EFFECTIVE THRUST TRANSFORMATION
INSIDE TUNNELS WITH JET FANS (BANANA JET)

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ABSTRACT

Every few years an idea comes along, which in its simplicity and clarity is so obvious that one is left to wonder: „Why only now?“. Such an idea is the Banana Jet. By bending the air jet of a jet fan in a tunnel away from the restrictive surface (walls / ceiling) the performance of the fan in the system can be dramatically improved. This can be done with silencers or ducts which are bent with an angle of 5 – 25 %. The source of the improvement is that not only are the losses directly behind the fan virtually eliminated, but the airflow profile down-stream in the tunnel can be improved, further significantly reducing aerodynamic losses. The net result is a reduction of the required installed thrust by 30 – 50 %. Not only does this mean that far fewer (or smaller) fans need to be installed, but the installation cost for cabling, mounting etc. is also reduced in the same proportion. A 30 – 50 % reduction in required thrust directly translates into a reduction in energy consumption in the same order of magnitude so there is a larger savings in operating costs in addition to the benefit of lower capital cost and environmental pollution.

Keywords: jet fan, tunnel, effective thrust, niche, CFD

1. THE BANANA JET PRINCIPLE

Jet fans are installed in road tunnels to move the air by giving it an impulse (measured as thrust in Newton) in the desired direction. In order to achieve a required air speed, a number of loss factors must be overcome. (see Table.1). The use of Banana Jet can reduce these losses by 25 – 50 %, depending on the design of the tunnel. All those losses described in chapter 2 are a result of an analysis performed by the author and the company Witt&Sohn AG. The physics behind this improvement is relatively straightforward:

<table>
<thead>
<tr>
<th>Table 1: Losses for traditional and Banana Jet fans in % of total losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Losses in bends, installations, road signs, niches, corners, lamps, etc.</td>
</tr>
<tr>
<td>Wall friction losses</td>
</tr>
<tr>
<td>Background velocity losses</td>
</tr>
<tr>
<td>Impulse loss</td>
</tr>
<tr>
<td>Inlet / outlet portal losses</td>
</tr>
<tr>
<td>Total*</td>
</tr>
</tbody>
</table>

* assuming an empty tunnel; traffic jam or piston effect not taken into account.
1.1. Friction loss

An air stream that blows along a surface becomes “glued” to the surface due to the induced swirl and one-sided low pressure. This effect, called “Coanda-Effect” creates a less uniform flow in the tunnel, with larger velocities along the wall, compared to the flow that is achieved with Banana Jet. With Banana Jet the highest velocity is in the centre and upper half of the tunnel. This effect can be seen Figure 1, 6 and 7.

Overall this results in lower friction losses along the walls of the tunnel. A 5 – 10 % improvement is realistic. In tunnels with a very rough surface the improvement can be even higher.

![Figure 1: Average flow rate in a tunnel (Uznaberg West)](image1)

1.2. Background velocity correction

The energy that a fan gives to the air flow in the tunnel is a function of the difference in airspeed at the outlet compared to the speed of the air at the inlet of the fan. The higher the background velocity is around the fan, the less impulse can be transferred to the air streaming by the fan. Due to the Coanda-Effect the actual air velocity around the down-stream jet fans is higher than it would be in a free field. The different airflow profile with Banana Jet means a slightly smaller correction factor is required. Measurements in various tunnels have shown a difference in airspeed around the fans of 10 – 20 %. A 3 – 5 % reduction in losses can be expected, more if the fans have to be spaced closely together. (< 100 m between the fans)

1.3. Impulse losses

10 – 20 % of total the thrust generated by traditional jet fans is lost right behind the fans as part of the air jet hits the surface the fans are mounted on with a high velocity (Fig. 2) due to friction and impulse losses.

![Figure 2: Impulse and friction losses behind a traditional jet fan](image2)
By bending the flow away from the surface this loss can be virtually eliminated. Since the losses are a fixed factor of the overall losses in the tunnel, so at least the above mentioned 10 – 20% can always be avoided by using Banana Jet.

### 1.4. Losses in corners, niches and other installations

Fans are generally hung outside the traffic area, typically in corners or niches of the tunnel. The same space is also used for lamps, road signs and other installations. Because the jet from a Banana Jet can be flexibly directed, the losses can be reduced, especially in corners and niches. (Fig. 3) Also, the jet can help to overcome losses from bends, changes in diameter etc. The actual design of the tunnel must be analysed to estimate the improvement that can be achieved.

