What a Drag!

Session Time: Three, 50-minute sessions

DESIRED RESULTS

ESSENTIAL UNDERSTANDINGS

The principles of aerodynamics allow an aircraft to fly, yet those same principles limit its ultimate performance and capabilities. (EU2)

Safe and efficient aviation operations require that pilots use math, science, and technology. (EU4)

A deep understanding of how an aircraft operates enables a pilot to fly the aircraft to its maximum capabilities in both normal and abnormal situations. (EU5)

ESSENTIAL QUESTIONS

1. Which parts of an airplane have the greatest impact on drag?
2. Does maximum lift create minimum drag?

LEARNING GOALS

Students Will Know

- The effect of drag on an aircraft
- Different types of drag
- How to minimize drag
- How to calculate drag using the drag equation
- The lift-to-drag ratio and its effect on an aircraft's maximum range and maximum glide distance

Students Will Be Able To

- *Explain* the two different types of drag (DOK-L2)
- *Explain* how wingtip vortices and ground effect influence drag (DOK-L2)
- *Calculate* elements of drag using the drag equation (DOK-L2)
- *Analyze* the impact of aircraft design elements on drag (DOK-L4)

ASSESSMENT EVIDENCE

Warm-up
During a quick demonstration, students will predict and test which of two similar, but not identical, objects will fall to the ground first. Their predictions and reasoning should relate to surface area and drag.

Formative Assessment
Students will complete an activity to demonstrate how landing gear contributes to parasite drag. At the end of the activity, students demonstrate what they have learned about parasite drag by explaining the differences between the three types of parasite drag and how airflow is affected by each of these types of drag.

Summative Assessment
Students will write a paragraph explaining the differences between parasite and induced drag, analyze aircraft design elements to determine their effect on drag, write a paragraph explaining ground effect, and answer a series of questions about the lift/drag ratio.

LESSON PREPARATION

MATERIALS/RESOURCES

- What a Drag! Presentation
- What a Drag! Student Activity 1
- What a Drag! Student Activity 2
- What a Drag! Student Activity 3
- What a Drag! Teacher Notes 1
- What a Drag! Teacher Notes 2
- What a Drag! Teacher Notes 3

Warm-Up Demonstration (per student)

- Two 8 x 11-inch pieces of paper

Drag Race (Per Group)

- Rubber band-powered propeller assembly (recommend using the propellers and rubber bands from the balsa wood airplane activity in lesson 4.D.1)
- Size #117B rubber band (if not included in the assembly above)
- Two drinking straws (recommend not using flexible drinking straws)
- Cardstock or manila file folders cut to size
    - One (1) - 5” x 7”
    - One (1) - 1 “ x 7”
    - One (1) - 3” diameter circle
- One brass fastener (brad fastener) size 1”
- 1 hook or pin to secure far end of rubber band propeller assembly (can use a paperclip)
- Transparent or masking tape
- Ruler/straight edge
- Protractor
- Tape measure or meter stick
- 5 meters of fishing line
- Permanent marker
- Scissors

- Hole punch (one per class)

Recommended Student Reading

- **Pilot's Handbook of Aeronautical Knowledge**
  Chapter Five, Section on Drag, Wingtip Vortices and Ground Effect https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf

LESSON SUMMARY

Lesson 1: What A Drag!

The lesson will begin with a warm-up to illustrate a familiar example of drag, using flat and crumpled pieces of paper. Students will discuss the importance of understanding drag for safe flight. Students will then be introduced to two types of drag: parasite drag and induced drag.

During the next part of the lesson, students will explore parasite drag in detail, with examples of form drag, interference drag, and skin friction drag. Students will learn about the relationship between parasite drag and airspeed. In a hands-on formative assessment, they will complete an activity to demonstrate how landing gear contributes to parasite drag.

Students will then explore induced drag and its relationship with airspeed, wing tip vortices, and ground effect.

In the last session, students will learn how to think about total drag, and even how to predict the effect of different flying parameters on drag using the drag equation. Students will learn to work with the drag equation and the lift/drag ratio.

