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THE ACCIDENT RECORD OF
TECHNOLOGICALLY ADVANCED AIRCRAFT

AN UPDATE FROM THE AIR SAFETY INSTITUTE

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INTRODUCTION

In 2007, the Air Safety Institute (then known as the AOPA Air Safety Foundation) published *Technologically Advanced Aircraft: Safety and Training* ("the 2007 report"), an update of its 2004 preliminary review. That analysis was based on 57 accidents, 18 of them fatal, that occurred in technologically advanced aircraft (TAA) between 2003 and 2006, and the report began by defining terms like "glass cockpit" that were then just entering aviation's common lexicon.

In the four years since, the major U.S. manufacturers of certified airplanes have delivered almost all their new production with so-called glass panels. These combine the functions of the six basic attitude instruments in a single 9-12" liquid crystal display screen, the "primary flight display" (PFD); a second screen known as the "multi-function display" (MFD) is available to show flight planning, navigation, and weather data. Electronic flight instrumentation has made progressively deeper inroads into both the amateur-built and certified fleets and is becoming broadly familiar within the aviation community, even among pilots who continue to fly with traditional analog instruments.

As the number of technologically advanced aircraft has increased, reports of accidents involving them have also accumulated. Whether their accident risk differs from that of conventionally equipped airplanes has remained unclear. Now the near-complete transition of new aircraft production from traditional to electronic instruments provides an opportunity to make direct comparisons between the two in long-established model lines as well as between those aircraft and newer designs that went to glass early in their production histories. With enough accident data, those comparisons can be extended to the analysis of possible causal factors and the role of potentially confounding differences in aircraft design, typical flight conditions, and patterns of use.

EXECUTIVE SUMMARY

The study tracked more than 20,000 certified piston airplanes manufactured between 1996 and 2010. Just under half were equipped with conventional instruments, almost all of them built before 2006. Analog aircraft averaged almost twice as much time in service as those with glass panels.

The most dramatic differences in the accident record were between three distinct groups of aircraft:

- Single-engine fixed-gear models producing less than 200 horsepower had the highest accident rates but the lowest rates of fatal accidents.
- Complex and/or high-performance models certified prior to 1980 had less than half as many accidents relative to time in service, but their fatal accident rates were no lower.
- The accident rate for models certified since 1998 with engines of 200 horsepower or more was more than 20% higher than in the most comparable legacy models, and their fatal accident rate was more than 60% higher.

Within each of those categories, differences between analog and glass panels were minimal.

Differences between aircraft categories partly reflected underlying differences in flight conditions and the types of flying done, with more accidents

TIMELINE: PRODUCTION HISTORY AND TRANSITION TO GLASS

- **1994** — *General Aviation Revitalization Act*
- **1996 – 1997** — *Cessna Resumes Production and Delivery of Piston Aircraft*
- **1998** — *Lancair Certifies Columbia 300; Cirrus Certifies Cirrus SR20*
- **2000** — *Production Begins on Cirrus SR22*
- **2001** — *Diamond DA-40 is Approved for Production and Deliveries Begin*
- **2002** — *Glass Panels Standard on Cirrus SR20 and SR22*

in the lower-powered fixed-gear singles taking place on instructional flights and in visual meteorological conditions in daylight.

In both groups of legacy models, glass-panel aircraft had lower rates of fatal accidents. This effect was not apparent in the newer models. In all three categories, glass-panel aircraft suffered demonstrably higher rates of accidents during takeoffs, landings, and go-arounds.

BACKGROUND

The 1994 General Aviation Revitalization Act established a "period of repose" shielding manufacturers from liability suits over accidents that occur more than 18 years after initial delivery of an aircraft. Cessna responded by resuming production of piston singles in 1996 after a 10-year hiatus; deliveries began in 1997. Production at Mooney and Piper, which had continued making piston aircraft during Cessna's absence, increased during the same period, while output at Hawker Beechcraft (then known as Raytheon) remained steady.

In September 1998, Lancair received FAA certification for a new version of its LC40, a 310-hp four-seat design already produced in kit form for the amateur-built market. To avoid confusion with the Lancair kitplanes, it was marketed as the Columbia 300. Five weeks later, Cirrus Design certified the 200-hp SR20, the first clean-sheet design to win approval in more than twenty years. The 310-hp SR22 followed in November 2000, and in August 2001 Diamond Aircraft obtained certification for the DA-40, a four-seat, 180-hp IFR-capable adaptation of its two-seat DA-20 Katana trainer. Certification of Lancair's Columbia 350, which used electric rather than vacuum-powered gyroscopic instruments, its turbocharged Columbia 400, and the twin-engine Diamond DA-42 followed in 2003, 2004, and 2005, respectively.

Cirrus was the first to begin mass production, delivering nine SR20s in 1999 and 95 in 2000. The SR22 went into production in 2001 and outsold the SR20 by more than two-to-one in its first year (124 to 59). Lancair got off to a slower start, delivering just five Columbia 300s in 2000 and 27 in 2001. Annual production did not exceed 50 aircraft until 2003, the year that the kitplane operation was spun off and the company was renamed the Columbia Aircraft Manufacturing Corporation. **In 2007 it was acquired by Cessna, but for simplicity this report will continue to**

- **2003** — ***Certifcation Obtained for the All-Electric Columbia 350; Piper PA-32R Changes to Glass***
- **2004** — ***Production Begins on Turbocharged Columbia 400; Glass Panels Standard on Piper PA-28R and PA-34, Cessna 182 and 206, Diamond DA-40, Columbia 350 and 430***
- **2005** — ***Production Begins on Twin-Engine Diamond DA-42; Glass Panels Standard on Cessna 172, Piper PA-28, and All Mooney and Hawker Beechcraft Models***
- **2007** — ***Cessna Acquires Columbia Aircraft Manufacturing Company***
- **2008** — ***Glass Panels Standard on All Piper Models***

refer to these models as ''Columbia'' and use ''Cessna'' to refer to its traditional high-wing designs.

Deliveries of the DA-40 began in 2002 with 85 aircraft. It shares a number of design features with the Cirrus and Columbia offerings, including composite airframes shaped into compound curves and castoring nosewheels that rely on differential braking for taxi steering. However, it also has much in common with the well-established Cessna 172 and Piper PA28-181: a 180-hp engine and maximum gross weight below 2,600 pounds, with 20-30% lighter wing loading and stall speeds at least 10 knots below those of the other new composite designs. Stall behavior is exceptionally docile, and typical cruise speeds are about 35 knots less than in the SR20, 50 knots below the SR22, and 100 knots slower than the Columbia 400. It was consciously designed to serve in high-volume training operations as well as for personal transportation.

The DA-40 shares another important characteristic with the Cirrus and Columbia models: Very early in their production history, all three manufacturers discontinued installation of traditional pitot-static and gyroscopic attitude instruments in favor of liquid-crystal displays (LCDs) that present electronically derived attitude and navigational data. After some initial variation, the industry has moved toward a convention in which a "primary flight display" (PFD) combines the functions of the six traditional attitude instruments by superimposing airspeed and altitude tapes and a compass rose over a large artificial horizon; a second "multi-function display" (MFD) can be cycled to provide various combinations of information including engine instrumentation, moving maps, and depictions of weather and terrain. Later generations of these "glass panels" have added features including GPS-based synthetic vision and "highway-in-the-sky" presentations. Increasingly sophisticated autopilots are capable of handling the controls for all but a few minutes of a cross-country flight under instrument conditions – provided they and the navigation sources they track are programmed correctly. (Refer to Appendix B for a more detailed description of glass-panel avionics.)

The 2007 report compared the characteristics of the 57 accidents (18 fatal) that had occurred up to that time in certified aircraft delivered with glass panels to those of the overall fixed-wing GA accident record during the same period (calendar years 2003-2006). The earlier study was hampered not only by the

scarcity of data from the TAA side but by the lack of a useful index of flight activity from which to estimate accident rates and the diversity of the general aviation fleet, in which aircraft of vastly different capabilities and roles are combined in the aggregate accident statistics.

In 2010, the National Transportation Safety Board (NTSB) published its *Report No. PB2010-917001, Introduction of Glass Cockpit Avionics into Light Aircraft*, which combined an analysis of 266 accidents that occurred between 2002 and 2008 with a detailed discussion of training strategies, industry practices, and FAA certification standards. The NTSB study focused on a fleet of 8,364 single-engine piston airplanes manufactured between 2002 and 2006 by the seven manufacturers discussed above and estimated accident rates during calendar years 2006 and 2007 using a specially extracted subset of the FAA's annual general aviation activity survey. It concluded that overall accident rates were lower but fatal accident rates were higher in glass-cockpit airplanes during that period and identified a number of characteristics that appeared to differ between accidents in glass-panel and analog aircraft, including pilot qualifications and experience, the proportions occurring on instructional vs. personal or business flights, and the planned lengths of the accident flights. **However, the NTSB study did not report or account for the changes in the composition of the fleet that coincided with the conversion to glass.**

METHODS

To overcome the latter difficulty, the present study restricted attention to piston airplanes manufactured since 1996 by seven companies that changed their standard panel configurations from analog to glass between 2001 and 2005: Cessna, Cirrus Design, Lancair/Columbia (now part of Cessna), Diamond, Hawker Beechcraft, Mooney, and Piper. Only accidents that occurred in the U.S. during the ten years between 2001 and 2010 (inclusive) were analyzed. The restriction to newer aircraft helps minimize the importance of aging-aircraft problems unrelated to avionics design; 1996 was arbitrarily chosen as the starting point because it was the year in which Cessna resumed piston airplane production. Panel configuration was determined based on year of manufacture and serial number via references supplied by the General Aviation Manufacturers Association (GAMA).

Amateur-built and other experimental aircraft were not included due to the lack of data on their equipment. Except in specific instances where that fact was noted in an NTSB report, the study was also unable to identify airplanes originally delivered with traditional instrumentation that were subsequently converted to glass; the numbers of both aircraft and accidents with conventional panels thus include an unknown number of glass retrofits.

The FAA does not publish estimates of hours flown in individual makes and models, much less broken down by type of instrumentation. Years in service per aircraft were therefore aggregated to provide a rough measure of exposure (so that, e.g., 300 aircraft operated for five years each would equal 1,500 aircraft-years). GAMA's aircraft shipment database provided the number of each eligible model produced per year. Aircraft manufactured prior to 2001 were counted as having been in service for the entire period (e.g., a 1998 model with no accident history would contribute 10 aircraft-years). Aircraft delivered in 2001 and later were credited with half a year's service in the year they were delivered and full years thereafter. An approximate adjustment for accident losses subtracted half a year for each non-fatal accident, while aircraft involved in fatal accidents were counted for half of the year in which the accident occurred but no subsequent service. No attempt was made to adjust for aircraft exported due to a lack of data at the make-and-model level.

This measure does not account for differences between models in typical annual flight time and is not directly comparable to published accident rates expressed as accidents per 100,000 hours flown. However, by FAA estimates piston singles averaged between 90 and 120 hours per year between 2001 and 2010, while piston twins (which made up only 5% of the study fleet) averaged 115-145 hours per year. The number of accidents per 1,000 aircraft-years therefore provides a similar scale to the number per 100,000 flight hours.

