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## Is “Green Dot” Always the Optimum Engines-Out Glide Speed on the Airbus A320 Aircraft?

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## Introduction<sup>1</sup>

As of today, more than 92% of the U.S. commercial aircraft fleet consists of twin-engine jetliners (Dolbeer, Wright, Weller, & Begier, 2013). Among these twin-engine jetliners, the Boeing 737 NG<sup>2</sup> and Airbus A320<sup>3</sup> aircraft families form the backbone of the U.S. airline industry fleet. In 2013, the Boeing 737 NG<sup>2</sup> and A320<sup>3</sup> aircraft families transported 196.2 and 138.1 million passengers, respectively, on all U.S. carriers (Research and Innovative Technology Administration [RITA], 2014). This totals 334.3 million annual passengers, which makes up 44.2% of all 756.6 million annual passengers on U.S. air carriers in 2013 (RITA, 2014). The A320<sup>3</sup> and Boeing 737 NG<sup>2</sup> are also the best-selling commercial aircraft families. In 2013, the A320<sup>3</sup> aircraft family received a total of 1,162 net orders (Airbus Industrie, 2014), and the Boeing 737 NG<sup>2</sup> aircraft family received a total of 1,046 net orders (The Boeing Company, 2014).

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<sup>1</sup> The accuracy of the results described in this paper is not verified by Airbus Industrie, which is the manufacturer of the Airbus A320 aircraft family. The results are merely based on the findings of the authors in the full flight simulator. The results are intended to explore the potential aircraft performance at a particular configuration that may be utilized through proper pilot training and proficiency.

The authors contacted Airbus Industrie and asked about the manufacturer's opinion on the findings. However, Airbus Industrie declined to provide any propriety data regarding the findings on the grounds that the University of Illinois at Urbana-Champaign does not have a contractual agreement with Airbus Industrie.

<sup>2</sup> Boeing 737 NG (Next Generation) family includes the single-aisle 737-700, 737-800, and 737-900 in the U.S. Commercial Fleet.

<sup>3</sup> The A320 aircraft family consists of the single-aisle A318, A319, A320, and A321 aircraft.

Today's twin-engine jetliners are more efficient than yesterday's three- and four-engine jetliners. However, they have vulnerabilities that are not shared by yesterday's three- and four-engine aircraft. Reduced engine redundancy is one of these vulnerabilities. Due to reduced number of engines, twin-engine aircraft can be more susceptible to total loss of power compared to three- or four-engine aircraft. Indeed, twin-engine jetliners such as the A320 are 15 times more likely to undergo total loss of power in the event of a bird strike compared to three- or four-engine jetliners (Avrenli & Dempsey, January 2015). In the near future, total loss of power due to bird strike is expected to occur more frequently due to the substantial increase in the North American large bird populations (Dolbeer et al., 2013; Nicholson & Reed, 2011; Dolbeer, 2009), and the fact that modern-day turbofan engines are not tested for large birds (Dolbeer et al., 2013; Transport Canada, 2004). Besides, total loss of power can also occur due to various other factors such as inclement weather (National Transportation Safety Committee [NTSC], 2006; National Transportation Safety Board [NTSB], 1991; NTSB, 1978), ice ingestion (Forsberg et al., 1993), fuel leakage (Aviation Accidents Prevention and Investigation Department of Portugal [AAPID], 2003), pilot error (NTSB, 2007; Associated Press, 1987), maintenance error (Paraffin Caused One-Eleven Crash, 1972) and volcanic ash clouds (Tootell, 1986; Witkin, 1989). Therefore, contemporary twin-engine jetliners, such as the popular A320 and Boeing 737 NG aircraft families, are imperiled by the hazard of total loss of power.

### **Problem Definition**

During total loss of power, flight crews have only one chance for landing because the aircraft cannot gain altitude. Thus, there is no room for pilot error. Otherwise, total loss of power may have severe consequences such as the recent Dana Air Flight 992 that resulted in 163 fatalities in June 2012 (Holland, 2012).

In the event of total loss of power, emergency checklists may help pilots act promptly to achieve a safe touchdown. While both the Airbus A320 and Boeing 737 NG aircraft families have a checklist designed for total loss of power, this study focuses on the checklist of the A320, which is called "Engine Dual Failure Checklist" (NTSB, 2010). According to Airbus, the checklist is primarily intended for use in the occurrence of a dual-engine failure above 20,000 ft because airliners spend most of the flight time at such high altitudes (NTSB, 2010). The checklist states that the optimum<sup>4</sup> airspeed at which to fly the aircraft is the "green dot" speed when an engine restart is considered impossible (NTSB, 2010). This is because the "green dot" speed maximizes<sup>5</sup> the distance that the aircraft glides per unit altitude loss in wings-level position (Airbus Industrie, 2002). Therefore, A320 pilots are generally trained to glide at the "green dot" speed<sup>4</sup> in the event of total loss of power.

While Airbus' engine dual failure checklist is primarily intended for use above 20,000 ft (NTSB, 2010), statistical analysis of the FAA Wildlife Strike Database (Federal Aviation Administration [FAA], 2013) shows that engine failure due to bird strike is most likely to occur below 5,000 ft above ground level (AGL) (Avrenli & Dempsey, 2014). If total loss of power occurs at a low altitude, it may require sharp turning maneuvers at bank angles as high as 30° rather than wings-level flight. For example, an aircraft may undergo dual-engine failure due to bird strike during the initial climb-out. If the airport environment is inhospitable, the pilots may have to attempt a sharp 180°-turn to the departure airport to increase the odds of survivability. In

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<sup>4</sup> If the aircraft is in "clean" configuration, i.e. flaps, slats and landing gear are fully retracted.

<sup>5</sup> In presence of tailwind, the airspeed that maximizes the power-off glide range may differ from the "green dot" speed.

such a landing maneuver involving turns at high bank angles, it is not known whether the “green dot” speed would still be the optimum airspeed.

### **Objectives and Potential Uses of the Study**

The objective of this study is to determine whether the “green dot” speed would still be the optimal airspeed for the A320 in the event of total loss of power at a low altitude, which subsequently requires turning maneuvers at high (i.e. up to 33°) bank angles to the departure airport. For this purpose, the study undertakes the following goals:

1. Develop a realistic scenario of total loss of power that occurs at a low altitude during the initial climb.
2. Compute the altitude loss required for gliding to the departure airport at different airspeeds.
3. Establish the relationship between airspeed versus the required altitude loss.
4. Determine the “optimum” airspeed that would require the minimum altitude loss in the given scenario, and find out if that airspeed equals the “green dot” speed.