During the summative assessment, students will write a paragraph explaining the differences between parasite and induced drag, analyze aircraft design elements to determine their effect on drag, write a paragraph explaining ground effect, and answer a series of questions about the lift/drag ratio.

BACKGROUND

Drag is one of the four forces of flight, and a major influence on aircraft performance. Since drag is the force that opposes thrust, minimizing drag is crucial to enabling higher airspeeds, faster acceleration, greater range and fuel savings.

Air is the fluid through which airplanes move. When an airplane flies through the air, it runs into air molecules that cause it to slow down. Energy from the moving airplane is transferred to the air molecules. In other words, some of the kinetic energy (energy it possesses because of its motion) from the airplane is given to the air molecules, slowing down the airplane and speeding up the surrounding air. The amount of energy lost by the airplane is exactly the amount of energy transferred to the air. Energy must go somewhere and in the case of drag, some of the energy in the movement of an object is transferred into moving the fluid in the path of the object (in the case of an airplane, moving the air around it). This transfer of energy results in two types of drag: parasite drag and induced drag.

Parasite drag is inherent in the design of the aircraft, and is caused by any aircraft surface that deflects or interferes with the smooth airflow around the airplane. There are three categories of parasite drag: form drag, interference drag and skin friction drag.

- Form drag is caused by the airplane pushing air molecules to the side so the airplane can pass by them. A streamlined shape (like an airplane wing) has very little form drag. A non-streamlined shape, like a parachute, has a lot of form drag.
- Interference drag is generated by the mixing of airflow streams where airframe components meet, such as the joint between the wing and the fuselage or between the engine pylon and the wing.
- Skin friction drag comes from air moving across the surface of the airplane. On a very small scale, the surface of an airplane is rough, like sandpaper. If you run your hand over sandpaper, the sandpaper catches your skin and slows

down your movement. The same thing happens with an airplane. The skin of the airplane catches the air particles next to it. This slows the airplane down.

Modern, streamlined aircraft designs are engineered to minimize parasite drag by maintaining laminar airflow, reducing interference and minimizing skin friction.

Induced drag is created at the tips of airplane wings. In order to achieve lift, the wings create a low-pressure region above the wings and a high-pressure region below the wings. At the tip of the wing, high-pressure air underneath the wing tries to move around the end of the wing to the low-pressure air on top of the wing. This creates a swirling vortex of air at the wingtip. The energy needed to move the air in the vortex is taken from the movement of the airplane, creating induced drag. Aircraft designers work to minimize induced drag by incorporating design elements such as winglets, high aspect ratio wings, and drag-efficient wing planforms.

Ground effect, which makes the airplane seem like it's floating on a cushion of air when near the ground, is an example of how reducing the amount of induced drag changes aircraft performance. As the airplane gets close to the ground, the vortices produced at the wingtips strike the ground, which interferes with the swirling motion and reduces the amount of induced drag produced.

The ratio of lift to drag (L/D) is the measure of how efficiently an aircraft produces lift. It helps us find (at L/D_{max}) the most amount of lift for the least amount of drag. L/D_{max} is useful in determining the angle of attack at which to fly an aircraft in order to get the greatest range for the least amount of energy. This is useful for conserving fuel or gaining distance in an engine-out scenario.

MISCONCEPTIONS

Students may believe that the mechanism for creating drag is always the same. In fact, the two types of drag – parasite drag and induced drag – have very different mechanisms and explanations. Students may find parasite drag more intuitive. It is similar to the drag they are familiar with from wading or swimming through water. Most students will understand that high speeds increase parasite drag and that streamlined design can be used to reduce drag.

Induced drag, which results from the production of lift, may be less familiar. Induced drag is a byproduct of lift production. It can be found at the tips of airplane wings where swirling vortices are created as air tries to move from the high-pressure area below the wing to the low-pressure area above the wing. Unlike parasite drag, induced drag is especially prominent at low airspeeds and high angles of attack.

In Student Activity 2, students may be surprised to discover that L/D_{max} occurs at a relatively low angle of attack (AOA). Since L/D is a ratio of lift to drag, the maximum depends on the variability of both lift and drag.

Students may not appreciate the parallels between drag and lift. In fact, the drag equation and lift equation are identical except for a single term. The coefficient of drag (C_D) in the drag equation is replaced by the coefficient of lift (C_L) in the lift equation.