Accidents were classified by ASI staff using the same methods employed in its annual *Joseph T. Nall Report*. Classifications are based on data extracted from NTSB findings but place each accident in a single category for statistical purposes based on independent review of the public record. ASI's identification of the crucial link in the accident

FIGURE 1: GLASS VS. ANALOG DELIVERIES, 1996-2010

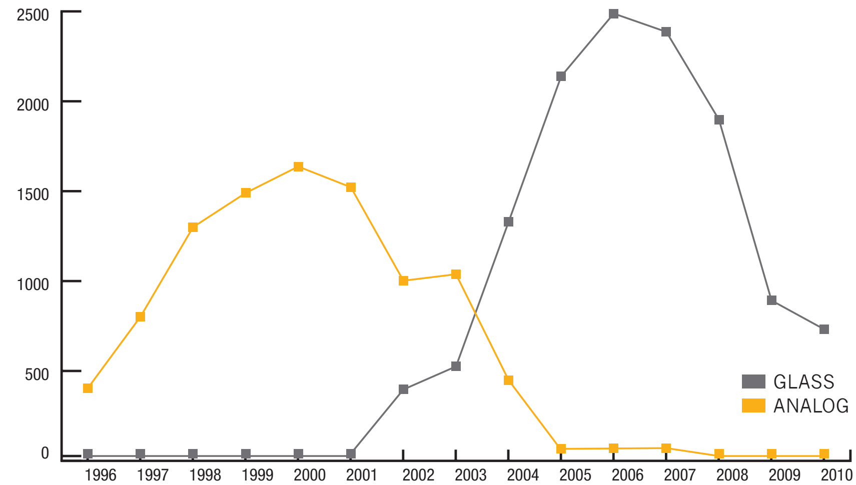
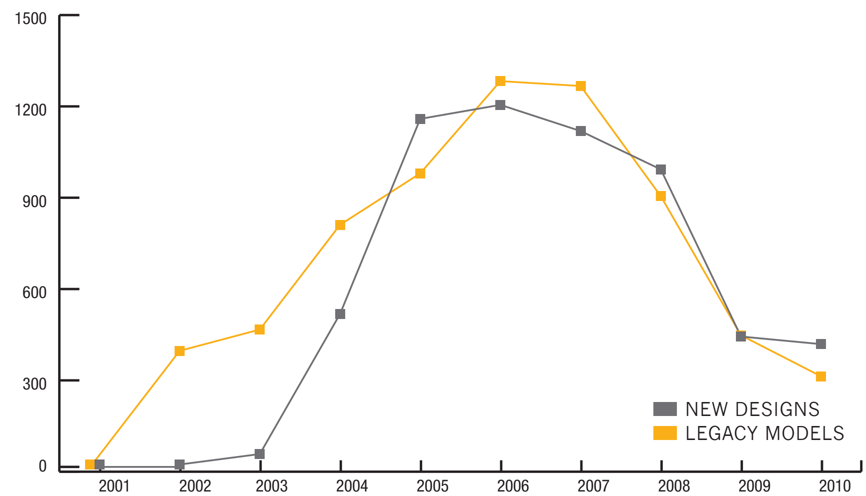


FIGURE 2: GLASS-PANEL DELIVERIES, 2001-2010

"Legacy models" were produced by Beechcraft, Cessna (excluding the Columbia model line), Mooney, and Piper. "New designs" are the products of Cirrus, Columbia (including those made after its acquisition by Cessna), and Diamond.



chain does not necessarily match the Board's findings of probable cause, particularly in complex multifactorial accidents. All fatal accidents were then reviewed a second time and grouped according to the aerodynamic or operational principles involved, so that, e.g., accidents during descent and approach might be attributed to stalls or spins, deficient instrument flying, or controlled flight into terrain.

INDUSTRY TRENDS

Cirrus began delivering glass-cockpit aircraft in 2002, the first major manufacturer to do so. Piper followed suit in 2003, but initially only in their PA-32R Saratoga model. They expanded glass-panel deliveries to the PA-28R Arrow and twin-engine PA-34 Seneca in 2004, the same year that Cessna began building the 182 and 206 with glass as the standard configuration and Diamond and Columbia also made the conversion. Beechcraft and Mooney followed suit in 2005, and by 2006 the Piper Seminole and Malibu were the only models tracked in this study that still offered analog instruments as standard equipment. More than 98% of 2006 production was delivered with glass cockpits, and by 2008 traditional panels were available only by special order, if at all.

Glass panels almost completely displaced conventional instrumentation in just four years (Figure 1), long before there was enough accident data to assess the safety implications of this change. It also coincided with the certification of the composite designs from

TABLE 1: CONVENTIONAL AND GLASS-PANEL PRODUCTION, 1996-2010

Manufacturer	Avionics	Production 1996-2000	Production 2001-2005	Production 2006-2010	Estimated Aircraft-Years of Service, 2001-2010
CESSNA*	Analog	2,946	2,214	0	47,676
	Glass	0	1,240	2,818	15,993
HAWKER BEECHCRAFT	Analog	717	394	0	10,338
	Glass	0	99	439	1,822
MOONEY	Analog	459	112	0	5,312
	Glass	0	85	240	1,271
PIPER	Analog	1,418	858	86	21,526
	Glass	0	311	683	3,702
CIRRUS DESIGN	Analog	104	183	0	2,741
	Glass	0	2,005	2,430	21,119
COLUMBIA**	Analog	0	52	0	364
	Glass	0	172	517	2,734
DIAMOND	Analog	0	238	0	1,863
	Glass	0	478	1,269	6,842

* Models 172, 182, and 206. Columbia/Cessna/Corvalis 350 and 400 aircraft produced by Cessna after their acquisition of Columbia are counted under "Columbia."
** Including those manufactured by Cessna after their acquisition of Columbia Aircraft.

Cirrus, Columbia, and Diamond ("new designs"), and with the commercial success that established Cirrus as Cessna's principal competitor in the volume of piston single sales. Glass panels accounted for 84% of SR20 deliveries, 88% of DA-40s, 93% of Columbia aircraft, and 97% of SR22s. Because the analog versions were introduced first, the differences in length of service are slightly less lopsided; still, glass panels account for 86% of the service experience of these three manufacturers (Table 1). Even more dramatically, they provided less than 6% of time in service with analog avionics. The established ("legacy") models from Cessna, Hawker Beechcraft, Mooney, and Piper have since produced almost as many glass-panel aircraft (Figure 2), but their long history of making conventionally instrumented airplanes means that glass represents only 22% of their relevant time in service.

Total production of these models came to 20,767 airplanes over a 15-year period, and was almost evenly divided between analog (9,781, or 47% of the total) and glass panels (10,986, or 53%). Since analog production was concentrated in the first half of the study period and glass dominated the second, the average of 9.2 years in service for aircraft with conventional panels was almost double that for glass-cockpit airplanes (4.9 years), and nearly two-thirds of total exposure (63%) was in airplanes with analog gauges.

[2]

ACCIDENT HISTORY

The records of the aircraft studied cluster into several distinct patterns. Relative to accrued time in service, accidents in fixed-gear singles of 180 hp or less are the most frequent but least severe. Complex aircraft, twins, and singles of 200 hp or more suffer fewer accidents per year of service, but those that do occur are at least three times as likely to be fatal. This reflects the effects of increased mass and velocity on the intrinsic physics of any impact. Systematic differences also emerged between the accident profiles of legacy models and those built by Cirrus and Columbia.

None of these patterns describe the record of Diamond Aircraft. In the decade from 2001 through 2010 (inclusive), there were only 13 accidents in single-engine DA-40s and one in a DA-42 twin. Three of the DA-40 accidents were fatal. Because the precision of the estimate depends on the number of events observed, accident rates estimated

TABLE 2A: ACCIDENTS AND ACCIDENT RATES, 2001-2010

Configuration	*Generation*	*Accidents*	*Fatal Accidents*	*Lethality (Percent)*	*Aircraft/Years (Thousands)*	*Accident Rate*	*Fatal Accident Rate*
ANALOG	Combined	506	97	19.2	87.96	5.8	1.1
	C172 and PA-28	301	31	10.3	34.54	8.7	1.0
	Legacy, 200+ hp	188	60	31.9	50.31	3.7	1.2
	Cirrus and Columbia	17	6	35.3	3.11	5.5	1.9
GLASS	Combined	220	59	26.8	46.64	4.7	1.3
	C172 and PA-28	60	4	6.7	6.75	8.7	0.6
	Legacy, 200+ hp	56	12	21.4	16.04	3.5	0.7
	Cirrus and Columbia	104	43	41.3	23.85	4.4	1.8

from these numbers cannot be considered reliable, but taken at face value they would be about two-thirds lower than those in other fixed-gear singles of 180 hp or less, and half those in the more powerful new composite designs. Since almost 80% of Diamond's fleet exposure is in glass-cockpit airplanes, combining Diamond with any other category biases the comparison in favor of glass. The uniqueness of these aircraft and their typical use precludes grouping them with any of the other models studied; at the same time, their accident record is too sparse to analyze them as a separate category. For these reasons, Diamond aircraft were excluded from the remainder of the analysis.

Among the remaining makes, conventionally instrumented airplanes in the study fleet suffered 506 accidents in U.S. airspace between 2001 and 2010 (Table 2A). Ninety-seven of these (19%) were fatal. More than 96% of the aircraft involved (489) were legacy models, which also provided 96% of overall analog time in service. Cessna 172s and fixed-gear Piper PA-28s accounted for 39% of time in service but 59% of all accidents, only 31 of which (10%) were fatal. Their estimated rate of 8.7 accidents per thousand aircraft-years was more than double the 3.7 estimated for the complex and high-performance models in the legacy fleet. However, accident lethality was more than three times as great in the higher-powered models, leading to a higher estimated rate of fatal accidents. Six of the 17 accidents in Cirrus and Columbia airplanes equipped with analog instruments were fatal (35%), not significantly different from the 32% in the most comparable legacy models.

The 220 accidents in glass-panel airplanes were almost equally divided between new (104) and established designs (116), but nearly three-quarters of the fatal accidents (43 of 59) occurred in the new models. There would be less than one chance in ten thousand of seeing such a wide disparity if the underlying risks of lethality were the same. Legacy models provided 49% of the estimated time in service with glass cockpits and suffered 53% of all accidents, but only 27% of fatal accidents. Within that group, more than half of all accidents (60) but only one-fourth of the fatal accidents (4) occurred in fixed-gear Skyhawks and Cherokees, which contributed 30% of the legacy fleet's glass-cockpit exposure and 14% of glass-panel service overall. As on the analog side, their overall accident rate of 8.7 per thou-

sand aircraft-years was more than double that of the higher-powered models from established lines (3.5) but the lethality of their accidents was two-thirds less. The lethality of glass-panel Cirrus and Columbia accidents was 41%, almost twice that of the legacy models of 200 hp or more, producing a fatal-accident rate 2.4 times as high (1.8 vs. 0.7) even though the overall accident rate was only 25% higher.

