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• Cover: Browning B-25 12-gauge shotgun from the FN custom shop in Belgium. Ribless 30" barrels, fine engraving and exhibition-quality wood. From the Andrew Tonkin collection. • Cover photograph: Japie van Reenen, Van Reenen Photography, Cell: 082 575 6219
• Contents photograph: Pierre van der Berg • Cover design: Thea Venter

BULLET BEHAVIOUR WHEN GOING THROUGH THE TRANSONIC VELOCITY RANGE

With reference to the .308 cal 168 gr Sierra bullet

Chris Bekker

When a bullet exits the muzzle of a rifle at maximum speed, i.e. its launched velocity, it loses velocity fairly quickly due to air-drag effects, especially over longer distances. Drag has a great effect on long range, as Palma and F-class shooters can attest to. This is why match bullets for competition shooters need a careful analysis of the effects of the shape of a bullet (the form factor) on the drag effects, so they minimise bullet drop, which is to flatten the trajectory curve as well as to minimise wind drift. In a nutshell, the idea is to design a streamlined bullet that is aerodynamically efficient.

The ballistic coefficient (BC) is a measure of how well a bullet can overcome drag; the higher the BC, the better the bullet can overcome the drag. The shape or form factor of a bullet (i) is the ratio of the drag coefficient for a test bullet to the drag coefficient of a "standard" bullet (for example G1 or G7). G1 and G7 both refer to aerodynamic drag models based on particular "standard projectile" shapes. The G1-shape looks like a flat-based bullet. The G7-shape is quite different and better approximates the geometry of a modern, long-range bullet.

The classic formulas are:

Sectional density = (weight in grains/7,000) / (Dia. x Dia.)
BC = SD/i (i being the form factor)

What is the speed of sound?

The **speed of sound** is the distance travelled per unit time by a sound wave as it propagates through an elastic medium. In dry air at 0 °C (32 °F), the speed of sound is 331.2 metres per second (m/s) or 1,087 feet per second (fps). At 20 °C (68 °F), the speed of sound is 343 m/s per second or 1,125 fps. In common everyday speech, speed of sound refers to the speed of sound waves in air. However, the speed of sound varies from substance to substance: sound travels most slowly in gases; it travels faster in liquids, and faster still in solids. Given normal atmospheric conditions, the temperature (and thus the speed of sound) varies with altitude:

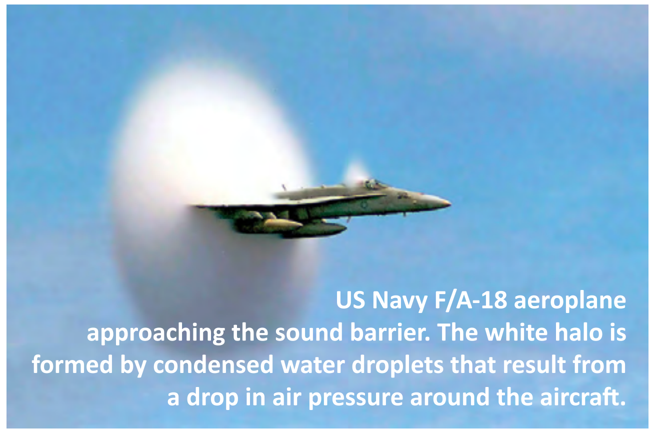
Altitude	Temperature	m/s	fps
Sea level	15 °C (59 °F)	340	1,116

The speed of sound is also referred to as Mach 1 and is divided into three categories, namely subsonic, transonic and supersonic, being the velocity ranges of importance to the shooter. The **subsonic range** is less than 273 m/s or 896 fps (translating to Mach 0.8). The **transonic range** is from 273 m/s to 409 m/s or 896 fps to 1,342 fps (translating to Mach 0.8 to Mach 1.3). Strange things happen to bullets in the transonic velocity range that affect stability as the "centre of pressure" point starts to recede from the tip. The **supersonic range** is thus from Mach 1.3 to Mach 5 or above 1,342 fps. Most, but not all, bullet velocities in rifles run from about 1,300 fps to 4,000 fps; in SI units that would be a high of 1219.2 m/s.

