The Science Behind the Art of Takeoffs

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by Charlie Page

News

The Science Behind a Beautiful Aircraft Takeoff

As you're relaxing into your seat, waiting for takeoff, the focus in the flight deck is at its peak. The culmination of the last two hours of briefings and checks is almost upon us. The flashing white strobes on the wingtips and tail are turned on and the bright landing lights illuminate the path ahead.

One final check of the approach path to confirm there's no aircraft landing. At 226 tonnes, we're almost at our maximum takeoff weight, but the Boeing 787-9 glides effortlessly onto the runway. The strip of lights ahead of us disappear 4 kilometres into the distance. We pause. Breathing slowly. Focused. Waiting for the call from ATC.

"Flight 254, runway two four left, wind 280 degrees at 8 knots, you're cleared take off".

"Cleared take off 24L, Flight 254".

Photo by Jordi Moncasi on Unsplash

The pilot flying (PF) squeezes the thrust levers slightly forwards, advancing the engines to around 20% of their maximum power. Another pause as we hear the engines spool up. All three pilots scan the engine instruments for any anomalies. Satisfied, the PF uses their index finger to press the Take Off/Go Around (TOGA) button.

With a whir of an electric motor, the auto throttle advances the thrust levers forward and sets the takeoff power. With a reassuring whine, the two massive engines under the wings are woken from their slumber. Forcing 65,000 pounds of thrust out of the back of each engine, the 787 Dreamliner starts to pick up speed.

“80knots”, calls the Pilot Monitoring (PM), scanning the engine and performance indications like a kestrel locating a rabbit.

“Check”, acknowledges the PF.

The bumps from the nosewheel hitting the runway lights get faster and faster as the aircraft approaches its takeoff speed.

“V1, rotate!”, calls the PM.

As the aircraft reaches its critical speed, the PF pulls gently back on the control column. The tail of the aircraft sinks down, raising the nose into the air. For a moment, the aircraft seems to crouch, nose pointed up, poised, ready to launch skywards. Then, in a magical moment, the wings bite the air rushing over them and the aircraft eases into the night sky.

This is the wonder of flight.

Takeoff appears to just be an art form...

Romance vs. Reality

As romantic as this all sounds, the few moments it takes for an aircraft to get airborne are actually based on pure science and maths. Every part of a takeoff is meticulously planned, briefed and executed by highly trained professionals — both in the flight deck and on the ground. From loading the aircraft to setting takeoff power, every departure is a well-drilled operation.

Aircraft don't just get airborne by luck. Pilots know exactly how much runway is needed, how much engine power to use and what speed to lift off at.

Before entering service, the manufacturer of a new aircraft must measure how it performs during different stages of flight, including takeoff.

'Net Performance' is used to calculate safety-related aspects of the takeoff, making sure that even in the worst scenario, the aircraft will get airborne safely. It ensures that the aircraft will clear any obstacles in the initial climb out by at least 35 feet. This is known as the screen height.

Now, you may have read that and been a little shocked — 35 feet doesn't sound like a great deal. However, remember that it is by *at least* 35 feet, and during normal operations, this height will be far greater. The rule is there for the worst case scenario, normally considering the loss of power from one engine.

Airfield Performance

In order to understand the part this 35 feet screen height plays in the takeoff, we first need to look at the various distances that affect the take off performance of an aircraft.

Take-Off Run Available (TORA)

The TORA is the distance from the point at which the aircraft can start its takeoff run to the point at which the the surface can no longer bear its weight. In most cases, this is equivalent to the length of the runway.

The Clearway

This is an area at the end of the TORA that is free from any obstructions exceeding 0.9 meters in height like buildings or trees. The aircraft can use this area in order to achieve the 35 feet screen height.