These disparities suggest a different comparison. Table 2B rearranges the same data to show the remarkable similarity in the rates and lethality of accidents in legacy-model aircraft regardless of instrumentation. **The raw data do suggest a possibility that fatal-accident rates might be lower in the glass-panel versions of these aircraft, though the small number of events involved leaves the significance of the difference in doubt. Cirrus' and Columbia's record shows almost no difference between glass and analog panels, though again small numbers in the analog fleet cloud the comparison. Like a number of other popular designs, they suffered a disproportionate number of accidents early in their initial operating experience, which drove up the estimated rates for the analog versions. However, there is little doubt that overall accident rates are at least 25% higher and fatal-accident rates at least 60% higher than in the most comparable models in the legacy fleet. Comparing only glass-cockpit examples, the fatal-accident rate was 140% higher.**

TABLE 2B: ACCIDENTS AND ACCIDENT RATES, 2001-2010

Category	Configuration	Accidents	Fatal Accidents	Lethality (Percent)	Aircraft/Years (Thousands)	Accident Rate	Fatal Accident Rate
C172 AND PA-28	All	361	35	9.7	41.29	8.7	0.8
	Analog	301	31	10.3	34.54	8.7	1.0
	Glass	60	4	6.7	6.75	8.7	0.6
LEGACY MODELS, 200+ HP	All	244	72	29.5	66.35	3.7	1.1
	Analog	188	60	31.9	50.31	3.7	1.2
	Glass	56	12	21.4	16.04	3.5	0.7
CIRRUS AND COLUMBIA	All	121	49	40.5	26.96	4.5	1.8
	Analog	17	6	35.3	3.11	5.5	1.9
	Glass	104	43	41.3	23.85	4.4	1.8

[3]

ANALYSIS

Differences in lethality often result from differences in use. Throughout the general aviation fleet, accidents that occur in visual meteorological conditions (VMC) at night are twice as likely to be fatal as those in daytime VMC, while accidents in instrument meteorological conditions (IMC), day or night, are fatal five to six times as often. This is one factor behind the contrasts seen in Table 2: Only about 15% of the accidents in the C172s and PA-28s occurred at night or in IMC compared to 25-35% of those in aircraft of 200 hp or more (Table 3). In the latter group, the conditions of the accident flights were very similar across both aircraft and panel configurations. The lack of data on flight activity by model and avionics design makes it impossible to tell whether all of these aircraft spent equal amounts of time operating in low-visibility conditions, or whether increases in exposure offset any reductions in risk. However, the results are remarkably

TABLE 3: PERCENTAGES OF ACCIDENTS (FATAL ACCIDENTS) BY LIGHT AND WEATHER CONDITIONS

	C172 and PA-28		Legacy Models, 200+ HP		Cirrus and Columbia	
Conditions	Analog	Glass	Analog	Glass	Analog	Glass
DAY VMC	85.7	85.0	65.4	75.0	64.7	67.3
	(48.4)	(50.0)	(28.3)	(16.7)	(16.7)	(55.8)
NIGHT VMC	10.3	15.0	16.5	16.1	11.8	15.4
	(32.3)	(50.0)	(20.0)	(41.7)	(33.3)	(9.3)
DAY IMC	2.3	0	10.6	5.4	11.8	8.7
	(12.9)		(28.3)	(25.0)	(16.7)	(16.3)
NIGHT IMC	1.7	0	7.4	3.6	11.8	8.7
	(6.5)		(23.3)	(16.7)	(33.3)	(18.6)

consistent in all four, with one conspicuous exception: **The majority of fatal glass-cockpit Cirrus and Columbia accidents occurred in day VMC, double to triple the share in any of the comparable groups and even more than in the lower-powered fixed-gear singles.** The proportion of all accidents that took place in these conditions were similar in all four groups, but 35% of them were fatal in glass Cirrus and Columbia compared to 5% in the most comparable glass-cockpit legacy aircraft and 14% in those same models equipped with analog gauges.

By way of comparison, the most recent FAA activity survey estimated that in 2009, piston singles with four or more seats logged 83% of their flight time in daytime VMC, while piston twins with six or fewer seats (which made up 7% of the aircraft tracked for this study) flew 69% of their time in daytime VMC. The resulting weighted average suggests that 82% of all flight activity in a fleet of similar composition could be expected to take place in visual conditions during daylight. However, Cirrus and Columbia aircraft made up less than 5% of the active piston fleet on which those estimates were based.

The heavy volume of training activity conducted in low-powered fixed-gear singles contributes directly to the disparity in accident rates and lethality while also explaining some of the difference in flight conditions. Training aircraft suffer less exposure to weather and terrain, and training flights can usually be rescheduled; personal or business cross-country flights are more likely to involve time-sensitive "missions." Training flights are also more likely to benefit from the involvement of multiple decision-makers: the student, the CFI, and possibly a chief flight instructor or dispatcher.

Almost 60% of accidents in Cessna 172s and Piper PA-28s occurred on instructional flights compared to less than 15% of all those in models producing 200 hp or more (Table 4). Instructional accidents have historically been among the least likely to be fatal, largely because a disproportionate share of them are landing accidents, consistently the most survivable category. Conversely, the proportion of accidents that occurred during personal flights was almost twice as great in the higher-powered models, accounting for more than 70%. In the entire fixed-wing fleet, accidents on

TABLE 4: PERCENT OF ALL ACCIDENTS (PERCENT LETHALITY) BY PURPOSE OF FLIGHT

Aircraft Category	Panel	Instructional	Personal	Other
C172 AND PA-28	Analog	59.1 (6.7)	38.5 (13.8)	2.3 (42.9)
	Glass	58.3 (0)	35.0 (14.3)	6.7 (25.0)
LEGACY MODELS, 200+ HP	Analog	17.0 (12.5)	70.2 (37.1)	12.8 (29.2)
	Glass	7.1 (25.0)	73.2 (19.5)	19.6 (27.3)
CIRRUS AND COLUMBIA	Analog	5.9 (0)	70.6 (41.7)	23.5 (25.0)
	Glass	9.6 (30.0)	78.8 (43.9)	11.5 (33.3)

personal flights have about twice the lethality of training accidents. The familiar association between aircraft weight, speed, and fatality also comes into play.

Very little difference is apparent between the glass and analog versions of the same aircraft. The apparent excess lethality in training accidents in glass-cockpit Cirrus represents just three accidents. The suggestion that among legacy models of 200 hp or more, accidents on personal flights were less often fatal in the glass-panel airplanes has somewhat stronger support, but in the absence of any wider pattern this should probably be viewed with skepticism.

Panel configuration might be expected to have the least effect on accident risk during takeoffs, landings, and go-arounds ("TLGs"), when pilots get most of their information from visual, auditory, and kinesthetic cues. Consistent with their frequent use as trainers and the consequent volume of flight in the traffic pattern, the Cessna 172 and fixed-gear Piper Cherokees have the highest proportion of TLG accidents (Table 5), which occurred at almost triple the rate of the complex and high-performance models. (Primary training in particular combines increased time in the traffic pattern with a higher risk per circuit.) The proportion of accidents occurring during takeoff, landing, and go-around was lowest in Cirrus and Columbia airplanes, and the fact that their estimated TLG accident rate was lower than that of comparable legacy models suggests that this is not merely an artifact of a higher accident rate overall. Whether this reflects a tendency for these airplanes to fly longer legs and therefore take off and land less frequently is not known.

The most striking feature of these data, however, is that glass-panel airplanes in all three groups had a higher rate of TLG accidents than the same models equipped with analog gauges. The apparent increase ranged from about 12% in the Cessna 172 and Piper PA-28 to 96% in Cirrus and Columbia, though the small number of analog TLG accidents in this group makes a point estimate unreliable. Among the larger legacy models, the increase was 23%. Unfortunately, investigators did not report the pilot's experience in the same make and model for most of these accidents, making it difficult to draw any conclusions about the extent to which this reflects temporary difficulties during transition training as opposed to intrinsic disadvantages in using "tape" displays instead of

TABLE 5: TAKEOFF, LANDING, AND GO-AROUND ACCIDENTS

Aircraft Category	*Panel*	*Number (% of All Accidents)*	*Aircraft/Years of Service (Thousands)*	*TLG Accident Rate*
C172 AND PA-28	Analog	215 (71.4)	34.54	6.2
	Glass	47 (78.3)	6.75	7.0
LEGACY MODELS, 200+ HP	Analog	97 (51.6)	50.31	1.9
	Glass	38 (67.9)	16.04	2.4
CIRRUS AND COLUMBIA	Analog	3 (17.6)	3.11	1.0
	Glass	45 (43.3)	23.85	1.9

needles and dials to present airspeed and altitude data. This would be an apt subject for controlled experimentation; failing that, some insight may arise from the extent to which this imbalance diminishes as more pilots receive their initial flight training in glass.

WITHIN-MODEL COMPARISONS The near-absence of analog instruments from models certified after 1997 is only one of the factors confounding the comparison of traditional and glass panels. Similar imbalances limit the usefulness of data from several individual model lines. After their conversions to glass, there were only six accidents in Mooneys and five in Hawker Beechcraft airplanes (Table 6A), too few to support estimation of accident rates or systematic analysis of their causes. Together, they accounted for less than 10% of glass-panel accidents in the legacy fleet and less than 15% of time in service (Table 6B). Piper's relatively modest production was divided between seven principal model lines, four of which saw either no glass-panel accidents or no accidents in airplanes with traditional instruments. The fixed-gear PA-28 accounts for only 3% of total glass-panel exposure in the legacy fleet, and only two accidents have occurred in those airplanes.

Of the seven manufacturers studied, only Cessna and Cirrus accumulated both substantial exposure and meaningful numbers of accidents in aircraft of both configurations within stable model lines. These two companies dominated sales numbers, time in service, and the decade's accident record, particularly within the glass-panel fleet, where each accounted for more than 70% of time in service and 75% of accidents in their respective generations. A direct comparison between analog- and glass-cockpit aircraft within these model lines offers an opportunity to reduce the influence of confounding effects at the cost of some loss of data.

Cirrus made glass cockpits standard in both its models in 2002, but Cessna began its transition to glass with the high-performance 182 and 206. At the same time, production of the 180-horsepower 172, widely popular as both a primary and instrument trainer, dropped from 56% of piston deliveries between 1997 and 2003 (all analog) to 46% of piston airplanes delivered between 2005 and 2010 (all glass). As a result, 172s account for 57% of Cessna's analog service but only 37% of its glass-panel exposure, and their accident

TABLE 6A: ACCIDENTS AND ACTIVITY BY MODEL LINES AND INSTRUMENTATION

	Analog Panels			Glass Panels		
Legacy Models	Aircraft/Years of Service (Thousands)	Accidents	Fatal Accidents	Aircraft/Years of Service (Thousands)	Accidents	Fatal Accidents
BEECHCRAFT	10.3	21	10	1.8	5	3
CESSNA*	47.7	317	45	16.0	90	8
172	27.3	256	25	6.0	58	4
182 AND 206	20.3	61	20	10.0	32	4
MOONEY	5.3	26	5	1.3	6	1
PIPER	21.5	125	31	3.7	15	4
PA-28	7.2	45	6	0.8	2	0
HP/COMPLEX	14.3	80	25	2.9	13	4
New Models						
CIRRUS	2.7	15	5	21.1	91	37
COLUMBIA**	0.4	2	1	2.7	13	6

* Excludes Columbia/Corvalis models produced by Cessna after their acquisition of Columbia.
** Includes aircraft manufactured by Cessna after their acquisition of Columbia Aircraft.

history looks very different from that of their larger cousins. As previously noted, training flights suffer relatively few fatal crashes but a disproportionate number of less serious accidents, particularly during landings. The 230-hp Cessna 182 and 300-hp 206 are primarily used for personal and commercial transport, much more analogous to the typical roles of the 200-hp SR20 and 310-hp SR22, respectively.

The difference in risk profiles is clear in Table 7. Cessna 172s, regardless of instrumentation, had triple the accident rate of the Cessna 182 and 206 models, but those accidents were less than half as likely to be fatal. The change from analog to glass panels produced little apparent change in overall accident rates in either group; the uncertainties in estimating exposure outweigh any observed effects. The fatal accident rate showed equally little evidence of change in the 172, but in the larger Cessnas a dramatic reduction in accident lethality accompanied the conversion to glass. Thirteen of the 20 fatal accidents in conventionally equipped examples were due to controlled flight into terrain, VFR into IMC, or deficient instrument flying, as were all four of those in the glass-cockpit versions. Relative to length of service, this represents almost a 40% reduction in fatal accidents arising from spatial disorientation or loss of situational awareness. By the same measure, however, landing accidents were one-third more common in the glass-equipped 182s and 206s, which had 20 compared to 30 in the analog fleet.

While the numbers are presented for the sake of completeness, comparisons between the two Cirrus models are problematic due to the very small numbers built with analog instruments and the difficult introduction of the SR22. The unexpectedly high number of accidents early in its history prompted revisions to the factory-sponsored training curriculum; because initial production was with analog gauges, those airplanes were heavily involved, but at least nine of the ten accidents appear to have been unrelated to avionics or instrument flying.

