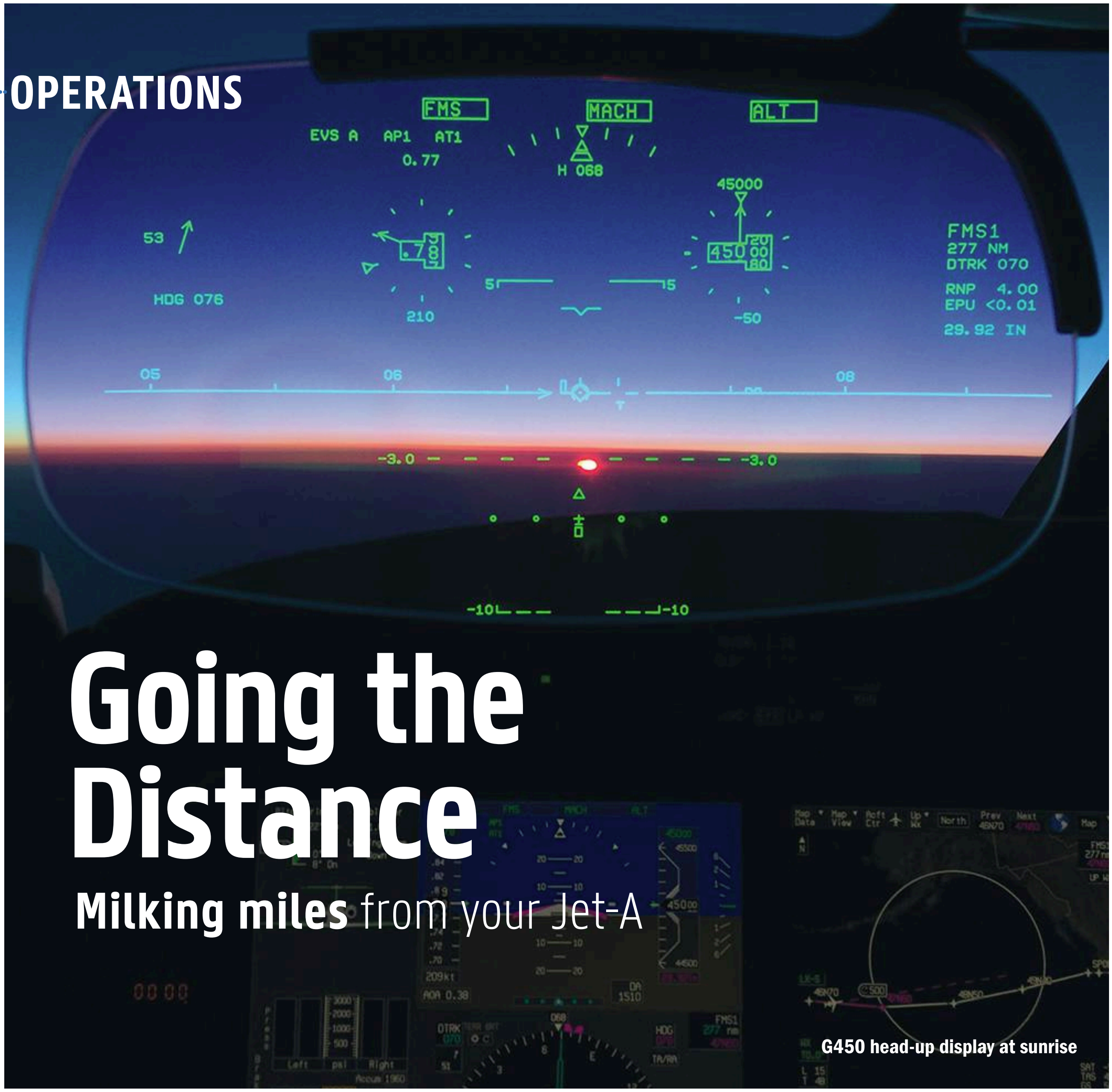
Going the Distance

Milking miles from your Jet-A



G450 head-up display at sunrise

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Most professional pilots earn their instrument ratings sitting behind one or more propellers, after having learned textbook definitions of maximum endurance and range speeds.

