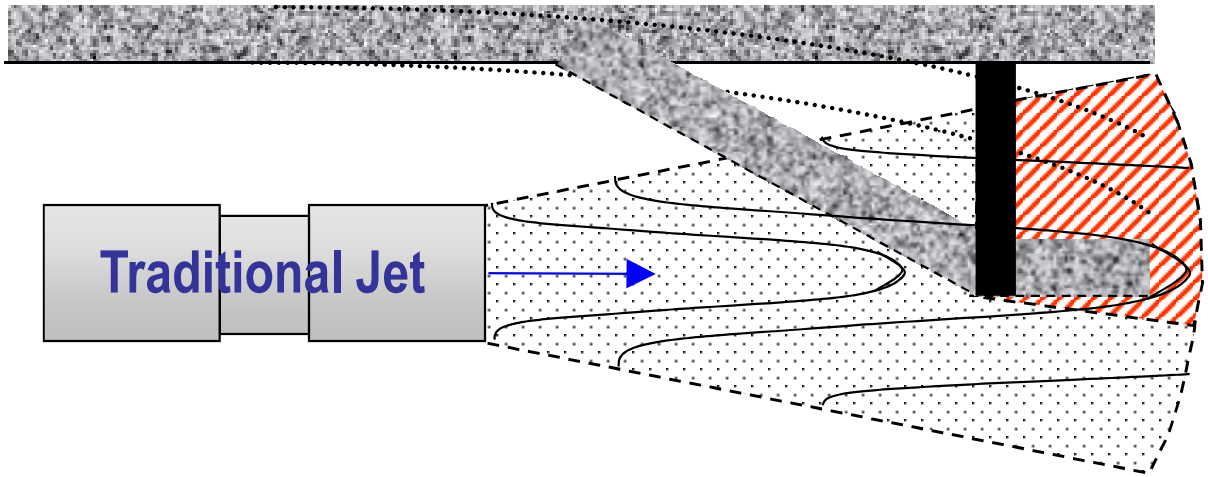


z = 1.08 to 1.25

z = 1.02 to 1.05

Effects - Geometry

- Losses by tunnel (case-to-case)
  - Geometry e.g. curves, slope
  - Obstacles close to the jet fan outlet
    - niches, traffic signs, etc.



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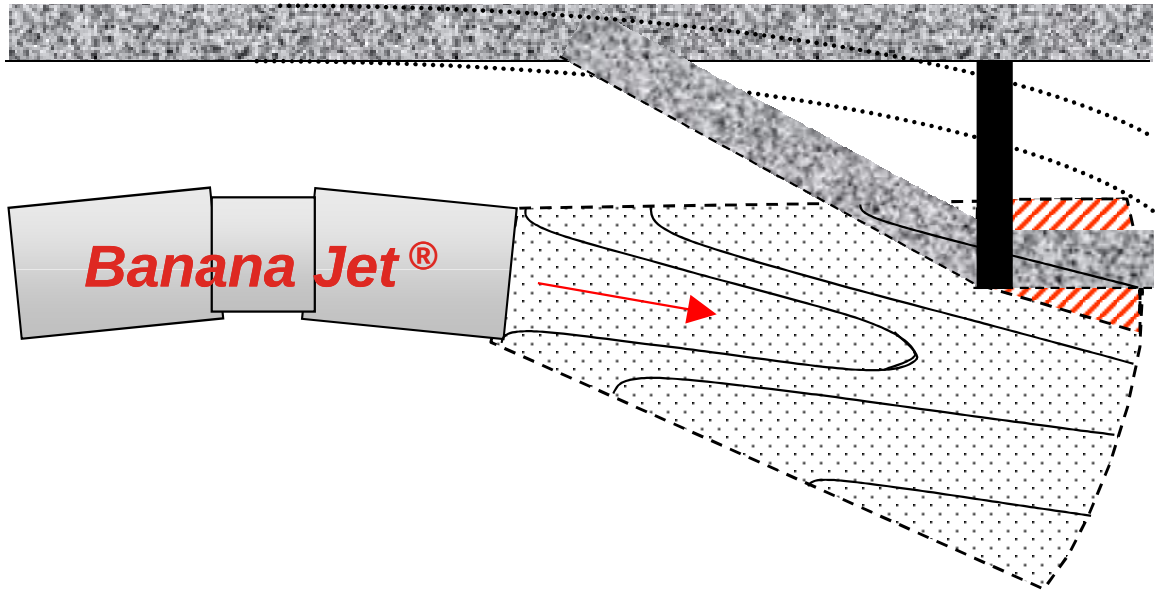
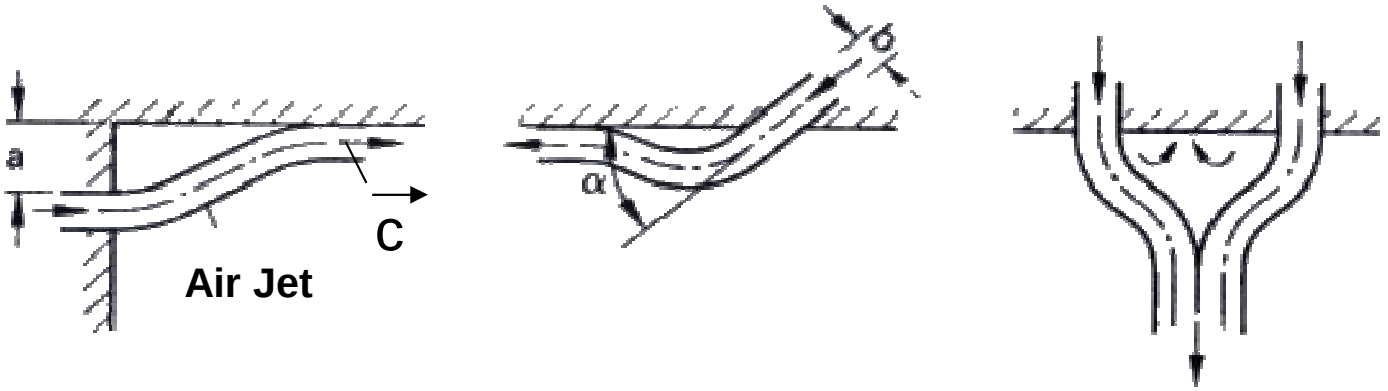
- The ***Banana Jet®***:
  - NO losses by wall effect
  - Reduced losses by obstacles