However, combining the data from the SR20 and SR22 shows a consistent pattern. Their accident rates are roughly half those of comparably equipped 172s but at least one-third higher than in similarly configured 182s and 206s. Fatal accident rates and accident lethality show no difference between digital and analog panels, and in both, fatal accident rates are about double those of the Cessna models.

TABLE 6B: ACCENTS AND ACTIVITY BY MODEL LINES AND INSTRUMENTATION

Legacy Models	Analog Panels Percent of Time in Service	Analog Panels Percent of All Accidents	Analog Panels Percent of Fatal Accidents	Glass Panels Percent of Time in Service	Glass Panels Percent of All Accidents	Glass Panels Percent of Fatal Accidents
BEECHCRAFT	12.2	4.3	11.0	8.0	4.3	18.8
CESSNA*	56.2	64.8	49.5	70.2	77.6	50.0
172	32.2	52.4	27.5	26.3	50.0	25.0
182 AND 206	23.9	12.5	22.0	43.9	27.6	25.0
MOONEY	6.3	5.3	5.5	5.6	5.2	6.3
PIPER	25.4	25.6	34.1	16.3	12.9	25.0
PA-28	8.5	9.2	6.6	3.4	1.7	0
HP/COMPLEX	16.9	16.4	27.5	12.9	11.2	25.0
New Models						
CIRRUS	88.3	88.2	83.3	88.5	87.5	86.0
COLUMBIA**	11.7	11.8	16.7	11.5	12.5	14.0

* Excludes Columbia/Corvalis models produced by Cessna after their acquisition of Columbia.
** Includes aircraft manufactured by Cessna after their acquisition of Columbia Aircraft.

Focusing on accidents within individual model lines also underlines the close connection between accident rates and aircraft use. Almost 60% of accidents in 172s occurred on instructional flights compared to about 10% of those in the other four models (Table 8). Conversely, about 80% of the accidents in the higher-powered models took place during personal flights, twice the proportion seen in 172s. Greater weight and speed added to the higher lethality that characterizes accidents on personal flights.

Table 9 shows that the increased rate of takeoff, landing, and go-around accidents in glass-panel airplanes is not an artifact of changes in the composition of the fleet. The same pattern applies within individual model lines, and the difference seems to increase with wing loading and stall speed. The apparent increase was only about 9% in the 172 but more than 60% in the larger Cessnas; it reached 75% in the Cirrus models, though again, the small number of TLG accidents in conventionally instrumented examples make this estimate unreliable. However, the consistency of this finding in comparisons of otherwise identical aircraft as well as within the larger fleet bolsters confidence that it represents a real difference rather than a chance result. Reliable data on flight time and numbers of landings would make it possible to determine whether the high-performance Cessna models make more takeoffs and landings than Cirrus airplanes or are truly more likely to be damaged during these operations.

CAUSES OF FATAL ACCIDENTS

As noted in Table 2, legacy designs accounted for almost half of all time in service with glass panels and 53% of glass-panel accidents, but barely one-fifth of the fatal accidents. Half the accidents in legacy models with glass panels, including one-third of the fatal accidents, were in Cessna 172s, which have no direct counterpart in the Cirrus or Columbia product lines.

Table 10 presents the Air Safety Institute's classification of the causes of fatal accidents in the remaining glass-cockpit aircraft as well as in comparable high-performance and complex aircraft with analog instruments. Once again, the data show little evidence of differences associated with avionics design. The dominant feature is the excess number attributed to inadvertent stalls (with or without spins) in the Cirrus and Columbia lines, where they account for almost three times the proportion of fatal

TABLE 7: ACCIDENT RATES BY MODEL FOR CESSNA AND CIRRUS

Manufacturer	Model(s)	Panel	Aircraft/Years of Service (Thousands)	Accidents	Accident Rate	Fatal Accidents	Fatal Accident Rate	Lethality (Percent)
CESSNA	172	Analog	27.3	256	9.4	25	0.9	9.8
		Glass	6.0	58	9.7	4	0.7	6.9
	182 and 206	Analog	20.3	61	3.0	20	1.0	32.8
		Glass	10.0	32	3.2	4	0.4	12.5
CIRRUS	SR20	Analog	1.6	5	3.2	2	1.3	40.0
		Glass	4.4	18	4.1	6	1.4	33.3
	SR22	Analog	1.2	10	8.6	3	2.6	30.0
		Glass	16.8	73	4.4	31	1.8	42.5
	Combined	Analog	2.7	15	5.5	5	1.8	33.3
		Glass	21.1	91	4.3	37	1.8	40.7

accidents as in the legacy models. The disparity is too wide to be plausibly attributed to chance ($p < .01$ by Fisher's exact test). Relative to estimated time in service, their rate of fatal stall accidents is almost five times as high.

This imbalance also has the effect of reducing the proportion of fatal accidents in those aircraft attributed to other causes. Comparisons of the prevalence of other types of accidents will be more informative if this is taken into account. One simple way to do this is to consider the corresponding proportions of the remaining causes after stalls are excluded. Thus, the 20 fatal accidents in analog aircraft ascribed to deficient instrument flying represent 38% of all those not attributed to stalls. The corresponding figures are 27% in legacy glass-cockpit airplanes and 28% in the Cirrus and Columbia. Attempts to fly VFR in IMC led to 21% of non-stall fatal accidents in legacy models with traditional instrumentation, 9% of those in the same models equipped with glass, and 17% of those in the newer designs. None of these differences reach conventional thresholds of statistical significance, though the small numbers of accidents involved limit the power of these comparisons.

Likewise, small numbers make other possible differences inconclusive, if interesting. While equipment problems have caused eight fatal accidents in legacy airplanes and only one in a Cirrus, none were due to electrical or instrument malfunctions. All involved losses of engine power: due to powerplant failures in the legacy models, and an error maintaining the fuel injection system in the Cirrus. The only two study aircraft involved in fatal mid-air collisions both had glass cockpits. Glass cockpits were also roughly twice as likely to be destroyed by controlled flight into terrain or icing encounters but only had one fatal accident attributed to thunderstorm encounters or turbulence compared to four in the analog fleet. The "other or unexplained" category includes a bird strike, three losses of control at altitudes that should have allowed recovery, and two aircraft that disappeared in flight and have not been found.

TABLE 8: PERCENT OF ALL ACCIDENTS (PERCENT LETHALITY) BY PURPOSE OF FLIGHT: CESSNA AND CIRRUS

Manufacturer	Model(s)	Panel	Instructional	Personal	Other
CESSNA	172	Analog	57.8 (6.1)	39.8 (12.8)	2.6 (50.0)
		Glass	58.6 (0)	34.5 (15.0)	6.9 (25.0)
	182 and 206	Analog	9.8 (0)	78.7 (35.2)	11.5 (42.9)
		Glass	6.3 (0)	78.1 (16.0)	15.6 (0)
CIRRUS	SR20 and SR22	Analog	6.7 (0)	80.0 (41.7)	13.3 (0)
		Glass	11.0 (30.0)	78.0 (42.3)	11.0 (40.0)

TABLE 9: TAKEOFF, LANDING, AND GO-AROUND ACCIDENTS

Manufacturer	Model(s)	Panel	Number (% of All Accidents)	Aircraft/Years of Service (Thousands)	TLG Accident Rate
CESSNA	172	Analog	192 (75.2)	27.3	7.0
		Glass	46 (79.3)	6.0	7.7
	182 and 206	Analog	31 (55.7)	20.3	1.5
		Glass	25 (78.1)	10.0	2.5
CIRRUS	SR20 and SR22	Analog	3 (20.0)	2.7	1.1
		Glass	41 (45.1)	21.1	1.9

TABLE 10: CAUSES OF FATAL ACCIDENTS IN GLASS-PANEL AIRCRAFT

	Cirrus and Columbia (Glass)		Legacy Models, 200+ HP (Glass)		Legacy Models, 200+ HP (Analog)	
	Number	Percent of Fatal	Number	Percent of Fatal	Number	Percent of Fatal
Aircraft/Years of service (000)	23.85		16.04		50.31	
Number of accidents	104		56		188	
Number of fatal accidents	43		12		60	
Lethality (Percent)	41.3		21.4		31.9	
Stalls and/or spins	14	32.6	1	8.3	7	11.7
Deficient IFR technique	8	18.6	3	25.0	20	33.3
VFR into IMC	5	11.6	1	8.3	11	18.3
Loss of control at low altitude	3	7.0	1	8.3	1	1.7
Mid-air collisions	2	4.7	0		0	
Controlled flight into terrain	3	7.0	2	16.7	3	5.0
Icing	3	7.0	1	8.3	1	1.7
Pilot incapacitation	2	4.7	1	8.3	2	3.3
Mechanical failure or power loss	1	2.3	2	16.7	6	10.0
Thunderstorms or non-convective turbulence	1	2.3	0		4	6.7
Other or unexplained	1	2.3	0		5	8.3

DISCUSSION

By 2011, glass cockpits had almost entirely supplanted traditional pitot-static and gyroscopic instruments in new production of certified piston airplanes for the U.S. market. This revolution was not motivated by data establishing its effects on flight safety. Marketing efforts and customer preference (perhaps cultivated) drove it to completion long before these systems had accrued sufficient operating experience to support any systematic evaluation of the safety implications.

Now that the glass-equipped fleet has accumulated more than 53,000 aircraft-years of service (and suffered 232 accidents in U.S. airspace), it has become possible to begin that evaluation, including direct comparisons within individual models where panel configuration is the only variable in play. The results are mixed. So far, the data provide no evidence that the typical primary flight display conveys attitude information more usefully or accessibly than the traditional "six-pack" of analog instruments; the increased rate of accidents in glass-panel airplanes during takeoffs, landings, and go-arounds suggests that in some respects it may be worse. Increasingly complex integration of stored and real-time data, sophisticated autopilots, and multiple display modes offer a wealth of information but also more opportunity for distraction and programming errors, and vigilance is required to keep more capable technology from becoming a crutch for deficient airmanship. Despite the presumed advantage of watching a larger artificial horizon and the improved situational awareness provided by moving maps with terrain depiction and weather overlays, the majority of accidents still occur in visual meteorological conditions in the daytime.

This suggests one reason that the effects of the transition to glass have been less sweeping than was perhaps expected: The most dramatic of the claimed benefits apply to the situations in which most general aviation pilots spend the least time. By FAA estimates, about 9% of the time flown by aircraft comparable to those analyzed here is in actual instrument conditions, and another 8% is in VMC at night. We lack the data to determine whether glass-cockpit aircraft undertake those flights more frequently; if so, the result would appear to be increased utility at an equivalent level of safety.

Early in the history of glass, there were concerns that pilots could be overwhelmed by complex technology, leading to increased numbers of CFIT accidents during instrument approaches. The data do not support this. Some pilots, perhaps intimidated by the equipment, restrict their flying to VMC. Most of those who do fly in IMC under instrument flight rules appear to have mastered the requisite skills.

The data have begun to hint that among the legacy models, the fatal accident rate may be lower in glass cockpits. If so, a higher rate of mostly non-fatal accidents during takeoffs, landings, and go-arounds prevents this from translating into a lower overall accident rate; if anything, total accident rates seem slightly higher in the glass-panel fleet. That difference is slight, however, compared to the differences between the different classes of aircraft. Lower-powered fixed-gear singles widely used as primary and instrument trainers see many more non-lethal

accidents; more powerful designs that serve chiefly as cargo haulers and high-speed travelling machines have about half as many accidents, but with triple to quadruple the lethality.

