# *The Trailing Edge*

May 2025

## The Hazards of Switching Fuel Tanks

Besides Loss of Control, the NTSB reports that a large cause of aircraft accidents is fuel mismanagement. While it is embarrassing to consume all of the fuel on board before reaching the intended destination (fuel exhaustion), a far more common problem is to have fuel available but not be able to get it to the appropriate powerplant. This can happen because of incorrectly set fuel selector valves, or some failure in the system that prevents the fuel from flowing.

In a car, fuel management is super simple. There is one tank and it feeds one engine. There is no fuel shutoff valve, and the fuel pump is probably electric and turns on with the same switch that activates the engine ignition.

In the J-3 Cub, there is one tank that gravity feeds to one engine. There is a fuel shutoff valve, but the pilot generally leaves it in the “0N” mode. The fuel is only shut off when required for maintenance.

As aircraft get bigger and more complex, the fuel system becomes more complex. In a low wing aircraft, such as a Piper Cherokee, there is a fuel tank in each wing. Because the wing is below the carburetor, a fuel pump must be used to move the fuel from the tank to the engine. Fuel pumps are effective at pumping liquid fuel, but very ineffective at pumping air or vapor. As such, a fuel selector valve is provided to connect the fuel pump to one tank at a time, either the left tank or the right tank. The pilot is required to alternately select the left tank or the right tank to prevent an excessive fuel imbalance, which would require active use of ailerons to keep the wings level. Because there is now a pilot action required to manage the flow of fuel, there is now an opportunity for the pilot to make a mistake or be distracted. A shut off position is also provided on the fuel selector for maintenance.

High wing aircraft with can rely on gravity to get the fuel from the wing tanks to the engine. This allows a BOTH position on the fuel selector that allows flow from both fuel tanks at the same time, theoretically removing the necessity of the pilot switching between tanks. Even with fuel injected engines requiring a fuel pump, gravity will still get the fuel from the tanks to the fuel pump. If one tank becomes empty, fuel will still flow out of the other tank by gravity to the engine. In theory, when using the BOTH position, no pilot action should be required to ensure fuel flow to the engine. In reality, many high wing aircraft, such as my Bearhawk, preferentially flow one tank more than the other with the fuel selector in the BOTH position, leading to a fuel imbalance. To deal with this fuel imbalance, the fuel selector also allows feeding from the left tank only or the right tank only. A shut off position is also provided on the fuel selector for maintenance.

Adding auxiliary fuel tanks, such as in the outer wing panels, under the wing, or on the wing tips, gives more locations to feed fuel from, thus requiring more positions on the fuel selector. Many twin engine airplanes provide the ability to cross feed fuel from one side of the aircraft to the other. All of these options provide many failure modes where the pilot can set the valves such that no fuel flows to the engine. One of Lindbergh’s major concerns when flying the Spirit of St. Louis was managing the multiple valves for all of the fuel tanks to ensure fuel flow to the engine.

According to **Jimmy Doolittle III**, the Skyraider had an internal main tank, and could carry three drop tanks and possibly an extra fuselage tank. One of a Skyraider pilot’s biggest concerns was to be on a mission in a location that required using the fuel in an external tank to get back to base, only to switch to that tank and find out that the fuel would not feed from it. This failure to feed could come from a multitude of problems, such as the tank was not properly connected when loaded on the airplane. To mitigate this possibility, the pilot would try to run the engine on each tank while still on the ground before takeoff. This led to the question of how long would it take running the engine on the ground to determine if a tank was feeding?

In a similar vein, a poor habit exercised by some general aviation pilots is to change the fuel selector from one tank to another immediately before takeoff. If the selected tank is not feeding, the engine will be starved of fuel just as the airplane gets to an unrecoverable condition, such as just after liftoff with insufficient altitude for a restart. This problem is significant enough that many flight safety outlets specifically warn against it.

### Estimating the Fuel System Volume

If a fuel tank is not feeding, selecting that tank will not immediately cause the engine to stop from fuel exhaustion. The time required for fuel exhaustion will depend on the fuel flow rate and the volume of the fuel system between the selector valve and where the fuel mixes with the air. To estimate the time required for an engine to stop running because a non-feeding tank was selected, I decided to analyze my own Bearhawk.

In the interest of flight safety, I was not willing to turn the fuel selector to the OFF mode while in flight and time until the engine quit. Instead, I decided to do some recreational maths (as popularized by Matt Parker on the Stand-up Maths YouTube channel). Even then, I was not willing to spend several hours pulling up the floorboards and otherwise disassembling the airplane to precisely measure the length of the fuel lines or the volume of the gascolator or carburetor bowl. Part of being an engineer is being comfortable with estimating. Estimates of the volume of the fuel system will not be exact, but the calculations will give results close enough to actual values to be useful operationally.