- Friction loss - “Coanda” effect
  - Air „sticks“ to the wall/ ceiling

    - Higher velocity c →
    - Higher friction, f(c) →

    } at the wall/ ceiling



Some Photos of Banana Jet®

Some Photos of Banana Jet®

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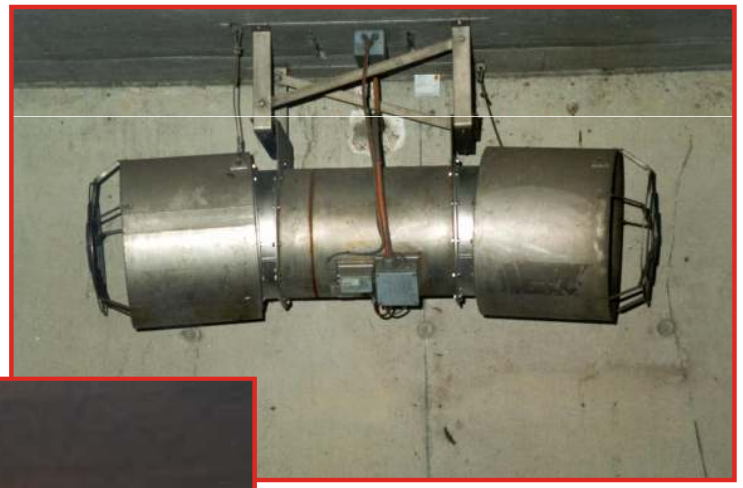
- Comparative tests in 3 tunnels

Uznaberg West Tunnel

Switzerland

Collombey Tunnel Switzerland



Krohnstieg Tunnel
Germany

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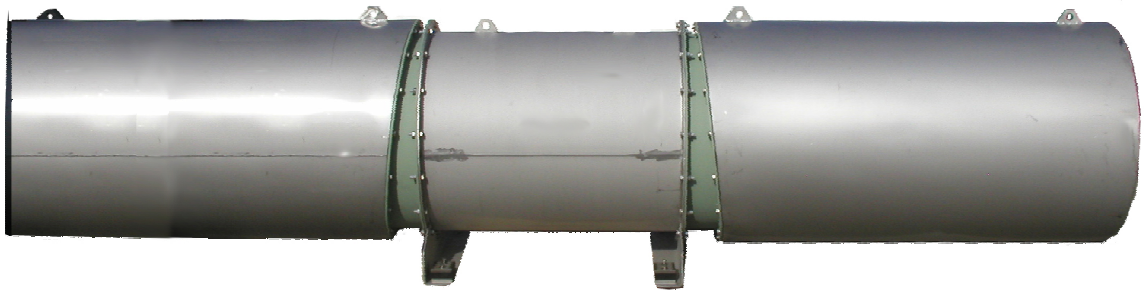
- Test set-up:
  - ***Banana Jet*®** Fan :

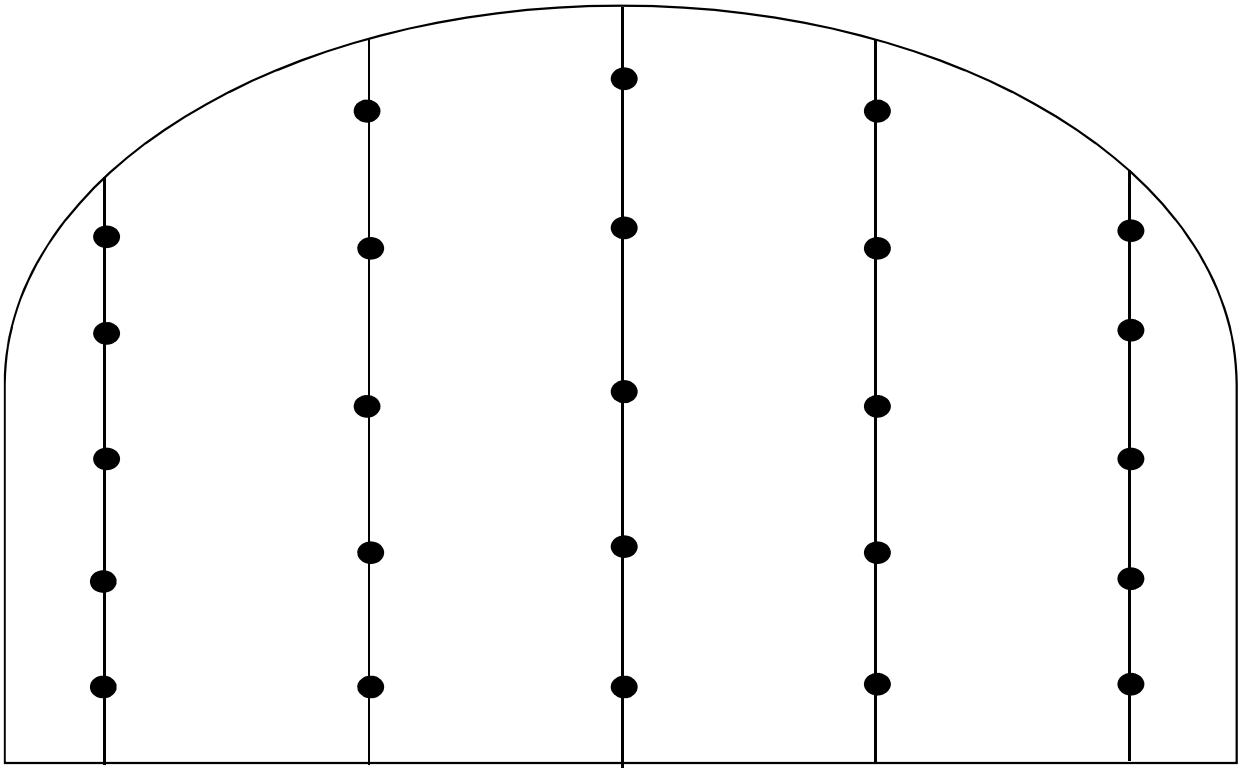
  - Modified to Traditional Jet Fan:



- Test set-up:
  - same quantity
  - same size
  - same performance

} same INPUT

- Test procedure:
  Grid-measurement of air velocity [1)]



[1)] acc. to Log-Tchebycheff-Method

- Hypothesis:

  „With same INPUT the ***Banana Jet®*** fan

  - has higher effective thrust, i.e.
  - produce higher tunnel air velocity, i.e.

