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Detecting Safety Events during Approach in General Aviation Operations

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General Aviation (GA) accounts for the vast majority of aviation accidents in the United States every year. As a result of the implementation of Flight Data Recorders (FDR) in GA aircraft, we now have FDR flight data that we can use to improve safety, by detecting and correcting unsafe behaviors and habits. Because of the high variability in GA operations and GA flight performance, detecting these safety events is not trivial. In this paper, we evaluate the usefulness of an event-driven method in characterizing the safety of the approach phase of a flight. In particular, we develop algorithms to detect safety events during the approach phase from FDR data from a G1000 glass cockpit display on a Cirrus SR-20 fleet. We adjust the current safety event definitions to the SR20, and then change the limits of the safety events, to make the safety events in our dataset more consistent with each other. While changing the definitions gave us meaningful results, we also suggest that new metrics are developed to be used together with safety events in future work.

Abbreviations

AGL	=	Above Ground Level
ALAR	=	Approach and Landing Accident Reduction
CFI	=	Certified Flight Instructor
FAA	=	Federal Aviation Administration
FDR	=	Flight Data Recorder
FPM	=	Feet per Minute
GA	=	General Aviation
ICAO	=	International Civil Aviation Organization
MSL	=	Mean Sea Level
NTSB	=	National Transportation Safety Board
POH	=	Pilot Operating Handbook

I. Introduction

THE International Civil Aviation Organization (ICAO) defines General Aviation (GA) operations as "*aircraft operations other than commercial air transport operations or aerial work operations*[1]." GA aircraft comprised almost 97% of the entire US civil aviation fleet in 2014[2]. In 2011, GA and air taxi operations (small commercial aircraft making short flights on-demand) together accounted for 63% of all aircraft towered operations in the United States[3]. In 2013, there were 1222 GA accidents, constituting 94% of all US civil aviation accidents. These accidents resulted in 387 fatalities and 216 injuries[2]. GA accidents are therefore disproportionate to their share of operations, and with GA playing such a big role in the national airspace, safety is a pressing concern.

Despite many safety efforts, GA accident rates in the United States remain high. One way of characterizing flight safety is by identifying instances of "safety events," or events that bring the aircraft into an unsafe state. By detecting safety events, we can identify areas for improvement. In particular, during the approach phase, detecting safety events can help the pilots see how they can improve their flying performance and enhance their safety, and as a result fly better approaches that result in better landings. For example, going too fast during touchdown is a safety event. While this abnormality will not usually cause an accident, it has the potential to result in an accident under the appropriate

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conditions. Because of the high variability in GA operations and GA flight performance, safety events are often difficult to detect. The question then is whether detecting such events can be useful in identifying unsafe behavior.

To begin answering this question, in this paper we focus on safety events in the approach phase. We develop algorithms to detect safety events during the approach phase, which we then test on 23 flights in a fleet of Cirrus SR20 aircraft, equipped with a Garmin G1000 Flight Data Recorder (FDR). We use a set of modified safety events based on earlier definitions by Higgins et al.[4] We show that by changing the safety event definitions, we can successfully detect safety events in GA flights that are consistent with each other. We conduct an ANOVA analysis to determine whether the safety events are internally consistent in each case.

II. Approach Flight Phase

An approach, in aviation, refers to the time between the aircraft entering the airport's traffic pattern, as shown in Figure 1, or 1000 ft above the runway elevation, as shown in Figure 2, to the beginning of the landing flare under visual flight rules (VFR), and from the initial approach fix to the beginning of the landing flare under instrument flight rules (IFR)[5].

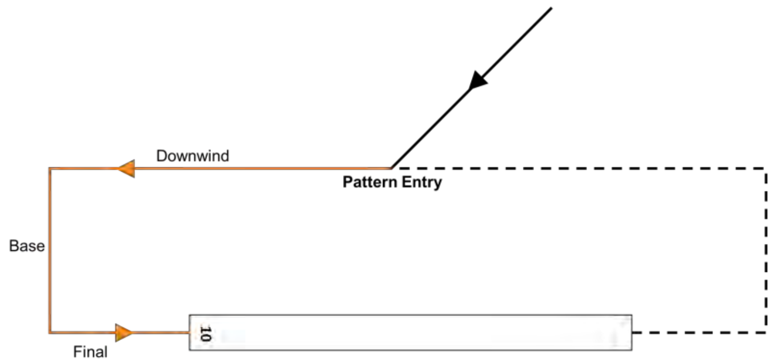


Figure 1: Approach following pattern entry.

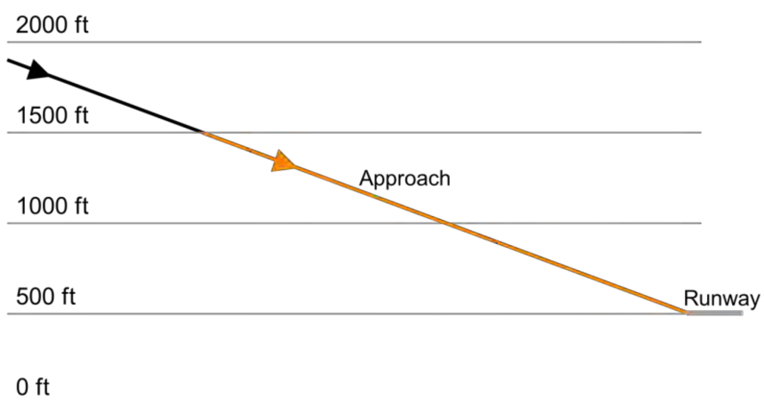


Figure 2: Approach from 1000 ft above ground level (AGL).

