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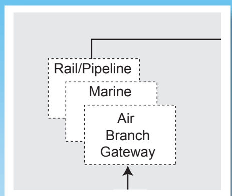
JOURNAL OF ACCIDENT INVESTIGATION

A biannual publication to promote transportation safety through science



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About The Cover

Featured on the cover is a Boeing 747. NTSB accident investigations in all modes, including aviation, use a variety of investigative techniques that are discussed in this issue, including wreckage examination, vehicle recorder analysis, and vehicle performance simulations and animations.

Editorial Policy

Research/Technical Articles

The NTSB Journal will publish research and technical articles on accident investigations that may be of interest to professionals in safety, accident investigation, engineering, and the behavioral sciences. Papers may be empirical or concerned with the development and use of accident investigation methods, techniques, or technologies. All papers should have a strong scientific or technical basis and be related to accident investigation or transportation safety analysis.

Organization of material for empirical investigations should follow standard reporting format: problem, method, results, discussion, and summary. Papers discussing accident investigation methods, techniques, or technologies should include a clear and concise description of the method, technique, or technology that uses accident data and information to illustrate the approach and a discussion of the added benefit the approach brings to accident investigation or transportation safety analysis.

Public Forums, Symposiums, and Hearings

The NTSB Journal will publish papers describing public forums, symposiums, and hearings conducted by NTSB. The papers will describe the purpose of the event, the participants, and the topics covered by the event. The paper should include clear and concise statements of the areas of open discussion, topics identified for further analysis, conclusions reached, and any recommendations that were made as a result of the event.

Special Features

Articles that treat policy issues related to transportation safety will be accepted for consideration as special features of the Journal. These papers may be solicited from both internal and external sources. These articles should represent a balanced view of the various aspects of an important safety issue.

Business of the Academy

The Journal will include short reports of major developments, news, events, research efforts, and announcements of upcoming courses, forums, symposiums, and topical public hearings.

Editorial Board

The Editorial Board comprises the NTSB Managing Director, the Director of the Office of Research and Engineering, and the Chief of the Safety Studies and Statistical Analysis Division. The Editorial Board may solicit critiques or counterpoints on matters open to debate. Unsolicited articles may be accepted subject to space availability. Special features may be edited for suitability and fit.

Guidelines for Submissions to the Journal

- Submissions to the NTSB Journal must be submitted as Word documents. Any documents submitted as PDF files will be returned to the author for reformatting.
- Graphics should be submitted in native format, preferably as high-resolution 300 dpi files in Jpeg or Tiff format.
- NTSB staff should ensure that text is edited to comply with the NTSB Style Guide prior to submission.
- Submissions must include a brief biography of all authors, including the following information: full professional name (initials are acceptable), professional titles (e.g., Ph.D., M.D.), education, and a brief description of professional experience specific to the subject of the article. Including an e-mail address or point of contact information is recommended but optional.

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Mission Statement

The Journal is an interdisciplinary publication that provides for the public exchange of ideas and information developed through accident investigations at the National Transportation Safety Board in all modes of transportation. The intended audience is professionals in safety, accident investigations, engineering, and the behavioral sciences.

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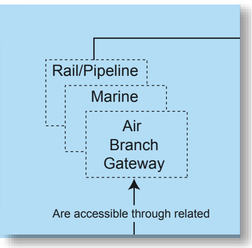

The NTSB Journal of Accident Investigation *Special Features* presents articles that treat policy issues related to transportation safety. These papers may be solicited from within the government or from public sources. These articles are intended to represent a balanced view of the various aspects of an important safety issue. They do not represent an official view of the Safety Board.

Special Feature

Transportation Safety Board of Canada Investigation Information Management System

Charles H. Simpson, Transportation Safety Board of Canada

I am highly appreciative of the invitation to contribute to this second edition of the NTSB's Journal of Accident Investigation. The Journal clearly enjoys a global readership and, as such, it provides an incomparable venue in which to share perspectives, experiences, and lessons learned. Many subjects could, and will, benefit from discussion in the pages of the Journal. However, I will focus my comments on a subject that is critical to all organizations, but particularly investigative organizations, around the world. I refer specifically to the challenge of information management.

National safety investigation agencies are universally charged with investigating occurrences in federally regulated sectors of the transportation industry. Their primary objective is to identify risks and ensure that mistakes are not repeated or that unsafe conditions are not allowed to persist. To achieve this, the Transportation Safety Board of Canada (TSB) has the sole authority under Canadian law to conduct safety investigations into transportation occurrences in the rail, marine, air, and pipeline industries, to collect and analyze the facts, and to convey the resultant information to agents of change via such mechanisms as investigation reports and recommendations. As in most countries, the TSB is not empowered to direct changes; change decisions and implementation are the purview of regulators and industry itself.

The primary products of the TSB are, therefore, information and knowledge. It is critical that the information it imparts be viewed as credible, comprehensive, and compelling in all respects in order that those who have the power to implement change will be motivated to take immediate remedial action. By extension, excellence in how information is gathered, employed, stored, and distributed is absolutely fundamental to the TSB in the achievement of its mandate.

Over the past several years, our management team has harbored a growing concern that the information management business practices in use at the TSB were not supporting its overall objective well. A comprehensive risk assessment confirmed that significant gaps did, indeed, exist. For example, traditional, paper-based techniques were no longer able to contend with the proliferation of electronic information. The discipline of centrally stored and controlled records had been eroded, making it increasingly difficult to access the right information in a timely manner. Information technology tools were amassing increasing amounts of information but were not designed to manage it in an enterprise-wide fashion. In short, technology was contributing to the problem, not helping to solve it. It was apparent that if the gaps were not dealt with in a substantive way, the strength of the TSB's product, quality information, would be weakened, its credibility would be negatively impacted, and its value to Canadians would diminish.

The challenge, of course, was how to address the problem. Like most safety investigation agencies, the TSB is relatively small with modest resources dedicated almost entirely to supporting day-to-day operations. Any commitment to address the information management shortcomings in a sustainable manner would require a substantial deflection of human and financial resources over a protracted period of time.

Convinced of the long-term imperative, the TSB embarked upon a project to develop an integrated IM/IT platform to support the organization and, in particular, our investigation teams. Known as the TSB Investigation Information Management System (TIIMS), the goal is to implement an integrated set of documents, content, records, cases, workflow, forms, and project management practices and tools. Another notable feature of the system is the development of a Reference Centre that will consolidate those often hard-to-find policies, guidelines, operations manuals, checklists, and other reference tools into a single area for easier access. Accomplishing this goal will require a major effort of employees who are already busy with their normal functions. "Buy in," particularly amongst managers, and the recognition that people and substantial financial resources would have to be diverted full-time to this undertaking, were the two first critical hurdles to overcome. Indeed, two and a half years into the project, they are never far from the surface.

Two other fundamental decisions concerned the software tools and the methodology to be employed in the project. The first was relatively straightforward; a small agency would never be able to afford development of new software from the ground up. A team-oriented plug and play environment was required and for that, Microsoft's Sharepoint Portal and Services products were chosen as the foundation pieces.

The change management tool employed is based upon the use of business reference models. These models provide a common description of, and context for, an organization's business practices. They are used to facilitate user consultation, to manage project scope, and to assist in the transition to the new practices and tools. The effort required to develop and obtain agreement with these models is considerable but, without that foundation, the development of an integrated information system would be impossible. In particular, their use leads to a standardization of practices and terminology that can only strengthen the organization in a variety of ways. However, in the early stages of the project, these eventual advantages were not apparent to everyone and sustaining momentum required ongoing effort.

The essential problem with our current system is that automated investigation tools, data systems, document management, and the various business practices by which information products are produced and stored are not connected. This results in multiple entry and information collation challenges that are not only time consuming but also create the risk that information will not be available for a specific requirement at the right time.

The new platform will replace the TSB's current Intranet and will comprise a hierarchy of gateways or portals and pre-defined investigation workspaces (figure 1). The gateways will be primarily information based while the investigation workspaces will organize and integrate the many tools needed by our investigation teams. Since it is recognized that the system will evolve with time, the approach has been to build the system in modules so elements can be easily added, removed, or modified and to establish the appropriate governance tools needed to manage these changes.

As part of the development and implementation process, a series of pilots has been undertaken, using real-life investigations, to validate the new tools. This approach maximizes input from those for whom the workspaces are being developed, thereby enhancing the potential for buy-in and successful implementation. The objective is to have the first version of the new system in operation by the end of March 2006. Other modules remain to be developed and incorporated in the following year(s). Nevertheless, we are confident that most of the critical gaps identified in our risk assessments will be resolved or significantly remediated by the first operating version; identified risks will have been substantially reduced.

There is one other key decision that has been required to optimize the probability of success for this project. The individual accountable for the developmental aspects of the system cannot be expected to also manage the transition to, and permanent operation of, that system. Therefore, the TSB has assigned those responsibilities to a full-time operations manager, once again from within current resources. It would be tempting to ignore this additional commitment simply because of its short-term impact on current activities. However, for an undertaking as fundamental and far-reaching as this, it would be unrealistic to assume that once development is "complete," transition and steady-state operations would automatically fall into place.

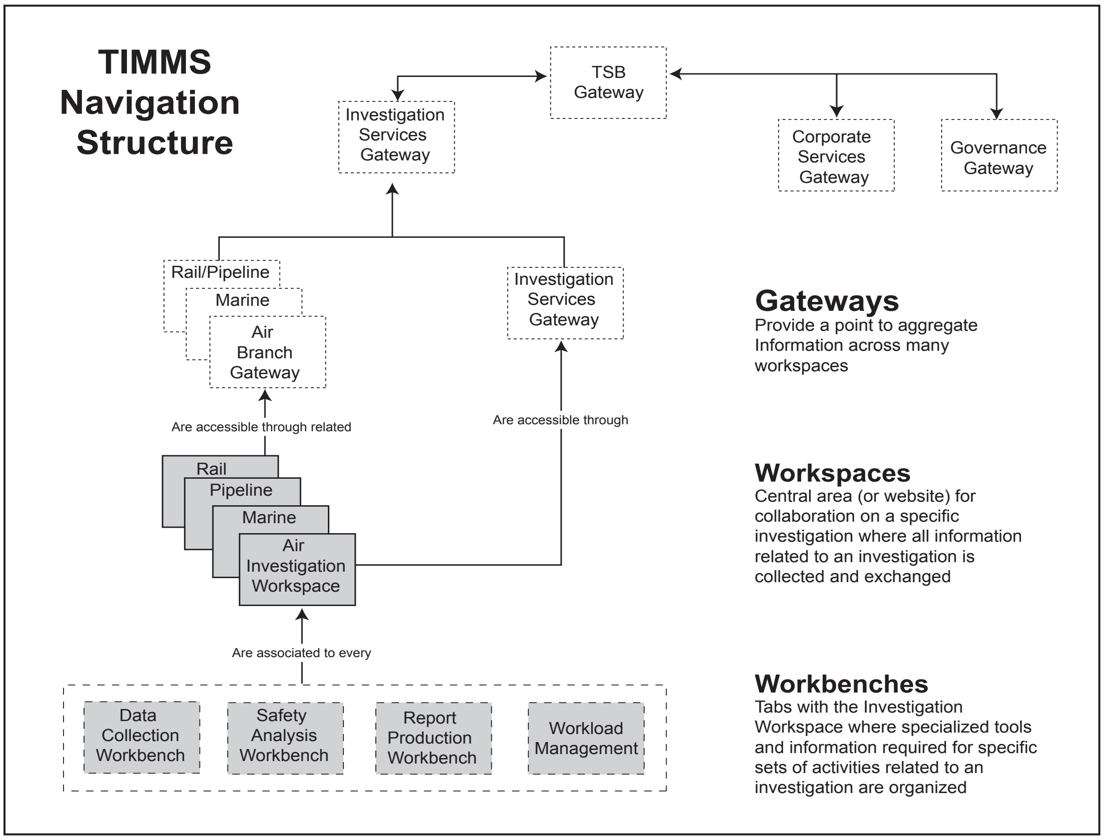

Figure 1.

Since undertaking the TIIMS project, it has become increasingly apparent to me that many organizations, and not just those with an investigation mandate, are wrestling with the same issues as the TSB faces. Most executives recognize the imperative to address these issues but they are all faced with the same challenges: time, money, and human resource constraints. The TSB experience to this point offers some valuable points to consider and some tangible product elements that could be applied with relative ease to other organizations. A recently signed memorandum of understanding with the Australian TSB is an example whereby the TSB's efforts will be applied to advantage by another agency with a similar mandate, objectives, and change imperatives. Furthermore, both agencies stand to benefit from an ongoing exchange of experiences with the system and developmental activities in the years to come.

The TSB has some way to go before it can declare victory with its TIIMS project. However, there is a high level of confidence that the organization-wide approach to managing information will be far superior to the piece meal approach fostered by the current series of independent information systems and paper-based protocols. We have already accumulated a number of important "lessons learned" that we would be happy to share with other organizations who have embarked upon or are considering a similar project.

Once again, I thank the NTSB for this opportunity to share the TSB's perspectives on this vitally important subject.

THE AUTHOR

CHARLES H. SIMPSON was appointed to the Transportation Safety Board of Canada in 1996 and was the Acting Chairman from 2004 to 2005. Before joining the TSB, he worked for many years for Air Canada, first as a pilot and flight instructor and later in various corporate positions, including Executive Vice-President, Operations. He also served on the Board of Directors of the Canadian Air Line Pilots Association, including a term as President. On January 12, 1988, Captain Simpson established the official speed record for Class C1 Jet Aircraft from Honolulu to Montreal with a Boeing 747 (8 hours, 26 minutes, 09 seconds), for which he was recognized by the National Aeronautic Association. On November 28, 2005, the Safety Board commemorated Captain Simpson's retirement from the TSB with a Special Recognition Award.

Investigative Techniques

Materials Examination of the Vertical Stabilizer from American Airlines Flight 587

Matthew R. Fox and Carl R. Schultheisz, National Transportation Safety Board
James R. Reeder and Brian J. Jensen, NASA Langley Research Center

ABSTRACT

The first in-flight failure of a primary structural component made from composite material on a commercial airplane led to the crash of American Airlines flight 587. As part of the National Transportation Safety Board investigation of the accident, the composite materials of the vertical stabilizer were tested, microstructure was analyzed, and fractured composite lugs that attached the vertical stabilizer to the aircraft tail were examined. This paper discusses the materials testing and analysis, the composite fractures, and resulting clues to the failure events.

INTRODUCTION

On November 12, 2001, shortly after American Airlines flight 587 took off from Kennedy International Airport, the composite vertical stabilizer and rudder separated from the fuselage, rendering the airplane uncontrollable. The Airbus A300-600 airplane crashed into a neighborhood in Belle Harbor, New York, killing all 260 persons aboard the airplane and 5 persons on the ground. This accident was unique in part because it was the first time a primary structural component fabricated from composite materials failed in flight on a commercial airplane.

As a result of its nearly 3-year-long investigation of the accident, the National Transportation Safety Board determined that the probable cause of the accident was "the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design that were created by the first officer's unnecessary and excessive rudder pedal inputs. Contributing to these rudder pedal inputs were characteristics of the Airbus A300-600 rudder system design and elements of the American Airlines Advanced Aircraft Maneuvering Program."[1]

1 National Transportation Safety Board, *In-Flight Separation of Vertical Stabilizer, American Airlines Flight 587, Airbus Industrie A300-605R, Belle Harbor, New York, November 12, 2001,* Aircraft Accident Report NTSB/AAR-04/04 (NTSB Public Docket, 2004).

Analysis of the flight data recorder revealed that the airplane had performed a series of yawing maneuvers in the seconds before separation of the vertical stabilizer, and that the separation of the vertical stabilizer occurred while the airplane was pointed to the left of its flight path. This orientation would have produced a bending moment on the vertical stabilizer, leading to tension on the right-side attachments and compression on the left.

Most of the separated pieces of the vertical stabilizer and rudder were recovered from the water of Jamaica Bay, some distance from the main crash site. The vertical stabilizer was largely intact, and had separated from the fuselage by fractures at the lower end where it had been connected to the fuselage. Although a detailed examination of the rudder was completed during the accident investigation, early indications from the performance analysis of the flight recorder data indicated that the rudder performed as designed through the accident sequence until the vertical stabilizer separated from the fuselage, and loads analysis indicated that the vertical stabilizer would fail before the rudder. Thus, investigators determined that the rudder failure was secondary to the failure of the vertical stabilizer. As part of the overall investigation into the accident, investigators examined and tested the composite materials of the vertical stabilizer and conducted a detailed examination of the fractures in the vertical stabilizer to determine the failure mechanism and direction of fracture propagation, where possible. The possibilities of pre-existing damage, fatigue cracking, or inadequacies in the manufacturing process were also addressed.

Using accident loads derived from analysis of recorded flight data, three lug tests were conducted on vertical stabilizer aft lugs from an unused skin panel and from another airplane. Fracture patterns for these three test specimens were compared to the corresponding structure on the accident airplane.

This paper describes the structure of the vertical stabilizer, the results of the materials testing and microstructural examination, fractography of the vertical stabilizer, and how the results led investigators to understand the failure. The paper also presents fractographic examination results for the three lug tests and significance of the fracture features.

DESCRIPTION OF THE STRUCTURE

Development of the Airbus A300-600 model began in 1980, and certification occurred in 1984. The accident airplane was delivered new to American Airlines in 1988.

Vertical Stabilizer Structure

An internal view of the vertical stabilizer is shown in figure 1. The vertical stabilizer for the Airbus A300-600 series airplane is a stiffened box with removable leading edge fairings and trailing edge panels. The stiffened box consists of two integrally stiffened skin panels for the left and right sides, spars for the forward and aft sides, and closure ribs at the upper and lower ends. The integral stiffeners in the skin panels consist of

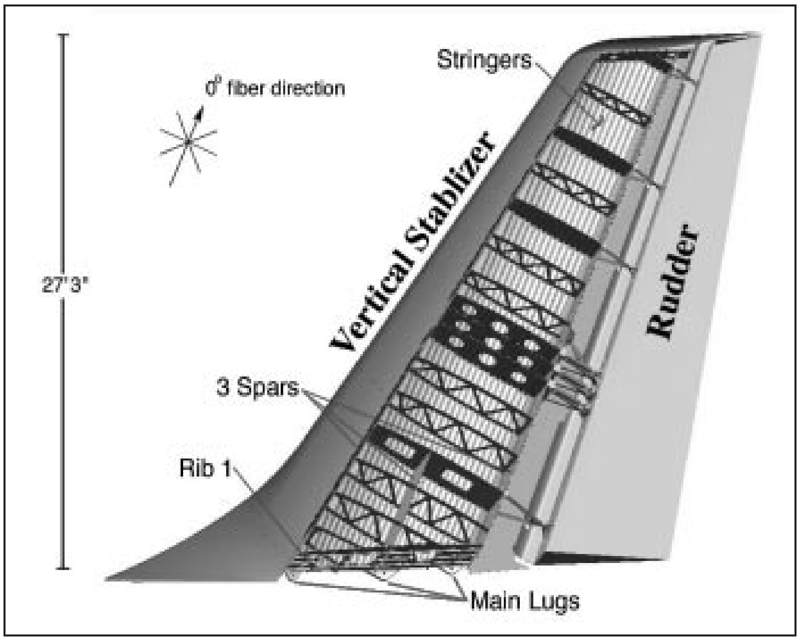

Figure 1. Airbus A300-600 vertical stabilizer construction. The vertical stabilizer and rudder for this model airplane, which has a symmetric airfoil shape, are 27 feet 3 inches tall and from leading edge to trailing edge, 25 feet wide at the base, and 10 feet 2 inches wide at the tip. The vertical stabilizer and rudder were made almost entirely of composite materials, including the composite lugs at the six main attachment locations for connecting the vertical stabilizer to the fuselage.

24 "I"-shaped stringers that span the length of the stabilizer, parallel to the aft spar. Internal stiffeners for the box consist of a center spar at the lower end of the span and 16 ribs, not including the two closure ribs. The components of the box are riveted together, and the leading edge fairings and trailing edge panels are attached with threaded fasteners.

Except for the fasteners, lightning protection strips, and trailing edge panel support frames, the vertical stabilizer is made entirely of composite materials. The stiffened box of the vertical stabilizer is a solid carbon-fiber reinforced polymer (CFRP) laminate composed of T300 carbon fibers in a CIBA 913 epoxy matrix. The laminate includes both unidirectional tape and eight-harness satin fabric layers in the construction.

The zero-degree fibers of the fabric and tape layers in the composite run parallel to the stringers and the aft spar, which are at a 33.3-degree angle aft of vertical. The leading edge fairings and the trailing edge panels are sandwich composites having a Nomex® honeycomb core with glass-fiber reinforced polymer (GFRP) facesheets for the leading edge fairings and both GFRP and CFRP facesheets for the trailing edge panels.

The vertical stabilizer is attached to the fuselage primarily by six CFRP lugs (main lugs) on the lower end of the vertical stabilizer, three on either side. These lugs connect by bolts approximately 2 inches in diameter to six metal clevis fittings on the fuselage.

Figure 2 shows a cross-section of a typical main-lug assembly. After the assembly is cured during manufacturing, the lug attachment boltholes are core-drilled out. At the thickest point, the forward main lugs are approximately 1.62 inches thick, the center lugs, approximately 2.48 inches thick, and the aft lugs, approximately 2.17 inches thick. The aft lugs alone are composed of more than 170 layers of fabric and tape: approximately 50 percent, ±45-degree fabric; 25 percent, 0/90-degree fabric; and 25 percent, 0-degree tape. The thickness of each lug decreases as plies are dropped in the lug-to-skin transition area. The skin layers are made of ±45-degree fabric. The I-shaped stringers have 0-degree tape at the caps and ±45-degree fabric in the web.

MATERIALS TESTING AND MICROSTRUCTURAL EXAMINATION

Materials Testing

The materials testing and microstructural examination of samples from the accident vertical stabilizer were completed primarily at the National Aeronautics and Space Administration's Langley Research Center (NASA Langley) in Hampton, Virginia. In addition, some testing and microscopy were completed at Airbus Industrie in Bremen, Germany.[2]

Samples were selected from multiple locations on the vertical stabilizer for materials testing and microscopic examination to determine chemical composition, extent of cure, glass transition temperature (Tg), fiber and void volume fractions, and ply stacking sequence (layup). (See table 1.)

Samples from each area were tested using differential scanning calorimetry (DSC) and infrared spectroscopy (IR). Samples from one area were tested using dynamic mechanical analysis (DMA) and modulated differential scanning calorimetry (MDSC). The fiber volume fraction, void volume fraction, and layup in each area were determined using microscopic examination of polished cross-sections, described later in this paper.

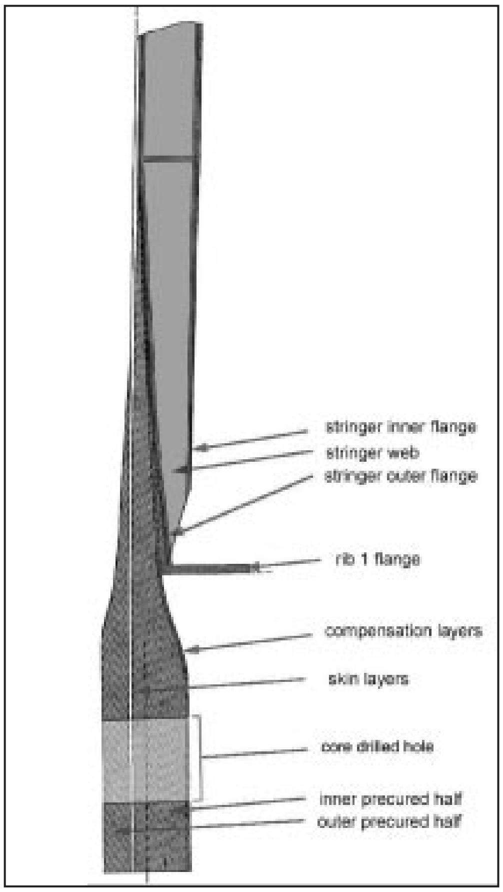

Figure 2. Cross-section of main lug assembly. Each lug contains two separate pieces that are cured separately before the final assembly. In the final assembly, the outer precured half is laid down, followed in order by the skin layers, the inner precured half, the compensation layers, the rib 1 attach flange, the stringer outer flange (tape) layers, and the stringer module layers. The boltholes are drilled after the assembly is cured.

2 National Transportation Safety Board, Materials Laboratory Factual Report 02-082, NTSB Public Docket, 2002.

Table 1. Fifteen samples were selected from both damaged and undamaged areas on the accident airplane vertical stabilizer.

Area	Number of samples	Damaged	Undamaged
Right skin panel, near the aft spar	4		X
Left skin panel, near the forward spar	3		X
Right aft lug	1	X	
Right forward lug	1	X	
Left forward lug	1	X	
Forward spar	1		X
Center spar	1		X
Aft spar	1		X
Rib 1	1		X
Rib 3	1		X

According to Airbus, the curing temperature for the CFRP laminate was specified to be 250 degrees Fahrenheit. According to Airbus material qualification data, the onset glass transition temperature ($T_{g\text{-onset}}$) was 144 degrees Celsius in the dry condition and 122 degrees Celsius after exposure to a climate of 50 percent relative humidity (corresponding to a moisture content of 0.7 weight percent). According to the engineering drawings, the fiber volume fraction for the CFRP laminate was 60% ± 4%. The maximum volume fraction porosity permitted in the cross-section was 2.5 percent.

The chemical composition of samples from each area was assessed using IR spectroscopy; results were typical for this composite material with no significant variances in the spectra for each specimen.

The extent of cure and the T_g of the sample from the upper end of the right skin panel were analyzed using MDSC, DMA, and DSC. Portions of this sample were tested in the as-received condition and after drying. The moisture content for the as-received condition was approximately 0.58 percent.

- The MDSC results showed an average residual heat value of 4.5 joules per gram, which corresponded to an extent of cure that was greater than 97 percent.
- The DMA results showed that in the as-received condition, the $T_{g\text{-onset}}$ measured 134 degrees Celsius, which was between the qualification values of 144 degrees Celsius for the dry condition and 122 degrees Celsius for the 50 percent relative humidity (0.7 percent moisture content) condition. The portion of sample from the upper end of the right skin panel that was tested in the dry condition had a $T_{g\text{-onset}}$ of 149 degrees Celsius.
- The extent of cure and the T_g of each sample, including the sample from the upper end of the right skin panel, were assessed using DSC. Results among all samples showed no significant variance, indicating that the extent of cure for each sample was sufficient.

MICROSTRUCTURAL EXAMINATION AND QUANTITATIVE ANALYSIS

Sections of each sample were cut, mounted, and polished for microstructural examination and quantitative analysis. Cross-sections from the vertical stabilizer were prepared and analyzed at NASA Langley and at Airbus. A typical cross-sectional view is shown in figure 3 for a sample from the lower end of the right skin panel.

Results of the microstructural examination and analysis indicated that the composite structure of the vertical stabilizer was constructed to the desired fiber volume fraction with acceptable void content. No evidence of microcracking was observed. The observed layups were compared to the engineering drawings obtained from the manufacturer and, among the 15 samples, only one sample from the right forward lug showed any discrepancies. Within the 124 layers of this sample, two layers had orientations that were different from the drawing. Also, two layers appeared to be missing from one position through the thickness, but two additional layers were present at another position. The total number of layers for each orientation in the right forward lug was correct, and the discrepancies represented a small fraction of the total number of layers.

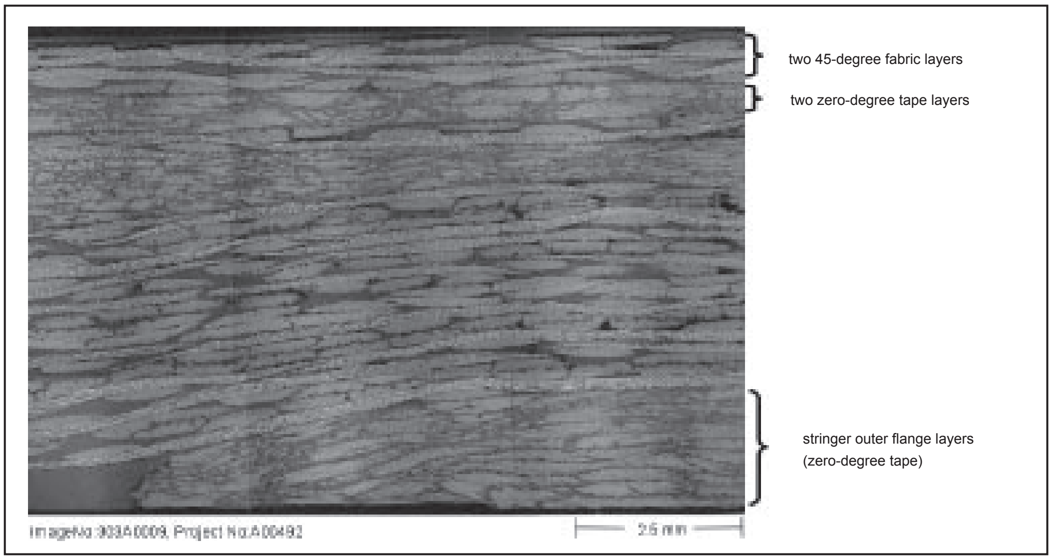

Figure 3. Microstructure of sample RS1. The cross-section shown is in a plane that is oriented parallel to the plus or minus 45-degree fiber direction. Fiber and void content were determined using computer optical image analysis of polished micrographs. The layup in each sample was determined from optical micrographs of the specimens that were assembled into mosaics like the one shown here.

Fractographic[3] Examination Procedures and Challenges

For most common airplane structural metals, visual inspection or low-power magnification is often sufficient to determine fracture mechanism and direction. For metals, the fracture plane, surface roughness, radial marks, chevrons, shear lips, and general deformation all provide macroscopic clues to the fracture mechanisms, direction of fracture propagation, and relative motion of mating surfaces. Preexisting cracks in metals often show staining or changes in color associated with corrosion.[4] Using these clues, experienced investigators can examine large areas of damaged structure relatively quickly to identify fracture origins and areas requiring closer inspection.

However, composites by their nature present their own set of challenges. Visual clues to preexisting fractures, such as flat fracture surfaces with curving boundaries or staining from corrosion, which are easy to see in structural metals, are in general not as visible in composites. Furthermore, visual cues to fracture propagation direction that are sometimes apparent in composite structures, such as crack branching in translaminar fractures (fractures that break fibers) or banding in delaminations (fractures between layers), were not apparent in many of the fractures of interest on the accident airplane. Because visual cues were not present in many of the fractures, the composite fractures in the accident airplane required an especially time-consuming examination because the area to be examined using high magnification was substantially larger than what is typically required for overstress fractures of similar metal structures.