We learn early on that max range speed not only gives our craft its longest legs, but it also gets us to our destination with the most fuel remaining. We also know that maximum endurance speed uses less fuel in a holding pattern and that gives us more time to wait for the weather to improve, to sort out abnormalities or to just make things right for an eventual landing. In each case, the correct answer to the question "how fast?" gives us needed flexibility. But some of the rules change when we graduate to jets. And in some cases the textbook theory doesn't work in the real world.

A propeller-driven aircraft with a reciprocating engine is sometimes said to be "altitude ambivalent," meaning altitude selection isn't critical when trying to get the most from the fuel on board. However, the same cannot be said of a turbine engine. A prop-driven aircraft also tends to have a "one size fits all" speed when determining maximum range or endurance, the speed where the ratio of lift to drag is highest. That isn't true for a jet. Only after learning to maximize fuel economy in a jet can we answer the questions: How high do we climb? How fast do we fly? And how much will it cost?

Back to School

A jet engine produces thrust by accelerating air and spent fuel aft, as Sir Isaac Newton's second law of motion states: F=ma. The "m" (mass) is the fuel and the air, the "a" is the acceleration, and the resulting force "F" is the thrust. Newton's third law tells us that for every action force — in this example, air and fuel going aft — there is an equal and opposite reaction force — or, the aircraft going forward. An aeronautical engineer can diagram the thrust versus the velocity to look at the relationship of one to the other. But how can we measure this?

Thrust depends on the acceleration of the mass, but that changes with the velocity of the aircraft itself. The only true measure of a jet engine's thrust is found on a test stand with the engine stationary, hence the term "static thrust." The best we can do for an airplane in motion is to look for an analog to thrust, such as drag or fuel flow.

In steady, unaccelerated flight, drag is equal to thrust. Total drag is the combination of induced and parasite drag. At low speeds, a jet aircraft requires high angles of attack, which spikes the induced drag. At high speeds, the entire jet aircraft becomes a speed brake, causing parasite drag to increase prohibitively. The result is the familiar Nike swoosh or "u" shape of the total drag curve, and that drives the theory behind the answers to "how high?" and "how fast?"

How High?

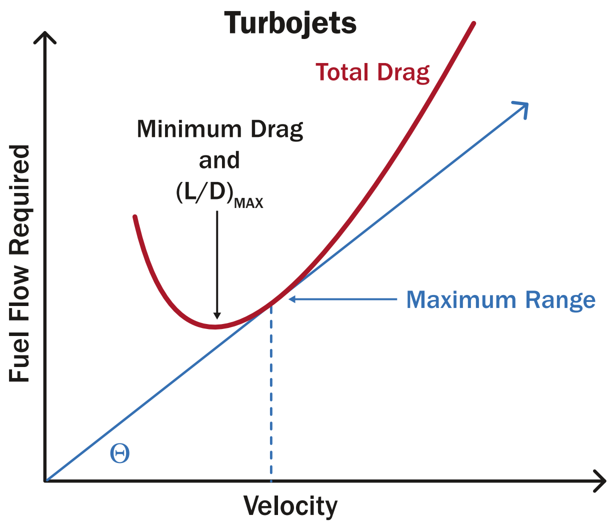
Many pilot and aeronautical engineering texts are confused on the subject of climbing to achieve maximum range. Most acknowledge a jet engine performs best at higher RPMs and that lower inlet temperatures reduce specific fuel consumption. But some claim all benefits end where the tropopause begins and fuel economy may actually suffer at higher altitudes. This theory ignores the fact that high technology fuel control units and full authority digital engine (or electronic) controls can extract performance gains at altitudes once thought impossible. So in theory, pilots need only refer to their airplane performance manuals to answer the "how high?" question. But does that track with actual operating experience?

