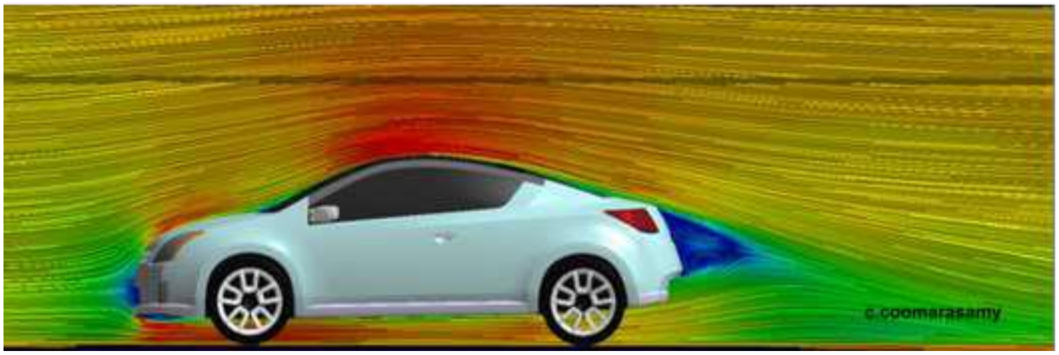
Unit II
VEHICLE AERODYNAMICS - Notes.

2.0. VEHICLE AERODYNAMICS - INTRODUCTION

- **Aerodynamics impacts** the **automobile** in **many ways.**
- **Fuel Consumption (pollution), Styling,**
  Noise & Vibration, Control and **Handling.**
- **Body shape** depends on a number of factors; these include **appealing shape to the buyer, providing comfort,** and **a good performance** during its **movement through the air.**
- A **car body** with the **aerodynamic shape** passes with **least resistance** through the **air,** as a **consequence** the **fuel economy** is **improved**.
- For a **vehicle without aerodynamic shape** of the **body,** a lot of **engine power** is **required** to **drive** through the **air.**



2.0. VEHICLE AERODYNAMICS - INTRODUCTION

- **What is aerodynamics?**
  Aerodynamics is a branch of **dynamics** concerned with studying the **motion of air**, particularly **when it interacts** with a **moving object.**

- Aerodynamics is the **study** of **air Flow around a moving vehicle.**
- **Good Aerodynamics** offer the **least resistance.**
- Aerodynamics address **four main areas of concern**.
  (Frontal Pressure, Lift/Down Force and Drag.)

Vehicle Aerodynamics : is the study of the aerodynamics of **road vehicles.**
Vehicle aerodynamics can be studied by using **computer modeling or** by testing the **vehicle** through **wind tunnels**.

The **wind tunnel** includes a **rolling road** which moves at the **same speed** as the **air flow.**

2.1. OBJECTIVES

Its main goals are **reducing drag** and **wind noise,** **minimizing noise emission,** and **preventing undesired lift forces** and other causes of **aerodynamic instability** at **high speeds.**

Depending on the **specific purpose** of **each type** of **vehicle**, the **objectives** of **aerodynamics differ widely.**
While low drag is desirable for all road vehicles,
other aerodynamic properties are also **significant.**
Negative lift down force to **improve traction** is **decisive** for the **cornering capability** of **some race cars,**
but is of **no importance** for **trucks.**
Cars and, even more so,
vans are **sensitive** to **cross wind,**
but heavy trucks are **not.**
Wind noise should be **low** for **cars** and **buses,**
but is of **no significance** for **race cars.**

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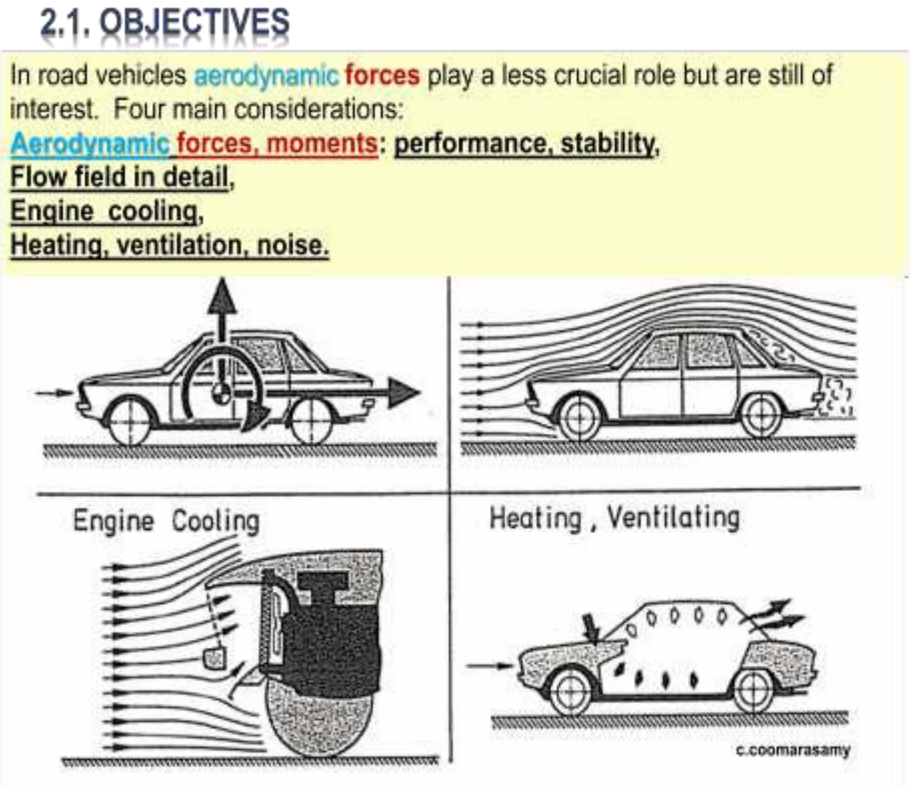

2.1. OBJECTIVES

In road vehicles aerodynamic **forces** play a less crucial role but are still of interest. Four main considerations:

Aerodynamic forces, moments: performance, stability,
Flow field in detail,
Engine cooling,
Heating, ventilation, noise.

2.1. OBJECTIVES

While the **process of weighing** the **relative importance** of **a set of needs** **from various disciplines** is generally comparable to that in other branches of **applied fluid mechanics,** the situation in **vehicle aerodynamics** is **unique** in that an additional category of arguments has to be taken into account: **art, fashion,** and **taste.**

In **contrast** to **technical** and **economic factors,** **these additional arguments** are **subjective in nature** and **can not be quantified**.

Exterior design (the term **"styling"** that was formerly used is today usually avoided) has to be **recognized** as **extremely important.**

"Design is **what sells"** rules **the car market worldwide**.

While **design gives technical requirements** a form that is in accord with **fashion,** the fundamental **nature** of **fashion** is **change.**

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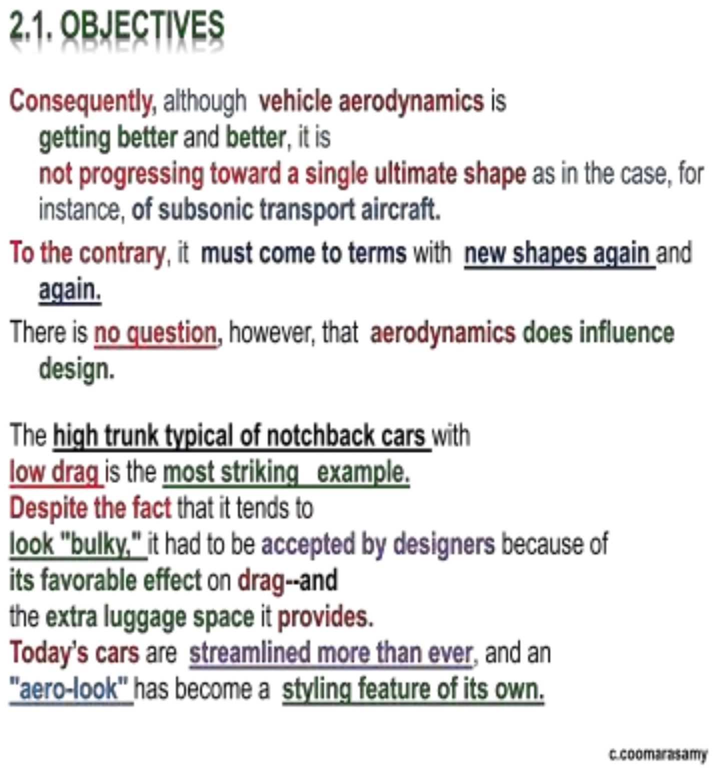

2.1. OBJECTIVES

Consequently, although vehicle aerodynamics is getting better and better, it is not progressing toward a single ultimate shape as in the case, for instance, of subsonic transport aircraft.

To the contrary, it must come to terms with new shapes again and again.

There is no question, however, that aerodynamics does influence design.

The high trunk typical of notchback cars with
low drag is the most striking example.
Despite the fact that it tends to
look "bulky," it had to be accepted by designers because of
its favorable effect on drag--and
the extra luggage space it provides.
Today's cars are streamlined more than ever, and an
"aero-look" has become a styling feature of its own.

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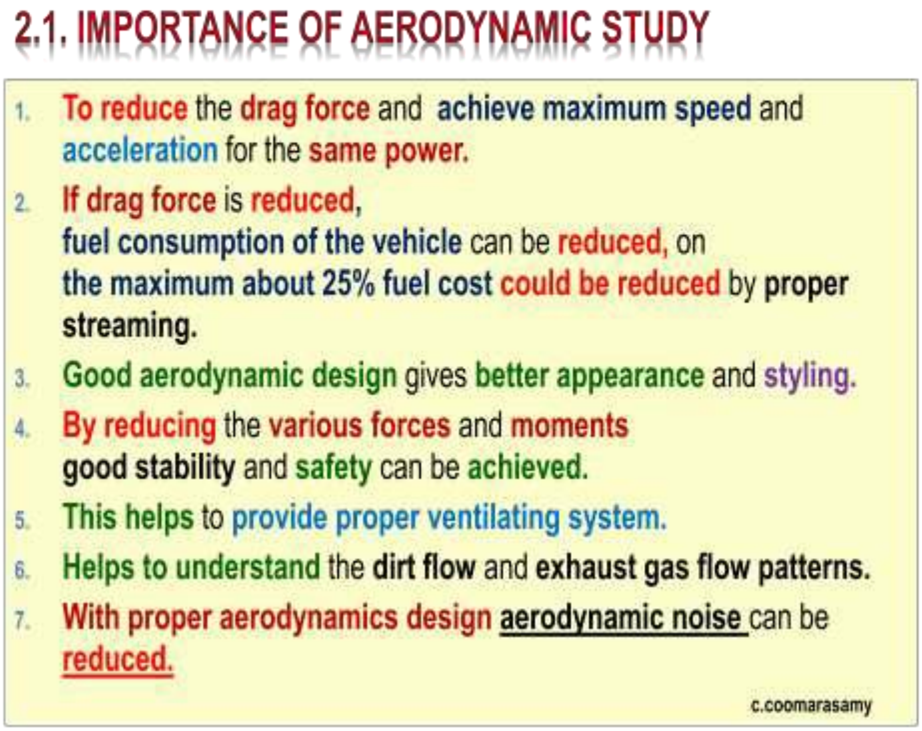

2.1. IMPORTANCE OF AERODYNAMIC STUDY

1. To reduce the drag force and achieve maximum speed and acceleration for the same power.
2. If drag force is reduced,
   fuel consumption of the vehicle can be reduced, on
   the maximum about 25% fuel cost could be reduced by proper streaming.
3. Good aerodynamic design gives better appearance and styling.
4. By reducing the various forces and moments
   good stability and safety can be achieved.
5. This helps to provide proper ventilating system.
6. Helps to understand the dirt flow and exhaust gas flow patterns.
7. With proper aerodynamics design aerodynamic noise can be reduced.

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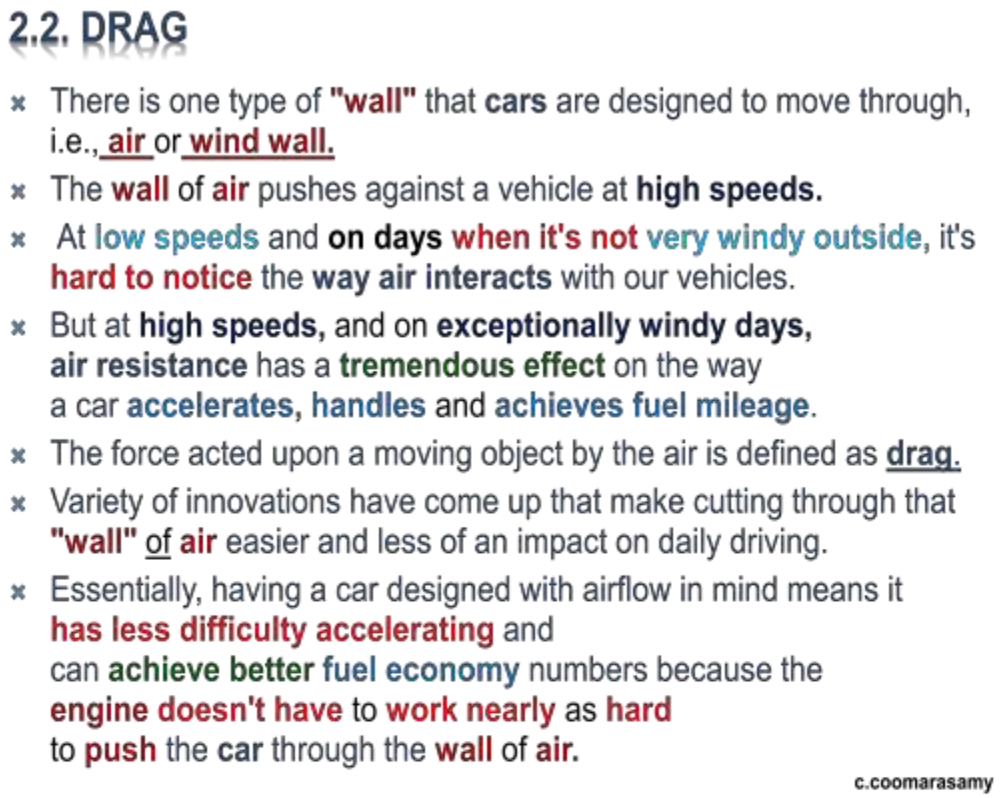

2.2. DRAG

- There is one type of **"wall"** that **cars** are designed to move through, i.e., air or **wind wall.**
- The **wall** of **air** pushes against a vehicle at **high speeds.**
- At low speeds and **on days when it's not very windy outside,** it's **hard to notice** the **way air interacts** with our vehicles.
- But at **high speeds,** and on **exceptionally windy days,** **air resistance** has a **tremendous effect** on the way a car **accelerates, handles** and **achieves fuel mileage**.
- The force acted upon a moving object by the air is defined as **drag.**
- Variety of innovations have come up that make cutting through that **"wall"** of **air** easier and less of an impact on daily driving.
- Essentially, having a car designed with airflow in mind means it **has less difficulty accelerating** and can **achieve better fuel economy** numbers because the **engine doesn't have** to **work nearly** as **hard** to **push** the **car** through the **wall** of **air.**