DIFFERENTIATION

To promote reflective thinking and guided inquiry in the **ENGAGE** section of the lesson plan, circulate around the classroom and assist students as they consider the significance of the paper drop results in the Warm-Up. It may not be obvious at first how a downward-falling piece of paper relates to a forward-flying airplane. Although we typically discuss drag as opposing forward thrust, it is the force that opposes motion through a fluid, so it applies to the falling paper in this case as well.

To support successful aircraft model construction for Student Activity 1 in the **EXPLAIN** section, create one of the models ahead of time and demonstrate how to "fly it" along the fishing line using the rubber band-powered propeller.

To support metacognitive skills in the **EXTEND** section of the lesson plan, provide multiple examples of the calculations that students are expected to perform for the drag equation. Walk through the examples and verbalize your thoughts, demonstrating what learners are expected to do in the assignment.

LEARNING PLAN

ENGAGE

Teacher Material: What a Drag! Presentation

Slides 1-3: Introduce the topic and learning objectives of the lesson.

Slides 4-5: Conduct the Warm-Up.

Dropping the flat and crumpled paper is a familiar, everyday example of drag at work. Students may intuitively expect the crumpled paper to fall faster because the smaller surface area results in less interaction with the air as it falls. But students may be surprised that this is the same basic phenomenon at work in airplanes, and one of the four forces of flight.

Warm-Up

Give each student two pieces of 8 ” by 11” inch paper. Ask the students to keep one of the pieces of paper flat and crumple the other piece into a ball. Then ask students to predict which piece of paper will reach the ground first when both are released simultaneously from the same height. Have each student write his or her predictions and reasoning on a piece of paper. Then have students test their hypotheses by dropping the flat and crumpled pieces of paper at the same time, from the same height.

Allow students to share and discuss their results before moving to the next slide.

Explain the result:

- They weigh the same
- Flat paper has more surface area than crumpled
- More surface area = more drag
- More drag = slower movement through the air

The crumpled piece of paper will hit first because it has less surface area and therefore, less drag. In a vacuum, both pieces of paper would hit the ground nearly simultaneously due to the lack of drag caused by air friction.

[DOK 2; predict, infer]

EXPLORE

Teacher Material: What a Drag! Presentation

Slides 6-7: Ask students to recall the four forces of flight: lift, weight, thrust, and drag.

- Lift is what pulls an airplane into the sky. Created by wings on an airplane, or the rotor blades of a helicopter or drone, lift, by definition, acts perpendicular to the relative wind or the line of flight.

- Weight is the force of two masses being attracted to each other. It is the force that pulls objects toward the center of the earth, and makes things fall down.
- Thrust is created by the jet engines or propellers of an airplane. Thrust is the push that moves an aircraft through the air.
- Drag is the resistance (or friction) to things moving through the air. It is caused by air particles bumping into the object.

Objects moving through a fluid (air or water) experience drag. Examples include a hand (or a dog's head) out a car window, or a golf ball flying through the air. Swimmers experience drag too, which is why they often shave their body hair.

When an airplane flies through the air, it runs into air molecules that cause it to slow down. Energy from the moving airplane is transferred to the air molecules. In other words, some of the kinetic energy (energy it possesses because of its motion) from the airplane is given to the air molecules, slowing down the airplane and speeding up the surrounding air.

Drag is not generally viewed as beneficial since pilots want airplanes to move forward very quickly and drag slows them down. Overcoming drag has always been a primary design challenge for aerospace engineers. Students should know that airplanes overcome drag by generating thrust.

Teaching Tips

Ask students if they can think of a situation where drag is a good thing.
Possible answers: *To help cars stop after a drag race, to slow down an airplane when it lands on a runway, etc. An excellent example of drag being a useful force is during skydiving. Skydivers rely on drag from their parachutes to slow down their descent.*

Slide 8: A good pilot needs a solid understanding of drag, as it is important for both safety and performance.