  ➡ provides higher „OUTPUT“

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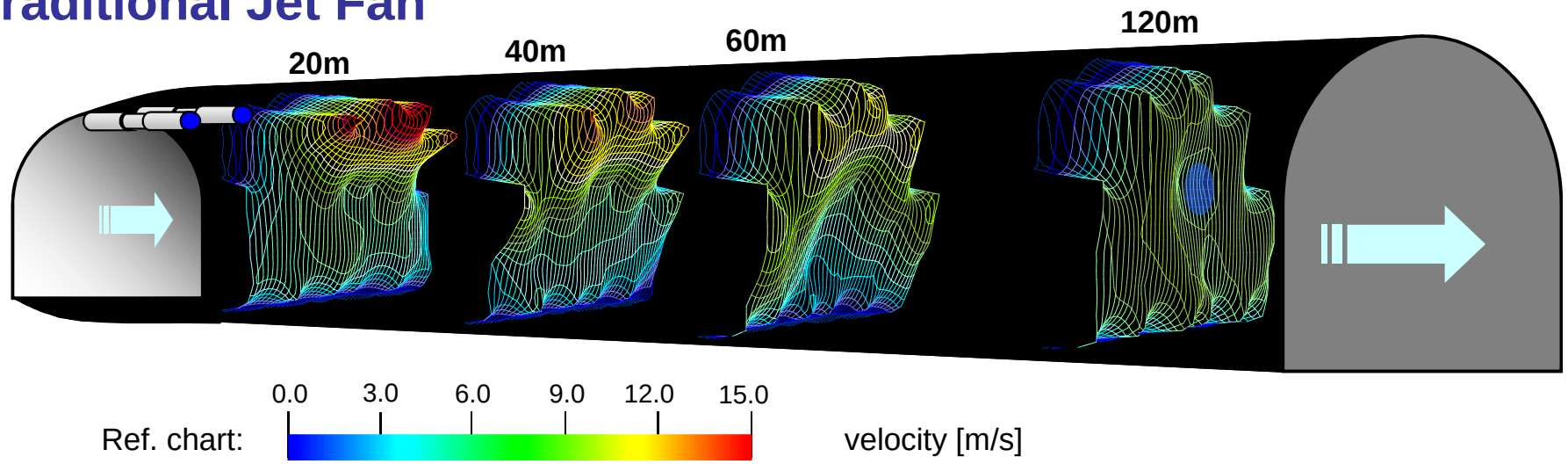
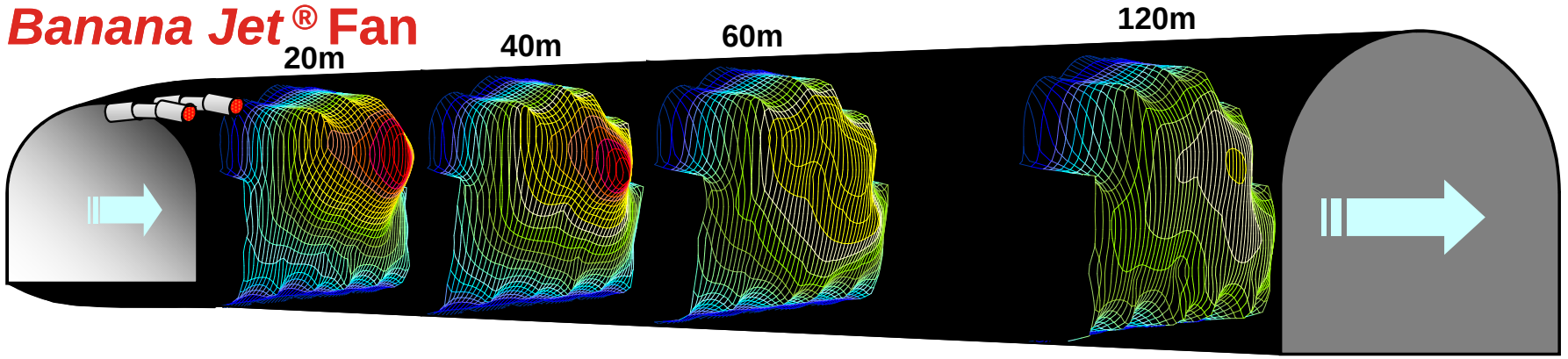
- Results of air velocity profiles (3D)

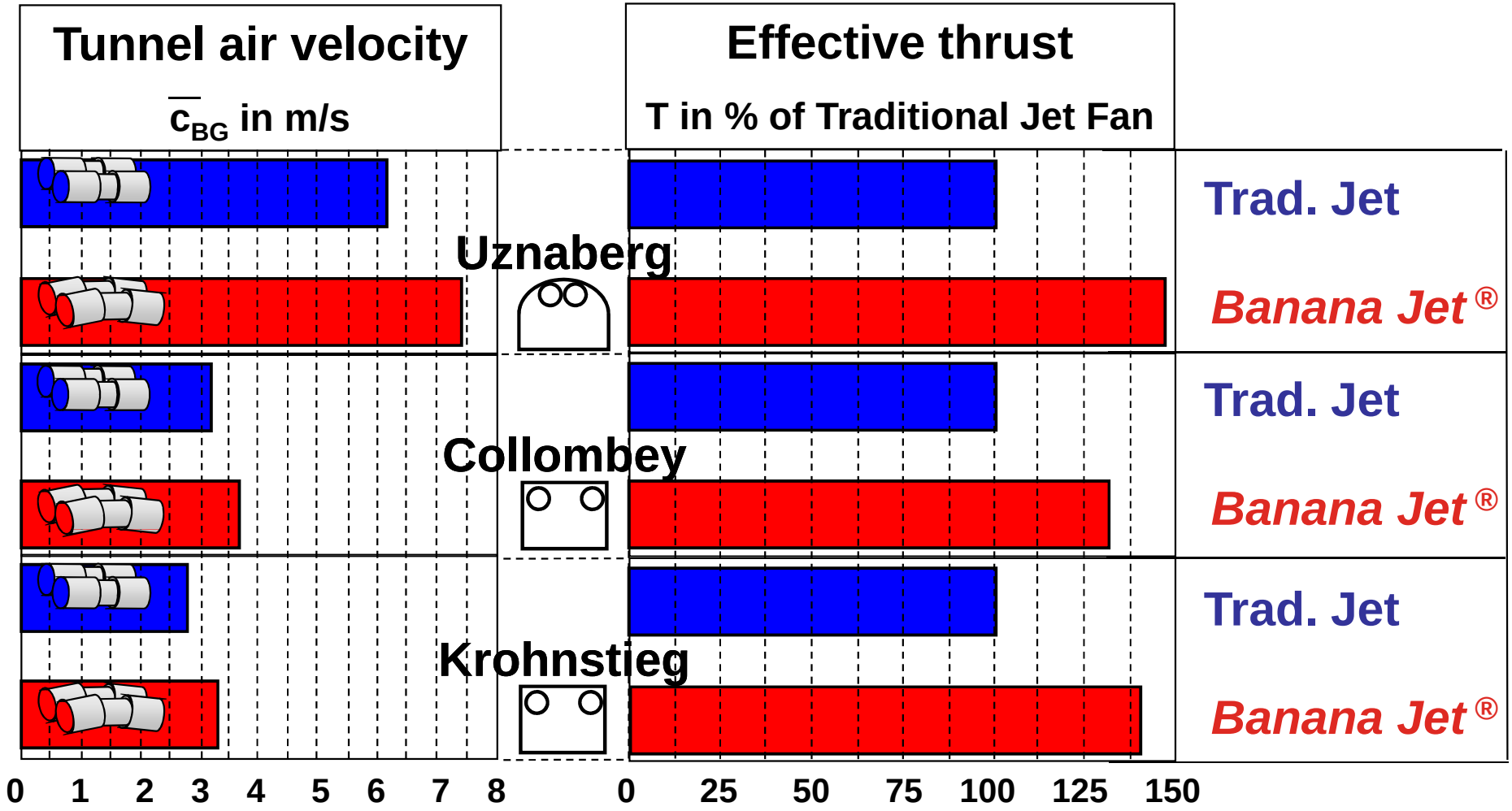
Traditional Jet Fan



Banana Jet® Fan



- Results of performance in tunnel



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- Reference: Bypass Schmerikon