The high number of fatal stalls in Cirrus and Columbia airplanes dominates the comparison of these designs to competing models from older lineages, and comes as a surprise. Both manufacturers took care to design these airplanes to be spin-resistant with easily manageable stall characteristics. Experienced pilots who have flown them (including members of the AOPA staff) suggest that a well-trained, attentive pilot should find them no more difficult to control than other airplanes in the same performance class. Cirrus' ballistic parachute system was intended to provide an additional margin of safety, though many of the fatal stalls began at altitudes too low to permit successful deployment. In others, it was attempted too late. However, dozens of lives have been saved by parachute deployments within the appropriate flight envelope. As an active system, it requires pilots to recognize danger while they can still activate the equipment. Some of the accident pilots failed to react in time.

Differences in the respective pilot groups do not appear to be a factor. There were no significant differences in the distributions of either the certificate levels or total flight experience of the pilots-in-command of the accident flights, either between the new and legacy models of 200 hp or more or between the pilots of conventional and glass-panel aircraft in any segment (data not shown). It has been noted that in the past, higher accident rates characterized the initial operating experience of other new models whose performance and handling differed from what was then familiar; the Beechcraft Bonanza and Cessna 177 Cardinal are frequently cited as examples. If that pattern repeats, the unexpectedly high rate of fatal stalls in these fast, aerodynamically slick composite models may eventually decline.

Finally, the introduction of flight data monitoring to glass aircraft is already beginning to provide accident investigators with a much clearer picture of the final minutes of an accident flight. Many new production aircraft track and record engine, attitude, and flight path parameters, which should help future analyses determine more precisely how the human-machine interface was functioning.

Of course, safety is not the only consideration in the choice of either aircraft or panel configuration. Data from the population doesn't determine what arrangement any individual will find most useful or intuitive. Taken as a group, pilots may be more attracted to new technology than most other segments of the population. Even for pilots not enamored with glass, other qualities of the aircraft – speed, range, payload, efficiency, or new safety equipment such as airbags or ballistic parachutes – may be attractive enough to justify making the transition. The evidence that's emerged so far, however, suggests that even sweeping changes in avionics design haven't diminished the fundamental importance of planning, decision-making, and skill.

CONCLUSION

Direct comparison of traditional and glass-cockpit airplanes is confounded by the concurrent emergence of new airframe designs with significantly different flight and handling qualities and characteristically different patterns of use.

Almost 95% of time in service with analog panels was in models that have been in production for decades; 57% of glass-panel exposure is in models certified since 1998.

Cessna and Cirrus each account for about 70% of glass-panel exposure within their respective groups. No other manufacturers have enough accidents in comparable models of both configurations to support meaningful comparisons within individual product lines.

Where direct comparisons can be made, they show little evidence of any difference in the safety records of glass and analog aircraft of the same model. Differences between airframe designs and patterns of use appear to be much more significant.

Regardless of panel design, the majority of accidents still take place in visual meteorological conditions during the daytime. Glass panels have also not eliminated accidents due to continuing VFR flight into instrument conditions or controlled flight into terrain. However, no data exist on the number of VFR pilots who have escaped IMC encounters in these airplanes, making it impossible to evaluate a potentially important safety benefit of glass.

Within the glass fleet, fatal stalls and low-altitude losses of control are significantly more common in Cirrus and Columbia airplanes than legacy designs of similar flight profiles. This points to a need for more thorough and systematic transition training and perhaps also better instrumentation for angle of attack, an area that has received little attention.

Glass-panel aircraft may be more susceptible to accidents during takeoffs, landings, and go-arounds. The available data aren't sufficient to determine whether this has more to do with transition training, a tendency to fixate on glass panels at the expense of external cues, or intrinsic disadvantages in reading airspeed and altitude tapes compared to interpreting analog instruments. This probably also contributes to weakening possible evidence of a lower fatal-accident rate in glass cockpits.

The technology continues to evolve. Additional features including GPS-based synthetic vision, terrain avoidance warning systems (TAWS), and highway-in-the-sky displays have become increasingly common in systems delivered in the past few years. It is still too early to know whether these will lead to significant reductions in the risk of accidents in the low-visibility conditions in which they are most likely to prove fatal. In the airlines, TAWS systems have proven successful in helping avoid controlled flight into terrain.

Pilot skill continues to be the main determinant of safety. Minor advantages may be conferred by various aircraft or instrument configurations, but a superior aircraft in the hands of a marginally competent pilot will not yield significant safety improvements. This has been demonstrated repeatedly in both air-carrier and corporate operations.

Additional study is recommended on complexity and distraction factors. Although more information may be useful in some situations, it can easily become a distraction in more critical flight circumstances. Increasing the amount of training needed to master the same basic skills is counterproductive from the standpoints of safety and efficiency. However, continued evolution in understanding what information pilots need may eventually produce better user interfaces, ultimately yielding significant safety gains.

Multiple generations of glass systems will remain in service for years to come. With the rate of changes in avionics approximating those of other non-life critical computer systems, the orphaning of hardware may become a problem. Because there is no standardization of critical flight functions, it can already be difficult to obtain accurate training materials, instructors who are knowledgeable in that model, or model–specific simulators. The learning burden is largely placed on pilots without much support from the airframe or avionics community. The Air Safety Institute proposed to both the FAA and the manufacturers in the early 1990s that standardization of critical flight and navigation functions would be beneficial to the GA community. The learning challenges posed by their refusal to do so are self-evident.

[6]

APPENDIX A: TAA TRAINING: RECOMMENDATIONS

Aircraft and avionics manufacturers have come to recognize the value of detailed training programs specific to their products. Traditional training providers and third-party suppliers of instructional equipment and materials have also been drawn to this growing market. Despite the economic downturn of the past few years, FBOs, commercial flight schools, and college aviation departments have continued to add TAAs to their fleets, and increasing numbers of new pilots are learning to fly in glass-panel airplanes. Those making the transition from analog instrumentation find a widening array of options for learning the new equipment—options that vary in accuracy and specificity.

In addition to live and on-line courses, non-interactive video and print references, and flight simulation programs for personal and tablet computers, dedicated non-moving training devices are becoming more widely available. These range from desktop displays that show the instrument panel and view ahead on a single screen to enclosed cockpit replicas with multiple screens depicting more than 200 degrees of the field of view. A handful of manufacturers have built full-motion flight simulators comparable to those used by airline and high-end corporate flight departments, primarily for aircraft at the upper end of the performance spectrum. Most recently, 2011 saw the introduction of a new class of relatively inexpensive advanced training devices that provide motion in three axes at displacements up to 40 degrees. While not "full-motion" by the accepted definition, they offer a more realistic on-the-ground training environment than has previously been available in their price range. Specific coverage of individual aircraft-avionics combinations continues to improve, but has not yet reached many current and recent models.

TRAINING REQUIREMENTS AND SOURCES

The nearly simultaneous introduction of digital avionics and new airframe designs raised concerns about pilots' ability to manage aircraft approaching the state of the art in both aerodynamics and avionics. Aircraft manufacturers responded to these concerns by offering factory-approved training for both pilots and instructors. The effectiveness of this solution to the pilot qualification problem has been limited, in part because to date relatively few CFIs have acquired or maintained the rigorous qualifications required by these manufacturers' programs. On the pilots' side, there is evidence that those buying used aircraft are less likely to seek certified training than those buying new from the factory. The lack of affordable, widely available task trainers specific to the avionics actually installed also continues to be a problem.

Early in the history of glass-cockpit TAA, insurance companies recognized the unknown level of risk they presented with higher premiums and more stringent training and flight experience requirements. Coverage rates have since decreased significantly thanks to competitive pressures as well as more extensive claims history. However, insurance requirements are still apt to impose more rigorous standards for initial training and supervised early experience than either the FARs or the inclination of some new owners.

A TRAINING SEQUENCE

In ASI's opinion, the best way to train pilots, either from the beginning *(ab initio)* or for transition into TAA, is to start learning the aircraft on the ground. This hasn't changed. We believe that both the efficiency and effectiveness of TAA training increase if the program is structured as follows:

1. Systems and basic avionics training should be done with CD/DVD, part-task trainer, or online. Surveys indicate that most pilots do not find print media particularly helpful for advanced avionics systems. Too much interactivity is required for passive reading to be an effective learning technique. After the pilot has a basic grasp, however, quick-tip cards with shortcuts can be useful. Much training can and should take place long before the pilot shows up at the training center or before starting with a CFI, especially as a transitioning pilot. Online training programs and simulator-like training software are available from an increasing number of vendors. Pilots can use these either prior to flight training or afterward to reinforce the concepts.

2. The next level might be a part-task trainer that simulates the GPS navigator or PFD/MFD cockpit. Exact replication of the actual knob/switch configuration and the system's reaction to all pilot inputs will go a long way to preparing the pilot for flight. Here is an area where both avionics manufacturers and training providers still struggle to catch up with a changing market and provide an accurate but inexpensive way to actually practice with the equipment outside of an aircraft. Some products fail to replicate all the functions of the units they depict, or represent them incorrectly. While certain older-generation GPS units came with ground power supplies and simulation software so pilots could practice by removing the unit from the aircraft and setting up at home or at the school, this is clearly not feasible with units accessed through large LCD displays. Short of having a dedicated ground trainer, the next best alternative is to plug the aircraft into a ground power unit. The disadvantage is that both the aircraft and power must be available.

3. Ideally, the next step is a cockpit simulator or flight-training device. This may or may not provide motion or depict the view outside the cockpit, but it duplicates all other aspects of the aircraft. Simulation has been proven very effective in larger aircraft. With the advent of relatively low cost visual systems and computers,

the new systems now typically cost much less than half as much as the aircraft they replicate and can prepare pilots more effectively than doing initial training in the aircraft themselves. This model has served airline, corporate, and upper-end charter operators very well, improving efficiency while greatly reducing risk.

4. Finally, it's time to go to the airplane. This doesn't preclude gaining familiarity with basic physical airplane handling on local flights before sim training is complete, but the full-fledged cross country VFR and IFR departures and arrivals should wait until the pilot has a solid grasp of the glass or MFD/GPS equipment. *Too much early training in the actual airplane is inefficient and increases the risks arising from pilot and instructor distractions. These include the possibilities of midair collisions, airspace violations, missed or misunderstood ATC clearances, and possible loss of control.* It may be entertaining for the CFI but is not optimal for a pilot attempting to learn the basics of the avionics. As soon as the pilot has mastered the most basic aircraft handling and demonstrated proficiency with the avionics on the ground, we recommend as much actual short, high-workload cross-country experience as possible.

In aircraft with a wide range of operating speeds, repeated low-speed practice in the traffic pattern does not prepare pilots for the critical transition phases of flight. Few pilots have difficulty leveling off at pattern altitude, throttling back to pattern speed, and performing the before-landing check. En route, at altitude, the workload and risk are also low. It is the airspeed/altitude transition that most often causes problems, particularly when combined with the need to modify flight plans, select waypoints, or load and activate approach procedures. Unless the pilot is very light on cross-country experience and dealing with weather, the training time is better spent in the high-workload areas such as the departure and arrival phases where problems invariably arise with altitude, speed, and configuration changes. Heavy use of the autopilot, as well as simulating autopilot and navigation systems failures during times of high pilot workload, and appropriate division of attention are all critical. A range of failure modes should be addressed, from discrete failures of individual avionics units such as nav receivers, GPS receivers, attitude heading reference systems, and air data computers to more systemic problems such as primary or stand-by alternator or bus failures.

Pilots making the transition from analog instruments would also do well to give particular attention to learning to read airspeed and altitude tapes and the associated trend indicators as quickly, comfortably, and reliably as their conventional counterparts. The change from reading moving indicators against fixed reference scales to the reverse may prove more difficult than anticipated, contributing to the excess number of accidents in glass-panel aircraft during takeoffs, landings, and go-arounds.