To ensure safety, a pilot may need to determine how to reduce drag in critical situations, such as on climb-out, go-arounds (an aborted landing), and during recovery from a stall. In another example, if a pilot experiences an engine failure, the airplane will become, in effect, a glider. It is essential for the pilot to know the best glide speed -- the airspeed at which the airplane will travel the most distance forward for each increment of altitude lost. As students will learn later in the lesson, the best glide speed is when drag is minimized, and the lift/drag ratio is maximized.

In terms of performance, good pilots know how to reduce drag. To fly efficiently, it's important that pilots understand how drag affects their airplane in different phases of flight. Reducing drag gives the airplane more effective thrust and increases its range by reducing the amount of fuel burned to travel a given distance.

But drag isn't always bad! For example, a pilot attempting to land on a short runway with trees on the end will need to make a very steep approach. To keep the descent speed under control, a pilot will add drag by extending flaps. This often happens in places like remote strips in Alaska.

Show students the video of a Cessna 180 making a short, steep approach into a landing strip in Alaska. Students should note that the pilot has the flaps fully extended.

- "Cessna 180K Short Landing Over Trees" (Length 00:37)
  http://video.link/w/ykye

EXPLAIN

Teacher Materials: What a Drag! Presentation, What a Drag! Teacher Notes 1
Student Material: What a Drag! Student Activity 1

Slide 9: There are two types of drag: parasite drag and induced drag.

Parasite drag is the drag created by the airframe's resistance to forward motion. Put your arm out of a car window as it's cruising down the road—your arm is creating parasite drag. Induced drag is a byproduct of lift. it is the drag produced when an airfoil creates lift.

In this lesson, parasite drag and its three forms will be covered first. Then, students will learn about induced drag.

Slide 10: Parasite drag is a part of the aircraft and is caused by any aircraft surface that deflects or interferes with the smooth airflow around the airplane. The faster an airplane flies, the greater the parasite drag. Double the airspeed, and parasite drag quadruples. For example, an airplane has four times as much parasite drag at 160 knots as it does at 80 knots.

Subtypes of parasite drag are form drag, interference drag, and skin friction drag.

This video describes the three types of parasite drag.

- "Principle of Flight -- Parasite Drag" (Length: 1:43)
  http://video.link/w/V2ee

Slide 11: Form drag is the result of an object's general shape in relation to the relative wind. It is caused by the airplane and its components pushing air molecules to the side so it can pass by them. When air flows around the aircraft or a component, the flow separates and rejoins on the other side. A more streamlined shape allows the flow of air to rejoin faster with less turbulence, reducing form drag.

Ask students if they've ever stuck their hand out the window of the car, first holding it parallel to the pavement, and then tilting it vertically, into the wind. They might have noticed that when their hand is horizontal like an airfoil, little effort is required to stick it outside. But when they tilt their hand upward into the wind, it has a tendency to fly backwards and more force is required to hold it in position. This is one of the easiest ways to understand form drag.

When it comes to airplanes, a Boeing 747 creates much more form drag than something small like a Cessna 172. Many aircraft are designed with retractable landing gear which, when raised, significantly reduces form drag. But the form drag from landing gear can also be used to a pilot's advantage when trying to slow down quickly, for instance.

Questions

Ask students what parts of an aircraft might produce the most form drag.

Possible answers include: The largest, flattest surfaces will produce the most form drag. The fuselage and wings create a lot of drag. Landing gear that doesn't retract, bulky wing struts, or floats all create form drag.

Slide 12: Interference drag is generated by the mixing of airflow streams between airframe components such as the wing and the fuselage or the landing gear strut and the fuselage. As air flows around different aircraft components and mixes, the turbulence that is formed creates a drag sum greater than the drag components would have by themselves.

One common example of interference drag is the corner created by the junction of the wing to the body of the airplane, also known as the wing root. Two currents of air -- one traveling over the fuselage, and one traveling over the wing -- meet in a turbulent collision. Perpendicular angles like this are particularly bad for interference drag, so designing vertical components away from the wings can help. In addition, fairings can be used to smooth out the junction and reduce interference drag.

Slide 13: Skin friction drag is the resistance of air moving across the surface of the airplane. On a very small scale, the surface of an airplane is rough, like sandpaper. If you run your hand over sandpaper, the sandpaper catches your skin and slows down hand movement. The same thing happens with an airplane. The "skin" of the airplane catches the air particles next to it and tries to pull the air particles along.