![Figure 3: Banana Jet mounted in corners or niches](image)

### 2. MEASUREMENTS

#### 2.1. Introduction phase of Banana Jet Technology

Banana Jet has been tested in 3 tunnels, 2 of which were measured by an independent Swiss engineering company. For comparison purposes, the Banana Jet was converted into traditional jet fans by means of transition pieces removing the bend of the silencers. The air speeds have been taken on a defined grid in each tunnel for the traditional jet fan version and the Banana Jet. As can be seen from Fig. 4, the measurements confirm the expected results.

<table>
<thead>
<tr>
<th>Location</th>
<th>Airspeed in m/s</th>
<th>Total loss in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collombey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trad. Jet Fan</td>
<td>3,7</td>
<td>100%</td>
</tr>
<tr>
<td>Banana Jet</td>
<td>5,6</td>
<td>70%</td>
</tr>
<tr>
<td>Uznaberg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trad. Jet Fan</td>
<td>6,4</td>
<td>100%</td>
</tr>
<tr>
<td>Banana Jet</td>
<td>7,3</td>
<td>68%</td>
</tr>
<tr>
<td>Krohnstieg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trad. Jet Fan</td>
<td>2,8</td>
<td>100%</td>
</tr>
<tr>
<td>Banana Jet</td>
<td>3,3</td>
<td>74%</td>
</tr>
</tbody>
</table>

![Figure 4: Comparison of measured airspeed in the tunnel](image)
The Banana Jet produced a significantly higher airspeed in the tunnel. This is equal to a reduction in total losses of 24 – 32 % (i.e. an increase in thrust of 32 – 47 %)

In all 3 tunnels further reduction in losses seemed possible if the orientation of the jet had been further exploited e.g. by better countering the effect from bends, walls, lamps, etc.

2.2. Bypass Schmerikon
(Tunnel Uznaberg/ Balmenrain)

<table>
<thead>
<tr>
<th>Location:</th>
<th>Switzerland, Kanton St. Gallen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length:</td>
<td>1 x 1318 m + 2 x 940 m</td>
</tr>
<tr>
<td>Traffic:</td>
<td>bi-directional + unidirectional</td>
</tr>
<tr>
<td>Realised:</td>
<td>2003</td>
</tr>
<tr>
<td>Tests:</td>
<td>Banana effect proven by independent measurements</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: Values and measurements Bypass Schmerikon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of fans</td>
</tr>
<tr>
<td>Thrust per fan</td>
</tr>
<tr>
<td>Installed thrust</td>
</tr>
<tr>
<td>P electric per fan</td>
</tr>
<tr>
<td>P electric total</td>
</tr>
</tbody>
</table>

By adding of the bent silencers the measurements gave the prove that the required air speeds could be achieved with lower installed thrust.

In a comparative 6x6 grid measurement in the Uznaberg west bore acc.to Log-Tschebyscheff-procedure\(^1\), the air speed for the traditional jet fan was 6.14 m s\(^{-1}\). The bent silencer version created an air speed of 7.45 m s\(^{-1}\). This results in an increase of 21,3% air speed and 47% effective thrust in the tunnel. Measured data for all cross sections are available.

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\(^1\) P. Pospisil, (2002), Hauptstrasse T8/A8, Tunnels Balmenrain und Uznaberg; Vorgaben an die Steuerung der Tunnellüftung; 87-95-08. HBI. Zurich
To give a more detailed view on the flow results a chart with the results of the grid measurement is given in figures 6 and 7. The grid diagram show the measured air speeds that had been taken 20m, 40m, 60m and 120m behind the fan group.

The measurements have been performed with a anemometer of type Schiltknecht. The resulting error of measurement is a combination of measurement and reading failures. An analysis of the components of failures resulted in a total margin of +/- 19%.

Figure 6: Air speed profile across the tunnel cross section of Uznaberg West tunnel Banana Jet

Figure 7: Air speed profile across the tunnel cross section of Uznaberg West tunnel Traditional Jet Fan

The measured air speeds in the tunnel show the effects of the above described principles. With the traditional jet fans the air speed along the walls and the ceiling with their frictions is a lot higher than with the Banana Jet. Even at 120m an air speed minimum is in the middle of the tunnel. In case of the Banana Jet the air speed peaks are directed to the upper half of the tunnel cross section. This results in lower friction losses.

3. CFD SIMULATION

A CFD simulation project was started to create an accurate simulation model in order to calculate realistic air flow values for tunnels in planning phase. In the first stage of the simulation project the air speed and the effective thrust in the tunnel have been compared for traditional and Banana jet fans installed in the tunnel centre or in the corner of the tunnel.

