Temporary Construction of Ramps and Their Effect on Aircraft Ride Quality

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ABSTRACT

The concept of overnight construction on runways has been limited to either thin asphalt overlays in nightly segments, replacement of portland cement slabs with accelerated Type III portland cements, or calcium sulfoaluminate Rapid Set cement concrete. Thin asphalt overlays have been used frequently with 2-inch (5cm) lifts that leaves a small grade change that is considered to have negligible effect if using an asphalt ramp that is kept to a maximum of 1-inch per 15 feet (.57% grade). Slab replacements have been relegated to keeping the existing grade because an overlay would be required to be at least 5 inches (13cm) of concrete.

However, what if a rapid setting durable concrete would allow a 6-inch (15cm) overlay to be constructed at night and opened to traffic in the morning. A ramp would obviously be required, but what would the aircraft response be if a temporary construction ramp of 6 inches (15cm) was used.

Using aircraft simulation, this paper explores the issues of introducing a 1% and 0.5% ramp used for overnight construction and its effect on aircraft response. These ramps will be integrated into three profile types; an artificial "glass smooth" runway, an existing in-service runway with known pavement roughness and finally, an existing in-service runway with average ride quality. This study identifies parameters that can impact aircraft response:

- Ramp location
- Profile of the existing surface
- Up-ramp vs down-ramp, etc.

The final objective is to provide guidance for the use of temporary ramps that would minimize aircraft dynamic response.

Keywords: Temporary Ramp, Runway Construction, Aircraft Response, Aircraft Simulation, Runway Roughness, Measured Pavement Profile

APR Consultants has been in the business of evaluating aircraft response to measured pavement profile roughness since 1993 and has performed runway profile measurements and analyses for hundreds of runways. The analysis used in this paper is typical of many analyses that have been conducted on runways at Part 139 airports. The analysis is conducted using a runway elevation profile measured in 1-foot (.3048m) intervals, and using mathematical models of commercial aircraft to determine the aircraft's response to the profile data. The vertical accelerations (in g's) are predicted at the pilot's station (PSA) and at the aircraft's center of gravity (CGA) defines .40g vertical acceleration to be the threshold of discomfort (*1*). As such, APR has used this threshold as a means to identify areas where the pavement produces poor ride quality. Additionally, the Boeing Commercial Aircraft Company has found that .40g (Nz) is the point where fatigue damage begins to occur in aircraft landing gear structure and other aircraft structural components.

The concept of using a six-inch (15cm) PCC overlay of rapid setting concrete to avoid significant runway closure is of great economic benefit to single-runway and highly congested airports. With asphalt runways, it's a relatively simple matter to lay down multiple lifts using temporary ramps to transition the operating aircraft from the old runway surface to the new. With PCC pavements, this proposition becomes more complex. The purpose of this study is to determine what effect a six-inch (15cm) temporary ramp will have on aircraft response. Traditionally, APR uses predicted aircraft response as produced by APR's APRas simulation software (*2*) at two locations on the aircraft as a threshold of acceptability; one at the aircraft's center of gravity (.40g) and one at the pilot's station (.60g). However, because this is a temporary situation, perhaps the .40g and .60g thresholds could be relaxed. Although how much relaxation in the threshold of acceptability is unknown and merits further study.

Aircraft Structural Limitations

The primary reason for maintaining a smooth airport pavement for day to day use is to minimize the surface irregularities that influence aircraft response during taxi, takeoff and landing. Operating with temporary 6-inch (15cm) ramps will cause an aircraft response. What are the concerns regarding pavement roughness and aircraft operations?

Aircraft Structures: The introduction of a temporary 6-inch (15cm) ramp during construction will cause increased aircraft response. The key is to design the ramp so that the aircraft will not experience *excessive* response. So what is the impact of operating on a rough surface? The primary concern is dynamic loads going into the aircraft structure. Aircraft have specific load limits at the main landing gear (MLG) and nose landing gear (NLG). APR uses a value of .4g at the CG and .6g at the pilot's station as acceptable for operations on existing surfaces. (Engineering judgement is required if there are multiple occurrences in the same general area.)

Pilot Complaints: The aircraft is at its heaviest during takeoff and is on a steeper part of the strut's load-stroke curve which will result in higher loads going into the aircraft structure. During landing, the aircraft has used up much of the fuel and is usually significantly lighter. This will result in more strut stroke available to absorb the roughness caused by changes in runway profile. Consequently, pilot and passenger complaints will be more likely during takeoff when the aircraft is heavy.

Aborted Takeoff: The high speed aborted takeoff coupled with the short stopping distance required mandates a maximum braking effort. The aircraft will pitch forward on the nose landing gear (NLG), compressing the tires and the NLG strut. The compressed tires will heat up and possibly blow the fuse plugs. The high loads also risk fracturing the NLG drag brace, which would cause the NLG to collapse. Up-ramps would aggravate this emergency operation.

Stopping Distance: It takes more distance to stop an aircraft on a rough runway than on a smooth runway. When an aircraft has vertical motion caused by bumps, the normal load on the main landing gear (MLG) varies, and therefore, the braking force varies. In addition, roughness can affect a pilot's ability to maintain steady brake pressure. However, since there will be only one temporary ramp encounter, it is unlikely that stopping distance will be significantly impacted.