Using pictures of my fuel system, I measured the approximate length of the fuel lines by drawing the fuel system onto a dimensioned CAD drawing I had made of the fuselage frame during construction. The length from the fuel selector to the carburetor was estimated as

$$\text{Tubing Length} = 136 \text{ inches}$$

The fuel tubing is 5052 aluminum with a 3/8 inch outside diameter. For purposes of this estimation, that is close enough to be assumed for the inside diameter. All fittings, such as the fuel flow sensor, fittings through the firewall, and the flexible Teflon hose to the carburetor were modeled as tubing with a 3/8 inside diameter.

$$\text{Tubing Diameter} = 0.375 \text{ inches}$$

The volume of the fuel tube is calculated as

$$\text{Cross section area} = \pi \left(\frac{\text{Tubing Diameter}}{2}\right)^2$$

$$\text{Cross section area} = \pi \left(\frac{0.375 \text{ inch}}{2}\right)^2$$

$$\text{Cross section area} = 0.110447 \text{ inch}^2$$

$$\text{Volume} = (\text{Cross section area})(\text{Tubing Length})$$

$$\text{Volume} = (0.110447 \text{ inch}^2)(136 \text{ inch})$$

$$\text{Volume} = 15.02 \text{ inch}^3 = 8.32 \text{ fl oz} = 0.065 \text{ gallon}$$

So the fuel lines alone contain at least one cup of fuel. That's slightly more than the half pint carton of milk that I used to get with my elementary school lunch.

For the gascolator volume, the plastic bowl is a slightly tapered cylinder. Rather than open up the airplane to measure it, I found a data sheet online and estimated the size of the bowl, modeling it as a simple cylinder. Again, this estimate should be within the uncertainty that still allows a meaningful answer. The estimated dimensions were

$$\text{Bowl Height} = 2.5 \text{ inches}$$

$$\text{Bowl Diameter} = 1.7 \text{ inches}$$

$$\text{Cross section area} = \pi \left(\frac{\text{Bowl Diameter}}{2}\right)^2$$

$$\text{Cross section area} = \pi \left(\frac{1.7 \text{ inch}}{2}\right)^2$$

$$\text{Cross section area} = 2.27 \text{ inch}^2$$

$$\text{Volume} = (\text{Cross section area})(\text{Bowl Height})$$

$$\text{Volume} = (2.27\ \text{inch}^2)(2.5\ \text{inch})$$

$$\text{Volume} = 5.67\ \text{inch}^3 = 3.14\ \text{fl oz} = 0.025\ \text{gallon}$$

The carburetor bowl volume was the biggest guess, since I certainly wasn't going to remove the carburetor and disassemble it. Trying to imagine the size of the carburetor bowl, I decided to estimate it as about twice the size of the gascolator bowl. Therefore

$$\text{Volume} = 11.35\ \text{inch}^3 = 6.29\ \text{fl oz} = 0.049\ \text{gallon}$$

Adding these three volumes together, we get that the total estimated volume between the fuel shutoff valve and the carburetor fuel jet is

$$\text{Volume} = 32.04\ \text{inch}^3 = 17.76\ \text{fl oz} = 0.139\ \text{gallon}$$

To get a feel for how much fuel that is, it is more than a pint (16 fl oz). If you are of the metric persuasion, that's more than half a liter. If you remember tall boy beer cans (16 fl oz) or 16 oz Pepsi bottles, it's more than that. If your reference is a 12 oz soda can, add about half of that volume to it. The point is, this is not an insignificant amount of fuel.

To be fair, the engine will probably be starved of fuel before all of this fuel is burned. I suspect that the gascolator will stop feeding once an air bubble makes it into the bowl, since the fuel flows in the top of the bowl, through the filter, and back out the top of the bowl. Also, we don't know how much fuel will be drawn out of the carburetor bowl before the flow of fuel ceases. However, if we model the fuel starvation as emptying all of this volume, that will give us the upper limit of how long the engine could run before the silence would indicate that the fuel tank was not feeding and the pilot's seat cushion would disappear.

**So How Long Does It Take To Determine If A Fuel Tank Is Feeding?**

Now that we have an estimate of the fuel system volume, we can estimate the time to empty that volume assuming different fuel flows. This time is given simply by

$$\text{Time to Empty} = \frac{\text{Volume}}{\text{Fuel Flow}}$$

Using typical numbers for the Bearhawk, this yields the result

| Flight Condition | Fuel Flow | Time to Empty |
|---|---|---|
| Ground Idle | 1.5 gallon/hour | 5 minutes 33 seconds |
| Cruise | 10.8 gallon/hour | 46 seconds |
| Takeoff | 21.6 gallon/hour | 23 seconds |

So, consider the case that started this analysis, the pilot who changes fuel tanks right before takeoff. Based on Bearhawk data, the takeoff ground roll is approximately 10 to 12 seconds. Ignoring the tiny amount of fuel burned before pushing up the throttle, that means that the engine will quit within the first 10 seconds of the climb, and probably earlier. That gives enough time to climb high enough that falling to the ground will hurt, but you won't be high enough to be able to turn back to the runway.