Location	Switzerland, Kanton St. Gallen
Length	1 x 1318 m + 2 x 940 m
Traffic	bidirectional + unidirectional
Realized	2003
Tests	Banana effect proven by independent measurements

		Design schedule	Realized with *Banana Jet*®
Quantity of fans	-	21	21
Thrust per fan	N	966 (100%)	770 (80%)
Thrust, total	N	20286 (100%)	16170 (80%)
$P_{electric}$ per fan	kW	30.5	26.1
$P_{electric}$ total	kW	640.5 (100%)	548.1 (85%)
Tunnel average velocity	%	100	115
Total thrust tunnel	%	100	132

Source: Witt & Sohn analysis

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- Reference: Tunnel Aubing

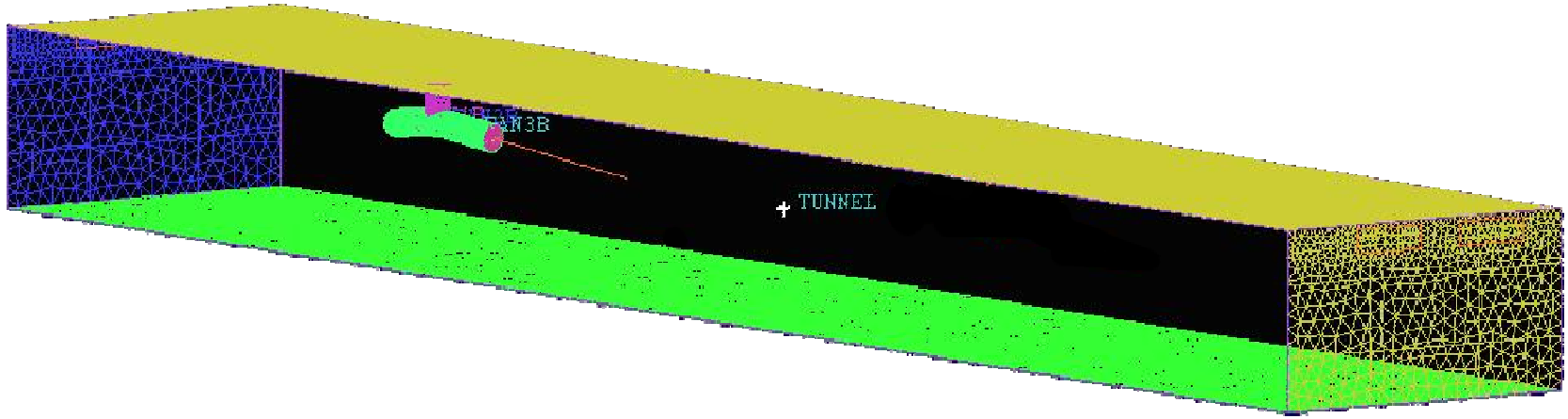
Location	Motorway ring (Munich)
Length	2 x 1950 m
Traffic	unidirectional
Realized	2005 - 2006
Tests	Banana effect proven by independent measurements

		Design schedule	Realized with *Banana Jet®*
Quantity of fans	-	60 (100%)	48 (80%)
Thrust per fan	N	516	516
Thrust, total	N	30960 (100%)	24768 (80%)
$P_{electric}$ per fan	kW	20.9	20.9
$P_{electric}$ total	kW	1254 (100%)	1003 (80%)
Tunnel average velocity	%	100	120
Total thrust tunnel	%	100	144

Source: Witt & Sohn analysis

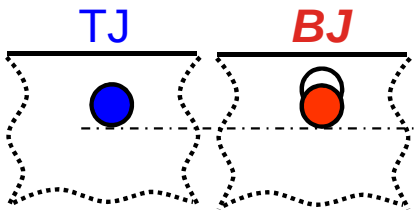
- By Büro Happold
- With ANSYS CFX
  (steady state)
- Matrix of cases for
  - Different tunnel profiles
  - Different jet fan configurations
  - Comparison:
    Traditional (T) vs. ***Banana Jet ® (B)***

- Boundary conditions:
  - Tunnel-segment geometry
    H: 7m, W: 8.5m, L: 100m,
    concrete surface

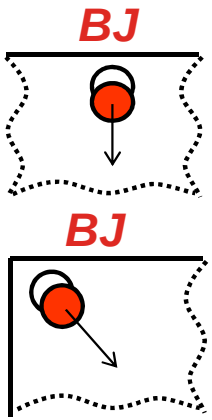


  - 20°C, 1.2kg/m³

- Boundary conditions:
  - Velocity profile of tunnel segement: inlet = outlet (Bernoulli-Law)
  - Jet fan bottom position
    TJ = ***BJ***

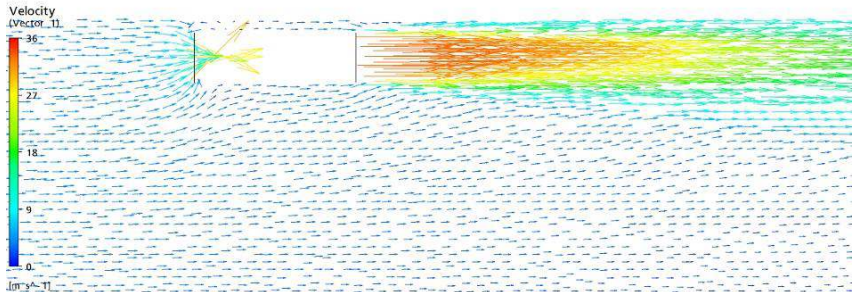


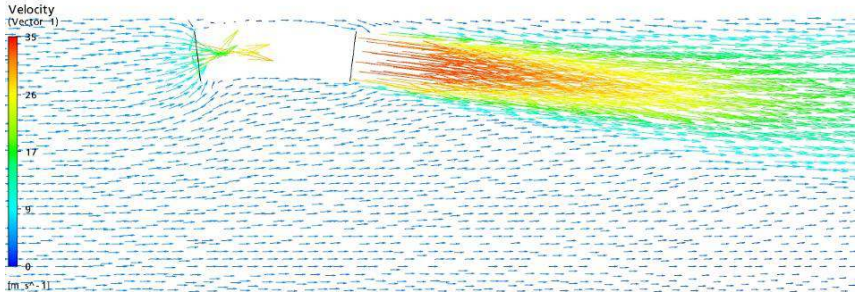
  - Velocity vector of ***BJ***
    - Centre position:
      7° downward
    - Corner position:
      7° under 45°