Case 1 – Perfectly Smooth Runway with Ramps

Two temporary 6-inch (15cm) ramp designs were considered for this paper. The first ramp has a 1% grade and is 50 feet (15.24m) in length. The second ramp has a .5% grade and is 100 feet (30.48m) in length. To see what effect the ramps themselves would have on aircraft response, both ramps were placed on a perfectly smooth artificial runway, 1,000 feet (305m) from the beginning of the runway and sloped up to an elevation of six inches (15.24cm). The remainder of this artificial runway was also perfectly smooth. Figures 1 and 2 shows the predicted responses of a 737-800 aircraft encountering the 1% ramp and .5% ramp respectively during a 95-knot constant speed taxi simulation. 95 knots was selected because it produced a relatively high response. The upper trace shows the accelerations predicted at the pilot's station (PSA). The middle trace illustrates the accelerations predicted for the aircraft's center of gravity (CGA) and the lower trace is the plotted pavement profile. Peak g's predicted are circled in red with their corresponding value listed nearby.

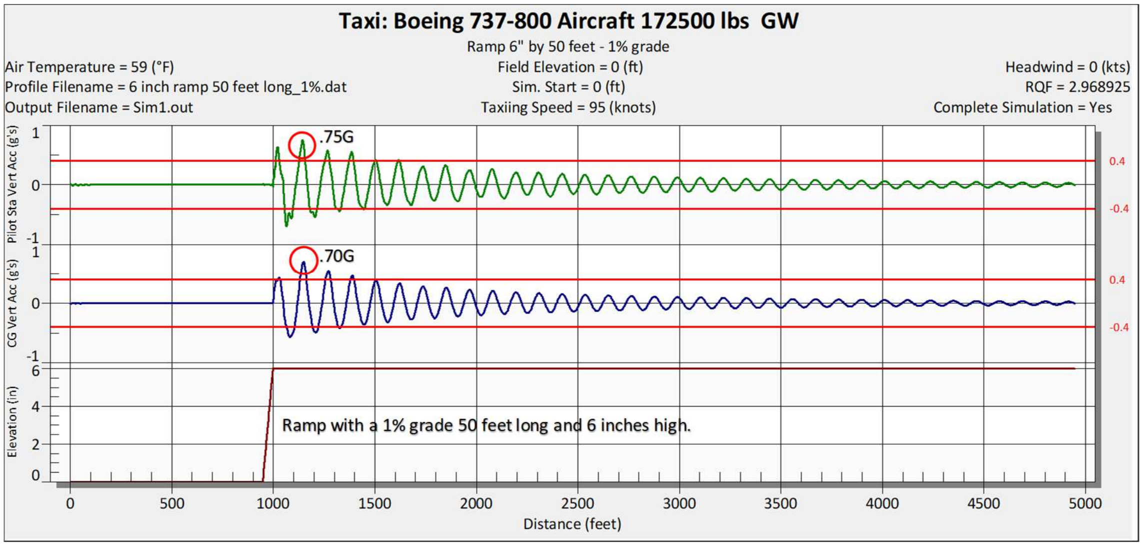

Figure 1. A 95-knot constant speed taxi simulation of a Boeing 737-800 encountering a 6-inch ramp with 1% grade on a perfectly smooth runway.

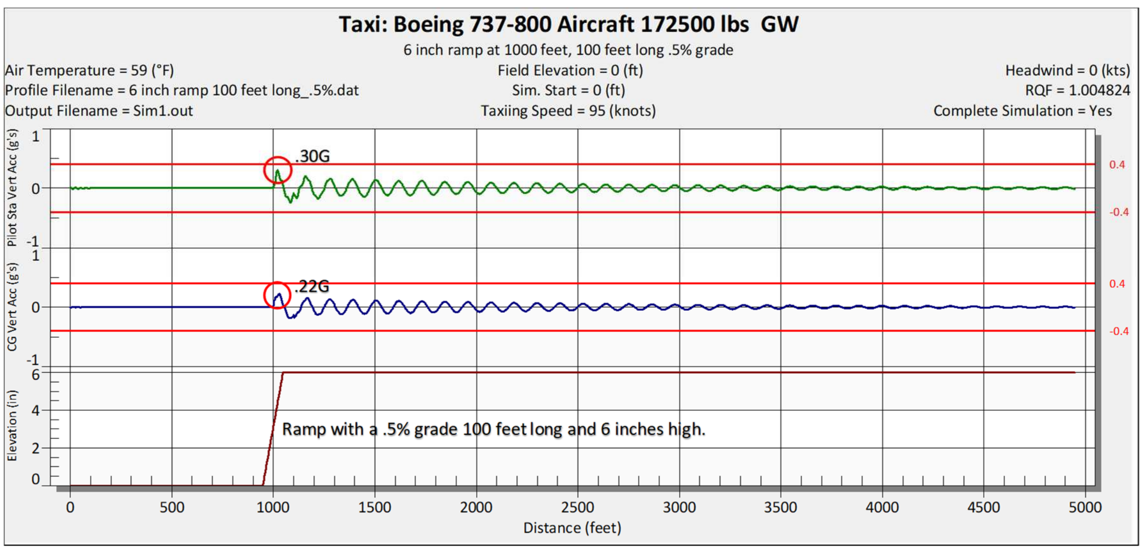

Figure 2. A 95-knot constant speed taxi simulation of a Boeing 737-800 encountering a 6-inch ramp with .5% grade on a perfectly smooth runway.