The Mach number in any media is the projectile speed compared to the speed of sound in that media. As a bullet passes through the atmosphere, it is subject to negative acceleration due to atmospheric drag, and as such, most rifle bullets will go from supersonic to transonic and eventually subsonic velocities at extended ranges. The **Mach number**, a useful quantity in aerodynamics, is the ratio of air speed to the local speed of sound.

What is a sonic boom?

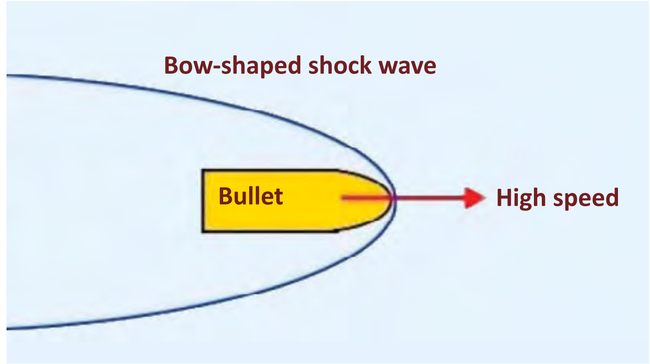
A **sonic boom** is the sound associated with the shock waves created whenever an object that is travelling through air travels faster than the speed of sound. It generates a significant amount of sound energy that is enough to sound similar to an explosion or a thunderclap to the human ear. This is the sound that we hear from a supersonic bullet or the crack of a bullwhip. The same happens to a warplane in supersonic flight that goes through the sound barrier.



US Navy F/A-18 aeroplane approaching the sound barrier. The white halo is formed by condensed water droplets that result from a drop in air pressure around the aircraft.

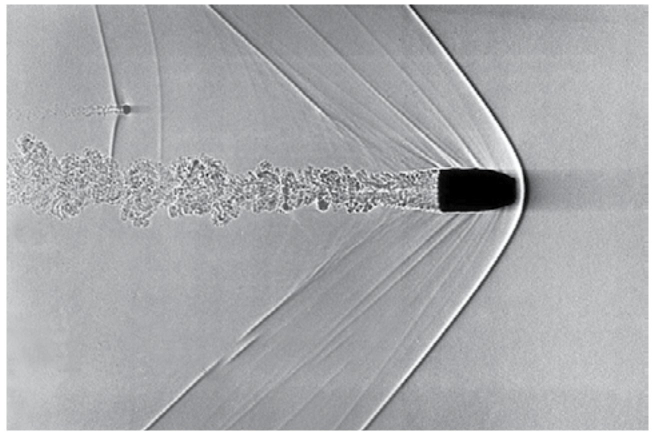
What is bullet bow shock wave?

A bullet bow shock wave is a **physical and audible wave** created in the air when a bullet travels at supersonic speeds, meaning faster than the speed of sound.



The bow shock wave image demonstrates the air pressure dynamics surrounding the bullet.

The bullet bow shock wave is the result of **air being greatly compressed** at the tip of the bullet. As the bullet slices through the air and moves forward, a broadening wave of compressed air trails out diagonally from the bullet tip. The sides of the bullet (bullet shaft) create a conical wave form that will be heard as a whip-crack sound. If the bullet passes close enough to a person, typically less than 2 ft, it can be felt against the skin. The bow wave is the primary force acting to slow the bullet. It stands to reason that the sharper the ogive or point of the bullet, the lower the bow wave drag will be, making it more aerodynamic. At subsonic velocities, the pressure wave travels ahead of the bullet, and so one will not hear the cracking sound of a passing bullet.



Shadowgraph image of a supersonic bullet showing the shock waves

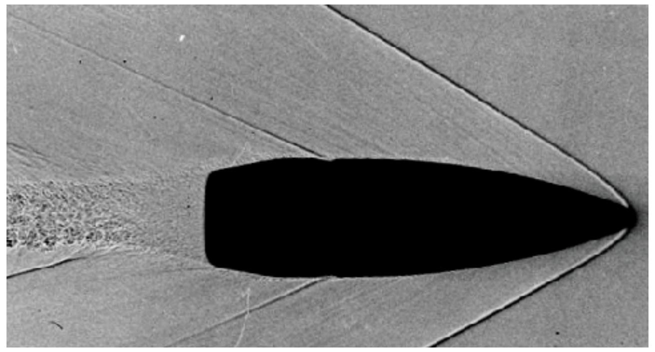
What is bullet surface drag?