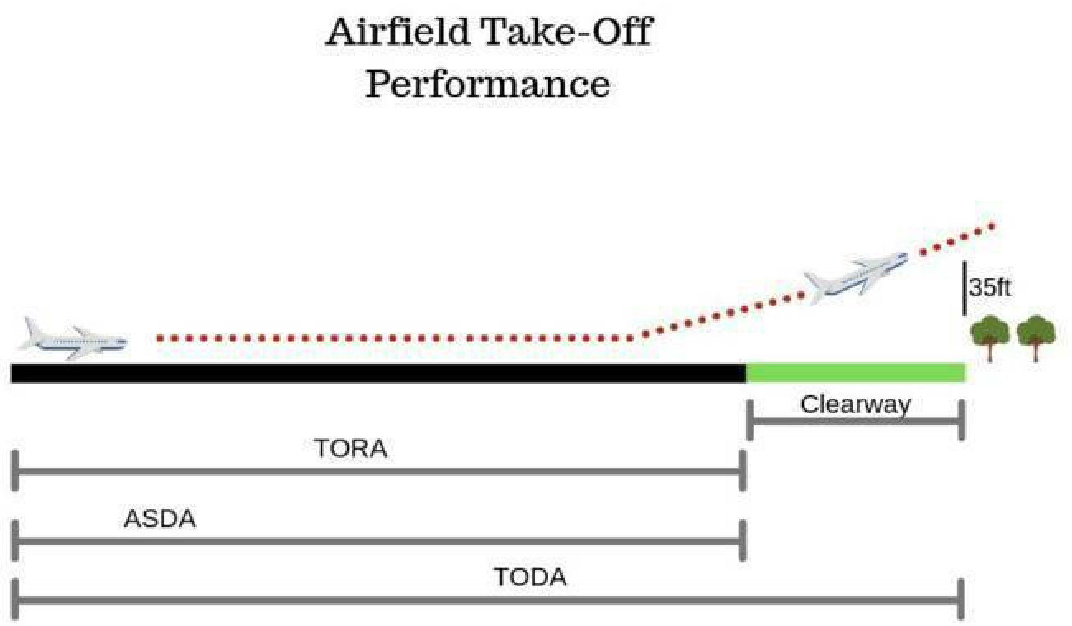
The clearway may not be immediately obvious, as it is not defined by a paved surface. It can include an area of open ground or even water, so long as it is under the control of the airport. When you add the clearway to the TORA, this gives you the…

Takeoff Distance Available (TODA)

The TODA is the total distance that the aircraft has to start its takeoff run and climb to the 35 feet screen height. On a runway without a Clearway, the TODA will equal the TORA.

Accelerate-Stop Distance Available (ASDA)

The final distance that must be considered for takeoff performance is the ASDA. This is the distance of weight bearing surface available to the aircraft to accelerate and then come to a safe stop in the case of a rejected takeoff.



The important distances for takeoff

In order to operate within the TODA, the takeoff speeds must be as slow as possible. This is why flaps and slats are used on take off. They increase the lift generated by the wing, allowing the aircraft to get airborne at a slower speed.

The Engine Failure Scenario

On a twin engine aircraft such as the 787 Dreamliner, the loss of power from one engine during the takeoff run is one of the more serious events that could happen. Although this is highly unlikely, we always plan for the worst possible scenario. This is where the performance for the 35 feet screen height comes in.

Should an engine fail just as the aircraft lifts off, the performance must still ensure that it reaches the screen height by the end of the TODA on the power of the remaining engine. This is the key part of the takeoff performance.

Even though an aircraft can safely climb away from the runway on just one engine, should the failure happen whilst still on the ground, it would be preferable for the pilots to reject the takeoff and stop on the runway. However, there comes a point where there will not be enough runway remaining in which to stop safely. So how do we know where this point is?

Before every takeoff, the pilots must calculate the speeds, flap setting and engine power required to takeoff safely. This includes the engine failure scenario.

One of the speeds that is calculated is called V1 — “the maximum speed in the takeoff at which the pilot must take the first action to stop the aeroplane within the accelerate-stop distance”.

If an event occurs before the aircraft reaches the V1 speed, the pilots know that they are able to stop safely. Any events occurring after V1, the pilots must continue to get airborne. The decision to stop or go isn’t made in the heat of the moment — it’s a binary decision calculated at a time of low workload.

Accurate Performance for Every Flight

The figures mentioned above vary from flight to flight, day to day and are affected by a number of variables. All these must be taken into consideration by the pilots when planning their takeoff performance.

