FLUCOME 03 – Sorrento - 25-28 August 2003

7th Int. Symp. on Fluid Control, Measurement and Visualization

From Steady-State to Unsteady Aerodynamics and Aeroacoustics

The Evolution of the Testing Environment in the Pininfarina Wind Tunnel

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Aerodynamic and Aeroacoustic Research Center

The Pininfarina Aerodynamic and Aeroacoustic Center

is a part of the Pininfarina Industries

The group activity includes

- **-Car Design**
- **-Engineering**
- **-Production**

For a total of about 2500 employees

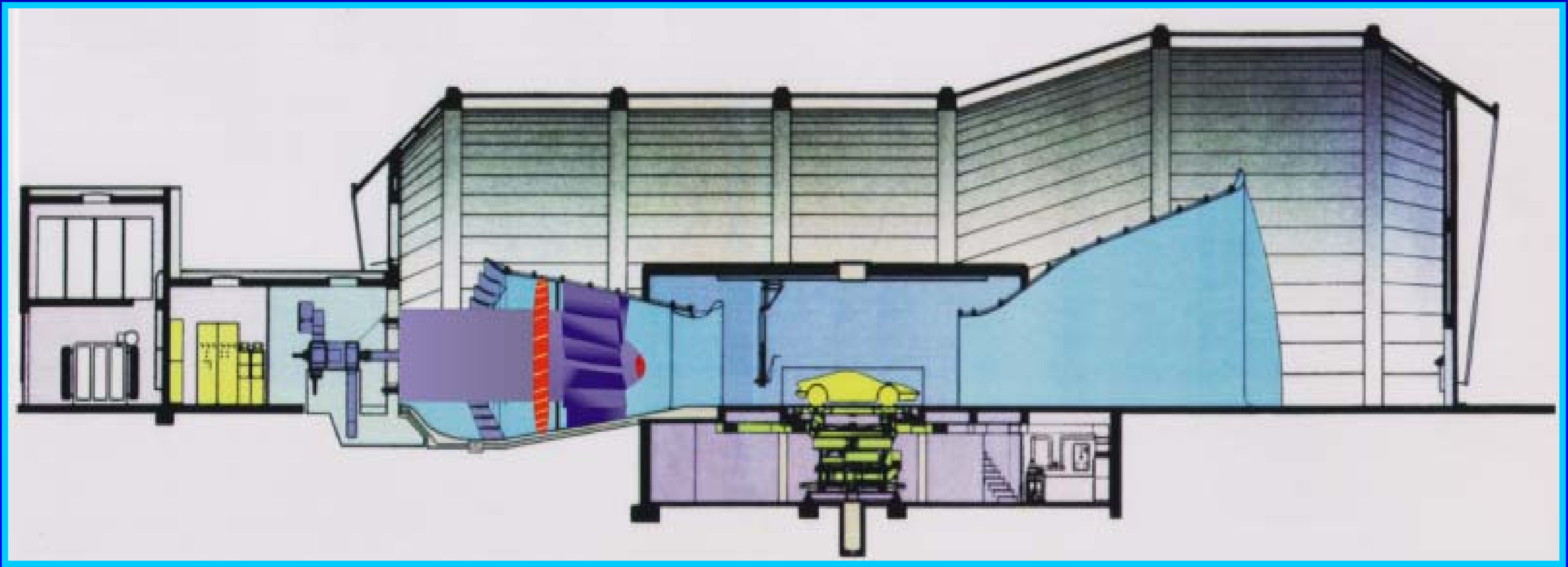
in several facilities

in Italy

Germany

France

The Aero-Center Main Facility is the Automotive Full-Scale Wind Tunnel



Its main Performances are (year 2003) :

- Jet Section = 11 m^2
- Max Wind Velocity = 202 Km/h
- Background Noise Level = 71 dBA at 100 Km/h

Aerodynamics and Aeroacoustics

Main Interest of Car Companies is to bring indoor the most of the testing activities regarding the development of the new car models.

Wind tunnels were and are built to reproduce and simulate as much as possible, the aerodynamic and aeroacoustic condition that a car finds on the road.

However the automotive wind tunnels of '1st generation' have several points of 'weakness':

1 - High ambient noise (usually due to the fan noise)

2 - Tests made in condition of fixed ground & static wheels

3 - Low turbulence flow (see explanation later…)

The Pininfarina Wind Tunnel was built in 1972.

At that time it was common place:

- **To test cars in condition of ‘fixed ground & static wheels’**
- **Aeroacoustics was not yet taken in due consideration**

(the w.t. was quite noisy)

A 1st important improvement was made in 1985.

The ambient noise was reduced by:

- -A new, more silent, fan–drive system
- -An acoustic treatment of the plenum

For the 1st time, we were able to measure the car aero-noise although in presence of a still important fan noise