Surface (aka skin) or parasitic drag is when the air flows across the bullet and **a boundary layer is created** between the surface of the bullet and the laminar flow, creating a surface drag on the bullet. When a bullet has grooves and a cannelure, it aggravates the surface drag situation. However, surface drag contributes less to bullet retardation than bullet bow drag. This is why match bullets used in long-range competitions are designed as smooth bullets without grooves and cannelures, so as not to lower the BC of the bullet.

What is bullet base drag?

This involves the rear end of the bullet – either a flat-base or a boat-tail design at various angles, yielding different drag profiles. As the air passes over the surface of the bullet, it drops over the base of the bullet, thereby creating a turbulence that creates a partial vacuum at the base. This vacuum pulls at the base, retarding forward velocity. The boat-tail design in effect helps the transition of **the laminar flow of area around the bullet** and reduces the area that is affected by base drag. The ogive or curve of the bullet is also affected by this base vacuum, increasing the drag of the ogive.

As can be seen, shock waves are created at every boundary change, the base in a flat-base bullet and the transition in a boat-tail design. Another wave is created at the end of the turbulence, following the bullet. The primary shock wave is formed at the tip of the bullet and the secondary wave on the bullet shaft, where one may find grooves or cannelures, and then the tail end of the bullet going on the wake that the flying bullet leaves.



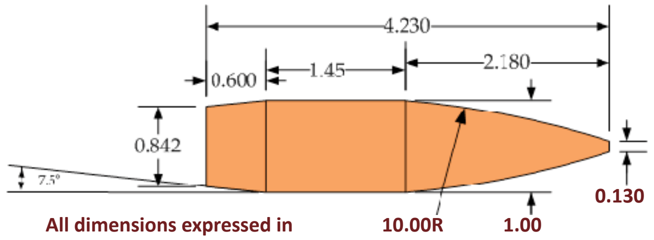
A boat-tail bullet, at the ideal angle range (7-9°), has as its objective to minimise the turbulence behind it and thus the overall drag.

Theodore von Kármán 11 May 1881–6 May 1963)

Theodore von Kármán was a Hungarian-American mathematician, aerospace engineer and physicist who was primarily active in the fields of aeronautics and astronautics. He was responsible for many key advances in aerodynamics, notably his work on supersonic and hypersonic airflow characterisation. Von Kármán was the inventor of the mathematical tools to study fluid flow, the mathematical background of supersonic flight, and the swept-back wing.

The G7-shape bullet (aka VLD bullet)

The abbreviation VLD denotes a "Very Low Drag" bullet, being the most efficient shape in terms of being aerodynamic. This bullet shape has been created specifically for long-range target shooting, yielding less bullet drop and velocity retention tendencies.



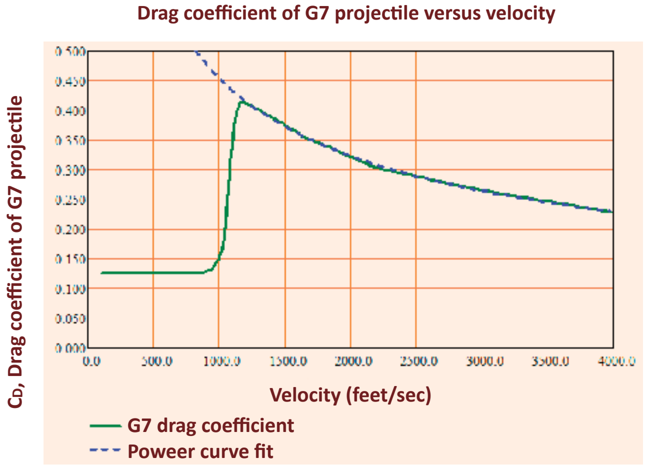
All dimensions expressed in calibres

The “drag coefficient”

The drag coefficient of a bullet has to be measured by live fire. By shooting many shots at various speeds (Mach numbers), a drag curve is established. This drag curve is used to determine the aerodynamic drag on a bullet at any speed. The aerodynamic drag coefficient is a measure of the effectiveness of a streamlined, aerodynamic body shape in reducing the air resistance to the forward motion.