The ramp featuring the 1% grade is predicted to produce moderate aircraft responses at both the pilot's station and the aircraft center of gravity. The responses gradually dampen out until the end of the profile is reached. Figure 2 shows that the ramp consisting of a .5% grade is predicted to produce acceptable response throughout the simulation for this condition.

Case 2 – Operations on a Known Rough Runway (No Ramps)

Obviously, a perfectly smooth runway is not a real-world scenario. Figure 3 is a plot illustrating a simulation of a Boeing 737-800 performing a takeoff on the runway with known *significant* pavement roughness (**with no temporary ramps**). The rough area is located in the first 1,000 feet (305m). The aircraft produces mild to moderate response during the encounter with that area of pavement roughness.

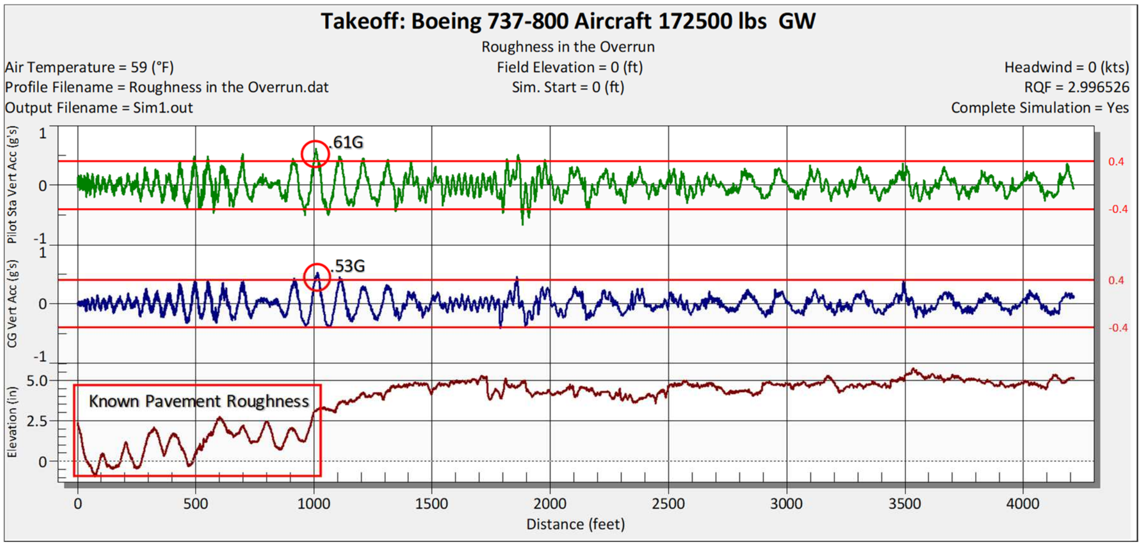

Figure 3. Simulated takeoff on a known rough runway (with no ramp) producing mild aircraft responses.

Case 3 - Operations on a Known Rough Runway (with Ramps of 1% and .5% Grade)

Operational runway profiles have a wide range of roughness levels. Most are acceptably smooth while a small number of others are quite rough and yield poor aircraft response without the complications of a temporary ramp. It is important to understand the ride quality (roughness) of the existing runway prior to placing these temporary ramps. The profile variation leading up to the ramp's location will influence the aircraft's response when it encounters the ramp. In order to understand the impact of a ramp placed on an existing runway the two ramp designs were inserted into a runway with known areas of significant roughness. Inserting a 6-inch (15cm) ramp with a 1% grade immediately following the area of known pavement roughness results in a significant increase in aircraft response. Figure 4 indicates the response predicted at the pilot's station is 1.09g and.83g at the aircraft's center of gravity. This response is significant and will likely produce pilot and passenger complaints even for temporary operations.

Figure 5 shows the aircraft response to the 6-inch (15cm) ramp with a .5% grade at the same location on the same runway. The aircraft response is improved but is still considered significant. The predicted response at the pilot's station is .78g and the aircraft's CG response is predicted to be .64g. This illustrates that the existing pavement roughness can significantly influence aircraft response.

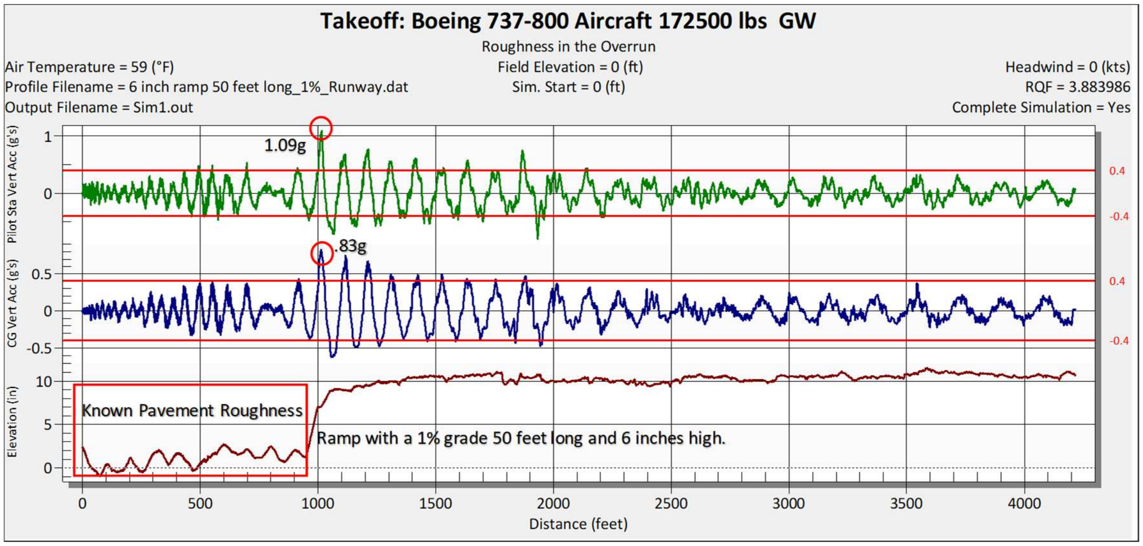

Figure 4. Simulated takeoff on a known rough runway with a 6-inch (15cm) ramp with a 1% grade.