Approach and landing are particularly risky aspects of flight. During an approach, the aircraft is flying at a reduced airspeed and closer to the ground, compared to its airspeed and altitude during cruise, and therefore requires more precision and focus from the pilot. While a loss of 300 ft of altitude during cruise at 7000 ft is easy to recover from, at 1000 ft it is a lot more significant and requires prompt action. At low altitudes, there can be obstacles such as towers, cranes, and windmills. An airspeed deviation can potentially result in a stall, and at low altitudes the pilot has less time to recover. Small deviations from the desired state require large corrective input, so that the aircraft can get back on course on time for landing. Approach and landing are closely related in that a bad approach can result in a bad landing, whereas a good approach is more likely to end in a smooth landing. Accidents most frequently occur during the approach and landing phases. In 2010, most personal flying accidents occurred during landing (334 accidents out of 997), with approach accidents ranking fourth (105 accidents)[6]. Among the worldwide commercial jet fleet, from

2005 to 2014, 32% of fatal accidents occurred during the approach phase, and 24% during landing[7]. The 24th Nall Report lists "*descent and approach*" as a high-risk phase of flight, with 50 out of a total of 1162 accidents occurring during descent and approach in 2012, 24 of which were fatal accidents[8].

The aviation safety community and airline Flight Operations Quality Assurance (FOQA) programs characterize approaches as "stabilized" or "unstabilized." In a stabilized approach, the aircraft is on the correct flight path, requiring only small changes in heading and pitch, at an appropriate airspeed, and in the correct landing configuration. Unstabilized approaches are currently identified when specific parameters are exceeded: (1) the descent rate must not be greater than 1000 fpm, (2) airspeed should not be more than 5 knots below or 10 knots above target airspeed[9], and (3) the deviation from the glideslope and localizer should not exceed one dot. Unstabilized approaches can result in hard landings, runway excursions, landing short of the runway, or controlled flight into terrain (CFIT) accidents. Therefore, if an approach is or becomes unstabilized below 1000 ft AGL, an immediate go-around must be executed. A go-around is completed by advancing the throttle to full power and adjusting pitch to gain altitude quickly. Pilots are reluctant to go around during an approach, and it is not clear if the concept of unstabilized approaches is useful for them. The FAA Loss of Control Series identified unstabilized approaches as a cause of approach accidents, and suggested that certified flight instructors (CFI) trying to salvage student approaches may be part of the problem[10]. They also provided pilots with suggestions on when to abandon the approach and rather go around. The Aircraft Owners and Pilots Association (AOPA) Air Safety Institute (ASI) suggested approach parameters to use in flying for CFIs by adjusting airline operations approach parameters to general aviation[11]. The Flight Safety Foundation (FSF) explained the concept of unstabilized approaches and published guidelines on flying stabilized approaches for commercial aircraft in the Briefing Notes of the Approach and Landing Accident Reduction (ALAR) Tool Kit[12]. Preliminary findings from a study conducted by the Flight Safety Foundation show that on average, 96% of unstabilized approaches do not result in a go-around. They also found that 54% of all aircraft accidents in 2011 could have been prevented by a go-around[13].

By characterizing approaches as either stabilized or unstabilized, we separate them into two distinct groups: safe, and unsafe. But the distinction between stabilized and unstabilized approaches is a grey area. A number of things can go wrong in an unstabilized approach. For example, an approach where the pilot was consistently left of the centerline and an approach where the pilot was oscillating about the glideslope, going from too high to too low and back, are both classified as unstabilized. The first approach was likely not nearly as dangerous as the second one, and grouping both into the same category of unstabilized approach may not be helpful. To improve their flying, pilots would also need to know why their approach was unstabilized. Aviation safety researchers also need to be able to do analysis on what lies behind an unstabilized approach, which makes just counting unstabilized approaches insufficient.

In this research, we use an event-driven method to identify behaviors during approach that can be unsafe, as an objective method to characterize approaches. The added resolution, compared to the stabilized/unstabilized characterization, can provide the pilot with more information on what exactly went wrong, so that they know how to fly the approach better next time.

III. Flight Data Recording on GA Aircraft

A flight data recorder (FDR) is a device that preserves the history of a flight by recording flight parameters. All commercial aircraft have one or more such devices, but in the past their cost precluded their use on most GA aircraft. However, with avionics systems becoming more technologically advanced, cheaper and smaller devices can now be installed on GA aircraft. It is now feasible to collect data from GA aircraft equipped with avionics systems like the Garmin G1000 and Avidyne Entegra. Data from these devices can be used to identify aircraft location and speed, engine information, aircraft attitude, and navigation information. The logs can also be used to recreate a visual representation of the flight and to perform performance analysis.

In this paper, we show how this type of data can be used to identify safety events during approach. We demonstrate our method using data collected on flights in Cirrus SR-20 aircraft equipped with Garmin G1000 glass cockpit displays. Our dataset includes 23 cross country flights in SR20 aircraft, starting and ending at Purdue University. Each flight includes on average four landings, and therefore four approach segments. The G1000 on the Cirrus SR-20 collects 66 parameters per second.

Figure 3: Example of a flight in our dataset.

IV. Definition of Safety Events in the Approach Phase

A safety event is an off-nominal operation that can be unsafe. In GA, safety events can be hard to detect for two main reasons: (1) because of how GA aircraft and pilots fly, and (2) because of the subjective nature of understanding of risk and safety. The large diversity in the GA fleet also makes it hard to determine with certainty that a safety event has (or has not) occurred.

The non-uniform nature of GA flight operations, and the high variation in parameters during each flight, can make it hard to distinguish errors from intentional maneuvers. For example, an aircraft turning at a bank angle of 45 degrees can be deemed safe. However, inexperienced pilots who are just starting their training may not be able to turn so steeply without losing altitude and colliding with obstacles or the ground. Additionally, among GA aircraft, we expect a higher deviation from assigned headings, altitudes, and airspeeds, compared to bigger aircraft and jets. The larger deviation is expected because: (1) pilots flying jets are generally more experienced than the average GA pilot, (2) most of the GA fleet is not equipped with an autopilot, and, (3) wind gusts generally affect smaller GA aircraft more than bigger jets. GA operations are non-uniform in that they include a wide range of operations such as training flights, where student pilots intentionally stall the aircraft during stall recovery training, and crop dusting operations, where the aircraft is flown at lower altitudes than normal operations. The definitions of the safety events must therefore be adapted to each type of operation. For example, the altitude limit for crop dusting operations will need to be lower, and since the altitude is lower, the bank angle limit will also be lower, to avoid steep turns at a low altitude.