Just because the book says you can make a certain altitude doesn't mean you will be allowed to, or even be able to do so. We deal with the first problem on just about every long-distance flight; the second is more insidious and surprises many pilots at the worst possible moment.

Due to increased air traffic and limited airspace, more and more countries are implementing 1,000-ft. vertical separation standards, typically between FL 290 and FL 410. Outside this airspace, 2,000-ft. vertical separation is the norm. Because most of the world also uses IFR cruising altitudes based on direction, you will likely have to select an altitude 2,000 or 4,000 ft. below optimal. But even these altitudes could be too high when flying across an ocean.

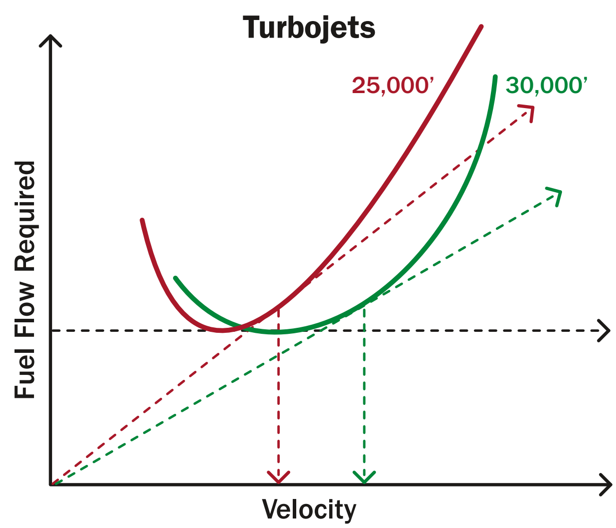
The North Atlantic has the most-crowded oceanic airspace in the world. And it may also be the most difficult in terms of altitude selection. Novice international pilots often select an altitude based on their airplane's apparent surplus of thrust

Drag or Thrust Required Versus Velocity



when leveling off over Newfoundland going east or over Ireland when going west. They cross their oceanic entry points and once over the warmer ocean are shocked to see their engines pushed up to the redline and their airspeed decaying toward stall. Because the North Atlantic Track system imposes strict longitudinal spacing rules (Mach number technique), the decay in speed is unacceptable so the only option is to descend. But even that option may disappear if all the lower flight levels are already taken. The only remaining option at that point would be to declare an emergency. (This will result in a loss of considerable international pilot style points and you could quite possibly lose your international pilot privileges to boot.)

Fuel Flow Required Versus Velocity, Impact of Altitude

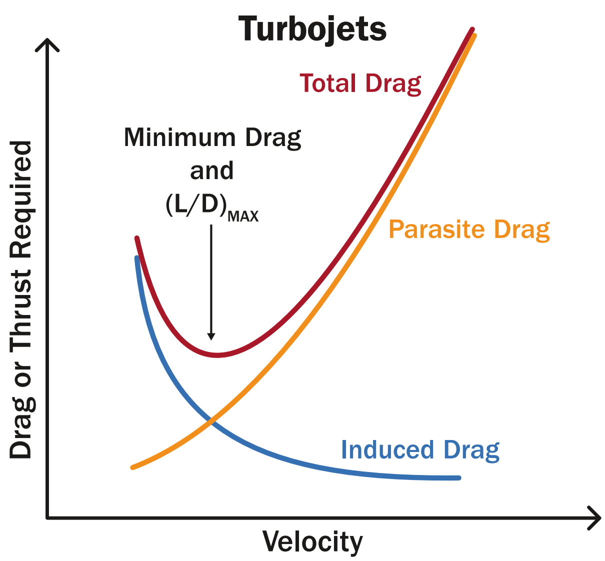


A good technique to avoid this embarrassment is to base your current altitude on the outside air temperature (OAT) at your next available climb waypoint. For example, let's say you are flying a Gulfstream IV from Westchester County Airport (KHPN) in White Plains, New York to Farnborough Airport (EGLF), outside London, England, and your flight plan shows you climbing to FL 410 just prior to coast out. The temperature is forecast to be right at -56C and you suspect the airplane will do just fine. The flight plan also says you can climb to FL 450 about 3 hr. later, where the OAT is predicted to be a balmy -46C. Does this sound like a reasonable plan?