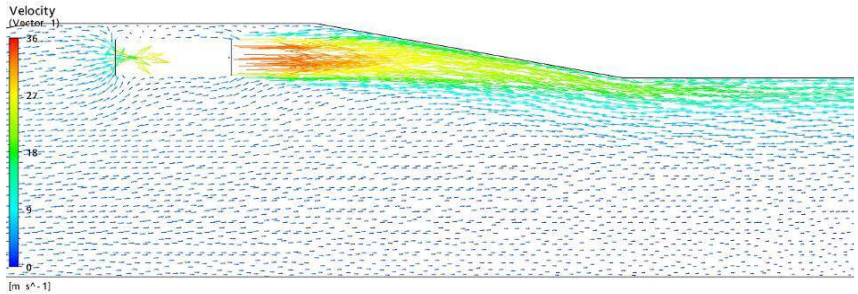
- Initial conditions:
  - Velocity profile of tunnel segment: $c_{Inlet} = c_{Outlet} = 0m/s$
  - Jet fan outlet speed $c_{out} = 35m/s$
  - Functions for
    - Friction (Coanda)
    - Wall effect (Kempf)
    - Background velocity

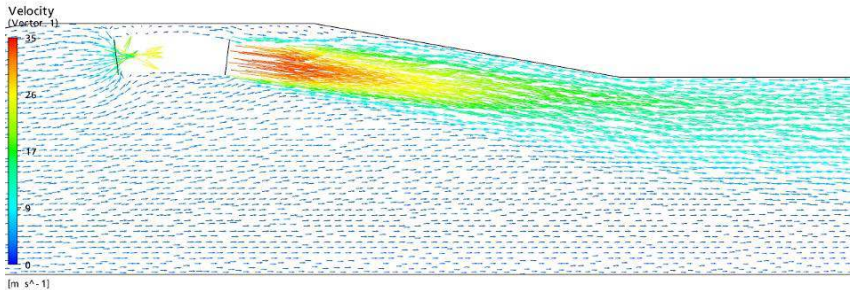
- Results – vector diagrams





6.T/***B*** : Round tunnel profile, 1 Fan @ centre, size 1250

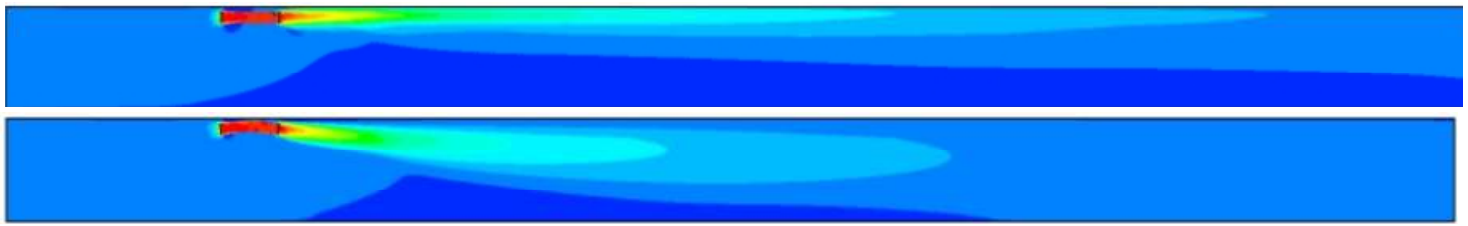


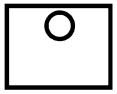


9.T/***B*** : Square tunnel profile, 1 Fan @ centre, size 1250

- Results – air velocity, empty tunnel

1.T/***B*** : Square tunnel profile, 1 Fan @ centre, size 710:

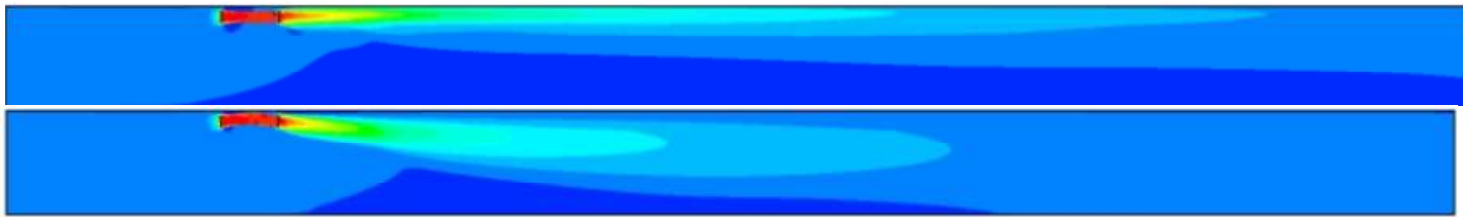


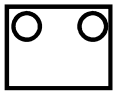


TJ

BJ

4.T/***B*** : Square tunnel profile, 2 Fans @ corner, size 710:

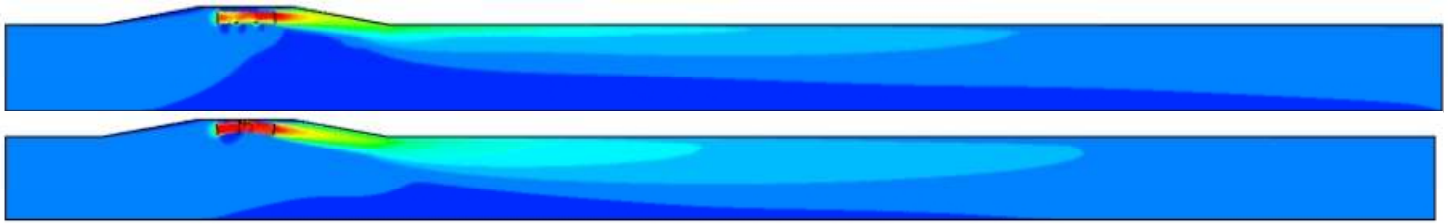


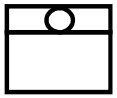


TJ

BJ

9.T/***B*** : Square tunnel profile, 1 Fan @ corner, size 1250:



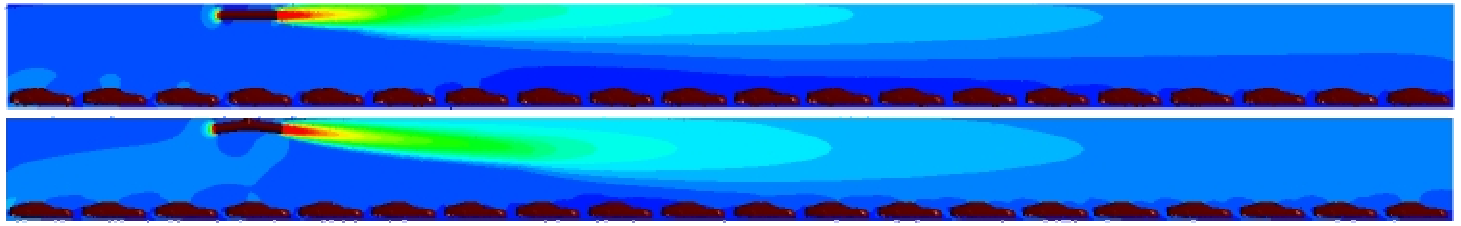


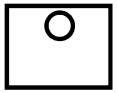
TJ

BJ

- Results – air velocity, traffic jam

1.T/***B*** : Square tunnel profile, 1 Fan @ centre, size 710:

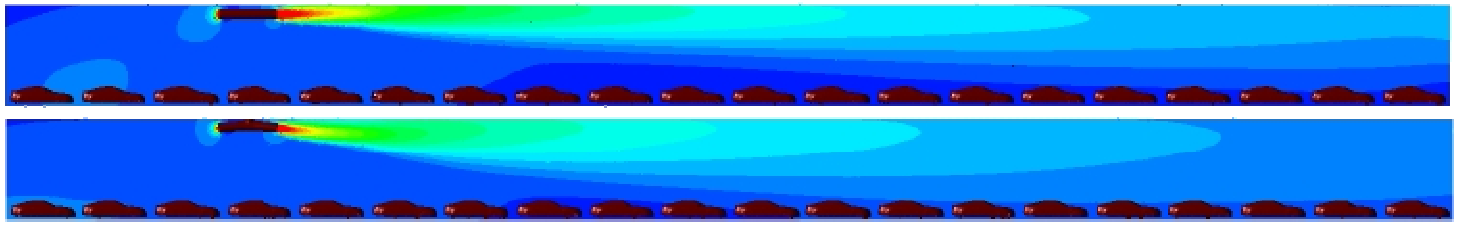


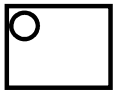


TJ

BJ

2.T/***B*** : Square tunnel profile, 1 Fan @ corner, size 710:



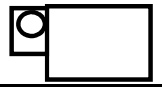
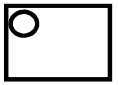
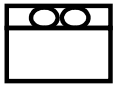
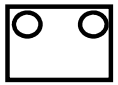
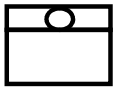
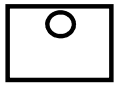


TJ

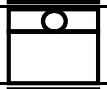
BJ

- Losses by cars: -2 .. -12%
  (compared to empty tunnel)

- Results – average velocity

Configuration	Size 710				Size 1250			
	c_{TJ} [m/s]	c_{BJ} [m/s]	Δc [%]	ΔT [%]	c_{TJ} [m/s]	c_{BJ} [m/s]	Δc [%]	ΔT [%]
	2.2	2.7	+21	+47				
	2.5	3.0	+20	+43	4.2	5.0	+21	+47
					6.8	8.5	+25	+56
					6.5	7.9	+22	+48
	2.8	3.3	+16	+35	4.6	5.4	+18	+39
	2.7	3.1	+14	+29				
	2.8	3.1	+10	+21	4.5	5.0	+12	+25
					6.5	7.4	+14	+30

- Prediction for ***Banana Jet®***-advantage

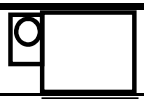
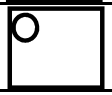
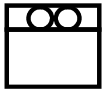
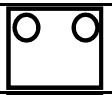
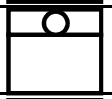
Configuration	Thrust improvement [%] [1] towards TJ at different tunnel air speeds [m/s]						
	2 m/s	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s
	45 %	**47 %**	50 %	52 %	55 %	57 %	60 %
	41 %	**43 %**	45 %	**47 %**	50 %	52 %	55 %
	38 %	41 %	44 %	47 %	50 %	53 %	**56 %**
	35 %	38 %	40 %	43 %	45 %	**48 %**	50 %
	33 %	**35 %**	37 %	**39 %**	42 %	45 %	48 %
	27 %	**29 %**	32 %	34 %	37 %	39 %	42 %
	19 %	**21 %**	23 %	**25 %**	28 %	31 %	34 %
	15 %	18 %	21 %	24 %	27 %	**30 %**	33 %

[1] tolerances: +/- 10%

○ → Actual measurements of tested tunnel

Bold → Results of CFD analysis

Rest → Predicted values

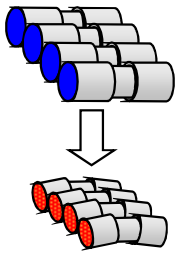
Configuration	Reasons for *Banana Jet®*-advantage
	Losses by the 3 sides of the niche reduced
	Losses by the 2 sides of the corner reduced
	Niche acts as **BJ** → Coanda effect reduced **BJ** reduces interaction between both fans
	Less interaction of both fans
	Niche acts as **BJ** → Kempf, Coanda effect reduced
	Air is not travelling down the side walls
	Wall friction losses (Kempf), Coanda effect
	Coanda effect + interaction of both fans

- Further factors[1] to adjust predicted thrust:
  - Smooth tunnel (painted/ tiles): - 8% to - 12%
  - Rough tunnel (blasted rock): + 3% to + 7%
  - Short tunnel (< 500m): - 8% to - 12%
  - Long tunnel (> 5km): + 4% to + 6%
  - Curved/ sloped road: + 1% to + 3%
  - Substantial no. of equipment: (interfering with air flow) + 6% to + 10%
  - Traffic: - 2% to - 12%

[1] to be added/ substracted from the table “Prediction for ***Banana Jet®***-advantage“

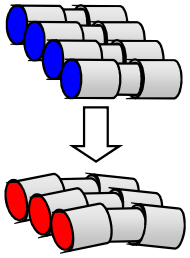
- Cost SAVINGS
  - Case A:

    Smaller size / same quantity of fans



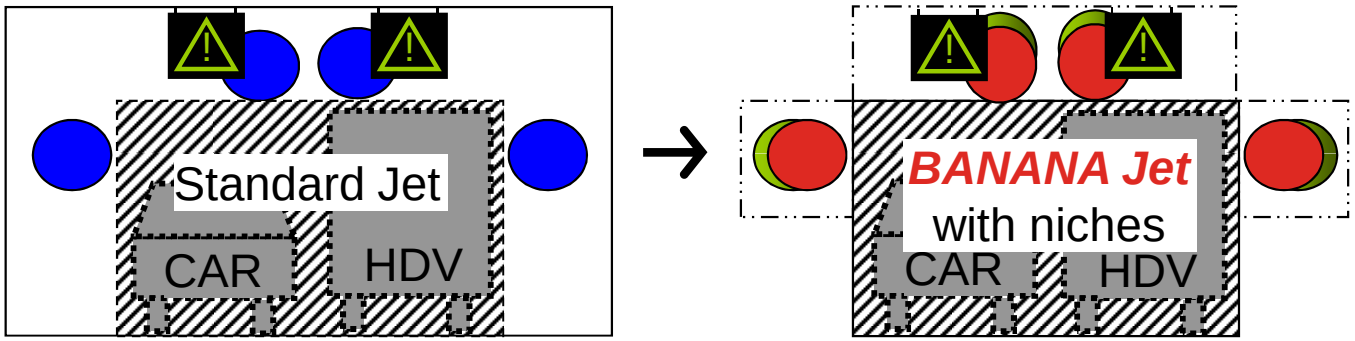
    - Less CONSTRUCTION costs
    - Less INVESTMENT costs
    - Less RUNNING costs
    - Smaller POWER SUPPLY PLANT