Investigators first conducted a visual inspection of the translaminar fractures and delaminations. This examination included mapping the fractures to help determine fracture propagation directions from crack branching patterns, recording features indicating translaminar fracture under tension or compression, and, in the delaminations, identifying any visual cues to changes in fracture mechanism or mode.[5]

Using results of the visual examination as a guide, investigators used scanning electron microscopy (SEM) to determine the fracture mechanism and fracture propagation direction on the translaminar fractures and on the delamination surfaces, and to identify the layers involved, fracture mechanisms, modes of fracture, and propagation directions. The SEM examination also enabled investigators to distinguish between fatigue fractures and preexisting cracks, which may appear similar during a visual examination. Results of the SEM examination were used to check construction of the vertical stabilizer and rudder against the manufacturing drawings and to determine how the fractures related to the loading of the overall structure.

Two samples, one from each of the two large delaminations, were not cleaned, and were examined first in order to explore

3 Fractography is the examination of fracture surfaces and adjacent areas to determine conditions that caused the fracture. See *ASM Handbook*, Volume 11: Failure Analysis and Prevention, eds. W.T. Becker and R.J. Shipley, ASM International, 2002.

4 K. Mills and others, eds., *Fractography, ASM Handbook Vol. 12* (ASM International: Metals Park, Ohio, 1987).

5 R.J. Kar, "Atlas of Fractographs," *in Composite Failure Analysis Handbook Volume 2: Technical Handbook* (Northrop Corporation, Aircraft Division, 1992).

the surface for matrix rollers (pieces of fractured matrix material rolled into cylindrical shapes by the relative motion of the fracture surface during cyclic loading), which would have indicated fatigue. Fracture surfaces of the remaining samples were cleaned ultrasonically in water before being coated with a conductive layer of gold and palladium.[6] Typically, delamination samples about 2 inches square were taken from widely spaced areas on the exposed fracture surfaces in an effort to identify overall trends. (See table 1.) Samples were also taken from areas where the delamination surface morphology changed (mostly at the ends of plies in the lay-up) to explore for local differences in stress state or crack propagation direction.

Investigators took more than 300 SEM photographs of translaminar fractures in the main attachment areas of the vertical stabilizer and examined more than 150 square inches of the delamination surfaces at high magnification. For translaminar fractures intersecting the lug attachment hole, they examined the entire fracture surface at high magnification, and for translaminar fractures above the lugholes, they examined several inches of the total extent of the fracture.

One challenge facing investigators during the fractographic analysis was the relatively small amount of reference material dealing specifically with fractographic examination of fabric-reinforced composites. Most of the literature describing fractography of composites focuses on unidirectional tape lay-ups. However, fabrics have unique characteristics, such as variation in resin content on delamination surfaces and less fiber pullout in translaminar fractures relative to tape-reinforced materials, as investigators found in the accident airplane. For example, in the unidirectional lay-ups reported in the literature, river marks were typically only observed in Mode I (opening displacement between fracture faces) loading. However, in the fabric construction of the accident airplane where evidence of Mode II (sliding displacement between fracture faces) loading was observed, river marks were also found in the matrix-rich areas near the bundle crossings, and in the base of hackles[7] where a bundle at one orientation transitioned to a perpendicular crossing bundle. River marks in the bundle crossings were used to identify a general direction of fracture propagation upward and aftward for both of the large delaminations (at the forward left and aft left attachments). (Investigators also explored the river marks at the base of the hackles during their examination of the delaminations at the forward right lug as described later in this paper.) Because manufacturers are increasing their use of composites with fabric reinforcements in airplane structures, more research is needed to characterize fracture surfaces generated under controlled laboratory conditions to help failure analysts in interpreting fractographic details.

6 A. Sjögren, L.E. Asp, and E.S. Greenhalgh, *Interlaminar Crack Propagation in CFRP: Effects of Temperature and Loading Conditions on Fracture Morphology and Toughness, in Composite Materials: Testing and Design, and Acceptance Criteria ASTM STP 1416,* Nettles and Zureick, eds., 2002.

7 "Hackles are matrix fracture features that indicate a significant component of shear across the fracture surface. Hackles are formed when matrix microcracks that are spaced fairly regularly along planes of maximum tension join together." National Transportation Safety Board, *In-Flight Separation of Vertical Stabilizer,* Aircraft Accident Report NTSB/AAR-04/04, NTSB Public Docket (Washington, DC: NTSB, 2004).

Fracture Surface Observations and Discussion

During the visual examination, investigators found that the vertical stabilizer was largely intact with no significant areas of skin buckling. An overall view of the vertical stabilizer as it was being recovered from the water of Jamaica Bay is shown in figure 4. At the lower end, each of the six attachment locations had separated from the fuselage either by fractures that intersected the lug attachment hole or by fractures through the structure above the hole. A schematic of the lower end of the vertical stabilizer is shown in figure 5, which shows a general fracture location for each lug, pointing to overall views of each lug fracture. Portions of rib 1, the rib 1 rib-to-skin attach angle, and the lower end of the forward spar also were fractured. In addition, the trailing edge panels were damaged in several locations.[8]

Description of Main Lug Fractures

Translaminar fractures on the right aft, right forward, and left forward main lugs intersected the attachment hole. For the remaining three main lugs, translaminar fractures intersected the structure above the lug. Each of the lugs had delaminations in the lug area and/or in the structure above the lug. Safety Board Materials Laboratory factual reports contain details of the fractographic examination.[9] Some of the delaminations extended into the main portion of the vertical stabilizer, and the extent of these delaminations was determined using nondestructive inspection (NDI), including ultrasonic inspection and x-ray-computed tomography scanning and imaging. Safety Board Materials Laboratory factual reports contain the results of the NDI.[10]

MACROSCOPIC FRACTURE FEATURES

On the right side of the vertical stabilizer, the roughness of the main lug translaminar fractures was in general consistent with overstress fracture in primarily tensile loading. Delaminations

8 National Transportation Safety Board, *Materials Laboratory Factual Report 02-083,* NTSB Public Docket, 2002.

9 (a) NTSB, *Materials Laboratory Factual Report 02-083,* NTSB Public Docket, 2002; (b) NTSB, *Materials Laboratory Factual Report 03-018,* NTSB Public Docket, 2003.

10 (a) NTSB, *Materials Laboratory Factual Report 02-078,* NTSB Public Docket, 2002; (b) NTSB, *Materials Laboratory Factual Report 03-033,* NTSB Public Docket, 2003.

Figure 4. Vertical stabilizer as recovered from Jamaica Bay.

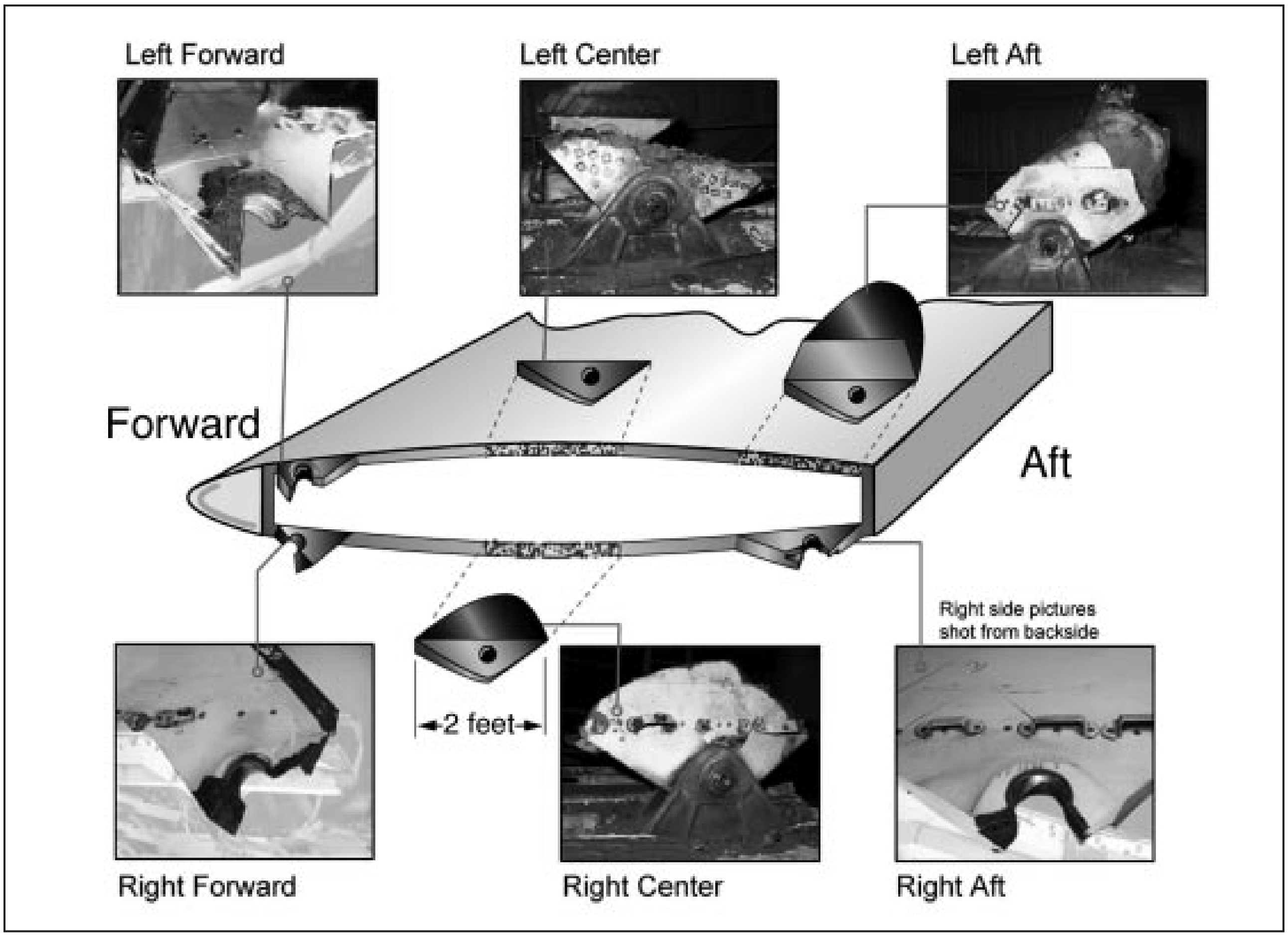

Figure 5. Overall views of main lug fractures with relative locations on vertical stabilizer.

were observed at the edges of each lug on the right side. The extent of the delaminations as determined using NDI was limited to within the fractured lugs or within approximately 4 inches of a translaminar fracture.

The right aft lug failed by translaminar fracture through the bolthole, as shown in figure 6. The rough appearance of the translaminar fracture surfaces was consistent with fractures under primarily tensile loading. Fractures on each leg of the lug were on different translaminar planes, and the change in planes occurred near the center of the lug thickness. On the aft side of the bolthole, the outboard side of the fracture was in a plane nearly perpendicular to the 0-degree fiber direction, and the inboard side of the fracture was in a plane approximately parallel to the 45-degree fiber direction. On the forward side of the bolthole, the outboard side of the fracture was in a plane approximately parallel to the 0-degree fiber direction, and the inboard side of the fracture was in a plane nearly parallel to rib 1. Bearing damage was observed at the bore surface near both fracture surfaces, as indicated by white unlabeled arrows in figure 6.

The right center lug failed above the bolthole in the lug-to-skin transition area above rib 1. Translaminar fracture features were relatively rough, consistent with overstress fracture under tensile loading.

Fractures on the right forward lug intersected the lughole. Translaminar fracture features were relatively rough, consistent with overstress fracture under tensile loading. Some evidence of local compressive loading was observed near the aft side of the lug, indicating that fracture first occurred at the forward side of the lug, allowing the lower ligament to hinge toward the aft side of the lug.

The rough appearance of the main lug translaminar fractures on the left side of the vertical stabilizer was also consistent with overstress fracture in primarily tensile loading, but the fractures also showed indications of bending to the left. The left forward lug had multiple delaminations in the lug area, and an impression on the left side corresponded to contact with the fuselage attachment clevis. This impression indicated that the left skin panel of the vertical stabilizer bent to the left, damage that can only be explained if the right side skin panel was already separated from the fuselage. The left forward lug also had a delamination that extended upward into the structure, up to 43 inches from the lower end of the vertical stabilizer. The left center lug showed compression fracture features at the outboard side of the translaminar fracture, consistent with bending loads

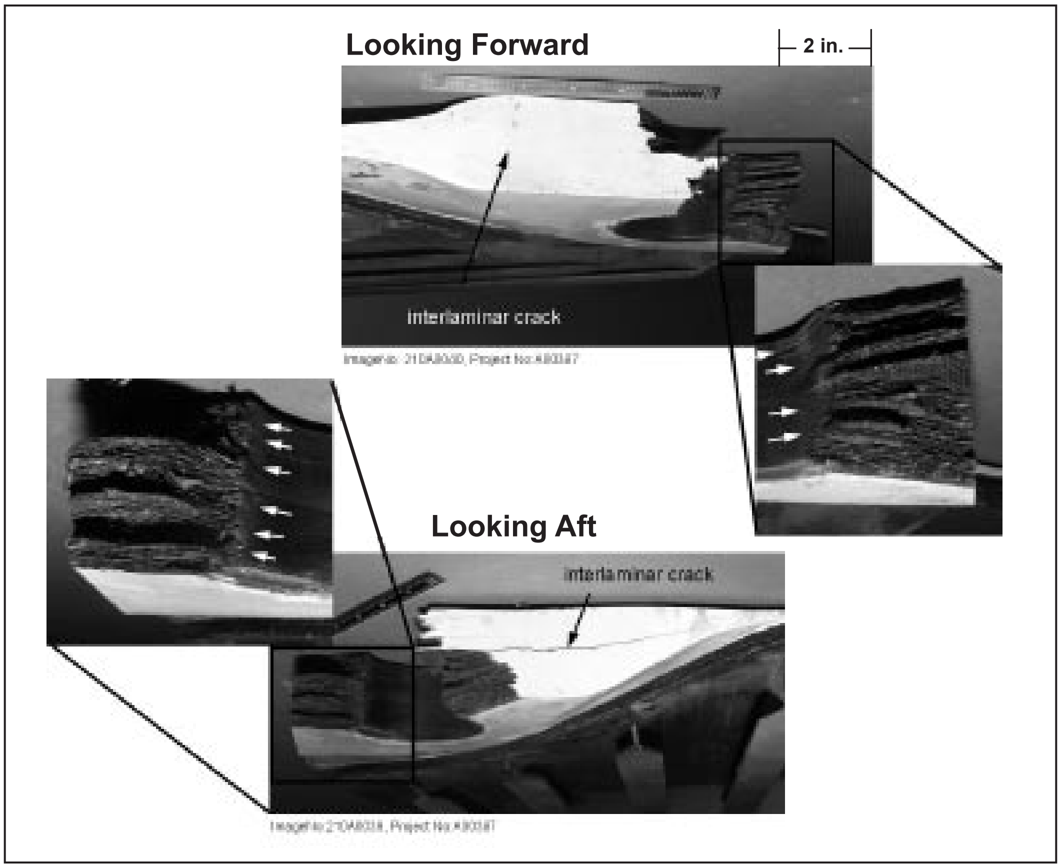

Figure 6. Right aft lug translaminar fractures (pictured from below the lug), which failed through the bolthole.

to the left. The left aft lug had delaminations extending up to 37 inches from the lower end of the vertical stabilizer. Multiple delaminations through the thickness were present in the lug-to-skin transition area, allowing most of the precured halves of the lug to separate from the rest of the structure.

MICROSCOPIC FRACTURE FEATURES

This section describes the investigators findings based on the SEM examination of the translaminar fractures and delaminations.

On the translaminar fractures, the ends of some fibers were oriented roughly perpendicular to the fracture plane. A typical SEM view of these fiber ends is shown in figure 7. Fiber ends like these were examined to help determine the fracture mechanism and propagation direction. For fibers with radial patterns indicative of tensile fracture, the local fracture propagation direction could be determined from the direction of the radial pattern of several fibers.[11] General directions of fracture propagation for the translaminar fractures could then be determined by averaging the directions indicated by the radial patterns across many areas of the fracture surfaces. In addition, because fatigue and overstress fractures can appear similar when examined visually, the microscopic examination also looked for evidence of fatigue, such as rounded edges on fiber ends[12] or striations in the matrix.[13] However, no evidence of fatigue was observed on any of the translaminar fracture surfaces.

Although fiber end fractures for fibers oriented perpendicular to the fracture plane generally showed radial fracture features consistent with fracture under tensile loading, the fiber ends in an area near the outboard surface of the left center lug were different, showing chop marks (lines across the fractured fiber ends) indicative of local compressive loading. Examples of these chop marks can be seen in figure 8 on the fiber ends marked with a "C." The combination of tension on the inside edge and compression on the outboard surface was associated with an overall lug bending to the left. Using the radial patterns on the lug translaminar fractures, investigators determined that fracture propagation directions extended outward from the lug hole bored for the right forward, left forward, and right aft lugs (all lugs with fractures intersecting the lug hole). For the right center lug, fracture propagated from aft to forward, and for the left center and left aft lugs, fracture propagated from forward to aft.

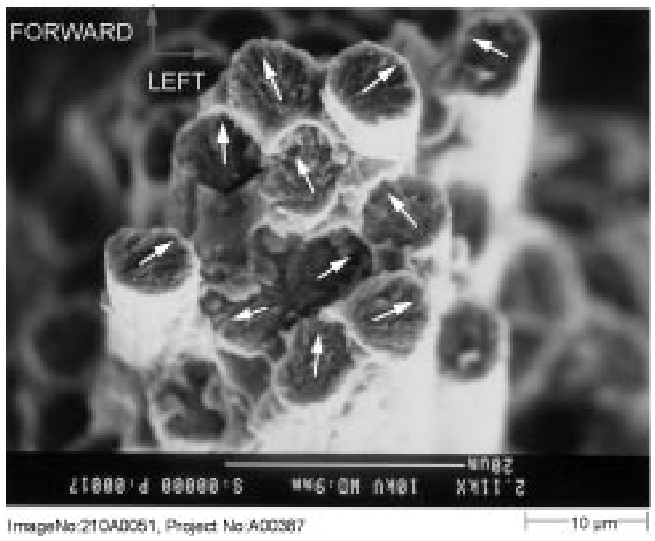

Figure 7. SEM photograph showing crack in the fractured carbon fibers. Radial patterns indicate tensile fractures and were used to determine the general direction of fracture propagation. Arrows indicate fracture direction in individual fibers that were averaged to determine direction at this location.

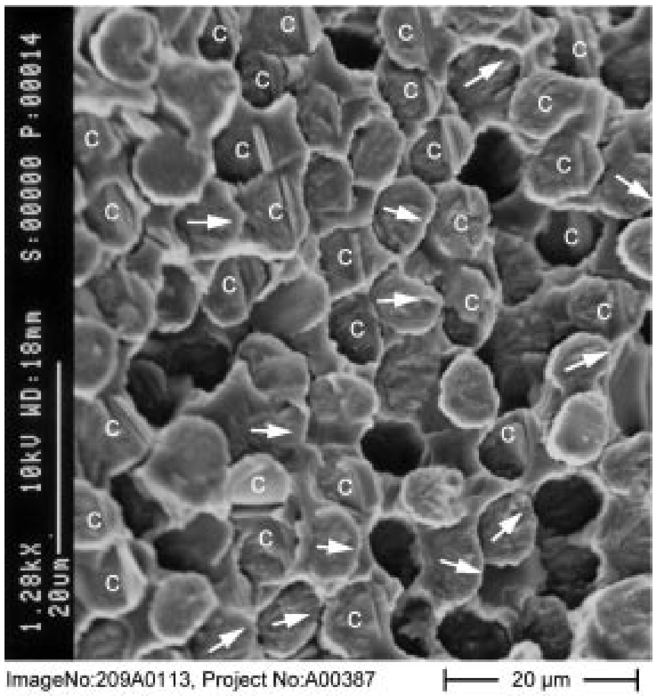

Figure 8. Fractured carbon fibers showing compression chop marks (C). Arrows indicate fracture propagation in fibers with radial patterns.

11 (a) D. Purslow, *Matrix Fractography Of Fibre-Reinforced Thermoplastics, Part 2. Shear Failures.* Composites Vol. 19, 1988; (b) P.L. Stumpff, *Fractography,* in *ASM Handbook, Vol. 21: Composites.* 2001. pp. 977-987.

12 P.L., Stumpff, *personal communication,* 2002.

13 (a) Sjögren, Asp, and Greenhalgh, Interlaminar Crack Propagation in CFRP; (b) Stumpff, *Fractography;* (c) J.F. Mandell, *Fatigue Behavior of Short Fiber Composite Materials*, in *Fatigue and Fracture of Composite Materials,* K.L. Reifsnider, Editor. 1990, Elsevier, pp. 231-337.

Samples of the delamination fracture surfaces were examined in the scanning electron microscope to determine the orientation of the shear stress at the fracture and to identify the direction of crack propagation. Fracture features that were used to make these determinations included hackles (thin plates of fractured matrix material between fibers oriented perpendicular to the fiber axis, with free edges that point in a general direction opposite to the local shear applied at the fracture surface)[14] and river marks (related to the initiation of matrix cracks that coalescence into larger cracks, indicating the direction of propagation).[15] A typical view of hackles and river marks observed on one of the delaminations is shown in figure 9. The fracture surfaces were carefully examined for indications of fatigue crack propagation, such as striations in the fiber impressions in the matrix,[16] matrix rollers,[17] or rubbed hackle formations[18]; however, no evidence of fatigue was observed on any of the delamination surfaces.

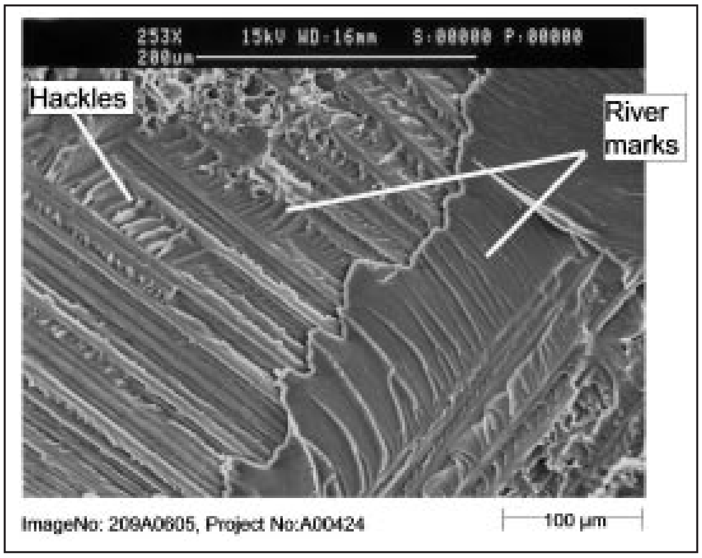

Figure 9. Typical fracture features observed on delamination fracture surfaces.

Hackles that form in CFRP laminates line up perpendicular to the fiber axes, so the hackles in the orthogonal bundles of the woven fabric would generally point in two orthogonal directions. In some cases, the superimposed imprints of unidirectional tape oriented at a 45-degree angle to those bundles added hackles at a third direction. Hackles also point generally opposite the locally applied shear at the fracture surface, so the multiple orientations of hackles from the different fiber bundles bound the direction of the local shear within an angle of 90 degrees.

River marks were observed in matrix-rich areas near the bundle crossings and could be seen at the base of hackles in the transition from a bundle at one orientation to a perpendicular crossing bundle. River marks in the matrix-rich bundle crossings were used to identify a general direction of fracture propagation upward and aftward for both of the large delaminations (at the forward left and aft left attachments). River marks at the base of the hackles were used to determine delamination growth direction in the forward right lug delaminations.

At the matrix-rich areas where bundles crossed, investigators observed some porosity with a somewhat angular appearance, as shown in figure 10. These pores were identified as arising from excess curing agent that had crystallized within the matrix but was physically removed during the fracture process or dissolved by the water of Jamaica Bay.

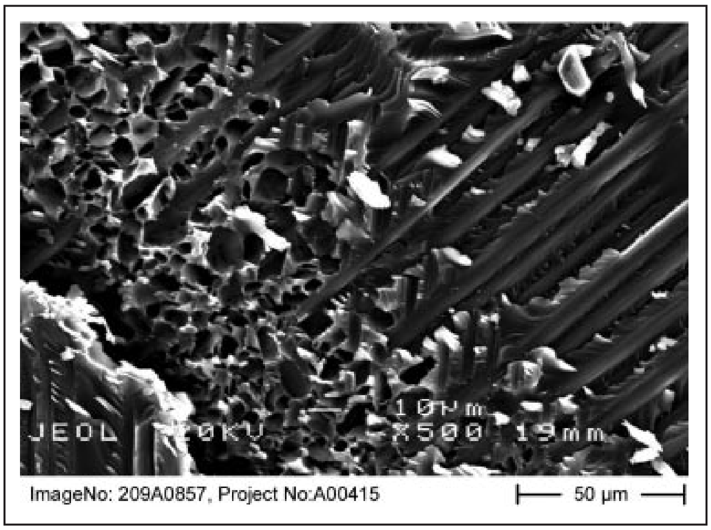

Figure 10. Porosity in matrix-rich regions where bundles cross as observed on delamination fracture surfaces.

On the left forward lug delamination surfaces, hackles on average pointed downward and forward on the outboard side of the delamination and upward and aft on the mating side, indicating a shear direction consistent with fracture under tensile loading and/or bending to the left. River patterns coalesced upward and aft, indicating crack propagation extending upward from the lower end. On the left aft lug delamination surfaces, hackles on average pointed downward

14 (a) S. Singh and E. Greenhalgh, "Micromechanisms of Interlaminar Fracture in Carbon-Epoxy Composites at Multidirectional Ply Interfaces," *4th International Conference on Deformation & Fracture of Composites* (Manchester, UK: UMIST, 1998); (b) M.F. Hibbs and W.L. Bradley, "Correlations Between Micromechanical Failure Processes and the Delamination Toughness of Graphite/Epoxy Systems," *Fractography of Modern Engineering Materials: Composites and Metals,* ASTM STP 948, J.E. Masters and J.J. Au, eds.(American Society for Testing and Materials: Philadelphia: 1987), pp. 68-97.

15 Kar, Atlas of Fractographs.

16 (a) Sjögren, Asp, and Greenhalgh, *Interlaminar Crack Propagation in CFRP;* (b) P.L. Stumpff, "Fractography," pp. 977-987.

17 (a) Sjögren, Asp, and Greenhalgh, *Interlaminar Crack Propagation in CFRP;* (b) P.L. Stumpff, "Fractography," pp. 977-987.

18 Sjögren, Asp, and Greenhalgh, Interlaminar *Crack Propagation in CFRP.*

and forward on the side of the delamination associated with the lug layers, and on average pointed upward and aft on the mating sides, consistent with the lug pieces moving downward relative to the remaining structure. In the portion of the delamination above the lug-to-skin transition, hackles generally pointed downward and forward on the outboard side and upward and aft on the mating side, indicating a shear direction consistent with fracture that occurred with bending to the left. River patterns generally coalesced upward and aft, indicating crack propagation extending upward from the lower end. Investigators looked for but did not find any evidence of fatigue, such as striations in the matrix or edge rounding of the fiber ends on the translaminar fracture surfaces or matrix rollers or striations on the delamination surfaces.

A schematic summarizing the observed fracture patterns is shown in figure 11. Results of the microscopic examination showed that the failure pattern of fracture in tension on the right side was consistent with an overall bending of the vertical stabilizer to the left. On the left side, the failure pattern of tension and bending to the left was consistent with an overall bending of the vertical stabilizer to the left after the lugs on the right side fractured.

Investigators noted that the only compression translaminar failure features were present on the vertical stabilizer at the outboard side of the center aft lug. Typically, composites have less strength in compression than in tension. However, the design of the vertical stabilizer was such that the magnitude of the load needed to fail a lug in tension was less than the load needed to fail the lug in compression. Furthermore, after the lugs on the right side failed, the curvature of the panel would have caused tension loading in the forward and aft lug and compression in the center lug with continued bending to the left. Other unknown factors, such as changes in air loading as the vertical stabilizer deflected after the initial fractures on the right side, would further influence the failure patterns on the left side.

Lug Tests

Using aerodynamic loads calculated from information gathered on flight data recorders, investigators conducted a comprehensive structural analysis in conjunction with the materials examination of the vertical stabilizer and rudder to determine stresses that developed in the structure during the accident flight. Structural analysis indicated that under accident

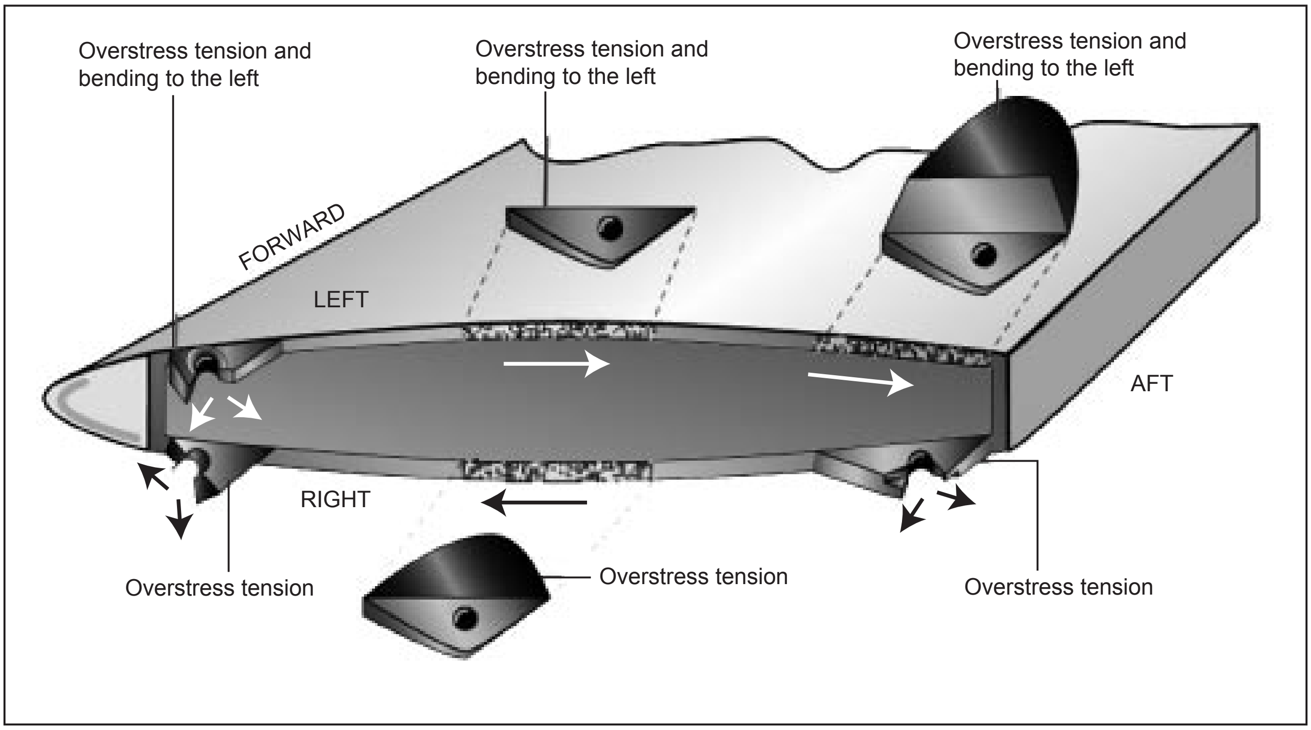

Figure 11. Main lug fracture pattern as summarized in a schematic view of the lower end of the vertical stabilizer. Fracture features on the right side were consistent with fracture under tensile loads. Fracture features on the left side were consistent with fracture under tensile loads and bending to the left. Unlabeled arrows in the schematic indicate fracture propagation directions at each lug as determined from translaminar fracture features. Both of the forward lugs and the right aft lug failed through the bolthole—that is, the lug fractured at the bolt location. Translaminar fracture features indicated that as these lugs failed, fracture propagated outward from the bolt holes. The two center lugs and the left aft lug failed above the bolthole, in the lug-to-skin transition area. Translaminar fracture features at the right center lug indicated that as the lug separated from the rest of the vertical stabilizer, fracture propagated aft to forward. Translaminar fracture features at the left center and left aft lugs indicated that as these lugs separated from the rest of the vertical stabilizer, fracture propagated forward to aft.