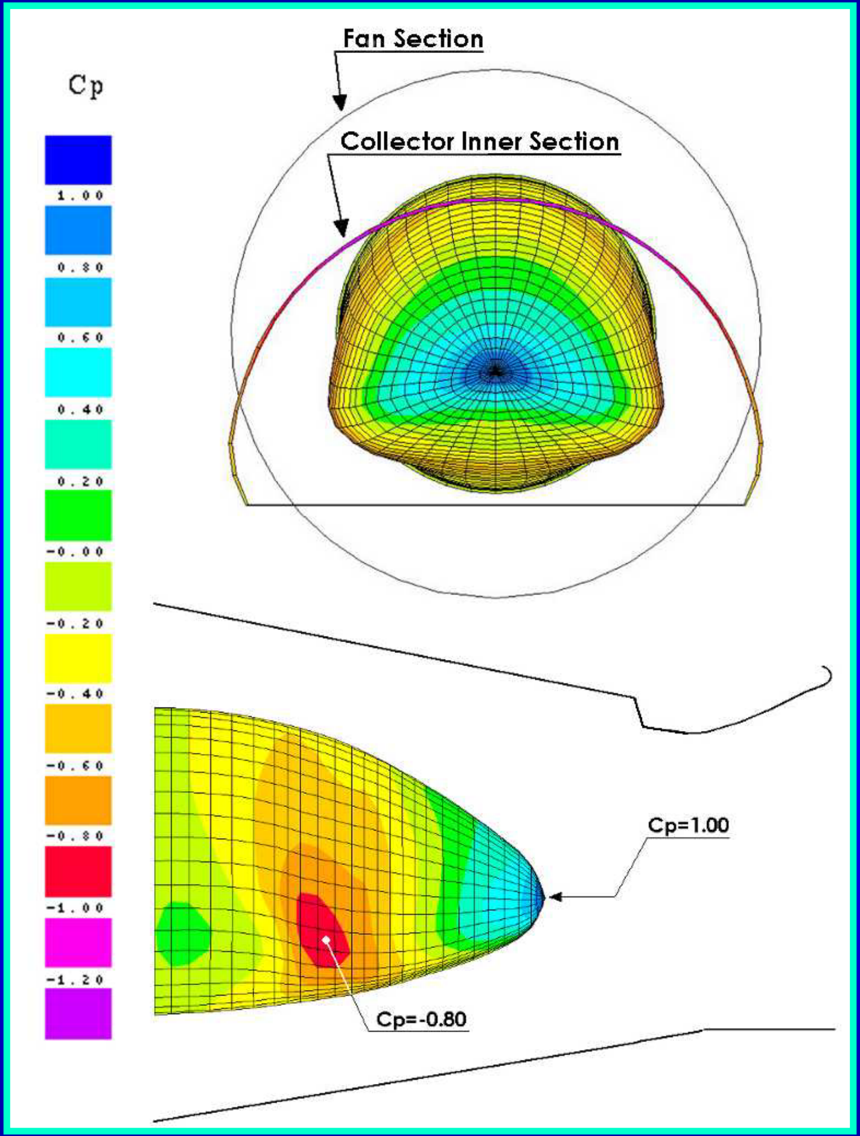
1985 - new 2nd fan–drive system

plenum - acoustic treatment

1996 – 1999…. on Aeroacoustics today

1996 – New (3rd) low-noise fan-drive system
29 blades, low rpm, new nose-cone

New Nose-Cone Front & Side View



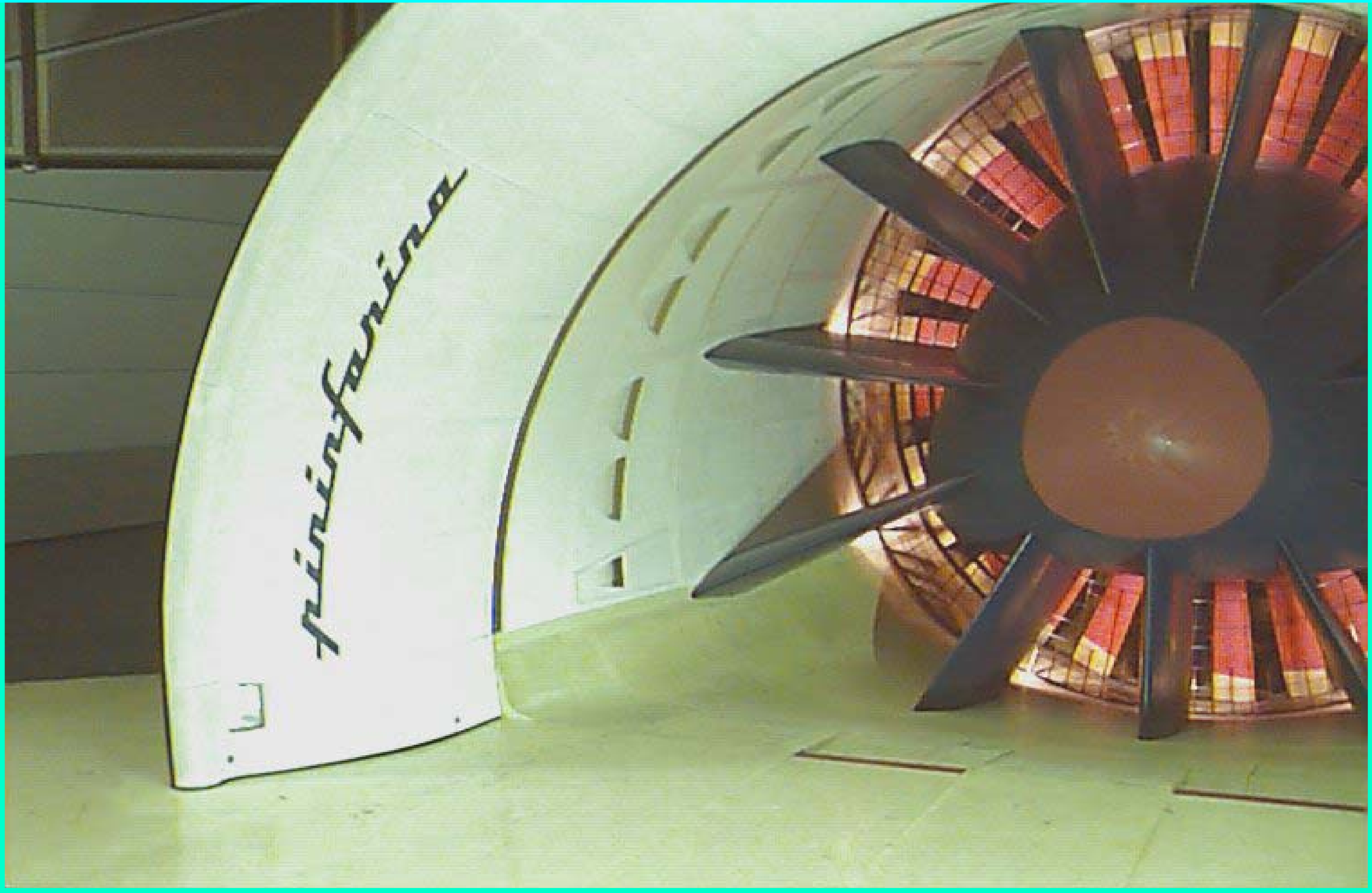
The new Nose-Cone is:

- **Aerodynamically shaped**
- **Acoustically treated**

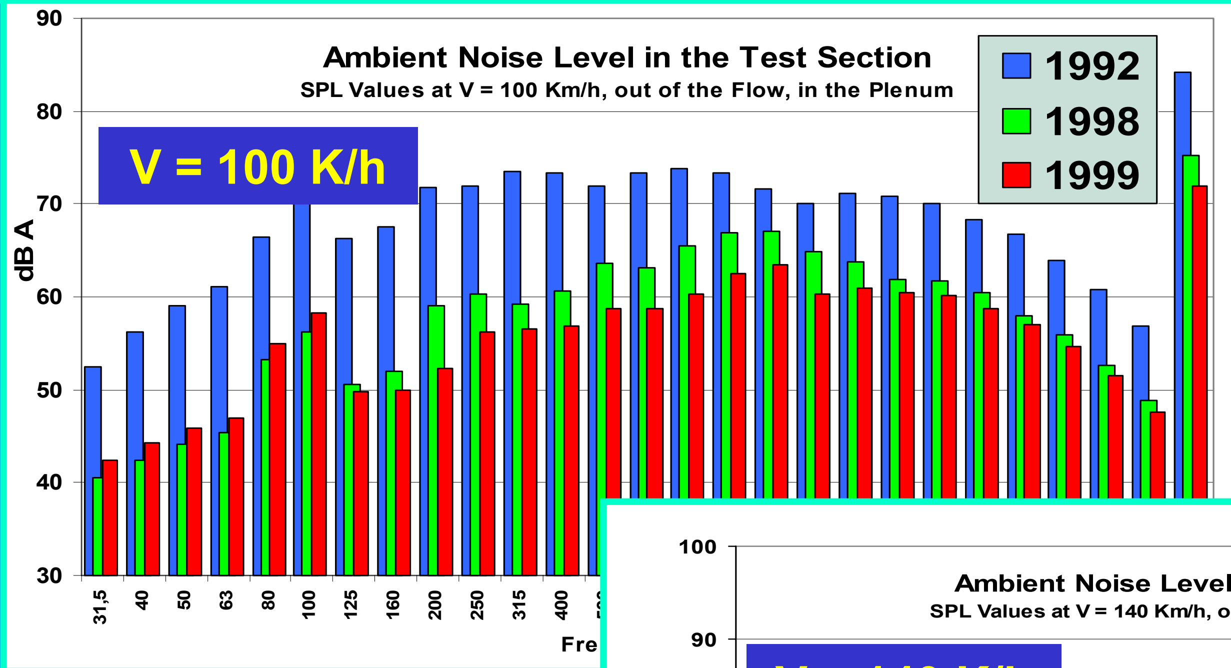
In color:

Static pressures on the nose-cone surface

1999 – New - Sound Absorbing Collector & Diffuser,
- Sound Absorbing Guide Vanes in front of the fan,
- Naca breathers



Ambient Noise reduction at the end of the modifications



Noise Levels SPL

- up to <u>20 dB lower</u>

(at low freq)

- about <u>10 dB lower</u>

(at mid-high freq)

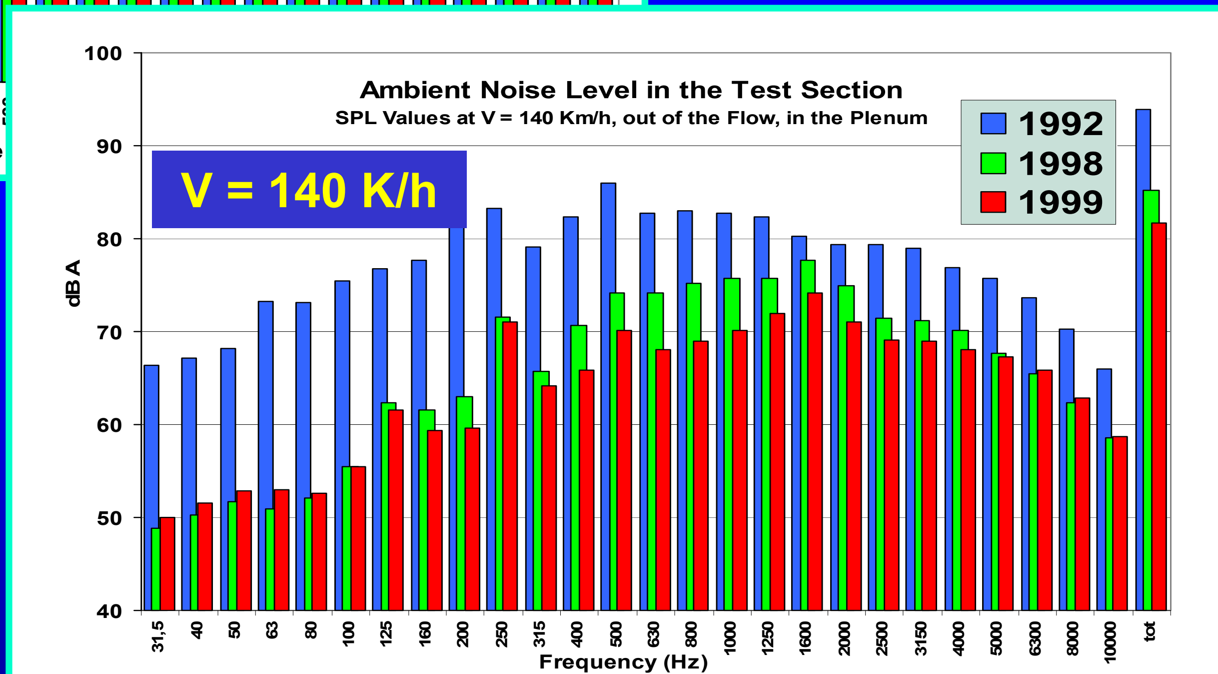
Interior & exterior

<u>Car noise</u>

is now <u>easily measurable</u>

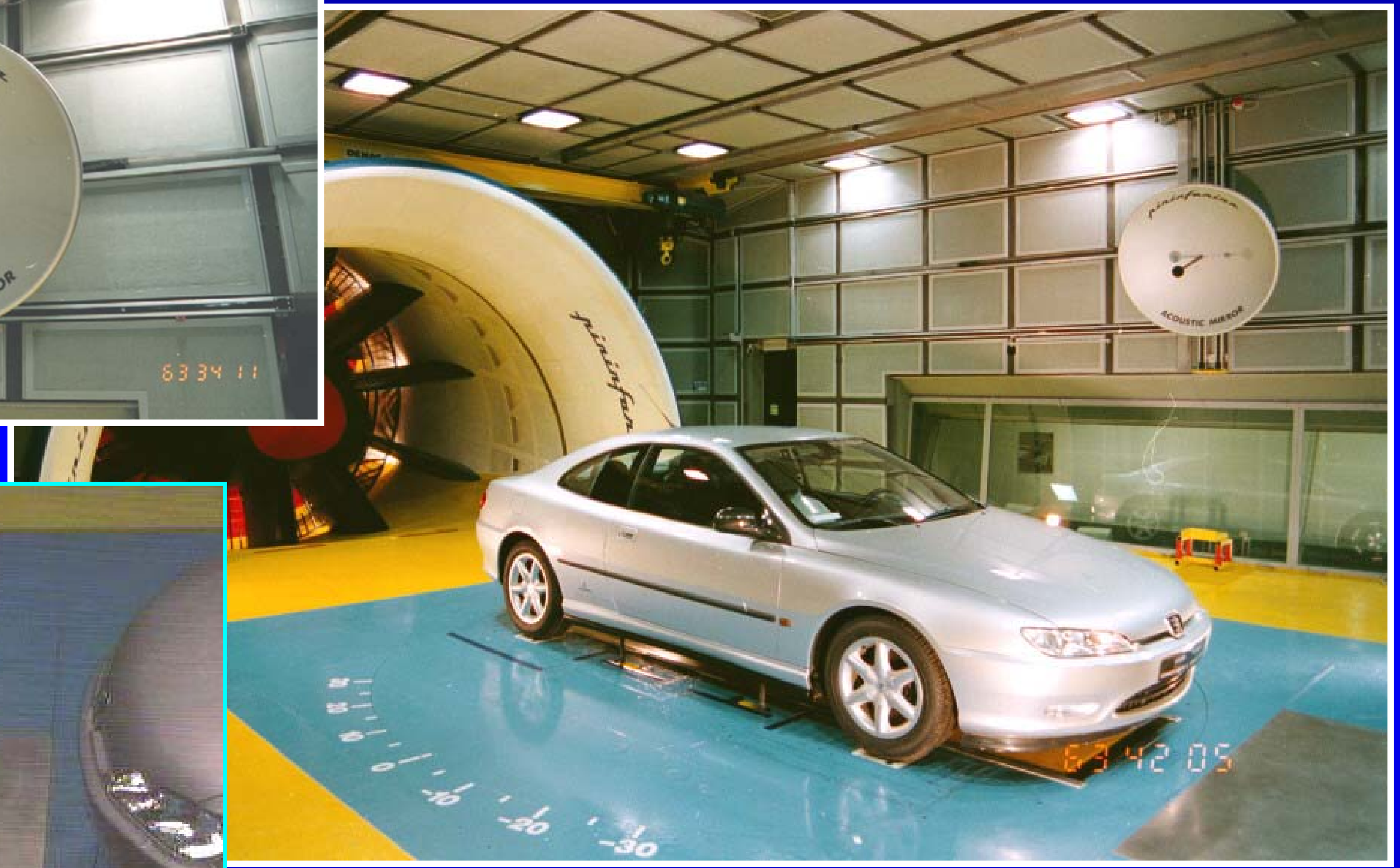
with various techniques.