To detect safety events, we start by defining safety events in terms of applicability to phase of flight, flight parameters, and lower and upper limits for these parameters. In this case, we use a set of definitions from Higgins et al., as shown in Table 2[4]. The safety events during the approach phase provide us with a list of parameters to track: airspeed, vertical speed, lateral and vertical position with respect to the glideslope and runway centerline, bank angle, wind components, and flap position.

Table 1: Airspeed Definitions for SR20

Event	Risk Level 1	Risk Level 2
Airspeed at or below 200 ft AGL (high speed with full flaps extended)	$\frac{66}{41}V_{s0}\sim1.6V_{s0}=90$	$\frac{71}{41}V_{s0}\sim1.7V_{s0}=95$
Airspeed at or below 200 ft AGL (low speed with full flaps extended)	$\frac{60}{41}V_{s0}\sim1.5V_{s0}=84$	$\frac{56}{41}V_{s0}\sim1.4V_{s0}=78$
Airspeed at or below 200 ft AGL (high speed with no flaps extended)	$\frac{75}{47}V_{s1}\sim1.6V_{s1}=104$	$\frac{80}{65}V_{s1}\sim1.7V_{s1}=110$
Airspeed at or below 200 ft AGL (low speed with no flaps extended)	$\frac{69}{47}V_{s1}\sim1.5V_{s1}=98$	$\frac{56}{47}V_{s1}\sim1.4V_{s1}=91$

The safety events were originally defined for a Cessna C172 aircraft. Since the Cirrus SR-20 is faster than the C172, we adjusted the limits for the airspeed safety events as follows. First, we expressed the C172 limits for each safety event in terms of its stall speed (41 knots[16,17]). For example, the Risk Level 2 limit for airspeed below 200 ft AGL is 56 knots, or 1.4 times its stall speed. Next, we applied these coefficients to the SR20 stall speed (56 knots[17]), as shown in Table 1.

Table 2: Defined Safety Events during Approach, with Numerical Limits for a Cirrus SR20. Adapted from Higgins et al.[4]

Event	Phase of flight	Risk Level 1	Risk Level 2
Vertical speed below 1000 ft AGL	Approach	> = 800 fpm	> = 1000 fpm
Airspeed at or below 200 ft AGL (high speed with full flaps extended)	Approach	90 kts	95 kts
Airspeed at or below 200 ft AGL (low speed with full flaps extended)	Approach	84 kts	78 kts
Airspeed at or below 200 ft AGL (high speed with no flaps extended)	Approach	104 kts	110 kts
Airspeed at or below 200 ft AGL (low speed with no flaps extended)	Approach	98 kts	91 kts
Deviation from extended centerline at 200 ft AGL	Approach	2 deg	3 deg
Glide angle at 200 ft AGL (high)	Approach	4 deg	5 deg
Glide angle at 200 ft AGL (low)	Approach	2 deg	1 deg
Flap position changes below 100 ft AGL	Approach		
Flap position at 100 ft AGL	Approach		
Bank angle at or below 200 ft AGL	Approach	20 deg	25 deg
Tail wind component at 200 ft AGL	Approach	10 kts	15 kts
Cross wind component at 200 ft AGL	Approach	> 15 kts	> = 20 kts

The events shaded in gray in Table 2 are detectable using G1000 data. We cannot detect safety events that require flap position information, which is not given in the FDR data.

Each safety event is defined with respect to two risk levels where Risk Level 2 is a more severe safety event than Risk Level 1. Having two risk levels provides information about the safety of the flight that we wouldn't have otherwise. For example, two different approaches that are either 5 knots faster than nominal, or 10 knots slower, will both be characterized as unstabilized. In an events-driven method, the former approach would result in a Level 1 safety event, and the latter approach in a Level 2 safety event.

Table 2 defines two different safety events for airspeed—one for an approach with full flaps extended, and one without flaps. The G1000 FDR does not record flap position. The SR20 Pilot's Operating Handbook (POH) cautions that landings should be made with full flaps unless they fail to deploy. Since pilots are trained to land with full flaps during normal flight, we assume that all landings in our dataset were flown with full flaps deployed.

V. Results: Current Safety Event Definitions

In this section, we use the safety event definitions in Table 2 to detect vertical speed, glide path angle, bank angle, airspeed, and wind component safety events in our dataset.

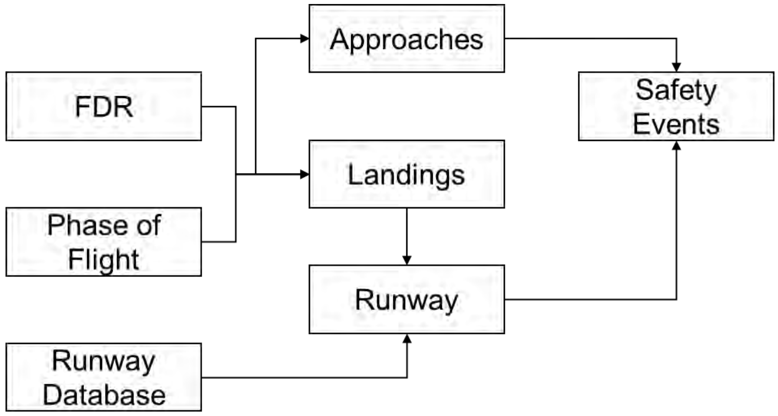


Figure 4: Using FDR data and runway information to detect safety events during the approach phase.

We use algorithms developed in related work to isolate the approach phases[14]. We then use location information and the Airport Runway database from the National Transportation Atlas[15] to detect at which airport and runway the approaches were flown, and then the runway information and FDR data during the approach phase to detect each safety event, as shown in Figure 4.