Consequently, A320 pilots can become more knowledgeable on appropriate landing procedures that can enable safe touchdown in the occurrence of total loss of power at a low altitude.

### **Literature Review**

A number of studies (Rogers, 1995; Hoffren & Raivio, 2000; Hyde, 2005; Shapira & Ben-Asher, 2005; Brinkman & Visser, 2007; Adler, Bar-Gill, & Shimkin, 2012) explored optimum landing maneuvers following total loss of power at a low altitude. All these studies focused on either single-engine general aviation aircraft or fighter jets, but not commercial jets. For example, Rogers’ study (1995) involved a Beech Bonanza aircraft; Hoffren and Raivio’s

study (2000) examined a BAe Hawk Mk.51 aircraft; Hyde's study (2005) focused on an RV-4 aircraft. Both Shapira and Ben-Asher's study (2005) and Brinkman and Visser's study (2007) analyzed the powerless landing performance of a Lockheed-Martin F-16. Adler, Bar-Gill, and Shimkin (2012) applied a 3-D trajectory planning algorithm to a Cessna 172 Skyhawk undergoing engine failure.

There has been no comparable study up-to-date that focused on commercial jets. Hence, this study will be the first of its type by addressing a commercial jet, and will bring this underdeveloped idea into maturity.

### **Nomenclature**

- D = Total drag force acting on the aircraft.
- L = Total lift force acting on the aircraft.
- L/D = Lift-to-drag ratio.
- $V_{LOEXT}$  = Maximum allowable airspeed for landing gear extension.
- $V_{LS}$  = Minimum selectable airspeed.
- $V_{S1g}$  = Airspeed that corresponds to the maximum lift coefficient, just before the lift starts decreasing in a given aircraft configuration.
- $V_{TIRE}$  = Maximum ground speed that can be reached without causing damaging heat elevation to the tire structure.

### **Review of Theory**

When an aircraft undergoes total loss of power, the engines cannot generate thrust. Therefore, the aircraft has to lose altitude (i.e. potential energy) in order to glide. In such emergency situations, the glide performance of an aircraft is described by the lift-to-drag ratio (i.e. L/D). During steady-speed glide, if the aircraft is in equilibrium, the L/D ratio equals the

horizontal distance travelled by the aircraft divided by the altitude loss (see Figure 1). This ratio is often referred to as “glide ratio” in engines-out emergency landings. For a given aircraft configuration, the glide ratio primarily depends on airspeed at lower altitudes such as below 10,000 ft.

There is a unique airspeed in a given aircraft configuration that maximizes the glide ratio (Smith, 1992). For the Airbus A320 aircraft family, this airspeed is called the “green dot” speed if the aircraft is in “clean” configuration (i.e. flaps, slats and landing gear are fully retracted). The “green dot” speed is represented by a green dot on the primary flight display of the A320 as shown in Figure 2. At altitudes below 10,000 ft, the “green dot” speed primarily depends on aircraft weight, and typically ranges from 200 to 235 KCAS (knots in calibrated airspeed) for the A320-200 aircraft model (Airbus Industrie, 2002).

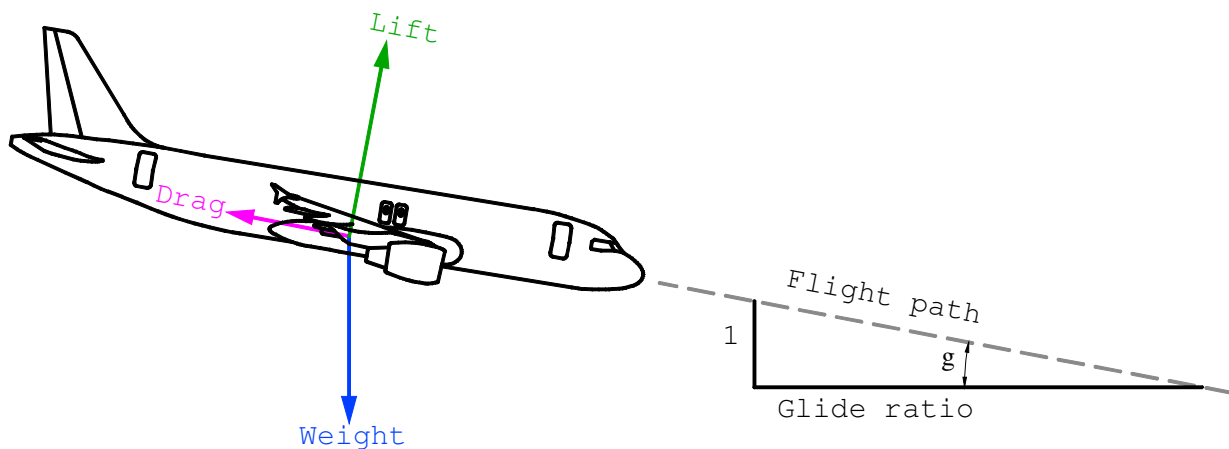


Figure 1. Illustration of glide ratio during total loss of power.

## Materials and Methods

### Assumed Scenario for Total Loss of Power

Statistically, engine failure due to bird strike is most likely to occur during the initial climb-out below 5,000 ft (Avrenli & Dempsey, 2014). Considering this, the study assumes the following scenario for total loss of power:

1. An Airbus A320-200 performs a northbound takeoff from Runway 36 shown in Figure 3, and starts the initial climb-out.
2. After the flaps are fully retracted, the A320-200 encounters a flock of birds, and multiple birds are ingested into both engines. The aircraft is assumed to weigh 70.0 tons at this particular moment.
3. Both engines of the A320 undergo total loss of power at a distance of 3.0 nautical miles (nm) north of Runway 18 while the aircraft is heading north (i.e. 0°; see Figure 3). At this exact location, the pilots initiate an emergency turn-back maneuver to Runway 18. The study will compute the altitude loss required turn back to Runway 18.

It is assumed that the A320 does not have sufficient hydraulic power to extend the flaps. Thus, the wings are assumed to be in “clean” configuration until touchdown. Since the flaps cannot be extended, the landing has to be achieved at a speed considerably higher than typical final approach speeds.