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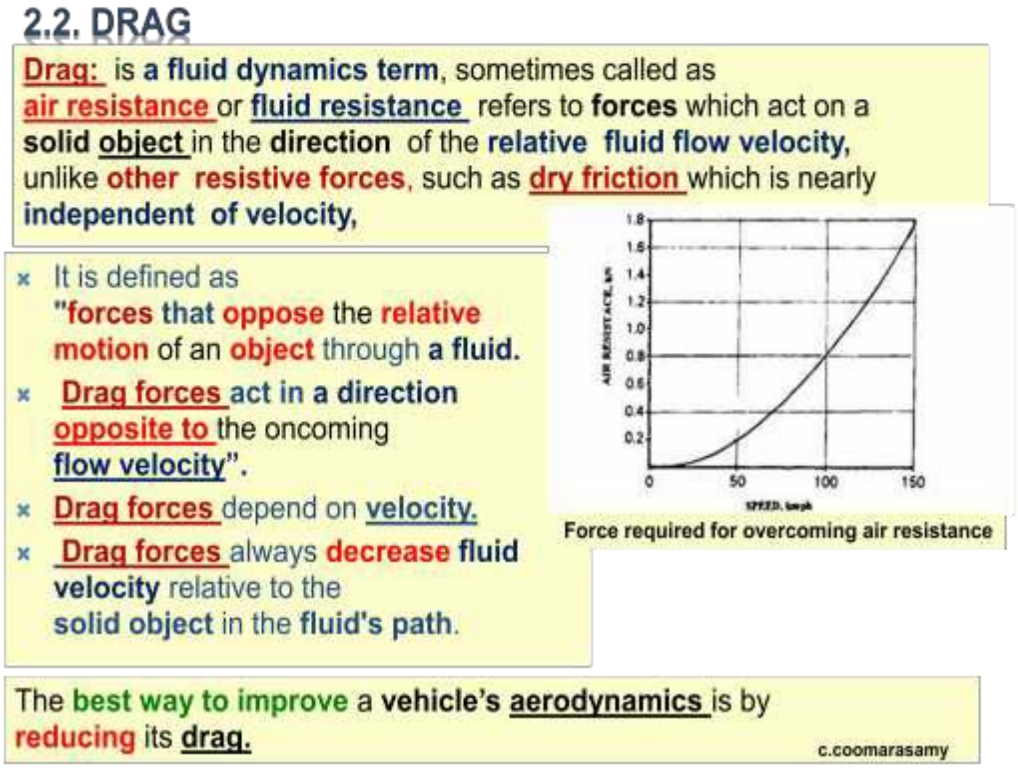

2.2. DRAG

Drag: is **a fluid dynamics term**, sometimes called as air resistance or **fluid resistance** refers to **forces** which act on a **solid object** in the **direction** of the **relative fluid flow velocity,** unlike **other resistive forces**, such as **dry friction** which is nearly **independent of velocity,**

- It is defined as **"forces that oppose** the **relative motion** of an **object** through **a fluid.**
- **Drag forces act in a direction opposite to** the oncoming **flow velocity".**
- **Drag forces** depend on **velocity.**
- **Drag forces** always **decrease fluid velocity** relative to the **solid object** in the **fluid's path.**

Force required for overcoming air resistance

The **best way to improve** a **vehicle's aerodynamics** is by **reducing** its **drag.**

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2.2. DRAG

- As an object moves through the atmosphere, it displaces the air that surrounds it. The object is also subjected to **gravity** and **drag.**
- **Drag** is generated when a solid object moves through a fluid medium such as **water** or **air.**
- **Drag increases** with **velocity** -- the faster the object travels, the more **drag** it experiences.
- An object's motion is measured using the factors in **Newton's laws.**
- These include **mass, velocity, weight, external force,** and **acceleration.**
- **Drag** has a direct effect on **acceleration.**
- The **acceleration** (a) of an object is its **weight (W) minus drag (D) divided** by its **mass (m).** a = (W - D) / m
- Remember, weight is an object's mass times the force of gravity acting on it. W= mg.
- Weight would change on the moon because of lesser gravity, but mass stays the same.

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2.2. DRAG

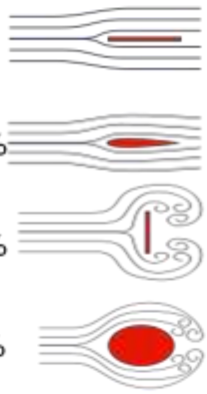
The air resistance is given by the expression, $R_a = 1/2\ C_d\ \rho\ AV^2$

where, C_d = aerodynamic drag coefficient,

ρ = density of air,

A = projected area of the vehicle,

and V = velocity of the vehicle.



Shape and flow	Form Drag	Skin friction
	0%	100%
	~10%	~90%
	~90%	~10%
	100%	0%

This expression shows that the air resistance increases very fast as the velocity of the vehicle relative to the air becomes high.

Skin friction

is the frictional force associated with the air rubbing against the surface of the vehicle.

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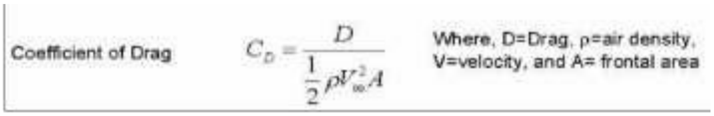
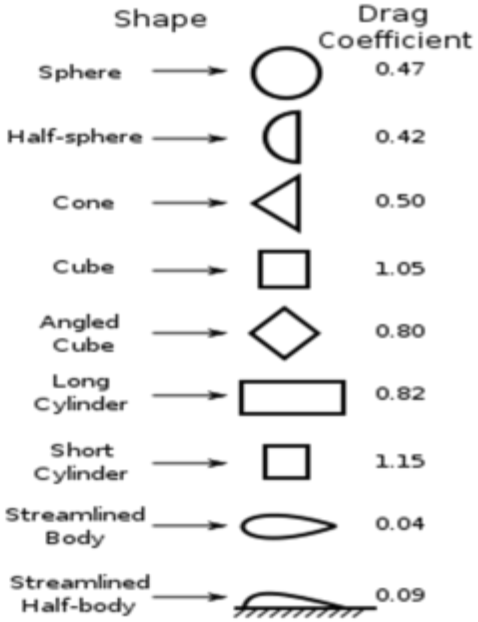
DRAG COEFFICIENT


Coefficient of Drag $C_D = \dfrac{D}{\frac{1}{2}\rho V_\infty^2 A}$ Where, D=Drag, ρ=air density, V=velocity, and A= frontal area

Drag Coefficient is a commonly **published rating** of a **vehicle's aerodynamic smoothness,** related to the **shape of the vehicle.**

The drag coefficient (Cd) is equal to the drag (D), divided by the quantity of the density (ρ), times half the velocity (V) squared times the area (A).
To make that more readable:
Cd = D / (ρ * ½ * V² * A)

Multiplying **a vehicle's drag coefficient** by the **vehicle's frontal area,** gives an **index of total drag** and **is sometimes referred** to as **drag area.**



Shape	Drag Coefficient
Sphere	0.47
Half-sphere	0.42
Cone	0.50
Cube	1.05
Angled Cube	0.80
Long Cylinder	0.82
Short Cylinder	1.15
Streamlined Body	0.04
Streamlined Half-body	0.09

Measured Drag Coefficients

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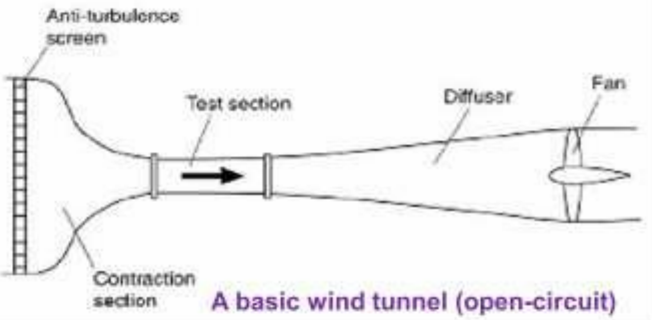
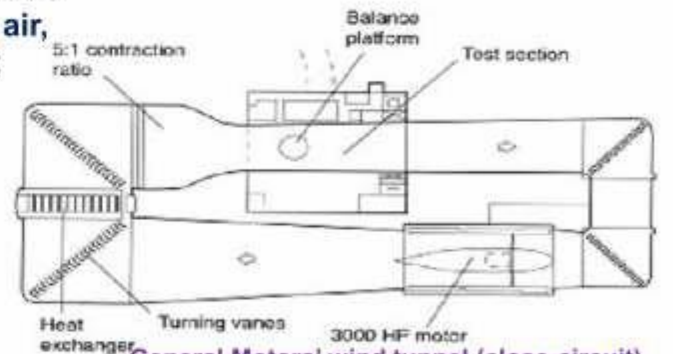
DRAG COEFFICIENT

The **air resistance of a vehicle** is measured through wind tunnel tests.



A basic wind tunnel (open-circuit)

Knowing the **cross-sectional area** of the vehicle and its **velocity relative to the air,** **aerodynamic drag coefficient** (Cd.) can be determined.



General Motors' wind tunnel (close-circuit)

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TYPES OF DRAG

Drag is a force that acts to retard the motion of the vehicle

Drag, also known as **"air resistance"** is categorized as follows

"viscous drag" arises from the effects of viscosity on the surface of the vehicle — sometimes called **"parasite drag"**

"induced drag" is the penalty paid for producing lift.

"compressibility drag" comes about at high speed ($M > 0.8$)

The viscosity of the air (μ) is a measure of the "stickiness."

Viscosity is a function of Temperature.

Reynolds number is a dimensionless parameter important in determining the viscous drag on a body.

$$\mathrm{Re} = \frac{\rho v l}{\mu}$$

The units of viscosity are kg/ ms

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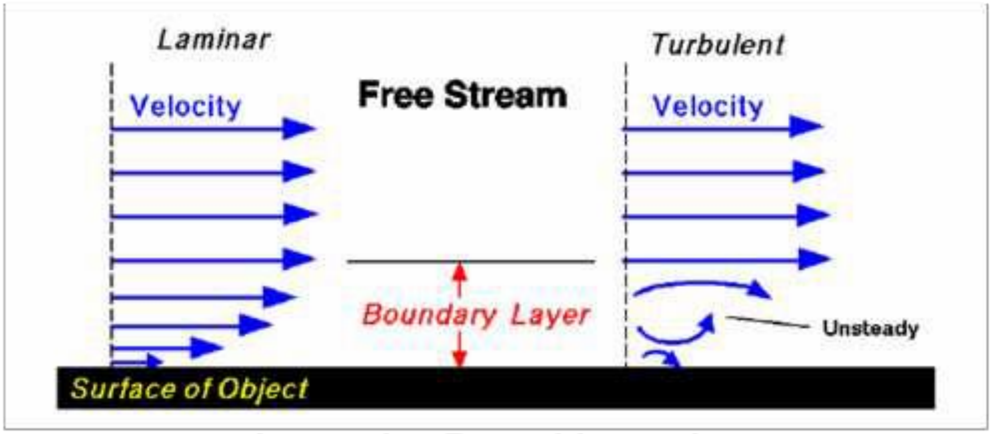
THE BOUNDARY LAYER



Increasing Reynolds number

The **turbulent boundary layer** has higher velocities, and is "rougher", but it also has **more energy** than the **laminar boundary layer.**

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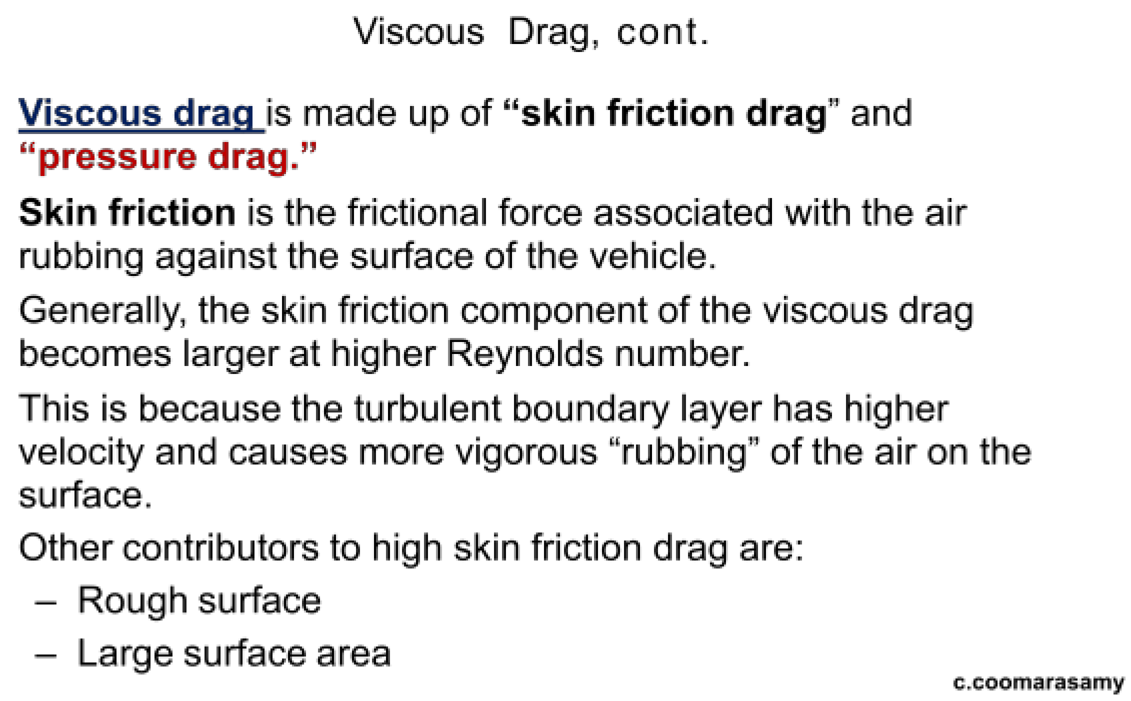

Viscous Drag, cont.

Viscous drag is made up of **"skin friction drag"** and **"pressure drag."**

Skin friction is the frictional force associated with the air rubbing against the surface of the vehicle.

Generally, the skin friction component of the viscous drag becomes larger at higher Reynolds number.

This is because the turbulent boundary layer has higher velocity and causes more vigorous "rubbing" of the air on the surface.