A. Vertical speed below 1000 ft AGL

Vertical speed measures how quickly the aircraft is losing or gaining altitude. During approach, the aircraft is very close to the ground and may also be close to obstacles, such as buildings and towers. At a high sink rate, the pilot has very little time until the aircraft reaches the ground or other obstacles. For example, if an aircraft maintains a vertical speed of −1000 fpm at an altitude of 1000 ft AGL, it only has 60 seconds until it reaches the ground.

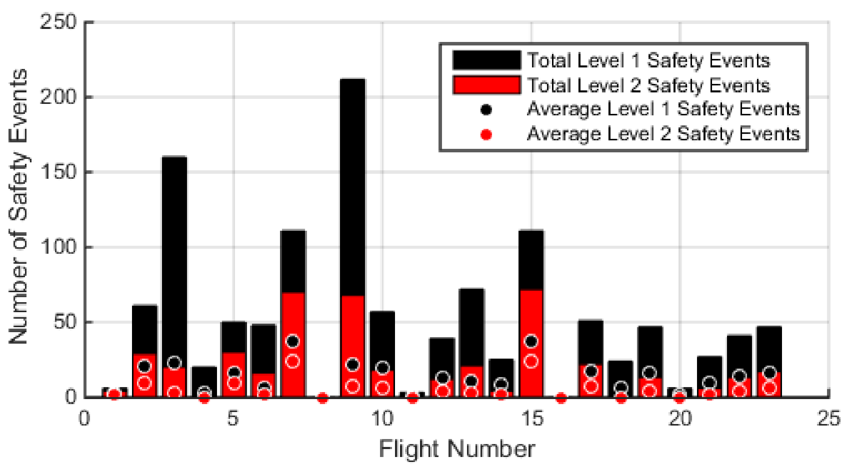


Figure 5: Vertical speed safety events. The black bars represent the number of level-1 vertical speed safety events per flight and the black node indicates the average number of level-safety events per approach. The red bars and nodes represent Level 2 safety events and average number of Level 2 safety events per approach, respectively.

Figure 5 shows the total number of vertical speed safety events detected in each flight, and the average number of vertical speed safety events per approach. Each flight in our dataset had a minimum of two approaches. We expect that a flight with more approaches will have more safety events than a flight with a single approach. For example, Flight #9 has the most vertical speed safety events in the dataset, but it includes ten approaches to two different airports. Flight #7, on the other hand, has fewer safety events, but only includes three approaches. Per approach, Flight #7 has more safety events than Flight #9. The total number of safety event instances is important in describing the overall safety of the flight, whereas the average number of safety event instances per approach can help us compare approaches to each other.

B. Glide path angle at 200 ft AGL

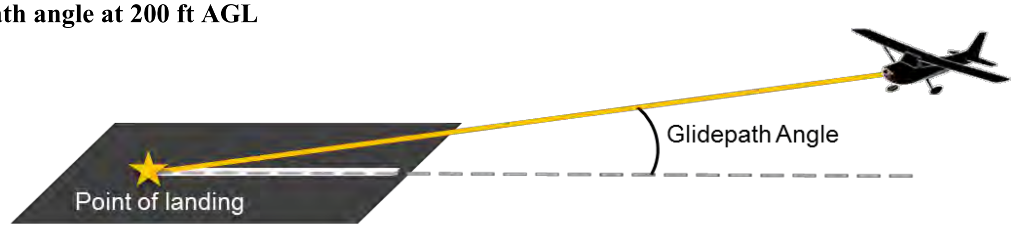


Figure 6: Glide path angle definition with respect to the point of landing.

We define the glide path as the path the aircraft would have to take from its current position to its eventual touchdown point (where the landing gear of the aircraft touch the runway). The glide path angle at each instant during approach is then the angle between the glide path and the plane of the runway (Figure 6). The recommended glide path angle for most airports is approximately three degrees. According to the definition in

Table 2, aircraft on an approach should be flying a glide path angle between two and four degrees.

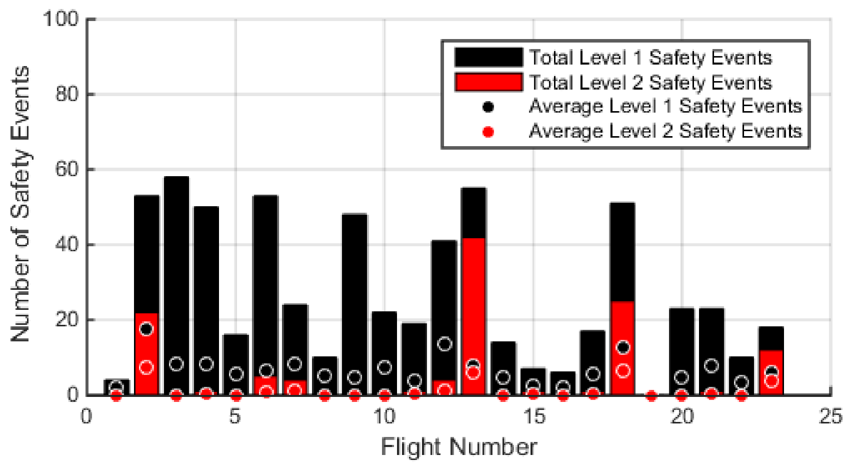


Figure 7: Glide path angle safety events.

Figure 7 shows the total number of glide path angle safety events and the average number of glide path angle safety events per approach for each flight in the dataset. Pilots deviated less from the safe limits in glide path angle than vertical speed.

C. Bank angle at 200 ft AGL

Bank angle measures the aircraft's inclination about its longitudinal axis with respect to the horizon. The safety event definition in

Table 2 recommends that aircraft bank less than 20 degrees at low altitudes (below 200 ft AGL). Steep banks cause a reduction in the vertical component of lift, which can result in a loss of altitude if the pilot does not compensate for it by adding power or increasing pitch angle. At low altitudes, any sudden or inadvertent loss of altitude can result in a collision with terrain.