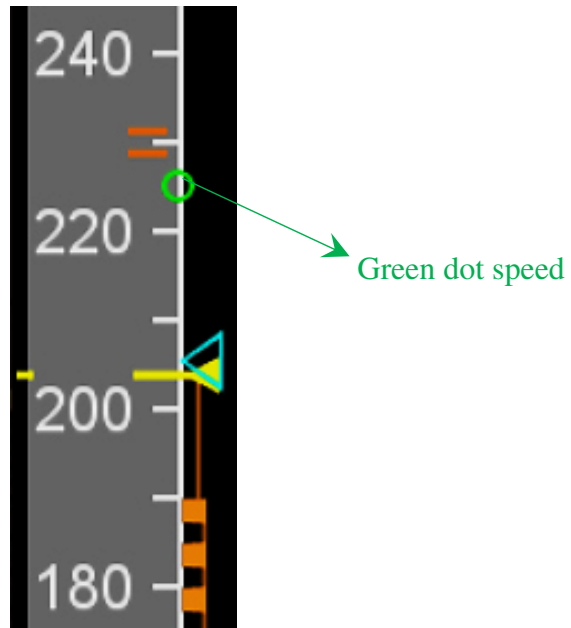


Figure 2. “Green dot” speed on the primary flight display of the Airbus A320.

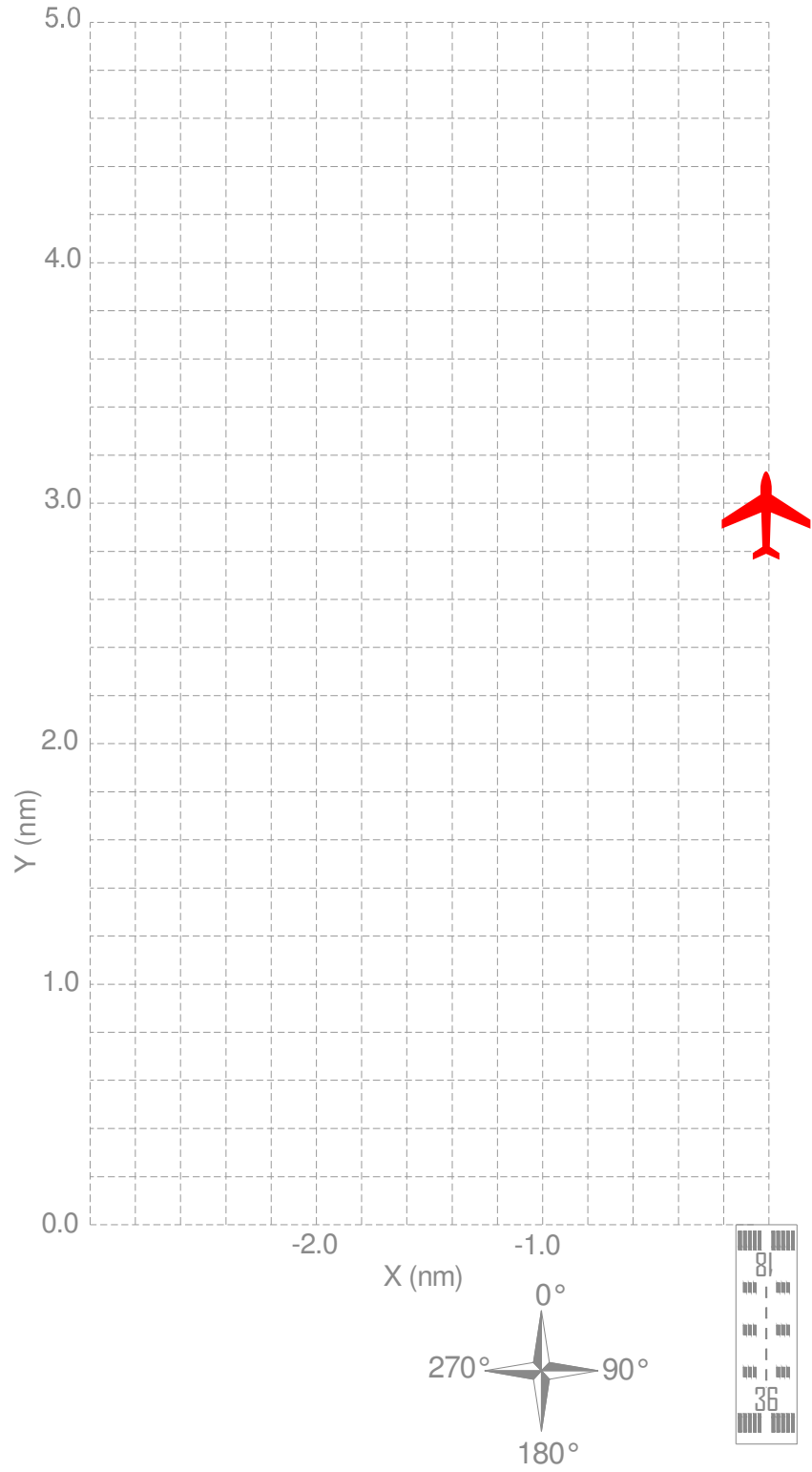


Figure 3. Aircraft location at the instant of total loss of power (runway not drawn to scale).

## **Airspeeds Considered in Analysis**

To find out the “optimum” airspeed in the given scenario, the altitude loss required for gliding from the initial aircraft location to Runway 18 is computed at five different airspeeds. These airspeeds are 205, 215, 225, 235, and 245 KCAS. Based on the authors’ observations in the full flight simulator, these airspeeds are briefly explained as follows:

- The lowest airspeed of 205 KCAS approximately equals the lowest selectable airspeed ( $V_{LS}$ ) when the aircraft is in clean configuration with a gross weight of 70 tons and is in 33°-bank. (If the aircraft is in wings-level position, i.e. 0°-bank,  $V_{LS}$  is observed to equal approximately 200 KCAS in clean configuration and 70-ton gross weight.)  $V_{LS}$  is defined as the minimum calibrated airspeed to be maintained during landing down to a height of 50 ft above the intended touchdown point.  $V_{LS}$  provides an appropriate margin to the stall speed in the given aircraft configuration. For fly-by-wire aircraft like the A320,  $V_{LS}$  equals 1.23 times  $V_{S1g}$ , which is the airspeed that corresponds to the maximum lift coefficient, just before the lift starts decreasing with increasing angle of attack in a given aircraft configuration (Airbus Industrie, 2002).
- The median airspeed of 225 KCAS approximately equals the “green dot” speed at the given weight of 70.0 tons.
- The highest airspeed of 245 KCAS is slightly lower than the maximum operating speed for landing gear extension, which equals  $V_{LO\ EXT} = 250$  KCAS for the A320-200 aircraft (Airbus Industrie, 2002).
- The other airspeeds of 215 and 235 KCAS are intermediary speeds that are included in analysis to better demonstrate the relationship between airspeed and the required altitude loss.