Other contributors to high skin friction drag are:

- Rough surface
- Large surface area

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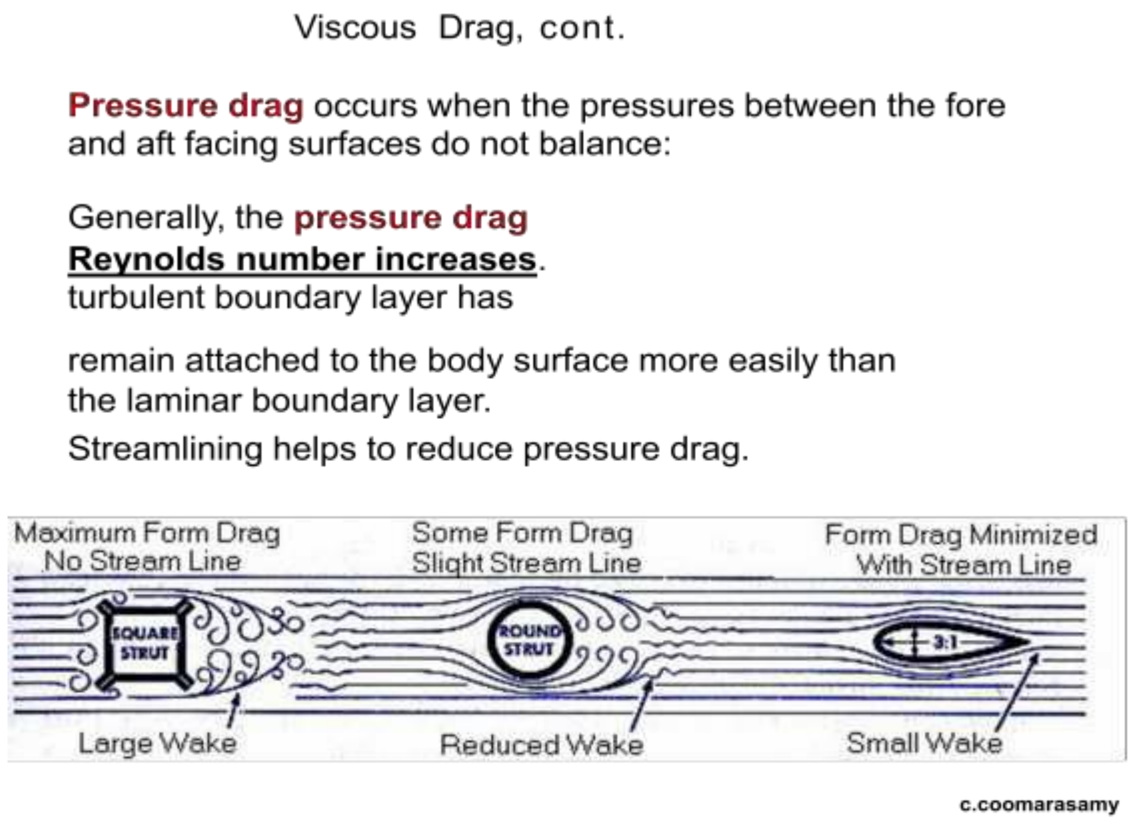

Viscous Drag, cont.

Pressure drag occurs when the pressures between the fore and aft facing surfaces do not balance:

Generally, the **pressure drag**
Reynolds number increases.
turbulent boundary layer has

remain attached to the body surface more easily than the laminar boundary layer.

Streamlining helps to reduce pressure drag.

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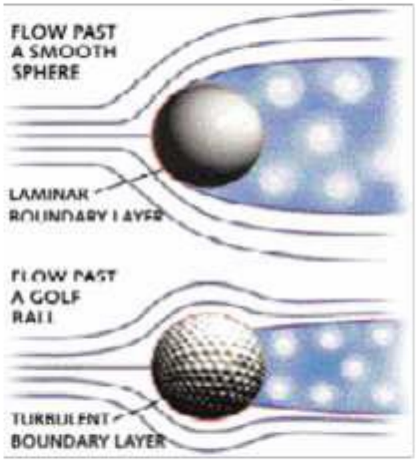
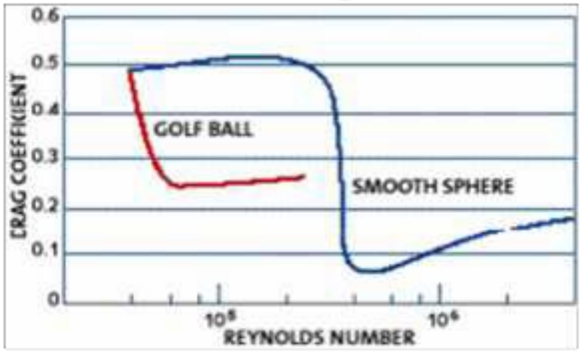
Pressure Drag vs Skin Friction Drag





$$C_D = \frac{D}{\frac{1}{2}\rho v^2 S}$$

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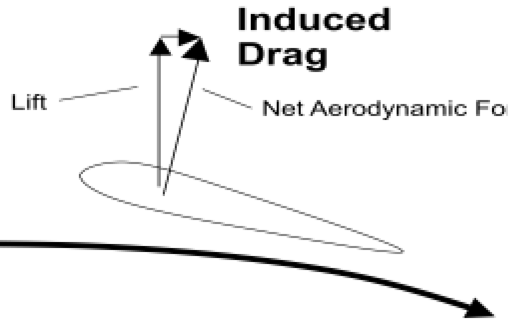
Induced Drag



The action by the wing is actually down and slightly forward, creating a reaction that is up (Lift) and slightly rearward (Induced Drag). The amount of induced drag depends on the amount of lift generated.

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Estimating Induced Drag

$$D_i = \frac{L^2}{\frac{1}{2}\rho v^2 \pi b^2}$$

$$C_{D_i} = \frac{C_L^2}{\pi AR}$$

where b = wing span and AR = wing aspect ratio = $\frac{b^2}{S}$.

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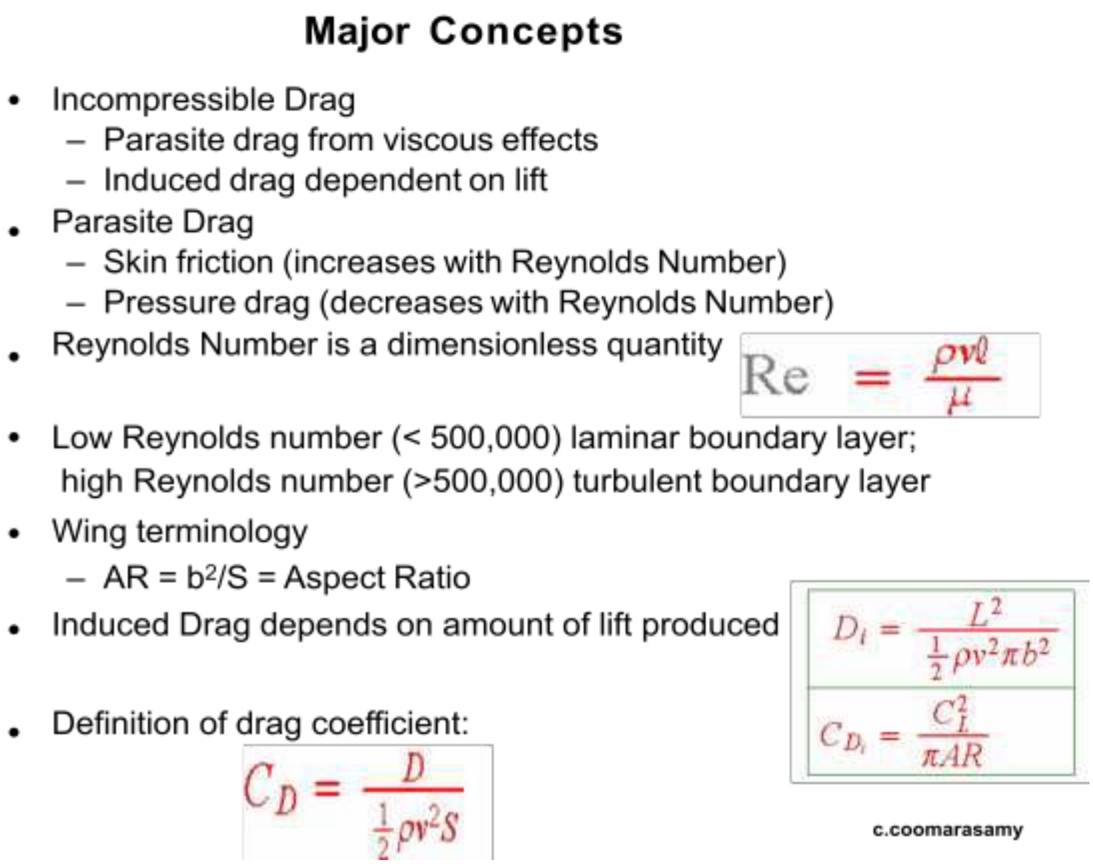

Major Concepts

- Incompressible Drag
  - Parasite drag from viscous effects
  - Induced drag dependent on lift
- Parasite Drag
  - Skin friction (increases with Reynolds Number)
  - Pressure drag (decreases with Reynolds Number)
- Reynolds Number is a dimensionless quantity $$\mathrm{Re} = \frac{\rho v \ell}{\mu}$$
- Low Reynolds number (< 500,000) laminar boundary layer; high Reynolds number (>500,000) turbulent boundary layer
- Wing terminology
  - AR = b^2/S = Aspect Ratio
- Induced Drag depends on amount of lift produced $$D_i = \frac{L^2}{\frac{1}{2}\rho v^2 \pi b^2}$$ $$C_{D_i} = \frac{C_L^2}{\pi AR}$$
- Definition of drag coefficient: $$C_D = \frac{D}{\frac{1}{2}\rho v^2 S}$$

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Aerodynamics effects on vehicle functions:

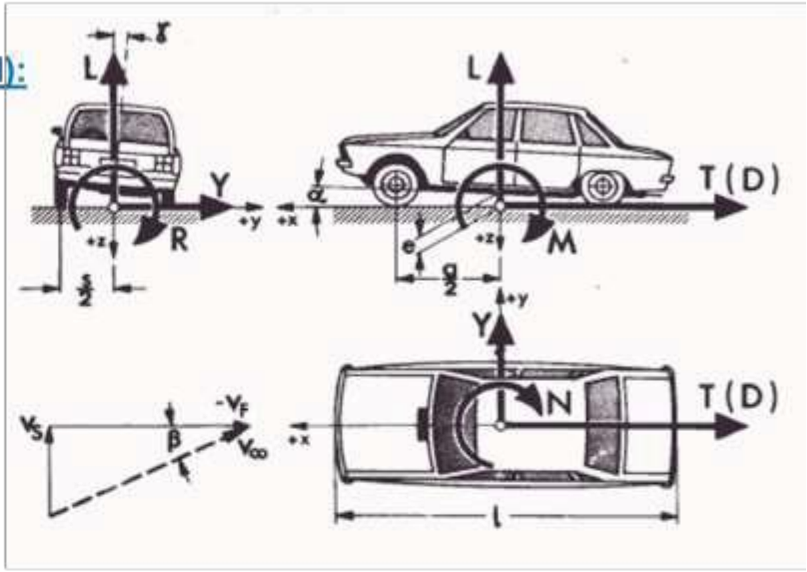
Air forces and Moments:

- Directional Control (Driving Safety) [pitching, yaw, and rolling moments]-left and cross wind force.
- Driving Performance and Fuel consumption [air resistance] — tangential forces.

Air flow behavior, and pressure distribution:

- Comfort
[wind noises, passenger compartment ventilation, dirty interior].
- Clear Visibility
[Dirty windows and lamps, Prevention of windshield misting].
- Auxiliary equipment functions
[engine cooling, engine compartment ventilation, brake cooling, air conditioning].

AERODYNAMIC FORCES AND MOMENTS

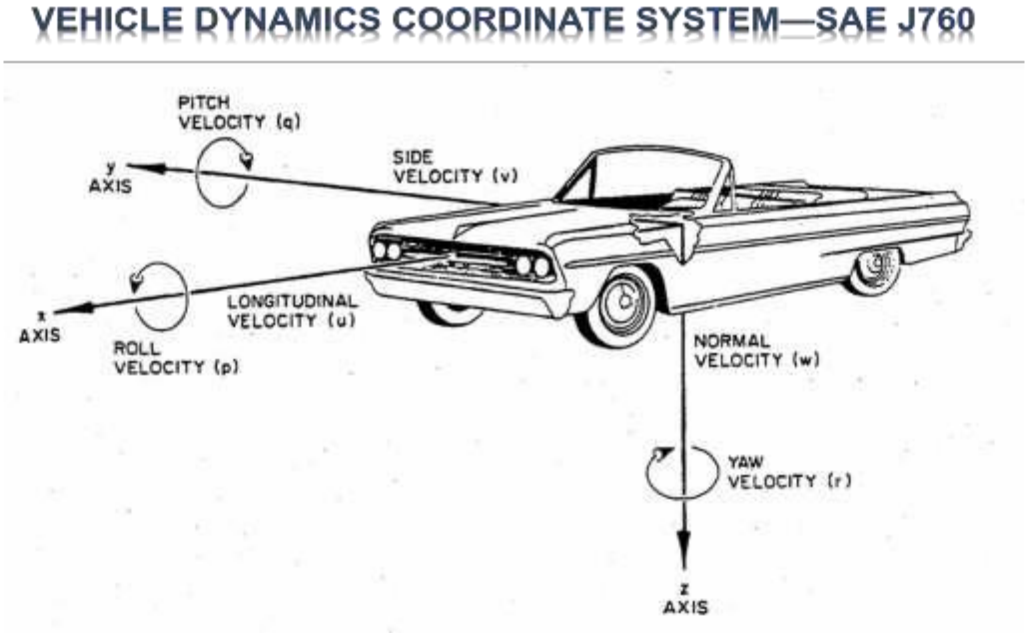


Longitudinal (+ backward):
- Drag force
- Roll moment

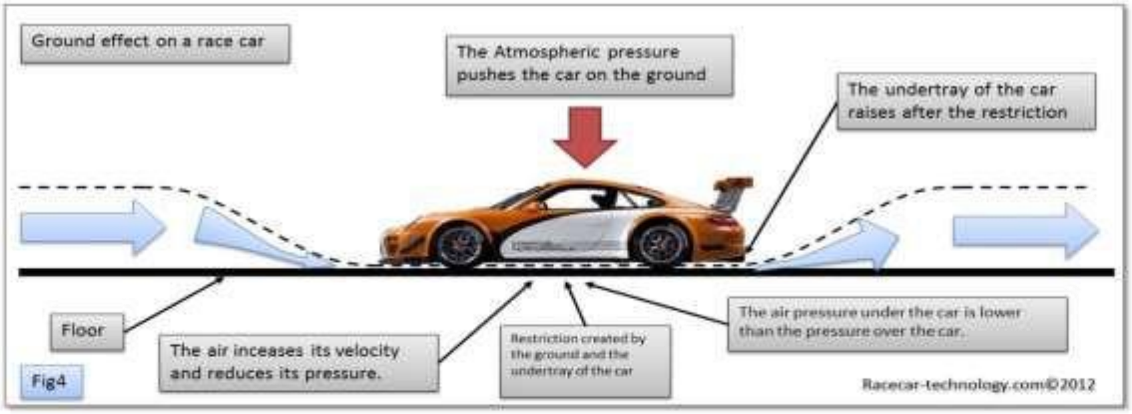
Side (+ to the right) :
- Side force
- Pitch moment

Vertical (+ upward)
- Lift force
- Yaw moment

Centre of aerodynamic frame at mid wheel distance on the ground



VEHICLE DYNAMICS COORDINATE SYSTEM—SAE J760



Ground effect on a race car

The Atmospheric pressure pushes the car on the ground

The undertray of the car raises after the restriction

Floor

The air inceases its velocity and reduces its pressure.