The behavior of the boundary layer is key to the function of the airfoil. Layers of air just above the wing surface move slowly, while those further away move faster, until finally higher layers move freely at the free-stream velocity. The layer between the surface and the free-stream velocity is the boundary layer, which acts almost like a physical surface in terms of the airflow's interaction. This creates an invisible "effective shape" to the airfoil that affects lift and drag characteristics.

Show students a video which describes skin friction drag in greater detail.

- "Skin Friction Drag" (Length: 2:56)
  http://video.link/w/P2ee

Slide 14: Complete the **Formative Assessment**. Provide **What a Drag! Student Activity 1** to each student. The objective of this activity is to demonstrate how landing gear contributes to parasite drag. The activity sheet provides step-by-step instructions for building air trolleys and test lines. Although students will work in groups to complete and test the air trolleys, each student will work individually to answer the formative assessment questions at the end of the activity.

The formative assessment will begin in the first session, and will continue into the second session.

Formative Assessment

In this activity, students will build an air trolley -- a propeller-driven carriage that travels along a fishing line. The "landing gear" is modeled using a round card on a leg attached to the body of the trolley with a brass fastener. This allows the landing gear to be fully extended, partially extended, or fully retracted. Students will test the effect of each condition on drag by measuring the distance moved along the fishing line. As long as the test conditions are otherwise the same (e.g., the propeller's band is twisted the same number of times and the air trolley starts at the same point), any change in distance traveled will reflect a change in drag.

At the end of the activity, students will answer questions about the effect of parasite drag on the air trolley. They will also explain the differences between the three types of parasite drag—form drag, interference drag, and skin friction drag—and how airflow is impacted by each of these types of parasite drag. Students will give an example of the parts of an airplane that produce each type of parasite drag. Answers can be found in **What a Drag! Teacher Notes 1.**

[DOK 3; draw conclusions, DOK 2; explain, cause/effect]

Teaching Tips

If students are done early, suggest that they compare the effect of the second, smaller Wheel B. They can also compare the drag effect of the landing gear retracted versus having the landing gear entirely removed. In other words, does retracting the landing gear fully ameliorate its effect on drag?

Slide 15: Induced drag is also called lift-induced drag, because it is an inherent part of production of lift by the airfoil. No system can be completely efficient, including lift production by a wing. The inefficiency in lift production is induced drag.

To produce lift, the airfoil is tilted with a positive angle of attack (AOA). The lift produced by the airfoil is always perpendicular to the relative wind. Since the relative wind follows the upper curve of the airfoil, the produced lift is not vertical, but tilted backwards. This "real lift" can be described as a vector with a vertical component (effective lift), and a horizontal rearward component (induced drag). So, unlike parasite drag, induced drag is a byproduct of the airfoil's production of lift.

Slide 16: As students will recall, an aircraft must constantly produce the correct amount of lift to counterbalance the weight of the aircraft. As an aircraft accelerates, it produces much more lift since lift increases with the square of increasing velocity. To avoid this unwanted excess lift, the pilot lowers the pitch of the aircraft to maintain level flight, and therefore the angle of attack, to maintain a constant amount of lift.

Looking at the diagram from the previous slide, it's apparent that reducing the angle of attack also reduces the rearward component of lift, meaning that there is less induced drag at lower angles of attack. Since low angles of attack correlate with high airspeeds, students should see that induced drag decreases with increasing airspeed.

Slide 17: As students learned in the lesson on lift, generating lift creates a high pressure area below the wing and and low pressure area above it. The high pressure area below the wing seeks to fill the low pressure area above it by swirling over the wingtip. As the airplane moves forward, this creates a corkscrew like pattern in the air. This corkscrew, or vortex, interferes with the downwash produced by the wing, creating induced drag.

- "Incredible Wingtip Vortices" (Length 00:45)
  http://video.link/w/kyze

Slide 18: Reducing induced drag has been a goal of aircraft designers as long as there have been airplanes. One of the approaches to reducing induced drag has been to eliminate or reduce the effect of wingtip vortices. If vortices could be prevented, it would significantly reduce the drag on the airplane. Turned up wingtips, called winglets, are one of the ways designers have found to decrease induced drag.