It should be noted that all airspeeds considered in analysis are well above typical landing speeds. They are also above  $V_{\text{TIRE}} = 195$  KCAS, which is the maximum ground speed that can be reached without causing damaging heat elevation to the tire structure (Airbus Industrie, 2002). Therefore, landing at such high airspeeds would most likely cause damage to the tire structure of the aircraft in real life emergencies.

### **Input Data**

To estimate the required altitude loss at the given airspeeds, some basic aerodynamic data specific to the A320-200 aircraft is required as input. The required input data is the steady-speed engines-out glide ratio of the A320-200 aircraft in “clean configuration” at the given airspeeds. Since these data are not released by Airbus Industrie, a flight simulation methodology is followed to estimate engines-out glide ratios. The simulations are conducted in a JAR-FSTD A, Level D full flight simulator that is certified under the European Aviation Safety Agency (EASA) and Joint Aviation Authorities (JAA). The exact model of the simulated aircraft is Airbus A320-232 with wingtip fences. The simulator has been tested in “normal”, “alternate”, and “direct” control laws of the Airbus A320 aircraft, and simulates real aircraft behavior in all normal and abnormal flight operations. A typical simulation run has the following steps:

1. The aircraft starts wings-level flight at 5,000 ft AGL in “clean” configuration with both engines running. The aircraft gross weight is frozen at 70.0 tons in each simulation run, which is slightly below the maximum take-off weight of 73.5 tons for this aircraft (Airbus Industrie, 2013).
2. Soon after the flight simulation starts, dual-engine failure occurs at 5,000 ft AGL. The aircraft starts losing altitude, and the dual-engine failure results in total loss of thrust in both engines.

3. By the time the aircraft reaches 3,200 ft AGL, the flight crew stabilizes the bank angle and airspeed at the given values for that simulation run.
4. From 3,200 ft AGL on, the aircraft power-off glides at the given constant airspeed and bank angle until it “crashes”. The position of the rudder is fixed at neutral during the power-off glide. Because both the airspeed and bank angle are kept constant, the power-off glide ratio also remains constant during this phase.
5. The simulator plots the descent profile of the aircraft between 3,200 ft AGL and 200 ft AGL. The engines-out glide ratio is directly read from the plot. No data below 60 ft AGL are used to avoid the ground effect (Smith, 1992).

The results from the flight simulations are plotted in Figure 4, and are interpreted as follows:

- For wings-level flight (i.e. bank angle =  $0^\circ$ ), the observed glide ratio of the A320-200 increases with increasing airspeed up to the “green dot” speed of 225 KCAS. When the airspeed equals the “green dot” speed, the glide ratio of the A320 is observed as approximately 17. In other words, the aircraft is expected to glide a horizontal distance of around 17,000 ft for every 1,000-ft altitude loss at the “green dot” speed in “clean configuration”. After the “green dot” speed, the observed glide ratio slightly decreases with increasing airspeed.

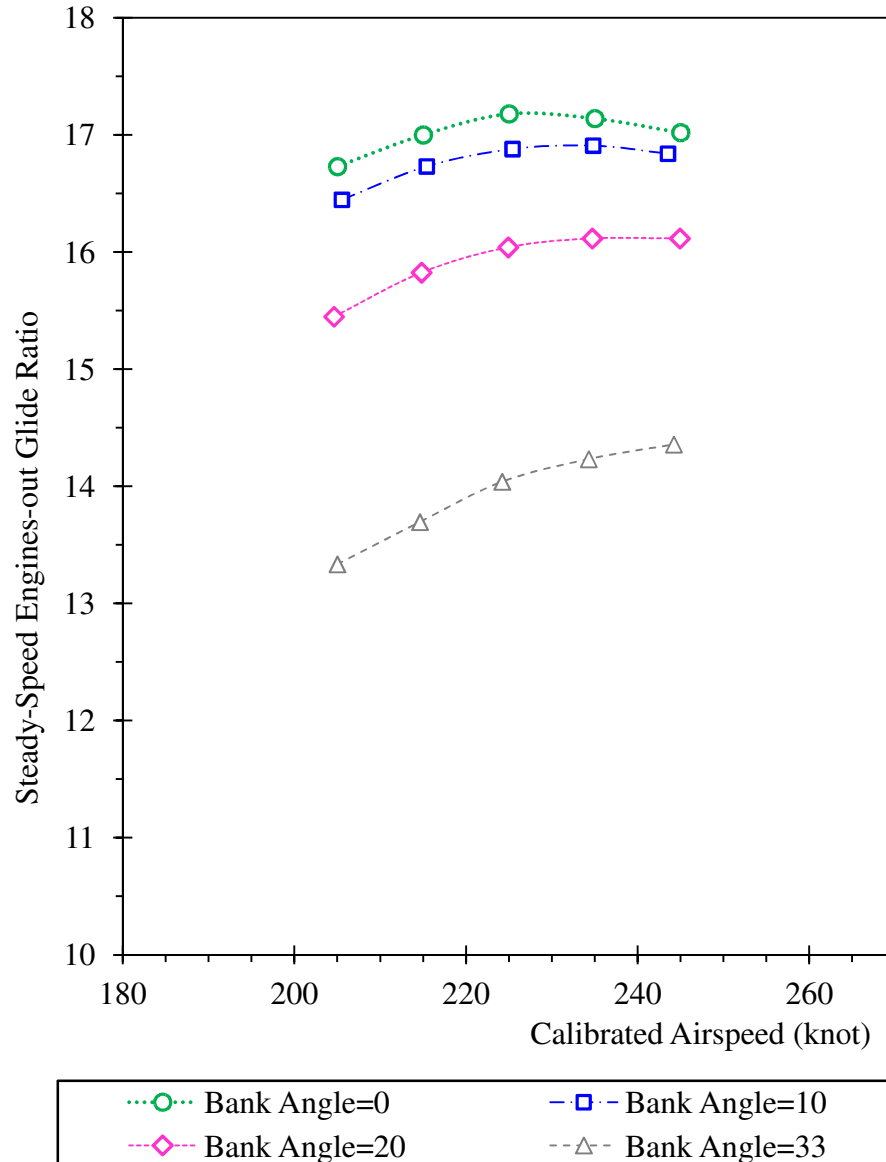


Figure 4. Steady-speed engines-out glide ratio vs. airspeed observed in the A320-200 full flight simulator (“clean” configuration, aircraft gross weight = 70.0 tons, center of gravity = 0%).

- For a given airspeed, the observed glide ratio decreases with increasing bank (roll) angle. This is because the drag force acting on the aircraft increases with increasing bank angle, and the aircraft loses some lift during banked turns.