- Cost SAVINGS
  - Case B:
    Less quantity/ same size of fans



- Less CONSTRUCTION costs
- Less INVESTMENT costs
- Less RUNNING costs
- Smaller POWER SUPPLY PLANT
- Less INSTALLATION costs
- Less MAINTENANCE costs

- Cost SAVINGS:
  1. CONSTRUCTION:
     - Smaller cross section/ excavation
     - No performance losses by
       → Obstacles (e.g. traffic signs, lights)
       → Use of niches



WITT&SOHN IGW Ventilatoren

2. INVESTMENT:

- Smaller size or reduced quantity (FANS and CABLES)

Savings for Fan & Cables ~ 25-30 %

in % of total costs		Standard Jet	Banana Jet®
	Uznaberg	~ 13 %	~ 10 %
	Collombey	~ 15 %	~ 11 %
	Krohnstieg	~ 22 %	~14 %
Cables (1)	Uznaberg	34 %	~ 23 %
	Collombey	41 %	~ 29 %
	Krohnstieg	~ 25 %	~ 18 %

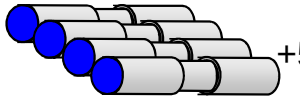
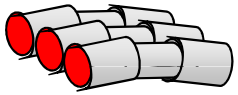
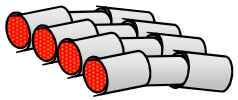
(1) E90-cable costs: 25 – 58 €/m (incl. installation)
(2) discount rate: 10%

WITT&SOHN IGW Ventilatoren

2. INVESTMENT:

- Shorter/smaller SILENCER
  → Same total SOUND level(*)
- Table:
  Sound pressure le

Savings for shorter silencers
~ 15 to 40 %

w/o. silencers	silencer's attenuation	increased level (battery)	with silencers
~93	2.0D: -12	 +5 (1)	~86
~92	**1.5D**: -10	 +4 (1)	~86
~91	**1.5D**: -10	 +5 (1)	~86

(*): with same total thrust (1): experienced values

3. RUNNING costs:

- Less unit power consumption or reduced quantity

Savings for Running costs ~ 25-30 %

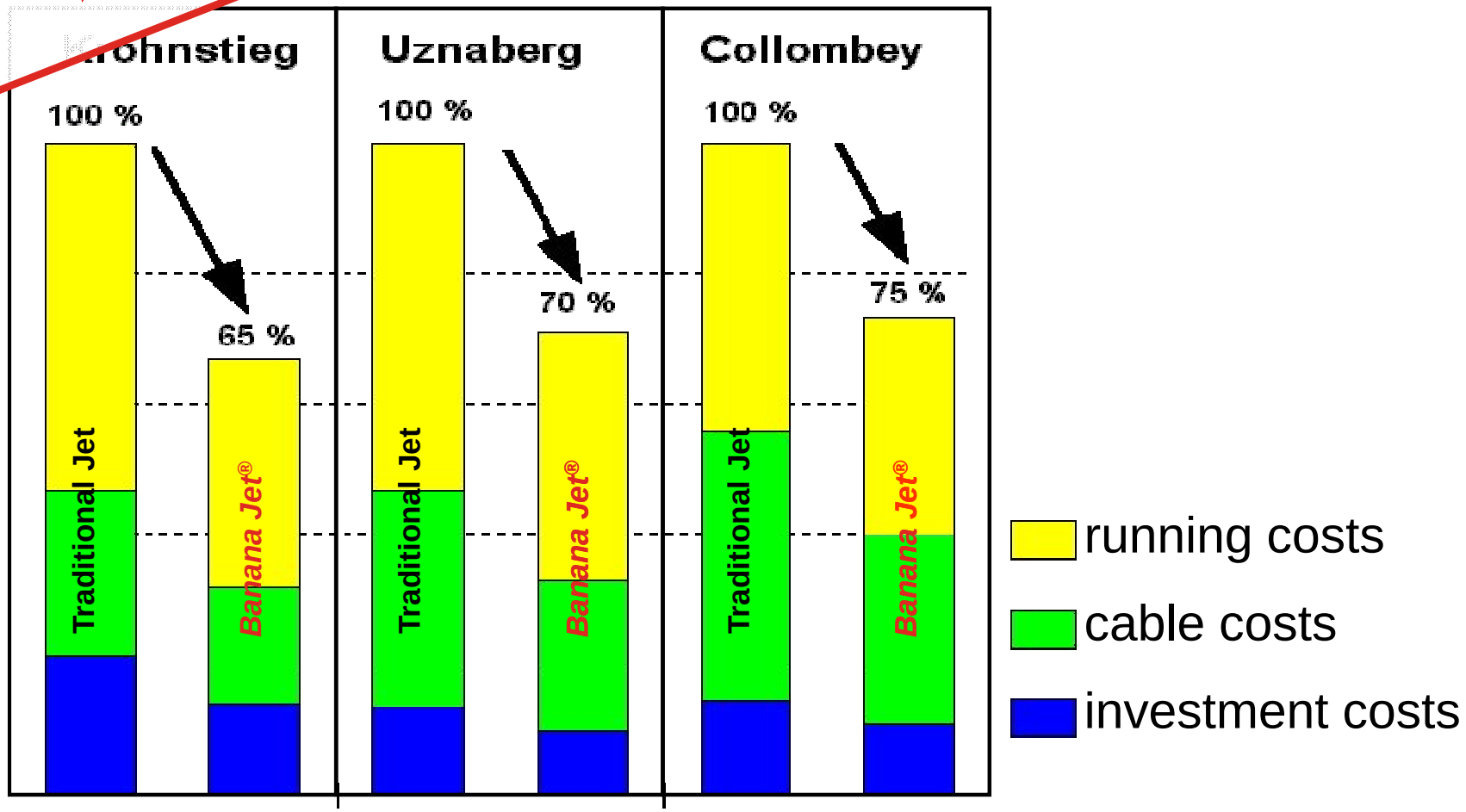
Impact on total costs	Standard Jet	*Banana Jet®*
Uznaberg	~ 53 %	~ 38 %
Collombey	~ 44 %	~ 33 %
Krohnstieg	~ 53 %	~ 35 %