Restriction created by the ground and the undertray of the car

The air pressure under the car is lower than the pressure over the car.

Fig4

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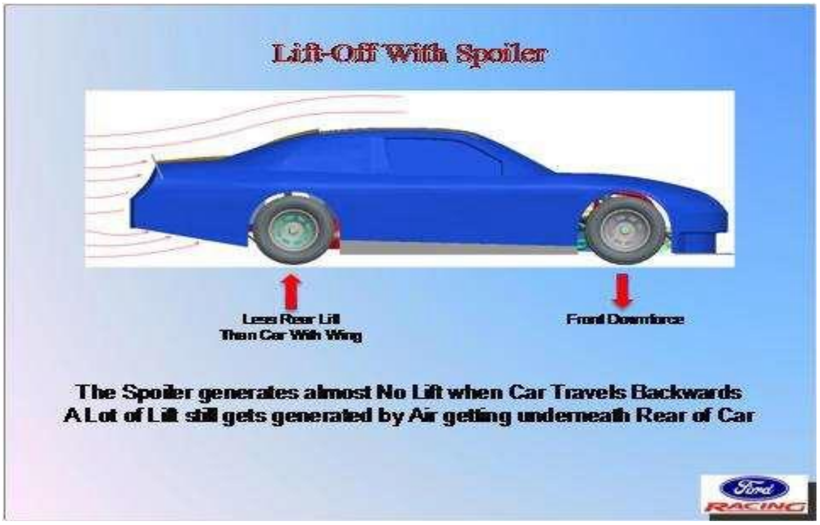


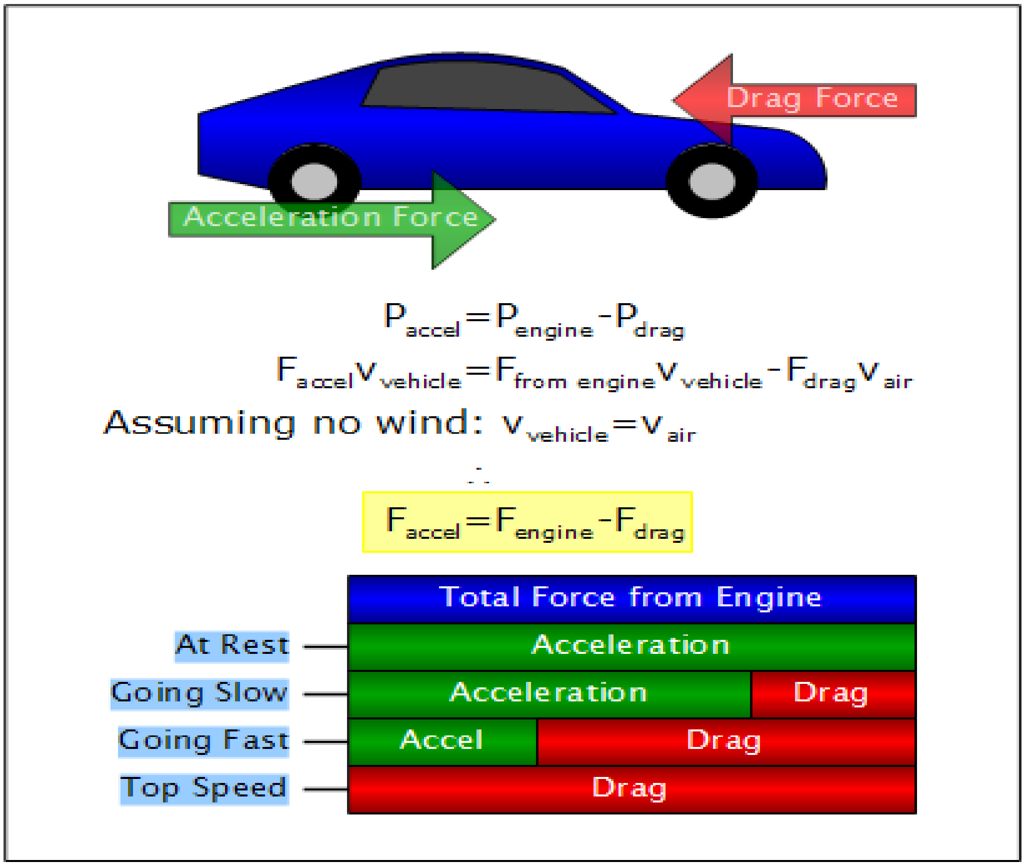
Lift-Off With Spoiler

The Spoiler generates almost No Lift when Car Travels Backwards
A Lot of Lift still gets generated by Air getting underneath Rear of Car

Coefficient of Lift $C_L = \frac{L}{\frac{1}{2}\rho V_\infty^2 A}$ Where, L=Lift, ρ=air density, V=velocity, and A= frontal area

Coefficient of Drag $C_D = \frac{D}{\frac{1}{2}\rho V_\infty^2 A}$ Where, D=Drag, ρ=air density, V=velocity, and A= frontal area

Coefficient of Side-Force $C_Y = \frac{Y}{\frac{1}{2}\rho V_\infty^2 A}$ Where, Y=Side-force, ρ=air density, V=velocity, and A= frontal area



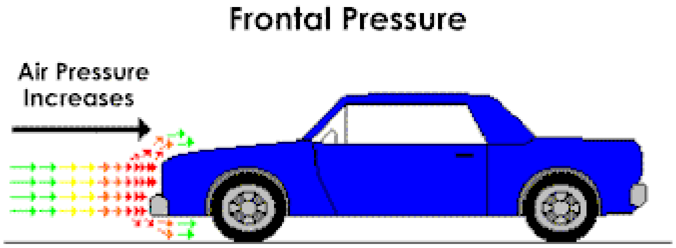
General Aerodynamic Principals

Drag

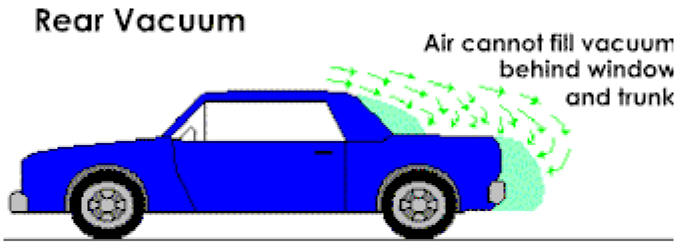
A simple definition of aerodynamics is the study of the flow of air around and through a vehicle, primarily if it is in motion. To understand this flow, you can visualize a car moving through the air. As we all know, it takes some energy to move the car through the air, and this energy is used to overcome a force called **Drag**.

Drag, in vehicle aerodynamics, is comprised primarily of two forces. **Frontal pressure** is caused by the air attempting to flow around the front of the car. As millions of air molecules approach the front grill of the car, they begin to compress, and in doing so raise the air pressure in front of the car. At the same time, the air molecules travelling along the sides of the car are at atmospheric pressure, a lower pressure compared to the molecules at the front of the car.

Just like an air tank, if the valve to the lower pressure atmosphere outside the tank is opened, the air molecules will naturally flow to the lower pressure area, eventually equalizing the pressure inside and outside the tank. The same rules apply to **cars**. The compressed molecules of air naturally seek a way out of the high pressure zone in front of the car, and they find it around the sides, top and bottom of the car. See the diagram below.



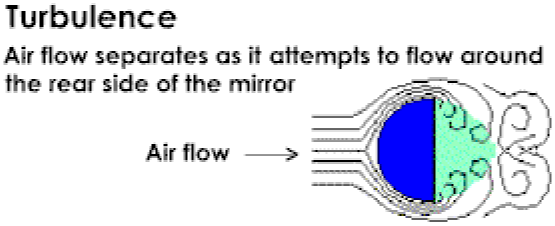
Rear vacuum (a non-technical term, but very descriptive) is caused by the "hole" left in the air as the car passes through it. To visualize this, imagine a bus driving down a road. The blocky shape of the bus punches a big hole in the air, with the air rushing around the body, as mentioned above. At speeds above a crawl, the space directly behind the bus is "empty" or like a vacuum. This empty area is a result of the air molecules not being able to fill the hole as quickly as the bus can make it. The air molecules attempt to fill in to this area, but the bus is always one step ahead, and as a result, a continuous vacuum sucks in the opposite direction of the bus. This inability to fill the hole left by the bus is technically called**Flow detachment.** See the diagram below.



Flow detachment applies only to the "rear vacuum" portion of the drag equation, and it is really about giving the air molecules time to follow the contours of a car's bodywork, and to fill the hole left by the vehicle, it's **tires**, it's suspension and protrusions (ie. mirrors, **roll bars**). If you have witnessed the Le Mans race cars, you will have seen how the tails of these cars tend to extend well back of the rear **wheels**, and narrow when viewed from the side or top. This extra bodywork allows the air molecules to converge back into the vacuum smoothly along the body into the hole left by the car's cockpit, and front area, instead of having to suddenly fill a large empty space.

The reason keeping flow attachment is so important is that the force created by the vacuum far exceeds that created by frontal pressure, and this can be attributed to the **Turbulence** created by the detachment.

Turbulence generally affects the "rear vacuum" portion of the drag equation, but if we look at a protrusion from the race car such as a mirror, we see a compounding effect. For instance, the air flow detaches from the flat side of the mirror, which of course faces toward the back of the car. The turbulence created by this detachment can then affect the air flow to parts of the car which lie behind the mirror. Intake ducts, for instance, function best when the air entering them flows smoothly. Therefore, the entire length of the car really needs to be optimized (within reason) to provide the least amount of turbulence at **high speed**. See diagram below (Light green indicates a vacuum-type area behind mirror):



Lift (or Downforce)

One term very often heard in race car circles is**Downforce**. Downforce is the same as the lift experienced by airplane wings, only it acts to press down, instead of lifting up. Every object travelling through air creates either a lifting or downforce situation. **Race cars**, of course use things like inverted wings to force the car down onto the track, increasing traction. The average street car however tends to create lift. This is because the car body shape itself generates a low pressure area above itself.

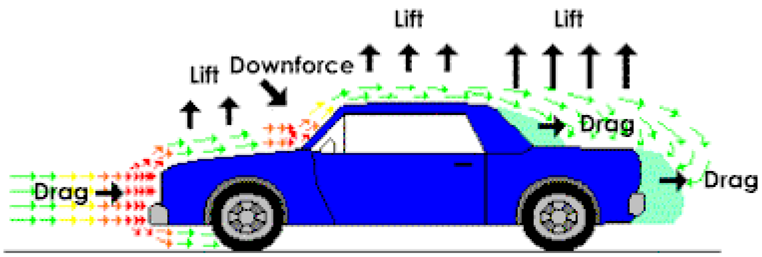
How does a car generate this low pressure area? According to Bernoulli, the man who defined the basic rules of fluid dynamics, for a given volume of air, the higher the speed the air molecules are travelling, the lower the pressure becomes. Likewise, for a given volume of air, the lower the speed of the air molecules, the higher the pressure becomes. This of course only applies to air in motion across a still body, or to a vehicle in motion, moving through still air.

When we discussed **Frontal Pressure,** above, we said that the air pressure was high as the air rammed into the front grill of the car. What is really happening is that the air slows down as it approaches the front of the car, and as a result **more** molecules are packed into a smaller space. Once the air **Stagnates** at the point in front of the car, it seeks a lower pressure area, such as the sides, top and bottom of the car.

Now, as the air flows over the hood of the car, it's loses pressure, but when it reaches the windscreen, it again comes up against a barrier, and briefly reaches a higher pressure. The lower pressure area above the hood of the car creates a small lifting force that acts upon the area of the hood (Sort of like trying to suck the hood off the car). The higher pressure area in front of the windscreen creates a small (or not so small) downforce. This is akin to pressing down on the windshield.

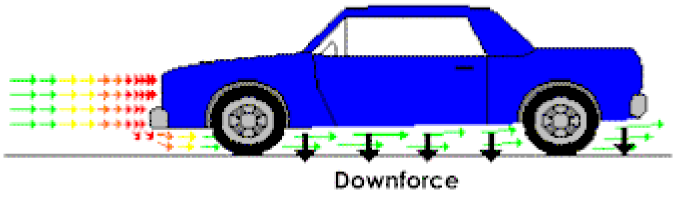
Where most road cars get into trouble is the fact that there is a large surface area on top of the car's roof. As the higher pressure air in front of the wind screen travels over the windscreen, it accellerates, causing the pressure to drop. This lower pressure literally lifts on the car's roof as the air passes over it. Worse still, once the air makes it's way to the rear window, the notch created by the window dropping down to the trunk leaves a vacuum, or low pressure space that the air is not able to fill properly. The flow is said to **detach** and the resulting lower pressure creates lift that then acts upon the surface area of the trunk. This can be seen in old 1950's racing **sedans**, where the driver would feel the car becoming "light" in the rear when travelling at high speeds. See the diagram below.

Lift and Downforce From Over Body Flow



Not to be forgotten, the underside of the car is also responsible for creating lift or downforce. If a car's front end is lower than the rear end, then the widening gap between the underside and the road creates a vacuum, or low pressure area, and therefore "suction" that equates to downforce. The lower front of the car effectively restricts the air flow under the car. See the diagram below.

Downforce by raked underbody



So, as you can see, the airflow over a car is filled with high and low pressure areas, the sum of which indicate that the car body either naturally creates lift or downforce.

Drag Coefficient

The shape of a car, as the aerodynamic theory above suggests, is largely responsible for how much drag the car has. Ideally, the car body should:

- Have a small grill, to minimize frontal pressure.
- Have minimal ground clearance below the grill, to minimize air flow under the car.
- Have a steeply raked windshield to avoid pressure build up in front.
- Have a "Fastback" style rear window and deck, to permit the air flow to stay attached.
- Have a converging "Tail" to keep the air flow attached.

- Have a slightly raked underside, to create low pressure under the car, in concert with the fact that the minimal ground clearance mentioned above allows even less air flow under the car.