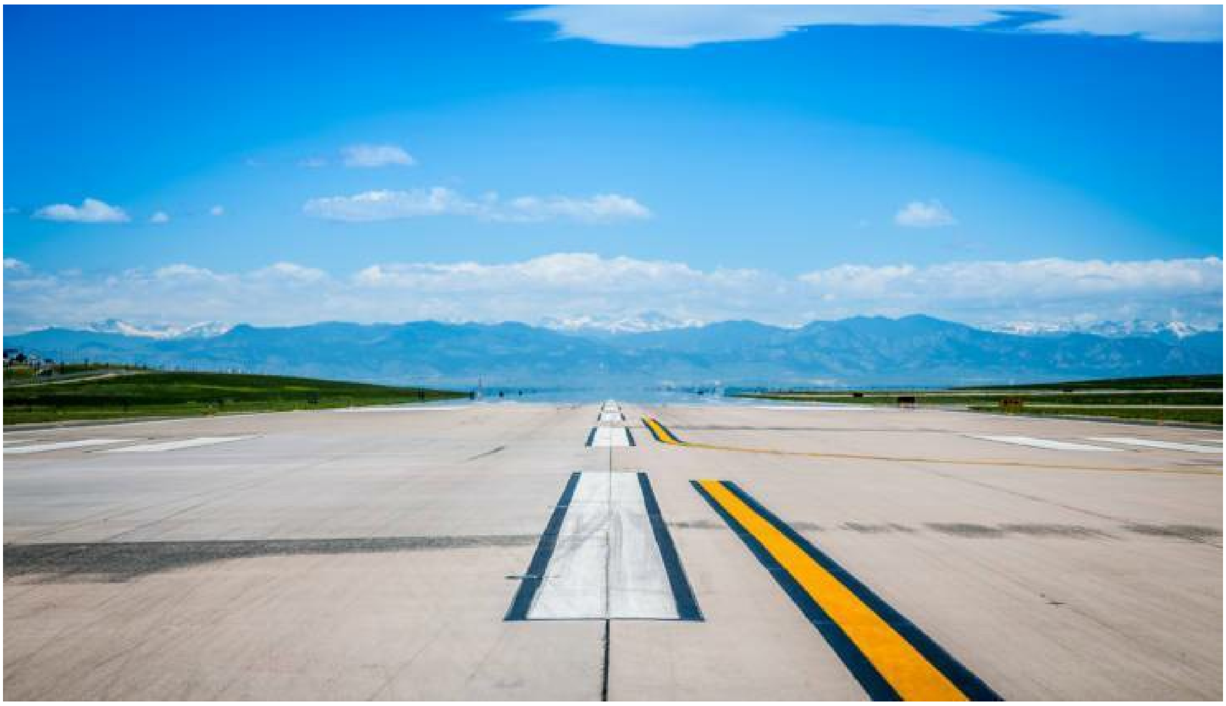
Aircraft Weight

The most obvious element in this equation is the weight of the aircraft. Just like in your car, the heavier the aircraft is, the slower it will accelerate. If you were to increase the weight of the aircraft, eventually you’d reach a weight at which it could no longer accelerate to the required speed before running out of runway.

Heavier weights also require more lift to fly. In order to generate this lift, the aircraft has to be travelling faster.

Runway Slope

Another fairly easy factor to understand is that if the runway is sloping upwards, it will naturally take longer for the aircraft to accelerate to the speeds required for flight.



The runway slope affects takeoff performance. The greater the upslope, the greater the engine power needed. (Photograph provided courtesy of Denver International Airport)

Outside Air Temperature (OAT)

The hotter the air temperature, the lower the air density. Because the engines rely on moving air backwards to accelerate the aircraft forwards, when the air density is low, less air is moved backwards by the engines. This results in less thrust being available and a longer takeoff run being required.

Wind

Aircraft like to takeoff into a head wind. With a stronger wind over the wings, the aircraft doesn't have to be moving as fast over the ground to reach the air speed required to lift off. This means that less runway is required.

Conversely, if there was a strong wind from behind the aircraft, the takeoff distance required would be much greater.

Airfield Pressure Altitude

The higher the pressure altitude, the lower the air density. When the air density is low, not only is thrust reduced (as mentioned above) but there are fewer air molecules flowing over the wing at a given speed. This results in less lift. The higher the pressure altitude, the greater the takeoff distance required.

Runway Condition

One of the less obvious aspects, the condition of the runway can affect the drag on the wheels. The greater the drag, the slower the acceleration, the greater the TOD required. Careful assessment by pilots of the current and potential future runway conditions is essential to ensuring a safe departure.