- The maximum bank (roll) angle is limited to  $33^\circ$  because bank angle is one of the flight dynamics parameters limited by the Airbus' fly-by-wire system. If the bank angle exceeds  $33^\circ$  with side-stick input from the pilot, the aircraft automatically reduces the bank angle to  $33^\circ$  upon side-stick release in "normal control law". Thus, it is not practically possible<sup>6</sup> to maintain a constant bank angle greater than  $33^\circ$  on the A320 aircraft when the aircraft is in "normal control law" (Bugaj, 2011).

The accuracy of the findings presented in Figure 4 have not been reviewed by Airbus Industrie. The results in Figure 4 are merely based on the authors' study in the full flight simulator, and will be used to estimate the altitude loss required for gliding from the initial aircraft location to Runway 18 at the five airspeeds.

### **Computation of the Landing Trajectories**

The landing trajectory at a given airspeed from the initial aircraft location to Runway 18 is formulated as an optimization problem. The objective function aims to minimize the altitude loss at the given airspeed. The data plotted in Figure 4 are used as input, and the following modelling assumptions are made:

- The aircraft has to be aligned with Runway 18 by the time it is 100 ft above ground level (AGL) with its landing gear fully extended and locked.

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<sup>6</sup> In the "normal control law", the maximum achievable bank angle equals  $45^\circ$  or  $67^\circ$ , depending on the particular flight conditions. In the "normal control law", if the side-stick is not released, the bank angle keeps increasing up to  $45^\circ$  or  $67^\circ$  and then remains constant at this value until the side-stick is released. With the release of the side-stick, the bank angle returns to  $33^\circ$  in the "normal control law". It is also possible to exceed the  $33^\circ$ -bank angle if the aircraft is in "alternate law".

- Once the flight crew configures “landing gear down”, it takes no longer than 15 seconds for the landing gear to be fully extended and locked (Avrenli & Dempsey, 2015).
- Standard weather conditions prevail, and there is no wind during the powerless landing.
- The roll rate of the aircraft equals  $10^\circ/\text{s}$ . An uncertainty analysis showed that the accuracy of the findings is not sensitive to assumed roll rate (Avrenli & Dempsey, 2015).

The optimization problem is solved using a kinematic methodology (Avrenli & Dempsey, 2015), which is an iterative procedure that converges to the optimum solution in two-to-three iterations. Once the optimization problem is solved for each airspeed, a total of five landing trajectories are generated. The following section presents the findings.

## Results

### Ground Tracks

Figure 5 illustrates the ground tracks of the five landing trajectories. Each landing trajectory minimizes the required altitude loss at the given airspeed under the given modeling assumptions. Inspection of the ground tracks in Figure 5 reveals that each landing trajectory is divided into four distinct flight phases described as follows.

1. An initial left-turn with  $33^\circ$  bank: The absolute change in aircraft heading during this turn is  $225^\circ$ ,  $232^\circ$ ,  $235^\circ$ ,  $243^\circ$  and  $267^\circ$  for the airspeeds of 205, 215, 225, 235, and 245 KCAS, respectively.
2. A wings-level, equilibrium glide: After the first banked turn, the aircraft performs some brief wings-level glide (i.e. at  $0^\circ$ -bank). The distance travelled during this phase equals 1.8 nm, 1.7 nm, 1.6 nm, 1.2 nm, and 0.1 nm for the airspeeds of 205, 215, 225, 235, and 245 KCAS, respectively.



3. A final right-turn with  $33^\circ$  bank: By the end of this phase, the aircraft is aligned with Runway 18 at an altitude of 100 ft AGL. The absolute change in aircraft heading during this turn equals  $45^\circ$ ,  $52^\circ$ ,  $55^\circ$ ,  $63^\circ$  and  $87^\circ$  for the airspeeds of 205, 215, 225, 235, and 245 KCAS, respectively. The pilots configure “landing gear down” at the beginning of this turn, which gives sufficient time (i.e. approximately 15 seconds) for landing gear extension.
4. Landing and safe touchdown: This phase starts when the aircraft is 100 ft AGL. At approximately 40 ft AGL, the pilots initiate landing flare and touch down on Runway 18. Based on the ground tracks illustrated in Figure 5, the landing trajectories are compared

as follows:

- The greater the airspeed is, the greater the turning radius becomes at a particular bank angle. This is because the turning radius at a given bank angle is proportional to the square of airspeed, which is shown in Equation (1) as follows (Anderson, 2007):