… see later



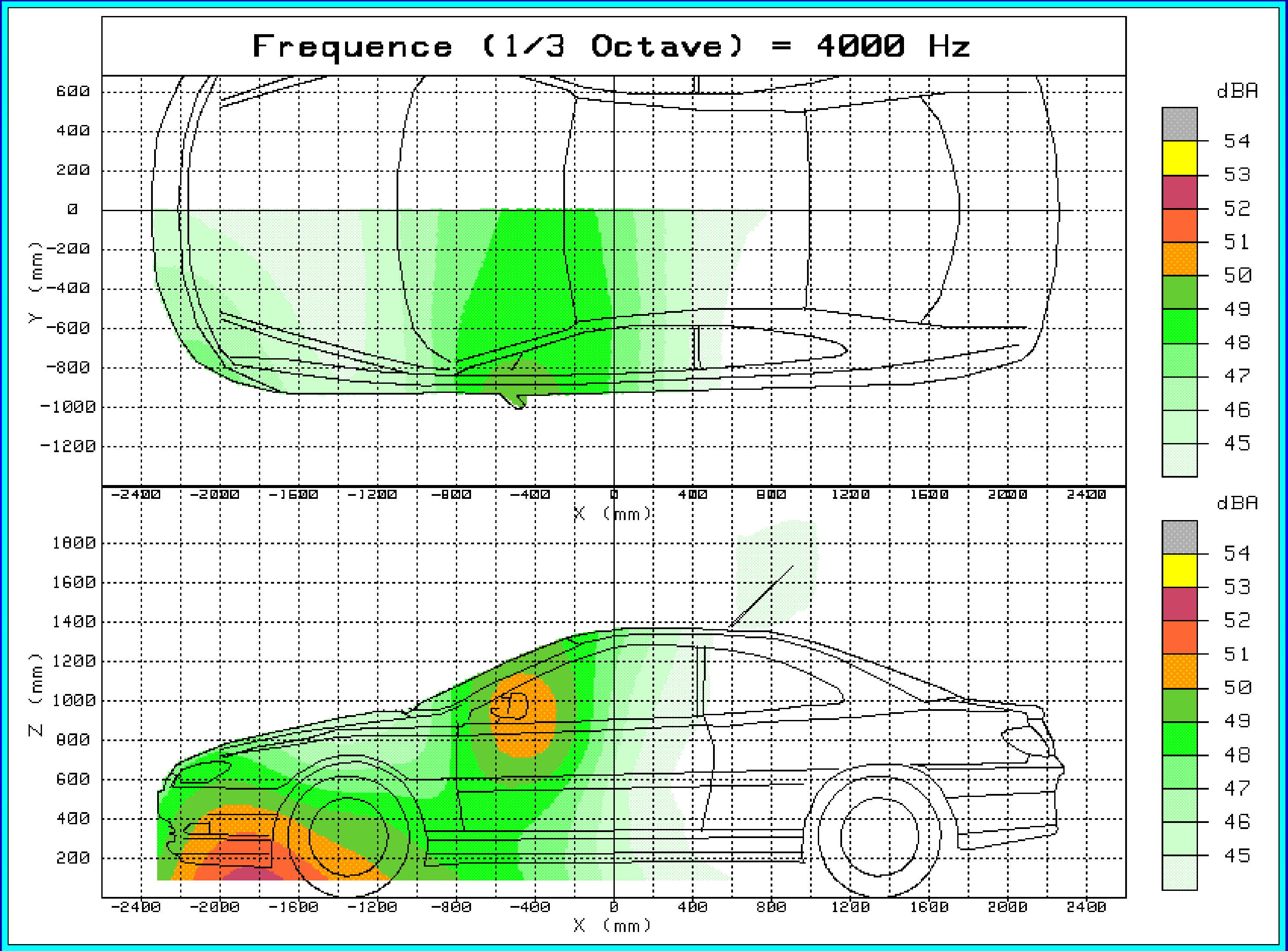
Main Technique to Measure noise inside the Car

Acoustic Mirror to Measure Noise outside the Car



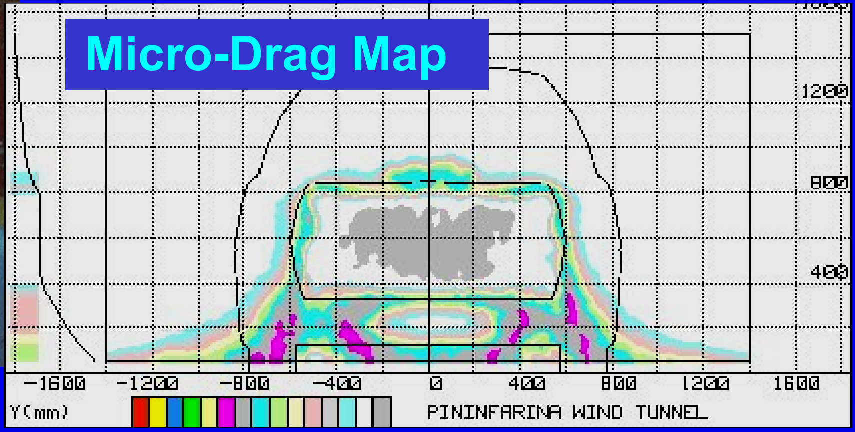
Ellipsoid Acoustic Mirror and its Traversing System on the Test Section Wall

Example of the acoustic sources found by the acoustic mirror



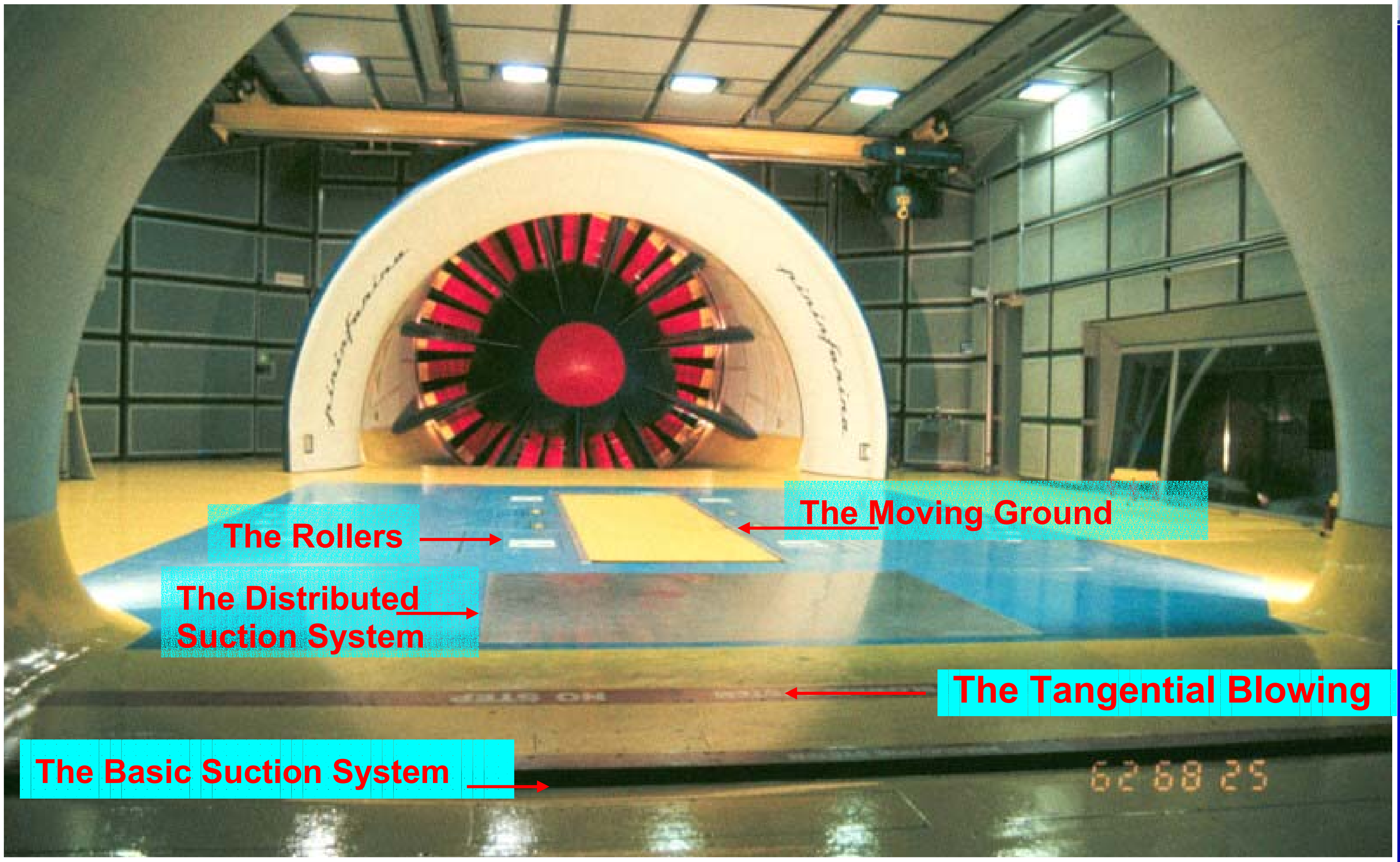
The 2nd point of weakness “ fixed ground & static wheels”
became evident in 1990
during the development of the CNR low-drag model (see pictures)

Most of the Drag
was in the underbody area
where the flow was wrong



It was fixed in 1995 by building a “Ground Effect Simulation System”
of New Design (Narrow Belt + Rollers + Tangential Blowing + B.L. suction)
integrated in the turntable and in the balance.