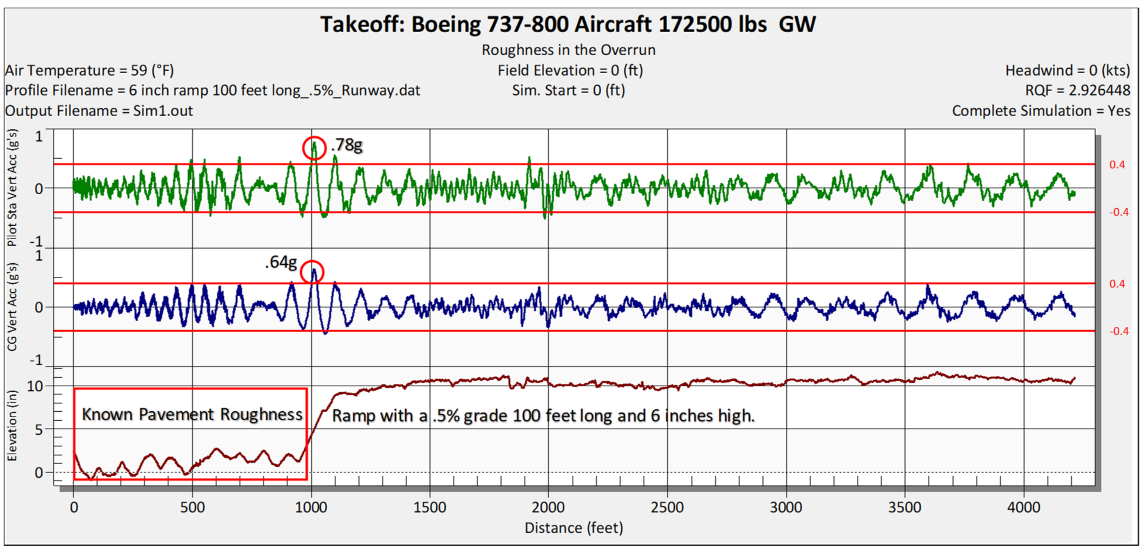

Figure 5. Simulated takeoff on a known rough runway with a 6-inch (15cm) ramp with a .5% grade.

Case 4 - Operations on an Average In-Service Runway (No Ramp and One with a 1% and a .5% Grade)

Figure 6 shows the ride quality predicted for an older, in-service runway with **no ramp**. This runway has a field elevation of about 5,000 feet (1,524m). For demonstration purposes, an air temperature of 90°F (32°C) was used. This temperature coupled with the high field elevation causes the aircraft to traverse more pavement during takeoff simulations. As you can see in Figure 6 shows that aircraft response is predicted to stay within the .40g threshold of acceptability through the simulation.

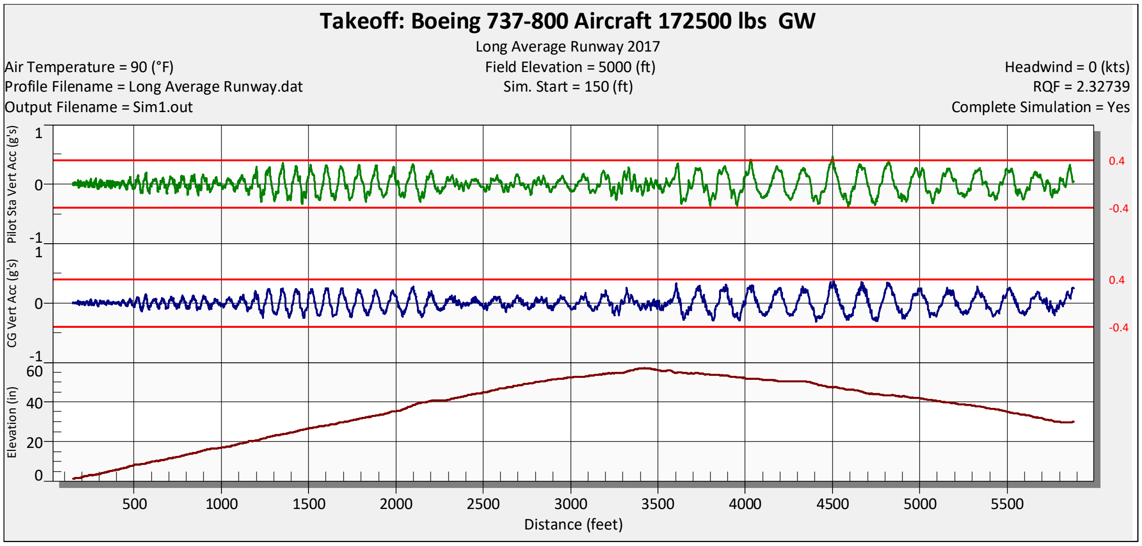

Figure 6. A takeoff simulation of a 737-800 on an average runway with no ramp.