Not so fast. Since you can't be sure when the temperature will actually rise, ask yourself if the airplane will hold speed at that warmer temperature at the coast-out point. If it can't, the cost of a poor forecast could force you to descend into someone else's airspace. One technique to preclude this is to base your initial cruise altitude and airspeed on the warmer temperature you expect 3 hr. later, not the cooler temperature at coast out. Then, when you get to the next predicted climb point, repeat the process and look for the next temperature rather than the current temperature.

Another technique would be to always head for the next lower altitude. This works well for many airplanes flying above RVSM altitudes, as flying 4,000 ft. lower gives ample margin. A GV, for example, may indicate FL 470 is optimal. Selecting FL

Maximum Range on a Fuel Flow Versus Velocity Graph



430 should work perfectly. If your maximum altitude is within RVSM airspace, however, flying only 2,000 ft. lower may not provide enough margin. A Challenger 604 with an optimal altitude of FL 370 over Gander may not be able to hold Mach once oceanic at FL 350. In this case, a careful check of the charts or the FMS with the next expected OAT would be prudent. In either case, after you've answered "how high?" there comes the companion question.

How Fast for Maximum Range?

Those pilot and aeronautical engineering textbooks usually give us two answers when it comes to selecting the best speed to fly: maximum range and maximum endurance. For maximum range, we need to go as fast as possible using the least amount of fuel. "Specific range," an airplane's measure of fuel economy, is simply the nautical miles an airplane flies per pounds of fuel consumed.

$$\textit{Specific Range} = \frac{\textit{Distance (in nm)}}{\textit{Fuel (in lb.)}}$$

Note that the term says nothing about the speed for maximum range. So we need to do a little mathematical manipulation to answer the "how fast?" question. We simply multiply both the distance and fuel by the fraction (1/hr.). Since we are multiplying the numerator and denominator by the same factor it is the same as multiplying by the number 1 and changes nothing. As pilots we call the top part (nautical miles per hour) "knots" and the bottom part (fuel flow) becomes pounds per hour. And now the formula shows us exactly what we need to know: In order to maximize range we need to go as fast as possible while burning the least fuel as possible.

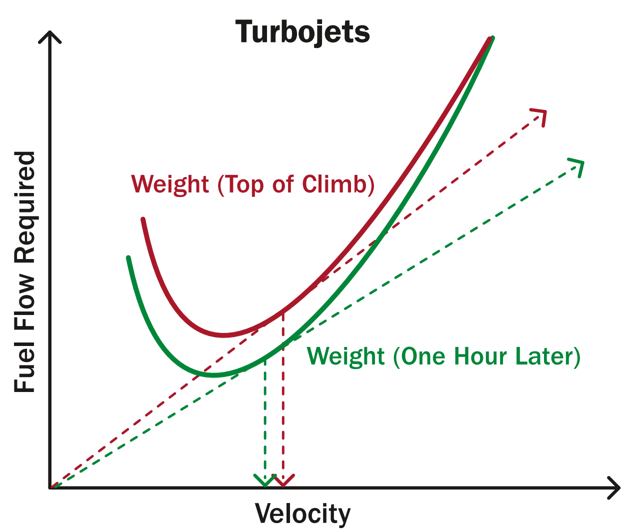
$$\textit{Specific Range} = \left(\frac{\textit{Distance (in nm)}}{\textit{Fuel (in lb.)}}\right) + \left(\frac{\frac{1}{hr.}}{\frac{1}{hr.}}\right) = \left(\frac{\frac{nm}{hr.}}{\frac{lb.}{hr.}}\right) = \frac{\textit{V (in kt.)}}{\textit{FF (in lb. per hr.)}}$$

Or, put another way, maximum range is obtained at the point where the ratio of velocity to fuel flow is highest. This is $(V/FF)_{MAX}$. This point can be shown on a graph by simply drawing a line from the graph's origin to the point where it just touches the curve. Flying this speed will result in the longest distance flown or, more practically, the greatest amount of fuel reserve at your destination. You could find this speed empirically by measuring your fuel flow versus speed at various speeds and doing the math. Fortunately your manufacturer did this for you and your manuals have the numbers in chart or tabular form.