1995 on - The new Ground Effect Simulation System



Narrow Moving Belt and Rollers for Wheel Rotation

Car Lifters integrated into the Balance

Car Lifters

To lift the car in 30”

and change underbody parts

As a result of these important / expensive modifications, i.e.

- the Low-Noise Fan-Drive System and
- the Ground Effect Simulation System (GESS)

the quality of the test environment was greatly improved as well as the level of aerodynamic / aeroacoustic optimization of the new car models

Several proprietary techniques were developed in the meantime to investigate the flow field and give a better understanding of the flow

examples : - the '14-hole' probe technique >>>>
To map the flow outside the cars

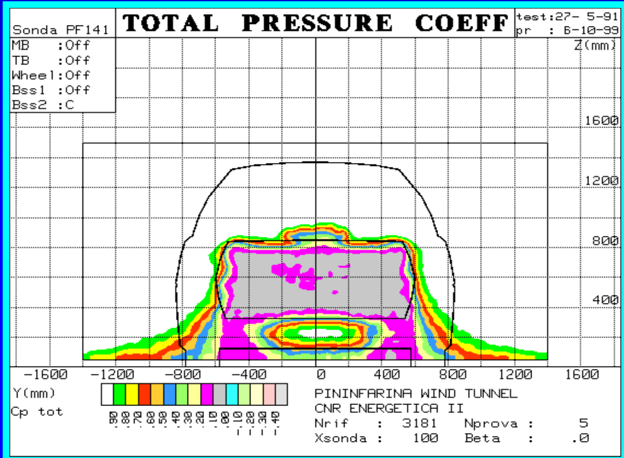
- the '3D-LDV'

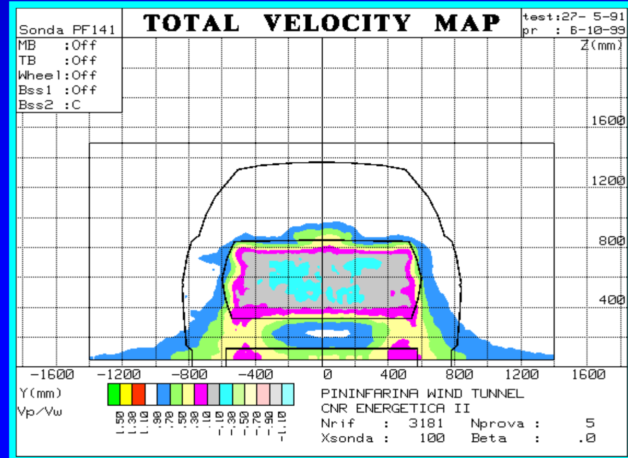
- the 'Test Radiator ' etc…

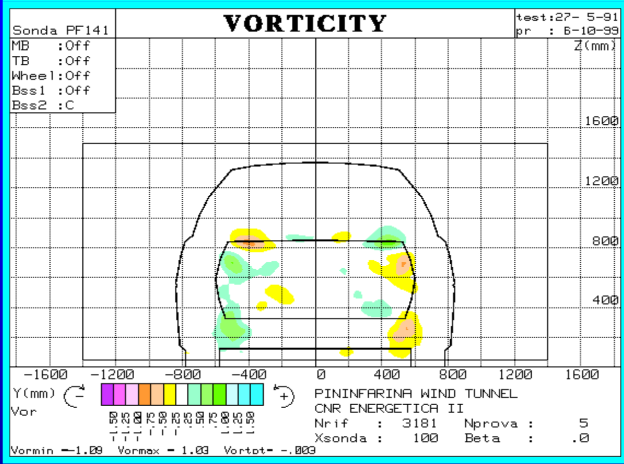
’14-hole’ probe technique

Example of Flow Field Survey made with a ‘14-Hole’ Probe

Technique developed by Pininfarina to measure local Pressures and Velocities in the Flow Field of a Car







CNR ENERGETICA II

FLOW MAPS
X = 100 mm
BEHIND THE CAR

Advantage:

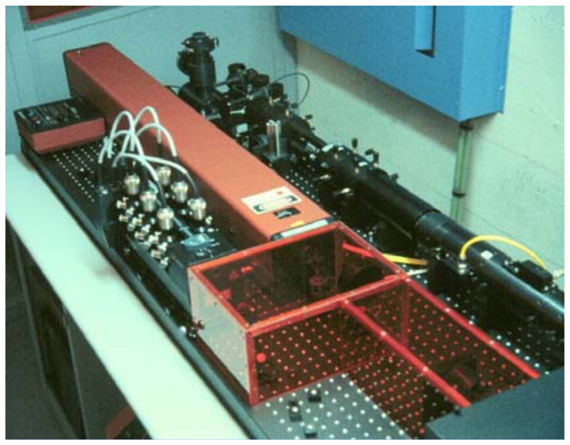
Very fast … about 30’ to produce a full set of maps on a 1.8*3.0 m area

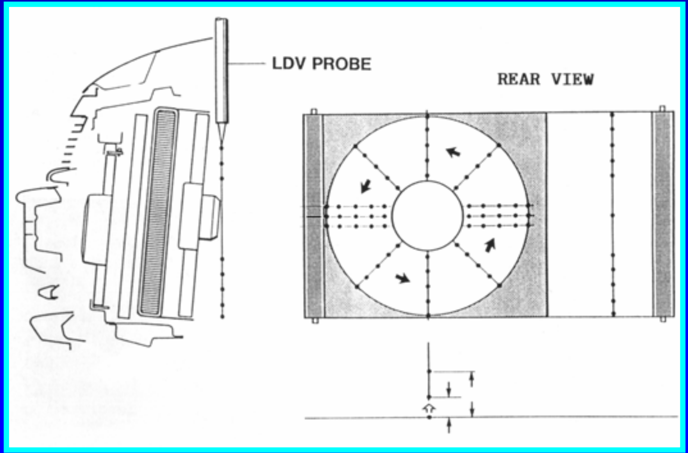
Limitation:

Only time-averaged values

3D-LDV Fiber-Optic technique >> measurement behind a Rotating Fan

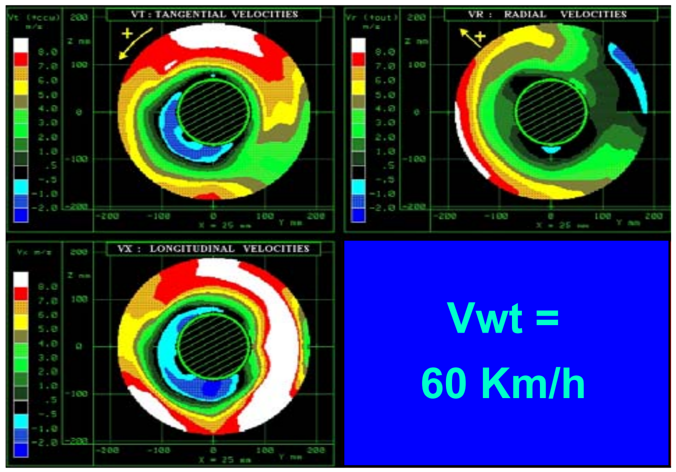
Example of LDV Meas. within a Vectra Engine Bay





Advantage:

- Accurate
- Good for difficult flows



Vwt =
60 Km/h

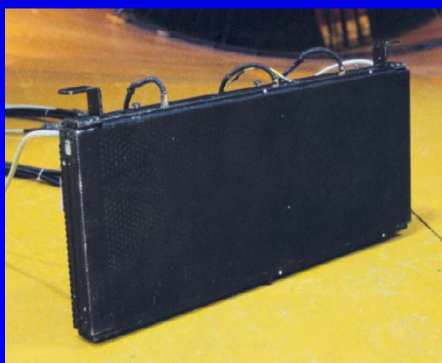
Limitation:

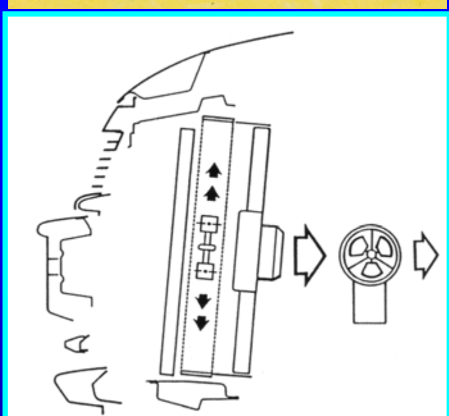
One point at a time
i.e. slow

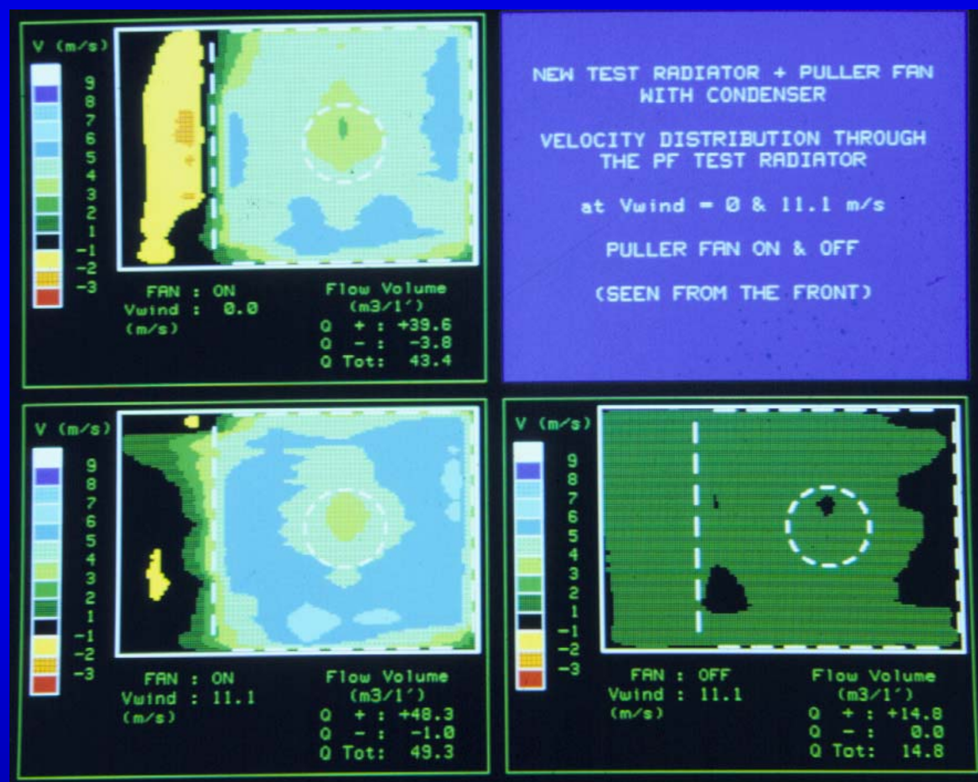
The 'Test Radiator' technique

Developed by Pininfarina to measure the Radiator Cooling Flow , i.e.:

- **the flow volume and the velocity distribution through the radiator**
- **the change of CD , CLift etc for every radiator configuration change**







Advantage:

Very fast … about 2' to produce a velocity map

Limitation:

Only time-averaged values

In principle all these techniques are more than enough to make a good car development work

However, a 3rd point of 'weakness' still remains in our w.t. simulation ….

- The wind tunnel flow has a pretty low turbulence intensity (0.3 %)
- The Turbulence Length Scale is very small, close to 'zero'
- The flow field is usually regarded as 'steady-state'
- The most of measurements are 'time-averaged'

Real life (the "Road"), is different, is not 'steady-state':

And our final target must be the simulation of the "Road"

…. that means:

- a Flow often Turbulent / Unsteady
- a Turbulence Intensity and Scale Lenght often large
- Aerodynamic & Aeroacoustic Data often Time-Dependent

…. that means … the need of new advanced measuring techniques

That is the new "Challenge" , for full-scale car testing

i.e. to go from 'time-averaged' measurements in a low turbulence flow,

to 'time–dependent' measurements in high turbulence/unsteady flows

To discuss and understand problems associated to car 'unsteady flows'

- a W.G. named 'Unsteady Aerodynamics' was formed in 1999 within ECARA (European Car Aerodynamic Research Association)
- Several types of flow unsteadiness were defined
  - Some of them may depend on the car geometry
  - Some others are dependent on the turbulence that a car finds on the road, due to ambient wind or the traffic.
- Both have aerodynamic and aeroacoustic effects
- New experimental or numerical techniques are needed to produce time-resolved results

This W.G. meets 1 or 2 times per year.

Some examples of unsteady flows typical of cars:

- Unsteady car wake .. Cd and CLift change in the time i.e. Stability issue
- Aeroacoustics .. The noise perceived inside the car is different if the incoming flow is turbulent i.e. Comfort issue
- Sun Roofs .. Booming at Low Velocity i.e. Comfort issue
- Soft Tops – Open .. Velocity Fluctuation (Buffeting) around the passenger's heads i.e. Comfort issue
- Soiling of the backlight (tested with moving ground and rotating wheels) i.e. Visibility / Safety issue
- Recirculation of exhaust gases into the passenger compartment i.e. Safety issue

All these aspects may become more important or different in presence of a turbulent flow

Examples of unsteady flows at the car rear end

Y = exhaust-pipe…
recirculation of exhaust gases

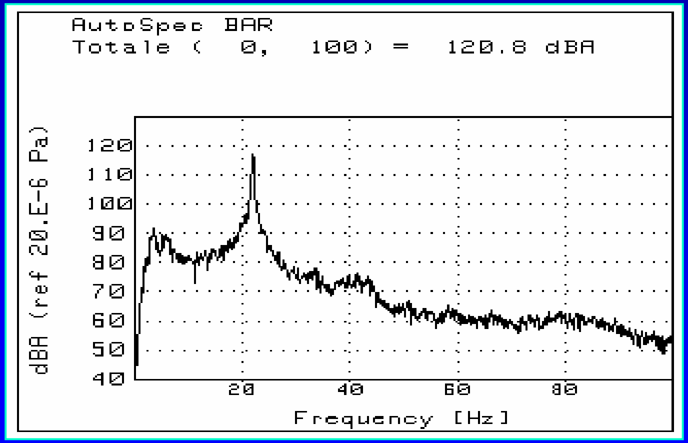
Y = 0 = center line
Example of **backlight soiling**

Visualisation by smoke and laser light sheet

V wt = 60 Km/h **GESS ON**

Sun Roof: Booming at Low Velocity

1- Measure of SPL (dBA) by Acoustic Heads



2- Flow Visualisation by Strobo Light

That is why

Pininfarina started 3 years ago a research program , aimed at:

1. To define which type of turbulent flow has to be simulated in the wind tunnel;

2. To design and build a 'Turbulence Generation System' that can produce a flow of controlled turbulence intensity and length scale, close to that defined at point 1;

3. To develop / setup new Measuring Techniques to investigate the various aspects that are specific of Unsteady Flows.

Key points from previous papers / presentations:

(Ecara UA4 - Torino, FKFS - Stuttgart, SAE 2003 - Detroit)

1a - According to previous works

(by J.Saunders, K.Cooper, J.Howell, S. Watkins etc.. …),

It can be stated that :

- the most of the time, vehicles are moving in a turbulent flow.
- the turbulence on the road is due to 2 main sources:
  - a - Ambient wind, often in presence of roadside obstacles
  - b - Other vehicles running on the road
  - c - A combination of ‘a’ and ‘b’

The work that is now in progress at Pininfarina
deals with point ‘a’, i.e. the simulation of the ‘ambient wind’

2.1 - Simulation in the wind tunnel of the flow turbulence on the road – Key Points.

it is important to remember that

• Aerodynamics of Passenger cars depends on:

- the flow conditions very close to the ground , from h = 0 to 1 ÷ 2 m max (the car stagnation point is typically at h ~ 0.5 m).
- the presence of road side obstacles
- for 95 ~ 98% of the driving time, the wind is ‘ low wind ‘ (3-5 m/s).

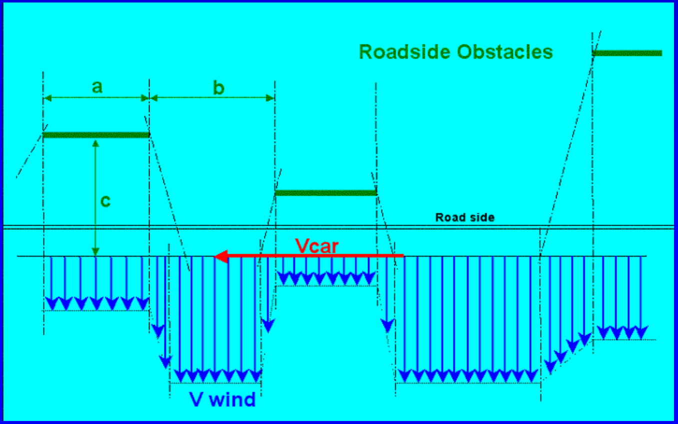
These turbulent flows are statistically the most common / important

• The ambient wind has to be combined with the car velocity, to find out the resultant velocity, its turbulence intensity, the turbulence components etc.

Following the data reported in the literature, and mainly

- data measured by JS & SW & others
  on vehicles moving on the road, in a low wind environment
- a numerical simulation of road side obstacles
  (by SW in 95 and recently by PF)

they increase the turbulence lateral intensity



The conclusion was:

The flow to be reproduced in the wind tunnel should fall – statistically- within these ranges.

- Total Turbulence Intensity in the range of I = 2÷7%;
  - I_v / I_u in the range of 0.7 ÷ 4
  - Iu in the range of 2 ÷ 6 %
  - Iv in the range of 2 ÷ 10 %

  (these results are in agreement with JS & SW data)

The ‘Turbulence Generation System’

It is designed to produce a flow of controlled turbulence intensity I and length scale TLS

That is a view
of the 5 prototypes tested in 2002.

It is an <u>active controlled system</u>

That is important to generate
- Iv > Iu
- TLS in the order of 1 m or more

The work started in 1999
The final system was ready
at the end of 2002.