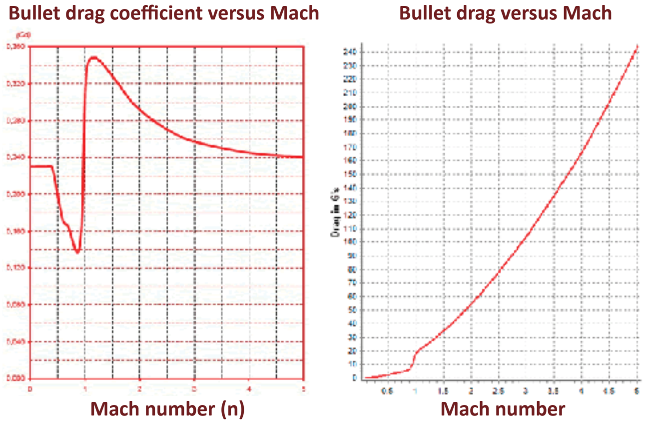
Just for clarification, herewith some observations on the drag coefficient:

- Below the speed of sound, in the **subsonic region**, drag follows a straight horizontal line, meaning the drag coefficient is constant.
- Drag shoots up in the **transonic region** to the point where the sound barrier is crossed and turbulence is experienced.
- Above the speed of sound, the **supersonic region**, the drag coefficient is **not** a constant.
- **Air drag is the strongest at about Mach 1**, but significantly weaker beyond that.
- **Air drag is lower below the speed of sound**, as indicated by a lower “coefficient of drag” in the diagram.
- The diagram below shows an example of the drag coefficient for the standard reference bullet, usually referred to as the G7 shape.



Drag coefficient plot (green line) for a G7 standard projectile

The formula for plotting the “drag coefficient” vs the “Mach number” isolates the bullet’s shape so that it can be compared to other shapes. While useful in designing bullets, it is difficult to visualise the drag a bullet experiences in flight from looking at a drag coefficient graph.



Bullet drag coefficient vs bullet drag

Taking into account all the factors affecting bullet drag, one should look at the graph entitled “Bullet drag vs Mach” (see above graph on the right) with drag in units of “G”. It is then easy to see that drag increases as velocity increases, with a large jump as velocity approaches Mach 1. It is now also clearer to see that beyond Mach 1 the bullet drag increases sharply in sympathy with velocity.

“G” represents the standard gravitational constant, which is defined as an acceleration of 9.81 m/s squared or the equivalent force of 9.81 newton per kilogram of mass. Thus, a drag of 100 Gs is the equivalent of 981 m/s squared, or a drag force of 100 times that of gravity acting on the bullet, which equates to a Mach number of 3.0 (roughly 3,348 fps).

The drag force can be expressed as:

$F_d = c_d \; 1/2 \; \rho \, v^2 \, A$

Where:

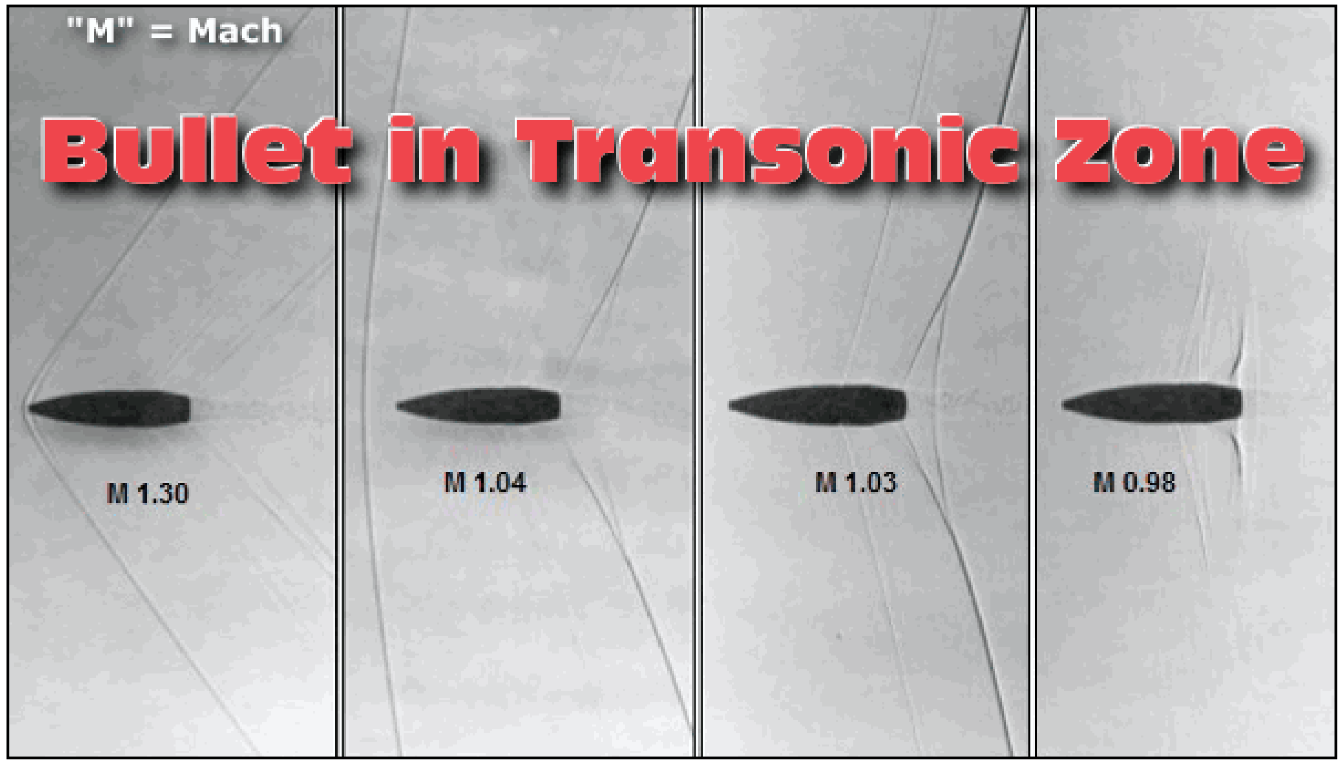
F_d = drag force (N)
c_d = drag coefficient
ρ = density of fluid (1.2 kg/m^3 for air at NTP)
v = flow velocity (m/s)
A = frontal area of the bullet (m^2)

The coefficient of drag (c_d) for a bullet is an aerodynamic factor that relates air drag to air density, cross-sectional area, velocity and mass. One way to view c_d is as the “generic indicator” of drag for any bullet of the same shape. Sectional density of the bullet can then be used to relate the drag coefficient to different bullet sizes.

The 168 gr Sierra bullet

This bullet was designed by Sierra for competition shooting at 300 yd, and later used by the US military. **The Sierra MatchKing bullet** with its 13° boat-tail angle experienced more turbulence at 1 000 yd than what was desirable, and it was all due to its large boat-tail angle not being ideal. Confirmation of this transonic performance phenomenon has since come from USMC snipers who say the M118LR bullet’s performance “falls off a cliff” beyond 800 m or 875 yd.

By contrast, **Berger 168-grainers** are designed as long-range bullets with 8.9°, 8.5° and a really nice 7° angle on the boat-tail, VLD and Hybrid respectively, and they perform much better on their journey through the transonic region. Bryan Litz, ballistician at Berger Bullets, says the ideal boat-tail angle is between 7° and 9°. Go much above 10° and it’s too steep for the air to follow around the bullet base. This seems to manifest itself as more increased drag and turbulence, leading to instability in transonic flight.