  If it sounds like we've just described a sports car, you're right. In truth though, to be ideal, a car body would be shaped like a tear drop, as even the best sports cars experience some flow detachment. However, tear drop shapes are not condusive to the area where a car operates, and that is close to the ground. Airplanes don't have this limitation, and therefore teardrop shapes work.

  What all these "ideal" attributes stack up to is called the **Drag coefficient (Cd)**. The best road cars today manage a Cd of about 0.28. Formula 1 cars, with their wings and open wheels (a massive drag component) manage a minimum of about 0.75.

  If we consider that a flat plate has a Cd of about 1.0, an F1 car really seems inefficient, but what an F1 car lacks in aerodynamic drag efficiency, it makes up for in downforce and horsepower.

Frontal Area

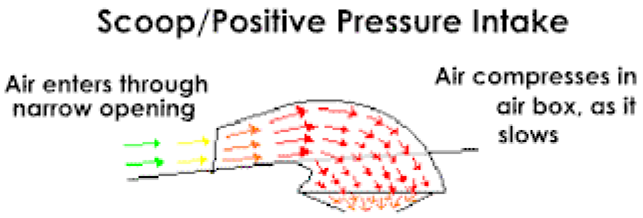
Drag coefficient, by itself is only useful in determining how "Slippery" a vehicle is. To understand the full picture, we need to take into account the frontal area of the vehicle. One of those new aerodynamic semi-trailer trucks may have a relatively low Cd, but when looked at directly from the front of the truck, you realize just how big the **Frontal Area** really is.

It is by combining the Cd with the **Frontal area** that we arrive at the actual drag induced by the vehicle.

Aerodynamic Devices

Scoops

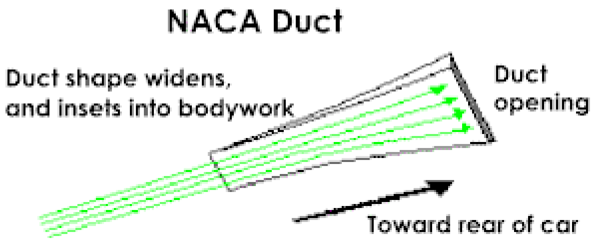
Scoops, or positive pressure intakes, are useful when high volume air flow is desireable and almost every type of race car makes use of these devices. They work on the principle that the air flow compresses inside an "air box", when subjected to a constant flow of air. The air box has an opening that permits an adequate volume of air to enter, and the expanding air box itself slows the air flow to increase the pressure inside the box. See the diagram below:



NACA Ducts

NACA ducts are useful when air needs to be drawn into an area which isn't exposed to the direct air flow the scoop has access to. Quite often you will see NACA ducts along the sides of a car. The NACA duct takes advantage of the **Boundary layer**, a layer of slow moving air that "clings" to the bodywork of the car, especially where the bodywork flattens, or does not accellerate or decellerate the air flow. Areas like the roof and side body panels are good examples. The longer the roof or body panels, the thicker the layer becomes (a source of drag that grows as the layer thickens too).

Anyway, the NACA duct scavenges this slower moving area by means of a specially shaped intake. The intake shape, shown below, drops in toward the inside of the bodywork, and this draws the slow moving air into the opening at the end of the NACA duct. Vorticies are also generated by the "walls" of the duct shape, aiding in the scavenging. The shape and depth change of the duct are critical for proper operation.



Typical uses for NACA ducts include engine air intakes and cooling.

Spoilers

Spoilers are used primarily on sedan-type race cars. They act like barriers to air flow, in order to build up higher air pressure in front of the spoiler. This is useful, because as mentioned previously, a sedan car tends to become "Light" in the rear end as the low pressure area above the trunk lifts the rear end of the car. See the diagram below:

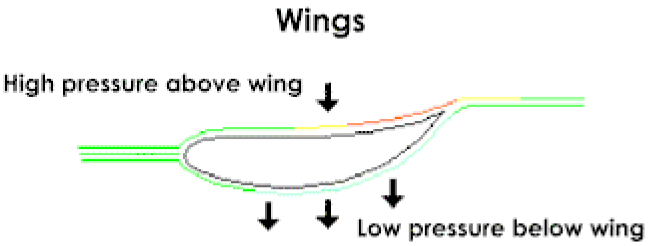
Front air dams are also a form of spoiler, only their purpose is to restrict the air flow from going under the car.

Wings

Probably the most popular form of aerodynamic aid is the wing. Wings perform very efficiently, generating lots of downforce for a small penalty in drag. Spoiler are not nearly as efficient, but because of their practicality and simplicity, spoilers are used a lot on sedans.

The wing works by differentiating pressure on the top and bottom surface of the wing. As mentioned previously, the higher the speed of a given volume of air, the lower the pressure of that air, and vice-versa. What a wing does is make the air passing under it travel a larger distance than the air passing over it (in race car applications). Because air molecules approaching the leading edge of the wing are forced to separate, some going over the top of the wing, and some going under the bottom, they are forced to travel differing distances in order to "Meet up" again at the trailing edge of the wing. This is part of Bernoulli's theory.

What happens is that the lower pressure area under the wing allows the higher pressure area above the wing to "push" down on the wing, and hence the car it's mounted to. See the diagram below:



Wings, by their design require that there be no obstruction between the bottom of the wing and the road surface, for them to be most effective. So mounting a wing above a trunk lid limits the effectiveness.

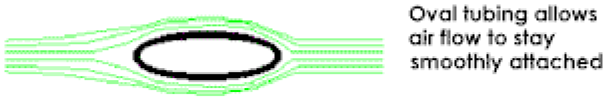
Aerodynamic Design Tips

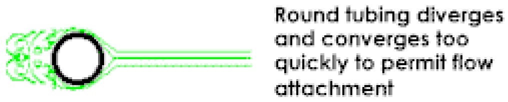
- **Cover Open wheels.** Open wheels create a great deal of drag and air flow turbulence, similar to the diagram of the mirror above. Full covering bodywork is probably the best solution, if legal by regulations, but if partial bodywork is permitted, placing a converging fairing behind the wheel provides maximum benefit.
- **Minimize Frontal Area.** It's no coincidence that Formula 1 cars are very narrow. It is usually much easier to reduce FA (frontal area) than the Cd (Drag coefficient), and top speed and accelleration will be that much better.
- **Converge Bodywork Slowly.** Bodywork which quickly converges or is simply truncated, forces the air flow into turbulence, and generates a great deal of drag. As mentioned above, it also can affect aerodynamic devices and bodywork further behind on the car body.
- **Use Spoilers.** Spoilers are widely used on sedan type cars such as NASCAR stock cars. These aerodynamic aids produce downforce by creating a "dam" at the rear lip of the trunk. This dam works in a similar fashion to the windshield, only it creates higher pressure in the area above the trunk.
- **Use Wings.** Wings are the inverted version of what you find on aircraft. They work very efficiently, and in less aggressive forms generate more downforce than drag, so they are loved in many racing circles. Wings are not generally seen in concert with spoilers, as they both occupy similar locations, and defeat each other's purpose.
- **Use Front Air Dams.** Air dams at the front of the car restrict the flow of air reaching the underside of the car. This creates a lower pressure area under the car, effectively providing downforce.
- **Use Aerodynamics to Assist Car Operation.**Using car bodywork to direct airflow into sidepods, for instance, permits more efficient (ie. smaller FA) sidepods. Quite often, with some for-thought, you can gain an advantage over a competitor by these small dual purpose techniques.

  Another useful technique is to use the natural high and low pressure areas created by the bodywork to perform functions. For instance, Mercedes, back in the 1950s placed radiator outlets in the low pressure zone behind the driver. The air inlet pressure which fed the radiator became less critical, as the low pressure outlet area literally sucked air through the radiator.

A useful high pressure area is in front of the car, and to make full use of this area, the nose of the car is often slanted downward. This allows the higher air pressure to push down on the nose of the car, increasing grip. It also has the advantage of permitting greater driver visibility.

- **Keep Protrusions Away From The Bodywork.**The smooth airflow achieved by proper bodywork design can be messed up quite easily if a protrusion such as a mirror is too close to it. Many people will design very aerodynamic mounts for the mirror, but will fail to place the mirror itself far enough from the bodywork.
- **Rake the chassis.** The chassis, as mentioned in the aerodynamics theory section above, is capable of being slightly lower to the ground in the front than in the rear. The lower "Nose" of the car reduces the volume of air able to pass under the car, and the higher "Tail" of the car creates a vacuum effect which lowers the air pressure.
- **Cover Exposed Wishbones.** Exposed wishbones (on open wheel cars) are usually made from circular steel tube, to save cost. However, these circular tubes generate turbulence. It would be much better to use oval tubing, or a tube fairing that creates an oval shape over top of the round tubing. See diagram below:





AERODYNAMIC TIPS

- Have a minimized frontal area / small grill, to minimize frontal pressure.
- Have minimal ground clearance below the grill, to minimize air flow under the car.
- Converge Bodywork Slowly. Bodywork which quickly converges, forces the air flow into turbulence, and generates a great deal of drag.
- Have a sloped windshield to avoid pressure build up in front.
- Have a "Fastback" style rear window and deck, to permit the air flow to stay attached. (Ideally 10° to 30°)
- Have a converging "Tail" to keep the air flow attached.
- Have a slightly raked underside, to create low pressure under the car.
- Cover Open wheels. Open wheels create a great deal of drag and air flow turbulence, similar to the diagram of the mirror above.

- When climatic tests are performed with (long) trains or coaches the wind speed on the side of the coaches has to be set as for the radiator test with buses.

16.1.7 Typical Vehicle Wind Tunnels

Classification of Wind Tunnels for Vehicle Aerodynamics

In the motor industry and research organizations a large variety of wind tunnels are in operation. Although their objects, namely cars and light-duty trucks, are very similar, the variety of the design of wind tunnels is surprising. In order to provide a survey they will be classified into four categories:

- large full scale
- small full scale
- thermal
- small scale.

Each will be characterized by one example. Additionally, some main design details will be emphasized. For further details see [16.1], where the major full scale wind tunnels worldwide are compiled, and some are described. In Europe, vehicle aerodynamicists prefer an open test section, and this type is gradually gaining preference in the US. All but one of the wind tunnels discussed have an open test section.

Large Full-Scale Aerodynamic and Aero-Acoustic Wind Tunnels

A typical large full-scale vehicle wind tunnel is that of the Institut für Verbrennungsmotoren und Kraftfahrwesen (IVK) at the University of Stuttgart; it was erected in 1988, when the wind tunnel built by Kamm in 1939 had to be given to Daimler-Benz AG. The air circuit (Göttingen type) together with its main dimensions are shown in Fig. 16.29. The cross section of the jet is 22.5 m².

Originally, this wind tunnel was built as a purely aerodynamic facility, and as such it came into service in 1988; the maximum wind speed was 270 km/h (168 mph). However, provision was made for later improvements concerning the possibility of the aeroacoustic testing (16.20). This upgrade was performed in 1993 with a novel silencing concept. The air path (Fig. 16.29) shows how the fan noise is blocked. Both cross legs, (1) and (2), together with their turning vanes are silencers. The plenum (3) is covered with absorbing elements tuned for two frequency ranges. In the low range, 80–200 Hz, the fan noise is damped by the novel membrane absorber sketched in Fig. 16.30a. The middle and

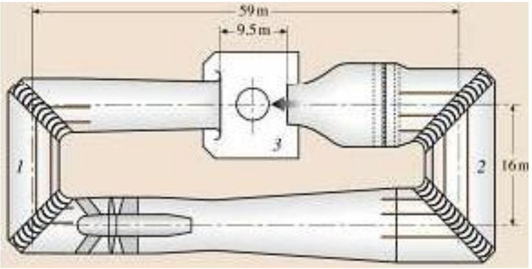


Fig. 16.29 Aero-acoustic wind tunnel of IVK (after [16.20]). Cross section $A_N = 22.5\,\mathrm{m^2}$, maximum wind speed $V_{max} = 257$ km/h, SPL at 140 km/h = 69 dB(A), ground simulation system, rotating wheels

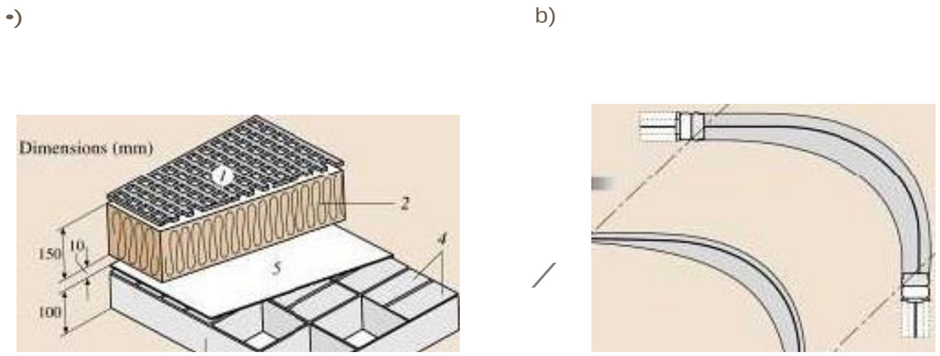
high frequencies are damped by porous polyester foam (Fig. 16.30b). The A-weighted sound noise level (SPL) measured out of flow and plotted versus tunnel speed (Fig. 16.31) is a proof of the effectiveness of this concept. The IVK aero-acoustic wind tunnel is one of the quietest full-scale wind tunnels ever built (Fig. 16.31). The maximum wind speed of the tunnel was only reduced by 7 km/h by the damping measures.

Another outstanding property of the IVK wind tunnel is its ground simulation, called the five-belt system. It is made up of a narrow belt (compared to a belt that spans the entire width of the test section) moving between the wheel tracks and four small belts, one under each wheel. Together with a system of tangential blowing and basic suction the boundary layer underneath the vehicle can be almost completely removed, and the wheels can be rotated, both up to full wind tunnel speed. Potthoff, the designer of this system and a similar one for the small-scale wind tunnel of IVK, has presented a description [16.21] and thoughts for future development.

Small Full-Scale Aero-Acoustic Wind Tunnels

The first small full scale wind tunnel (A_N = 11.75 m²) built for vehicle aerodynamics was designed on behalf of the Italian designer Pininfarina by Morelli (1971) [16.3]. Another, small full scale wind tunnel (A_N = 10 m²) designed on behalf of BMW by L.J. Janssen (1988), both with an air path according to Eiffel.