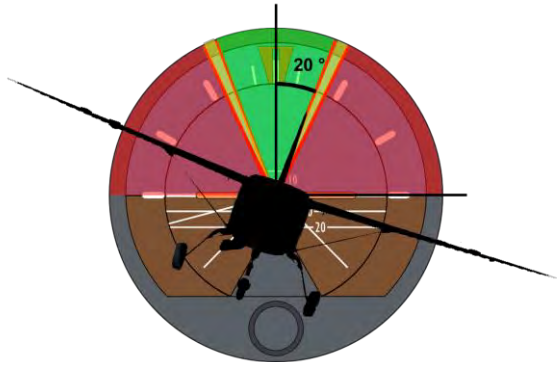


Figure 8: 20 degree bank angle.

Using the current definition for the bank angle safety event, we only detected a steep turn in one of the flights (Flight #9) in the dataset. As shown in Figure 8, a 20 degree bank is quite steep, especially for a low altitude, suggesting that the safety event definition is too narrow. Making the definition wider, by either increasing the altitude limit, or decreasing the bank angle limit, would result in more safety events. The average bank angle below 200 ft AGL in our dataset is 0.6 degrees, with a standard deviation of 2.9 degrees.

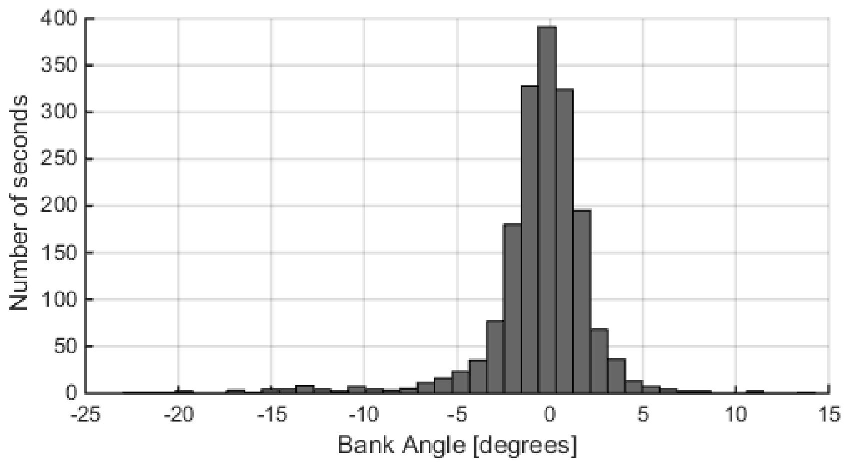


Figure 9: Bank angle below 200 ft AGL histogram.

Figure 9 shows how much time the aircraft spent at each bank angle when it was below 200 ft AGL. The FDR records data at a frequency of 1 Hz, therefore each instance of a particular bank angle corresponds to 1 second. Few bank angles are below 20 degrees (Level 1 safety event), and none are below 25 degrees (Level 2 safety event).

D. Airspeed at or below 200 ft AGL

Low airspeed during approach can result in a stall close to the ground, while too high an airspeed may result in a fast and hard landing. Figure 10 shows the number of airspeed safety events we detected in each flight. Approximately 73% of all safety events detected are Level 2 safety events, meaning that the airspeed is either extremely high or low. Almost all of the safety events detected in our dataset are from slow approaches. In general, the distribution of airspeed safety events in our dataset is similar to the vertical speed and bank angle safety events. However, the proportion of Level 1 to Level 2 safety events is smaller for the airspeed safety event.

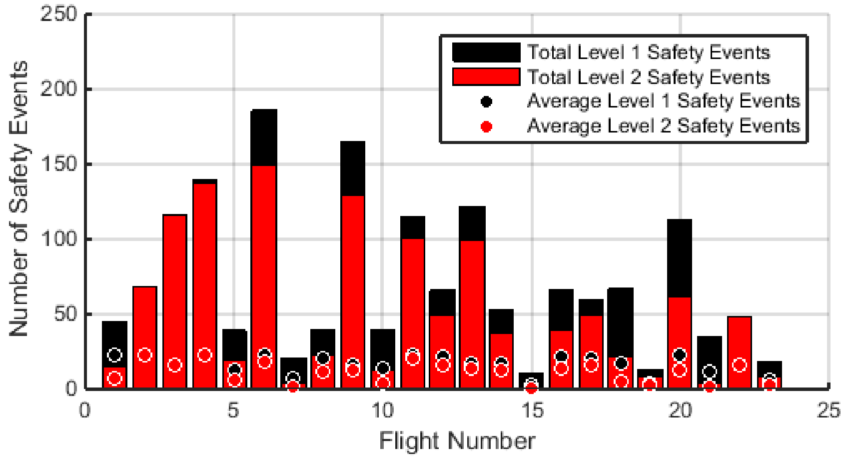


Figure 10: Airspeed safety events.

E. Wind components

There are two safety events defined for wind components–crosswind and tailwind, as shown in Figure 11. The G1000 records wind direction and wind speed once per second. When landing, the pilot can minimize the crosswind component of the wind by choosing the runway that is most aligned with the wind direction. For example, at Purdue University, a pilot has runways 10, 28, 5, and 23 available to them. If the wind blows directly from the west (270 degrees), landing on runway 28 minimizes the crosswind component.

Landing in a tailwind results in landing at a higher groundspeed, which increases landing distance and stopping distance. The aircraft may overshoot the end of the runway and end up in an accident, as was the case with a Piper PA-28-140 in New Philadelphia, OH, in June 2011, where the pilot attempted a tailwind landing and floated past the touchdown zone, resulting in insufficient runway for the landing roll. Since the aircraft touched down too far down the runway to safely abort the landing, the pilot decided to direct the airplane into a field off the side of the runway, colliding with an electrical service box (NTSB ID: CEN11LA426)[18].

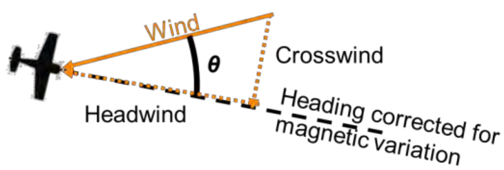


Figure 11: Wind components.