Another way to reduce induced drag is to increase the aspect ratio of the wing. Aspect ratio is the ratio between the wing's length and chord. A high aspect ratio wing is long and narrow, like the wings of a glider. (It is very important to reduce drag on gliders as much as possible.) Some wing planforms also reduce vortices and induced drag. An elliptical wing is the most successful, but is difficult to manufacture. Tapered wings aren't as effective as elliptical, but are easier to construct and therefore a common compromise.

Slide 19: When flying close to the ground (within half a wingspan) the ground interferes with the the airflow patterns (vortices, upwash and downwash) around an airfoil that create induced drag. This has the effect of reducing induced drag. To a pilot, it feels as if there is a cushion of air near ground.

Slide 20: Ground effect can be a double edged sword on takeoff. On the positive side, it will allow an airplane to fly at a slower speed than it could outside of ground effect. This can be used to get the airplane into the air more quickly to allow easier and faster acceleration than would be possible on the ground. This is most often encountered on unpaved runways, especially runways with soft or muddy ground, that would significantly reduce an airplane's ability to accelerate, and increase takeoff distance.

On the other hand, if the aircraft lifts off at too low an airspeed because of ground effect, it may not have enough speed to fly outside of ground effect, and could end up settling back onto the runway.

Slide 21: During landing, ground effect can cause an aircraft to "float" just above the runway, past the intended point of landing. This could be a problem on short runways or in cases where the pilot has excessive speed. An aircraft will not land as long as it has flying speed, and ground effect can make it difficult to slow down to that speed. Pilots must plan for ground effect.

Slide 22: These videos illustrate how clever design can lead to the development of unusual aircraft that take advantage of ground effect.

- "Caspian Sea Monster Ekranoplan Flight Video" (Length: 1:10)
  http://video.link/w/e4ee
- "Hovercraft Meets Aircraft | World's Strangest" (Length: 2:11)
  http://video.link/w/f4ee

These videos conclude the second session.

EXTEND

Teacher Materials: **What a Drag! Presentation**, **What a Drag! Teacher Notes 2**
Student Material: **What a Drag! Student Activity 2**

Slide 23: Engineers calculate the drag on airplanes by using information about the size, shape and speed of the airplanes. Using this information, they can decide how much thrust is needed to overcome drag and keep the airplane aloft.

Drag calculations must account for all forms of drag.

Total Drag = Induced Drag + Parasite Drag

This video explains how to think about total drag.

- "Drag" (Length: 2:49)
  http://video.link/w/p4ee

Slide 24: Because induced drag is caused by the production of lift, it should be no surprise that it is greatest at high angles of attack and low airspeeds. This is because at lower airspeeds, a higher angle of attack is needed to produce enough lift to counteract the aircraft's weight. (Remind students that weight is the force pulling the aircraft toward the center of the Earth. It acts in the direction opposite to lift.) The result is that induced drag increases proportionally to the increase in angle of attack. Or, to put it another way, the amount of induced drag varies inversely with the square of the airspeed.

The opposite is true of parasite drag, which increases as the square of airspeed.

When graphed, it's easy to see that there's a point where induced drag and parasite drag are minimized. For every aircraft there will be a specific airspeed at which total drag is minimized.

Slide 25: The drag equation can be used to calculate drag on an aircraft. But students can make inferences about the factors affecting drag based on the equation itself, without the need to make any calculations. The elements of the equation indicate what factors affect drag. These include density, velocity, and surface area. The relationships among these elements indicate the magnitude of their impact on drag. For instance, since air density (ρ or "rho") is in the numerator of the drag equation, we know that drag will vary directly with changes in air density. Because velocity squared is in the numerator (V^2), we know drag will vary with the square of velocity.

You can explain to students that ρ ("rho") is used here instead of "d" for "density", because "d" typically indicates distance. Students should also understand that, like the coefficient of lift, the coefficient of drag is difficult to calculate directly. Instead, it is determined through experimentation and testing.