Looking to the cruise fuel flow, it will take up to 46 seconds before you can assume the current tank is feeding. After something like two minutes you can be confident that the current tank is feeding.

The ground idle fuel flow warns of a different danger. Because of the low fuel flow rate, it can take six minutes or more to convince yourself that a particular tank is feeding. Since you may not even spend that much time on the ground with the engine running, your best strategy might be to takeoff on the tank position that you started on.

**Final Recommendation**

As taught to me by many Test Pilots, if you move a valve or switch and the airplane does something you don't like, undo whatever you just did that caused the problem. As Gene Wilder said in *Young Frankenstein*, "Put…the…candle…back!"

**- Russ Erb**

**True Confessions**

Within three hours of publishing the previous article, I received the following stories from my good friend and fellow pilot Mujahid Abdulrahim. Whereas I chose to investigate this issue through the safety of Modeling and Simulation, Mujahid chose to investigate it through unintentional flight test…twice!

Good evening Russ!

Thanks for another installment of the **Trailing Edge**, and particularly the variety where you engage in recreational maths!

To your question of experimental validation of your maths, I have two relevant incidents to report:

**<u>Incident 1:</u>**
Cessna 150
Sometime in 2000
Near Flying 10 Airport
Mujahid Abdulrahim, Student Pilot
Frank Ogborn, CFI

It appears that I'm gullible and prone to flattery. I was on my fourth hour of flight training and my hundreds of hours of flying Microsoft Flight Sim appeared to have good transference to proper flying. We had covered controls, landings, takeoff, pattern, ground reference maneuvers, and we were just starting to cover emergency procedures. My instructor pointed to some industrial building on the horizon and said "Hey, is that the new power plant over there?". I didn't have a wealth of local knowledge, but I felt quite proud that this old man would turn to me to answer this important question. I looked, studied, and pondered for a moment, then turned back to him in proud confirmation and said "Yes sir, it sure looks like it!" Before I could revel too much in pride at a job well done as a local guide, the engine sputtered and quit, leaving the prop stuck against the compression stroke right in front of my face. I promptly sucked up the seat cushion, re-stained it a contemporary shade of brown, then returned it to the original location.

"Oh no", he said in the dry, performative way of someone who expected the engine might fail. "It looks like we should find a place to land. Where should we go?"

I had been so consumed by looking at the far away power plant, I hadn't really studied the immediate local area. I stammered something about "A, B, C" and tried to find a place that would nicely satisfy the "B" part. As I continued to struggle, he offered, "What about that grass field right below us that's shaped like a runway?". I immediately accepted distribution of tasks in our crew roles. I would be responsible for identifying power plants on the horizon, while he would be in charge of choosing emergency landing fields. Not coincidentally, our engine quit right over "Rudy's Glider Port".

We did the usual energy management maneuvers, flew a modified pattern, and did a tidy touchdown on the grass field before rolling to a stop. The sound of air whooshing past the cabin gave way to the sound of tires rolling through the grass, but as the speed diminished, the sound of the tires died down to a silent nothing as the airplane came safely to a stop on the grass runway. We didn't say much for a moment, so the silence persisted, interrupted only by the soft sound of wet squishing from my seat cushion as a I fidgeted.

Twenty-five years later, I finally got my glider ratings and now come to relish this lovely silence that follows the whooshing of air and the rolling of tires. The flight is over, we're back safely, and my pants are reusable.

Conclusion: Fuel valve cut-off to fuel exhaustion time: ~30 seconds

**Incident 2:**
Cessna 172
January 2024
Over the Atlantic Ocean
Mujahid Abdulrahim, Pilot
<Name Withheld, for she was innocent>, Passenger

I take tremendous care in protecting the safety of my passengers. Many hundreds of people have flown with me, and I owe it to them, their families, and their loved ones to bring them home safely. Some of this care is invisible to them in my pre-flight preparation, weather briefing, and pilotage. Other forms of care are overt and narrated. I'm a flight instructor, and sometimes I can't help but discuss safety considerations in lesson-style to my passengers, whether or not they are flight students.