If you place the 6-inch (15cm) ramp with a 1% grade 2,250 feet (686m) from the runway's end, aircraft simulations predict that the 737-800 aircraft will produce moderate responses (Figure 7). If you place the ramp with a .5% grade at the same location, aircraft response is predicted to be acceptable and not exceed the .40g threshold during this operation (Figure 8).

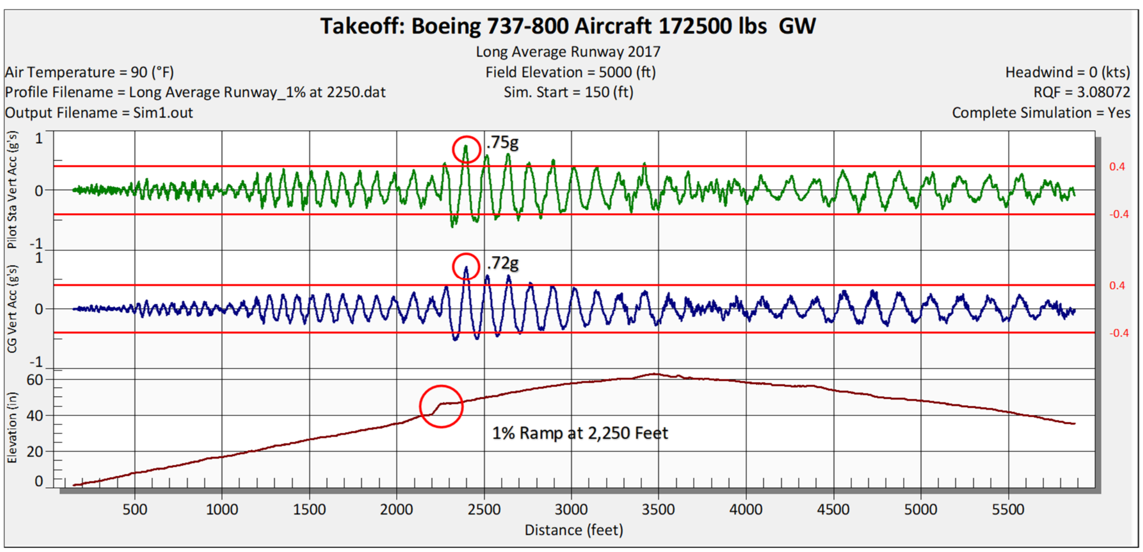

Figure 7. A takeoff simulation of a 737-800 on an average runway with 1% ramp located at 2,250 feet past threshold.

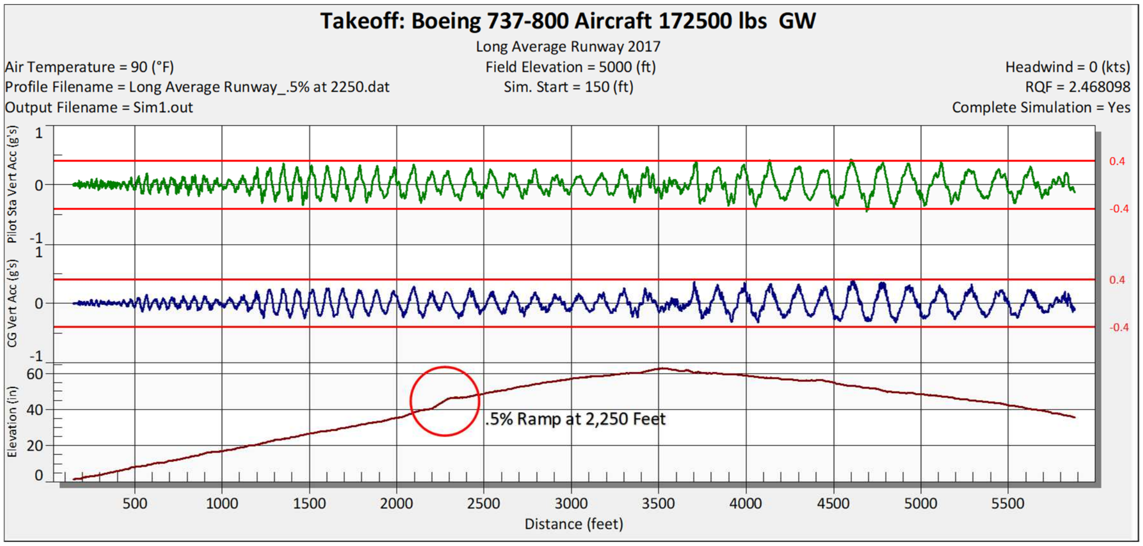

Figure 8. A takeoff simulation of a 737-800 on an average runway with .5% ramp located at 2,250 feet past threshold.

Case 5 - Ramp Location and Other Variables

There are many variables that come into play when determining the aircraft response to a runway. For example, a 737 can be quite sensitive to an event located at 1,500 feet (457m) and conversely, not respond to it at all when encountered at 6,000 feet (1,829m). However, a larger aircraft such as a Boeing 777 may not respond to the event at 1,500 feet (457m), but may produce significant response when encountered at 6,000 feet (1,829m). The same logic will apply to temporary ramps. To help illustrate this point, the following series of figures will show the effects of changing the ramp's location, as well as alternating the aircraft type.