In our dataset, we did not detect any safety events for the tailwind component. This suggests that a 10 knots tailwind component is not strict enough. The SR20 POH suggests that pilots add 10% to the calculated landing distance for each 2 knots tailwind up to 10 knots[17]. A 10 knot tailwind would therefore double the landing distance. The crosswind component is also not strict enough–we detected crosswind safety events in two flights, for six seconds in Flight #4 and two seconds in Flight #9, probably during a wind guest. In our dataset, 7 flights had a tailwind at some point on the approach. The definitions of the wind component safety events are concerning. The safety events in Table 1 were originally defined for a Cessna C172 aircraft, which has a demonstrated crosswind component for landing of 15 knots[16]. The demonstrated crosswind component is the highest crosswind at which a test pilot has safely landed during certification. However, a crosswind of just over 15 knots would only constitute a Level 1 safety event.

VI. Results: Revised Safety Events

The results in the previous section suggest that there may be some inconsistencies in the safety event definitions. For example, we saw that we detected many more airspeed safety events than bank angle safety events. We expect that the definitions of safety events are internally consistent, i.e. if a pilot exhibits unsafe behavior in one aspect of their flying abilities (for example, they cannot hold a constant glide path angle), they will likely show similar behaviors in all aspects of their flight (such as banking too steeply). That is, we expect in general to see a similar trend in all safety events, with flights having the most detections for one safety event also showing a high frequency of other safety events.

Here, we use an ANOVA analysis to determine how the average number of safety event instances per approach differs for each safety event in Table 2. We then revise the limits for the safety events in an attempt to obtain definitions that are more consistent in terms of risk.

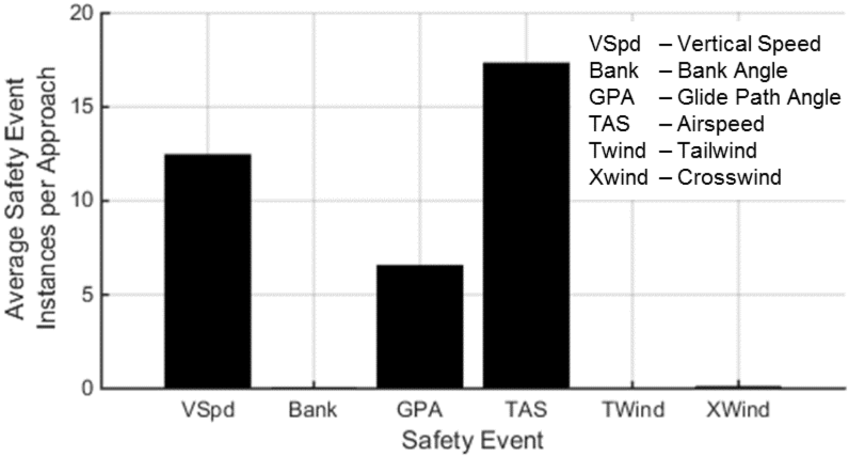
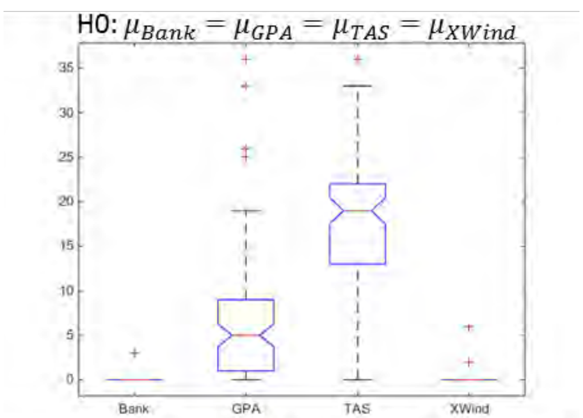


Figure 12: Average safety event instances per approach for safety event definitions from Table 1

As shown in Figure 12, while there are very few bank angle, tailwind, and crosswind safety events, there are many vertical speed, glide path angle, and airspeed safety events. We expect that there will be relatively more vertical speed safety events since it is defined for flight below 1000 ft AGL (the other safety events are defined for flight below 200 ft AGL). However, glide path angle and airspeed events should be consistent with the bank angle and crosswind events. We expect to detect the tailwind component safety event a lot less often than the other safety events. Given the choice of a runway, pilots will choose the runway with a headwind, assuming they have the correct wind information. If a particular runway is oriented with the wind, the opposite side of the runway will be oriented against the wind. Therefore, any instances of the tailwind component safety event should be accidental, and the tailwind in those cases will be low, especially at towered airports, where air traffic control will guide the pilot to the right runway.



ANOVA TABLE

Source	SS	df	MS	F	Prob > F
Columns	18901.7	3	6300.56	223.53	3.25265e-83
Error	10598.3	376	28.19		
Total	29500	379			

Figure 13: ANOVA analysis results.

The ANOVA analysis in Figure 13 shows the differences in the average safety event instances for each safety event. We exclude the vertical speed safety event because it is defined for the flight segment that is below 1000 ft AGL, whereas all other safety events apply to the segment below 200 ft AGL. We also exclude the tailwind component safety event because we do not expect any instances of this particular safety event. In this case, we reject the null hypothesis, which says that the average number of instances for the bank angle, glide path angle, airspeed, and crosswind component safety events are equal.

The inconsistency could be due to several reasons: for example, some of the event limits might be too strict (such as the airspeed safety event), or some safety event definitions are too forgiving (such as the bank angle safety event). For some safety event definitions, like the glide path angle safety event, the Level 1 limit is safer than other safety events, such as the crosswind component, where the Level 1 limit is very unsafe, and we therefore do not expect it to occur as frequently.