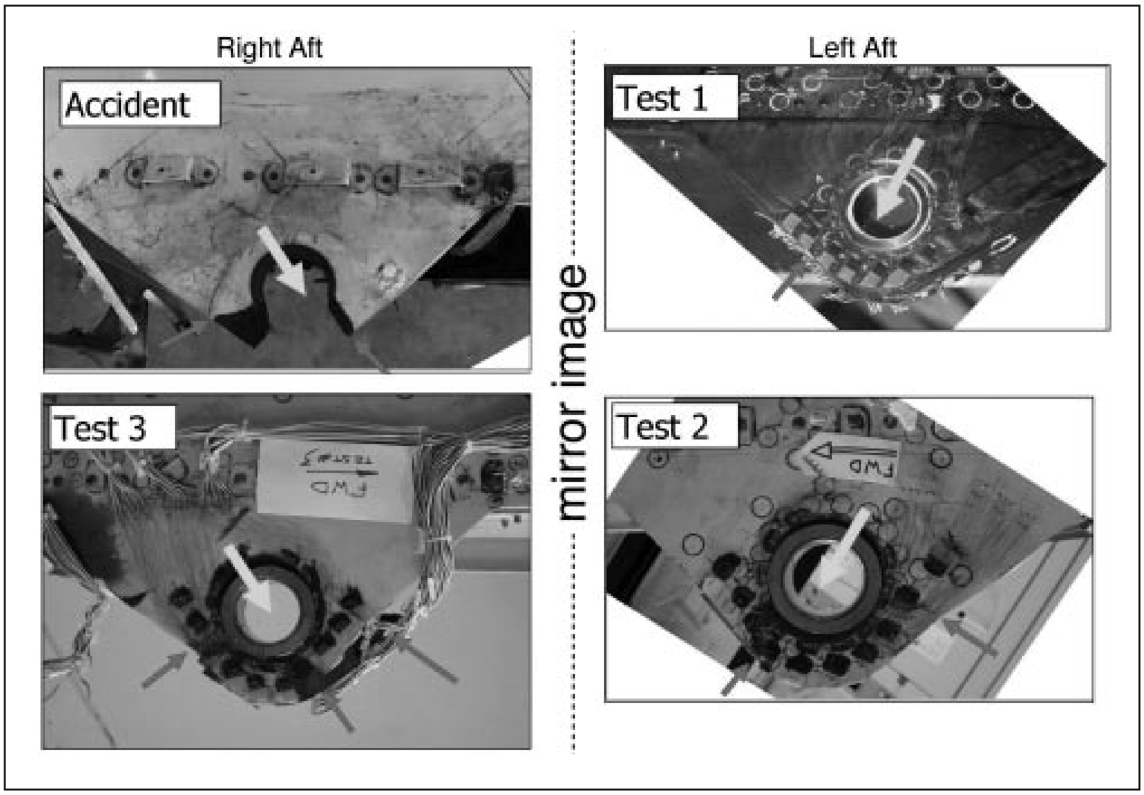

Figure 12. Comparison of aft lugs from the accident vertical stabilizer and subsequent subcomponent tests. In each photo, the small, unlabeled arrows indicate where translaminar cracks or fractures intersected the outboard surfaces of the lugs, and a large, unlabeled arrow indicates loading direction (the force vector for the horizontal and vertical loading components for each lug). The lugs from the first and second tests were left aft lugs, and as such, the orientations are mirror images of the accident right aft lug and the third test lug.

loading conditions, fracture of the vertical stabilizer would have initiated at the right aft lug. Accordingly, three aft lugs were obtained for mechanical testing under applied loads that matched those that were derived from recorded flight accident data. The lug for the first test was obtained from a production left skin panel from which sections were cut for destructive testing, while the aft lug was not disturbed. Lugs for the second and third tests were obtained from a vertical stabilizer that had been removed from service after experiencing loads exceeding design limit loads. The three lug specimens were tested at Airbus under Safety Board supervision in a loading fixture that applied the prescribed forces and moments to the lugs. Testing of each lug continued until a load change associated with a translaminar fracture or crack was observed. Fracture loads for these three tests were consistent with calculated accident loads and with earlier tests completed by Airbus during certification.[19]

19 (a) National Transportation Safety Board, Structures Group Factual Report Addendum 17, NTSB Public Docket, 2004; (b) National Transportation Safety Board, Structures Group Factual Report Addendum 16, NTSB Public Docket, 2004; (c) National Transportation Safety Board, Structures Group Factual Report Addendum 15, NTSB Public Docket, 2004; (d) National Transportation Safety Board, Structures Group Factual Report Addendum 8C, NTSB Public Docket, 2004; (e) National Transportation Safety Board, Structures Group Factual Report Addendum 6 (Rev A), NTSB Public Docket, 2004.

A fractographic examination of each lug was conducted after completing the tests, as documented by the Safety Board.[20]

Before being tested, each lug was examined for non-visible defects or damage using ultrasonic inspection.[21] No defects were observed in the first test lug. Some damage was detected in the second and third test lugs near the lug attachment hole and in some areas, in the lug fitting assembly transition area above the lowermost rib, but these lugs had experienced in-service loads exceeding design limit loads. Following the tests, the lugs were examined again using ultrasonic inspection, which showed that the preexisting damage in these lugs grew in size during the testing. Overall views of the lugs from each test are shown in figure 12 (outboard surface view).

Results from the fractographic examination showed that the test lugs fractured at locations similar to those on the accident right aft lug. In test 1, loading was interrupted after a translaminar crack occurred at the location indicated by the large arrow in the upper right photo in figure 12. The translaminar fracture was located on the forward part of the

20 National Transportation Safety Board, Materials Laboratory Factual Report 04-065, NTSB Public Docket, 2004.

21 National Transportation Safety Board, Materials Laboratory Factual Report 04-065, NTSB Public Docket, 2004.

lug in a plane nearly parallel to the resultant force direction, similar to one of the translaminar fractures in the accident right aft lug. Fracture features for the lugs from tests 2 and 3 were similar to each other. The outboard side of each of these lugs had a translaminar fracture on the forward sides of the holes in a plane nearly parallel to the loading direction and another translaminar fracture at the aft side of the hole in a plane approximately perpendicular to the loading direction. These fractures were similar to those of the accident lug. In addition, on the outboard sides, a compression buckling fracture was observed on the forward sides of each lug above the fracture parallel to the loading direction; this fracture was different from fractures on the accident lug but was attributed to constraints of the loading fixture. On the inboard sides of lugs 2 and 3, fracture locations were on translaminar planes different from those of the outboard side of the lugs. This change in fracture planes was similar to that of the accident right aft lug.

A delamination within the first test lug was similar in extent to that of the accident right aft lug and was located through the thickness, slightly outboard of that of the accident right aft lug. Delaminations also were detected above the translaminar fractures in lugs 2 and 3. In test 2 and 3 lugs, the locations of the delaminations through the thickness were similar to those of the accident right aft lug, but the extent of the delaminations in the test lugs was slightly less.

Delaminations in each lug, as well as translaminar fractures that intersected the lughole, were features similar to the accident right aft lug. Each lug had a translaminar fracture at the forward lower side of the hole on the outboard side of the lug, including the first test, which was interrupted and had no other translaminar fractures. The fracture at the forward lower side of the hole corresponded to one of the translaminar fracture locations on the accident lug. The second test lug showed changes in translaminar fracture planes that were qualitatively similar to those of the accident right aft lug. These results indicated that the fracture features of the accident right aft lug were consistent with its being the first lug to fracture from a substantially intact vertical stabilizer and rudder under accident load conditions.

CONCLUDING REMARKS

The materials testing and microstructural examination of the vertical stabilizer indicated that the vertical stabilizer's composite material had sufficient cure, desired fiber volume fraction, and acceptable void content with no evidence of microcracking in the areas examined. Discrepancies representing a small fraction of the total number of layers were observed in the layup of one of the samples. However, throughout the testing and examination, no deviations from the original design and materials specifications were found that would have contributed to the vertical stabilizer separation.

The fractographic examination revealed no evidence of pre-existing damage or fatigue cracking in the vertical stabilizer, supporting the conclusion that the separation of the vertical stabilizer was a result of high aerodynamic loads. Fractographic results for the main attachment lugs of the vertical stabilizer showed that failures on the right side of the vertical stabilizer were overstress failures under tension loading, consistent with an overall bending of the vertical stabilizer to the left. Fractographic results for the main lugs on the left side of the vertical stabilizer showed overstress failure in tension and bending to the left, consistent with bending of the vertical stabilizer to the left after failure of the main lugs on the right side. Structural analysis of the vertical stabilizer conducted as part of the overall investigation indicated that under accident loads, fracture of the vertical stabilizer would initiate at the right aft main lug, which was consistent with the fractographic analysis.

The failure mode in the accident was further confirmed by a series of three aft lug tests. The failure loads for these three tests were consistent with predicted failure loads and with earlier tests completed by Airbus during certification. Fracture patterns for the three test specimens were compared to the corresponding structure on the accident airplane, and good correlation was observed.

Analysis of the fractographic evidence was incorporated into the overall analysis of the accident. As one of the findings of the Safety Board's report stated, "Flight 587's vertical stabilizer performed in a manner that was consistent with its design and certification. The vertical stabilizer fractured from the fuselage in overstress, starting with the right rear lug while the vertical stabilizer was exposed to aerodynamic loads that were about twice the certified limit load design envelope and were more than the certified ultimate load design envelope." [22]

22 NTSB/AAR-04/04 (NTSB Public Docket, 2004)

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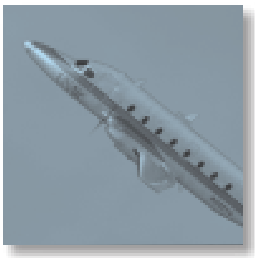

Developing Animations to Support Complex Aviation Accident Investigations

Alice Park and Christy Spangler, National Transportation Safety Board

ABSTRACT

In their quest to find the probable cause of airplane accidents and ensure public safety, National Transportation Safety Board engineers and investigators collect and analyze a variety of complex data that may be difficult to visualize or explain to a nontechnical audience. The NTSB uses three-dimensional (3-D) graphics and animations to show what happened during the accident and to illustrate the engineering work performed to reconstruct the accident sequence. This paper describes how animation can be used to support complex aviation accident investigations.

INTRODUCTION

NTSB aviation accident investigations can involve highly dynamic and complex scenarios. After exhaustive collection and analysis of data, the NTSB determines the probable cause and makes recommendations for improving transportation safety. Animation has a critical role in accident investigations: to clearly explain the sequence of events leading to an accident. This discussion focuses on two accidents: American Airlines flight 587 (November 12, 2001, in Belle Harbor, New York) and Air Midwest flight 5481 (January 8, 2003, in Charlotte, North Carolina).

DATA COLLECTION PROCESS

During an aviation accident investigation, information and data are gathered from a variety of sources: cockpit voice recorder (CVR), flight data recorder (FDR), radar data, wreckage scene measurements, eyewitness interviews, photos, videos, and site survey evidence. These data are processed and analyzed using a wide variety of aircraft performance and simulation codes to precisely define the airplane's motion throughout the accident sequence. The combined and comprehensive data set that describes the motion is used to develop detailed 3-D animations.

Accident 1

On November 12, 2001, American Airlines flight 587, an Airbus Industrie A300-600, was destroyed when it crashed into a residential area of Belle Harbor, New York, shortly after takeoff from runway 31L at John F. Kennedy International Airport. Before impact, the vertical stabilizer, rudder, and left and right engines departed the airplane. The 2 pilots, 7 flight attendants, 251 passengers, and 5 persons on the ground were killed.

The NTSB dispatched approximately 40 personnel to the scene. Investigators included specialists in operations, structures, power plants, systems, air traffic control, weather, aircraft performance, and voice and flight data recorders. After a 3-year investigation, the NTSB determined that the probable cause of the accident was the in-flight separation of the vertical stabilizer as a result of loads beyond ultimate design that were created by the first officer's unnecessary and excessive rudder pedal inputs, characteristics of the Airbus A300-600 rudder system design, and elements of the American Airlines Advanced Aircraft Maneuvering Program. During the investigation, it was determined that the first officer made his rudder pedal inputs at the time the airplane encountered wake turbulence from a Boeing 747. [<http://www.ntsb.gov/events/2001/AA587/default.htm>]

Accident 1: Data Integration

During the flight 587 investigation, performance engineers analyzed the first officer's control inputs using FDR data. Figures 1 and 2 show the first officer's column, wheel, and pedal inputs, plotted as a function of time during the accident's two wake turbulence encounters. The blue line on the plots indicates the mechanical limits of these controls.

Figure 1, illustrating the first officer's control inputs during the first wake turbulence encounter, shows that the column and wheel limits remained constant, but the pedal limit varied in accordance with the rudder control system's design. The figure also shows that the first officer responded to the first wake turbulence encounter with column and a series of large wheel inputs, but did not use the rudder pedals.

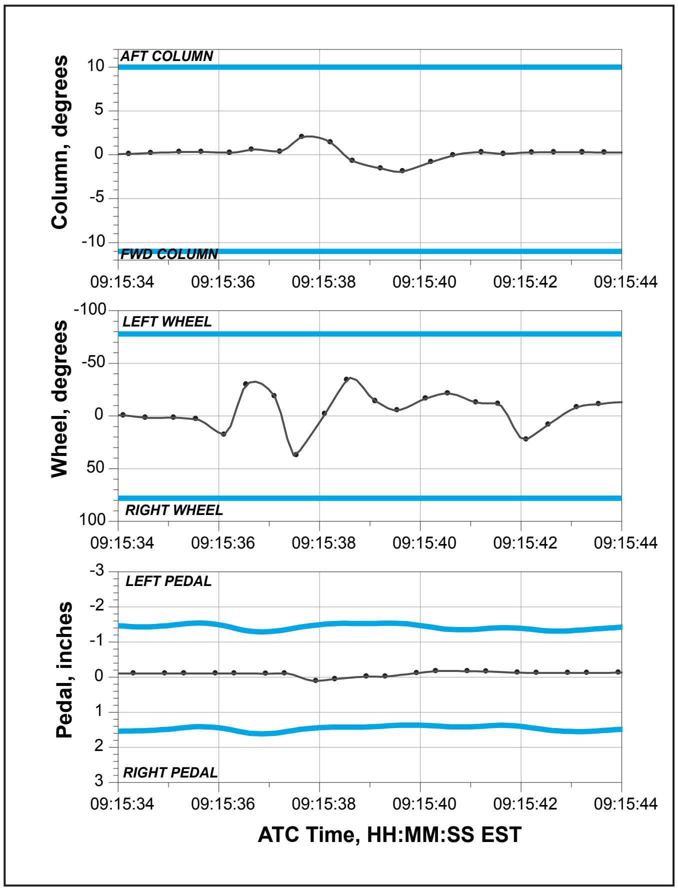

Figure 1. Control input during first wake encounter.

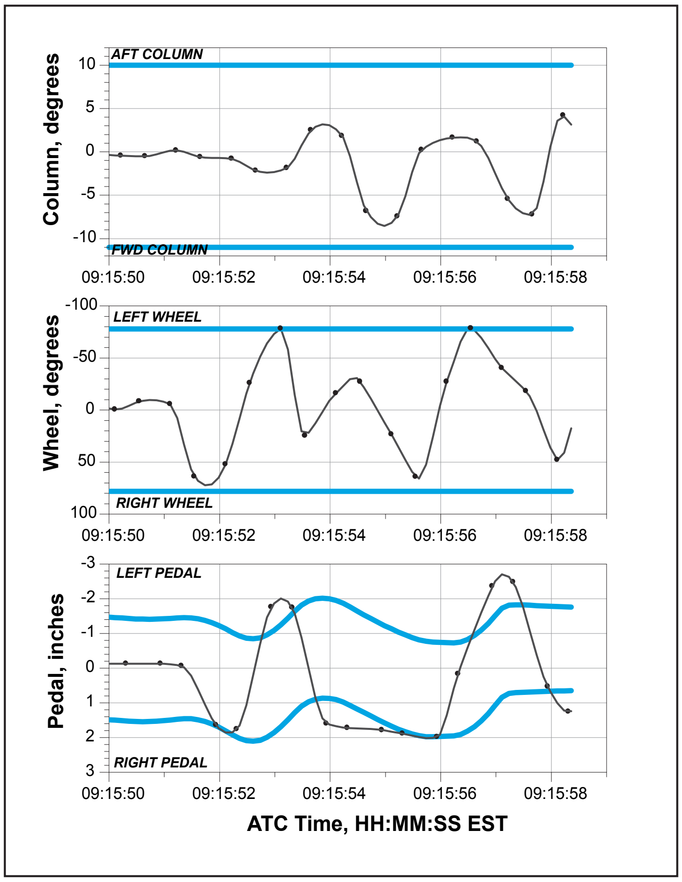

Figure 2. Control input during second wake encounter.

Figure 2, illustrating control inputs during the second wake turbulence encounter, shows that the first officer responded to the second wake turbulence encounter much differently than he did to the first. Wheel inputs during the second wake turbulence encounter were about twice as large as those made during the first, and the first officer also made rudder pedal inputs. The NTSB found that the full wheel and rudder inputs made in response to the second wake turbulence encounter were unnecessary and excessive.

Figures 1 and 2 show individual parameters: column, wheel, pedals, and time. However, it is not easy to understand the magnitude of the data within the timeframe. In particular, the pilot's reaction to the first and second wake turbulence encounters is hard to visualize using only the data in the figures. Given these difficulties, staff decided to animate the first officer's input to make it easier to grasp the data. The following is the detailed process used in the animation reconstruction:

- Storyboarded the first officer's control inputs.
- Modeled the human legs, pedals, and control column according to the scale and measurements of the A300-600 cockpit.
- Wrote XSI script to read the CVR text file, and MS Excel spreadsheet containing the FDR data of the flight control inputs.
- Textured the legs to show only their outlines, and textured the cockpit components to represent the A300-600 cockpit.
- Synchronized digital time in accordance with flight control input.
- Reviewed data accuracy against the pedal and column motion to ensure accurate representation.
- Composited the data-driven control input and digital time with selected cockpit communication (figures 3 and 4).

As the list above shows, translating field data to an animation is not a single-step process. In addition to being factually correct, the animation must demonstrate a high degree of data analysis, conveyed so that the data are easy for an audience to understand. In addition, the animation scene must be simple so that the main focus is on the probable cause and the audience is not distracted by extraneous factors. For these reasons, only the control column and pedals were included for the cockpit environment. However, the scene seemed incomplete without a human figure, even though an entire human figure seemed to distract attention from the control inputs. The solution was to include only the lower torso of the figure, which worked well to demonstrate the human movements without detracting from the control inputs. Photographs, engineering drawings, and survey data were used to accurately model the cockpit environment and placement of the lower torso according to the actual A300-600 cockpit. The green regions under the rudder pedals were used to depict the range of available pedal travel prior to reaching the pedal travel limits. (These limits correlate to the grey lines in the pedal plots of figures 1 and 2.) The animation also included digital time and selected cockpit communications to round out the sequence of events.

Although extensive effort was required to animate the sequence of flight control inputs, the effort was clearly worthwhile since it demonstrates in real time the first officer's unnecessary and excessive rudder inputs during the wake turbulence encounters and shows how his actions changed from the first wake encounter to the second. Further, by showing events in real time using the cockpit orientation, the animation thoroughly represents the sequence of events and enhanced investigators' understanding of the control inputs. Finally, the animation allows a nontechnical audience to watch the actions associated with the control input data rather than viewing a static diagram that must be explained by the presenter. Figures 1 and 2 show the data, but the animation (figures 3 and 4) shows the human actions that resulted in that data. This 3-D animation reconstruction effectively explains the first officer's actions and enables both the investigators and the audience to visualize the complex control input data associated with the accident.

Accident 2

On January 8, 2003, about 0847:28 eastern standard time, Air Midwest flight 5481, a Raytheon (Beechcraft) 1900D, crashed shortly after taking off from Charlotte-Douglas International Airport, Charlotte, North Carolina. Two flight crewmembers and nineteen passengers aboard the airplane were killed, one person on the ground received minor injuries, and impact forces and a postcrash fire destroyed the airplane. NTSB determined that the probable cause of the accident was the airplane's loss of pitch control during takeoff. The loss of pitch control resulted from incorrect rigging of the elevator control system, compounded by the airplane's aft center of gravity, which was substantially aft of the certified aft limit. [<http://www.ntsb.gov/events/2003/AM5481/default.htm>]

Accident 2: Data Integration

The challenge in analyzing and presenting data from flight 5481 was to explain how the airplane's mis-rigged elevator cable control system affected airplane motion, resulting in loss of pitch control. Investigators found that they could not effectively demonstrate the physical evidence associated with the mis-rigged elevator control system or the airplane's flight

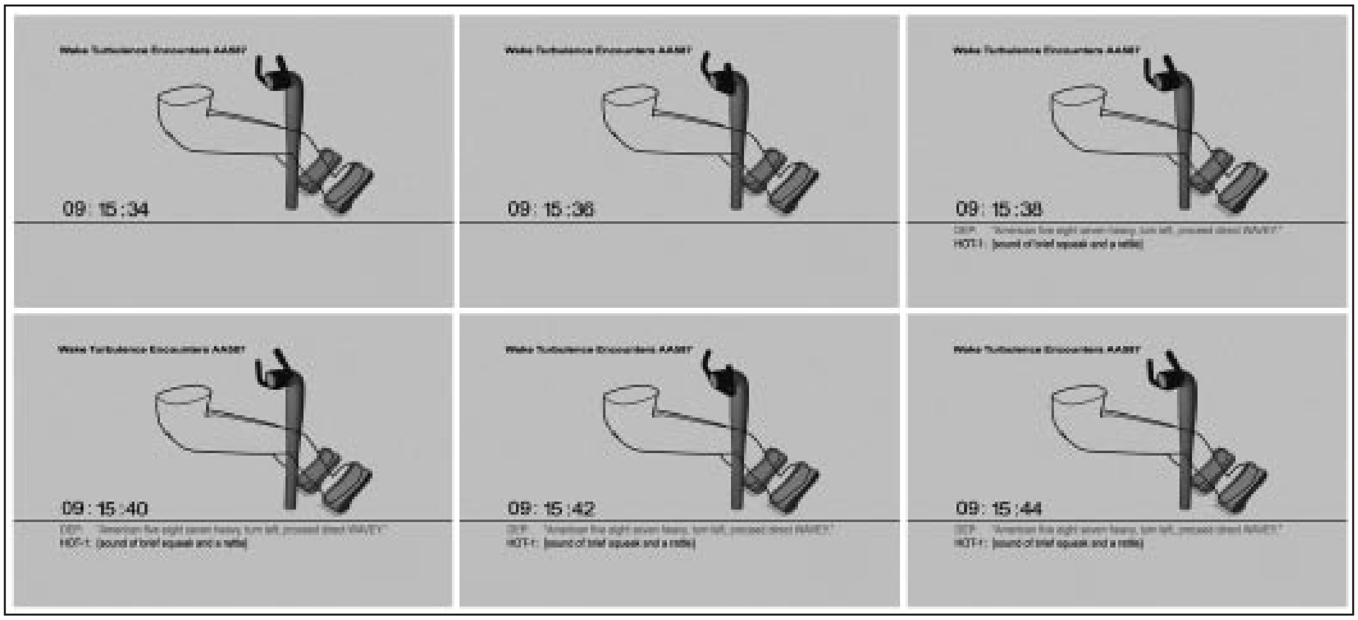

Figure 3. Control input during the first wake encounter (still images from the animation).

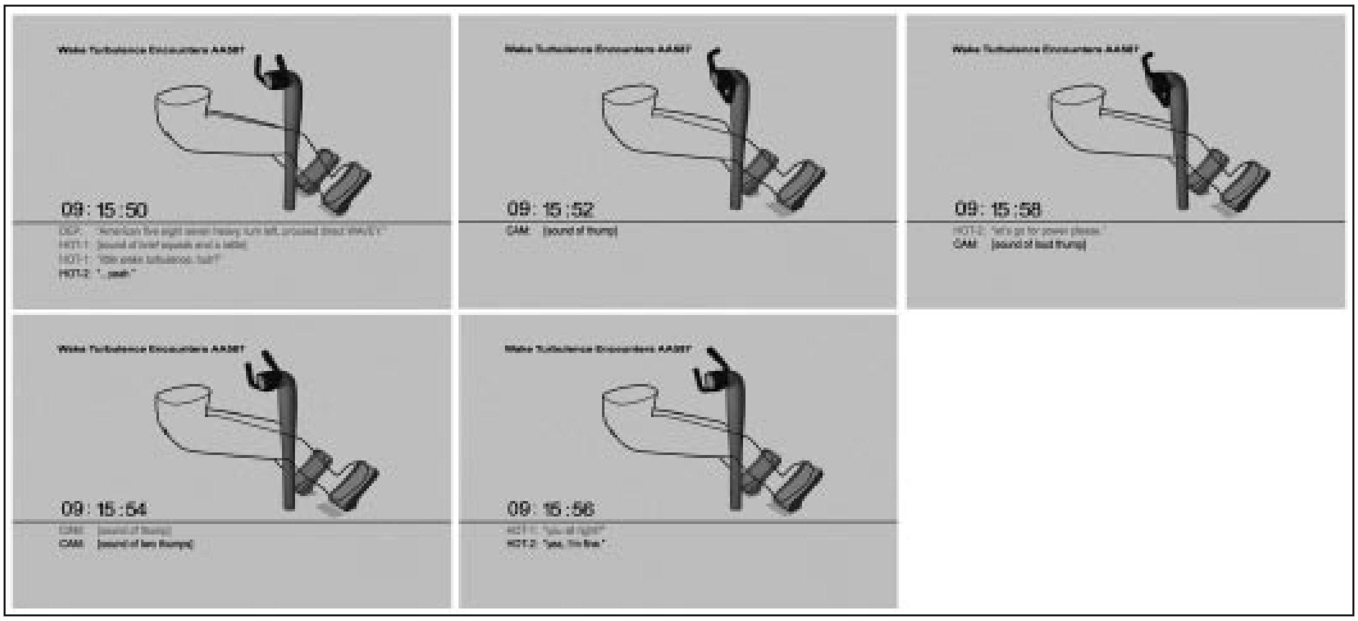

Figure 4. Control input during the second wake encounter (still images from the animation).

path using figures and still images only. Using animation, however, they could present the data clearly. The elevator control system animation was divided into two parts, the first being an overview, and the second depicting the components, functions, and motions of the cable system, demonstrating both a properly and an improperly adjusted cable system.

The flight path animation was based upon the FDR, radar data, and simulations. Figure 5 illustrates the process of turning the raw FDR data into a workable format and then importing it into a 3-D software package to drive the airplane motion. Engineering drawings like those in figure 6, as well as photographs, were used as references to represent the elevator control system and an accurate relationship and functions of its components. The following process was used in the animation reconstruction:

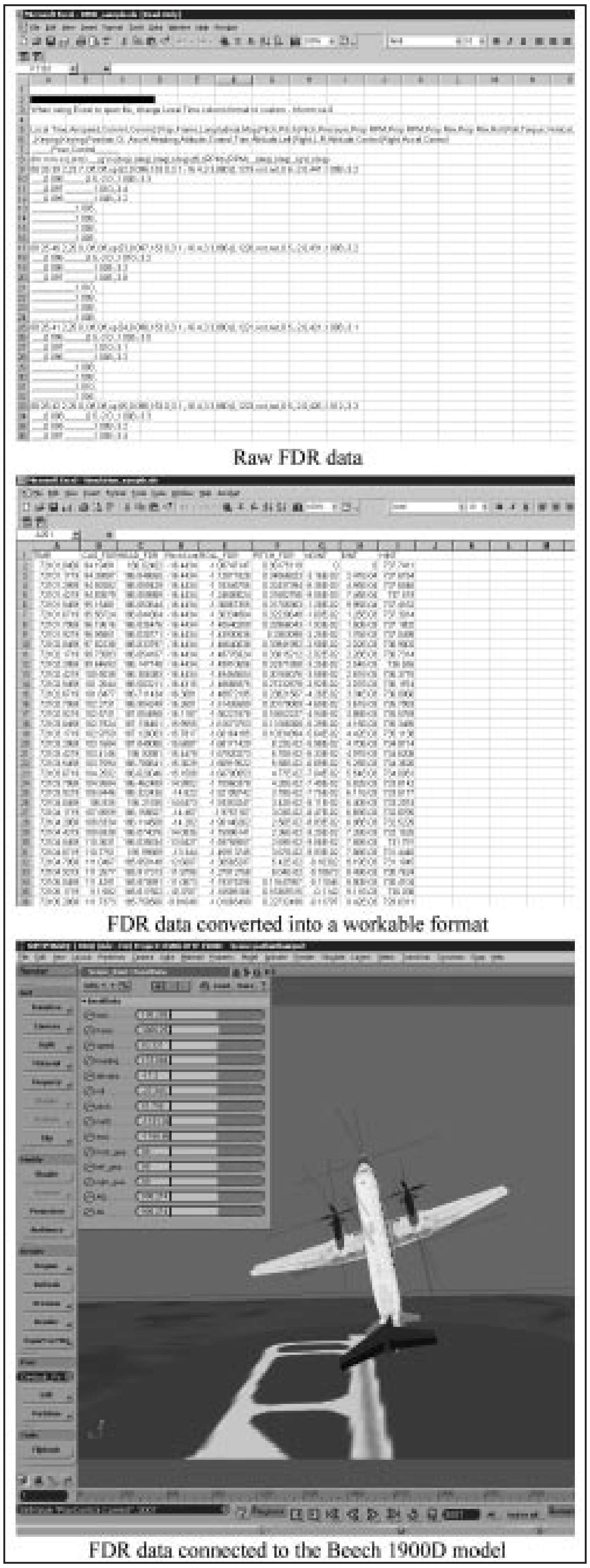

Figure 5. FDR data converted and inserted into the animation. (still images from the animation).