New pilots who have limited cross-country experience—arbitrarily defined as less than several hundred hours on cross-country trips of more than 200 miles—should fly with a mentor in actual weather. This seasoning process should not be rushed as the new pilot develops the level of respect and knowledge that cross-country planning and flying require, regardless of onboard hardware and software. In the latter stages the mentor may not necessarily need to be on board provided he or she is available to offer guidance on flight planning and the final decision on whether to go or not.

How long should all this take? As always, it will depend on the pilot's experience and the tools available, as well as whether the training is conducted full- or part-time. An inexperienced pilot studying full-time could expect to need five days or more, and very low-time pilots, particularly those simultaneously transitioning to faster airplanes, should insist on a reasonable mentoring period that could extend for several months. Pilots should be gradually introduced to the broad range of conditions that the aircraft will ultimately encounter.

An experienced and instrument-competent pilot with considerable high-performance time—and a good grasp of the avionics—might complete the transition in two or three days of full-time study. If they haven't mastered the GPS navigator, the time to gain real-world IFR proficiency at least doubles. Regardless of the pilot's prior experience, part-time training can be expected to increase the total amount of instruction required, though perhaps with the offsetting benefit of greater retention.

One size certainly does not fit all, as convenient as that might be for the training schools, CFIs, or manufacturers. Each pilot will bring different strengths and weaknesses that need to be addressed, and flight instructors should perform an assessment to specifically identify those weaknesses and tailor the training accordingly. *After training it is essential for all pilots to get out and practice what they've learned. Wait longer than one week to get back into the aircraft or into a simulator and much of what was learned will be lost, requiring additional instruction. Considerable practice is the only way that pilots will develop and retain a high skill level. This is more critical now than it has ever been with the new complexity and capabilities that these aircraft introduce. This can be done in conjunction with supervised operating experience (mentoring) to develop operational proficiency (for example, dense traffic areas).*

A final point—the complexity and lack of standardization between the new panels makes the traditional method of spending a few hours in ground school before hopping in the aircraft for a familiarization flight increasingly outmoded. Any training institution or CFI that attempts to do in-the-air training on advanced IFR GPS navigators, FMSs, or glass-cockpit aircraft without first providing a thorough introduction and practice on the ground via simulator, ground-powered aircraft, or computer-based instruction is not acting in the best interests of the client.

TRAINING A NEW BREED OF PILOTS?

Anecdote and market analysis suggest that a significant change may be taking place in the pilot population. Highly automated high-performance aircraft are being sold to financially successful professionals who are not necessarily aviation enthusiasts. These owners buy aircraft strictly for personal and business transportation and view them, like cars or computers, as business tools. Using those tools effectively requires minimizing the restrictions imposed by weather. Consequently, they need to earn the private pilot certificate with instrument rating quickly and efficiently.

The traditional training approach needs modification for these customers. They are apt to be focused on results and, perhaps, impatient with the process of getting there. They may also place unwarranted trust in technology to compensate for inexperience and still-developing skills. The persistence and decisiveness needed to run a successful business are traits that don't always serve new pilots well.

There is little evidence to document the purposes to which new owners put their aircraft. It makes sense, though, to acknowledge that pilots who buy airplanes capable of cruising at more than 150 knots may be interested in going somewhere. The pilot population has always included "fast burners" who stepped up to high-performance cross-country machines a year or two after learning to fly in basic aircraft. However, relatively few of those pilots traditionally received their initial training in those same cross-country airplanes.

Many pilots still follow the traditional sequence: Start in a basic trainer, upgrade to a slightly larger four-place model, and gain several years of cross-country and instrument experience before making the jump to a high-performance aircraft. This adds seasoning and judgment to formal training in circumstances that offer a little more margin for error.

The speed and capabilities of the newest TAAs make it increasingly attractive for those with the financial wherewithal and a need to travel to enter general aviation via the purchase of a high-performance aircraft. Features including near-complete automation, on-board weather depiction, anti-icing systems, and airframe parachutes make the flight environment less intimidating. Training for these owners needs to emphasize the importance of a thorough knowledge of aircraft systems, procedures, aerodynamics, and performance and an understanding of the value of gaining experience after the checkride by flying with a mentor—particularly for owners who aren't naturally fascinated by "that pilot stuff."

At the other extreme, the anticipated influx of new sport pilots had yet to materialize by the end of 2011. Earlier predictions were also wrong in anticipating that many sport pilots would learn to fly with only the most basic instrumentation. Instead, market forces have driven the light-sport market to adopt glass almost as universally as the makers of FAA-certified airplanes; but here there is an even greater diversity of aircraft models and avionics systems. More than five dozen special light-sport models have been offered for sale in the U.S. market, and because they are not certified for instrument flight, some offer panels from companies that are not significant players in the IFR-certified market. By FAA figures, at the end of 2010 fewer than 4,000 people held sport pilot certificates alone, so the challenge of retraining them to fly larger, faster airplanes with cosmetically similar but functionally different instrumentation has scarcely arisen.

AUTOPILOT USE

TAA avionics are designed to be integrated systems that include autopilots as essential components. Following the model of single-pilot jets, in which autopilots are required, manufacturers assume they will be used routinely in day-to-day operations. Although TAAs are simpler and slower than jets, the workload can be almost as great. Pilots operating TAAs are expected to function more as programmers and managers, delegating much of the physical aircraft handling to the hardware. Factory-approved training stresses treating the autopilot as second-in-command and using it appropriately.

While this is not the traditional approach to training light GA pilots, it has become standard in airline and corporate flying. The FARs also require single-pilot IFR flights under Part 135 to have a fully functional three-axis autopilot.

Pilots will need to practice departures, en route operations, arrivals, and approaches—including mid-course changes in routing, altitude requirements, and approaches—until they are comfortable and completely proficient. It is also essential to do enough hand-flying to be certain that the pilot can safely manage an unexpected autopilot disconnect, or failure of the unit itself or any of the inputs or control systems on which it relies.

Correctly used, autopilots can greatly reduce workload while flying with a degree of precision few human pilots can match—but correct programming is essential. Mismanage the machine and at best, the workload increases well beyond normal. At worst, errors configuring autopilots have been fatal. The accident record includes examples of crashes caused by setting autopilots to “altitude hold” rather than to maintain a constant rate of climb, or failing to engage GPS steering. Pilots must learn all the modes and their limitations as well as the corresponding panel annunciations. It is crucial that the pilot constantly confirm that the aircraft is doing what it should be and know how to recognize and react when the autopilot is, inevitably, misprogrammed. Learning from those mistakes should reduce the frequency with which they crop up in critical situations.

Some potential problem areas include fighting the autopilot by holding onto the control yoke or side stick, reducing the system’s accuracy and effectiveness. At the other extreme comes runaway trim. The autopilot will methodically trim against the pilot and will either win the fight or disconnect with the aircraft badly out of trim and very difficult to control. Pilots must be able to diagnose an autopilot problem quickly, know how to disable both electric trim and autopilot without delay—and still be able to fly the airplane afterwards.

Some autopilots have a vertical speed mode selection. In ASI’s view, this capability is a potential trap, especially in piston aircraft. In a few documented cases, vertical speed mode was selected—for example, at 700 fpm—and as the aircraft climbed, the engine performance declined with altitude. As the airspeed decreased, the autopilot attempted to maintain the selected rate and caused the aircraft to stall. Some of the newest autopilots now offer the more attractive option of a vertical speed function, which instead allows for constant-airspeed climbs (sometimes referred to as “flight level change” or FLC mode). Instruction in the proper use of this feature does not allow the pilot to stop paying attention to the climb profile of the aircraft, but it can help avoid the stall scenario described above. As with vertical speed mode, however, the pilot must consider the performance of the airplane in determining how and when to use this option.

Autopilot malfunctions are even rarer than the physical incapacitation of human pilots, but they must be recognized and handled appropriately. Malfunctions would ideally be practiced in a simulator where pilots could actually experience the sensations and learn the proper responses. In actual IMC this should include advising ATC that the flight has an abnormal situation. The concept of an abnormal situation may be new to GA pilots, but it’s simple to understand. It falls between normal operations and a full-blown emergency. The situation may not yet require drastic action, but if not handled properly, a real emergency could be imminent. When in an abnormal situation, ask for help. This might be nothing more than insisting upon radar vectors to the final approach course and no changes in routing. It may also be prudent to divert to an area of better weather, lower traffic density, or an easier instrument approach. It is not the time to show just how good you might be. Studies have shown that pilots persistently believe their skills to be higher than they actually are.

The FAA has recognized the realities of autopilot use in TAA and modified the Instrument Practical Test Standards to require a demonstration of autopilot skills (in aircraft so equipped) during the course of the Instrument Airplane flight test.

ANALYZING PILOT PERFORMANCE

This ASI report found relatively few differences between accidents in TAAs and those in comparable aircraft with traditional instruments. In particular, the majority of accidents still occurred in day VMC when the presumed advantages in situational awareness offered by glass are least valuable. This suggests that regardless of equipment, much of the accident risk still resides in the decision-making and airmanship practiced in the cockpit, where it's traditionally been almost impossible to document.

That opacity has begun to change. Since their introduction, each new generation of TAA avionics has gained the capacity to log increasing amounts of flight data. Impact or fire damage sometimes destroys the devices that record them, but in many cases these observations have been recovered from severely damaged units. Variables tracked by the newest systems include airspeed and GPS-derived ground track, altitude, ground speed, and vertical speed; engine rpm, manifold pressure, fuel flow, and cylinder head and exhaust temperatures; and attitude information including angles of pitch, bank, yaw, and attack. These data have proven invaluable to accident investigators attempting to reconstruct fatal accidents with no witnesses as well as to corroborate or disprove pilot and witness statements.

Beyond its value in accident investigation, data logging offers applications to flight training. While it's unlikely that most Part 91 operators will follow the lead of the airlines, which for years have conducted routine pre-emptive analysis of flight performance data to identify anomalies before they lead to accidents, some of the largest training providers have begun to follow suit. Data downloads also enable operators to verify that their instructors follow the prescribed syllabus and observe school procedures and restrictions. Data from training flights can be extracted and compared to the lesson's ideal flight profile, much as ground-based instrument procedure trainers can display or print a comparison of the path actually "flown" to that charted on the approach plate.

Research in other fields also substantiates that the mere knowledge that one's behavior can be observed or reconstructed helps discourage impulsivity and any tendencies toward mischief.

THE AUTOMOTIVE EXPERIENCE

There is no doubt that human behavior changes when participants know they are being watched. Drivers slow down when they believe police are using radar, laser, or camera devices to monitor their speed. Automotive fleet studies have shown that the installation of event data recorders (EDRs) can reduce collisions by 20 to 30 percent. Since 1990, General Motors has equipped millions of vehicles with this monitoring capability. Events commonly recorded by automotive "black boxes" include vehicle speed, brake and accelerator pedal application forces, position of the transmission selection lever, seatbelt usage, driver seat position, and airbag deployment data—very similar to some of the control-input channels of the flight data recorders (FDRs) used in transport-category aircraft. The data collected belongs to owners except when requested by police or court order. Auto manufacturers also will use it as a company defense in a product liability lawsuit.

GM was an early advocate for EDRs, maintaining that potential improvements in auto safety outweighed any increase in litigation risk. Other manufacturers appear to have been persuaded; by 2010, EDRs had become almost universal in new automobiles. Analysis of EDR records found that in most cases, accidents were caused by driver mishandling rather than the vehicles—exactly the same situation as with aircraft. Here are some examples:

- Data from a black box caused jurors to question the prosecution's argument that the driver was speeding recklessly before a fatal head-on crash with another

vehicle. The driver was found not guilty after his truck's black box showed 60 mph at impact—not above 90 mph, as a witness had claimed.