Maximum range cruise (MRC) speed should give you this theoretical optimum point where you are covering the greatest distance using the least amount of fuel. However, many manufacturers opt for slightly less range (99% of the max range) for slightly greater speed (3 to 5%); this is known as long range cruise (LRC). Some aircraft manufacturers give you one or the other, while others offer both.

Flying MRC or LRC only guarantees the promised performance at the stated weight, altitude and temperature. As the airplane burns fuel and gets lighter, or as the temperature changes, pilot action is required to keep the fuel flow optimal. But why?

The Impact of Reduced Weight on Maximum Range



As the aircraft burns fuel and gets lighter, the theoretical curve moves down and to the left. In other words, MRC and LRC decrease. So, if you want to continue to stretch your range as you burn fuel, either the throttles have to come back or you have to climb. If the throttles can't come back (as over the North Atlantic) then your only option is to climb.

Before climbing, you may want to gather some information. Can you maintain Mach at the proposed higher altitude? A quick check of the FMS performance page should answer that

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Gulfstream G450 FMS cruise page

question. Alternatively, some pilots rely on N1 or EPR spreads to gauge performance, with rules of thumb such as "every 2% below maximum continuous thrust means you can climb 1,000 ft."

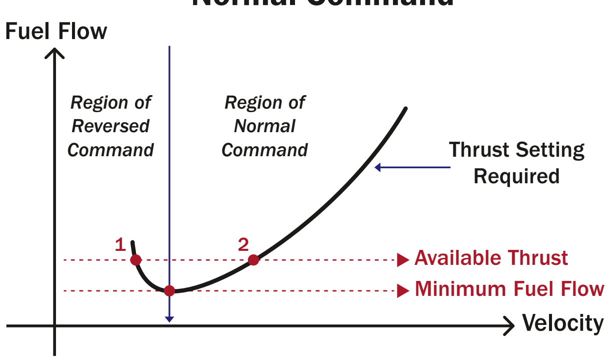
Another question that should be answered is what are the actual (not forecast) winds and temperature at the proposed altitude? ATC or a friendly PIREP from someone on the tracks should fill in those blanks. If the headwind is significantly stronger, you may be better off staying put. The same holds true if the temperature is warmer. When in doubt, consult your flight manuals and remember to be conservative when estimating down-range temperatures.

If you have the luxury of changing your speed en route, you should bring the speed back as you decrease weight, climb when you can make the next available flight level, and then recompute your MRC based on the new weight and altitude. For a given weight, MRC increases with altitude.

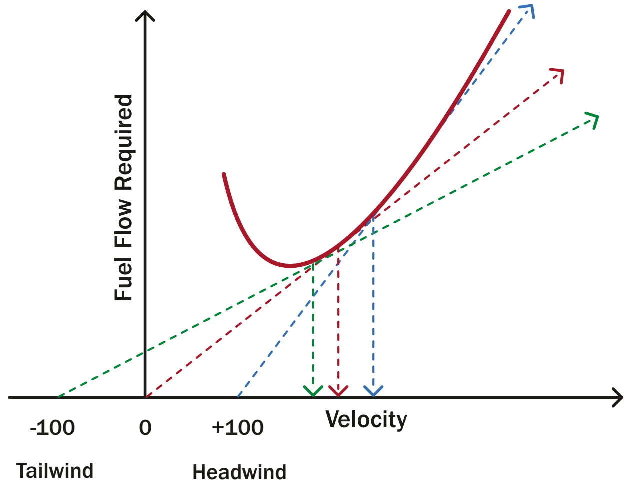
Another consideration in MRC is the impact of winds. Many aeronautical engineering texts claim that flying slower with a tailwind and faster with a headwind will reduce overall fuel consumption, but usually with the caveat that the winds must be at least 25% of the true airspeed to yield benefits. The trigonometry of the chart seems to lend credence to this claim. Some manufacturers even provide recommended speed adjustments.