Elevator Control System

- Studied the control system and used engineering perspective to illustrate the mechanical systems.
- Modeled the system with great detail using manufactured engineering drawings and actual images (figure 6).
- Textured the components to produce a close representation of the actual system.
- Assembled the complex system and applied expressions to animate and ensure all parts functioned accordingly.
- Used appropriate effects and lighting to focus on essential parts of the cable system.
- Used multiple camera settings to capture the relationship of the various components of the cable system.
- Composited the rendered sequence with recorded narration (figure 8).

Flight Path

- Imported a commercially available Beechcraft 1900D model to XSI and modified it to meet our needs.
- Created the airport runway and hangar with documented and measured data using CAD; drew and mapped the surrounding images of the airport.
- Wrote XSI script to read the CVR text file and MS Excel spreadsheet containing the simulation-derived kinematics of the flight path as a function of time (figure 5).
- Set up multiple cameras to best capture the attitude deviations during takeoff.
- Synchronized digital time, airspeed, and altitude data with flight motion.
- Reviewed data accuracy against airplane attitude and motion to ensure accurate representation.
- Composited the data-driven flight path, digital time, altitude, and airspeed with selected cockpit communication (figure 7).

During the Board Meeting, investigators had to convey their findings clearly. It would have been challenging to explain the airplane motion associated with the cable system using the still image in figure 6. The animation provided a simple demonstration of the cable system and showed how the nose-down control

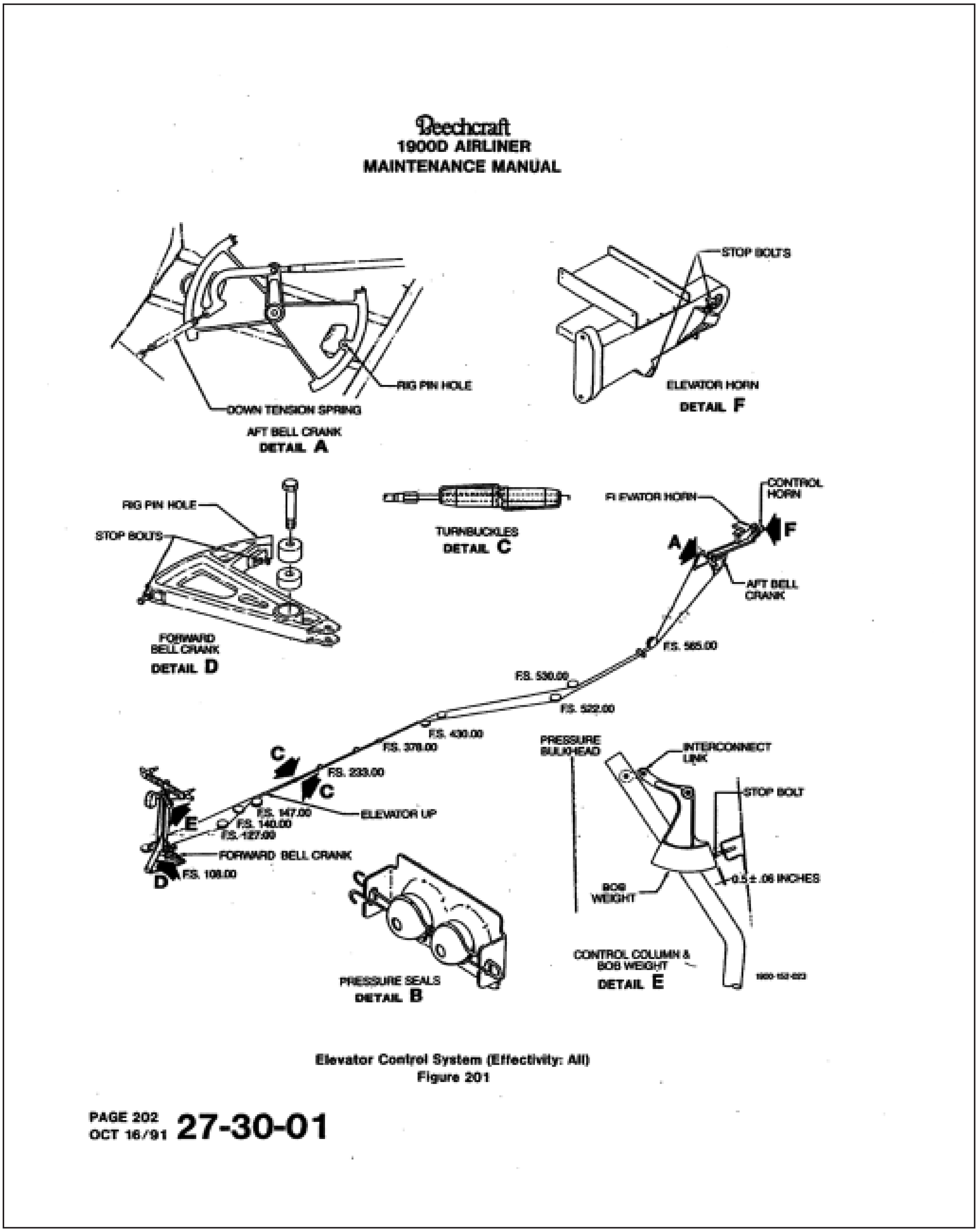

Figure 6. Engineering drawing of the elevator cable system.

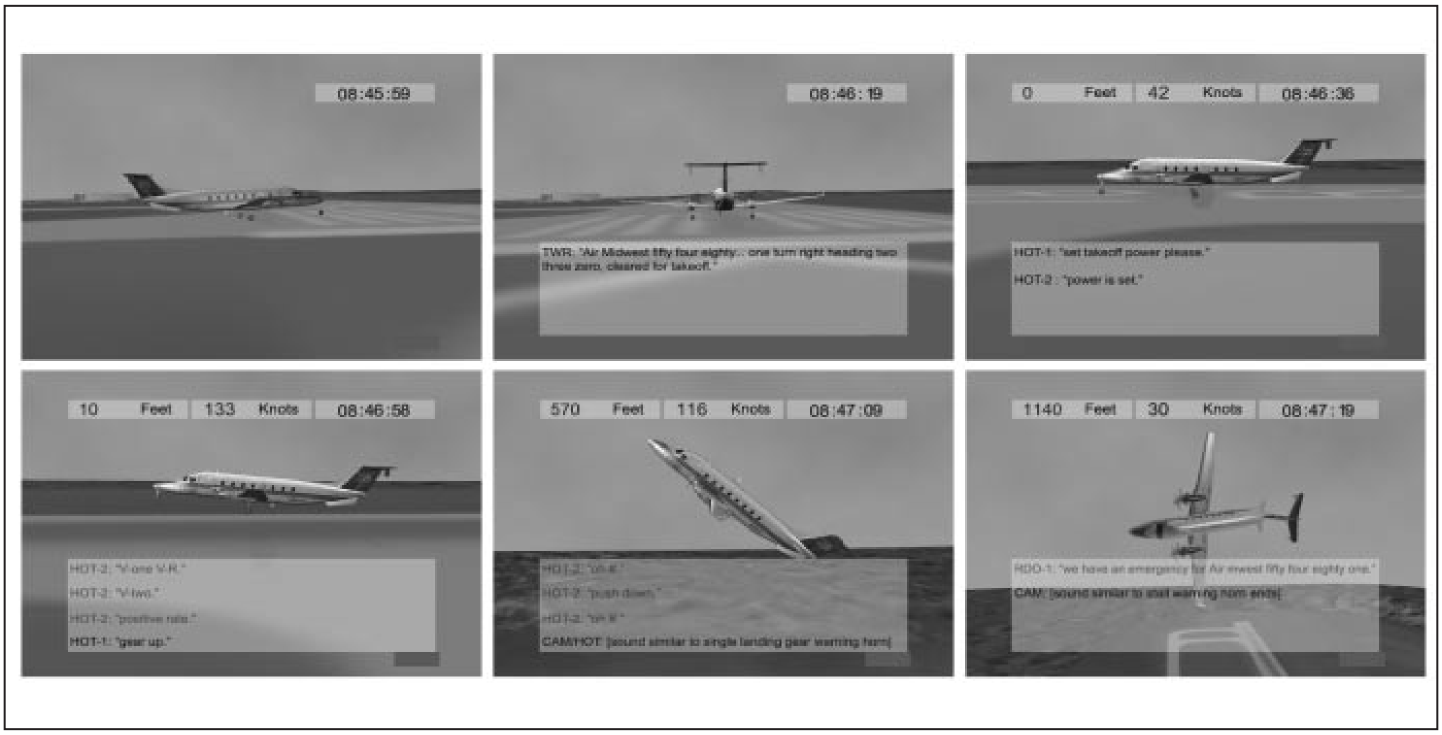

Figure 7. Still images from the flight path animation.

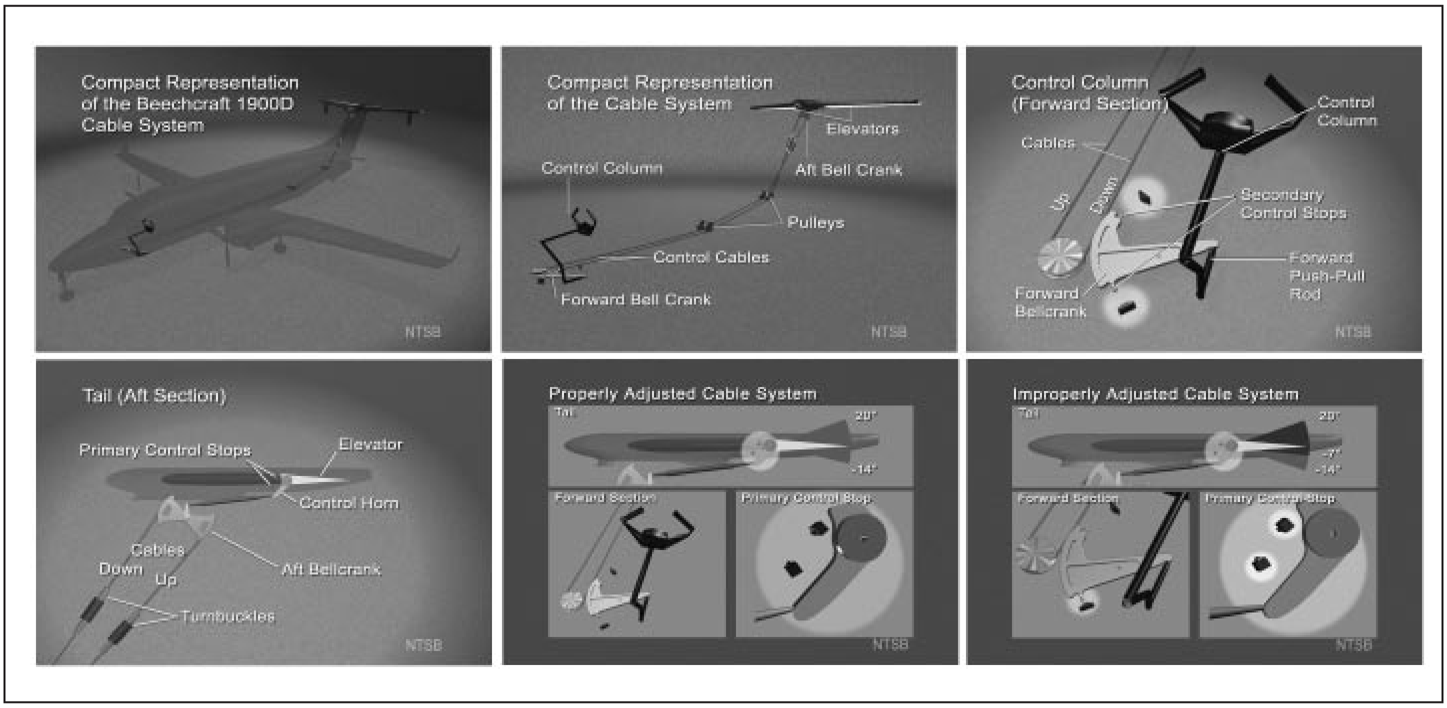

Figure 8. Still images from the elevator control system animation.

restriction resulting from incorrect rigging of the elevator control system caused the aircraft's loss of pitch control.

In the flight path animation, it was important to focus on the airplane motion. Therefore, the environment was simplified, showing only the runway and the hangar that was hit by the airplane. Similarly, only that part of the flight path that was significant to the probable cause was included. The time, altitude, speed, and selected cockpit communications were also shown to place the animation in perspective (figure 7). Because the elevator control system is quite complex, only certain components were needed to effectively communicate the functions and adjustments pertinent to this accident (figure 8). These animations of the cable mechanical system and the properly and improperly adjusted elevator control system effectively presented its correlation with the airplane's loss of pitch control during takeoff.

CONCLUSION

To determine and analyze the motion of an aircraft and the physical forces that produce that motion, accident investigators gather a variety of data that may not be easy to visualize. These data define aircraft position and orientation through the flight and are used to determine aircraft response to control inputs, system failures, external disturbances, or other factors that could affect its flight. Although figures and still images can be used to replicate this physical evidence, a concise and simple but detailed animation can greatly enhance investigators' ability to visualize and analyze the accident sequence of events. Animations also enable investigators to simultaneously depict individual data points in real time so that they can draw conclusions and identify probable cause based on that data. Similarly, animation can greatly simplify the explanation of those findings for a nontechnical audience, enabling them to understand the probable cause and any associated safety recommendations. For these reasons, the animations used to convey complex accident investigation data must incorporate simplicity, elegance, and scale of design. Engineers and animators work closely to achieve this result by carefully crafting a storyboard that lays out the data to tell a clear and coherent story. It is important to emphasize that such animations are worthwhile only if they are based on data that has been scrupulously measured, recorded, and calculated to ensure accuracy of results.

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- Air Midwest flight 5481. Animations: http://www.ntsb.gov/events/2003/AM5481/board_meeting_presentations/presentations.htm

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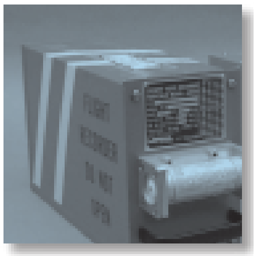


Aviation Recorder Overview

Dennis R. Grossi, National Transportation Safety Board

INTRODUCTION

A wide variety of airborne and ground-based aviation recording devices are available that can provide vital information for accident prevention purposes. The primary information sources include the mandatory crash-protected flight recorders, airborne quick access data recorders, and ground-based recordings of air traffic control (ATC) radar returns and radio communications. Other sources of recorded information, such as aircraft system internal memory devices and recordings of airline operational communications, have also provided vital information to accident investigators. These devices can range from nonvolatile memory chips to state-of-the-art solid-state flight recorders. With the exception of the mandatory flight recorders, these devices were designed primarily to provide recorded information for maintenance troubleshooting or specific operational requirements. Regardless of their original purpose, they have all been used in one form or another to investigate aviation accidents. This paper will give an overview of the evolution of flight recorder technology and regulatory requirements, and will describe the capabilities and limitations of the various types of recorded information available to the aviation community for accident prevention and, in particular, accident/incident investigation.

CRASH-PROTECTED FLIGHT RECORDERS

Evolution of Regulatory Requirements

First Flight Data Recorder

The need for a crash-survivable recording device became apparent following a series of airline crashes in the early 1940s. This spurred the Civil Aeronautics Board (CAB) to draft the first Civil Aviation Regulations calling for a flight recording device for accident investigation purposes. However, recorder development was delayed by shortages brought about by World War II. As a result, such a device was not available, and after extending the compliance date three times, the CAB rescinded the requirement in 1944. The CAB issued a similar flight recorder regulation in 1947, after the war, but a suitable recorder was still not available and the regulation was rescinded the following year.

During the 9 years that followed, the Civil Aviation Authority (CAA), the CAB, and aviation industry representatives studied the capabilities of recorder technology in an effort to develop new recorder requirements. Finally in 1957, after determining that suitable recording devices were available, the CAA issued a third round of flight recorder regulations. These regulations called for all air carrier airplanes over 12,500 pounds that operated above 25,000 feet to be fitted with a crash-protected flight recorder by July 1, 1958, that recorded altitude, airspeed, heading, and vertical accelerations as a function of time. This marked the introduction of the first true crash-protected flight data recorder in the U.S.

First Cockpit Voice Recorder (CVR)

As a result of a CAB recommendation to record flight crew conversation for accident investigation purposes, the Federal Aviation Administration (FAA) conducted a study in 1960 that established the feasibility of CVRs. The FAA produced airworthiness installation approval criteria and operating rules that called for the installation of a CVR in transport-category aircraft operated in air carrier service. The compliance dates were July 1, 1966, for all turbine-powered aircraft, and January 1, 1967, for all pressurized aircraft with four reciprocating engines.

1972 Flight Data Recorder Rule Change

FDR requirements remained virtually unchanged until December 10, 1972, when the rules for transport-category airplanes that received type certification after September 30, 1969, were amended to require an expanded parameter digital flight data recorder (DFDR) system. The expanded parameter requirements included existing parameters plus parameters for pitch and roll attitude, thrust for each engine, flap position, flight control input or control surface position, lateral acceleration, pitch trim, and thrust reverser position for each engine. Unfortunately, this rule change, which was retroactive to include the Boeing 747, did not affect airplanes like the Boeing 707, 727, and 737, and the McDonnell Douglas DC-8 and DC-9, all of which had type certificates issued before 1969. Therefore, existing and newly manufactured versions of these older aircraft types could be operated under the same FDR rules established in 1957. Flight recorder requirements remained essentially unaltered until the rule changes in 1987 and 1988.

1987 and 1988 Flight Recorder Rule Changes

During the 30 years following issuance of the original 1957 FDR regulations, the National Transportation Safety Board and its predecessor, the CAB, issued numerous safety recommendations to the FAA requesting upgraded recorder standards to meet the needs of accident investigators. The recommendations called for the following:

1. Replace original foil-type oscillographic recorder with digital recorders.

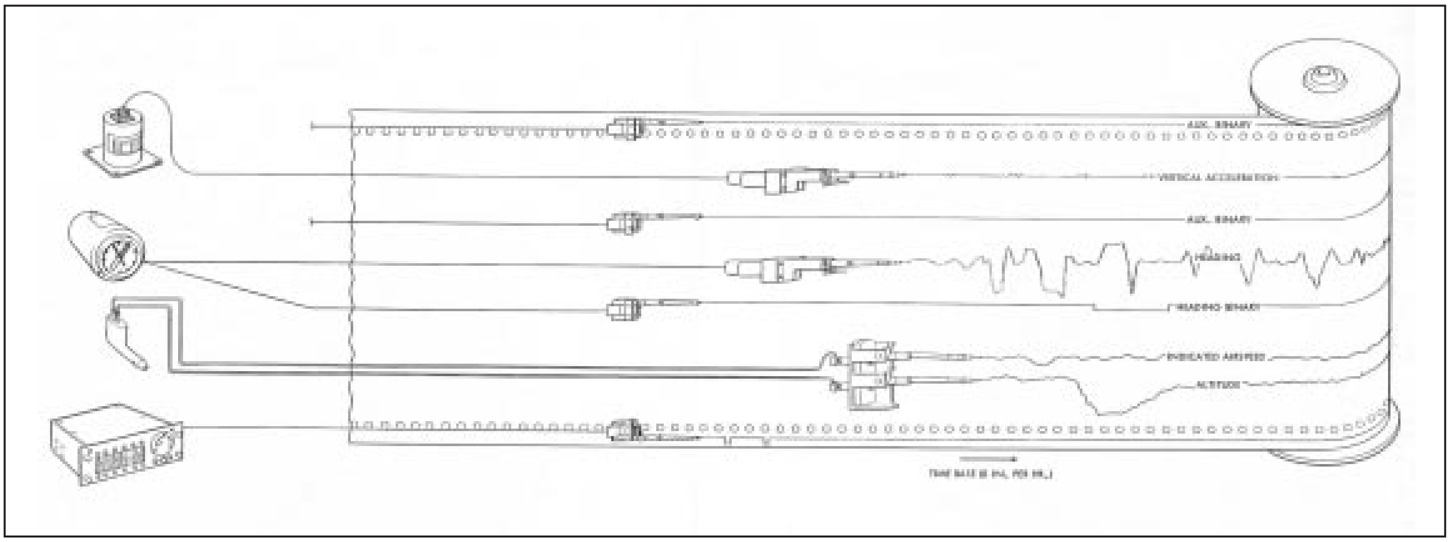


Figure 1. System schematic for a typical oscillographic foil recorder.

2. On existing transport-category airplanes, retrofit five-parameter FDRs with six additional parameters.

3. Expand parameter requirements for newly manufactured transport-category airplanes.

4. Require the flight crew to use hot-microphones below 18,000 feet.

5. Record hot-microphone channels on CVRs.

6. Require CVRs and FDRs for some air taxi and corporate executive aircraft.

The FAA repeatedly cited cost as the primary reason for not adopting the recommendations.

Following a series of high visibility accidents in the early 1980s, the FAA issued flight recorder rule changes in 1987 and again in 1988. These rule changes called for the following:

1. Replace oscillographic foil-type FDR digital recorders by May 26, 1989.

2. Increase the number of mandatory parameters for airplanes type-certificated before October 1969 to include pitch and roll attitude, longitudinal acceleration, thrust of each engine, and control column or pitch control surface position. (The original compliance date, May 26, 1994, was extended by 1 year to May 26, 1995.)

3. Require transport-category airplanes (20 or more passengers) manufactured after October 11, 1991, to record 28 parameters in a digital format.

4. Require existing transport-category airplanes (20 or more passengers) fitted with a digital data bus to record 28 parameters in a digital format.

5. Require all multiengine turbine-powered air taxi aircraft capable of carrying 10-19 passengers and manufactured after October 11, 1991, to have a 17-parameter FDR.

6. Extend the CVR requirements to multiengine turbine-powered aircraft capable of carrying six or more passengers and requiring two pilots.

7. Require flight crews to use existing CVR hot-microphone systems below 18,000 feet.

1997 Flight Data Recorder Rule Changes

Following two fatal Boeing 737 accidents (United flight 585, Colorado Springs, Colorado, July 1989, and USAir flight 427, Pittsburgh, Pennsylvania, September 1994), the Safety Board reexamined FDR parameter requirements, and as a result, made safety recommendations to the FAA that called for the following:

1. Require additional parameters for most existing air transports that focused on recording crew flight control inputs and the resulting control surface movements, with parameter retrofits to be completed by January 1, 1998.

2. Increase parameter requirements for transport airplanes manufactured by January 1, 1996.

3. Urgent retrofit of all Boeing 737 airplanes with FDR parameters to record lateral acceleration, crew flight control inputs, and the resulting control surface movements by the end of 1995.

The FAA responded by issuing a notice of proposed rulemaking (NPRM) in August 1996 and a final rule on August 18, 1997. Although the final rule generally met the requirements of the safety recommendations, the compliance dates were significantly relaxed from those recommended by the Safety Board. In addition, the FAA did not agree with the urgent recommendation to retrofit Boeing 737s by the end of 1995. However, the final rule did require that air transports record flight control crew inputs and control surface position. The final rule called for the following:

1. Transport airplanes type certificated before October 1, 1969, and manufactured before October 11, 1991, must record as a minimum the first 18 to 22 parameters listed in the rule by August 18, 2001.

2. Transport airplanes manufactured after October 11, 1991, and before August 18, 2001, must record as a minimum the first 34 parameters listed in the rule by August 18, 2001.

3. Transport airplanes manufactured after August 18, 2000, must record as a minimum the first 57 FDR parameters listed in the rule.

4. Transport airplanes manufactured after August 18, 2002, must record as a minimum all 88 FDR parameters listed in the rule.

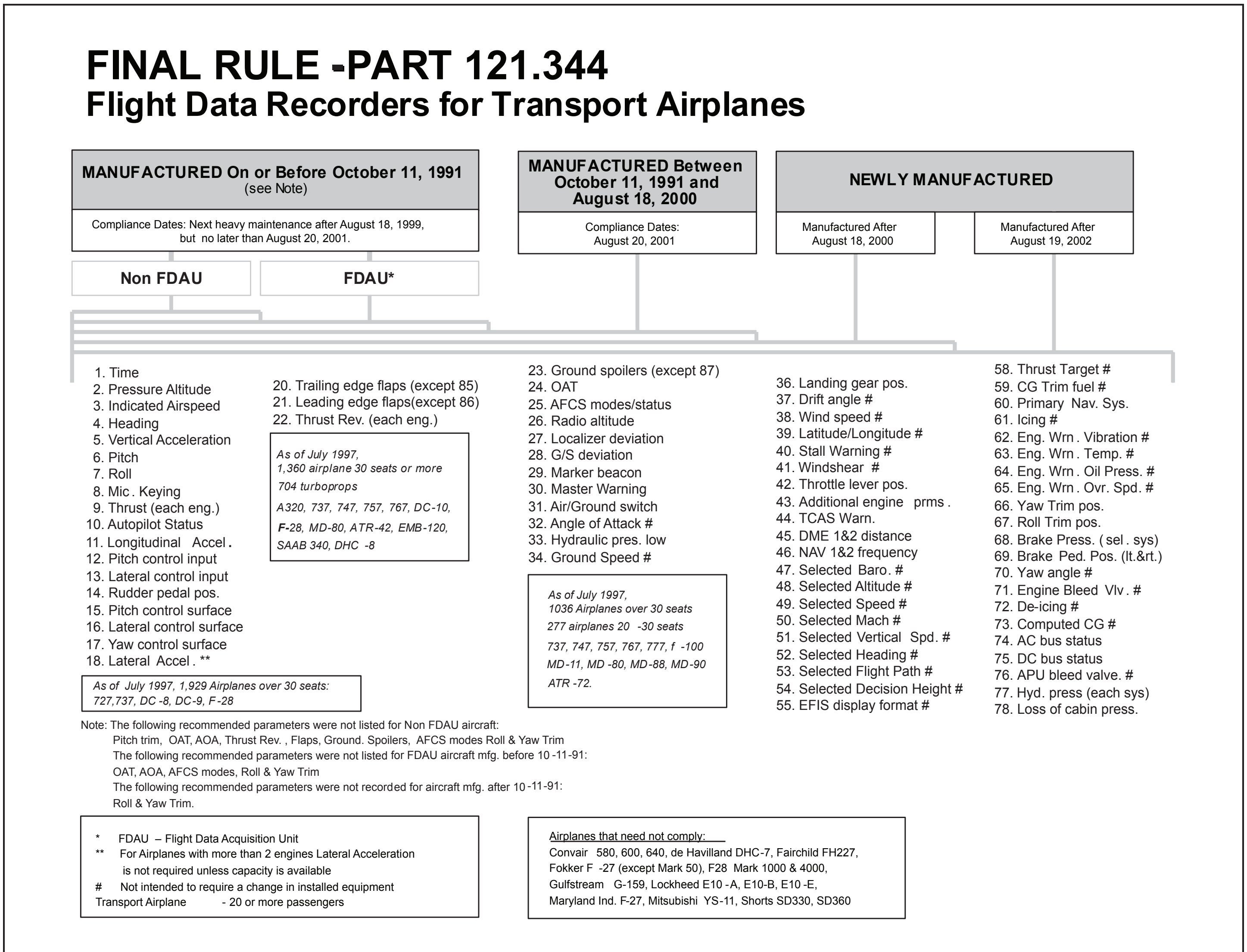
The specific parameter requirements are contained in table 1.

March 9, 1999
NTSB and TSB Flight Recorder Recommendations

The Transportation Safety Board of Canada (TSB) and the Safety Board worked together to develop the March 9, 1999, recommendations following the September 2, 1998, accident of Swissair flight 111, an MD-11. The regularly scheduled passenger flight from New York to Geneva, Switzerland, diverted to Halifax after the crew reported smoke in the cockpit. The airplane crashed into the waters near Peggy's Cove, Nova Scotia, killing all 229 passengers and crew on board. The investigation was severely hampered by the lack of data from the CVR and FDR, which stopped nearly 6 minutes before the airplane hit the water.

The Swissair accident was another in a long history of accident and incident investigations that were hindered by the loss of flight recorder information due to the interruption of aircraft electrical power to the flight recorders. However, innovations in recorder and power supply technologies have resulted in the development of an independent power source that would provide sufficient power to operate a solid-state flight recorder for 10 minutes. In addition, the availability of combined voice and data recorders has introduced the possibility of fitting two combined recorders on newly manufactured airplanes, with one recorder near the cockpit to reduce the probability of a mechanical or electrical interruption of the signals and power supply, and the second recorder as far aft as practical to enhance survivability. The Embraer-170, a recently introduced regional jet (RJ), is the first aircraft to be fitted with fore and aft "combi" recorders.

Table 1. Parameter requirements for air carrier flight data recorders.



As a result of the Swissair accident, the Safety Board and the TSB issued safety recommendations on March 9, 1999, to require the following:

1. By January 1, 2005, retrofit aircraft with a 2-hour solid-state CVR that is fitted with an independent power supply capable of operating the CVR and area microphone for 10 minutes when aircraft power to the CVR is lost.

2. By January 1, 2003, fit all newly manufactured airplanes that are required to carry both a CVR and FDR with two combined voice and data recorders, one recorder located as close to the cockpit as practical and the other as far aft as practical.

3. Amend Title 14 U.S. *Code of Federal Regulations* to require that CVRs, FDRs, and combination flight recorders be powered from separate generator buses with the highest reliability.

In a March 19, 1999, letter, the FAA agreed to the recommendations without revision and promised to issue an NPRM by the end of the summer. However, the promised NPRM was not released until February 2005, and the Safety Board made additional flight recorder recommendations in the interim. These recommendations were prompted by the lack of recorder data for some air taxi accidents involving aircraft not required to have a recorder, the need for cockpit image recordings for a series of air carrier accidents, and the need for increased sampling rates for some FDR parameters. These recommendations if adopted would require the following:

1. Issue an image recorder technical standard order (TSO), followed by installation of an image recorder on existing and newly manufactured turbine-powered aircraft engaged in Part 121, Part 135, and commercial or corporate Part 91 operations not currently required to have a flight recorder.

2. Retrofit all turbine-powered aircraft that have the capability of carrying six or more passengers engaged in Part 121, 135, or 91, with a 2-hour CVR.

3. Equip existing and newly manufactured Part 121, 125, and 135 aircraft required to have a CVR and FDR with a 2-hour crash-protected image recorder capable of recording a color image of the entire cockpit.

4. Require that all transport-category aircraft FDRs be capable of recording values that meet the accuracy requirements through the full dynamic range of each parameter at a frequency sufficient to determine a complete and unambiguous time history of the parameter.

The February 2005 NPRM addressed most of the Safety Board's recommendations for flight recorder enhancements, proposing that CVR duration be increased to 2 hours, that the sampling rate for some FDR parameters be increased, and that physical separation of the CVR and FDR be required. The NPRM also allowed a single combined CVR/FDR on some rotorcraft, improved power supply reliability including a 10-minute independent power supply, and the recording of data-link communications when so equipped. The NPRM did not address cockpit image recorders or the installation of forward- and aft-mounted combined FDR/CVR recorders on newly manufactured transports.