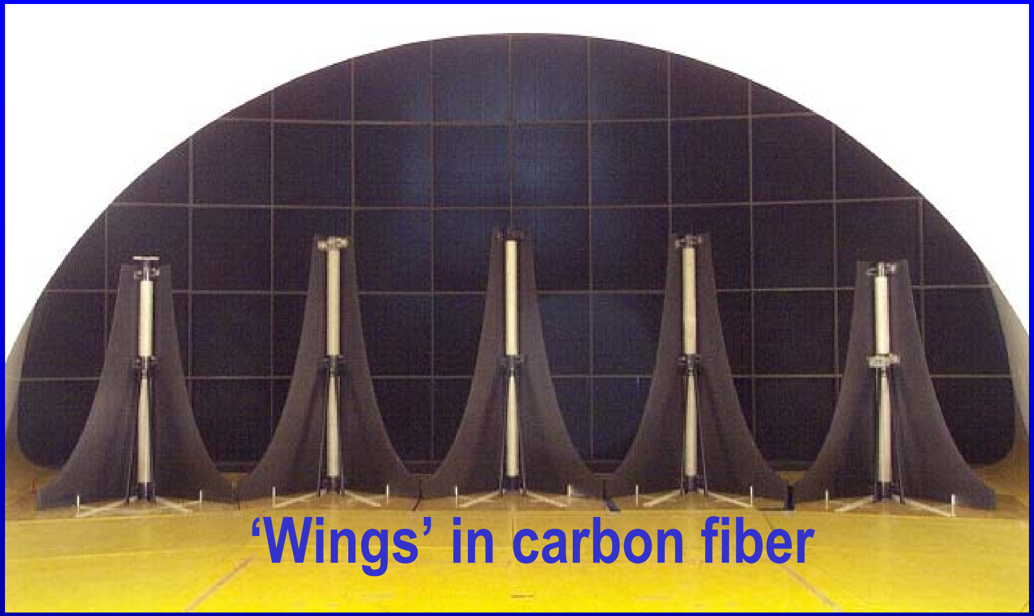
That is the final system (in operation since Jan 2003)

Main Characteristics
(depending on mode of operation)

- Log law of the wall velocity profile, α ~ 0.16 - 0.24
- Turbulence intensity up to 7- 8 % [0.3 ~ 0.7 %]
- Iv / Iu ~ 1.3 – 1.4
- TLS up to 1.0 – 2.0 m

  [< 0.1 m ?]

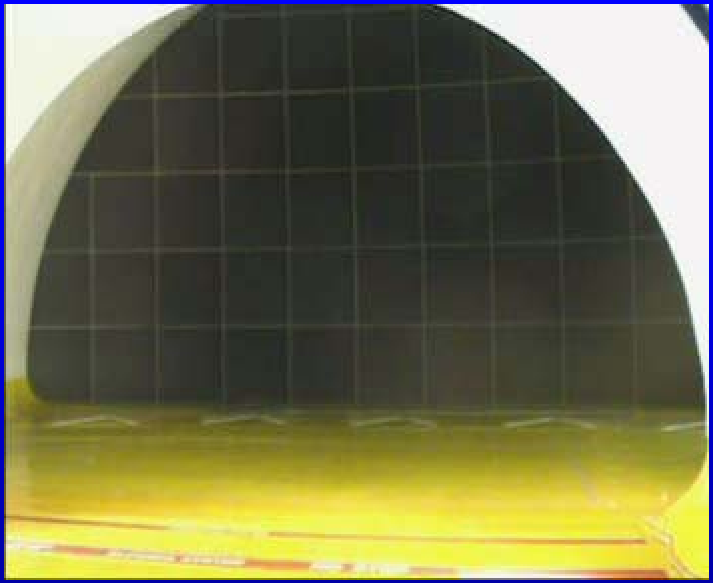
values [ ] = base wind tunnel without T.G.S.



The 5 Turbulence Generators are installed on Lifters:

- They are normally parked under the nozzle
- When needed, they can be raised into the nozzle in a short time (< 1’ 30”) and can be removed in the same short time.

The aim is to use the TGS in addition to the standard tests to check aerodynamics and aeroacoustics of new car models in a turbulent flow during the usual development process .



Possible modes of operation include:

- Fixed wings, at a given angle of aperture
- Wings flapping at constant frequency from < 0.1 up to 1.0 Hz ,
- Wings flapping at a frequency varying continuously from Min to Max in a given Period T following different possible laws, to simulate a 'pseudo–random' behavior.

The 5 Vortex Gen. can be operated in-phase or out-of-phase.

See some examples in the following slides

Examples of wings flapping in different modes (Top View)

0.1 Hz constant - in phase

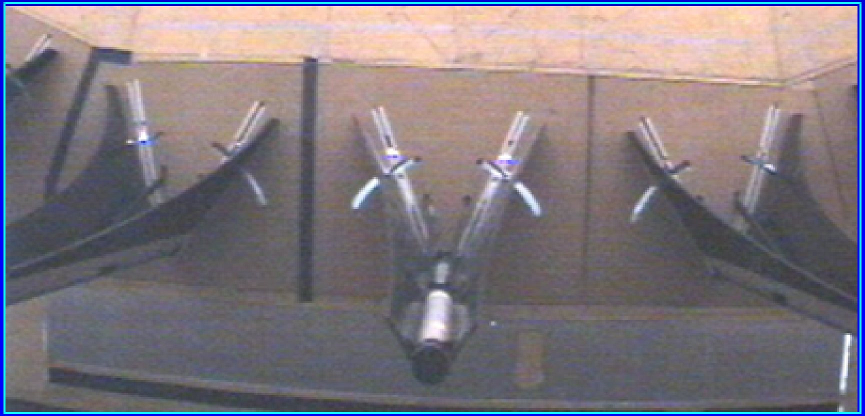
Examples of wings flapping in different modes (Top View)

0.1 Hz constant - in phase

1 Hz constant – in phase

Examples of wings flapping in different modes (Top View)

0.1 Hz constant - in phase



1 Hz constant – in phase

0.10 – 0.75 Hz periodic out-of-phase

(preferred mode … used at present)

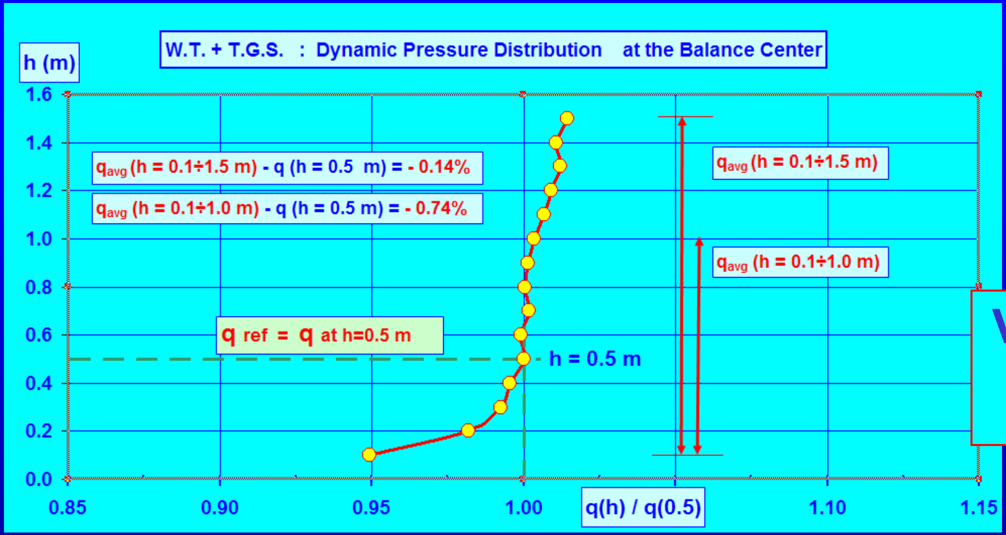
Remark:

a - The **Velocity profile is no longer uniform** ($\alpha = 0.20$)

the **Reference Velocity** or **Dynamic Pressure** to compute the Aero Coeffs. can be either (the choice is a bit arbitrary):

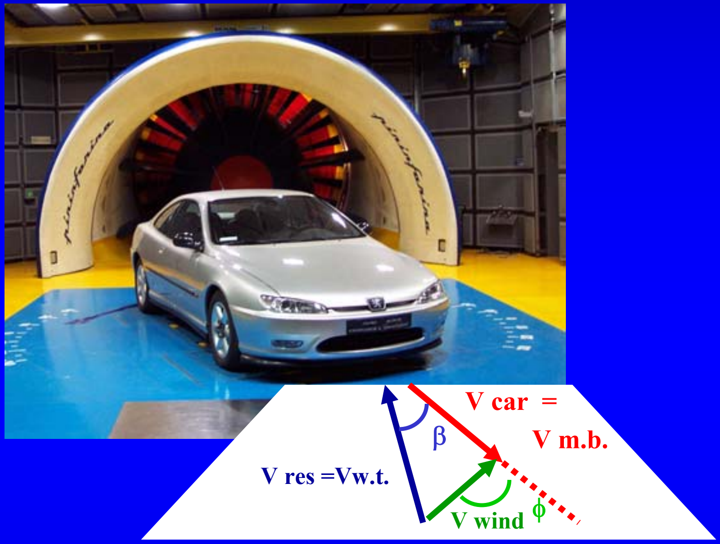
- The **Dyn. Pressure at the height of the stagnation point (at h= 0.5 m)**, or
- The **mean Dyn. Press. between 0 and 1~1.5 m** or …… ?

The difference is **negligible**, whatever reference is taken



Velocity profile and Reference Dynamic Pressure

Tests made up to now in conventional wind tunnels
to simulate the presence of side wind are rather rough,



1 - the wind tunnel wind velocity is kept constant when the car is yawed

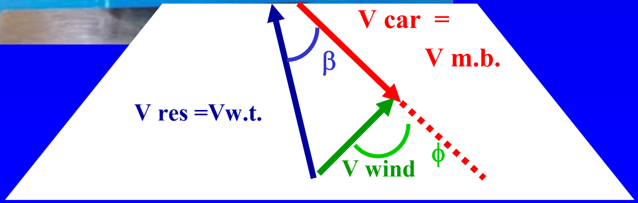
2 - no difference is made between car velocity and wind tunnel velocity

3 - the aero coefficients are referred to a "wind tunnel dynamic pressure" that is supposed to correspond to the car velocity.