Table 3: Redefined Safety Events during Approach, with numerical limits for a Cirrus SR20

Event	Phase of flight	Risk Level 1	Risk Level 2
Vertical speed below 1000 ft AGL	Approach	> = 800 fpm	> = 1000 fpm
Airspeed at or below 200 ft AGL (high speed with full flaps extended)	Approach	~~1.6~~ 1.5 * V_{s0}	~~1.7~~ 1.6 * V_{s0}
Airspeed at or below 200 ft AGL (low speed with full flaps extended)	Approach	~~1.5~~ 1.3 * V_{s0}	~~1.4~~ 1.2 * V_{s0}
Glide angle at 200 ft AGL (high)	Approach	4 deg	5 deg
Glide angle at 200 ft AGL (low)	Approach	2 deg	1 deg
Bank angle at or below ~~200~~ 1000 ft AGL	Approach	20 deg	25 deg
Tail wind component at 200 ft AGL	Approach	~~10~~ 0 kts	~~25~~ 5 kts
Cross wind component at 200 ft AGL	Approach	~~15~~ 5 kts	~~20~~10 kts

To see whether we could get more consistent detections, we modified the definitions of the bank angle, airspeed, and wind component safety events, as shown in Table 3. The original limits are shown in strikethrough text. The vertical speed safety event definitions remained unchanged, because the limit agrees with the FAA Instrument Procedures Handbook[19], which states that "descent rates greater than 1,000 fpm are not permitted in either the instrument or visual portions of an approach and landing operations." The definition for the glide path angle safety event also remained unchanged, as the suggested glideslope at most airports is 3 degrees, which agrees with the current definition.

A. Bank angle

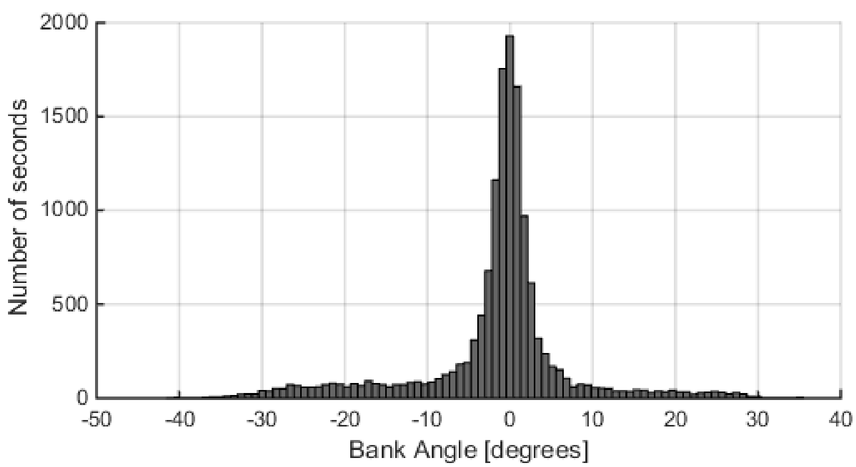


Figure 14: Bank angle below 1000 ft AGL histogram.

The bank angle safety event limits remained the same, but we increased the altitude definition from 200 ft AGL to 1000 ft AGL. Below 1000 ft AGL, the average bank angle is 1.62 degrees, with a standard deviation of 9.06 degrees. As shown in Figure 14, we do have bank angles below 1000 ft AGL that exceed the 20 degree limit set in Table 2.

B. Airspeed

As shown in Table 1, the original limits for safe airspeed during approach are between 1.5 * V_{s0} and 1.6 * V_{s0}. This definition is in disagreement with the Approach and Landing Accident Reduction (ALAR) Tool Kit[20] and the POH[17], which suggest that airspeed during final approach should be 1.3 * V_{s0}. We therefore changed the airspeed safety event definition, as shown in Table 3. We also generalized the definition to apply to all aircraft by expressing it in terms of stall speed. The original definition only applied to C172. There is a wide range of aircraft in the GA fleet, and while it is not possible to define safe airspeed ranges for all aircraft, the stall speed for each aircraft is given in its POH.

C. Wind components

The wind component safety event limits were high and didn't detect any safety event instances in our dataset. We therefore changed the definitions of both the tailwind and crosswind components to make the limits lower. The presence of any amount of tailwind is now flagged as a Level 1 safety event, and we consider anything exceeding 5 knots of tailwind a Level 2 safety event. We also decreased the limits of the crosswind safety event to a more cautious range.

D. ANOVA results

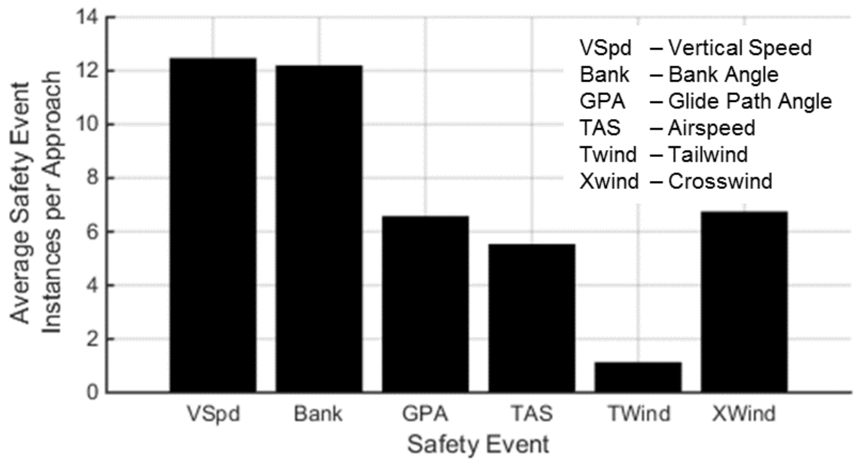
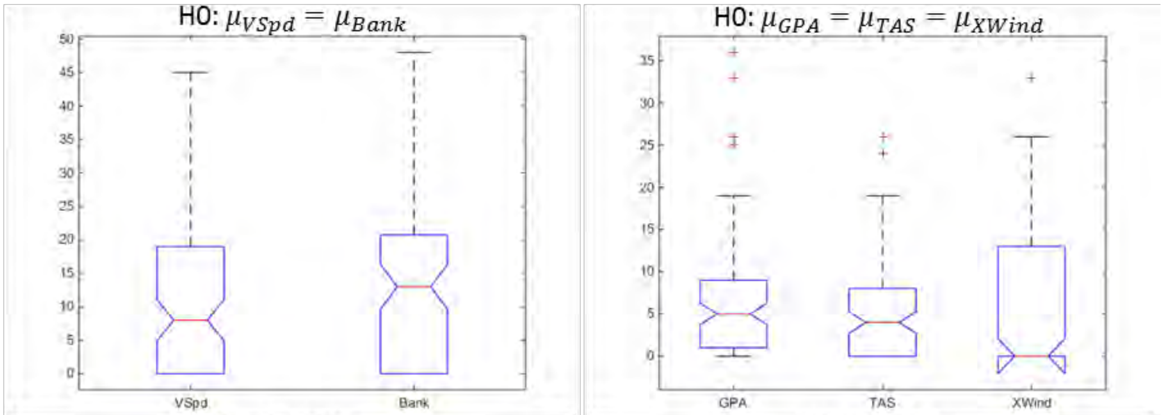