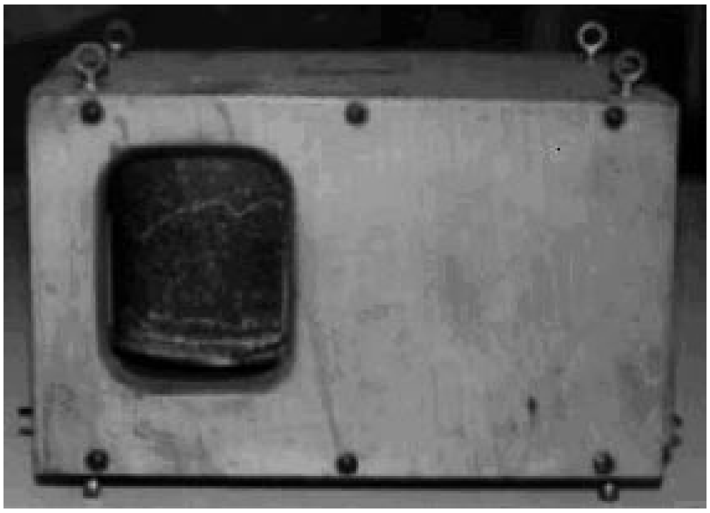


Figure 2. Spirit of St. Louis flight recorder.

EVOLUTION OF FLIGHT RECORDERS

Flight data recorders can be traced back to the origins of power flight. Wilbur and Orville Wright's historic first flight was documented by the first flight data recorder. This rudimentary device recorded propeller rotation, distance traveled through the air, and fight duration. Charles Lindbergh's airplane the *Spirit of St. Louis* was also fitted with a flight-recording device. Lindbergh's recorder was a bit more sophisticated, employing a barograph that marked changes in barometric pressure or altitude on a rotating paper cylinder (see figure 2).

These early recordings survived because they were designed to record historical events, not mishaps. The first practical crash-protected flight data recorder was not introduced until 1953. This recorder used styli to produce individual oscillographic tracings for each parameter on metallic foil. Time was determined by foil movement, which typically advanced at a rate of 6 inches per hour. This often resulted in an entire accident sequence being recorded within a 0.1 inch of foil movement. Investigators recovered the recorded information by optically reading the scribed markings through a microscope, and then converting the displacement of the scribed marks from the reference line to engineering units. This process was very time consuming and required a significant amount of reader interpretation.

The 1957 regulations that mandated the installation of FDRs by July 1958 created a market for FDRs that attracted other manufacturers who also used the metal foil oscillographic technique (see figures 3 and 4). The regulations also required compliance with TSO C-51. This TSO defined range accuracy, sampling interval, and type parameters to be recorded (altitude, airspeed, heading, vertical acceleration, and time) and specified the requirement to survive a crash shock of 100 g and envelopment in an 1100° C flame for 30 minutes. The TSO also defined three basic types of flight recorders:

Type I: a non-ejectable recorder, unrestricted location

Type II: a non-ejectable recorder, subjected to a minimum 15-minute fire test, restricted to any location more than ½ of the wing root chord from the main wing structure through the fuselage and from any fuel tanks

Type III: an ejectable recorder, minimum 1.5 minutes fire test, unrestricted location.

Figure 3. Early Lockheed model 109.

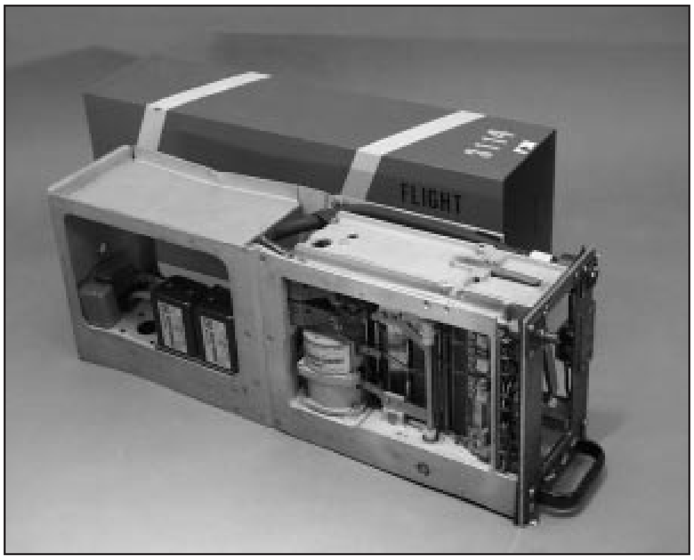


Figure 4. Sundstrand Model 542 FDR, 1/2 ATR long format.

The early recorders were all of the Type I design and most were mounted in the cockpit area or in the main gear wheel well. Unfortunately, these locations subjected the recorders to fire and impact forces that destroyed or severely damaged the recording medium. Type II and III recorders were never fitted to commercial air carriers; however, type III ejectable recorders are currently in use on some military aircraft.

In the early 1960s, the CAB made a series of recommendations to the FAA that called for additional protection for FDRs against impact force and fire damage, and also recommended relocating the recorders to the aft area of the fuselage to provide maximum protection of the recording media. As a result, the FAA issued rule changes that specified the location of the recorder as far aft as practical and upgraded the performance standards in TSO C-51, reissuing it as C-51a. The upgraded TSO specifications increased the impact shock test from 100 g to 1,000 g and introduced static crush, impact penetration, and aircraft fluid immersion tests. The fire test was not changed. Unfortunately, neither TSO contained an adequate test protocol to ensure uniform and repeatable test conditions.

At about the same time as the foil recorders were being developed in the United States, recorders that used magnetic steel wire as a recording medium were being developed in the United Kingdom. The wire recorders were the first to use digital pulse coding as a recording method. The robust design of the wire recorder made it a fairly reliable recorder for its time. Although the wire-recording medium was fairly impervious to postimpact fires, it did not fare as well with impact shock. The wire would often brake into several sections and become tangled, making it difficult and tedious to reassemble in the proper sequence.

In the late 1940s, the French developed an FDR that used a photographic system that recorded data on light-sensitive paper.

Table 2. Early flight recorder crash/fire survivability standards.

	TSO C84 CVR Requirements	**TSO C-51 FDR Requirements**	**TSO C-51a FDR Requirements**
Fire	1100°C flame covering 50% of recorder for 30 minutes	1100°C flame covering 50% of recorder for 30 minutes	1100°C flame covering 50% of recorder for 30 minutes
Impact Shock	100 g	100 g	1000 g for 5 ms
Static Crush	None	None	5,000 pounds for 5 minutes on each axis
Fluid Immersion	None	None	Immersion in aircraft fluids (fuel, oil, etc.) for 24 hours
Water Immersion	Immersion in sea water for 48 hours	Immersion in sea water for 36 hours	Immersion in sea water for 30 days
Penetration Resistance	None	None	500 pounds dropped from 10 feet with a ¼-inch-diameter contact point

Its obvious disadvantages were flammability and the tendency of the recording to disappear when subjected to light. The French later adopted the metal foil oscillographic recorder.

Cockpit Voice Recorder

In response to CAB recommendations, the FAA conducted a study in 1960 to determine the feasibility of recording the spoken words of the flight crew for accident investigation purposes. Although cockpit ambient noise levels posed a significant obstacle to 1960 recording technology, the study showed that recording crew conversation was feasible. The following equipment capabilities were initially proposed:

1. Record each crewmember's conversation, both transmitted and received, with ground facilities and on the airplane's intercommunication system. Also, record other conversation in the cockpit not conducted over those media. Provide sufficient channels to preclude the possibility of more than one crewmember recording on a channel at one time.
2. Retain the last 30 minutes of the crew's conversation.
3. Provide for stopping the recorder in the case of a crash so that the last 30 minutes of conversation is not erased or overwritten.
4. Ensure that recorder can withstand the crash conditions required in TSO-C51.
5. Ensure that recording is intelligible over the ambient noise of the cockpit or that unwanted noise can be filtered from the record with appropriate ground equipment.
6. Ensure that recorder is capable of recording crew voices, other than on the communication and intercommunication systems, without the use of lip or throat microphones.
7. Inform the crew when the recorder is operating properly.

As a result, the FAA issued rules mandating the use of CVRs on all transport-category aircraft and issued TSO C-84, which established crash fire survivability and equipment approval standards.

Magnetic Tape Flight Recorders

The introduction of the CVR in the late 1960s and DFDRs in the early 1970s made magnetic tape the recording medium of choice until the introduction of solid-state flight recorders in the late 1980s. Recorder manufacturers used a variety of tapes and tape transports. The most widely used tapes were Mylar®, kapton, and metallic. The tape transports were even more varied, using designs such as coplaner reel-to-reel, coaxial reel-to-reel, endless loop reel packs, and endless loop random storage.

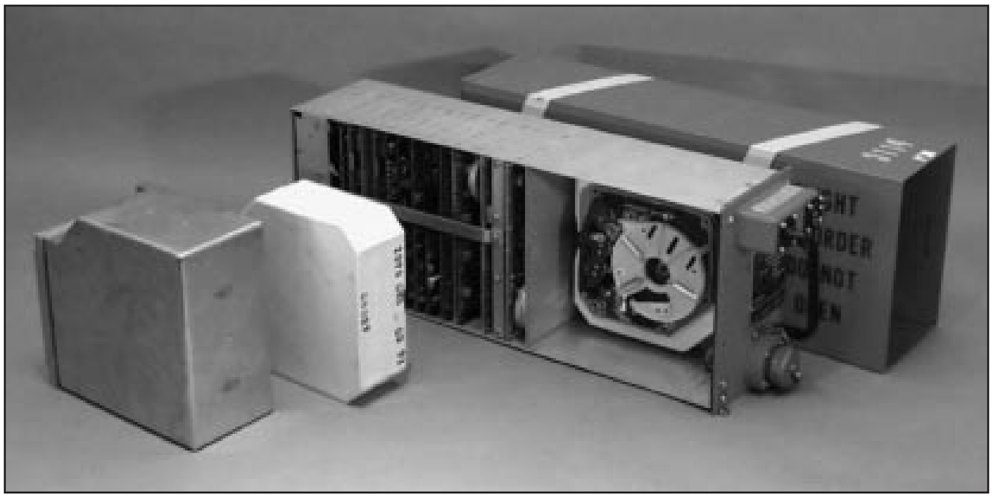


Figure 5. Fairchild model F800 DFDR, 1/2 ATR long format.

Tape CVRs recorded four channels of audio for 30 minutes, and the DFDR recorded 25 hours of data. CVRs and FDRs recorded over the oldest data with the newest data in an endless loop-recording recording pattern. The DFDR tape transport and protective enclosure shown in figure 5 is an endless loop real pack design adapted from a 1960s CVR.

All of the magnetic tape flight recorders, including the units that used metallic tape, were found to be susceptible to thermal damage during postcrash fires. Although the TSOs called for a high-intensity fire test, the lack of a detailed test protocol allowed for a less than adequate design to be approved. In addition, the real world experience would show magnetic tape flight recorders to be most vulnerable when exposed to long duration fires, a test condition not required at the time tape flight recorders received TSO approval. In addition, metallic tapes were found to be vulnerable to impact shock, which tended to snap the tape, releasing the spring tension and unwinding the tape, causing further tape damage and loss of data.

Digital Recording Method

The DFDR and its companion recorder, the quick access recorder (QAR), were introduced about the same time. DFDRs and QARs use the same recording techniques, but as the name implies, the QAR can be quickly accessed and downloaded. Most early model QAR systems recorded far more parameters than the mandatory DFDR systems. As nonmandatory recorders, QARs were not designed to survive a crash impact and postimpact fire, although a number have survived fairly significant crashes.

Most DFDRs and QARs require a flight data acquisition unit (FDAU) to provide an interface between the various sensors and the DFDR. The FDAU converts analog signals from the sensors to digital signals that are then multiplexed into a serial data stream suitable for recording by the DFDR. Industry standards dictate the format of the data stream, which for the vast majority of tape-based DFDRs is 64 12-bit data words per second. The recording capacity of the tape DFDR is limited by the length of tape that can be crash-protected and the data frame format. The capacity of the tape DFDRs was adequate for the first generation of wide-body transports, but was quickly exceeded when aircraft like the Boeing 767 and Airbus A320 with digital avionics were introduced.

Digital Avionics Systems

The introduction of digital avionics systems into commercial aviation in the early 1980s significantly increased the amount of information available to DFDRs and QARs. Digital avionics also brought about digital data buses, which carry digital data between systems. This made vast amounts of critical flight and aircraft system information available to the DFDR and QAR simply by tapping into the buses. The introduction of digital data buses also brought about digital FDAUs (DFDAU). The FDAU and DFDAU perform the same function except that DFDAUs can interface with the data buses and analog sensors.

Solid-State Flight Recorders

The introduction of solid-state flight recorders in the late 1980s marked the most significant advance in evolution of flight recorder technology. The use of solid-state memory devices in flight recorders has expanded recording capacity, enhanced crash/fire survivability, and improved recorder reliability. It is now possible to have 2-hour CVRs and DFDRs that can record up to 256 12-bit data words per second, or 4 times the capacity of magnetic tape DFDRs. Survivability issues identified over the years have been addressed with new crash/fire survivability standards developed in close cooperation between accident

Figure 6. Typical solid-state CVR and DFDR.

investigators and the recorder industry (see table 3). The lack of moving parts in solid-state recorders has greatly improved recorder reliability.

Future Flight Recorder Capabilities Requirements

As proposed in the Safety Board's March 9, 1999, recommendation letter to the FAA, two combination voice-data recorders built to TSO C123a and C124a standards will provide the redundant recording capabilities that separate CVRs and DFDRs cannot. Locating one recorder in the nose of the aircraft and the other in the tail will further enhance the probability of capturing catastrophic events that would otherwise compromise the CVR and DFDR when they are colocated. The forward-mounted flight recorder will be close to the cockpit and the avionics compartment, which reduces the possibility of signal loss. The addition of a 10-minute, independent alternate power supply adjacent to the flight recorder will further enhance the possibility that the recorder will be powered and critical data will be recorded until the end of the flight.

The next-generation combination flight recorders will be required to record more than the traditional voice and data parameters. The FAA's February 2005 flight recorder NPRM calls for the recording of Controller Pilot Data Link (CPDL) messages if an aircraft is equipped to use data-link communications. Recent advancements in video technology have made video recording a distinct possibility in the not-too-distant future. The International Civil Aviation Organization (ICAO) Flight Recorder Panel has concluded that video technology has matured to the point that specific technical aspects must be determined. The European Organization for Civil Aviation Equipment (EUROCAE) has since issued its image recorder standard, which was recently incorporated into a notice of proposed technical standard order C176, *Aircraft Image Recorder Systems*.

Table 3. Current flight recorder crash/fire survivability standards.

	TSO C123a (CVR) and C124a (DFDR)
Fire (High Intensity)	1100°C flame covering 100% of recorder for 30 minutes. (60 minutes if ED56 test protocol is used)
Fire (Low Intensity)	260°C Oven test for 10 hours
Impact Shock	3,400 g for 6.5 ms
Static Crush	5,000 pounds for 5 minutes on each axis
Fluid Immersion	Immersion in aircraft fluids (fuel, oil etc.) for 24 hours
Water Immersion	Immersion in sea water for 30 days
Penetration Resistance	500 pounds dropped from 10 feet with a ¼-inch-diameter contact point
Hydrostatic Pressure	Pressure equivalent to depth of 20,000 feet

AIR TRAFFIC CONTROL RADAR AND AUDIO RECORDINGS

Ground-based recordings of the air traffic control (ATC) radar and radio transmissions provide aircraft communication and position time history information. The FAA records all radio communications between controllers and pilots, and also landline communications between controllers. Air Route Traffic Control Centers (ARTCC) provide complete radar coverage of the United States and parts of Canada and Mexico. In addition, most ATC airport approach radar facilities also record.

ATC Communication Recordings

Recordings of the two-way radio communications between controllers and pilots and inter-controller communications via landlines are maintained for 30 days. In the event of an accident or incident, the original recording of the event can be set aside and retained for investigators; otherwise, the recording medium will be reused and the information lost.

The ATC communications recordings have provided vital information to investigators. In instances where the aircraft are not fitted with a CVR, these recordings provide the only record of flight crew communications and have at times provided background sounds (for example, wind noise, rotor speed, sounds of cockpit warnings) that have proven to be vital to the investigations. A time code is also recorded with the audio communications to provide a time reference independent of any subtle recording anomalies.

ATC and Other Radar Recordings

Recorded radar data can provide aircraft position time history information by recording the position coordinates of individual radar returns, time, and when available, altitude and identification information transmitted from the aircraft. Altitude and identification data are produced by a transponder[1] fitted to the aircraft that also reinforces the radar return.

The rate at which the radar antenna rotates will determine the sampling interval between returns. ARTCC rotates at between 5 to 6 revolutions per minute (that is, generating radar returns every 10 to 12 seconds), whereas airport approach radar antennas do a complete rotation every 4.8 seconds. The most accurate position coordinates recorded by the ARTCC are in latitude and longitude, whereas approach radar records position coordinates as range and azimuth values, and both record the transponder-generated altitude values.

Military and private radar facilities can provide similar position time history information. Military aircraft Airborne Warning and Control Systems (AWAC) and naval vessel radar data are also recorded and are available to investigators upon request.

Use of ATC Recordings by Accident Investigators

The importance of ATC recorded data is determined by the circumstances surrounding an accident or incident. Accidents or incidents involving very dynamic conditions, such as aerodynamic stall and loss of control, are difficult to evaluate with ATC data alone. ATC data are more significant for less dynamic accidents, such as controlled flight into terrain, or when used in conjunction with FDR and CVR data.

Correlation of events common to the ATC recordings and the FDR and CVR recordings can provide a very accurate local time reference. This can become critical because the FDR and CVR are only required to record relative time, and the local time reference may vary from one ATC facility to the next. ATC radar and FDR data can be correlated by comparing the altitude time histories, and ATC communication recordings can be correlated by the radio transmission time histories recorded by the various ATC facilities and the CVR and FDR.

In addition to a time reference, ATC-recorded information also provides ground track reference, which is essential in performance-related accidents. A wind model can be developed when radar flight path data are combined with FDR parameters, such as altitude airspeed and heading and airplane acceleration parameters. This is particularly useful in accidents or incidents involving dynamic meteorological conditions, such as wind shears or crosswind and turbulence conditions.

ATC radar data are particularly useful in evaluating the relative position of aircraft when multiple aircraft are involved. Investigations of mid-air collisions and wake turbulence encounters rely heavily on this information.

Significant accuracy and resolution limitations must be considered when using recorded radar data. The accuracy limitations are known and should be factored into the ground track calculations. The sampling intervals of 4.7 to 12 seconds present a significant limitation on usefulness of recorded radar data.

NONVOLATILE MEMORY DEVICES

Modern aircraft use an increasing number of microprocessor-based electronic devices for operational and maintenance purposes. As a result, aircraft are fitted with nonvolatile memory (NVM) to store information, such as flight

1 A transponder is a receiver/transmitter that generates a reply signal upon proper interrogation from a radar facility.

crew entries to the navigation database, system fault messages generated by electronic control devices, and system status messages. These devices, generally known as electronically erasable read-only memory (EEROM), provide temporary storage of transitional information during power interruptions. The term "nonvolatile" implies that the stored information will be available if the system is electrically powered or not.

Accident investigators have found NVM to be a valuable source of information. However, because NVM is not crash- or fire-protected, there is no assurance that it will be available following a catastrophic accident. That said, NVM has survived severe impacts and postimpact fires in a significant number of cases.

The recovery of information from undamaged NVM systems can be as simple as powering the system and reading or downloading the information. Damaged units may require system experts at the manufacturer's facility to disassemble the unit to recover the information using specialized equipment and software.

The amount of effort and technical expertise needed to recover information from NVM is generally determined by the amount of damage and system complexity. The first step in the recovery process is a visual inspection of the disassembled unit to determine the amount of damage. It may be possible to simply replace a damaged connector or place the circuit board containing the memory device in a serviceable unit to recover the data. However, extreme caution must be taken when applying power to units that are suspected of receiving impact shocks that exceed the normal design requirements: an undetected short or open circuit might result in the loss of the stored data.

Example: Lauda Air, Flight NG004, May 26, 1991

The May 26, 1991, fatal accident of Lauda Air flight NG004, a Boeing 767 that crashed in Suphan-Buri Province, Thailand, demonstrated the importance of NVM. The aircraft departed controlled flight while climbing through 24,000 feet and experienced an in-flight breakup during the recovery maneuver and subsequently crashed in the jungle. The FDR magnetic tape recording medium was destroyed by the postcrash fire and provided no data. However, crew comments recorded by the CVR indicated a problem with an engine thrust reverser just before the loss of control.

The electronic engine control (EEC) units for both engines were removed from the aircraft wreckage and brought to the manufacturer's facility in Windsor Locks, Connecticut, to recover the fault messages stored in the NVM. The EECs showed signs of severe impact shock. As a result, the EEROMs containing the NVM were removed from the circuit board and mounted on an identical laboratory test unit. A normal fault message download was performed and the data were subsequently processed using the manufacturer's proprietary software.

Each time an EEC fault message was generated, the following information was captured and stored in NVM:

- diagnostic fault messages codes
- values for N1 (high pressure compressor rotation speed), P2 (fan inlet total pressure), mach number, temperature (cold junction compensation)
- fault time in elapsed hours
- logging of flight and leg cycles

The recovered data contained diagnostic messages from the last 390 hours of operation, which spanned 95 flights. The EECs from the left engine, which experienced the uncommanded thrust reverser deployment, provided a significant amount of information specifically relating to the faulty thrust reverser and ancillary altitude, airspeed, and engine thrust values provided key reference values, which gained significance in light of the loss of the FDR data. The EEC from the right engine, which did not record any faults during the accident flight, yielded little additional information.

CONCLUSIONS

As far back as the early 1940s, the aviation community realized that, if commercial aviation were to prosper, public confidence must be gained and maintained through a quick and accurate determination of probable cause of any aviation mishap. It was also obvious that the nature of aviation accidents would require the use of recording devices to provide accident investigators with the information needed to determine the cause of a mishap and take the proper corrective action to prevent a similar mishap from recurring.

The first flight recorders introduced over 40 years ago gave accident investigators their first appreciation of the recorder's safety potential. However, the data provided by these early recorders were limited and often of such poor quality that investigators could at best determine what happened, but not with a high degree of certainty as to why it happened.

Flight recording technology has had to adapt to a rapidly evolving commercial aviation industry and the corresponding needs of accident investigators. One of the most significant changes in recorder technology occurred in the early 1970s with the introduction of digital data recorders. The amount and quality of data provided by DFDRs, CVRs, and other recorded data, like ATC radar, gave accident investigators their first real opportunity to pursue an in-depth evaluation of the facts, conditions, and circumstances surrounding an occurrence. The introduction of digital recordings also made it practical to use flight recorder data proactively.

The introduction of digital avionics and fly-by-wire technologies in the 1980s provided investigators with challenges and opportunities. This new technology eliminated some well-established investigative techniques while offering an opportunity to record and recover vast amounts of previously unattainable information. Indeed, the amount of available information overwhelmed early-model DFDRs. However, the advent of solid-state recorders has solved the recorder capacity problem while improving survivability and reliability.

The future of flight recording is promising. Advances in recorder and aircraft systems will allow for the introduction of recording techniques to record video images of the cockpit and data link messages, as well as providing more opportunities for the proactive use of flight data to prevent accidents.

THE AUTHOR

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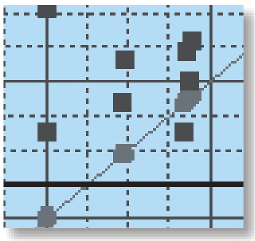

A Mathematical Cross-Correlation for Time-Alignment of Cockpit Voice Recorder and Flight Data Recorder Data

Joseph A. Gregor, National Transportation Safety Board

ABSTRACT

A new method is described for performing timing correlations between flight data recorder and cockpit voice recorder information. This method involves the use of the cross-correlation function to "search" the typically larger FDR data file for a best match to the event pattern present in the CVR data file. The results of this search give a first-order estimate of the time differential between identical events as recorded on both units. A simple curve fit may then be employed to obtain a general conversion from time as represented in the CVR, t_{cvr}, and time as represented in the FDR, t_{fdr}.

INTRODUCTION

Investigators are often called upon to utilize electronic data acquired from multiple sources in the course of the data collection and analysis phase of an accident investigation. The two most common sources of electronic information available in the event of a major aviation accident are the flight data recorder (FDR) and the cockpit voice recorder (CVR) although many other sources of data are present on modern-day aircraft, and these other sources are being utilized with increasing frequency. Currently, most on-board data sources have one negative characteristic in common: they typically operate on an independent time-base. In addition, virtually all recorded data are currently acquired and stored without a time-stamp. As a result, there is usually little or no independent information on the relative or absolute time at which an electronically "recorded" event occurred. All that is known is the relative time between the beginning of each recording, and the time at which the event occurred. A key first step in the accident investigation process is the synchronization of all collected electronic data to a common time-base, followed by a determination of the relationship between this elapsed "ship-time" and an appropriate local or global clock (local time or UTC[1]). This task is typically accomplished by matching the electronic signature of

1 Coordinated Universal Time - equivalent to mean solar time at the prime meridian (0° longitude).

a common event or series of events recorded on each electronic data source to obtain a common elapsed time-base. One of these events, occurring at a known local or UTC time, is then used to translate from elapsed time to local time or UTC.

THE DATA REDUCTION PROCESS

FDR information is typically recorded in digital form as a continuous series of interleaved samples representing data obtained from various sensors located aboard the aircraft. These sensors are used to measure various flight and aircraft systems parameters such as airspeed, altitude, pitch, roll, and yaw. Sampled integer data are interleaved and organized into groups – or "subframes" – and identified by a subframe reference number (SRN). A ***subframe*** is similar to the ***type structure*** in an object-oriented programming language. The parameter data within each subframe are akin to the individual ***fields*** within the structure. A typical FDR can record 64, 128, or 256 samples per subframe, and store anywhere from 25 to 100 hours of flight data. Newer installations will be capable of storing even larger subframes. In a typical installation, each subframe represents data acquired over a one-second timeframe. Some parameters are sampled only once per second, so that one sample of data from this source will appear within each subframe. Some parameters are sampled several times per second, yielding several samples within each subframe. A few parameters are sampled at a rate less than once per second, and these data will only be present in a certain subset of the available subframes. Individual parameters will always appear in the same relative order within each subframe. This order, together with the SRN number,[2] may be used to determine the acquisition time of the data represented by any parameter.

CVR information may be recorded in either analog or digital form, depending on the model of recorder employed. If in analog form, the information is digitally sampled in the laboratory as step one of the data reduction process. CVR information is eventually expressed in the form of digital WAV[3] files containing audio information sampled at a rate of ≥ 22,050 Sa/s.[4] A typical CVR recording contains three to four tracks of audio from independent sound transducers (microphones). Older units employ magnetic tape as the storage medium, recording 30 minutes of audio simultaneously from each transducer in a closed-loop system wherein older information is overwritten by new information. Newer units employ semiconductor flash memory. These units typically include two tracks of audio information recorded for 2 hours on a simulated closed-loop system, in addition to four tracks of higher fidelity 30-minute recordings representing the last half-hour of operation.

Once the CVR and FDR information is expressed in digital form, it is important to know which sample within the FDR data corresponds to a given sample in the CVR data. Both units operate in independent, uncorrelated time-bases and the data is generally not time stamped. As a result, there is no straightforward way to correlate the data between these two units. The method generally employed is to compare a sample from each source known to coincide with an identical recorded event. The event most easily exploited in this way is an activation of the microphone switch for initiation of an external radio transmission. This so-called 'mic-key' event is recorded as a Boolean variable in the FDR, sampled at a rate of 1 Sa/s. This means that within each subframe there will be one *datapoint* indicating the state of the microphone switch at the time the sample was taken. The corresponding radio transmission will appear as an audio signal on one or more tracks of the CVR recording. Often, an electronic artifact (transient) coinciding with the activation of the microphone key will also be present in the recorded audio. The sample number for this "event" within the digitized CVR data may be compared with the corresponding FDR SRN to determine the offset time between these two units. Assuming that both time-bases operate at the same rate, all that remains is to identify an external event recorded on either unit for which the time of occurrence is known. One example would be an external radio transmission recorded on both the CVR and by an external FAA facility. The local or UTC time assigned to the ATC[5] recording of this transmission may then be used to convert from CVR / FDR time to the appropriate global time.

Several additional issues present themselves when making any real-world attempt at obtaining a mapping between the recorded CVR and FDR data. First, in the case of a tape-based analog CVR, variations in tape speed may cause the time-base within the unit to operate at an effective data rate different than that within the FDR. In fact, the effective CVR data rate may vary over the course of the recording if power fluctuations or mechanical difficulties within the tape drive mechanism occur. Second, pilots typically make many external radio transmissions during the course of a flight. This can lead to a large number of recorded microphone keying events. Depending on the integrity of the FDR data, there may be some uncertainty in the position of the accident flight (the SRN range) within what can be an extremely large data file. Both factors may lead to

2 A number representing the number of subframes since the beginning of the FDR recording. The current standard creates and stores one subframe of data every second.

3 A file format developed by Microsoft and used extensively in Microsoft Windows for the recording, storage, and playback of audio sound.

4 Sa/s = samples per second.

5 Air Traffic Control.

ambiguity, creating difficulty in determining which FDR SRN corresponds to a given keying event within the CVR recording. These difficulties can be practically eliminated by employing a strictly mathematical approach to the problem.

TIME ALIGNMENT USING A MATHEMATICAL TRANSFORM

As a strictly mathematical problem, the task at hand is to obtain a transform from the elapsed time in the CVR timeframe, t_{cvr}, to the elapsed time in the FDR timeframe, t_{fdr}. The resulting transform and its inverse may then be used to convert from any given time in one frame to the corresponding time in the other frame. The simplest such transform is given by the equation,

$$t_{cvr} = t_{fdr} + C \qquad \text{Eq. (1)}$$

where C is a constant giving the offset between elapsed time in the CVR data and elapsed time in the FDR data. Equation (1) would be valid in the case where the timebase in each unit is operating at the same rate. If the timebase in one unit is running at a constant, but different, rate compared with that of the other unit, the resulting transform would take the form of,

$$t_{cvr} = b * t_{fdr} + C \qquad \text{Eq. (2)}$$

where *b* represents the difference in rates between the two units.

For a solid-state CVR and digital FDR, the transform is expected to take the form of Eq. (1). For a tape-based CVR where the tape transport operating speed is slightly different from the design speed – but is still a constant – the transform is expected to take the form of Eq. (2). If the tape transport speed were to fluctuate during the recording – due to electrical or mechanical problems – the required transform would take a more general form. Note that this model is completely general, and does not require any a priori assumption concerning the behavior of the time-base in either unit.