- A police officer won a major settlement for severe injuries he suffered when a hearse struck his squad car. The hearse driver claimed a medical condition caused him to black out before he hit the police car. But the hearse's black box showed the driver accelerated to 63 mph—about 20 miles more than the posted limit— seconds before he approached the intersection, then slammed his brakes one second before impact. The black-box information was an unbiased witness to the crash.

- After a high-profile crash that killed a former pro football player, the family filed a $30 million civil suit that claimed the vehicle's air bag deployed after the car hit a pothole and that caused him to hit a tree. Data from the black box showed the air bag deployed on impact as designed, and the survivors lost the case.

- The National Highway Traffic Safety Administration (NHTSA) analyzed EDR data from 58 cars in its 2010 investigation of episodes of unintended acceleration in various Toyota models and found no evidence of malfunctions in electronic throttle controls.

TRAINING, LIABILITY, AND FLIGHT DATA RECORDERS

Some large U.S. flight training institutions using TAAs have installed small digital cameras and flight data recorders to enable fast, comprehensive reviews of what actually occurred in the cockpit or simulator. The electronics revolution of the last decade—which has helped make TAA possible—offers small and relatively inexpensive digital devices ideally suited for this purpose. The fact that these are usually installed at the time of manufacture versus an expensive retrofit have made them an inexpensive benefit in training. There's nothing like seeing video or a flight path of a training scenario to guide instructors and students. Olympic athletes, skiers, golfers, and swimmers all use monitoring to improve performance.

Consumer legal action claiming defective equipment has caused sharp increases in the airframe liability insurance premiums paid by some aircraft manufacturers. Improving their ability to record and download data from the PFDs and MFDs has been among their responses. In addition to reducing their liability to speculative lawsuits, detailed performance data offers the opportunity to improve the aircraft. Full-scale FDRs and cockpit voice recorders (CVRs) are attractive to the builders and operators of light jets for similar reasons.

When accidents lead to lawsuits against manufacturers seeking millions of dollars in compensation, it benefits the entire aviation industry to see that facts are presented accurately, completely, and unemotionally. From the manufacturers' standpoint, claims for maintenance and warranty service can often be more fairly adjudicated with data from the devices. Historically, about 90 percent of the accidents investigated by the NTSB show no design or manufacturing defect.

Data logging can also support the legitimate claims of pilots. In those cases where an aircraft or piece of equipment is proven to be defective or improperly maintained, the manufacturer or maintenance provider has a strong incentive to settle the claim fairly, then quickly resolve the technical or procedural problem for the rest of the fleet. The opportunity for pilots, instructors, and manufacturers to learn from data recorded in accident aircraft may do more to improve safety at less cost than recourse to the legal system.

APPENDIX B: TAA HARDWARE AND SOFTWARE

Modern integrated avionics systems use large liquid crystal display (LCD) screens to provide data to the pilot. The primary flight display (PFD), as its name implies, provides the most important information needed to operate the aircraft. In streamlined format, the PFD shows:

- Attitude
- Airspeed
- Altitude
- Primary navigation data
- Supporting data, including synthetic vision and highway-in-the-sky (HITS) presentations on units with those capabilities

Multifunction displays (MFD) come in a variety of forms and accept input from aircraft and datalink sources. MFD data can include:

- Checklists
- Engine and systems status

- Moving maps with airports, navigation aids, waypoints, and airspace depictions
- Approach, taxi, and navigations charts
- Terrain and obstructions
- Traffic avoidance
- Datalinked weather information including NEXRAD precipitation, TAFs, and METARs

INTEGRATED AVIONICS

Integration has been a consistent goal of glass-panel design, and simply means that most information about the airplane and its environment can be controlled, displayed, and used through a single system. The two main displays can be configured to meet the pilot's needs and preferences. Useful information is brought up as it is needed while less important material remains hidden, but available.

Common hardware components in integrated systems allow the displays to be switched back and forth in the event of equipment failures. Such reversionary capabilities greatly reduce the risk posed by critical instrument failures. It also puts an increased burden on manufacturers to ensure that single-point or cascading failures do not catastrophically degrade safety. Utility can be adversely impacted when an essential component in an integrated system results in an unable-to-fly condition. Non-critical instrument or system failures in conventionally equipped aircraft are minor inconveniences but not flight-cancelling.

PRIMARY FLIGHT DISPLAY

In general, the PFD replaces all six of the traditional flight instruments, plus some. The "directional gyro" mimics the more sophisticated HSI (horizontal situation indicator) combined with a radio magnetic indicator (RMI). Newer systems also provide a capability rarely available to light GA pilots—the flight director. The flight director provides computed attitude commands that allow the pilot to hand fly the aircraft with precision comparable to the autopilot's provided the pilot reacts to the flight director's cues in a timely fashion. Some PFDs offer the option of showing a moving-map inset in a small section of the screen with features that can include GPS course, navaids, terrain depiction, and traffic alerts. There are also models that can superimpose traffic and terrain data on the primary attitude display.

ELECTRONIC CHECKLISTS

While paper checklists are also provided, aircraft manufacturers have recognized the advantages of making stored checklists available for display on the MFD. Pilots proficient with the search hierarchy can locate the necessary checklist more quickly in emergencies and other high-workload situations. Unlike the printed versions, there is no risk of their being left behind, and updates or revisions can readily be made via software.

WEATHER DISPLAYS

Until TAA, anything approaching real-time display of convective weather in the cockpit was limited to aircraft with onboard radar. Radar is the gold standard for tactical avoidance of thunderstorms but is expensive, somewhat fragile, and heavy; interpreting on-board radar images is also an art requiring considerable training and practice. Smaller GA aircraft were fortunate to have any on-board weather information at all; those that did usually made do with lightning detection devices such as a Stormscope or Strikefinder whose displays required skilled interpretation. Of course, a full glass panel is not needed to get datalinked weather, which is available on an ever-widening array of portable devices. In addition to being an order of magnitude less expensive than panel-mount displays, these are easily moved between different aircraft.

However, in-flight access to weather data and the ability to overlay it on large, bright displays was one of the goals motivating the development of TAA. Datalink weather providers now serve most of this market because their products significantly improve the utility of light GA. Superimposing NEXRAD radar images on the moving map improves the pilot's understanding of the location and intensity of any precipitation. Earlier and more detailed awareness gives increased flexibility to both the pilot and air traffic control in requesting and coordinating routing changes or diversions. This simplifies in-flight decision making while making it easier to maintain a safe distance from hazardous conditions. Depending on aircraft and pilot capability, the decision can be made to divert, delay, continue, or land ASAP. Likewise, the availability of the latest TAFs, METARs, PIREPs, winds aloft, and other products allow both VFR and IFR pilots to monitor the weather ahead and around them. There will be very few excuses for being surprised—though of course pilots are always capable of getting themselves into trouble, whether by failing to understand the limitations of the product or not knowing how to interpret the information provided.

TERRAIN AWARENESS

Integral to most new GPS navigator units these days is terrain and obstruction awareness, usually displayed on an MFD in a format using different colors to indicate different elevations. Symbols show obstructions such as towers and buildings and their relative height. In some cases, the terrain shown near the aircraft will change color, based on the GPS-derived separation between the aircraft and the ground.

TAWS (TERRAIN AWARENESS WARNING SYSTEM)

While GPS mapping modules with integrated vertical dimensions (elevation data) displayed via different colors are becoming an expected part of new TAA displays, full terrain awareness warning systems (TAWS) are most typically offered as an additional option at additional cost. Their value in helping prevent perfectly good airplanes from smacking into the ground while under positive control has made them popular nevertheless. TAWS became mandatory on March 29, 2005, for all turboprop or jet aircraft with six or more passenger seats, including those operated under FAR Part 91. TAWS has become a common component of the piston TAA cockpit as well.

TAWS evolved from radar altimeters, devices that emitted a warning when terrain directly below the aircraft became closer than a preset value. The original device, called a ground proximity warning system, or GPWS, used ground return radar to measure the altitude from the airplane to points directly below. The devices worked fairly well, and the rate of controlled flight into terrain (CFIT) accidents in the late 1960s and early 1970s was significantly reduced. But the radar altimeter GPWS units had a major shortcoming: altitude measurements and thus the warnings of potential CFIT were unable to prevent fast-moving aircraft from striking rapidly rising terrain if the aircraft had a high rate of descent. The integration of GPS navigation and terrain database technology allowed the design of equipment that computes aircraft position, groundspeed, altitude, and flight path to calculate a dangerous closure rate or collision threat with terrain or obstacles, and provides predictive warnings. This is the technology behind TAWS.

The five functions provided by TAWS units most commonly installed in high-end general aviation TAA include the appropriate audio alerts for:

- **Reduced required terrain clearance or imminent terrain impact.** This is the forward-looking terrain-alert function. This warning is generated when an aircraft is above the altitude of upcoming terrain along the projected flight path, but the projected terrain clearance is less than the required terrain clearance. The warnings depend on the phase of flight, and whether the aircraft is in level or descending flight. There are sixty-second and thirty-second warnings. Sixty-second aural warning: "Caution, terrain; caution, terrain" (or "Terrain ahead; terrain ahead") and "Caution, obstacle; caution, obstacle." Thirty-second aural warning: "Whoop, whoop. Terrain, terrain; pull up, pull up!" or "Whoop, whoop. Terrain ahead, pull up; terrain ahead, pull up." The "whoop, whoop" sweep tones are optional.

- **Premature descent alert.** This alerts the pilot if there's a descent well below the normal approach glidepath on the final approach segment of an instrument approach procedure. Aural warning: "Too low, terrain!"

- **Excessive descent rate.** This is a carryover from GPWS, and alerts you if the rate of descent is dangerously high compared to the aircraft's height above terrain—and, for example, if flying level over rising terrain. Caution alert: "Sink rate!" Warning alert: "Whoop, whoop! Pull up!"

- **Negative climb rate or altitude loss after takeoff.** Another GPWS function, this is to assure a positive climb rate after takeoff or a missed approach. Caution alert: "Don't sink!" or "Too low, terrain!"

- **The 500-foot "wake-up call."** This occurs whenever terrain rises to within 500 feet of the aircraft, or when the aircraft descends within 500 feet of the nearest runway threshold elevation during an approach to landing. It's intended as an aid to situational awareness, and doesn't constitute a caution or warning. Call-out: "Five hundred."

AIRSPACE DISPLAYS

Most current generation GPS navigators include airspace information in their databases. The pilot can superimpose graphic depictions of complex airspace such as Class B on the MFD maps and access relevant altitude and communications information. Using datalink sources, temporary flight restrictions (TFRs) can also be displayed, though these are not generally activated in real time; rather, the receiver will download location, range, and altitude data with a text description of its effective times. The pilot always has the option of simply avoiding the airspace; otherwise, additional paging is required to determine whether a TFR is currently active.

TRAFFIC AVOIDANCE

Today, many TAA have the ability to display symbols representing other transponder-equipped aircraft on their MFD. This helps alert the pilot to traffic that might otherwise have gone unnoticed, particularly at times of high workload or heavy traffic density. While these system are useful, they have important limitations: Not only are they unable to detect aircraft without transponders, but certain combinations of aircraft position, attitude, and antenna placement may temporarily block transponder signals, making those aircraft undetectable. Most traffic-alerting systems are unable to determine rate or angle of convergence. False alarms may result, and these can become annoyingly frequent in the traffic pattern—where more than half of all mid-air collisions occur. These systems sometimes also detect and report their own aircraft as "ghost" returns.