Figure 9 shows the response on the high-altitude runway with a 6-inch (15cm) ramp (1% grade) located 5,000 feet (1,524m) past the runway's end. The ride quality is predicted to be degraded significantly. The 737 encounters the 1% grade change about 850 feet (259m) before the aircraft's rotation is initiated, and is predicted to experience 1.04g at the pilot's station and .94g at the aircraft's center of gravity. These responses would be considered unacceptable.

Figure 10 shows the response for the same conditions except with a .5% ramp. The response is predicted to be less, but still considered moderate with .60g at the pilot's station and .56g at the aircraft's center of gravity.

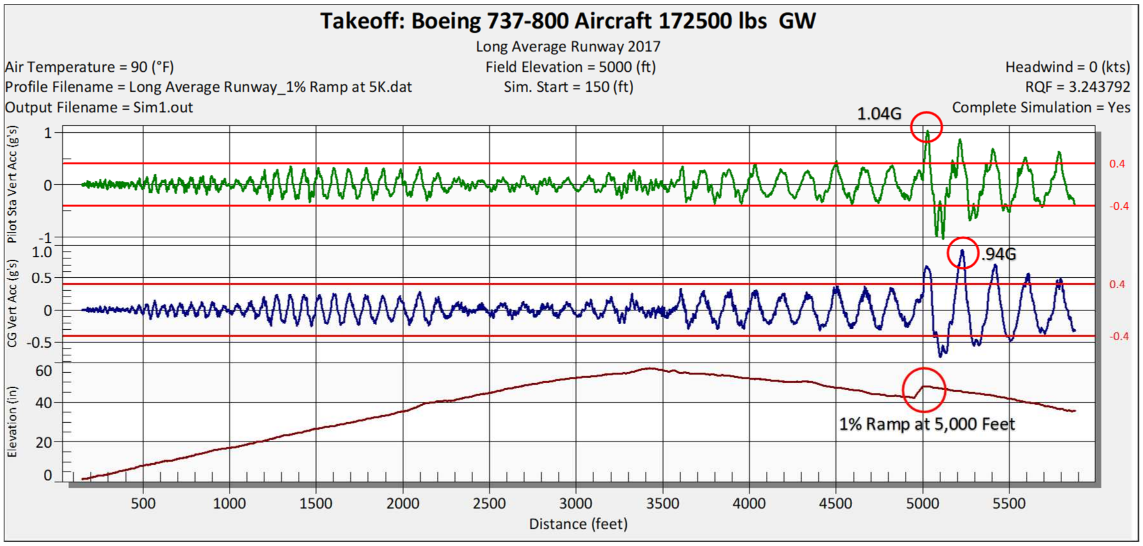

Figure 9. A takeoff simulation of a 737-800 on an average runway with 1% ramp located at 5,000 feet past threshold.

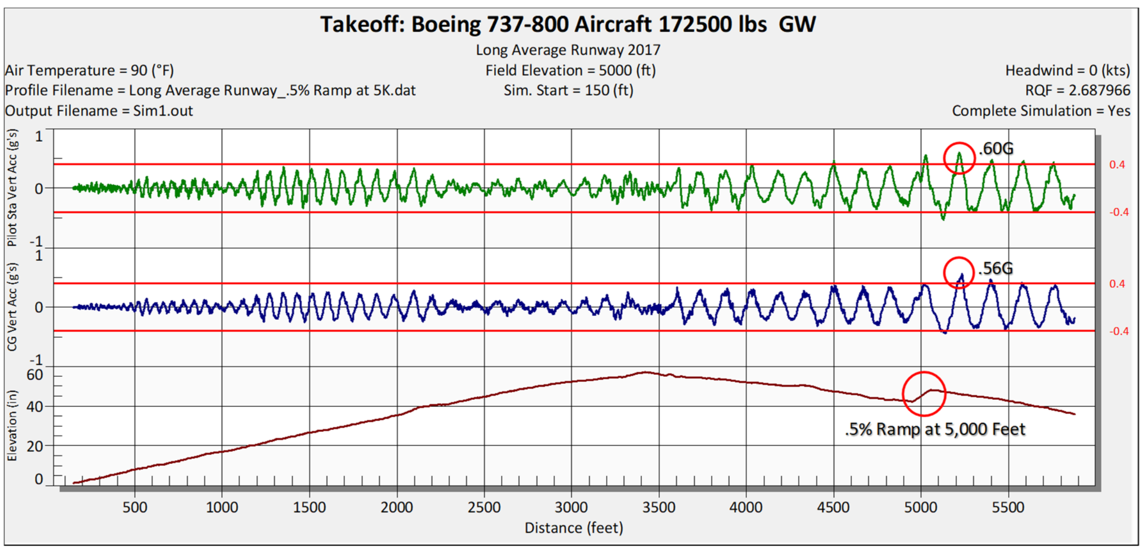

Figure 10. A takeoff simulation of a 737-800 on an average runway with .5% ramp located at 5,000 feet past threshold.

Aircraft type also plays a role when evaluating the response for different ramp locations. In this instance, a Boeing 777-200 was simulated with both ramps. The 777-200 has a gear spacing (distance from nose gear strut to the main landing gear strut) of 84 feet 11 inches (26m). When encountering the 6-inch (15cm) ramp with a 1% grade, this larger aircraft is predicted to produce significant responses as well. As shown in Figure 11, encountering the 1% grade at 5,000 feet (1,524m) produced .94g at the pilot's station and 1.13g at the aircraft's center of gravity. Responses at both stations are considered unacceptable and would produce pilot and passenger complaints.