USING CROSS-CORRELATION TO DETERMINE AN OFFSET TIME

The first step in the determination of an appropriate transform is the identification of those samples in each data set corresponding to a common event. The event typically used for this purpose is a keying of the microphone switch for the purpose of making an external radio transmission. This event shows up as a Boolean "1" in the appropriate field of the FDR subframe for all SRNs during which the microphone was sensed as *keyed-on.* The initiation and termination of a microphone *on-key* event generally shows up as a transient in the CVR recording. Where this transient is not detectable, the start time and stop time of the corresponding audio signal may be used as a surrogate. The latter method is less accurate, however, since the pilot may not begin and end speaking the instant the microphone is keyed on or off.

Given the potentially large number of such *on-key/off-key* events, it would be preferable to employ an automated method for determining which region within the FDR data best matches the available CVR data. This may be done most easily using the mathematical cross-correlation function, given by,

$$Z(t) = \int_{-\infty}^{\infty} x(\tau) \cdot h(t+\tau) d\tau \qquad \text{Eq. (3)}$$

For sampled data, the integral in Eq. (3) becomes a summation and the cross-correlation function takes the form of,

$$Z(n) = \sum_{k} FDR(k) \cdot CVR(k+n) \qquad \text{Eq. (4)}$$

where FDR*(n)* and CVR*(n)* represent the state of the microphone key (on = '1', off = '0') at sample time $t = n/R$, R is the sample rate in Sa/s, and n is the sample number. The resultant, Z*(n)*, represents the degree of similarity between FDR and CVR for every possible time shift – or lag – between these two vectors. If the pattern of information appearing within the CVR data is reflected somewhere within the larger FDR data set, plotting Z*(n)* as a function of the number of lags, n, will result in a figure exhibiting a clear maximum at the offset required to obtain the best match between these two data sets.

Figures 1 – 3 illustrate the concept using a LabView[6] simulation of the discrete cross-correlation function. The top graph in each figure represents elements 300 through 2000 of a notional FDR *on-key/off key* data vector. The middle graph represents a CVR *on-key/off-key* data vector. The cross-correlation of these two vectors is shown in the bottom graph. In figure 1, we see that at zero lags there is no overlap between FDR and CVR, so that Z(n = '0') = 0. In figure 2, the cross-correlation has progressed and we see that Z*(n)* is now non-zero for certain values of $n \leq 530$. In figure 3, we see the final result for $0 \leq n \leq 1024$, indicating that the FDR and CVR *on-key/off-key* vectors match most closely for $n = 698$ lags.

6 A graphically-based instrument automation and data analysis tool produced by National Instruments.

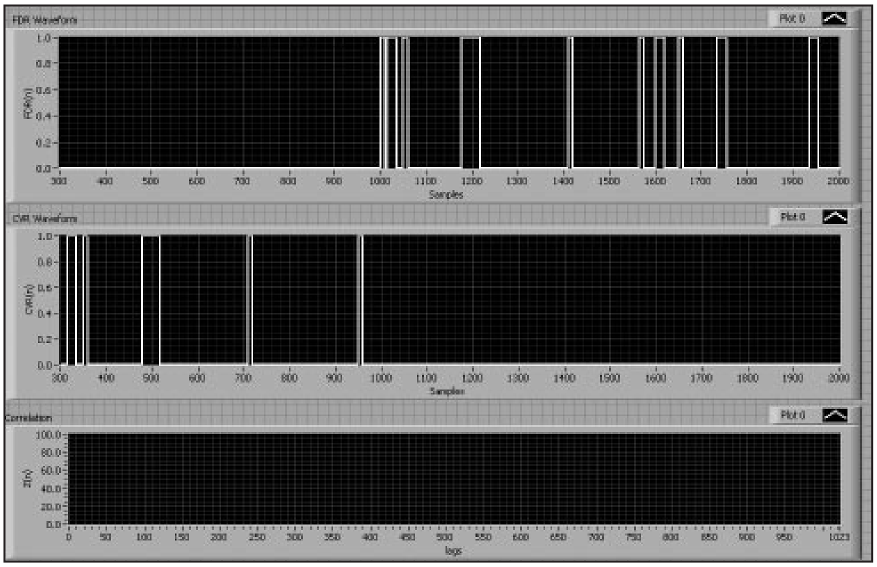

Figure 1. Example of running cross-correlation (bottom) of FDR *on-key/off-key* data vector (top) with CVR *on-key/off-key* data vector (middle) for $n = 0$.

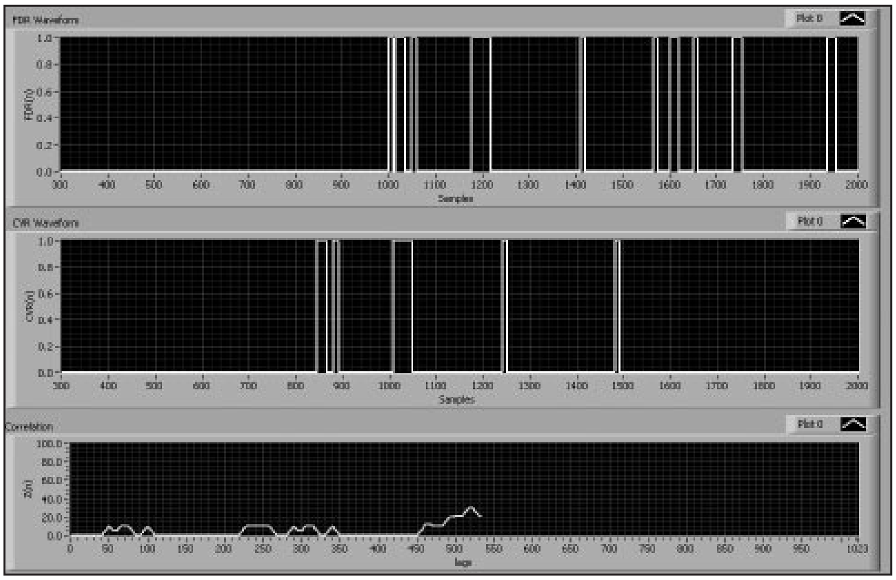

Figure 2. Example of running cross-correlation (bottom) of FDR *on-key/off-key* data vector (top) with CVR *on-key/off-key* data vector (middle) for $0 \leq n \leq 530$.

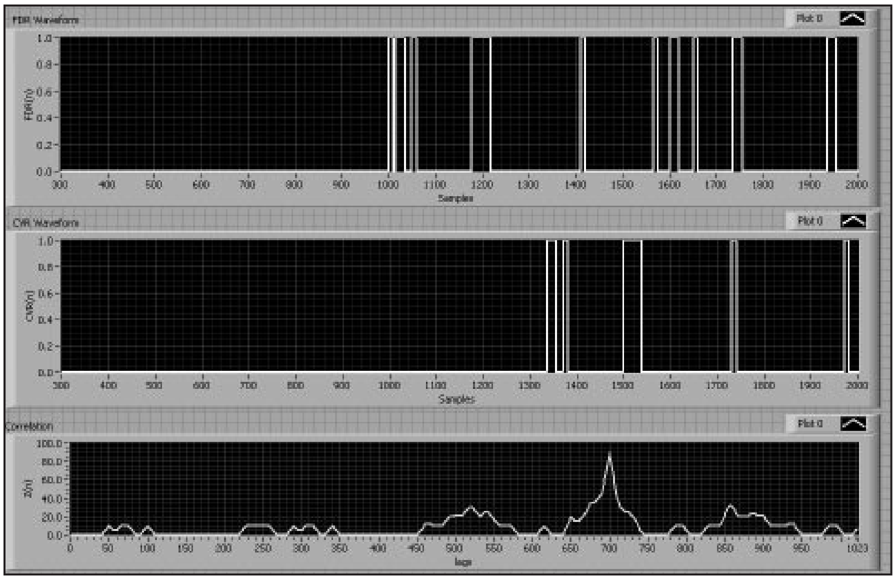

Figure 3. Example of running cross-correlation (bottom) of FDR *on-key/off-key*.

Cross-correlation results for a real-world case are illustrated graphically in figures 4 – 8. The individual FDR and CVR *on-key/off-key* data vectors are shown in figures 4 and 5 respectively. The x-axis in both figures represents elapsed time into the respective recording. For the FDR data in figure 4, this corresponds to the SRN. For the CVR data in figure 5, this corresponds to elapsed time in seconds, since the *on-key/off-key* data was re-sampled at 1 Sa/s to make it compatible with the FDR *on-key/off-key* data. The y-axis in both figures represents the Boolean variable for the microphone *on-key/off-key* event, where a "1" indicates that the microphone was *keyed-on* at the indicated sample time, and a "0" indicates that the microphone was *keyed-off*. Figure 6 shows the result of a discrete cross-correlation between these two vectors, indicating that the best match occurred for $n = 1763$ lags. Figures 7 and 8 show the CVR data shifted by this amount and plotted atop the FDR data to illustrate the goodness of the match. Note that some on-key events are not simultaneously reflected in both data vectors. This will often occur for extremely short transmissions, where the microphone was keyed-on for less than 1 second. In this case, the data are effectively undersampled at 1 Sa/s, and so instances will occur where the FDR fails to register an *on-key/off-key* event. Similarly, the algorithm gathering and re-sampling the CVR data may misidentify the presence or absence of an external transmission. These errors, unless extreme in number, will not invalidate the cross-correlation. Such mismatches will reduce the magnitude, and cause an apparent broadening of, the correlation peak. To first order, they will not change the number found for *n*. Once the number of lags is known, the time shift in seconds required to transform from FDR-time to CVR-time may be easily determined. This will yield the constant, C, required for any transform between elapsed time in each unit.

At this point, all we have done is to obtain the offset between elapsed time in the CVR and elapsed time in the FDR. This may or may not be sufficient to specify the required transform, depending on the behavior of the time-base in each unit. The exact form taken by this transform will fall into three broad classes:

1. the time-base in each unit operates at the same constant rate,
2. the time-base in each unit operates at a different constant rate, or
3. the time-base operates at a different and variable rate in one or both units.

For the first situation described above, the transform given by Eq. (1) applies and a determination of C suffices to solve the problem. For the second situation described above, the transform given in Eq. (2) may be employed. This requires the calculation of a slope, *b*, reflecting the difference in rate between the two time-bases. For the third situation, which may occur in the event of a malfunctioning tape based CVR unit, the transform will take on a more complex, possibly non-analytical, form.

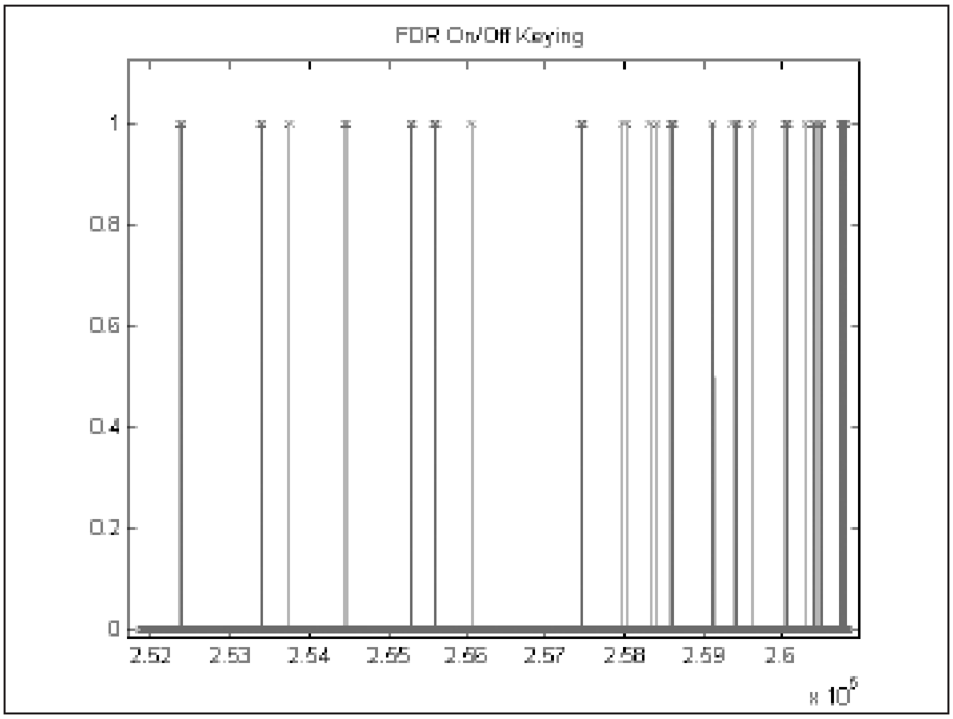

Figure 4. FDR *on-key/off-key* data, FDR(*n*), where "*n*" represents the subframe reference number (SRN) corresponding to the number of seconds since the FDR first began recording. A "1" indicates that the microphone was found keyed-on at the sample time.

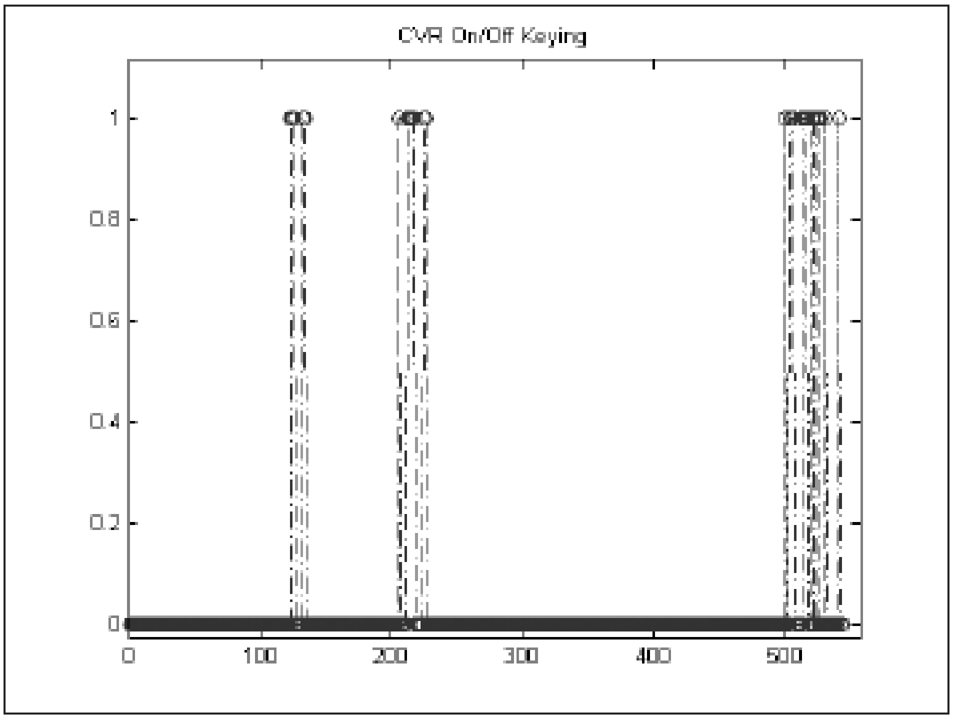

Figure 5. CVR *on-key/off-key* data, CVR(*n*), where "n" represents the sample number. The data in this figure were sampled at a 1 Hz rate to facilitate comparison with FDR(*n*). A "1" indicates that the microphone was found keyed-on at the sample time.

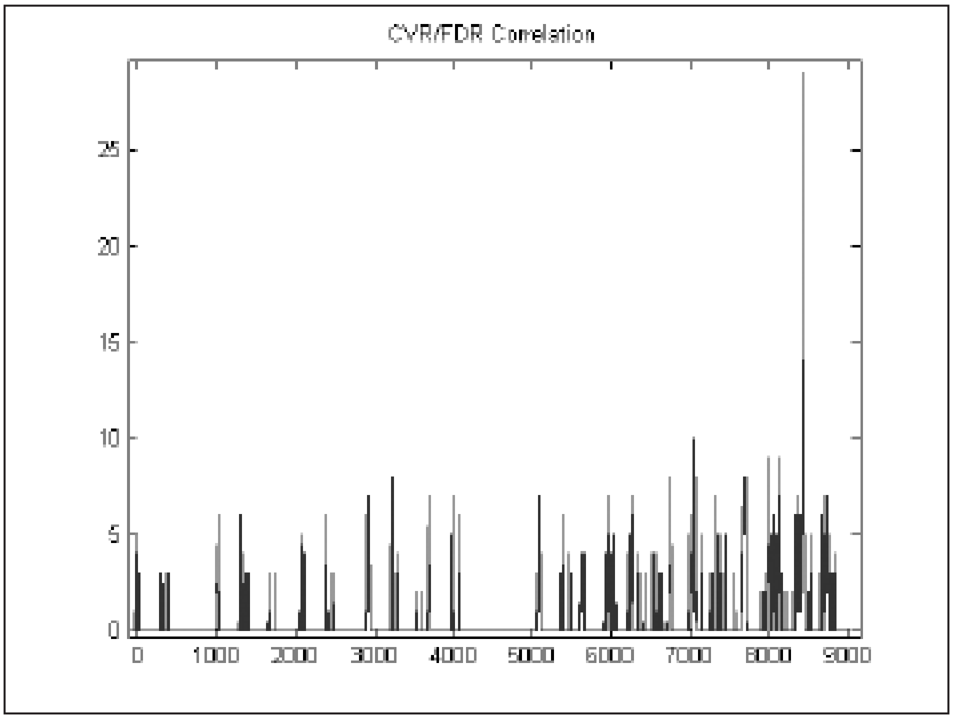

Figure 6. Results of the cross-correlation between FDR(n) and CVR(n) showing a well-defined peak at n = 1763 lags.

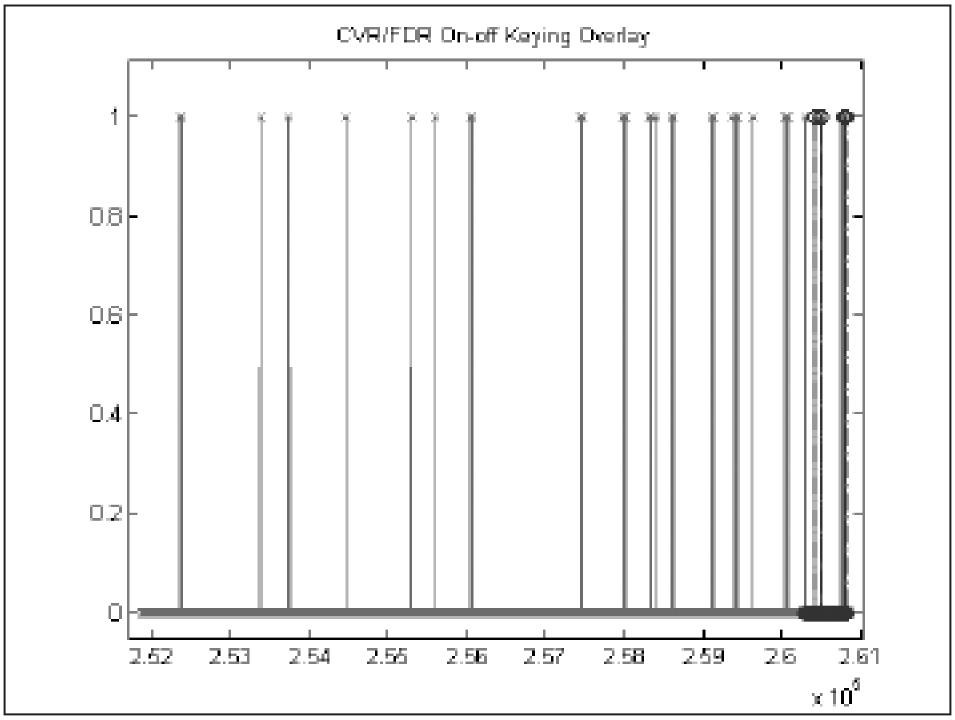

Figure 7. Overlay of FDR(n) [designated by x's] with CVR(n) [designated by o's] showing the alignment of identical events once the offset found via the cross-correlation was applied.

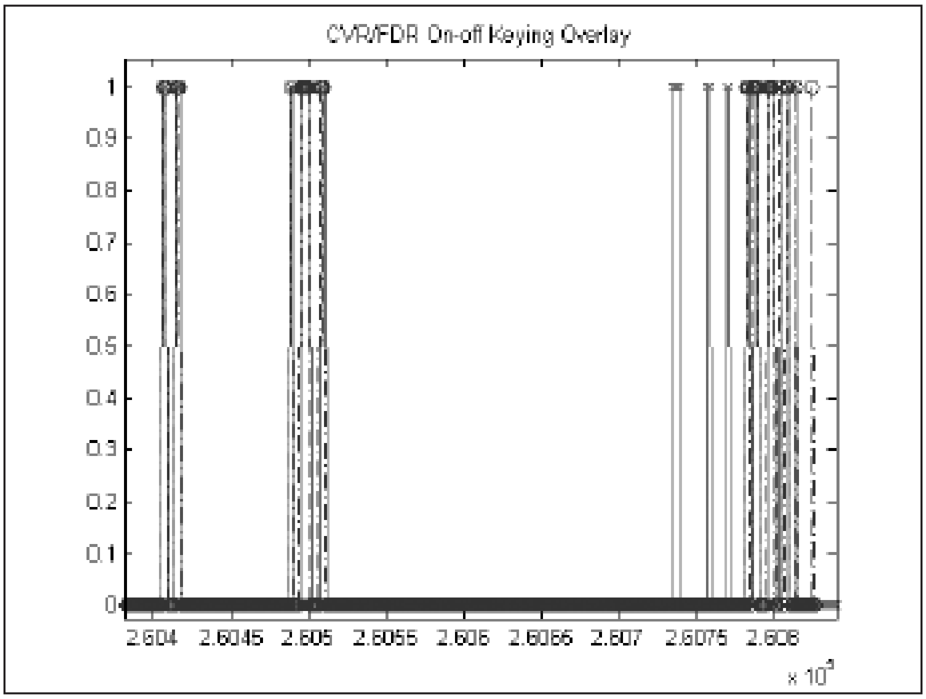

Figure 8. Overlay of FDR*(n)* [designated by x's] with CVR*(n)* [designated by o's] with the x-axis expanded to show the goodness of fit between the two data sets.

USING CURVE-FITTING TECHNIQUES TO OBTAIN A FINAL TRANSFORM

The exact form of the transform required to convert from elapsed FDR time to elapsed CVR time may be found most generally by performing a simple curve fit on the time-aligned FDR and CVR data. If we subtract the value for C in Eq. (1) – obtained using the cross-correlation function – the times found for each corresponding *on-key/off-key* event should be identical to within experimental measurement error. The magnitude of this error is primarily driven by the 1 Sa/s sample rate[7] of the FDR *on-key/off-key* data. The goodness of the resulting transform may be seen most easily by producing a scatter plot of the data. Figure 9 shows such a plot for data corresponding to the simplest case, where the time-base operates at an identical, constant rate in both units.

Each data point in this figure corresponds to a unique *on-key/off-key* event, with elapsed FDR time plotted on the x-axis and elapsed CVR time plotted on the y-axis. The solid line corresponds to a minimum least squares fit to the data using a linear transform corresponding to Eq. (2). The results of this curve fit yield $b = 1.0001$ and $C = 0.6557$, indicating that the timebases in both the CVR and the FDR were operating at the same rate to within a small fraction of a percent. Since the data are normalized prior to performing the curve fit, we find $C \approx 0 \pm 1$ s – well within the known error bar of ± 1 Sa. Also plotted in this figure is a variable, called Delta, representing the difference between the elapsed CVR time as calculated using the resulting linear curve fit, and the corresponding elapsed time actually measured and plotted on the graph. This comparison is performed for each *on-key/off-key* event to quantify the error in calculating elapsed CVR time from the elapsed FDR time using the calculated transform. The resulting error should fall within the ± 1 s error bar established by the 1 Sa/s sample rate; the exact distribution is dependent on the relative phase of the actual *on-key/off-key* event, the FDR sample acquisition time, and the CVR sample acquisition time [since the CVR data were also sampled at a 1 Hz rate to obtain a vector CVR*(n)* appropriate for correlating with FDR*(n)*].

The situation highlighted in figure 10 is typical for a properly functioning solid-state CVR and FDR. Each unit in this case is operating from a precisely controlled digital time-base. In this case, the transform required to move from elapsed FDR time to elapsed CVR time should take the form of Eq. (1), with C given by the cross-correlation function. The curve fit in figure 9 serves as a validation that the data in FDR*(n)* and CVR*(n)* were acquired accurately. Any problem data would show up in the figure as an outlier, signalling the need for closer scrutiny and possibly a re-run of the algorithm once the problem with the data has been resolved.

7 Several other sources of error may apply in setting the error bars for this calculation, but the sampling error is considered by far the largest source.

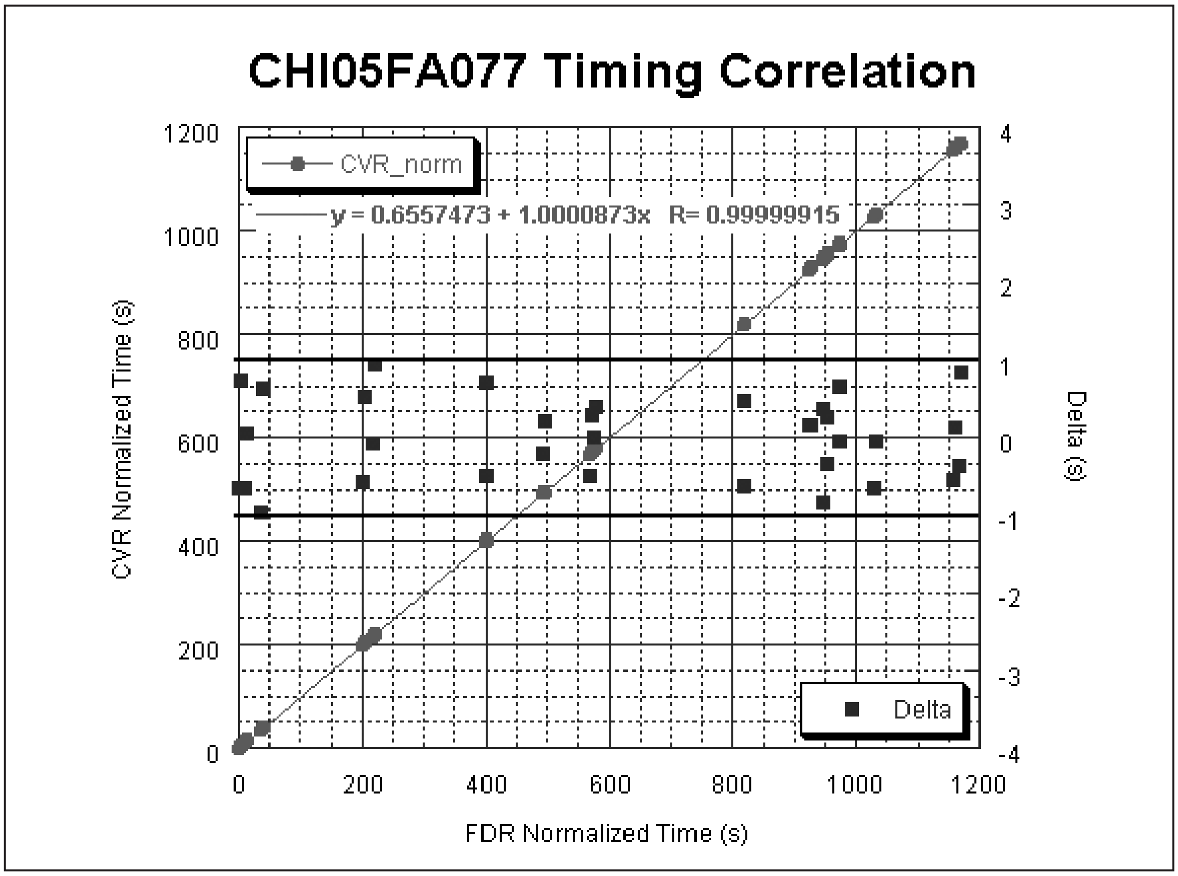

Figure 9. Scatter plot showing the results of a cross-correlation between FDR *on-key/off-key* data and corresponding CVR *on-key/off-key* data. Times are normalized to remove the calculated shift between CVR and FDR times, and normalized so that the data begin at time t=0.

CASE STUDY INVOLVING A SLOPE ≠ 1

On May 2, 2002, an Atlantic Coast Airlines Dornier 328, tail number 429FJ, experienced a smoke-in-the-cockpit emergency while en route from Greensboro, South Carolina, to LaGuardia International Airport, New York. Data were recovered from two flight recorders on-board the aircraft at the time of the mishap: a Fairchild Model FA-2100-403 solid-state CVR, and an L-3 Communications Fairchild F-2100 FDR. Attempts at correlating the CVR and FDR data proved resistant to the standard technique normally employed in such cases. This technique involved engineers manually applying a piecewise linear fit to the data. Since both units were solid-state, the assumption was made that a one “piece” fit should suffice to characterize the entire data set. If this failed to work, an additional assumption could be made that one of the units experienced a momentary power failure, thus causing a discontinuity in the time-base for that unit. In this case, a two-piece linear fit could be applied – one covering the period before the power upset, and one covering the period after the upset. If this did not satisfy, one could assume two power upset events, requiring a 3-piece linear fit, and so on. In the case of the Dornier 328, the number of “pieces” required to effect a fit across the entire data set threw into question the validity of the entire procedure. The cross-correlation technique was developed as an independent method of identifying the most likely match between these two data sets – independent of any assumptions on their behavior, save that they should correlate with one another to some degree, since they represented two records of the same event.

Data from the Dornier 328 CVR were cross-correlated with data from the FDR, resulting in the correlation peak illustrated in figure 10. Note that, while it is far less prominent than the peak found in figure 6 for a typical CVR/FDR combination (one yielding to standard correlation techniques), there is still a clearly identifiable peak. This illustrates the robust nature of the cross-correlation technique. The broadening and flattening of the correlation peak are indications that, while a unique best-match has been found at the specified location, this match is not perfect.

When the correlated data for this case were plotted as in figure 9, the resulting curve fit turned out to be linear, but with $b = 0.9831$. This indicated that the time-base in one unit was operating at a constant but different rate when compared with the other. If the CVR had been a tape-based unit, the assumption would have been that the tape speed was off, and the resulting transform applied to adjust the CVR data to match the FDR data. However, since both units were solid-state in this case, a different assumption was required.

Researching these correlation problems with the manufacturer turned up an anomaly in the FDR recording system. In a typical installation, data are fed to the FDR in groups identified by SRN. Each group represents a repeating set of data points for the various parameters being measured. These groups are sent to the FDR at a rate of 1 per second – and each SRN is assumed to represent 1 second of flight data. In this particular installation, however, the data stream was being fed to the FDR at a rate of 61 groups per minute. As a result, each SRN represented roughly 60/61 = 0.9836 seconds of data, consistent with transform results found for b. Once this transform was applied, the corrected FDR *on-key/off-key* data were found to overlay clearly with the CVR data at the offset originally determined by the cross-correlation function.