I've run the numbers on a variety of aircraft, from the Pilatus PC-12 to the ultra-long-range Gulfstream G650, and the results are similar. I've found that making the recommended speed adjustments has a 50-50 chance of improving fuel burn but only marginally. The adjustments will hurt fuel burn about as often but again, only marginally. My advice: Don't bother adjusting your speed to account for a headwind or tailwind without doing the math first.

The Regions of Reversed and Normal Command



Wind Impact on Maximum Range



How Fast for Maximum Endurance?

If you arrive at your destination and find you need to hold for an extended period, your focus shifts from getting the most range to getting the most time from your fuel. In our previous Gulfstream IV example we were headed to Farnborough. If the runway there is suddenly closed for 45 min. to clear a disabled aircraft, you may decide it is better to hold for 1 hr. rather than fly to Stansted (EGSS) and subject your passengers to a 2-hr. drive into London. But what speed should you fly to safely loiter while minimizing your fuel burn?

In theory, the point at which there is minimum drag on the airplane is where the thrust requirement is lowest and the endurance is highest. So that's the speed you fly, right? Before you answer, take a look at that fuel flow versus velocity chart one more time.

The shape of the curve is critically important because the minimum drag/minimum thrust required point sharply divides two dissimilar aircraft behaviors. When in the area to the right of the minimum thrust required point, the thrust levers operate conventionally. To fly faster, the pilot adds thrust until reaching the desired speed and then reduces thrust to a setting higher than the original thrust to maintain the faster speed. Likewise, to fly slower, the pilot reduces thrust until reaching the desired speed, and then adds thrust to a setting lower than the original setting to maintain the slower speed. This behavior is fully expected.

But when in the area to the left of the minimum thrust required point, things are not so straightforward. To fly slower, for example, reducing thrust will cause the speed to decrease. But to stabilize at the new, slower speed, more thrust is needed than the original setting. When attempting to accelerate, a large burst of thrust may suffice, but the only way to ensure an increase in speed is to sharply decrease the angle of attack. These actions are contrary to normal pilot behaviors.

Consequently, this area is called the "region of reversed command" or what many call flying "behind the power curve."

To safely stay out of the region of reversed command, most aircraft manufacturers publish holding and endurance speeds that are well above the true maximum endurance speeds. Turbojet pilots are well advised to treat these published endurance speeds as absolute minimum speeds.

Even these artificially increased maximum endurance speeds bear caution. At that speed the aircraft's deck angle may be too high for passenger comfort. Your aircraft manufacturer may have minimum speeds for flight in icing conditions or operating in RVSM airspace. The old adage, "if the minimum wasn't good enough it wouldn't be the minimum" may hold true for taking a written exam, but it is foolish policy when flying airplanes.

Now let's circle back to our White Plains to Farnborough example. During our flight we could very well ask for and receive altitudes and Mach numbers that are spot on with our book's maximum range cruise getting to the initial approach fix, and maximum endurance waiting for the runway to reopen. But this doesn't necessarily mean we've minimized costs. It is far more complicated than that.

How Much Money?

Selecting an en route altitude and speed greatly impacts the amount of fuel burned, but there are other costs that may outweigh the price of Jet-A. The major airlines have long recognized this and that's why some airline flight management computers (FMC) incorporate a Cost Index (CI) as a performance initialization input. Boeing defines CI as the time cost of the airplane divided by the fuel cost. The time cost includes the crew, maintenance programs and just about everything else that is paid for by the hour. If the fuel is more expensive than everything else, it pays to slow down. If the "everything else" is more than the fuel, you may want to speed up. Few business aircraft FMCs have CI entries, but you can figure this out on your own.