Contaminants such as snow and slush affect the takeoff performance (Photo by Thomas Cooper/Getty Images)

TODA

The final element that can affect the performance calculations is the TODA. As mentioned before, the aircraft must clear any obstacles in the climb out by at least 35 feet. The shorter the TODA, the higher the power and more flap setting will be needed.

Reduced Thrust Takeoffs

The engines on modern jet aircraft are so powerful that very rarely is full power required to get airborne. The harder the engines work, the more fuel they use, the sooner they need servicing and the more noise pollution they create. If you can reduce the power used on takeoff, the engine life will be increased and residents around the airport will be subject to less noise. This is called a reduced thrust takeoff.

This is managed by making maximum use of the TODA. Why get airborne 2 kilometrers down a 4 kilometer runway when you could use more of it and save some engine power?

A Real-Life Example: Los Angeles to London

So now that we know the factors that affect the takeoff performance, we can look at how the data was calculated in the flight described at the start.

Bad Data in = Bad Data out

The performance figures are only as good as the data which is fed into the calculations. Before each flight, the pilots are given a load sheet by the ground staff. This informs us of the weight of the empty aircraft, plus the weight of the passengers, baggage, cargo and fuel. This gives us our takeoff weight.

We then obtain the latest airfield and weather information. This will tell us which runway we can expect to use for departure, its condition (dry, wet, covered in snow), the wind, the temperature and the air pressure — all the variables that can affect our performance.

The Onboard Performance Tool (OPT)

The OPT enables us to enter the data collated above and calculate our takeoff performance. This is one of the most critical stages of the flight. An error here could have serious consequences on the takeoff run. In order to reduce the chances of a mistake during the performance calculations, we follow strict procedures to make sure that it is done correctly.

Each pilot has their own OPT, situated on a screen to their side. Working the left column first, we load the airfield data from the Flight Management Computer (FMC) flight plan by pressing the 'Load FMC' button. This populates the airport, runway, OAT, QNH (air pressure) and aircraft weights.

We then select the INTX box (which runway intersection we intend to use, thus affecting the TODA) and enter the runway condition and wind.

After this, we select if we'd like to do a reduced thrust takeoff, if we have a flap setting preference and whether anti icing will be required for the takeoff. When all the boxes have been completed, it's time to hit CALC and let the computer work its magic.

The Takeoff Data

Depending on the aircraft, it can take a couple of minutes to calculate the data. The 787-9 and 787-10 tend to take a little longer than the 787-8, as there are more takeoff flap setting options. Once the calculations are complete, the OPT displays the figures for flap setting, engine power and takeoff speeds that will be used for takeoff.

The final takeoff performance figures.

Once both pilots have a set of figures, it's time to check them. One pilot then reads exactly what their OPT has calculated. The other pilot checks that they have *exactly* the same figures on their screen.

If there are any errors, both pilots must work out why they have different figures. This is often due to one side having a different OAT or QNH setting to the other side. Once the discrepancy has been resolved, the whole process must be completed again. This ensures that no errors slip through.

Once both pilots have confirmed that their numbers tie up, it's time to load them into the FMC. As the OPT calculations are independent, one pilot sends their numbers to the FMC and once loaded, the other pilot then checks the FMC numbers against their calculated OPT numbers. Yet another chance to catch any errors.

Once the data has been loaded and checked and the auto flight modes for takeoff have been selected, the procedure is complete. All that is left now is to complete a departure briefing and complete the checklists.

Bottom Line

Takeoff is one of the most safety-critical points of the flight. As a result, meticulous care and attention is taken to ensure that every eventuality is prepared for.

Aircraft are tested before even carrying passengers so that pilots know how they will perform in a variety of scenarios. Even if an engine was to fail at the most critical stage of takeoff, the aircraft can still climb safely away from the ground.

Airline pilots are professionals who take immense pride in what they do. Even though you don’t see it, our attention to detail on every single takeoff ensures that you get to your destination safely every time you step on board our aircraft.

Featured photo courtesy American Airlines.

Charlie Page Charlie Page is an airline pilot flying the Boeing 787 Dreamliner. Each Saturday he gives you a 'behind the cockpit door' insight to life in the flight deck.