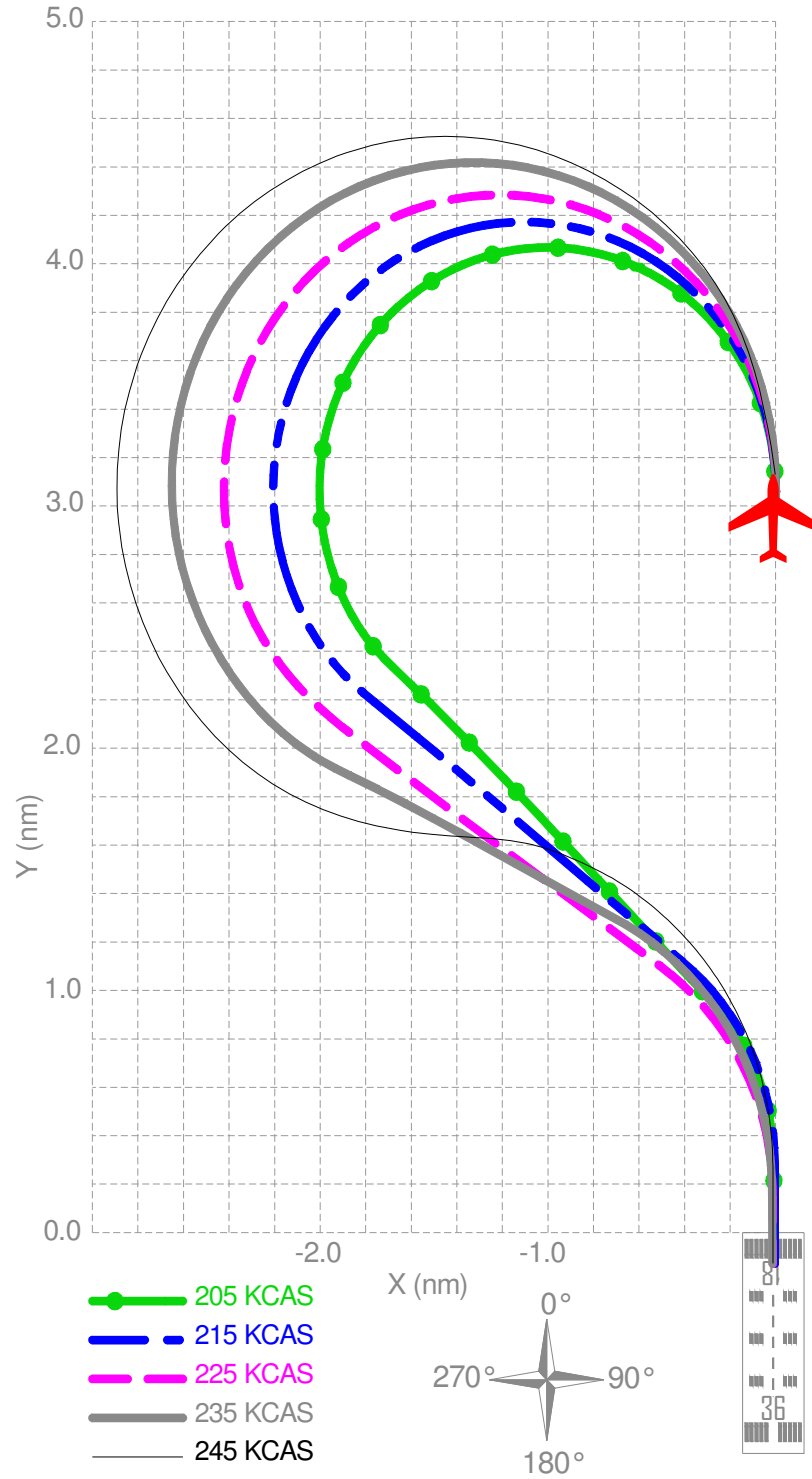


Figure 5. Ground tracks for the minimum-altitude-loss landing trajectories from the initial aircraft location to Runway 18 (no wind).

$$R = \frac{v_T^2}{g \cdot \tan \phi} \quad (1)$$

where

R = Turning radius,

$v_T$  = True airspeed,

g = Gravitational acceleration,

$\phi$  = Bank angle.

Based on the relationship given in Equation (1), the turning radius corresponding to a particular bank angle is approximately 20%<sup>7</sup> longer at the “green dot” speed of 225 KCAS compared to that at  $V_{LS} = 205$  KCAS. Since arc length is directly proportional to turning radius, the trajectory distance required to perform a particular heading change is 20% greater at the “green dot” speed than that at  $V_{LS} = 205$  KCAS.

- The required change in aircraft heading during a given turn increases with increasing airspeed. For example, while the airspeed of 205 KCAS requires a 225°-change in aircraft heading during the initial left turn, the “green dot” speed of 225 KCAS requires a 235°-change in aircraft heading during the same turn. Likewise, while the airspeed of 205 KCAS requires a 45°-change in aircraft heading during the final right turn, the

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<sup>7</sup> Assuming true airspeed is directly proportional to calibrated airspeed:  $(225/205)^2 = 1.20$ ,  $1.20 - 1.00 = 0.20$  or 20%.

“green dot” speed of 225 KCAS requires a 55°-change in aircraft heading during the same turn. This is another contributing factor as to why the required landing trajectory distance increases with increasing airspeed in this particular scenario.

- The lowest airspeed of  $V_{LS} = 205$  KCAS requires the shortest trajectory to glide to Runway 18 compared to the other airspeeds in this particular scenario. Since required altitude loss is proportional to trajectory distance,  $V_{LS} = 205$  KCAS would be the most favorable airspeed in terms of required trajectory distance in this particular scenario.
- $V_{LS} = 205$  KCAS would also require the shortest runway length for landing roll compared to the other airspeeds. Landing at a lower speed is particularly critical in this scenario because the aircraft has limited braking capability on account of dual-engine failure.

To sum up, the “green dot” speed is not the optimum airspeed in this particular scenario as far as trajectory distance is concerned. Instead,  $V_{LS} = 205$  KCAS would be most advantageous airspeed in terms of trajectory distance in this particular scenario since it results in the shortest landing trajectory to Runway 18.

### **Bank Angle History**

Figure 6 illustrates the aerodynamic bank angle vs. time for the five landing trajectories. Figure 6 shows that the optimum bank angle is found as 33° for all turning maneuvers. Thus, in such emergency situations, the use of high bank angles (i.e. up to 33° for the A320 aircraft in “normal control law”) may help preserve energy during turning maneuvers, which can in turn increase the odds of reaching the intended touchdown point.