Consider a Gulfstream G450 cruising at 37,000 ft. in a 100-kt. headwind starting at 70,000 lb. gross weight under ISA conditions. The crew know LRC will be Mach 0.80 but are wondering if the owner will see an improved bottom line if they fly Mach 0.03 slower, or even Mach 0.03 faster.

"It depends," is the right answer. But it depends on more than just what the aircraft's design engineers thought; rather it depends on what the company accountant thinks. You won't find the following equation in any aeronautical or pilot texts, but it might help answer the question, "How fast do you want to fly?"

In this equation:

D — Distance to cruise (nm, since the climb and descent fuel will be about the same, we consider only the cruise portion)

TAS — True air speed during cruise (kt.)

WF — Wind factor (kt., positive numbers for headwinds, negative for tailwinds)

FF — Fuel flow (pounds per hour), average in cruise

FC — Fuel cost ($ per gallon)

FD — Fuel density (pounds per gallon)

VA — Variable airframe costs ($ per hour)

VC — Variable crew costs ($ per hour)

VE — Variable engine costs ($ per hour)

$$\mathit{Total\ Cost} = \left(\frac{D}{TAS - WF}\right) \times \left(FF \times \left[\frac{FC}{FD}\right] + VA + VC + VE\right)$$

To compute the answer, values must be inserted. Are the pilots paid hourly or by salary? A salaried crewmember doesn't add to variable costs and so that expense does not lend to any incentive to fly faster. Are any of the maintenance programs billed by flight hour? Some aircraft maintenance programs are fixed rate to a certain level of activity and then add per hour charges, while others count every hour from the first at one hourly rate. Is the aircraft on a lease program, and billed by flight time as opposed to calendar time? All of these variable costs can amount to $3,000 or more for a typical business jet and may overwhelm the cost of fuel, making it financially advantageous to burn more Jet-A to reduce total flight time.

Mach	No Variable Costs	$1,000 Variable Costs	$3,000 Variable Costs
0.77	$12,035	$20,828	$38,413
0.80	$12,278	$20,648	$37,389
0.83	$13,245	$21,233	$37,207

Meanwhile, the cost of fuel is always a factor. At $1.00 per gallon there are usually incentives to fly fast. But at $5.00 per gallon? Not so much!

For the sake of our example, let's say it is an ISA day, the fuel costs $3.00 per gallon and has a density of 6.5 gal. per pound. The first hour fuel burn at Mach 0.77 will be 2,996 lb.; at Mach 0.80 it will be 3,178 lb.; and at Mach 0.83 it will be 3,593 lb. The speed up/slow down question depends entirely on those variable costs:

These numbers can be fine-tuned by adjusting fuel burn rates on an hourly basis, but for demonstration purposes the conclusion in this example is clear: It doesn't pay to fly faster until the variable costs exceed the cost of the increased fuel burn.

In other words, when fuel costs are low, there's a strong incentive to fly faster. Conversely, when fuel costs are high, there's a strong incentive to fly slower. Similarly, as variable costs increase, the incentive to fly fast increases.

The Answer: It Depends

Considering the forgoing about distance and endurance, it's clear that setting your throttles and selecting an altitude based on textbook knowledge may not work. Your aircraft is likely more technologically advanced than the textbook's authors ever imagined. And you're unlikely to get a complete answer from the airplane flight manual, either; the accountants have just as much to say about costs as do your computerized fuel control units.

The correct answer depends on all of these variables and it is up to you, the pilot, to sort it all out. If you understand a little of the theory you will have a starting point when evaluating the performance of your jet. You should also consider any variable costs in your operation.

Only with these parts of the puzzle in place can you really have a well thought out answer to the question: How fast? BCA