In 1999 the small full-scale aero-acoustic wind tunnel at Audi AG became operational [16.22]; air path is reproduced in Fig. 16.32 (A_N = 11 m²). Based on the correction method developed by Mercker and Wiedemann [16.4] the dimensions of the test section were fixed so as to minimize corrections. The tunnel is in



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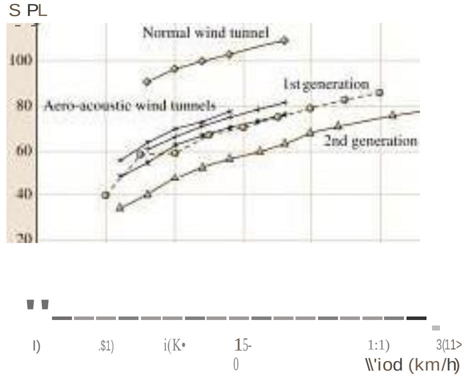

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Therma lWind Tunnels

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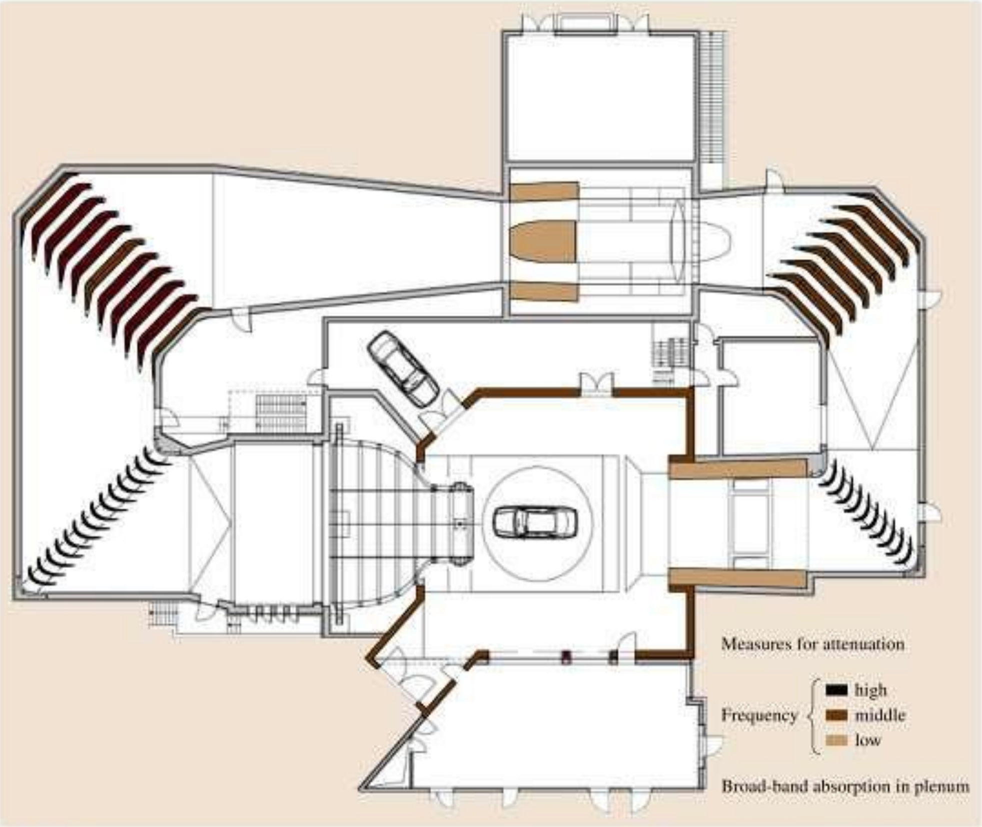


Fig. 16.32 Aero-acoustic wind tunnel of Audi AG; design *Wiedemann* [16.22]; cross section $A_{\mathrm{N}} = 11\,\mathrm{m}^2$, maximum wind speed $V_{\max} = 300\,\mathrm{km/h}$, OSPL at $140\,\mathrm{km/h} = 57\,\mathrm{dB}(A)$, moving floor, rotating wheels.

For thermal tests with cars a cross section of $12\,\mathrm{m}^2$ is more than sufficient. From the investigations mentioned in [16.25, 26] and from experience $A_{\mathrm{N}} = 6\,\mathrm{m}^2$ has proven to be sufficient. However, in order also to be able to test full-size trucks and buses, several of these thermal tunnels are equipped with nozzles that allow for different cross sections: $6\,\mathrm{m}^2$ for cars and $10-12\,\mathrm{m}^2$ for large vehicles. The loss of top speed with the greater nozzle area can be accepted because of the speed limit of these larger vehicles. Two types of nozzles have been developed for this purpose:

- nozzles with a flexible upper wall (Fig. 16.35)
- tandem nozzles (Fig. 16.36).

A particular vehicle type comes with a variety of cooling systems (engine, oil, intercooler, condenser, exhaust gas, etc.). To develop these different systems requires a large effort. However, many of the related tests can be performed at ambient temperature. This work is performed in wind tunnels or with blowers with a nozzle cross section of ca. $2\,\mathrm{m}^2$. Only fine-tuning is done in a hot tunnel.

For tests with *rolling stock* for railways and street cars a large wind tunnel is needed. Coaches are about 30 m long. The only way to simulate the flow on all four sides of the coach is in a *closed* test section. In its design a compromise has to be made between reproducing the axially constant flow velocity and a zero axial pressure

WIND TUNNEL

- A wind tunnel is a specially designed and protected space into which air is drawn, or blown, by mechanical means in order to achieve a specified speed and predetermined flow pattern at a given instant.
- The flow so achieved can be observed from outside the wind tunnel through transparent windows that enclose the test section and flow characteristics are measurable using specialized instruments.
- An object, such as a model, or some full-scale engineering structure, typically a vehicle, or part of it, can be immersed into the established flow, thereby disturbing it.
- The objectives of the immersion include being able to simulate, visualize, observe, and/or measure how the flow around the immersed object affects the immersed object.

c.coomarasamy

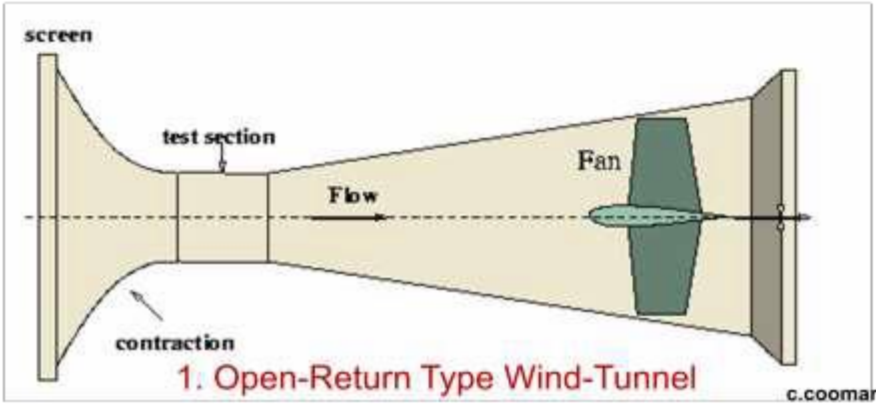
CLASSIFICATIONS OF WIND TUNNELS

Wind tunnels can be classified using **four different criteria** as given below.

1.Type 1 classification – The criterion for classification is the path followed by the drawn air: Open- vs. closed-circuit wind tunnels

(i) Open-circuit (open-return) wind tunnel. If the air is drawn directly from the surroundings into the wind tunnel and rejected back into the surroundings, the wind tunnel is said to have an open-air circuit.

A diagram of such a wind tunnel is shown in Figure 1.



1. Open-Return Type Wind-Tunnel

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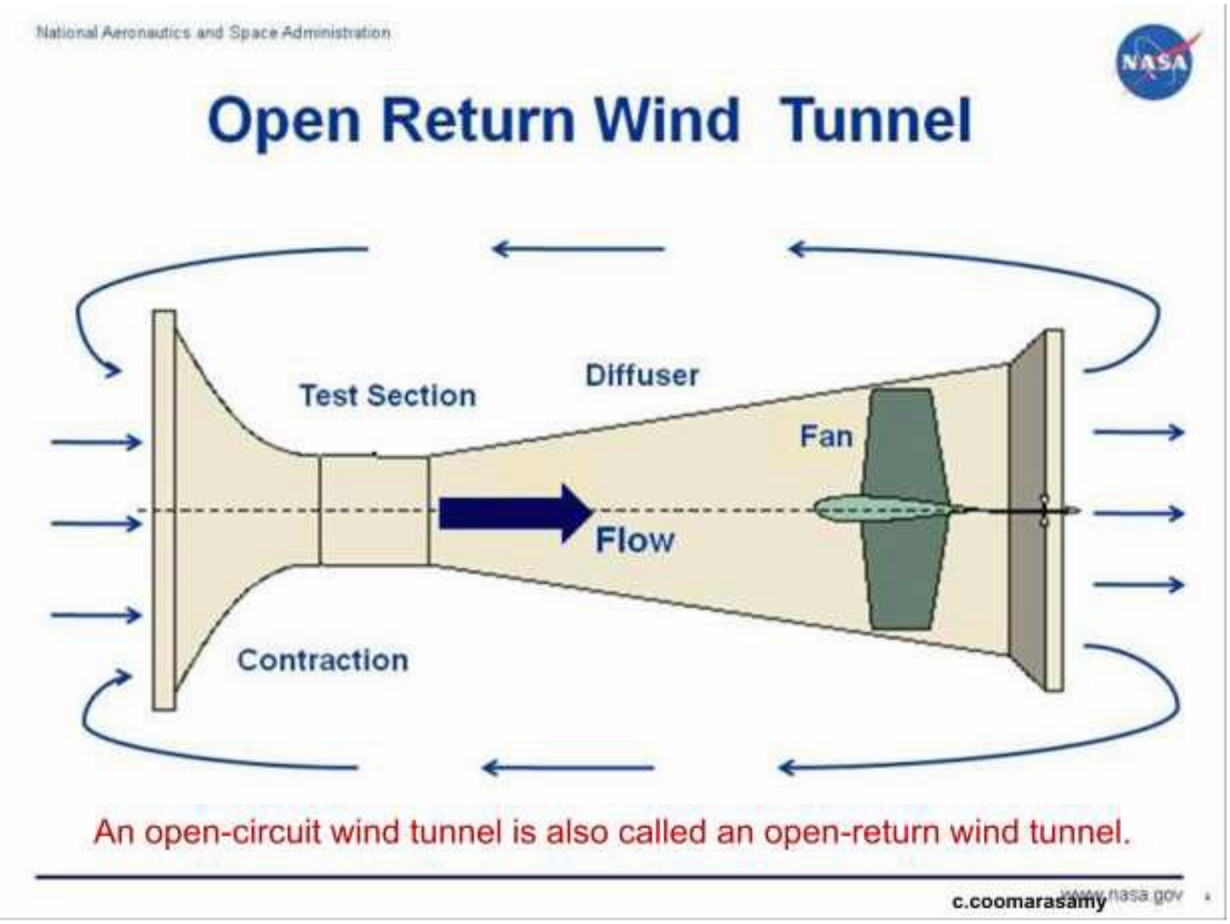

National Aeronautics and Space Administration

Open Return Wind Tunnel

An open-circuit wind tunnel is also called an open-return wind tunnel.

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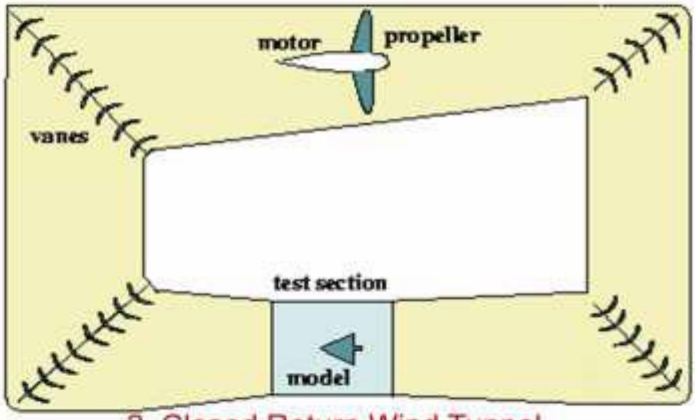
CLASSIFICATIONS OF WIND TUNNELS

(ii) Closed-circuit, or closed-return, wind tunnel. If the same air is being circulated in such a way that the wind tunnel does neither draw new air from the surrounding, nor return it into the surroundings, the wind tunnel is said to have a closed-air circuit. It is conventional to call that a closed-circuit (closed-return) wind tunnel. Figure 2 illustrates this configuration.



2. Closed Return Wind Tunnel

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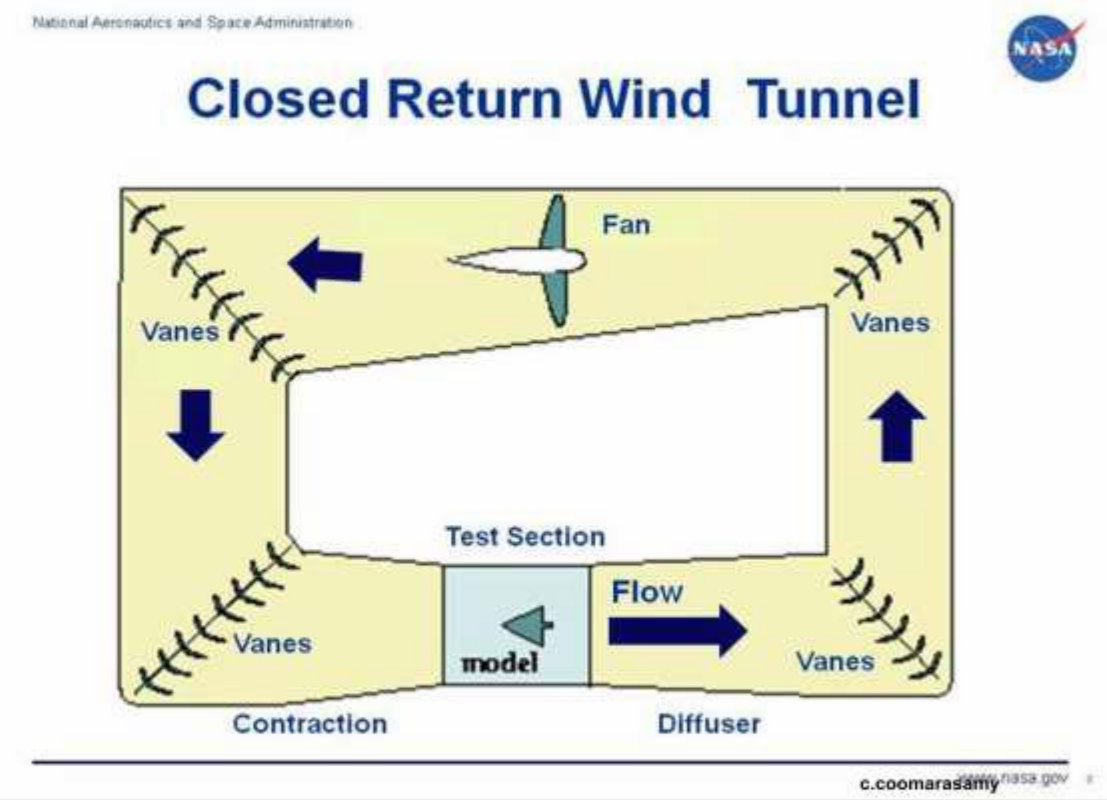