(1) **basis:**
operation time: 1000h p.a.
energy cost: € 0,1 kW/h

WITT&SOHN
IGW Ventilatoren

Savings of 20 years Total Project Costs ~ 25-30 %

Total Savings (investment + running)



- Project Cost Calculation

  Assumptions made: Fan size 710, Thrust 600 N, reversible, heat resistant 300°C/2h (F300), 20 fans required (≙ 12000 N $Thrust_{tot}$)

A.) Traditional jet fan cost each: 5500 Euros
Total fan costs = 5500 x 20 fans => 110 000 Euros
Cable costs: Average cable length per fan = 800 m @ 7.40 €/m = 5920 Euro/fan
Total Cable costs = 20 fans x 5920 Euro => 118 400 Euros
Total fan and cable costs = 110 000 Euros + 118 400 Euros = **228 400 Euro**

B.) Number of Banana jet fans required: 16, Fan cost = 5500 Euros
Total fan costs = 5500 x 16 => 88 000 Euros
Cable costs: Average cable length per fan = 800 m @ 7.40 €/m = 5920 Euro/fan
Total Cable costs = 16 fans x 5920 Euro => 94 720 Euros
Total fan and cable costs = 88 000 Euros + 94 720 Euros = **182 720 Euro**

Total Cost savings of 25%! already for Contractor

Example Operating Costs Calculation

WITT&SOHN
IGW Ventilatoren

Fan running 6 hours a day(25%), costs for 20 years, Electricity cost: 0.1 €/kWh,

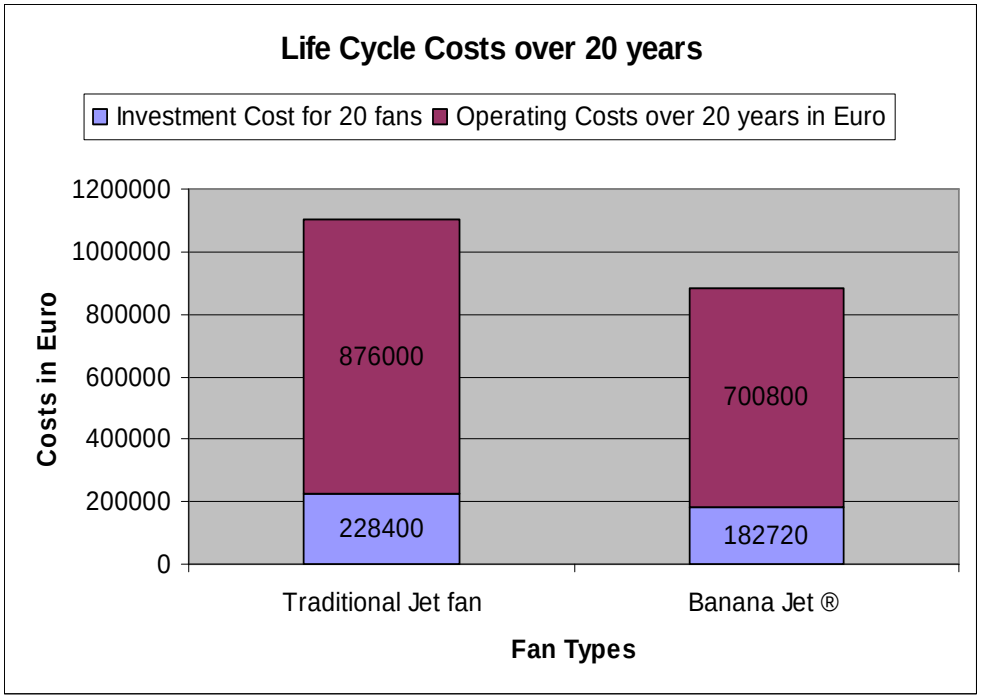
Power consumption each fan 22 kW/h

A.) Traditional jet fans:

20 fans x 6 hours/day x 365 days x 20 years = **876 000 Euro**

B.) Banana jet fans:

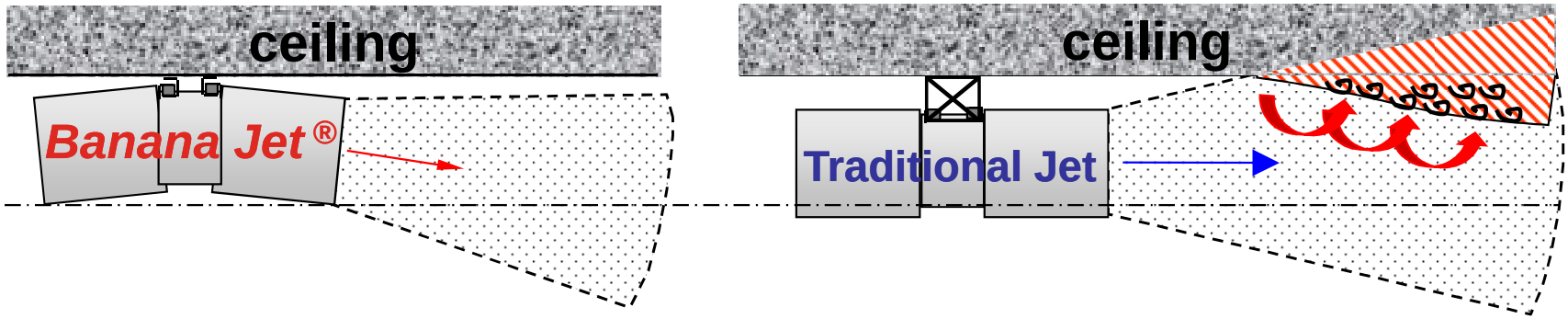
16 fans x 6 hours/day x 365 days x 20 years = **700 800 Euro**



Operation Cost savings of 25%! for end user

4. Installation (mounting):

- E.g. directly under ceiling
  - ➢ No wall effect (Kempf)



- ➢ Less space consumption
- ➢ Simple mounting structure
- ➢ Less quantity of fans (Case B)

5. Environment:

- Pollution: 550g CO_2 / kWh (1) (or higher)
- ~ 30 % CO_2-reductio (in line with reduced power consumption)
- Fulfilment of latest UN-report, part 3 (climate crisis)

(1) based on 60% fossil, 30% nuclear, 10% renewable (German Energy Mix/ Power Generation Standards)

6. References - worldwide:

Country	Tunnels	Country	Tunnels
Australia	4	Russia	1
Austria	1	Singapore	1
Chile	3	Spain	5
China	2	Sweden	1
France	4	Swizerland	8
Germany	13	U.A.E.	1
Norway	9	UK	1
Portugal	1	Venezuela	1
		Total	**56**

Summary

- 20-60% higher effective thrust with Banana Jets (same fan size)
- Easy selection
- Comfortable integration into tunnel concept
- Great benefits (cost savings) for all parties
- Helps to reduce CO_2
- Proven in over 50 tunnels WORLDWIDE

Banana Jet®
Patent No. 1050684