The 7.5mm Swiss rifle bullet shadowgraph

The four photos above show the substantial changes in the **shock wave and turbulence patterns** for the same bullet **at different velocities**. The “M” stands for Mach and the numerical value represents the velocity of the bullet relative to the speed of sound at the time of the shot (Photos are by Beat Kneubuehl). Transonic effects come into play, starting about Mach 1.2, as the bullet drops below 1,340 fps; this is when a bullet needs to have a more appropriate boat-tail angle to deal with the effects of the transonic region to remain dynamically stable. Clearly this is of no concern to hunters, as it is only an issue at extended range for target shooters.

When the bullet slows to transonic speed, approaching the speed of sound, the turbulence behind the bullet starts to have a destabilising effect on it, which is not good for accuracy. Essentially what happens is that the **“centre of pressure”** moves forward, which makes the “lever arm” longer between the “centre of pressure” and the **“centre of mass”**. Consequently, the **overturning moment** on the bullet gets bigger, resulting in the bullet experiencing more pitching and yawing in its flight and in group sizes opening up. The bullet may even start to tumble.

Handgun bullets

Since most of the drag on a subsonic bullet is on the base rather than the tip, the bullet can afford to have a “round-nose” profile as opposed to a “spitzer” profile. The blunter or rounder the exposed lead tip, the easier the bullet will expand on impact, especially with a hollow-point design. The BC of a handgun bullet is therefore immaterial, as it has a short-range application. Drag on handgun bullets is generally much lower than on rifle bullets flying at supersonic velocities.

Typically, subsonic ammunition is loaded to achieve speeds of between 950 and 1,050 fps to avoid crossing the sound barrier at around 1,125 fps. One finds these velocities in the .380 and .45 ACP pistols and .38 Special revolvers, etc.

Subsonic ammunition is specifically loaded so that the bullet does not exceed the sound barrier and create a sonic crack. The 9mm Parabellum, for example, is mostly loaded at supersonic velocities with a 115 gr bullet. When loaded with a 147 gr bullet, however, the round can be made subsonic.

It is not always true that subsonic bullets will be deflected less by crosswinds, as the higher deflection forces are compensated for by the reduced time of flight and thus the crosswind has more time to act on the bullet. However, at short range this is only of academic importance, but it is practically a non-event.

Equations of motion

Every bullet or projectile problem is essentially two one-dimensional motion problems with different equations for horizontal and vertical acceleration. The trajectory of a simple projectile is a parabola.

Equation	Horizontal	Vertical
Acceleration	$a_x = 0$	$a_y = -g$
Velocity time	$v_x = v_0x$	$v_y = v_0y - gt$
Displacement time	$x = x_0 + v_0xt$	$y = y_0 + v_0yt - ½gt^2$
Velocity displacement		$v_y^2 = v_0y^2 - 2g(y - y_0)$

Use the horizontal direction to determine the range as a function of time:

$$x = x_0 + v_0xt + \tfrac{1}{2}a_xt^2$$
$$x = 0 + (v\cos\theta)\,t + 0$$
$$x_{final} = (v\cos\theta)\,t_{final}$$

Use the vertical direction to determine the time in the air:

$$y = y_0 + v0_yt + \tfrac{1}{2}a_yt^2$$
$$y = y_0 + (v\sin\theta)t - \tfrac{1}{2}gt^2$$
$$0 = 0 + (v\sin\theta)t_{final} - \tfrac{1}{2}gt^2_{final}$$
$$t_{final} = \frac{2(v\sin\theta)}{g}$$

Combine these two equations:

$$x_{final} = (v\cos\theta)\,\frac{2(v\sin\theta)}{g}$$
$$x_{final} = \frac{v^2\sin 2\theta}{g}$$
$$x_{max} = \frac{v^2}{g}$$