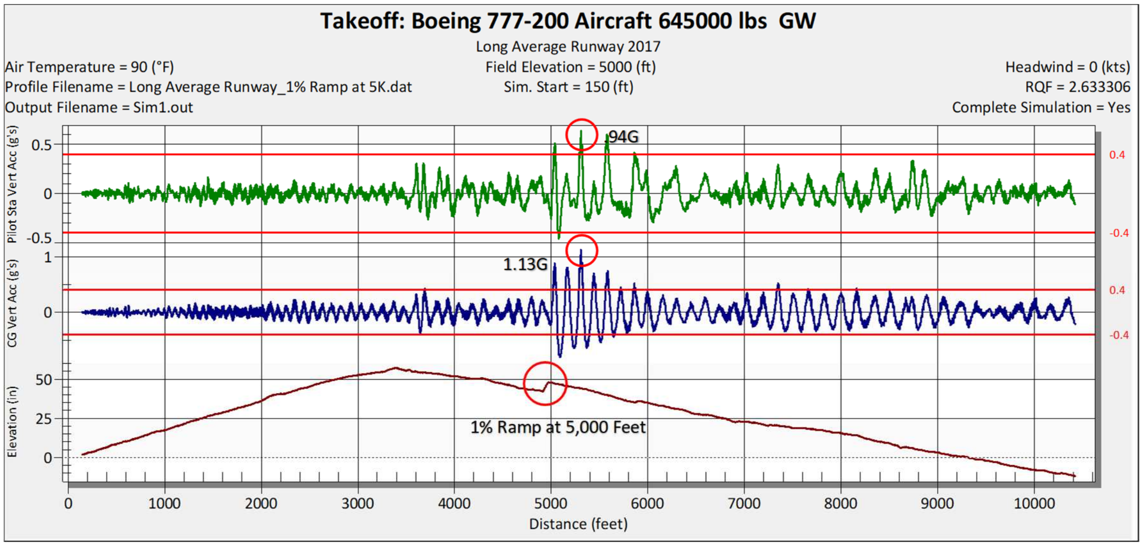

Figure 11. A takeoff simulation of a 777-200 on an average runway with 1% ramp located at 5,000 feet past threshold.

Figure 12 shows that the same 777-200 conditions with the .5% grade ramp responded more favorably.

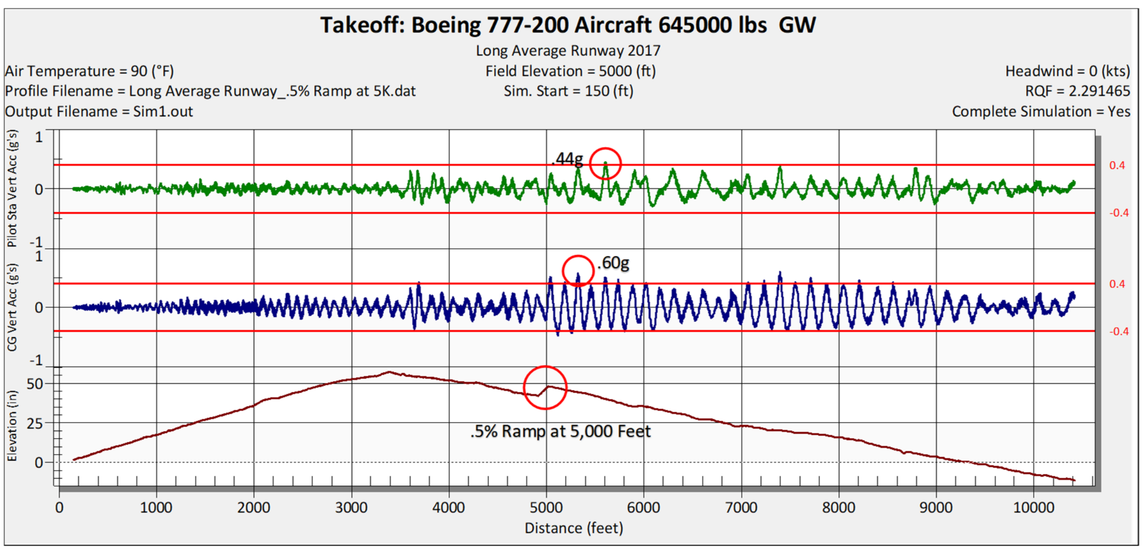

Figure 12. A takeoff simulation of a 777-200 on an average runway with .5% ramp located at 5,000 feet past threshold.

Down-Ramps are better than Up-Ramps

Given the choice, down-ramps will generally produce less aircraft response than up-ramps, therefore, it is advisable to pave in the direction of travel dictated by prevailing winds. It would not be advisable to touch down on an up-ramp. An up-ramp will add to the sink speed of a landing aircraft whereas a down-ramp will reduce the effective sink speed. A 1% up-slope will increase effective sink speed by 2.5 feet per second (fps) (.76mps) at a touchdown speed of 250 fps (148 knots). Sink speed design limit for most aircraft is 10 fps (3mps).