ENGINE/SYSTEMS MONITORING

Another area where the MFD excels is in helping pilots manage their engines. TAA are typically equipped with detailed engine instrumentation. Multiple measures of performance and condition are monitored continuously and logged at frequent intervals. The MFD can be configured to display basic operational data such as manifold pressure, engine RPM, and oil temperature and pressure on a sidebar or set to show a full page of engine parameters at the individual cylinder, alternator, and bus level. In either case, variables that exceed defined thresholds trigger specific alerts on the MFD, advising the pilot that something is out of tolerance before it becomes critical.

Recorded operational data can be downloaded during maintenance to allow technicians to review an engine's history. This holds great promise to increase reliability. Routine engine parameters such as cylinder head temperatures, EGTs, fuel flows, and duty cycles are now monitored as an accepted part of TAA instrumentation. This is often more data than most pilots know how to interpret, making this another fruitful area for model-specific training.

TECHNOLOGY ABUSED?

All tools have the potential to be misused. The risk is greatest with new tools, as users may be less aware of those tools' limitations and the pitfalls of ignoring them. Much glass-panel technology falls into this category, though increasing operational experience has reduced its novelty. However, wider familiarity with this equipment has not always produced greater awareness of its design envelope or the hazards of using the technology in ways its builders did not intend. Misunderstanding or deliberate misuse of some TAA capabilities can put pilots and their passengers in real danger.

SOME CONCERNS

Weather datalink—There is a potential danger if TAA pilots mistakenly believe their datalinked radar images constitute true real-time weather, as would be the case with onboard radar. The time lag between capture of the radar image and the datalink display may be anywhere from five minutes to 20 minutes. In a very active thunderstorm situation, a pilot attempting to navigate around cells using old data could be in serious jeopardy, a risk that has been realized on several occasions. Similar dangers exist with radar-equipped aircraft if a pilot gets too close to a cell or tries to pick a way through a narrow gap. This has happened infrequently in both airline and corporate flight. Occasional misuse of these technologies is scarcely an argument that flight would be safer without them, but rather an object lesson to other operators.

Terrain—As with weather graphics, terrain databases can potentially be misused to attempt scud-running or VFR flight in IMC. A Cirrus POH Supplement warning states: "Do not use the Terrain Awareness Display for navigation of the aircraft. The TAWS is intended to serve as a situational awareness tool only and may not provide the accuracy fidelity on which to solely base terrain or obstacle avoidance maneuvering decisions."

VFR into instrument conditions is a leading cause of fatal accidents in all aircraft, TAA or legacy. Another is controlled flight into terrain in darkness or poor visibility. A classic accident occurred in 2005 when a Cirrus SR22 piloted by a 1,100-hour flight instructor and the plane's owner struck a mountain while scud-running up the Columbia River gorge at night. Friends noted that the pilot had done this sort of thing in the Cirrus a number of times before. Even with the latest avionics, including terrain awareness systems on a large MFD, this activity is as deadly as it has always been.

Traffic avoidance—As mentioned earlier, on-board avoidance systems can help pilots visually acquire conflicting traffic more quickly. Airline and corporate collision avoidance systems have worked very well to date. To be sure, there are two pilots and they tend to operate in highly controlled environments. In the more open areas and smaller nontowered airports there will be more transponder-less traffic. Nuisance alerts in traffic patterns may spur pilots to deactivate the alert system. In any case, positive identification of other aircraft still requires visual contact, so for the foreseeable future pilots will have to continue to scan outside.

One drawback observed with traffic alerting systems is a tendency for pilots to focus excessively on trying to locate one reported target, neglecting their scan of other sectors. This "tunnel vision" risks missing aircraft that pose a more immediate threat but have not been detected electronically.

Parachutes—A minor drawback to airframe parachutes is that pilots may come to rely on them when better decision making would have avoided a dangerous situation in the first place. Several fatal accidents have occurred when pilots may have rationalized that the chute would save them if problems got out of hand and then either failed to deploy when needed or attempted deployment at excessive airspeeds. One proposed solution is an "auto-deploy" system activated when the aircraft senses itself in grave danger. Aside from any pilot resistance to the concept, that level of machine intelligence is probably still a number of years away.

Another downside to the parachute is the possibility that it can drag the aircraft along the ground after touchdown if deployed over an area with surface high winds. This happened after a fatal accident near Maybell, Colorado, in 2006. Evidence at the scene suggested ground impact caused deployment of the parachute recovery system, resulting in fragmentation of the airplane over a 1.5-mile area as it was pulled along by the wind.

With more than two dozen accidents prevented or mitigated to date, however, evidence is mounting that the benefits of whole airplane parachutes outweigh their drawbacks.

Integrated Systems—Modern integrated avionics systems offer a high level of flexibility and allow the pilot to set up preferences that suit personal operating style. In a rental environment, this could lead to pilots not knowing just what data is going to be displayed without a comprehensive inspection of the many setup pages on the MFD. One solution offered by some newer systems is a memory-card slot in the panel which enables the pilot to store and reload individual setup preferences. A one-step option for resetting the panel to its default configuration would also be desirable.

Excess Capability—To appeal to the broadest possible market, manufacturers have designed their avionics suites to offer as many options and capabilities as practicable. While each of these will appeal to some users, most pilots will find that they routinely use only a small subset. The complex operating logic needed to place these features within a hierarchical programming structure is a significant obstacle to both learning and using all the resources the system offers. However, certification costs and relatively low production mean that the alternative of offering several simpler versions tailored to narrower market segments is unlikely to become economically feasible.

AVIONICS MAINTENANCE AND OWNERSHIP

The owners and operators of TAA are finding that modern avionics change several maintenance aspects of these aircraft. First, not every avionics shop is trained or equipped to work on such systems, and even if they are they often troubleshoot down to the line replaceable unit (LRU) level only, exchanging the malfunctioning unit for a functioning one. LRUs often can only be opened and repaired by the manufacturer. It should be noted that FAR 91.187 requires the pilot on an IFR flight plan to report loss of any navigation, approach, or communication equipment as soon as practical to ATC. It's also a good idea to have the avionics technician fill out a Service Difficulty Report, or SDR, on any significant problem.

Software updates are another maintenance consideration. Pilots using GPS navigators are likely familiar with the need to update the navigation database on a regular basis. Like other computers, however, TAA's sophisticated computers and software are updated regularly to add new features and correct errors. Occasionally, these updates also require hardware updates. Almost all new technology goes through growing pains and it is no different with TAA. Several MFDs have had multiple software updates and reconfigurations to address slow update rates, mislabeling, or outright failures. As with all computer equipment, upgrades and updates are prone to potential failures and it is critical for manufacturers to advise pilots of problems and address them immediately.

EMERGING TECHNOLOGIES

Since manufacturers first began offering certified airplanes with glass panels almost a decade ago, their designs and features have continued to evolve. Both competitive pressures and the lessons of experience have led manufacturers to continue adding new features and refining existing ones, a process that was not interrupted by this report. As of this writing, several new technologies have entered the market that hold promise to offer meaningful safety improvements. Others are still under development but expected to be introduced in the near future, while some remain more speculative.

ENHANCED VISUAL DISPLAYS

Two technologies have just entered the market that further increase the situational awareness offered by glass panels. GPS-based synthetic vision combines course and position information with a densely detailed database to depict terrain, obstacles, and even runway thresholds and numbers on the primary flight display. A good implementation makes flying an instrument approach almost as straightforward as landing in VMC in daylight. Of course, the presentation is only as good as the database, and obstructions such as cell phone towers may have gone up since the last revision. Obstacles less than 200 feet high may not have been reported at all. These concerns should inhibit any temptation to use synthetic vision to attempt VFR flight in IMC, a purpose for which it was not designed. It can be very valuable, however, on visual approaches at night, particularly to so-called "black hole" airports where few lights in the vicinity mark the terrain.

Highway-in-the-sky (HITS) presentation of the aircraft's planned course dates back to at least 2001, when it became an element of NASA's Small Aircraft Transportation System project. It has recently been introduced into commercial products. It represents the course defined by the airplane's current flight plan plus reasonable tolerances for altitude and heading deviations as a series of rectangular boxes on the PFD. Flying through them assures that the aircraft is at the correct altitude and following the intended ground track.

IMPROVED TERRAIN ALERTING

Competitive pressures may lead manufacturers to provide the full Terrain Awareness Warning Systems now offered as options in their standard packages. If not, terrain presentation is likely to continue to become more detailed, with more gradations of color to represent the airplane's projected vertical separation based on its current rate of climb or descent. It is even possible that terrain warnings can be interfaced with the airplane's autopilot or its servos to enable the airplane to guide itself away from obstructions. The course, speed, altitude, and rate of descent reported by the GPS and the level of the detail in its database would enable the system to distinguish a normal approach to a runway from an unintended altitude deviation or premature descent below MDA on an instrument approach.

INTERVENTIONAL AUTOPILOTS

Active terrain avoidance would be only a small step beyond the current capabilities of the latest generation of autopilots, which can recover the aircraft from an upset or help prevent one in the first place. In 2010, Avidyne began offering models that included a "straight-and-level" button. When engaged, it uses computed attitude information and the aileron and elevator servos to return the airplane to level flight from several types of unusual attitudes (though not spins, since the system does not include a rudder servo) without overstressing the airframe.

Garmin has incorporated a similar feature in its Electronic Stability Protection (ESP) system, but gone a step further: When the autopilot is disengaged, pitch, roll, and airspeed are monitored automatically, and if any of these exceed predefined thresholds, its servos deflect the flight controls in the directions that would return the aircraft to its normal flight envelope. The pressure of these deflections increases as the degree of exceedance becomes greater.

These achievements lend credibility to reports that the industry is actively attempting to develop autoland capability, requiring the pilot only to retard the throttle at the appropriate times and lower the gear (if retractable). The precision with which WAAS GPS measures aircraft position, the level of detail captured in the associated databases, and the computing power available in the control circuitry make this appear increasingly feasible.

ANGLE-OF-ATTACK DISPLAYS

The high number of fatal stall/spin accidents in glass-panel Cirrus and Columbia airplanes suggest that direct display of angle of attack, perhaps augmented by a series of audible and visual warnings as it nears its critical value, would be an important safety improvement. Angle of attack can be measured directly by external devices and input to the panel or, in theory, estimated in real time from the combination of airspeed, attitude, and vertical speed data already being measured. An angle-of-attack input to the autopilot could help prevent the autopilot-induced stalls that sometimes arise from the use of the constant vertical speed mode and, in an interventional system, help guard the airplane from inadvertent stalls during hand-flying.

IMPROVED TRAFFIC ALERTING VIA ADS-B

A key element of the FAA's planned "Next Generation Air Transportation System" (NextGen) is the requirement to equip most general aviation aircraft with equipment that will automatically transmit their location (as determined by GPS) via a system termed "automatic dependent surveillance—broadcast" (ADS-B). By January 1, 2020, the broadcast equipment ("ADS-B out") will be required in all airspace where transponders are required today.

While ADS-B out will be required, operators will also have the option to equip their aircraft with receivers and signal processors that can interpret the transmissions of other aircraft as well as ground-based broadcasts of traffic and weather data ("ADS-B in"). Unlike current commercial datalink services, these will be provided free of charge. The detailed position, course, and groundspeed information provided by ADS-B out transmissions will also make it possible to develop traffic-alerting algorithms that are much more sensitive than today's transponder-based approaches, eliminating spurious alerts caused by same-direction traffic in the pattern or aircraft on the ground.

While ADS-B out will be required for all aircraft in the affected airspace and ADS-B in will be available to conventionally instrumented airplanes as well as glass, the large LCD screens of TAA offer a natural platform to display the traffic, weather, and other information it provides. The FAA maintains that ADS-B will eventually provide other advantages as well, including lower approach minimums, wider coverage permitting more frequent IFR arrivals and departures, and the ability to reduce the separation required between aircraft at equivalent levels of safety.

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