CONSIDERATIONS FOR MORE COMPLEX TRANSFORMS

Valid correlations may always be obtained by assuming a linear transform as given in Eq. (2), provided that the time-bases in both units are operating at a fixed, constant rate. This will not be the case, however, if the time-base in one or both units changes rate during the recording. This may occur in the case of a solid-state recorder if power is momentarily lost to one of the boxes. In this instance, a linear fit as in Eq. (2) would still be valid on each side of the discontinuity. This may also occur for a tape-based CVR due to power supply fluctuations or mechanical changes in the tape drive mechanism. Either of these factors could change the tape speed, and hence the amount of information corresponding to 1 second of digitized data. When played back at a constant speed, the effect will be an apparent change in the time-base for that audio recording. Note that, since a tape-based CVR is an analog device, there is no reason to assume that the tape speed must change from one discrete constant value to another discrete constant value. Instead, the tape speed – and hence the time-base for the playback – may in principle take on any analog value. A linear transform as in Eq. (2) will not suffice in this case.

In the past, such correlations have been performed by employing a piecewise linear fit to subsets of the recorded data. These sections are then reassembled to obtain a single contiguous data set. This is essentially equivalent to employing Eq. (2) over segments of the data, and performing a curve fit to obtain the values for *b* and C corresponding to a unique solution within each segment. Matching solutions at each end, one could obtain a transform for the entire data set of the form,

$$\begin{aligned}
t_{cvr} &= b_1 * t_{fdr} + C_1 \quad & t_0 < t_{fdr} \leq t_1 \\
t_{cvr} &= b_2 * t_{fdr} + C_2 \quad & t_1 < t_{fdr} \leq t_2 \\
t_{cvr} &= b_3 * t_{fdr} + C_3 \quad & t_2 < t_{fdr} \leq t_3 \\
t_{cvr} &= b_4 * t_{fdr} + C_4 \quad & t_3 < t_{fdr} \leq t_4
\end{aligned} \qquad \text{Eq. (5)}$$

This method is not without its disadvantages. Picking the limits required to obtain a correlation using a minimum number of segments for the desired accuracy involves a significant amount of labor. If the flow of time in one of the units varies continuously, as may be expected for an analog device, the number of segments required to obtain a good fit could become extremely large. In addition, while the magnitude of the data may match at the boundaries, the derivative of the resulting curve will necessarily be discontinuous at the ends of each segment – an unphysical result.

We may, however, extend this method to obtain a more accurate result with far less labor by recalling from basic calculus that any continuous function can be represented by a number of straight line segments. The larger the number of segments, the closer the resulting representation will come to the true curve. The original curve can be reproduced exactly in the limit that an infinite number of segments are employed. This is nothing more than the description of a generalized curve fit. An accurate correlation to any data set not yielding to a linear fit may then be obtained by cross-correlating the data to obtain a first-order time alignment, and then calculating a cubic spline fit or similar generalized curve fit. This procedure may be easily implemented on any desktop computer using a wide variety of software tools. The results may be plotted as in figure 9 to check the validity of the final solution.

CONCLUSIONS

A new method has been described for performing the correlation of time as represented in the CVR with time as represented in the FDR. This method employs the use of the cross-correlation function to obtain an offset value representing the difference in elapsed time between a single event as recorded in each unit. This *offset time* may be used to normalize the data to a common elapsed time-base. A curve fit performed on the normalized data will then give the transform required to convert between elapsed FDR time and elapsed CVR time. This transform may be employed to correct the time in one unit so that all identical events occur at identical times in both the CVR transcript and the FDR report. Since this method uses common mathematical functions and algorithms, it can be easily automated on a desktop computer under a wide variety of software applications and programming languages. A priori assumptions regarding the behavior of the data can be avoided, since this method supports the use of any appropriate fitting function. The validity of the transform is easily checked graphically by comparison of the transformed data with independent measurements. The results of this effort are to be incorporated into a new state-of-the-art CVR transcription tool being developed for the NTSB by the Information Directorate of Air Force Research Laboratory (AFRL/IF).[8]

8 Cockpit Voice Recorder Transcription and Timing Tool. Funded through the Technical Support Working Group of the Combating Terrorism Technology Support Office; TSWG Task T-1925.

THE AUTHOR

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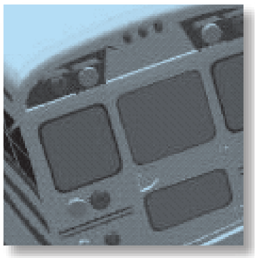


Occupant Safety in Large School Buses: Crash Investigations, Testing, and Modeling

Kristin M. Poland, National Transportation Safety Board,
Linda McCray, National Highway Transportation Safety Administration
and Aida Barsan-Anelli, Information Systems and Services, Inc.

ABSTRACT

School bus travel is one of the safest forms of transportation on the road today. A number of factors play into this excellent record, including the size and color of school buses, special traffic requirements, and specific safety specifications covering joint strength, roof strength, and occupant protection. This excellent record may be improved further as new research identifies ways to better protect school bus passengers. This paper summarizes work accomplished by both the National Transportation Safety Board and the National Highway Traffic Safety Administration to address the safety of large school buses.

INTRODUCTION

School buses are one of the safest forms of transportation on the road today. The passenger fatality rate in school buses is 0.2 fatalities per million vehicle miles traveled (VMT), compared to 1.5 per million VMT for passenger cars and 1.3 per million VMT for light trucks.[1] Each year on average, 10 school bus occupants are fatally injured in school bus crashes, and 16 school-age pedestrians are fatally injured by school buses. Students in the United States are almost eight times safer traveling in a school bus than in another form of transportation, like the parent's car. These safety statistics are true for a number of reasons, including the school bus's operating environment, color, joint and roof strength requirements, fuel system integrity, and compartmentalization.[2]

Despite the excellent safety record, research continues to explore ways to ensure the continued safety of school buses and to identify improvements. Since the late 1960s,

1 *Federal Register,* October 26, 1998 (Volume 63, Number 206), on the National Highway Traffic Safety Administration's School Bus Research Plan.

2 Compartmentalization provides a protective envelope consisting of strong, closely spaced seats that have energy-absorbing seat backs. Compartmentalization is regulated under Federal Motor Vehicle Safety Standard No. 222, and is applicable to all school buses.

researchers have studied the crashworthiness of large school buses and the associated occupant safety systems inside the bus.

The main focus of this paper is to review large school bus crashworthiness and the role of compartmentalization in protecting occupants. Included are reviews of recent crash investigations, full scale crash tests, sled tests, and simulation modeling conducted by the NTSB and the National Highway Traffic Safety Administration (NHTSA).

Crash investigations, testing, and modeling are reviewed in an effort to assess the level of current protection provided to school bus occupants and also to assess potential future design considerations.

INVESTIGATIONS AND TESTING

Accident Investigations

The Safety Board investigates many of the severe, though rare, school bus accidents that occur in the United States. In each of these cases, investigators thoroughly reconstruct the accident by collecting detailed physical evidence, documenting vehicle damage, impact points, and witness marks, and studying the crash sequence through the use of simulation. The Board investigated more than six large school bus crashes as part of its 1999 *Bus Crashworthiness Issues* report.[3] Since that time, four additional large school bus crashes have been investigated.[4] Two of the crashes investigated by the Board are discussed here to illustrate the process and to reinforce the recommendations from the 1999 Board report.[5]

Monticello, Minnesota

On April 10, 1997, a 77-passenger-capacity school bus was traveling west on Wright County Road 39, near Monticello, Minnesota, toward the intersection with Wright County Road 11. On board were 13 children, ages 5 to 11, and the driver. Meanwhile, a Mack truck tractor, pulling an empty semitrailer, was traveling north on Wright County Road 11, at a witness-estimated speed of 50 to 55 mph.

As both vehicles approached the intersection, the truck combination failed to stop for a posted stop sign and, leaving skid marks extending into the intersection, collided with the school bus. At impact, the front of the school bus hit the right front side of the truck tractor at the tractor's right front wheel with about 43 inches of overlap. A second impact occurred when the right truck tandems and the right front corner of the semitrailer struck the left side of the bus body, about 9 feet behind the forward edge of the bus body. A third impact occurred when the rear of the school bus rotated clockwise into the right side of the semitrailer. See figure 1.

Figure 1. Damage to the bus in the Monticello, Minnesota, crash.

The lap/shoulder belt-restrained truck driver and three bus passengers were killed. The lap belt-restrained school bus driver received moderate injuries, five students received minor to moderate injuries, and five students received serious to severe injuries. The bus was not equipped with any form of passenger restraints.

Using a human vehicle environment system,[6] m-smac software,[7] and Mathematical Dynamical Models (MADYMO),[8] the Safety Board conducted vehicle dynamics and occupant kinematics simulations for this investigation. Six simulated occupants, located in the rear of the bus, were modeled. These occupants were chosen because the passengers who sustained fatal injuries in the Monticello accident were reportedly riding in three rear seats on the driver's side and because of the potential interaction with the surrounding occupants.

The vehicle simulation results indicated that, at impact, the tractor semitrailer was traveling approximately 49.4 mph and the bus, approximately 50 mph. Figure 2 details the linear and angular acceleration time history of the bus as predicted by the simulation. The three impacts, described earlier, can be seen in the plot. The severity of this crash is indicated by the peak linear

3 National Transportation Safety Board, *Bus Crashworthiness Issues,* Highway Special Investigation Report, NTSB/SIR-99/04 (Washington, DC: NTSB, 1999).

4 Conasauga, Tennessee (HWY00MH036); Central Bridge, New York (HWY00FH001); Omaha, Nebraska (HWY02MH004); and Mountainburg, Arkansas (HWY01MH025)

5 See <http://www.ntsb.gov/publictn/1999/SIR9904.pdf>.

6 HVE Human Vehicle Environment, Version 3, Engineering Dynamics Corporation, Beaverton, Oregon 97008.

7 R.R. McHenry, B.G. McHenry, *McHenry Accident Reconstruction,* 1998 McHenry Seminar, McHenry Engineering.

8 MADYMO, *User's Manual 3D Version 5.4,* May 1999, Copyright 1999, TNO Automotive. MADYMO is a general-purpose software package that allows users to design and optimize occupant safety systems using both a rigid and flexible body.

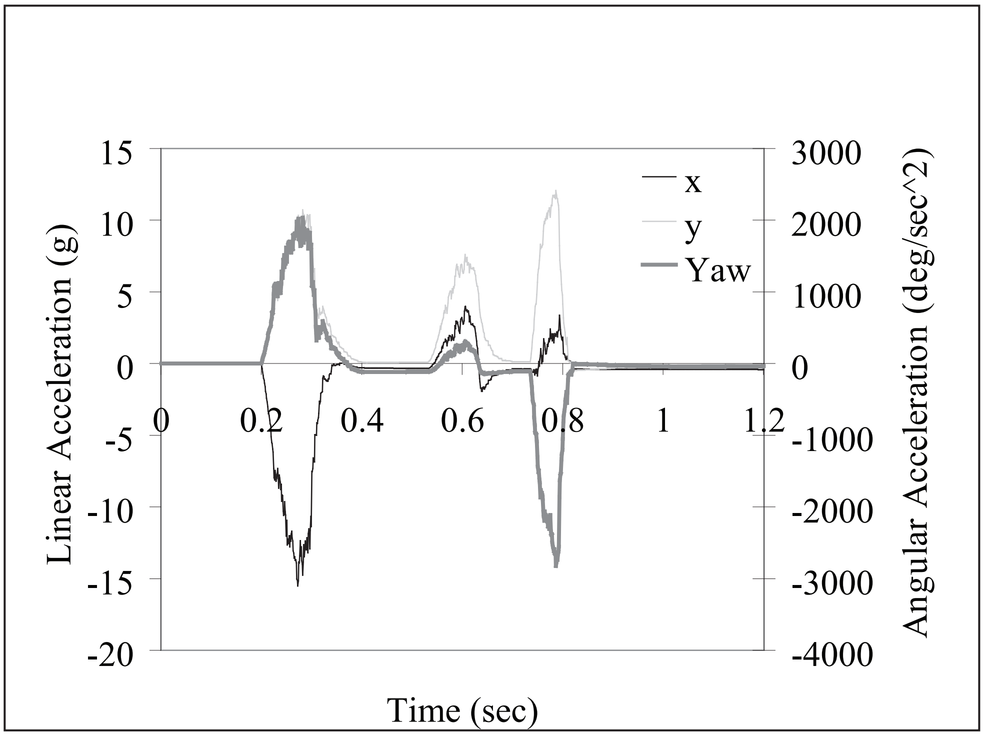


Figure 2. The two-dimensional linear and angular accelerations of the school bus during the collision with the tractor semitrailer in the Monticello, Minnesota, crash.

accelerations on the bus, which occurred immediately after impact with a resultant 18.5 g. The side slap of the semitrailer into the side of the rotating bus during the third impact (time = 0.8 seconds) was extremely severe, resulting in a 2821 deg/sec2 maximum yaw angular acceleration of the bus.

Simulation results revealed significant differences in the crash pulse and the change in velocity between the center of gravity of the bus and points at the rear of the bus, possibly contributing to the severity of the injuries for passengers seated there. Table 1 illustrates these differences.

The greatest variance occurred during the last collision when the bus side-slapped the semitrailer. The simulation showed that, as a result of this collision, the change in velocity at the rear of the bus was 44 mph versus 12 mph at the center of gravity of the bus. The simulation also showed that during this same collision, portions of the bus located forward of the center of gravity underwent a smaller change in velocity than the center of gravity.

In the compartmentalized condition, the simulated occupants in the rear of the bus first went forward in their seats and then contacted the seat in front of them with their legs, chests, and heads. As the bus rotated clockwise, the simulated occupants slid toward the right side of the bus. Those seated on the right side of the bus quickly contacted the side of the bus and the windows and stayed in that position until the third impact (side slap) of bus and semitrailer. Those originally seated on the left side of the bus contacted the edges of the adjacent seats and also hit other simulated occupants during the motion. The bus continued to rotate clockwise until the third impact of the bus with the semitrailer. This impact started a counterclockwise rotation of the bus, which caused the simulated occupants to slide back toward the left side of the bus. Those closest to the left side of the bus originally impacted the left-side windows and the left side of the bus, typically with their heads or upper torsos. Injuries were predicted for these occupants. Those seated farther from the left side of the bus impacted other simulated occupants while sliding toward the left and toward the impacting semitrailer.

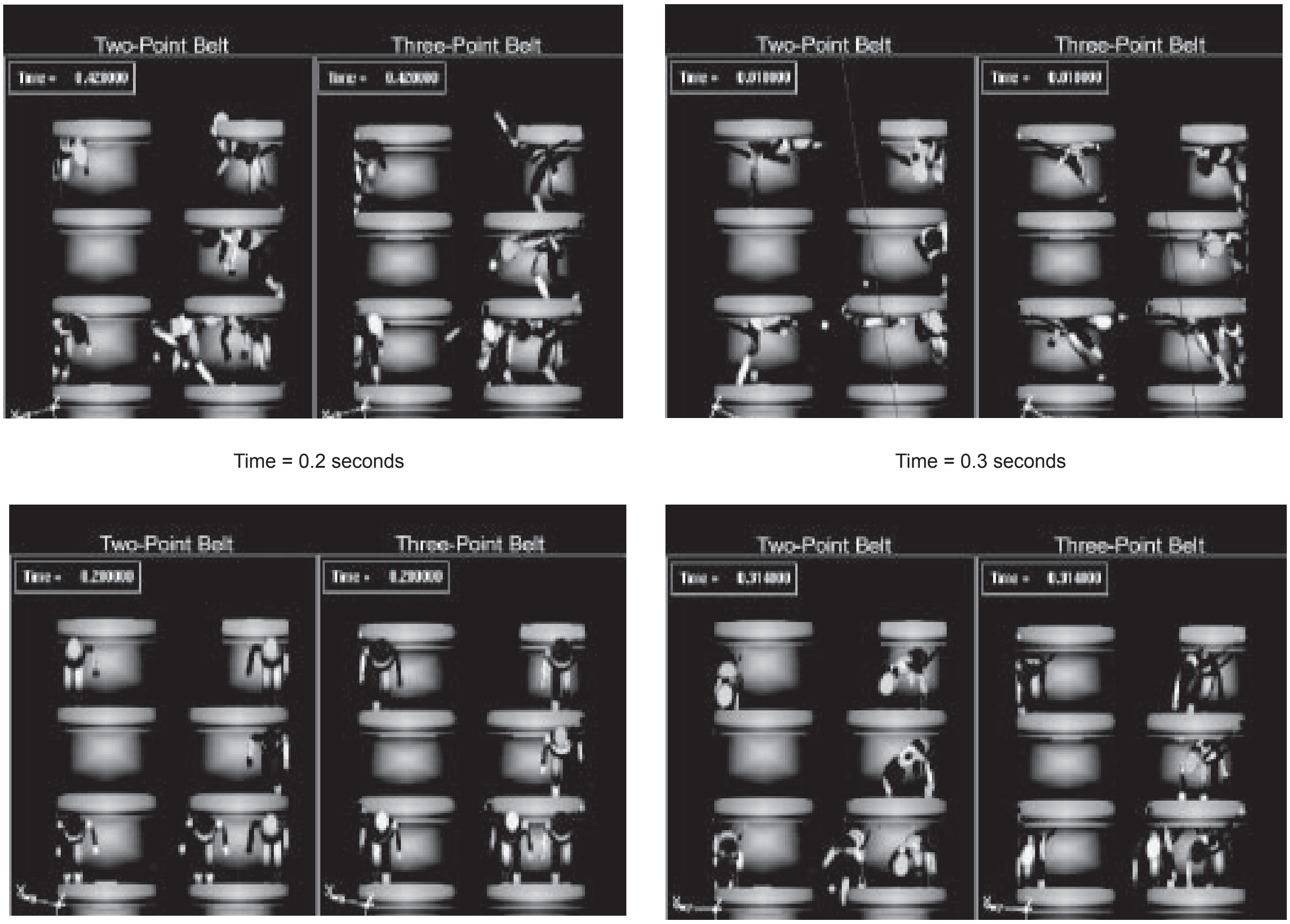
Figure 3 illustrates the occupant kinematics simulated for lap-belted and lap/shoulder-belted occupants. (The figure does not show the actual or compartmentalized condition.)

In the lap belt restraint simulation, the simulated occupant's pelvis was essentially fixed to the seat, causing a whip-like action for the upper torso. This whip-like action caused the simulated occupants seated opposite the impact to pivot about the pelvis and impact their heads and torsos on the seat cushions. Head injuries were predicted from these impacts. In addition, because of the configuration of the seats and the dynamics of the bus, hyperextension of the neck was documented as simulated occupants on both sides of the bus rotated about the seat back.

For the lap/shoulder restraint, the simulated occupants displayed similar kinematics as with the lap restraints. During

Table 1. The change in velocity at the center of gravity and left rear corner of the school bus involved in the Monticello, Minnesota, crash.

Impact	Delta V (mph)	
	Center of Gravity	Left Rear Corner
1st	31	34
2nd	18	18
3rd	12	44



Time = 0.2 seconds

Time = 0.3 seconds

Time = 0.4 seconds

Time = 0.8 seconds

Figure 3. Time lines for occupant motion in the lap (left side) and lap/shoulder-belted (right side) conditions (simulated).

the final impact (the side slap), the upper torsos of simulated occupants seated on the side opposite of the impact slid out from their shoulder belts. Although previous research[9,10] indicated that the belt typically absorbs sufficient energy before the torso is released, these simulations indicated a potential for head injury after the torso slid from the upper restraint and the head contacted the seat cushion.

Conasauga, Tennessee

On March 28, 2000, a southbound CSX Transportation, Inc., 33-car freight train, en route to Atlanta, Georgia, collided with the passenger side of a westbound Murray County, Georgia, school bus at a railroad/highway grade crossing near Conasauga, Tennessee. The school bus was on its morning route to pick up children and had entered Liberty Church Road from U.S. Route 411. On board were seven children and the driver. As the school bus traversed the passive grade crossing, it was struck by the train. Figure 4 shows the final resting position of the bus body.

Figure 4. The bus body came to rest against the side of the train (Consauga, Tennessee).

The school bus was equipped with video recording equipment to monitor passenger behavior on the bus. These videotapes showed that, on the day of the accident, the school bus did not stop as required before attempting to cross the railroad tracks, nor had it stopped at this crossing on eight previous occasions.

During the accident sequence, the driver and three children were ejected. Two ejected passengers received serious injuries and one was fatally injured. The driver, who had been wearing a lap/shoulder belt that broke, received minor injuries. Of the four passengers who were not ejected, two were fatally injured, one sustained serious injuries, and one, who was restrained by a lap belt, received minor injuries. The two train crewmembers were not injured.

Using the human vehicle environment system and MADYMO, the Safety Board conducted vehicle dynamics and occupant kinematics simulations for this investigation.

The vehicle dynamics simulation (figure 5) verified that the train was traveling about 51 mph and the bus, about 15 mph at impact. The resultant peak accelerations experienced by the bus during its initial lateral impact with the train were 30 g at the center of gravity, 39 g at the last row of seats, and 31 g at the first row of seats. The peak angular acceleration at the center of gravity was approximately 2,500 deg/sec2. The angular accelerations were higher at the last row due to the school bus's clockwise rotation away from the impact point, the pivoting of the bus about the front axle, and the distance of the last row of seats from the impact location. During the initial lateral impact, the velocity of the train changed by 1 to 2 mph due to emergency braking, while the lateral velocity of the bus increased due to the velocity of the striking train. Because the train was much larger and heavier than the school bus, the severity of the collision was more extreme for the bus.

Occupant simulations showed that the occupant seated at the rear of the bus was exposed to the highest forces and thus was predicted to sustain the highest level of injury. This occupant sustained high levels of injury in all simulated restraint conditions (compartmentalized, lap-belted, and lap/shoulder-belted). The combination of high-lateral accelerations and high-rotational accelerations, which occurred at the same time, contributed to the rapid lateral progress of this occupant across the aisle (figure 6) and the high contact forces experienced when impacting the side of adjacent seat back, side wall, and window frame screw housing. In the front of the bus, the opposite was true. Simulated occupants restrained by either the lap belt or the lap/shoulder belt, as shown in figure 7, were subjected to less-severe accelerations and were therefore predicted to sustain less-severe injuries.

9 D. Cesari, R. Quincy, and Y. Derrien, "Effectiveness of Safety Belts under Various Directions of Crashes," Society of Automotive Engineers, Paper No. 720973.

10 J. Horsch, "Occupant Dynamics as a Function of Impact Angle and Belt Restraint," Society of Automotive Engineers, Paper No. 801310.

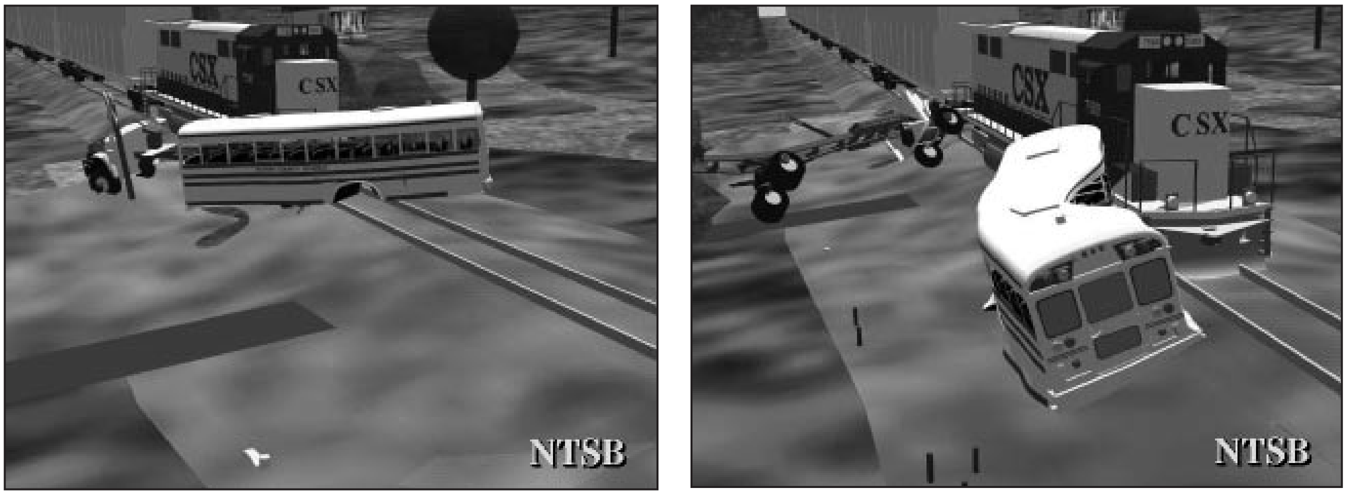


Figure 5. Two still images from the vehicle dynamics simulation show the impact between the bus and train and the separation of the bus body and chassis as the impact continued (Consauga, Tennessee).

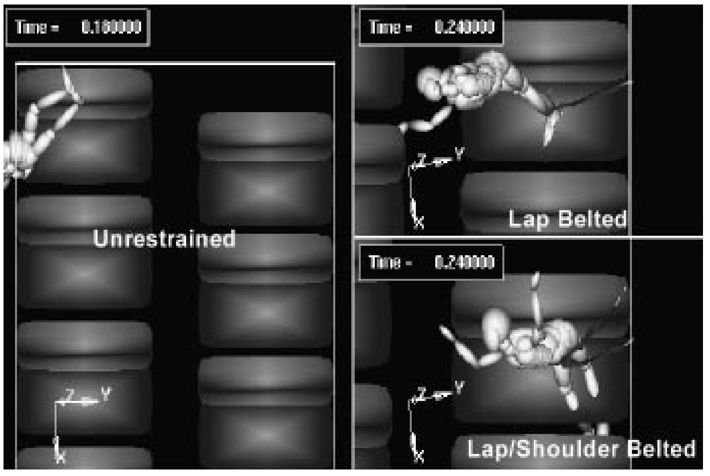


Figure 6. Kinematics of the rear-seated occupant in all three restraint conditions. (The front of the bus is toward the bottom of the image.)

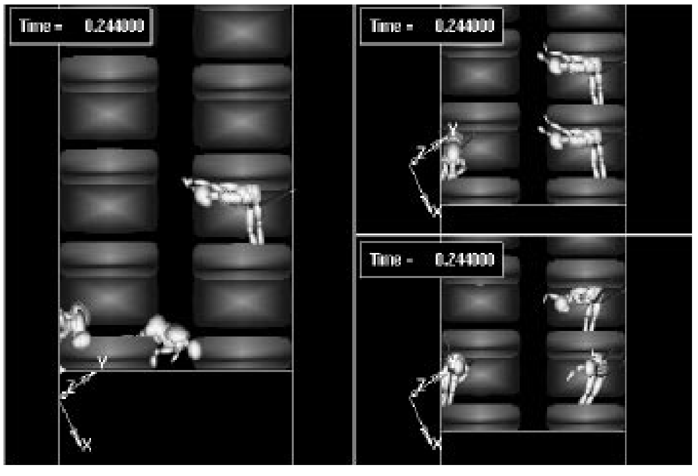


Figure 7. Kinematics of the three occupants in the front of the bus in all three restraint conditions (Consauga, Tennessee). (The actual restraint condition is shown on the left. The lap-belted condition is in the upper right and the lap/shoulder-belted condition is in the lower right.)

Testing and Simulation

Full-Scale Crash Testing

NHTSA reviewed data from its Fatality Analysis Reporting System (FARS), National Automotive Sampling System (NASS), General Estimates System (GES), and Special Crash Investigations (SCI), as well as State and local crash data and data from the Safety Board. NHTSA found that the most significant factors in two-vehicle, fatal school bus crashes were that they occurred on roadways with posted speed limits between 55-60 mph and that they involved heavy trucks. Based on these findings, NHTSA designed two full-scale crash tests to represent the real-world environment of large school bus crashes.

Frontal Crash Test - The first crash test was conducted by frontally impacting a conventional school bus into a rigid barrier at 30 mph. The impact speed was chosen to ensure that sufficient energy would be imparted to the occupants to evaluate the protective capability of compartmentalization, and to provide a level at which other methods for occupant injury mitigation could be evaluated during sled testing. A 30-mph impact into the rigid barrier is also equivalent to two vehicles of similar size impacting at a closing speed of approximately 60 mph, which NHTSA found to be prevalent in their review of crash data sources.

Figures 8 and 9 show the frontally impacted bus before and after the impact. As is typical of large school buses, the body of the bus was mounted to the frame rails of the chassis by a series of clips or clamps. This non-rigid mounting feature allowed the bus body to slide forward approximately 36 inches during impact (see figure 10). This dissipation of impact energy over a longer time reduced the acceleration levels experienced by the vehicle's occupants.

Accelerometers were positioned along the center aisle of the bus body to record accelerations during the crash. Ten dummies were used in the test: five Hybrid II and III 50th percentile adult male (representing adult and large, teenaged occupants), two Hybrid III 5th percentile adult females (representing average 12-year-old occupants), and three Hybrid II and III 6-year-olds. Four of the ten were ballast dummies, which were placed throughout the bus. See figure 11.

Table 2 contains the dummy injury values for the frontal crash tests. The neck injury (Nij) value was calculated based on the criteria being used for the revised FMVSS No. 208,[11] "Occupant Protection." The pass/fail criterion for Nij was 1.0,

11 *Code of Federal Regulations,* Title 49, Chapter V–National Highway Traffic Safety Administration, Department of Transportation, Federal Motor Vehicle Safety Standard (FMVSS) No. 571.208; Occupant Crash Protection.

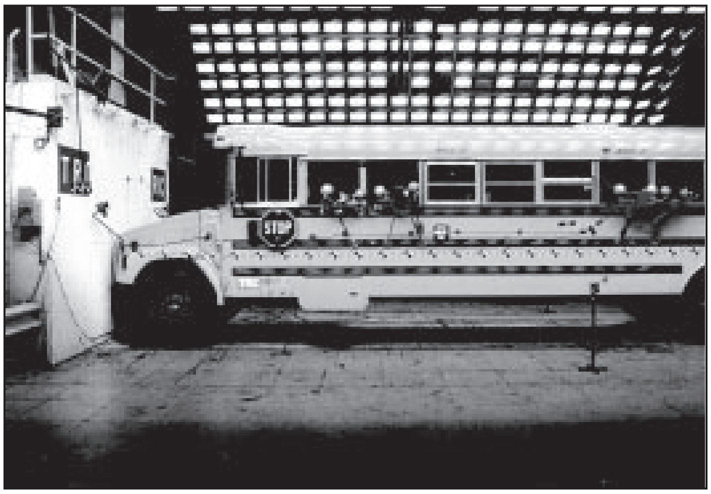


Figure 8. The school bus in the frontal impact scenario before the impact.