In reality we must differentiate between:

Vcar = Car velocity relative to the ground

… given by the Moving Belt velocity



Vwt = Wind tunnel test velocity = Car velocity relative to the flow

… i.e. the resultant of the Car velocity and the Ambient Wind velocity

Today, we can do that !

i.e. we can have a 'wind velocity' > than the 'road velocity'
as it happens on the road.

Aerodynamics – time-averaged values

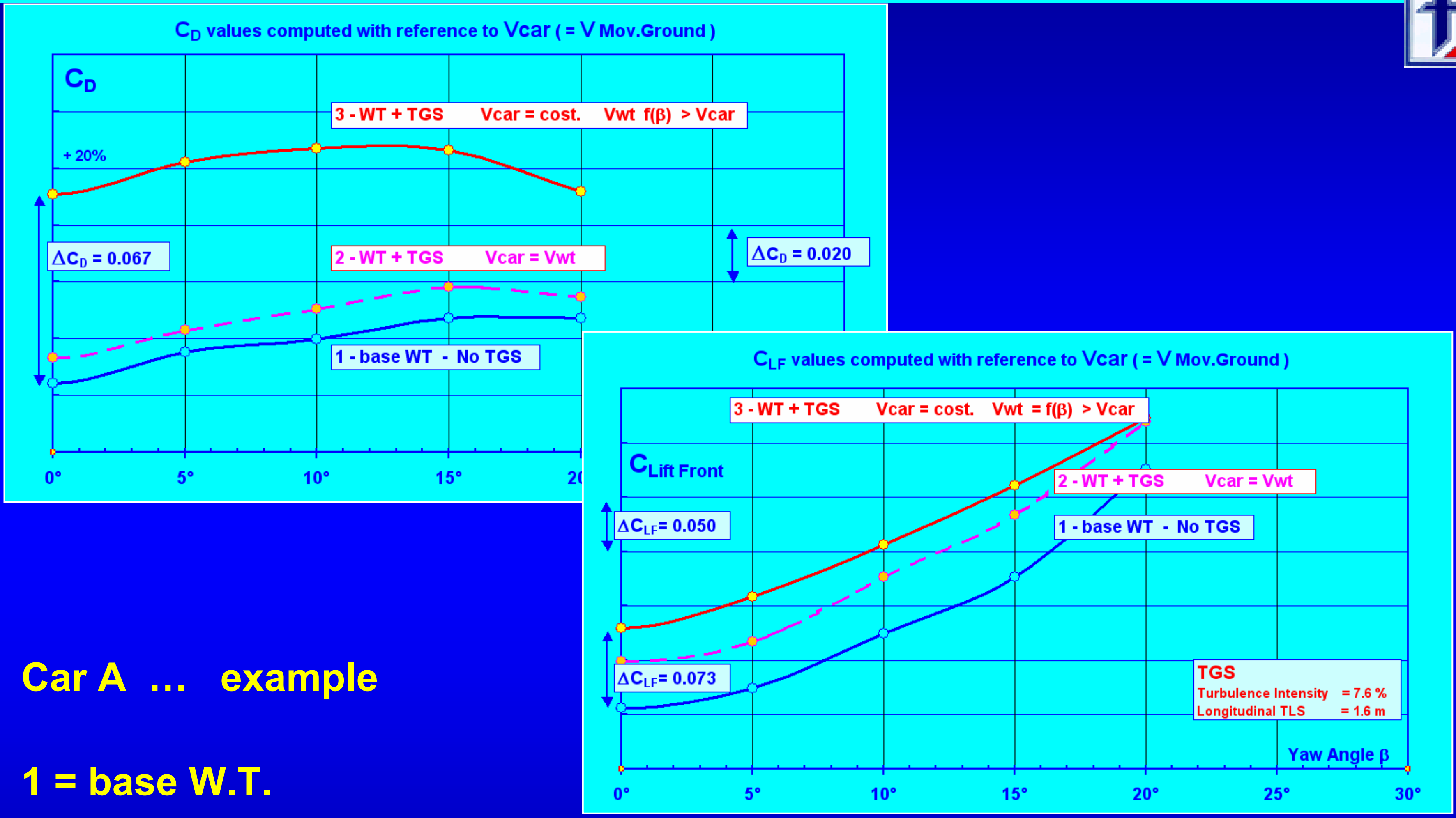
Examples of measurements in 3 different test conditions:

1- in the base Wind Tunnel : Low Turb. Flow
Flow Vel. = Car Vel.
(conventional test condition)

2 - in the W.T. + TGS : Turb. Flow
Flow Vel. = Car Vel.
(to check the effect of the increased turbulence only)

3- in the W.T. + TGS : Turb. Flow
Flow Vel. = Car Vel. + Wind Vel.
(to check the effect of the increased turbulence and wind vel.)
(= Road conditions)

4 Aerodynamics - some results C_D and C_{LF} at Yaw



Car A … example

1 = base W.T.

2 = effect of Turbulence (I + TLS + Vel. Profile)

3 = effect of Turb. + increase of Vel. caused by the Ambient Wind

Aeroacoustics / Psychoacoustics

Examples of measurements in different test conditions:

1- in the base Wind Tunnel : Low Turb. Flow
Flow Vel. = Car Vel.
(conventional test condition)

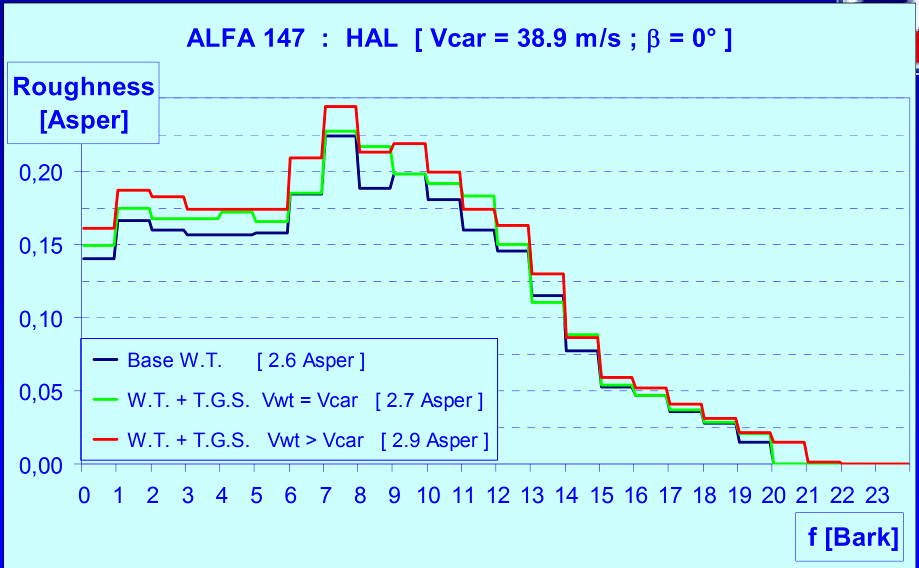
2 - in the W.T. + TGS : Turb. Flow
Flow Vel. = Car Vel.
(to check the effect of the increased turbulence only)

3- in the W.T. + TGS : Turb. Flow
Flow Vel. = Car Vel. + Wind Vel.
(to check the effect of the increased turbulence and wind vel.)
(= Road conditions)

5 Aeroacoustics / Psychoacoustics - some results

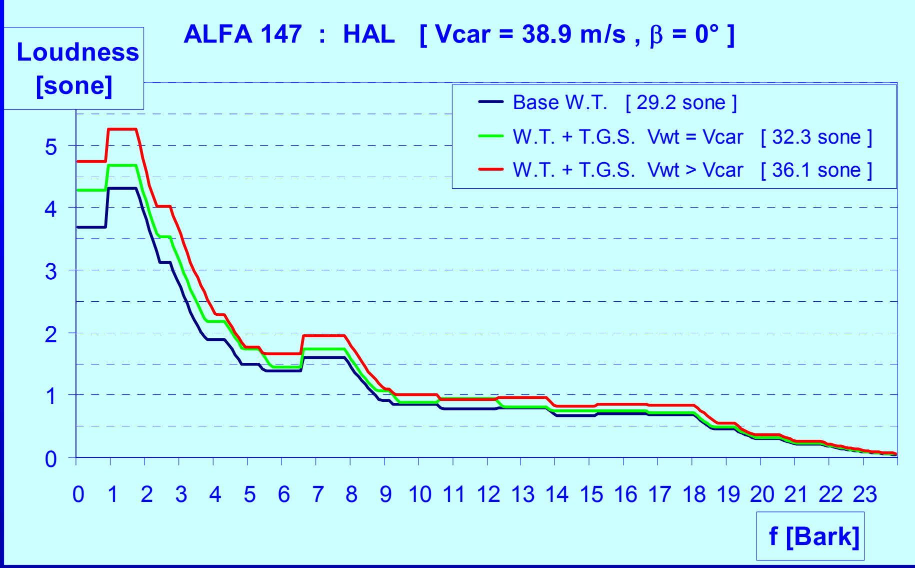
Roughness [Asper] :

Fluctuation of each band,
between 20 and 300 Hz
perceived as tone modification
> the tone sounds " Rough "



Loudness [Sone] :

Perceived Acoustic Level



Comparison of Roughness and Loudness
measured by an "Head Acoustics" :

HAL = Head A (driver side) , Left ear

V_{car} = 38.9 m/s , $\underline{\beta = 0°}$

For 3 different test conditions :

1 - Base W.T. Low Turbulence

2 - W.T. + T.G.S. $V_{wt} = V_{car}$

3 - W.T. + T.G.S. V_{wt} = 42.1 m/s > V_{car}

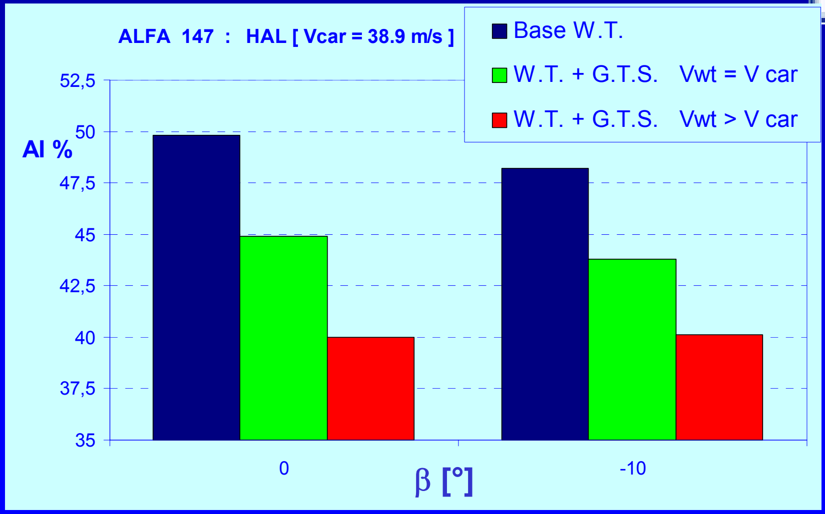
V_{wind} = 3.2 m/s ϕ = 0°

Articulation Index AI [%] :

AI indicates the extent to which a noise reduces intelligibility of speech .