National Aeronautics and Space Administration

Closed Return Wind Tunnel

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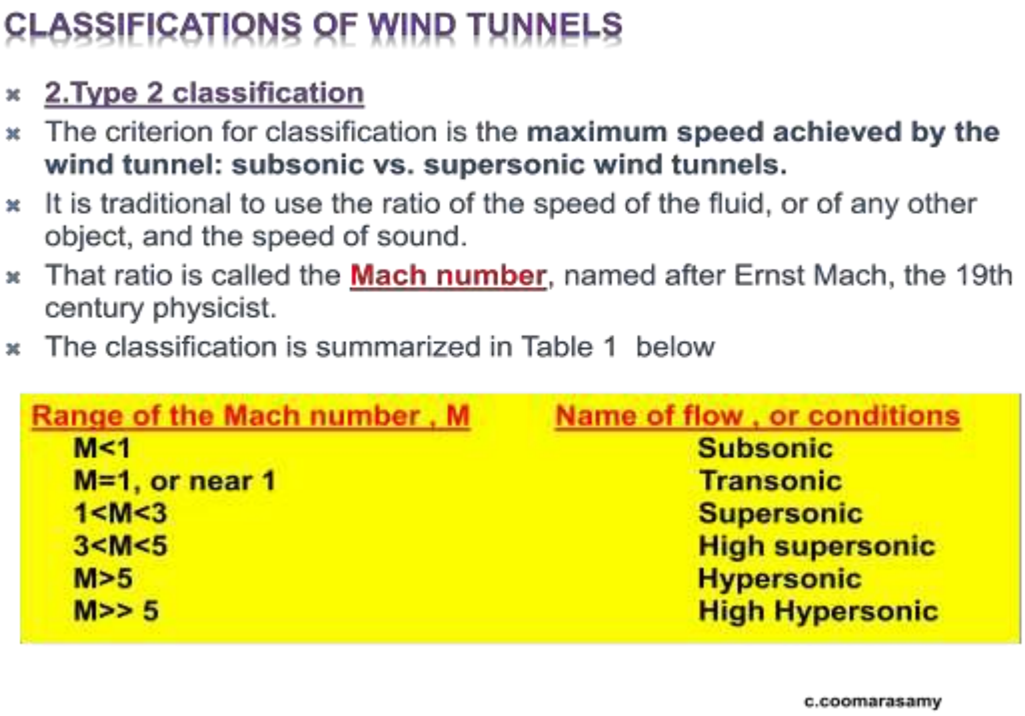

CLASSIFICATIONS OF WIND TUNNELS

- **2.Type 2 classification**
- The criterion for classification is the **maximum speed achieved by the wind tunnel: subsonic vs. supersonic wind tunnels.**
- It is traditional to use the ratio of the speed of the fluid, or of any other object, and the speed of sound.
- That ratio is called the **Mach number**, named after Ernst Mach, the 19th century physicist.
- The classification is summarized in Table 1 below

Range of the Mach number , M	Name of flow , or conditions
M<1	Subsonic
M=1, or near 1	Transonic
1<M<3	Supersonic
3<M<5	High supersonic
M>5	Hypersonic
M>> 5	High Hypersonic

c.coomarasamy

CLASSIFICATIONS OF WIND TUNNELS

Schematic designs of subsonic and supersonic wind tunnels are compared in Figure 3.

Subsonic wind tunnels.

- If the maximum speed achieved by the wind tunnel is less than the speed of sound in air, it is called **a subsonic wind tunnel.**
- The speed of sound in air at room temperature is approximately 343 m/s, or 1235 km/hr, or 767 mile/hr. **The Mach number, M <1.**

Supersonic wind tunnels.

- If the maximum speed achieved by the wind tunnel is equal to or greater than the speed of sound in air, it is called **a supersonic wind tunnel.**

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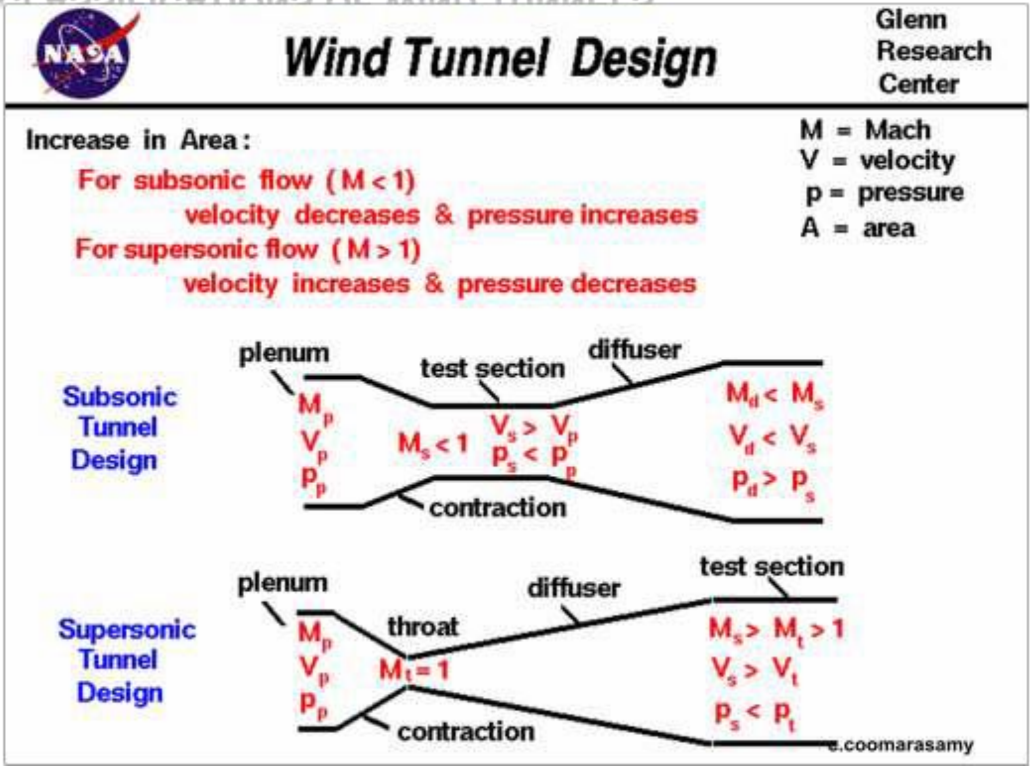
CLASSIFICATIONS OF WIND TUNNELS



Wind Tunnel Design

Glenn Research Center

Increase in Area:

For subsonic flow ($M < 1$) velocity decreases & pressure increases

For supersonic flow ($M > 1$) velocity increases & pressure decreases

M = Mach
V = velocity
p = pressure
A = area

c.coomarasamy

CLASSIFICATIONS OF WIND TUNNELS

Wind tunnels are designed for a specific purpose and speed range and there is a wide variety of wind tunnel types and model instrumentation. The model to be tested in the wind tunnel is placed in the test section of the tunnel. The speed in the test section is determined by the design of the tunnel. The choice of speed range affects the **design** of the wind tunnel due to compressibility effects.

For subsonic flows, the air density remains nearly constant and decreasing the cross-sectional area causes the flow to increase velocity and decrease pressure. Similarly, increasing the area causes the velocity to decrease and the pressure to increase. We want the highest possible velocity in the test section. For a subsonic wind tunnel, the test section is placed at the end of the contraction section and upstream of the diffuser. From a knowledge of the conservation of mass for subsonic flows, we can design the test section to produce a desired velocity or Mach number since the velocity is a function of the cross-sectional area. On the figure, we note the changes in Mach number, velocity and pressure through a subsonic wind tunnel design. The **plenum** is the settling chamber on a closed return tunnel, or the open room of an open return design.

CLASSIFICATIONS OF WIND TUNNELS

- For supersonic flows, the air density changes in the tunnel because of compressibility. In fact, the density changes faster than the velocity by a factor of the square of the Mach number. In a supersonic flow, decreasing the cross-sectional area causes the flow to decrease in velocity and increase pressure. Similarly, increasing the area causes the velocity to increase and the pressure to decrease. This change in properties is exactly the opposite of the change that occurs subsonically. In addition, compressible flows experience mass flow choking. As a subsonc flow is contracted, the velocity and Mach number increase. When the velocity reaches the speed of sound (M = 1), the flow chokes and the Mach number can not be increased beyond M = 1. We want the highest possible velocity in the test section of the wind tunnel. For a supersonic wind tunnel, we contract the flow until it chokes in the **throat** of a nozzle. We then diffuse the flow which increases the speed supersonically.

CLASSIFICATIONS OF WIND TUNNELS

The test section of the supersonic tunnel is placed at the end of the diffuser. From a consideration of conservation of mass for a compressible flow, we can design the test section to produce a desired velocity or Mach based on the area in the test section. On the figure we note the changes in Mach number, velocity and pressure through a supersonic wind tunnel design.

Notice that in both supersonic and subsonic designs, the velocity is increased and the pressure is decreased relative to the station upstream of the test section. In a subsonic tunnel the area is contracting into the test section; in a supersonic tunnel the area is increasing.

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CLASSIFICATIONS OF WIND TUNNELS

3. Type 3 classification

- The criterion for classification is the **purpose for which the wind tunnel is designed: research or education.**
- If the wind tunnel is for **research** it is called **a research wind tunnel.**
- If however, it is **designed to be used for education,** then, it is called an **educational wind tunnel.**

4. Type 4 classification

- The criterion for classification is **the nature of the flow: laminar** vs. **turbulent flow.**
- **Boundary- layer wind tunnels** are used to **simulate turbulent flow near and around engineering and manmade structures.**

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LOW SPEED WIND TUNNEL

- Universities and commercial organisations have wind tunnels for student use, for research and for hire.
- Some tunnels have moving floors for testing models of vehicles or full sized vehicles.
- They will be in all sizes but only a few will be very large so that the power needed to operate them can only be provided at night.
- Frequently the design of the tunnels is to a very poor standard when compared with design standard of the models that are tested in them.
- We need to have a clear idea of the goals of those who design wind tunnels. Discussion is for uses of fans and in this case their use in wind tunnels, not about model testing
- Mostly wind tunnels are used to investigate the flow of air over solid bodies of specified shapes with a view to measuring the forces exerted on the bodies and possibly reducing or increasing these forces as may be required by changing or refining the shape of the body.

- The tunnel will have a working section where the air flows over the models.
- This working section will be of uniform cross-section.
- Its size must be such that the flow pattern over the model is only marginally influenced by the presence of the walls of the working section.
- The rule is "the larger the better" but cost sets a constraint on size.
- The shape of the cross-section of the working section is influenced by what is to be tested.
- For example a model of a racing car would be tested in a tunnel where the working section is much wider than it is high whereas an aerofoil will be tested in one that is higher than it is wide.
- Engineers, who frequently have to exercise judgment, like to know with some certainty the test conditions especially the size and shape of the tunnel.

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- Generally the air flowing in the empty working section should have a velocity that is as nearly uniform across the section as possible and that the flow should be as free from turbulence as far as is possible.
- Turbulence can be in the form of eddies but that should not be the case for a well-designed tunnel.
- The turbulence could also be fine grain turbulence which cannot be eliminated but can be minimised.
- However if the tunnel is open, it takes in free air from the atmosphere and rejects to atmosphere.
- The open wind tunnel is a duct that is usually straight.
- Air enters one end at atmospheric pressure and at low velocity and leaves at atmospheric pressure.
- There is no reason why the air should not also leave at low velocity.
- If it does, the loss of energy and therefore the power required to drive the tunnel, is almost entirely due to friction.

For the air to leave at low velocity, the duct must be shaped to minimise the losses and guide blades, that act as flow straighteners, must be fitted and a diffuser. The fan must be fitted with a hub of suitable diameter and have the appropriate pitch.

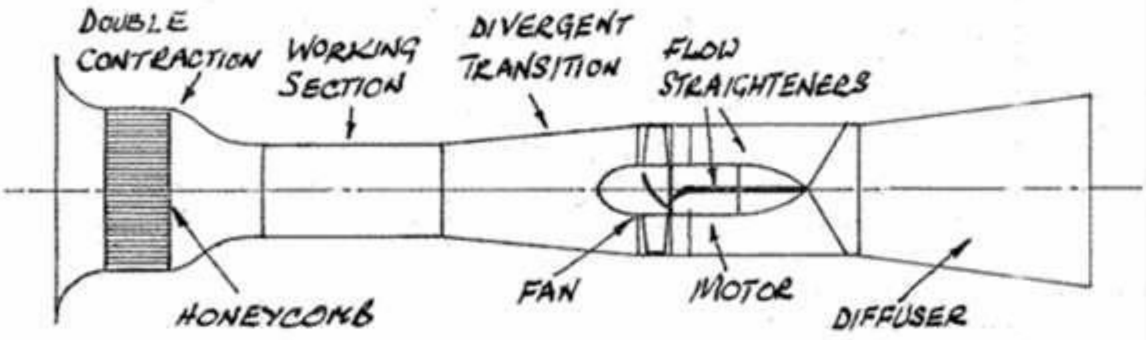

Fig 25-35

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- We can track the air as it flows through the tunnel.
- The fan is used to "suck" air through the working section. (Tunnels are never blown.).
- In order to get a high velocity the area ratio between the inlet and the working section must be as high as is practical and a double contraction with a honeycomb flow straightener in the short parallel section between the two contractions.
- This design of intake gives low turbulence and very acceptable uniformity of velocity in the working section.
- It seems that the fact that it is rectangular and not circular has no noticeable effect on the uniformity of the flow and a rectangular working section is desirable so that prismatic models can be used and understood by anyone.

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- However this rectangular section must change to be circular for the air to enter the fan.
- This involves a transition that must be designed to deliver the air to the fan at uniform velocity and still without large scale turbulence.
- Often this transition is seen as a job for a technician or to be a ready-made fitting for air-conditioning but this will not be enough; the transition must be designed properly in that the flow must not separate from the walls of the transition, and the loss to friction must be minimised.
- Further, depending on the areas of cross-section at exit from the working section and the intake to the fan, it may be possible to design this transition as a diffuser, that is, to recover some of the kinetic energy that has been created in the working section as a pressure rise.
- At the very least it must be designed for a minimum loss.

Fig 25-36

USES OF WIND TUNNELS

- There are **many uses of wind tunnels.**
- **They vary from ordinary to special: these include uses for Subsonic, supersonic and hypersonic studies of flight; for propulsion and icing research; for the testing of models and full-scale structures** Fig.4.**, etc.**
- Some common uses are presented below.

Wind tunnels are used for the following:

1. To determine aerodynamic loads

- Wind tunnels are used to determine aerodynamic loads on the immersed structure.
- The loads could be static forces and moments or dynamic forces and moments. Examples are
- forces and moments on airplane wings, airfoils, and tall buildings.