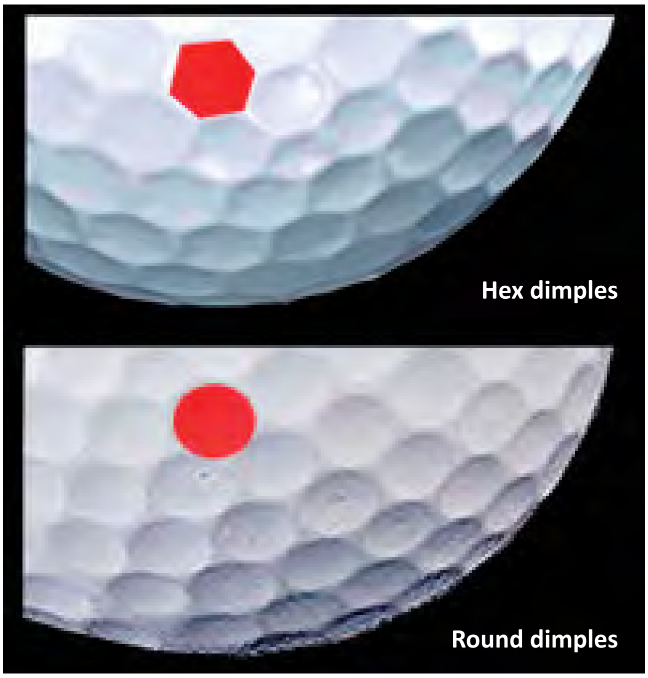
Why do golf balls have dimples?

Looking at a closely related phenomenon in golf balls, I wish to elaborate the mechanics of how design can affect drag. Have you ever wondered why a golf ball has dimples? The simple but amazing reason is that a smooth golf ball would travel only about half as far as a golf ball with dimples. When a golf ball is hit, its trajectory is controlled entirely by gravity and aerodynamics. As such, aerodynamic optimisation achieved through the dimple pattern design becomes a critical part of the development of a golf ball.

Dimples create a **turbulent boundary layer** as air flows past the golf ball. This allows the air to "hug" the surface further round the ball as it passes, reducing the size of its wake and, consequently, its drag. For this reason a ball with dimples of the right depth is more aerodynamic than a smooth ball.

Dimples also affect lift. A smooth ball with backspin creates lift by warping the airflow such that the ball acts like an airplane's wing. The spinning action makes the air pressure on the bottom of the ball higher than the air pressure on the top; this imbalance creates an upward force on the ball. Ball spin contributes about one half of a golf ball's lift. The other half is provided by the dimples, which allow for optimisation of the lift force.

The dimples on a golf balls have **a depth of about 0.010 inches (or 10-thou)**. The lift and drag forces on a golf ball are very sensitive to dimple depth: **a depth change of 0.001 inches (or 1-thou)** can produce a radical change to the golf ball's trajectory and the overall distance it can fly. Dimples have traditionally been spherical in shape, but it is possible to optimise the aerodynamic performance of other shapes.



Hex dimples vs round dimples

The HX golf ball by Callaway, for example, uses hexagons. A golf ball covered with **hexagonal and pentagonal dimples**, rather than the traditional circular ones, has been launched during March 2002. Its creators say it could improve player performance by travelling through the air more aerodynamically. According to Callaway, the HX ball was less affected by crosswinds than round-dimpled balls in testing. Each HX ball has a lattice network of 332 hexagons and 12 pentagons. The bottom of each dimple is flat and the edges curved, which Callaway says achieves the right aerodynamic balance between a small turbulent layer and drag.

In closing

By lowering drag and thus increasing the BC of a bullet, cartridges are now able to shoot at much longer distances than before by making a bullet with a G7 drag profile, as opposed to a G1 drag profile. With today's precision-made bullets for competition shooting, the appropriate twist rate to stabilise bullets at long range, as well as boat-tail profiles between 7 and 9°, bullets can now better cope with flying through the transonic range in 1 000 yd matches. For example, for a .308"-calibre bullet to arrive at the 1 000 yd target above the speed of sound, custom-made .308 Win Match rifles are fitted with very long (31") barrels to "milk" the velocity out of a relatively small-volume cartridge case, having a small energy source.

Increasing the velocity in these match cartridges also helps to minimise wind drift. Didion demonstrated this in his 1859 publication, stating that crosswind deflection is directly proportional to the difference of the time of flight through the atmosphere, minus the time of flight if the same bullet is shot at the same muzzle velocity through a vacuum.

It is also true that lowering the drag reduces wind deflection, but not if it is achieved by increasing the time of flight.