Slide 26: Compare the drag equation to the lift equation students used in previous lessons. Note that the only difference is that the coefficient of drag replaces the coefficient of lift. This is significant because it means the same factors--density, velocity, and surface area--affect both drag and lift. And, like the coefficient of lift, the coefficient of drag is specific to the shape of the airfoil and the angle of attack.

Slide 27: By holding all but one variable steady, students can easily see the impact of individual factors on drag. In this example, only the air density changes while velocity and coefficient of drag are held constant. Students have already inferred that drag will vary directly with changes in density. By calculating how drag changes when density changes, students can see the significance of this single factor in determining drag. Before showing students the calculation on the next slide, ask them to predict how the decrease in air density will affect drag. Will the change be large or small?

Slide 28: Looking at the drag equation, we see that drag is directly proportional to air density. Therefore when air density changes, drag will change by the same relative amount. Because all other variables are held constant, we can determine the relationship between drag at the surface and drag at 10,000 feet by dividing. On this day, the change in air density means that at 10,000 feet, drag is 73.9 percent of the drag at the surface--a reduction of 26.1 percent.

Slide 29: Now let's consider just the effect of a difference in velocity. In this case, the airspeed doubles but all other variables are held constant. If airspeed is doubled, does that mean that drag is doubled too? Looking at the drag equation, students can infer what will happen when airspeed doubles. Because drag is proportional to velocity squared, when airspeed doubles, drag will quadruple.

Slide 30: A quick calculation can demonstrate the relationship between velocity and drag more precisely. When using the drag equation students should first convert knots to feet per second (1 kt = 1.7 ft/sec).

Because we are holding all other variables constant, students can determine how airspeed affects drag by squaring each of the velocities and then dividing. They will see that, as predicted, when velocity doubles, drag quadruples.

Questions

Ask students if it is necessary to convert the units to determine that a doubling of speed would quadruple drag.Also ask them if it is necessary to know the exact speeds at all. Why or why not?

Possible Answer: No, and no. We could make the calculation using knots--but only because the rest of the variables were held constant. We also can determine the relationship between airspeed and drag just by looking at the equation, without the need for specific numbers.

Slide 31: L/D ratio is the ratio of lift to drag. The L/D ratio can be used as a way to determine whether an aircraft or an airfoil produces lift efficiently. The higher the L/D ratio, the more efficiently the aircraft produces lift. (The most amount of lift for the least amount of drag.) Remind students that the lift and drag equations are almost identical. The only difference is that the lift equation includes the coefficient of lift while the drag equation uses the coefficient of drag.

As a result, we can calculate the L/D ratio by finding the ratio of the coefficients. In other words, $L/D = C_L/C_D$.

Slide 32: L/D_{max}, or the maximum L/D ratio, is important because it represents the point where drag is minimized and the aircraft produces lift most efficiently. This is also the point where the aircraft has maximum range and maximum glide range. Why might it be important to know how to achieve the maximum glide distance? Answer: In an emergency, a pilot may have to glide to a landing. Using the longest glide distance allows the pilot to glide farther to a safe place to land. It is important to note that for a given aircraft, L/D_{max} will occur at a particular angle of attack. A higher or lower angle of attack will reduce the aircraft's efficiency.

Slide 33: Help students gain confidence in using the drag equation with **What a Drag! Student Activity 2.** Remind them that they should hold constant any variables for which they don't have information. They should see similarities with their previous work on the lift equation.

Find the answers in **What a Drag! Teacher Notes 2.**

EVALUATE

Teacher Materials: What a Drag! Presentation, What a Drag! Teacher Notes 3
Student Material: What a Drag! Student Activity 3

Slides 34-39: Quiz students on questions related to ground effect for the Private Pilot Knowledge Test.

Slide 40: Conduct the **Summative Assessment.**

Summative Assessment

At the end of the lesson on drag, students will complete a summative assessment that requires them to write a paragraph explaining the differences between parasite and induced drag, analyze aircraft design elements to determine their effect on drag, write a paragraph explaining ground effect, and answer a series of questions about the lift/drag ratio.

Sample student responses are contained in **What a Drag! Teacher Notes 3**.