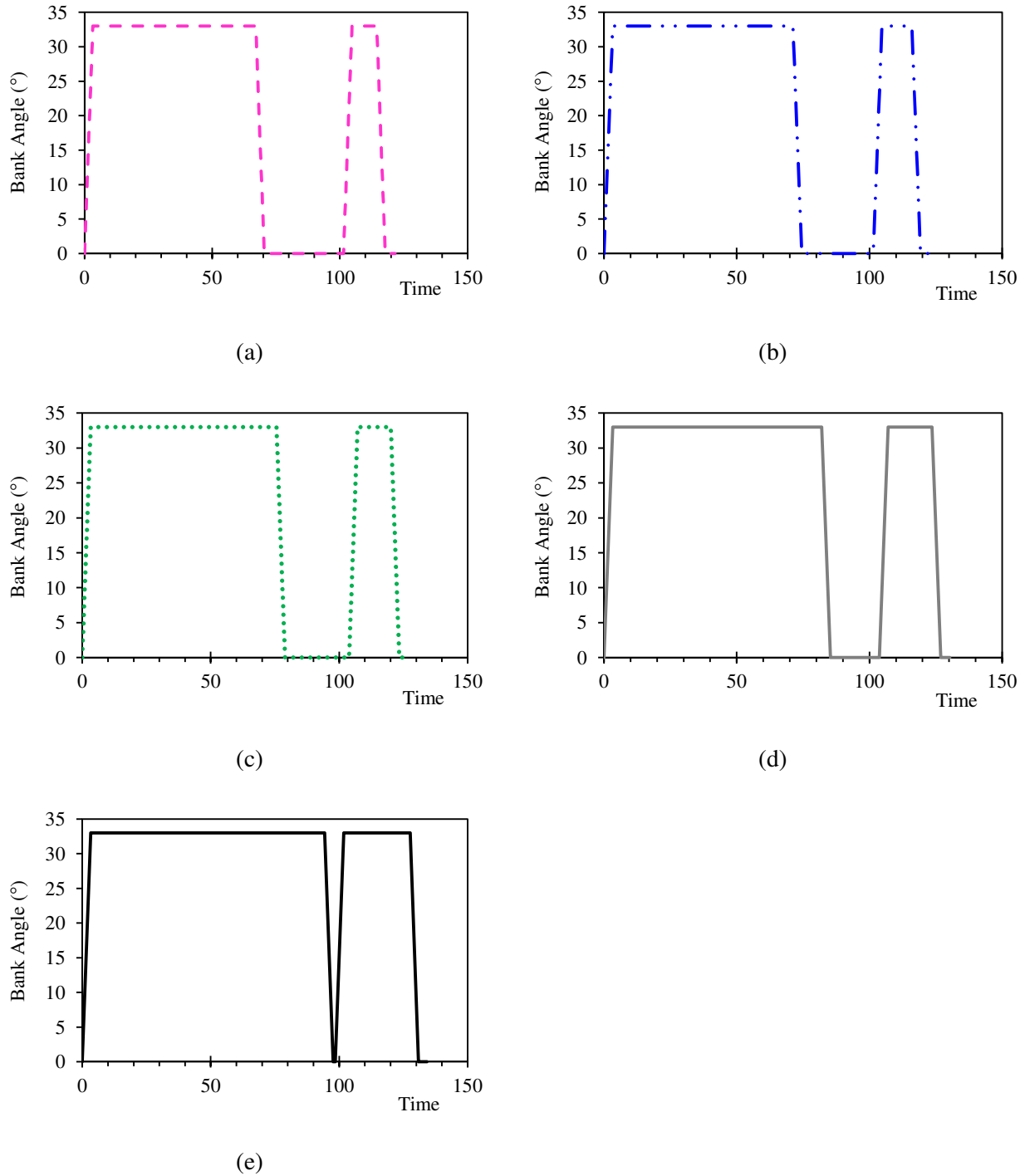


Figure 6. Aerodynamic bank (roll) angle vs. time for the landing trajectory at:  
 (a) 205 KCAS, (b) 215 KCAS, (c) 225 KCAS, (d) 235 KCAS, (e) 245 KCAS.

Although this study does not consider the use of bank angles greater than  $33^\circ$ , bank angles greater than  $33^\circ$  may be utilized if the A320 aircraft is in “alternate” or “direct” control

law. For instance, the “alternate” control law is engaged if the A320 aircraft undergoes dual-engine flameout due to fuel starvation. Future research studies can investigate the potential effects of using bank angles greater than  $33^\circ$  in such emergency situations.

### **Required Altitude Loss**

Figure 7 illustrates the altitude above ground level (AGL) vs time (t) for the five landing trajectories, assuming that the aircraft touches down at the beginning of Runway 18 touchdown zone. The altitude AGL corresponding to  $t = 0$  is simply the required altitude loss for a given landing trajectory. The results plotted in Figure 7 show that:

- The altitude loss required for gliding to Runway 18 increases with increasing airspeed. The airspeed that requires the lowest altitude loss is  $V_{LS} = 205$  KCAS, which requires a total altitude loss of approximately 3,100 ft. Thus,  $V_{LS} = 205$  KCAS is the optimum airspeed in terms of required altitude loss in this particular scenario. On the other hand, the “green dot” speed of 225 KCAS requires an altitude loss of approximately 3,450 ft to glide to Runway 18, which is 350 ft greater than that at  $V_{LS} = 205$  KCAS.
- If the aircraft altitude is, for example, 3,200 ft AGL at the location of total loss of power, the aircraft would not be able to glide to Runway 18 when flown at the “green dot” speed in this particular scenario. On the contrary, it would most likely be able to glide to Runway 18 provided that it is flown at  $V_{LS} = 205$  KCAS in this particular scenario.

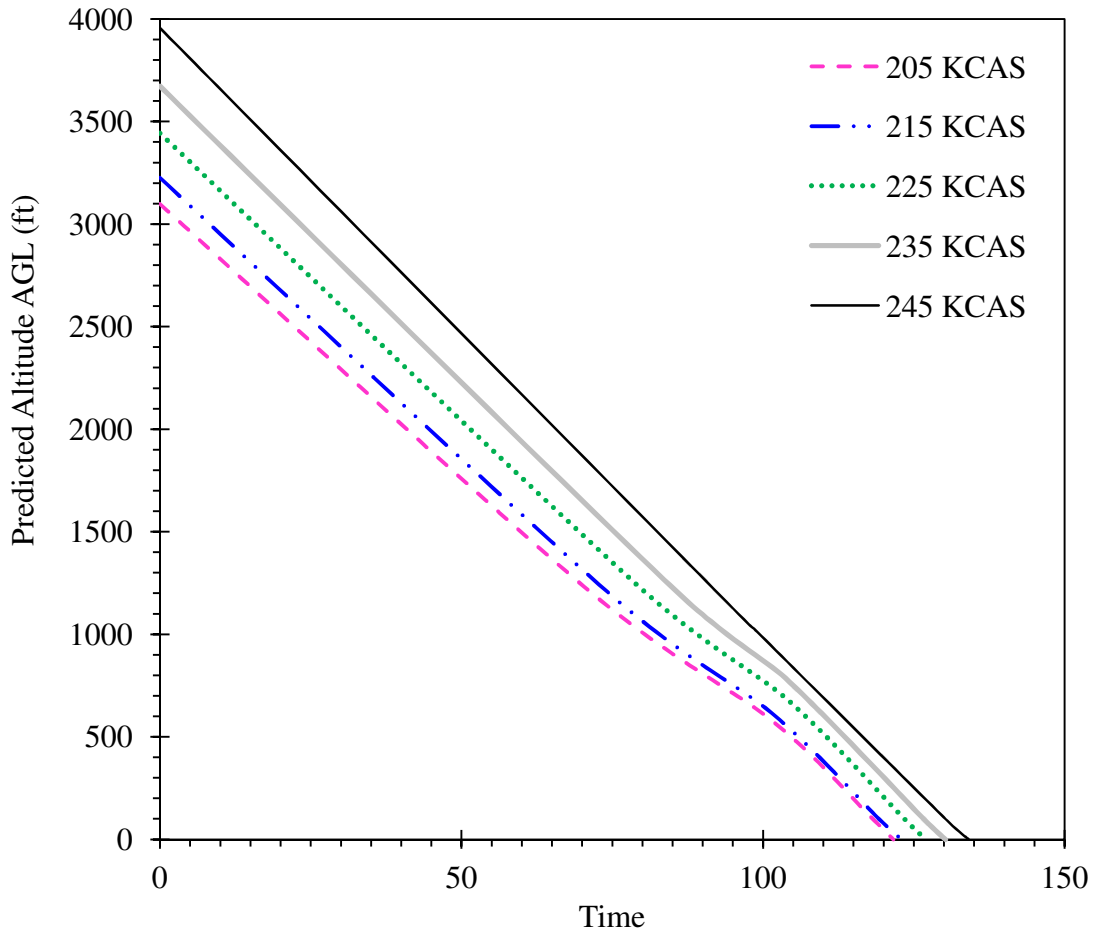


Figure 7. Altitude above ground level (AGL) vs. time for the computed landing trajectories.