My passenger and I were outbound to the Bahamas from Melbourne, FL. A quick trip to the Bahamas preceding our week-long conference at SciTech. Much of our 250 nm route was over land or island chains, but some of the legs were over open water, far from gliding distance to shore. As the engine hummed and we waited with measured patience for the horizon to come closer, I took some time to glance at the instruments to make sure the aircraft systems were operating nominally. The engine appeared healthy, but the right tank showed several more gallons of fuel than the left tank. It's a gravity fed Cessna with the fuel valve set to "Both", so a little imbalance is not a big deal. The inaccuracies of aircraft fuel gauges combined with the crossflow connection between the tanks made this a non-issue, yet it bothered me a bit.

As I monitored this fuel imbalance, I announced proudly to my passenger that the seasoned over-water pilot **always** made it point to make changes to the fuel system when over land. When flying over open water, nothing in the fuel system configuration should be touched.

There! I sat back with some satisfaction of having identified myself to be among that set of pilots who anticipate possible issues and coordinate their cockpit actions with safety contingencies.

As we continued to sit, I alternated bored glances between the stubbornly slow advancing horizon and the increasing fuel disparity.

I'm not going to change tanks. I will dutifully wait until I'm over land before interrupting this fine-running propulsion system. Now is **not** the time to make a big change to the fuel configuration.

But the fuel disparity persisted, so what's the harm in a small change?

The engineers at Cessna who designed the now-30-year-old Skyhawk included quite thoughtful features for pilots in my exact predicament. The gravity-fed fuel system featured a fuel valve with the options "Left", "Both", "Right", and "Off". "Off" had the fuel valve pointed backward, away from the anticipated direction of the advancing horizon. "Left" pointed to the left, and "Right" pointed to the right - as every system other than the magneto switch usually does. "Both" pointed forward, 90-degrees away from the "Left" and "Right" tank settings. Those clever engineers didn't stop at these four options, they also included a graduated set of radial marks between the "Left", "Both", and "Right" options. The fuel valve didn't have the boring, discrete choices of lesser airplanes, it provided pilots with the option to *bias* the fuel toward one tank or another, much like a thermostat control that provided temperature setting options between full cold and full hot. Average Cessna pilots would blindly leave the fuel valve on "Both", but esteemed Cessna pilots, like the kind willing to take a single-engine airplane far over open water, could exercise the fine adjustment controls of the fuel valve.

Sure, I had **just** paraded a diatribe about not touching the fuel system, but I had meant not doing **major** changes to the fuel system. With the confidence that you might not expect from someone who had never exercised this unique fuel selection feature in 25 years of flying, I reached down to the fuel valve and turned the selector to one mark away from "Both" toward "Right". I would feel really foolish if I landed on the island with a bunch of fuel in one tank and none in the other, with the airplane leaning over and compressing one side of the landing gear in the mark of shame that has graced so many student pilots of Piper Cherokees.

I wondered if moving the selector one mark was enough, so I mulled this second-guessing a bit, then reached down to put the selector two marks away from both. Now this should be enough to bring balance to the fuel.

Few things are as damaging to the self-satisfaction a pilot feels after finely-tuning the airplane controls than the engine coughing, sputtering, and stumbling as the airplane threatens to plummet toward the not-so-terra firma below. I'll admit that I would have welcomed something to interrupt the boredom of a 250 nm straight flight, but engine failure was most certainly **NOT** what I had in mind.

My passenger gasped and clutched the door handle, as she prepared to grab the life jacket and pop open the door, just as I had briefed her.

I, as the pilot, did the thing that any pilot should do when an action causes badness. I undid that action. I reached down and put the fuel selector back to both, and the engine stumbling quickly ceased, allowing it to return to the mundane, boring hum that we suddenly realized was quite underappreciated.

I was caught between the disappointed glare from my passenger and the humbling realization that those marks on the fuel valve didn't indicate variable flow control—they were just decorative. In 25 years of flying, I didn't find a need to touch the fuel controls of a Cessna 172 in flight, but then one day in the most perilous situation possible, I decided to test an unproven theory that had never been discussed before and had never graced the pages of any pilot operating handbook. I made a change when I wasn't supposed to make a change, and worse yet, the change I made was not based on any actual understanding of the fuel system. I was led astray by a decorative sticker and my imagination.

Thankfully, my passenger calmed down after a few more boring miles and we returned to the anticipation of our arrival on the island. I was sure that she would soon forgive me for this blunder and it would not affect her opinion of me as a seasoned, careful, and deliberate pilot.

Minutes later, I gasped, causing my passenger to look at me, thinking “What fresh hell is this?”

"I forgot my passport. Again."

Conclusion: Fuel valve cut-off to engine sputtering time ~15 seconds. Fuel back to "Both" to engine not-sputtering time: ~5 seconds

Take care,

- **Mujahid Abdulrahim**