A 630mm jet fan with 21 m s\(^{-1}\) outlet velocity was used as the reference fan in a 100 m long, rectangular, empty tunnel segment.
3.1. Installation in the centre of the tunnel ceiling

![Figure 8: Case 1:]
Traditional jet fan, located centre of tunnel, 100m tunnel length, $v_T$ outlet = 21 m s$^{-1}$

![Figure 9: Case 2:]
Banana Jet fan, located centre of tunnel, 100m tunnel length, $v_B$ outlet = 21 m s$^{-1}$
Result: Average air speed $v_B = 2.81$ m s$^{-1}$ $v_T = 2.49$ m s$^{-1}$ $\Rightarrow v_B = 1.13 v_T$. The simulated thrust increase is approx. 27%

3.2. Installation in the corner of the tunnel ceiling

![Figure 10: Case 3:]
Traditional fan, located centre of tunnel, 55m tunnel length, $v_B$ outlet = 21 m s$^{-1}$

![Figure 11: Case 4:]
Banana Jet fan, located centre of tunnel, 55m tunnel length, $v_B$ outlet = 21 m s$^{-1}$
Result: Average speed $v_B = 2.61$ m s$^{-1}$ $v_T = 2.09$ m s$^{-1}$ $\Rightarrow v_B = 1.24 v_T$. The simulated thrust increase is approx. 53%

3.3. Forecast
The project is still running for different tunnel cross sections (round and rectangular), for jet fans with different static thrust and for different installation positions (centre, corner and niches). The results will be presented in later publications.
4. REFERENCES

4.1. Krohnstieg Tunnel
Location: Germany, Hamburg
Length: 420 m
Cross section: rectangular
Traffic: bi-directional + unidirectional
Realised: 1998
Tests: Comparative measurements with standard and Banana Jets

By adding of the bent silencers the air speed could be increased from 2.8 m s\(^{-1}\) to 3.3 m s\(^{-1}\). These air speeds result in an effective thrust increase of 35%.

4.2. Tunnel Aubing
Location: Germany, Munich
Length: 2 x 1950 m
Cross section: rectangular
Traffic: unidirectional
Tests: Onsite performance test of the Banana Jet performed by independent body

By replacing 2x30 standard fans by 2x24 Banana Jets the specified air speed of 2.92 m s\(^{-1}\) was exceeded to 3.28 and 3.59 m s\(^{-1}\).

4.3. Banana Jet projects
The Banana Jet has been installed in tunnels all over the world, e.g. in the following countries:

- Australia
- Austria
- Chile
- France
- Germany
- Norway
- Portugal
- Russia
- Switzerland
- Spain
- UAE
- UK
- Venezuela
- …
5. ENVIRONMENTAL AND ECONOMIC IMPLICATIONS

A reduction in the thrust required to move the air in a tunnel has dramatic consequences for the general contractor and also the end user / tunnel operator.

- Fewer (or smaller) fans are required, proportional to the reduction in thrust required.
- Less cabling (or smaller cable cross sections) necessary. Often the total cabling cost incl. installation is more than the price of the fans.
- Less energy consumption, CO₂ production, operating cost, proportional to the reduction in thrust achieved.
- Fewer (or smaller) niches can be built.
- More flexibility in the choice of the fan locations.
- Ability to increase the volume flow rate in old tunnels by 10 – 20 %, without changing the cabling and power supply.

The effect that was achieved for the 3 tunnels measured by installing Banana Jet resulted in an overall life cycle costs reduction of 25 – 35 %. The capital costs were so much reduced that the savings were almost as large as the total price of the fans.

6. CONCLUSION

The use of the Banana Jet can reduce the installation and operating cost for longitudinal road tunnel ventilation significantly. An improvement of 25 – 50 % compared to traditional jet fans is realistic.

The improvement is in principle due to an aerodynamic adaptation of the fans to their real purpose. Instead of aligning fans geometrically to the contours of the tunnel, the air flow is directed away from the tunnel walls, thus greatly reducing the losses.

There seem to be no disadvantages from using the Banana Jet. Excessive airspeeds at lower levels can be avoided, just as increased turbulence in potential smoke layers or other secondary effects can be minimized. In addition, a better flow profile, also when there are traffic jams or other obstructions in the tunnel, can more readily be taken into account compared to traditional jet fans. The Banana Jet effectively come “free of charge”, the saving in the electrical installations pay for the remaining fans that need to be installed.