Summative Assessment Scoring Rubric

- Follows assignment instructions.
- Writing shows evidence of the following:
    - Understanding of the different types of drag and their causes
    - Understanding of impact of aircraft design and construction on drag
    - Understanding of ground effect and its impact during takeoff and landing
    - Understanding of the lift/drag ratio and its importance for aircraft
- Contributions show understanding of the concepts covered in the lesson
- Contributions show in-depth thinking including analysis or synthesis of lesson objectives

Points **Performance Levels**

9-10 Student clearly explains the differences between parasite drag and induced drag. Student shows a clear understanding of how aircraft design elements affect drag. Student writing shows a strong understanding of ground effect and its role during takeoff and landing. Student clearly defines the lift /drag ratio and shows understanding of its importance to pilots. There are no gaps in understanding.

7-8 Student writing adequately explains the differences between parasite drag and induced drag. Student shows an adequate understanding of how aircraft design elements affect drag. Student writing shows sufficient understanding of ground effect and its effects during takeoff and landing. Student adequately defines the lift/drag ratio and explains its importance to pilots. There are minor gaps in understanding.

5-6 Student writing partially explains the differences between parasite drag and induced drag, the role of aircraft design in creating drag, the role of ground effect during takeoff and landing, and the importance of the lift/drag ratio to pilots. There are several gaps in understanding.

0-4 Student writing inadequately explains the differences between parasite drag and induced drag, the role of aircraft design in creating drag, the role of ground effect during takeoff and landing, and the importance of the lift/drag ratio to pilots. There are many gaps in understanding.

GOING FURTHER

Drag's Importance for Aircraft Design - Some students will be interested in drag from the point of view of a pilot, while others may be more interested in how drag considerations influence aircraft design. Encourage those students to explore how aircraft have become more streamlined since 1903.

For instance, the Wright Flyer and other early airplanes had two sets of thin wings supported by struts and wires. It was later discovered that even those thin wires created surprising amounts of drag, and thus later airplanes had thicker single wings that did not require such bracing.

To inspire further exploration, ask the students to predict how unmanned aircraft (UAS) might be improved in the future to reduce drag. How do the different requirements of a drone lead to novel drag challenges? How might these be ameliorated?

STANDARDS ALIGNMENT

NGSS STANDARDS

Three-dimensional Learning

- **HS-ETS1-2 -** Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering
    - Science and Engineering Practices
        - Asking Questions and Defining Problems
        - Constructing Explanations and Designing Solutions
    - Disciplinary Core Ideas
        - ETS1.A: Defining and Delimiting Engineering Problems
    - Crosscutting Concepts
        - None
- **HS-ETS1-3 -** Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.
    - Science and Engineering Practices
        - Constructing Explanations and Designing Solutions
    - Disciplinary Core Ideas
        - ETS1.B: Developing Possible Solutions
    - Crosscutting Concepts
        - None

COMMON CORE STATE STANDARDS

- **RST.9-10.2 -** Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.
- **RST.9-10.4 -** Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics.
- **WHST.9-10.2 -** Write informative/explanatory texts to examine and convey complex ideas, concepts, and information clearly and accurately through the effective selection, organization, and analysis of content.
- **WHST.9-10.6 -** Use technology, including the Internet, to produce, publish, and update individual or shared writing products, taking advantage of technology's capacity to link to other information and to display information flexibly and dynamically.
- **WHST.9-10.8 -** Gather relevant information from multiple authoritative print and digital sources, using advanced searches effectively; assess the usefulness of each source in answering the research question; integrate information into the text selectively to maintain the flow of ideas, avoiding plagiarism and following a standard format for citation.
- **WHST.9-10.9 -** Draw evidence from informational texts to support analysis, reflection, and research.
- **HSN.VM.A.1 -** Recognize vector quantities as having both magnitude and direction. Represent vector quantities by directed line segments, and use appropriate symbols for vectors and their magnitudes (e.g., v, |v|, ||v||, v).
- **HSN.VM.A.2 -** Find the components of a vector by subtracting the coordinates of an initial point from the coordinates of a terminal point.
- **HSN.VM.A.3 -** Solve problems involving velocity and other quantities that can be represented by vectors.

REFERENCES

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