### Validation of the Results

Flight simulation tests are conducted to find out if the computed altitude loss values are accurate. The simulations are conducted in a JAR-FSTD A, Level D full flight simulator that is certified under the European Aviation Safety Agency (EASA), and Joint Aviation Authorities (JAA). The simulator has been tested in “normal”, “alternate”, and “direct” control laws of the Airbus A320 aircraft, and simulates real aircraft behavior in all normal and abnormal flight operations. Three type-rated A320 pilots participated in the flight simulation tests. A typical simulation run starts with “freezing” the aircraft position at 3.0 nautical miles from the runway

threshold at an altitude of 3,100 ft, 3,300 ft, 3,500 ft, 3,700 ft and 4,000 ft AGL for the airspeeds of 205, 215, 225, 235 and 245 KCAS, respectively. The aircraft heading is initially frozen at 0°, and the aircraft weight equals 70.0 tons. The aircraft is in “clean” configuration during the entire simulation run, and the landing gear is initially fully retracted. The simulator is programmed to simulate dual-engine failure on the A320 aircraft.

When dual-engine failure occurs, both the aircraft position and heading initially remain frozen. During this time, both engines gradually lose thrust. When total loss of power occurs, both the aircraft position and heading are “released”, and the aircraft starts gliding at the airspeed programmed for that simulation run. From this moment on, one of the three type-rated A320 pilots flies the aircraft while one member of the research team issues the following oral commands to the pilot in charge:

At 205 KCAS (i.e.  $V_{LS}$ ):

1. Turn left heading 135° with 33° bank. Maintain 205 kt.
2. Maintain present heading and speed. Descend to 600’.
3. Turn right heading 180° with 33° bank. Maintain 205 kt. Landing gear down.
4. Clear to land on Runway 18.

At 215 KCAS:

1. Turn left heading 128° with 33° bank. Maintain 215 kt.
2. Maintain present heading and speed. Descend to 700’.
3. Turn right heading 180° with 33° bank. Maintain 215 kt. Landing gear down.
4. Clear to land on Runway 18.

At 225 KCAS (i.e. “green dot” speed):

1. Turn left heading 125° with 33° bank. Maintain 225 kt.



2. Maintain present heading and speed. Descend to 750'.
3. Turn right heading 180° with 33° bank. Maintain 225 kt. Landing gear down.
4. Clear to land on Runway 18.

At 235 KCAS:

1. Turn left heading 117° with 33° bank. Maintain 235 kt.
2. Maintain present heading and speed. Descend to 800'.
3. Turn right heading 180° with 33° bank. Maintain 235 kt. Landing gear down.
4. Clear to land on Runway 18.

At 245 KCAS:

1. Turn left heading 93° with 33° bank. Maintain 245 kt.
2. Maintain present heading and speed. Descend to 1,100'.
3. Turn right heading 180° with 33° bank. Maintain 245 kt. Landing gear down.
4. Clear to land on Runway 18.

These oral commands enable the pilots to follow the computed landing trajectories. Each pilot flies each landing trajectory at least once. If the pilot in charge fails to promptly follow the oral commands, that simulation run is repeated to ensure that the trajectory is simulated accurately. After each run, the simulator plots the ground tracks and descent profile of the A320 aircraft. Using the ground tracks plots, the research team verifies that each trajectory is simulated accurately. Using the descent profile plots, the research team measures the total altitude loss (to the nearest 50 ft) from the initial aircraft position until the aircraft projects onto the beginning of Runway 18 touchdown zone.

In Table 1, the altitude loss values observed in the simulation runs are compared with the computed values. The results in Table 1 are explained as follows:

- The first column of Table 1 gives the airspeed to identify the corresponding landing trajectory (see Figure 5),
- The second column shows the average altitude loss observed from the three simulation runs for a given trajectory,
- The third column gives the computed altitude loss for the same trajectory,
- The fourth column presents the deviation of the computed values from the observed values,
- The fifth column gives the percent error of the computed values based on the observed values.

Table 1

*Simulated vs. Computed Values for Required Altitude Loss*

Airspeed (KCAS)	Simulated altitude loss (ft)	Computed altitude loss (ft)	Error (Computed – Simulated) (ft)	Percent Error (%)
205	3,017	3,098	81	2.7
215	3,167	3,226	59	1.9
225	3,367	3,443	76	2.3
235	3,583	3,672	89	2.5
245	3,867	3,957	90	2.3

The results in Table 1 show a consistent pattern: the computed values are marginally greater than the observed values. Nevertheless, the computed values are within 2.7% of the observed values, and are accurate enough for practical purposes.

## **Conclusions and Recommendations**

The Airbus A320 aircraft family has a checklist designed for use in the occurrence of total loss of power due to dual engine failure. The checklist is called “engine dual failure”, and it specifies the “green dot” speed as the optimum airspeed at which to fly the aircraft when an engine restart is considered impossible. According to Airbus, the checklist is primarily intended for use above an altitude of 20,000 ft since commercial jets spend most of the flight time at such high altitudes (NTSB, 2010).

Meanwhile, statistical analysis of the FAA Wildlife Strike Database shows that engine failure due to bird strike is most likely to occur during the phase of climb below 5,000 ft AGL. Considering this, this study explored the optimum airspeed for a turn-back maneuver to the departure airport after a dual-engine failure, which is assumed to occur during the climb at a distance of 3.0 nm from the departure airport. The findings show that the lowest selectable airspeed (i.e.  $V_{LS}$ ) would require the minimum altitude loss to glide to the departure airport in the assumed scenario. The required altitude loss at the “green dot” speed is found to be approximately 350 ft greater than that at the  $V_{LS}$ . The difference in required altitude loss is attributed to the fact that the  $V_{LS}$  would require shorter turning radii during banked turns compared to the “green dot” speed. Consequently, reduced turning radii at  $V_{LS}$  result in reduced landing trajectory distance, which in turn results in reduced required altitude loss in the assumed scenario.

This study is the first of its type to involve a commercial jet. A similar study can be conducted for other commercial jets. Future research can also focus on the effects of headwind, tailwind and crosswind on the optimum landing maneuver.

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