AI → 0 % > communication is difficult

AI → 100 % > communication is not disturbed



HAL = Head A (driver side) , Left ear

V_{car} = 38.9 m/s

For 3 different test conditions :

1 Base W.T. Low Turbulence

2 W.T. + T.G.S. $V_{wt} = V_{car}$

3 W.T. + T.G.S. $V_{wt} > V_{car}$

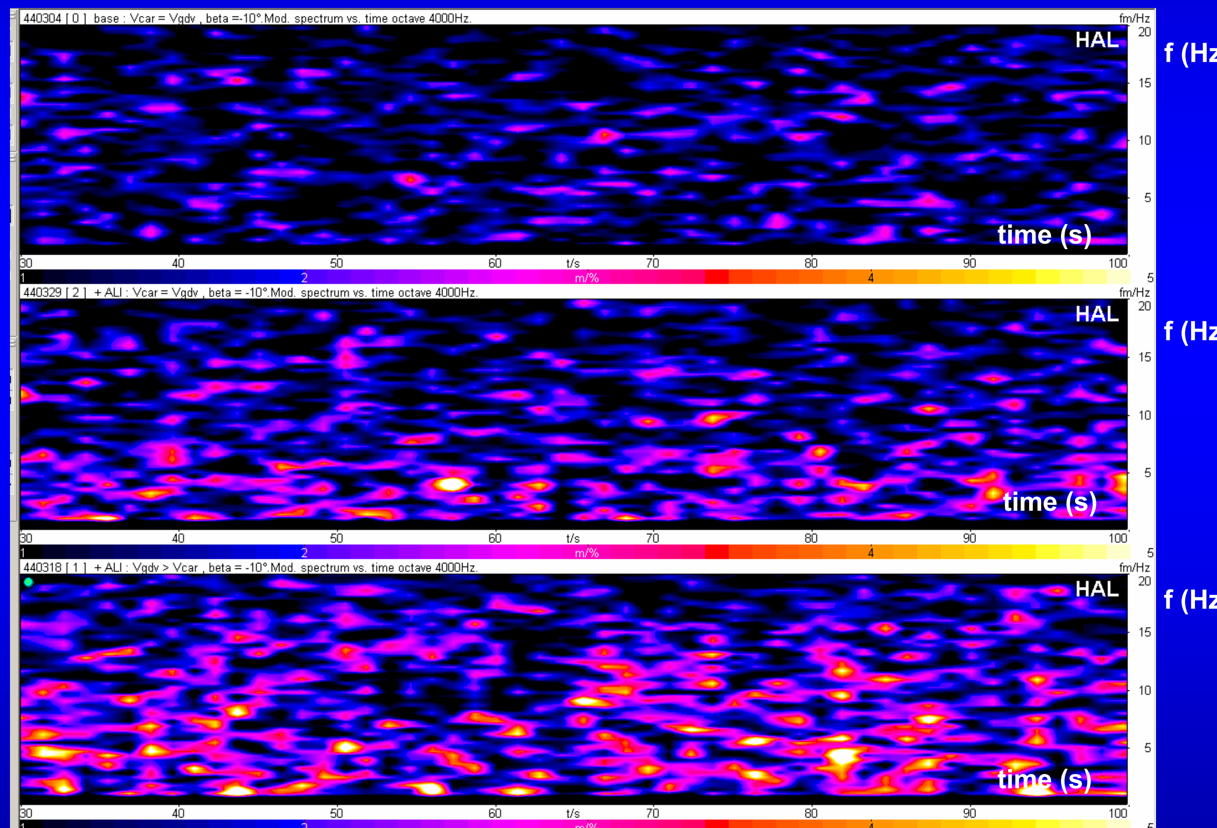
Modulation in the time, of the 4 Khz Band at low frequency (0-20Hz)

[V_{car} = 38.9 m/s ; β = -10°]

1 - Base W.T.

2 - W.T. + T.G.S.
$V_{wt} = V_{car}$

3 - W.T. + T.G.S.
$V_{wt} > V_{car}$



Additional features of the tests in presence of the turbulent flow appear to be much more similar to the car behavior on the road.

In particular:

- The vibrations of the car body, of the bonnet and so on
- The subjective feeling of the interior noise
- The measure of the time-dependent forces

All that confirms that the Wind Tunnel simulation
thanks to the Ground Effect Simulation System
and now to the Turbulence Generation System
is getting more and more close to the road condition.

New techniques are necessary to measure time÷dependent flows

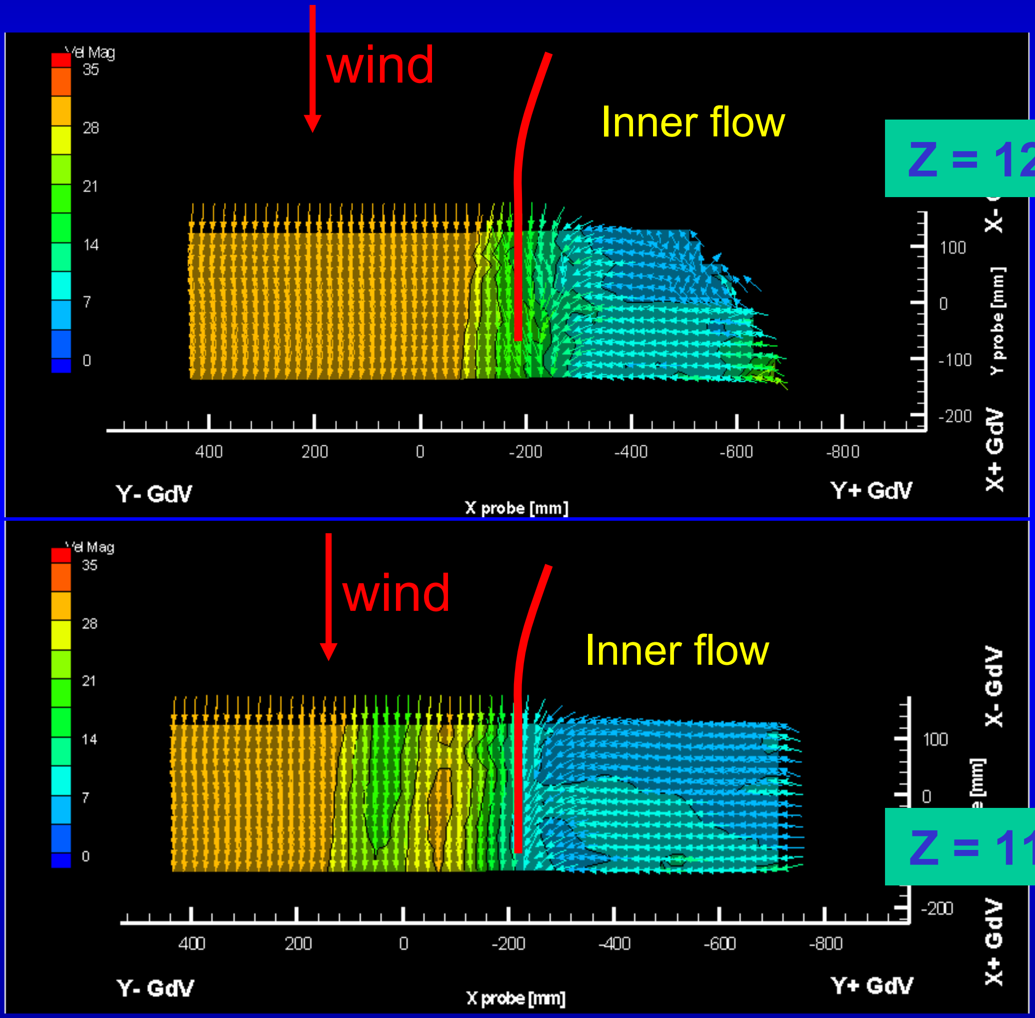
In addition to 'old techniques' like LDV and Hot Films, and new probes (see the Cobra probe)

a PIV system of new design is now in the commissioning phase

Example of a time-dependent flow-field (3D-DPIV)

Car Left Side

Open Window



Z = 1200 mm

Z = 1100 mm, close to the RVM

7 Conclusion

1 - the Wind Tunnel simulation

thanks to the Turbulence Generation System

is getting more and more close to the road condition.

2 - New Techniques are needed

to investigate the effects of unsteady flows

on car aerodynamics and aeroacoustics

Some are already available,

others are in course of development.

The Evolution of the Testing Environment in the Automotive Wind Tunnels

and of the relevant measuring techniques

it is just started …..

In future we will have more and more investigations of unsteady flows

and time-dependent measurements.


Thanks for your attention