2. To study how to improve energy consumption by automobiles

- They can also be used on automobiles to measure drag forces with a view to reducing the power required to move the vehicle on roads and highways.

3. To study flow patterns

- To understand and visualize flow patterns near, and around, engineering structures.
- For example, how the wind affects flow around tall structures such as sky scrapers, factory chimneys, bridges ,fences, groups of buildings, etc. How exhaust gases ejected by factory, laboratories, and hospitals get dispersed in their environments.

4. Other uses include

- To teach applied fluid mechanics, demonstrate how mathematical models compare to experimental results, demonstrate flow patterns, and learn and practice the use of instruments in measuring flow characteristics such as velocity, pressures, and torques.

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The wind tunnel is used to measure fluid flow parameters.They are:

1) measurement of air speed;
2) verification of the existence of the boundary layer over a flat plate;
3} determination and characterization of the boundary layer over a flat plate;
4) searching for evidence of turbulence in boundary ayer flow;
5) measurement of pressure distributions around a circular cylinder in cross flow;
6}determination of the viscous wake behind a circular cylinder in cross flow;
7) determination of lift and drag force&around airfoils;
8) reduction of drag by the introduction of turbulence in the boundary layer; and
9) determination of the Richardson's annular effect in flow through a duct.

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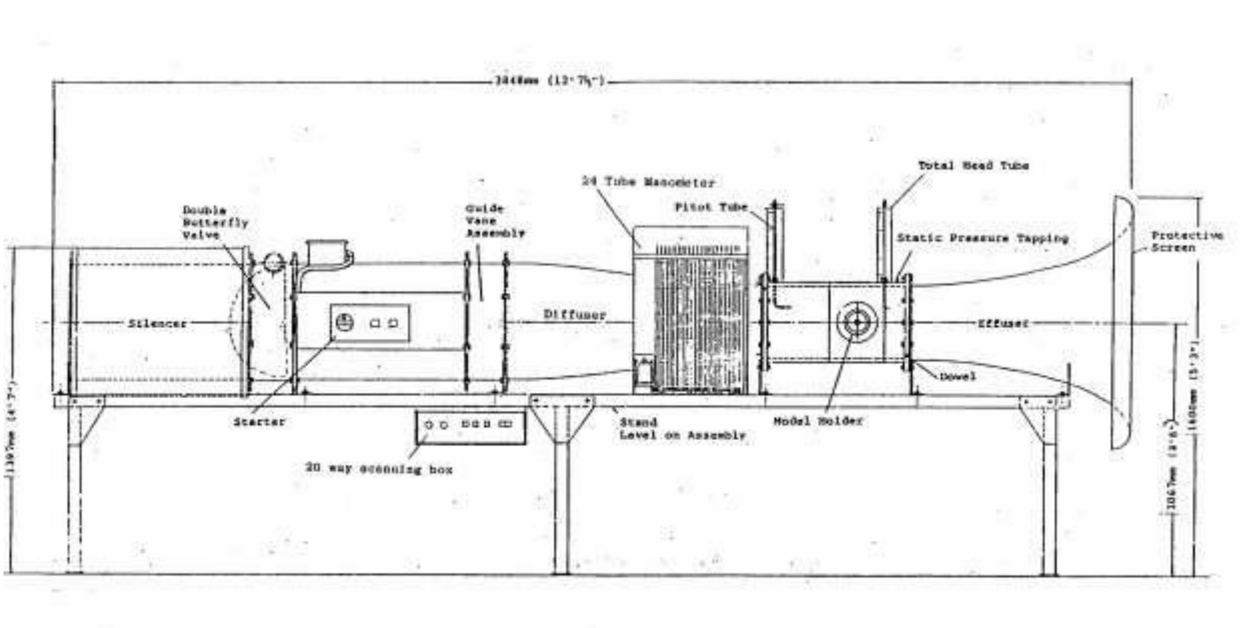

Fig.4. 7 300 mm x 300 mm Suction Wind Tunnel

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Figure .5. is a schematic of the wind tunnel setup for the normal flow case. The static pressure was measured with a series of static wall taps and the total pressure was measured with a pitot probe.

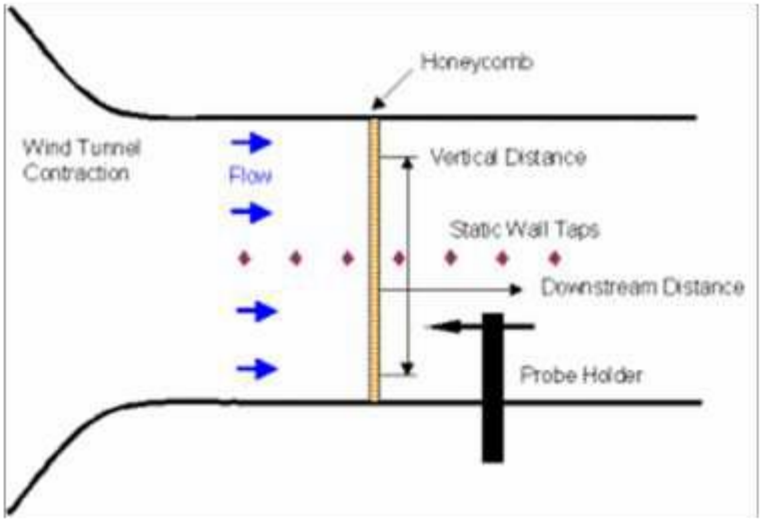

Fig.5. Normal Flow Wind Tunnel Schematic

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Figure 6 is a schematic of the wind tunnel setup for the grazing flow orientation. The total and static pressure was measure at all three stations. The velocity was also measured at station 1 and station 2 with a hot-wire anemometer.

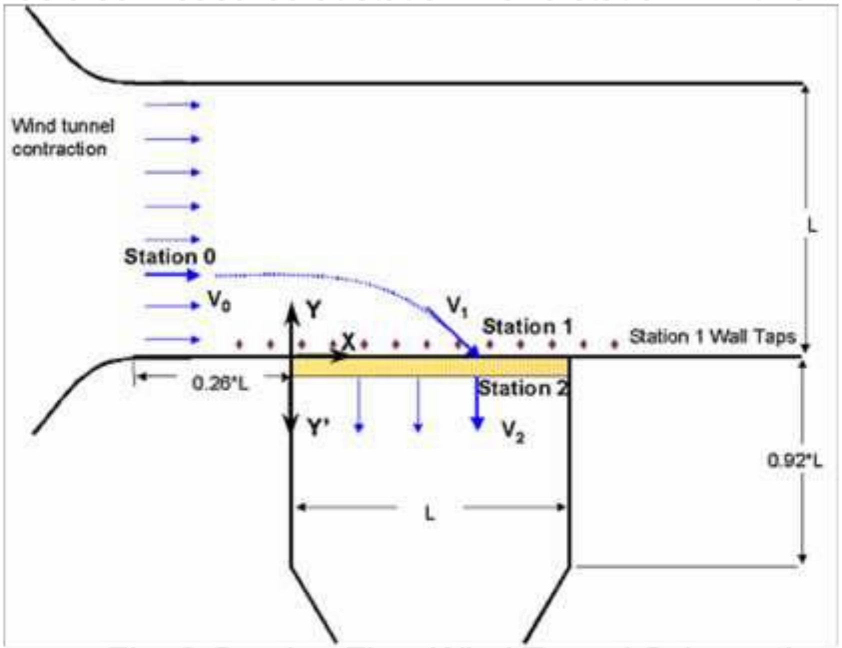
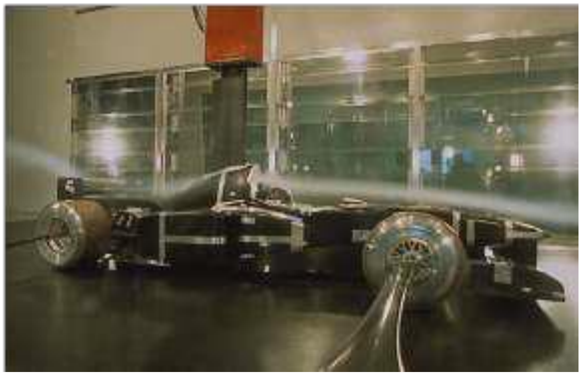


Fig. 6.Grazing Flow Wind Tunnel Schematic c.coomarasamy

Automobile Wind Tunnels



WIND TUNNEL TESTING

Wind tunnel testing

•The flow field around road vehicles is very complex:
–Large regions of flow separation
–Ground effect
•Simulation is less adapted to road vehicles than to aircraft
•Wind tunnel tests are more suitable.

Wind tunnels

•The types of wind tunnel that can be used in road vehicle tests are the same as for aircraft tests.
• However, full-scale tests are much more popular (and feasible) for cars than for aircraft.
•For full-scale tests, the size of the wind tunnel is of crucial importance:
– If it is too small the blockage effects will be enormous
–If it is large, it will be very expensive to build and run

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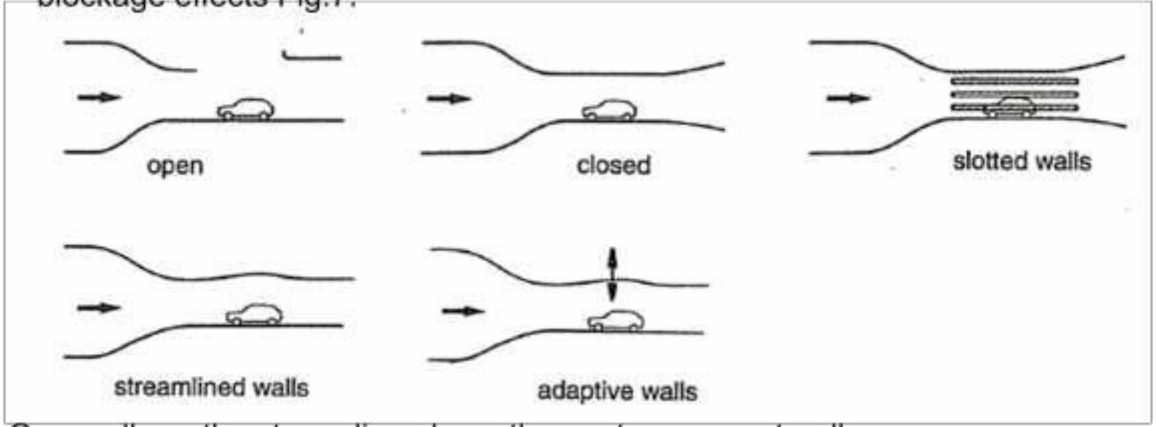
Types of working section

Apart from the closed section, all the working sections attempt to limit the blockage effects Fig.7.



Open: allows the streamline above the car to curve naturally.
•Slotted walls: allows the streamlines around the car to expand to a certain Extent.
•Streamlined walls: the walls follow the natural curves of the streamlines.
•Adaptive walls: same as streamlined walls but can be used for any geometry / wind condition

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WIND TUNNEL TESTING

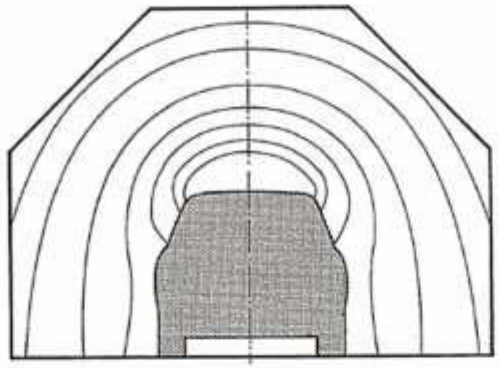

Fig. 8.Streamline matching

It is possible to match the cross-section of the working section to the isobars around the car.

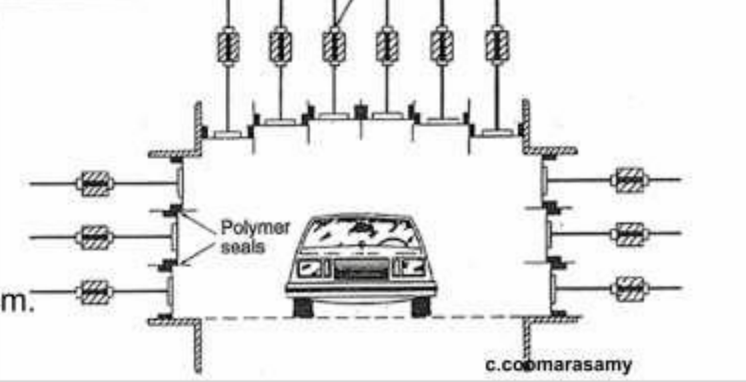

Fig.9.Adaptive walls

In practice, streamline matching is carried out using an adaptive wall mechanism.

Road representation

•In reality a car moves on a static road inside static air and its wheels roll.
•In a wind tunnel the car and floor are static and the air moves.
The wheels may or may not roll.
•This is representative of the air-car relative motion but not of the air-floor relative motion.
•In order to represent the latter, the floor must move with the free stream airspeed.

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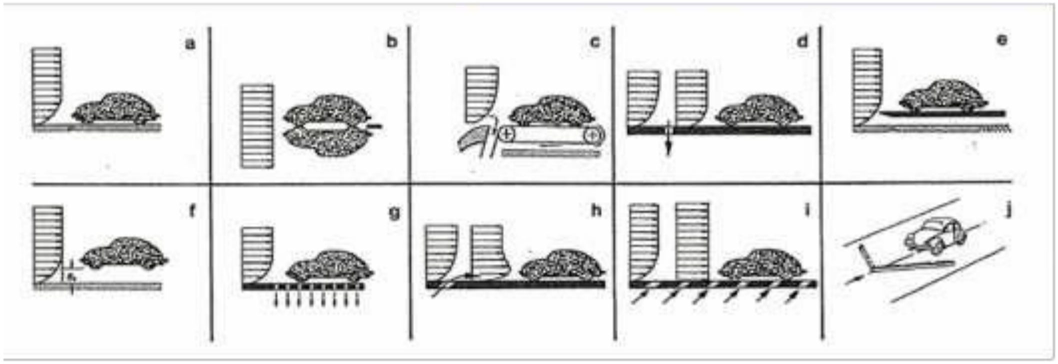
Fig.10.Possibilities for road simulation



a. No road simulation
b. Car and mirror image in the middle of the working section
c. Rolling floor and boundary layer suction
d. Boundary layer suction
e. Lifting the car and floor outside the boundary layer
f. Lifting only the car outside the boundary layer
g. Sucking air through the floor
h. Injecting air in the boundary layer to straighten it
i. Multi-point air injection
j. Blocking the boundary layer

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Choice of floor simulation

- The choice of the solution depends on the size of the wind tunnel, its configuration and the available budget.
- A moving floor is ideal but very expensive:
  - it must be perfectly synchronized with the free stream
  - it must not be sucked up into the working section because of the pressure difference
- Solutions without a moving floor are cheaper but they cannot force the wheels to turn – motors must be attached to the wheels.

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