Figure 15: Average safety event instances per approach for custom definitions of safety events, as shown in Table 3.

Figure 15 shows the average instances of each safety event we detected per approach using the new definitions shown in Table 3. Compared to Figure 12, the average instances of each safety look closer to each other when using the new definitions to detect them. We used a one-way ANOVA analysis to evaluate whether the averages of each safety event are similar to each other.



ANOVA TABLE

Source	SS	df	MS	F	Prob > F
Columns	3.6	1	3.558	0.02	0.8772
Error	27922.7	188	148.525		
Total	27926.3	189			

ANOVA TABLE

Source	SS	df	MS	F	Prob > F
Columns	81.7	2	40.8456	0.71	0.4941
Error	16298.6	282	57.7965		
Total	16380.3	284			

Figure 16: ANOVA analysis results.

Figure 16 shows the results of the ANOVA analysis. We separated the safety events into two similar groups. Vertical speed and bank angle are defined below 1000 ft AGL, whereas the rest of the safety events are defined below 200 ft AGL. This means that the duration of the flight for the vertical speed and bank angle safety events is longer, and we therefore expect to see more instances for those safety events. We also do not consider the tailwind safety event in our analysis, because of how different the tailwind component safety event is compared to the other five events. Pilots are aware of the risk of landing in a tailwind, and they therefore avoid approaches to tailwind runways. Instances of tailwind on final approach are therefore rare, and the tailwind components in those instances are small.

At a 5% significance level, the mean number of instances per approach for the vertical speed and bank angle are similar, and the mean number of instances for the glide path angle, airspeed, and crosswind component safety events are all similar to each other.

VII. Conclusion

In this paper, we used the approach segment of 23 flights and a list of defined safety events that pertain to the approach phase to evaluate whether detecting safety events is useful in describing approach risk. Using FDR data, we can detect 9 out of the 13 events. We were not able to detect all safety events defined in Table 1, because the FDR on the fleet used does not record all the parameters we need. In particular, we do not have information on flap position.

There was an inconsistency in the number of safety events detected for each safety event definition. Specifically, bank angle, tailwind component, and crosswind component safety events occurred rarely, whereas vertical speed, glide path angle, and airspeed safety events appeared in most flights in the dataset used. The limits of some safety events, like airspeed at or below 200 ft AGL, have to be adjusted depending on the aircraft and how fast it is. Others, like the tailwind component safety event, are not affected by small changes in aircraft speed.

Safety events are relatively easy to detect using FDR data. They are also objective since they are based on hard limits. However, it is not always clear how the limits were chosen. Our algorithms flag every instance that specified parameters are outside of the specified range in Table 2. In the case of the G1000 flight data, the FDR records one data point per second. Safety events by themselves do not distinguish between sporadic exceedances and exceedances in a sequence. For example, in the case of an airspeed approach where we detected five safety events, five safety events over five seconds and five safety events at five different times are treated the same way. Most safety events are not useful by themselves, as we do not have all the necessary information to understand how safe the flight actually was. For example, the vertical speed safety event tells only us how much time the aircraft spent outside the parameter range in Table 2. However, when combined with airspeed, pitch, or engine speed information, we can determine why the vertical speed was high and whether it did indeed need to be high. The required vertical speed to maintain a constant glideslope also depends on groundspeed. At a faster groundspeed, the aircraft has less time to lose the same altitude, and therefore needs to descent at a higher vertical speed.

For an event-driven approach to successfully characterize the safety of an approach, the safety event definitions need to be internally consistent, i.e. the parameter limits need to correspond to the same level of risk to the flight. For example, in our definitions, a 20 degree bank at 1000 ft AGL must be as unsafe as an 800 fpm sink rate at the same altitude. In this paper, we managed to re-define safety events in a way that makes them more consistent in our flight dataset.

VIII. Future Work

While some of the safety events are largely based on aircraft performance, such as airspeed, others depend on pilot skills and comfort levels. For example, more experienced pilots will be able to land better in high crosswinds compared to new pilots. Pilot experience must therefore be considered in determining whether a flight is safe or not. To make safety events more useful, we suggest that (1) only information that we have available in the flight data is considered in a list of safety events to track, (2) limits for each safety event definition are further refined to reflect the same level of safety, and (3) personal minimums are included in the definitions for safety events. For example, we can choose to apply different limits to pilots of different levels of experience. Pilots that are just starting out should be more cautious than commercial pilots with hundreds of hours of experience.

In future work, we plan to expand the algorithms to detect safety events in different phases of flight (taxi, landing, takeoff, cruise, climb, and descent). We will then detect the safety events with different sources of flight data, which may be more limited in the parameters they record, such as smartphone data, or flight data from different FDRs, such as the Avidyne FDR.

Metrics based on safety events (for example, high vertical speed and high airspeed concurrently) have the potential to be more useful than individual safety event counts for characterizing the safety of a flight. For example, one could devise a scoring system for approaches that weighs safety events differently, based on their severity, and the distance or time remaining for the pilot to get out of the unsafe situation. This method will provide the pilot with a safety scale, so that they can see how unsafe they were, instead of a binary result that tells them whether their flight was or was not a safety concern.

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