FAA AC 150/5380-9 (Guidelines and Procedures for Measuring Airfield Pavement Roughness)

FAA AC 150/5380-9 (*3*) says that temporary transitions are limited to 1-inch per 15 feet (2.54cm in 4.6m). This is a .57% grade. Consequently, the .5% grade proposed in this paper is less than that. However, according to the FAA chart, the limit is 3 inches (7.6cm). This limit is intended to provide acceptable aircraft response for all ramp locations and a mix of aircraft. Extending this limit to 5 (12cm) or 6 inches (15cm) would need further study.

Case History

APR was involved with a runway project that had an intersecting runway located approximately 4,500 feet (1,372 m) from the western threshold of the 10,000-foot (3,048 m) runway. This intersection had a crown with a 5 inch (12.0 cm) rise in 65 feet (20 m). That is a .65% grade. This was an up-ramp followed by a similar down-ramp. And it was surrounded with moderate roughness before and after the intersection. This runway was used for narrow and wide-bodied aircraft and had been in service for serval years. The intersection did cause occasional pilot complaints for wide body aircraft under certain conditions and was reconstructed because of that. The point is that here was a *permanent* in-service runway with a grade larger than that suggested for the *temporary* construction considered in this paper. This case serves as a real-world example that operations using a 6-inch (15cm) ramp with a .5% grade are not unrealistic. Figure 13 is a plot of the intersection profile.

It is important to know the existing profile

In order to allow a waiver for a 6-inch (15cm) ramp in less than the distance the FAA AC's call for, the engineer must have knowledge of the existing runway profile and how that profile, coupled with the ramp design, will impact aircraft response.

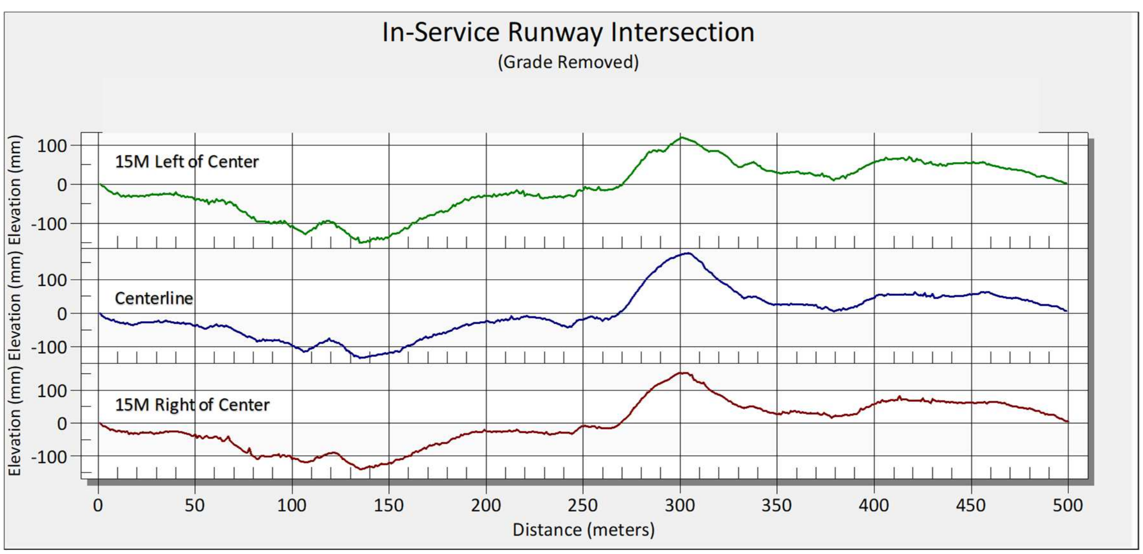

Figure 13. Profile plot of an in-service runway intersection

CONCLUSIONS

Temporary construction ramps are a necessary tool for airports that have only one runway or for airports that are so congested that closing a single runway for an extended period is not feasible. Creating a PCC overlay of six inches (15cm) can create unique challenges when evaluating the pavement for aircraft response. This study identified several factors to consider when designing 6-inch (15cm) temporary ramps:

1. Evaluate the roughness level of the existing surface to help optimize the location and design of the temporary ramps. The addition of a temporary ramp may aggravate the aircraft response if areas of roughness precede or follow the planned ramp location.
2. In most cases, simulations predict that the .5% grade produced acceptable aircraft response. However, a 5% ramp coupled with a known rough existing pavement may require a less aggressive slope.
3. When possible, place the ramp in the direction of traffic (using prevailing winds) so that the aircraft encounters the ramp as a down-ramp to help minimize responses.
4. If located in a touch-down zone, an up-ramp will add to the sink speed of a landing aircraft, whereas a down-ramp will reduce the effective sink speed. An up-ramp will reduce the aircraft's sink-speed safety margin.

This brief study evaluated two scenarios for the use of a 6-inch (15cm) temporary ramp: one with a 1% grade and the other with a .5% grade. Simulations predicted that a 1% grade will most likely result in unacceptable aircraft response for takeoff operations on a known rough runway and an average runway. Simulations predicted that a .5% grade will in most cases result in acceptable aircraft response for takeoff operations on an average runway. Operations on a 6-inch (15cm) ramp on a rough runway may require a less aggressive slope.

There are a variety of operations that were not considered in this study when evaluating aircraft response. For example, the results of performing a landing or an aborted takeoff using these ramp features were not conducted. Evaluating these scenarios are recommended for further study.

This brief study provides an initial look at the feasibility of using a 6-inch (15cm) temporary ramp runway reconstruction. It is the author's opinion that additional research be conducted prior to any implementation.

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