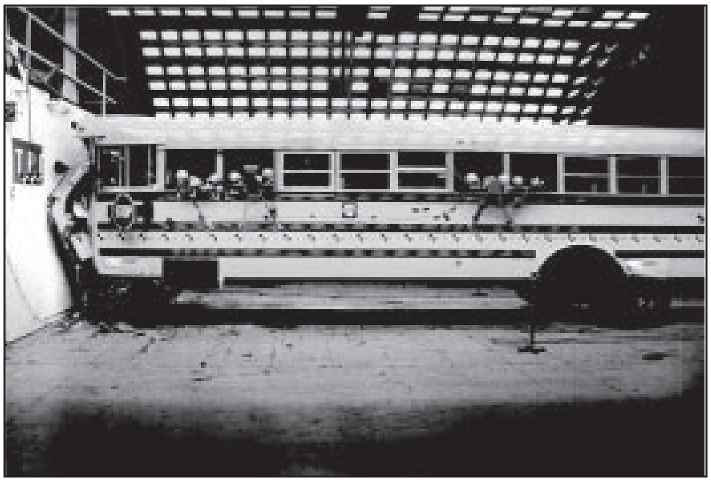


Figure 9. The school bus in the frontal impact scenario after the impact.

Figure 10. Displacement of the bus body on the chassis during frontal impact.

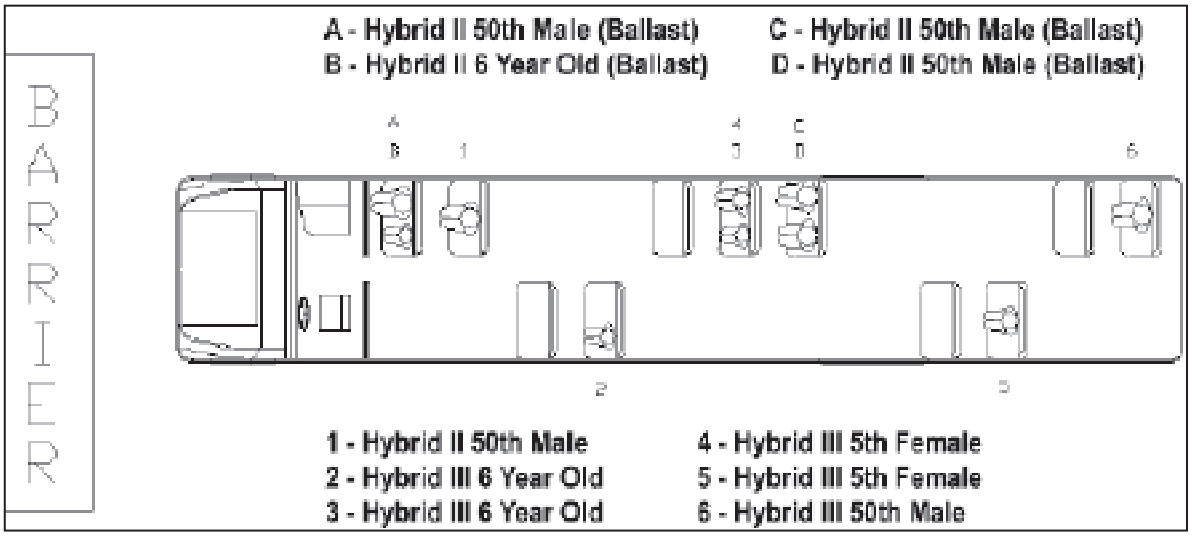


Figure 11. Position of dummies during the frontal crash test.

Table 2. Frontal crash test results.

Dummy	Nij	HIC	Chest G
#1 (50th M)	0.91	244	26.0
#2 (6 yo)	1.57	93	30.8
#3 (6 yo)	1.06	251	30.9
#4 (5th F)	1.15	105	No Data
#5 (5th F)	1.38	330	22.6
#6 (50th M)	0.84	150	22.3

which represented the onset of serious injuries. The FMVSS No. 208 head injury criterion (HIC) based on a 15-millisecond (msec) duration, was 700 for the 50th percentile adult male, 5th percentile adult female, and 6-year-old dummies. The FMVSS No. 208 pass/fail criterion for chest acceleration based on a 3-msec duration was 60 g for the 50th percentile adult male, 5th percentile adult female, and 6-year-old dummies.

HIC and chest injury values were low during the frontal crash test, but the neck injury criterion was exceeded in four of the six dummies.

Side Impact Crash Test - The second crash test was conducted by towing a 25,265-pound cab-over truck, at 45 mph and 90 degrees, into the side of a stationary, transit style school bus. The impact point was chosen so that the left front edge of the truck was directly behind the front axle of the school bus to eliminate contact with rigid structures on the frame during the initial penetration of the truck into the bus body. (See figures 12 and 13.) During impact, the truck penetrated the bus side approximately halfway into the compartment and remained engaged while rotating 180 degrees before coming to a stop. The front axles were severed from both vehicles (figure 13).

Figure 12. The heavy truck relative to the side of the school bus before impact.

Accelerometers placed along the length of the school bus recorded a peak lateral acceleration of 72 g at the center of impact. Acceleration levels dropped significantly with distance from the point of impact, largely because the deformation that occurred at the point of impact absorbed and dissipated much of the energy that would otherwise have been transmitted to the occupants of the bus. Unlike the frontal crash, no single pulse fully represented the range of vehicle responses observed in the side-impact crash. However, the overall pulse shape and pulse duration were similar for most of the measured locations along the length of the bus.

Figure 13. The heavy truck relative to the side of the school bus after impact.

The seating positions of the dummies are shown in figure 14. As in the frontal crash tests, the Hybrid III 5th female and 6-year-old dummies were used. Replacing the Hybrid III 50th male dummies were two 50th male side impact dummies (SID), which are capable of measuring lateral head, chest, and pelvic accelerations. One of the SID/Hybrid III dummies was positioned a row behind the direct impact zone of the truck (position 2 in figure 14). One Hybrid II 50th male dummy with a single triaxial accelerometer array in the head was centered at the point of impact to determine survivability within the impact zone (position 1 in figure 14).

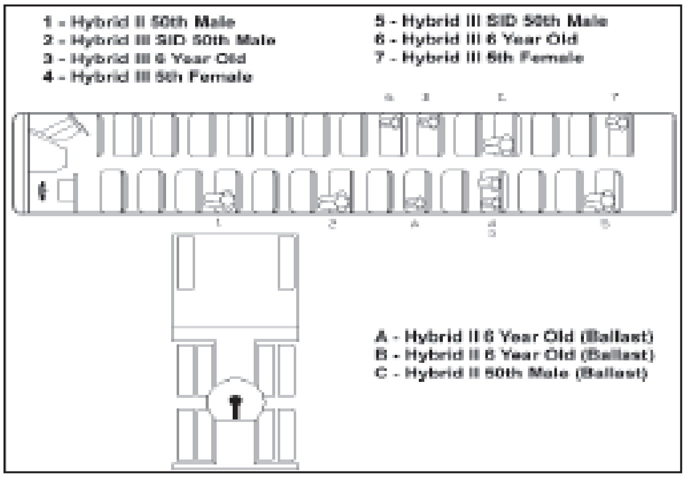


Figure 14. Positions of the dummies in the side impact crash scenario.

Table 3 shows the results for the side-impact crash test. HIC values were based on a 15-msec duration, and chest acceleration values were based on a 3-msec duration, with the same pass/fail criterion as in the frontal tests. For the SID dummies, the Thoracic Trauma Index (TTI) was also recorded. A value of 85 g indicated the onset of serious injuries and served as a pass/fail criterion under FMVSS No. 214.[12]

Table 3. Side impact test results.

Dummy	HIC	Chest G	TTI
#1 (HII)	2164	N/A	N/A
#2 (SID)	277	N/A	54.7
#3 (5th F)	85	27.7	N/A
#4 (6 yo)	124	11.1	N/A
#5 (SID)	133	N/A	7.1
#6 (6 yo)	54	22.7	N/A
#7 (5th F)	1	7.4	N/A

The head injury criterion was exceeded for the dummy centered in the impact region. All other injury criteria were below the thresholds.

The two crash tests conducted for this program represented severe crash conditions. In general, school bus mass effectively minimizes the acceleration forces experienced in a vehicle-to-vehicle crash with most passenger vehicles. The potential acceleration loads from frontal and rear crashes with vehicles of similar mass are also effectively minimized by the manner in which the body of the bus is coupled to the chassis of the bus. The frontal crash test demonstrated that, by allowing the body to slide along the frame of the bus, much of the kinetic energy of the bus could be dissipated before loading the passenger compartment.

In a side impact, the construction of the body of the bus does very little to prevent passenger compartment intrusion. However, due to the high ground clearance of the school bus, passenger vehicles are not a serious threat in generating passenger compartment intrusion. Vehicles large enough to pose a significant probability of intrusion are of a sufficient mass that no feasible body structural design will effectively prevent them from intruding into the passenger compartment.

In the test, passenger compartment intrusion at the point of impact was severe. The high degree of deformation at the point of impact was very effective at absorbing and dissipating the energy of that impact. The side impact test conducted for this program showed that an occupant seated only a few feet outside

12 *Code of Federal Regulations,* Title 49, Chapter V–National Highway Traffic Safety Administration, Department of Transportation, Federal Motor Vehicle Safety Standard No. 571.214; Side Impact Protection.

the direct impact zone had a high probability of surviving the crash with only minor to moderate injuries.

Sled Testing

Sled tests were conducted to replicate the acceleration time history of the school bus full-scale frontal impact test. The derived sled pulse[13] agreed very well with the time duration (approximately 210 msec) and the peak acceleration (approximately 12-13 g). The leveling off of the acceleration pulse of the crash test from about 40 to 90 msec was a result of the bus body sliding along the chassis. The sled test did not exactly replicate this plateau and allowed a somewhat higher acceleration level at this point in the curve. The result was a slightly more severe test pulse because the peak velocity of the sled was approximately 4 to 5 mph higher than the barrier-equivalent velocity measured during the frontal crash test.

Two different test bucks were used to evaluate bus safety restraint systems. For the first test buck, a section from the body of the school bus was mounted on the sled. This test buck was used to assess the degree of deformation/energy absorption by the bus floor and the floor's interaction with the seats, and to assess any potential for occupant interaction with portions of the interior other than the seats themselves. The finished test buck is shown in figure 15. The bus body contained three rows of seats on both the right and left side of the center aisle. This allowed for testing a maximum of two rows of dummies per test.

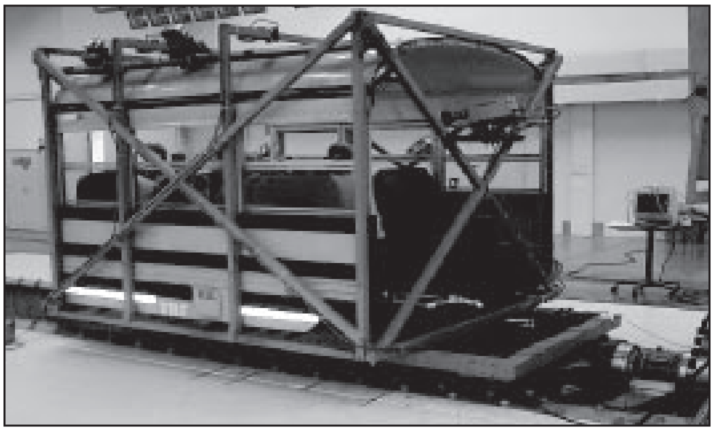


Figure 15. This photograph shows the sled buck for the frontal crash testing.

Testing with the first sled buck showed no significant interaction between the dummies and the walls or ceiling of the bus shell, although the floor of the bus shell sustained some incremental damage from loading by the mounted bus seats.[14] For that reason, an open-frame, rigid-floor, test buck was used to provide a more consistent test platform. (See figure 16.) This test buck allowed for better high-speed imaging of the test event, which improved the analyses of the dummies and their interaction with the bus seats and restraint systems.

Figure 16. A photograph of the modified sled buck used in the second test series.

The sled tests were designed to evaluate occupant size, restraint strategies, loading conditions, seat spacing, and seat back height. The occupants were represented by Hybrid III 50th-percentile male dummies, Hybrid III 5th percentile female dummies, and Hybrid III 6-year-old dummies. The restraint strategies that were evaluated included compartmentalization, use of lap belts (with compartmentalization), and use of lap/ shoulder belts on bus seats with a modified, non-FMVSS 222-compliant seat back.[15] Other conditions evaluated were seat spacing, seat-back height, and rear occupant loading.

Results indicated that compartmentalization is an effective restraint strategy for frontal school bus crashes, in part due to the relatively low acceleration load in even a relatively severe crash condition. The padded seat backs appear to be effective in minimizing the potential for leg and head injury. During the frontal crash, occupant kinematics were such that chest loading was not a significant problem. However, these conditions created some degree of risk for neck injury as measured by the

13 "Report to Congress on School Bus Safety: Crashworthiness Research, April 2002" page 19, Figure 6, at http://www-nrd.nhtsa.dot.gov/departments/nrd-11/SchoolBus/SBReportFINAL.pdf .

14 The deformation was very small for any single test and accounted for an insignificant amount of energy absorbed by the seats during the crash simulation.

15 *Code of Federal Regulations,* Title 49, Chapter V–National Highway Traffic Safety Administration, Department of Transportation, Federal Motor Vehicle Safety Standard No. 571.222; School Bus Passenger Seating and Crash Protection.

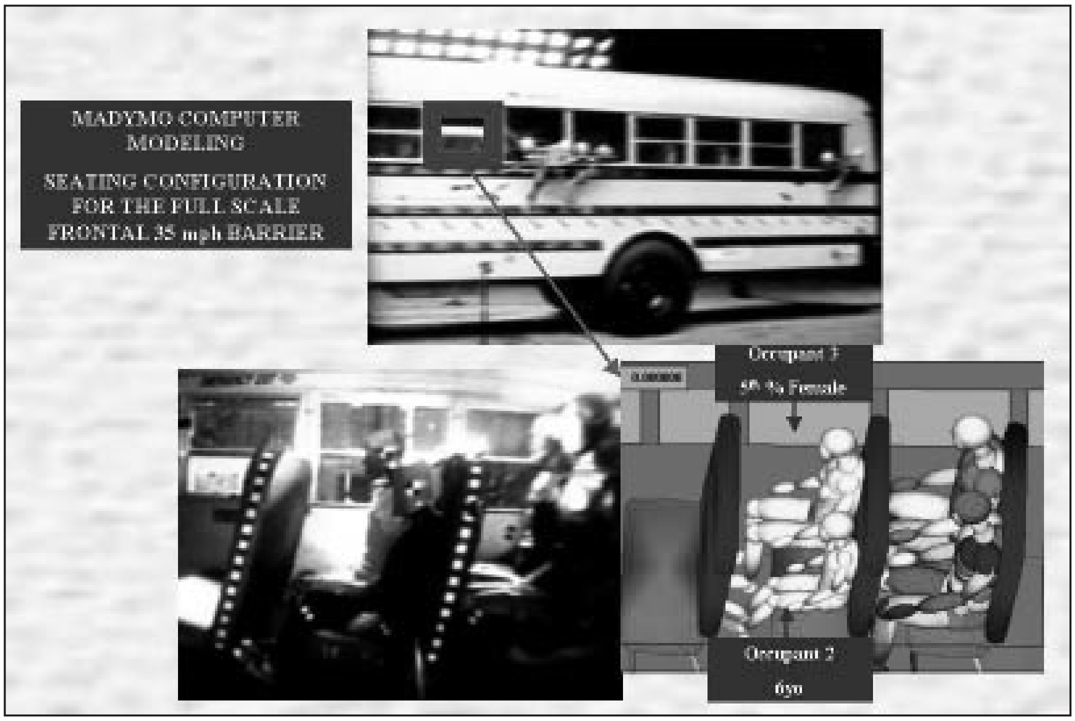


Figure 17. Comparison of full-scale crash tests with simulations.

injury criterion, Nij. About half of the compartmentalized tests had Nij values over the reference value of 1.0.

Although sled testing indicated that lap belts represent an increased risk for neck injury in a frontal crash, the belts did keep passengers within the padded confines of the compartmentalized seat design. They also prevented larger occupants from overriding standard-height seat backs to strike other passengers seated in front. High-back seats were also shown to prevent overriding.

The lap/shoulder belt restraint system performed best overall, restraining the upper body and pelvis of the dummy and either preventing or significantly reducing head impact into the seat back. The primary loading on the head and neck became inertial loading as the body stopped moving forward. The seats deflected and absorbed enough of the deceleration energy that chest loading by the shoulder belt was not significant and the forward snap of the head did not produce significant loads on the head or neck. The adjustable features on both belt systems tested allowed the belt to safely and comfortably fit a wide range of age/size passengers. When used improperly, however, the effectiveness of the lap/shoulder belts degraded, resulting in high neck loads, as seen with the lap belts alone.

Simulations

NHTSA also conducted occupant simulation modeling to represent the full-scale frontal crash test and several of the sled tests.[16] MADYMO was used to simulate the occupant kinematics. Figure 17 shows how the full-scale crash test was modeled in MADYMO.

Simulation and test results were compared for both the head-resultant and chest-resultant accelerations. The signals were compared based on six evaluation criteria designed by Ray.[17] These validated models are planned for future use in evaluating new occupant protection strategies in school buses.

SUMMARY

As stated earlier, school buses are one of the safest forms of transportation on the road today. Despite this excellent record, research continues to focus on the evaluation of school bus occupant protect systems. The Safety Board's accident investigations indicate that in severe accidents, injuries and fatalities do result and that simple changes in the occupant protection systems may not be enough to protect occupants in very severe crashes. NHTSA's work indicates that most occupants receive good protection from compartmentalization alone in both front and side impact collisions. However, the results of NHTSA's research program have shown that lap/

16 L. McCray and A. Barsan-Anelli, "Simulations of Large School Bus Safety Restraints," NHTSA, 17th International Technical Conference on the Enhanced Safety of Vehicles, Paper # 313, 2001.

17 M.H. Ray, *Repeatability of Full-Scale Crash Tests and Criteria for Validating Finite Element Simulations,* Transportation Research Board No. 1528, Transportation Research Board (Washington DC, 1996).

shoulder belt systems produce lower dummy head and neck injury measures than compartmentalization and lap belt systems. However, potential negative consequences of lap/shoulder belt systems have not been adequately researched at this time to allow a full determination of overall cost/benefits.

Future work will focus on using real-world accident investigations, testing, and computer simulations to evaluate various crash scenarios, to improve the crashworthiness of the school bus and to assess potential new occupant protection systems.

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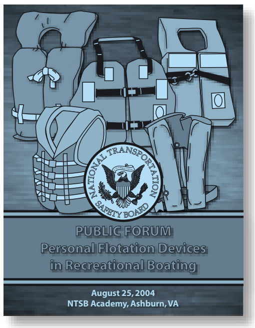

Public Forums, Symposiums, and Hearings

Personal Flotation Devices in Recreational Boating

Bruce G. Coury, National Transportation Safety Board

Will It Float? was the title of Canadian Safe Boating Council's presentation at the NTSB's public forum Personal Flotation Devices (PFD) in Recreational Boating. Those three words describe the discussions about PFD policy that occurred among more than 80 participants from government and the recreational boating industry who gathered at the NTSB Academy in August 2004. The forum covered a range of topics including adult and child PFD use, accident and injury risk factors, boating education, and operator licensing, with much of the discussion focusing on the merits of a mandatory PFD wear requirement for adults in recreational boats.

Participation in recreational boating increased from 78.3 million in 1999 to 91.1 million in 2004, according to the *National Survey of Recreation and the Environment* (NSRE) cited by the U.S. Coast Guard and the boating industry. At the same time, the total number of accidents decreased by 30 percent, and the number of accidents per million participants declined more than 40 percent.

Despite the decreasing accident rate, forum participants agreed that the number of people who drown every year in recreational boating was unacceptable, and that PFD use by adult boaters remains too low. Conclusions were based on Coast Guard recreational boating accident statistics that showed a persistent and constant number of drownings from year to year. From 1999 to 2003, for example, almost 7 of 10 fatalities were due to drowning, averaging approximately 500 deaths per year. The most common factor among drowning victims was the lack of a PFD. The Coast Guard estimates that 84 percent of the people who drowned would have been saved had they been wearing PFDs.

The forum enabled the Safety Board and the recreational boating community to explore actions that might be taken to reduce the number of drownings. The 15 presentations were organized into the 4 panels shown in table 1. The first panel set the stage by presenting accident data, current state of approved PFD technology, studies of PFD use among adults and children, and an analysis of acceptability and feasibility of mandatory PFD legislation done in Canada. Subsequent presentations provided public safety, recreational boater, and industry perspectives on PFD use and requirements. Many presenters felt that a mandatory adult PFD requirement would *not* float in the recreational boating community, and suggested alternatives for increasing PFD use including boater education, operator licensing, and better design and marketing of PFD technologies.

SAFETY BOARD STUDIES OF RECREATIONAL BOATING

The Safety Board has a long history of working to improve recreational boating safety including five safety studies dating back to 1969. The early studies focused on the safety risk factors in recreational boating, with studies in 1983 and 1988 specifically addressing the role of alcohol in boating accidents. The most comprehensive examination of PFD wear by the Board was completed in 1993. Using 407 fatal accident investigation reports provided by 18 States, the study was able to compile statistics on a number of factors, including PFD use, boat operating skills and knowledge, and alcohol involvement. The study found that 73 percent of the fatalities were due to drowning, a figure consistent with the Coast Guard's 1999-2003 average of 70 percent. In addition, the study found as few as 7 percent, and no more than 22 percent, of first-time boat operators had taken some type of voluntary boating course.

One aspect of the 1993 study that continues to be a concern today is the proportion of children who drown, especially those without PFDs. The 1993 study resulted in five recommendations. Safety Recommendation M-93-1, issued to the Governors and legislative leaders of the States, U.S. Virgin Islands, and Puerto Rico, and the Major of Washington, DC, called for a requirement that all children wear PFDs. Most of the States (45) have since enacted mandatory PFD wear requirements for children, but variability in requirements remains. As of February 2005, 5 States (Iowa, New Mexico, Virginia, Wisconsin, and Wyoming) did not require children to wear PFDs, and 13 States had inconsistent age requirements.

In 2002, the Coast Guard enacted 33 *Code of Federal Regulations* (CFR) Part 175 Subpart B, *Personal Flotation Devices,* regulations governing Federal waters (with the final rule going into effect in July 2004). These regulations require any child under 13 to wear a PFD while the boat is underway unless the child is below decks or in an enclosed cabin. During its rulemaking activities for the 2002 Federal regulation change, the Coast Guard showed evidence to justify a requirement that children under the age of 13 wear PFDs.

The need for better education of recreational boaters was also addressed in Safety Recommendation M-93-1, as well as in M-93-9 to the National Association of State Boating Law Administrators (NASBLA) and M-93-14 to the Coast Guard. Those recommendations asked the Coast Guard and NASBLA to develop guidelines that would be used by States to implement recreational boating standards to reduce the number and severity of accidents, and to consider requirements that operators demonstrate knowledge of safe boating rules and skills. The recommendations were based in part on accident data that indicated that boaters involved in fatal boating accidents exhibited a lack of safe boating knowledge, practices, and skills. Safety Recommendation M-93-13 asked the Coast Guard to use its funding authority, through the memorandum of understanding signed biennially by the States, to require a plan for increasing PFD use.

THE ADULT PFD USE PROBLEM

Little has changed since the Safety Board issued recommendations in 1993: about the same number of people drown each year in recreational boating; adult PFD use remains stubbornly low; and a large majority of boaters involved in fatal boating accidents have not received any boating safety instruction. Although the data seem to indicate that a PFD requirement for all occupants in small recreational boats could save lives, no States have passed such laws. These accident data and inaction at both the Federal and the State levels led the Safety Board to conclude that a public forum exploring issues related to PFD wear in recreational boating was warranted.

The extent of the problem was clearly and succinctly presented by the Coast Guard at the forum. In 2003, there were 703 fatalities in recreational boating accidents; 481 (68 percent) were drowning victims, and 416 of them (86 percent) were not wearing PFDs. In addition, nearly 70 percent of all drownings (and more than 60 percent of all fatalities) occurred as the result of capsizing, falls overboard, and swamping (table 2). The size of the boat also matters; 7 of 10 people who drown were in a boat 21 feet or less in length. These statistics are remarkably similar to the statistics reported in the 1993 study; 73 percent of the fatalities were due to drowning, and 80 percent of those who drowned were not wearing PFDs. Using the 2003 data presented at the forum, the Coast Guard estimated that approximately 84 percent of the people who drowned would have been saved if they had been wearing PFDs.

The 2003 statistics were consistent with data from previous years. Beginning in 1999, the number of fatalities remained relatively constant, varying less than 5 percent from an average of 714 per year (table 3). Coast Guard accident and fatality data for that period indicated that 71 percent of these deaths were due to drowning (table 4). In addition, Coast Guard statistics showed that the drownings per 100,000 registered boats remained constant. As previously mentioned, the most common factor among drowning victims was the lack of a PFD.

Table 1. Panels, presenters, and presentations.

Presenters	Topics
Panel I: Facts, Figures, and Studies of PFD Use	
Capt. Scott E. Evans U.S. Coast Guard, Office of Boating Safety	Report on PFDs in Recreational Boating
Samuel Wehr U.S. Coast Guard, Lifesaving & Fire Safety Standards	PFD Wear, New Technology and PFD Approval Process
Thomas W. Mangione and Maria Rangel JSI Research and Training Institute, Inc.	Highlights from the 1998 – 2003 National PFD Wear Rate Observational Studies
Barbara Byers Canadian Safe Boating Council	Will it Float?
Susan Balistreri Balistreri Consulting, Inc.	Mandatory Wear of PFDs on Recreational Boats
Panel II: Public Safety Perspective	
Fred Messman, John M. Johnson, and Ed Carter National Association of State Boating Law Administrators (NASBLA)	A Position Paper from the National Association of State Boating Law Administrators
James P. Muldoon National Boating Safety Advisory Council	PFDs in Recreational Boating
William S. Griswold National Safe Boating Council	Rethinking Mandatory PFD Wear
Panel III: Recreational Boater Perspective	
Jim Ellis Boat Owners Association of the United States (BOAT/US)	Report to the National Transportation Safety Board on Mandatory Wear of PFDs on Recreational Boats
Pamela Dillon American Canoe Association (ACA)	The American Canoe Association Response to Mandatory Wear of PFDs on Recreational Boats
Panel IV: Recreational Boating Manufacturer Perspective	
Bernice McArdle, Ralph Steger, and Scott Swanby Personal Flotation Device Manufacturers Association	PFD Technology and Wearability
Larry R. Innis Marine Retailers Association of America (MRAA)	Mandatory Wear of PFDs on Recreational Boats
Monita W. Fontaine National Marine Manufacturers Association (NMMA)	An Assessment of Mandatory PFD Wear Requirements
Charles B. Husick OWA, Inc.	NTSB Boating Accident Forum

Table 2. Most frequent accident types in recreational boating in 2003.

Type of Accident	Number of Accidents	Number of Injuries	Number of Fatalities	Number of Drownings
Collision with Vessel	1,469	1,063	70	9
Collision with Fixed Object	558	491	50	19
Capsizing	514	330	206	136
Falls Overboard	508	353	201	155
Skier Mishap	451	466	6	1
Swamping	274	61	41	36

Table 3. Accidents, accident rates, and participation in recreational boating, 1999-2003.

Year	Number of Accidents	Total Fatalities	Number Drowning	Number of Participants (millions)	Accidents per 1.0 mil Participant	Fatalities per 1.0 mil Participant
1999	7931	734	517	78.3	101.3	9.4
2000	7,740	701	519	77.6	99.7	9.0
2001	6,419	681	498	75.3	85.2	9.0
2002*	5,705	750	524	81.7	69.8	9.2
2003	5,438	703	481	91.1	59.7	7.7

* In 2002, the Coast Guard changed its criteria for reporting accidents by raising the damage limit for reporting from $500 to $2000. This could result in fewer accidents reported than in previous years.

A 6-year observational study funded by the Coast Guard (T. Mangione, M. Rangel, and K. Watson, *National PFD Wear Rate Observational Study*) confirmed the consistently low adult PFD use. The study, completed in 2003, found that less than 10 percent of adults 18 years of age and older wore PFDs, even in States with child wear requirements and mandatory boating safety courses. The highest PFD wear observed was among boaters on personal watercraft (95 percent), sailboards (94 percent), and in kayaks (84 percent). Although the perceived risk of kayaking, sailboarding, and personal watercraft use may influence those boaters to wear PFDs, the risks of small boats on calm waters may not be so obvious.

Arguments for and against a mandatory PFD wear requirement for adults were presented by NASBLA. Although the presenters were quick to point out that presently there is no consensus among boating law administrators regarding universal mandatory PFD wear for recreational boaters, they did articulate the key arguments. The advocate for a mandatory requirement cited the persistent number of drownings every year and the potential for saving lives if boaters were required to wear a PFD. The advocate against such a requirement disagreed, citing the significant decrease in recreational boating accidents and fatalities since 1970, the effectiveness of boating safety programs, and the fallacy in assuming that 100 percent compliance can be attained. Enforcement would be easier, argued the advocate for, because PFD wear would be easily observed, while the advocate against countered that enforcement would be complicated by the myriad conditions under which a boater may or may not be required to wear a PFD. Significant differences occurred with respect to the potential costs to boaters. On the one hand, boaters are already required to have sufficient PFDs onboard, but the potential costs for enforcing such a requirement could result in increased indirect costs to all recreational boaters. Both advocates agreed that there were alternatives to a mandatory wear requirement.

WHY BOATERS DO NOT WEAR PFDS

Swirling among the pro/con arguments was the fundamental question, why don't boaters wear PFDs? Forum participants gave a long list of answers. High on that list were lack of comfort, lack of safe boating education, and personal choice.

BOAT/US presented results from a recent survey conducted by the Michigan State University Recreational Marine Research Center that showed considerable resistance among boaters to an adult PFD wear requirement. The survey indicated that 86 percent of the respondents opposed a requirement for adult boaters to wear PFDs while underway in *all* boats. When asked for all the reasons why they would not support such a requirement, 76 percent of the respondents indicated that the skipper can make the decision, 64 percent indicated that wearing PFDs was not necessary in all types of boats, and 61 percent indicated that additional regulations were not necessary. More than a third indicated that they would boat less if they were required to wear PFDs while underway. However, in the same survey, 62 percent of the respondents supported a PFD wear requirement based on certain types of boats, and 78 percent supported a requirement that all children 12 and under wear a PFD while underway. When the organizers of the International Boating and Water Safety Summit in March 2005 surveyed attendees, they found that 65 percent of the 235 respondents agreed or strongly agreed that PFDs should be mandatory for those in boats under 22 feet. Personal choice appeared to be the basis for resistance to any Federal or State legislation, but was tempered by the realization that some boating activities are more risky than others and may require more aggressive action.

Personal choice—whether stated in terms of boat captain discretion or as freedom of choice—was of primary concern to many forum participants. Balancing government oversight with intervention and individual freedom and responsibility was a common theme, especially in light of the perceived economic impact of a mandatory PFD requirement on boaters and the boating industry. Participants were concerned, too, that a mandatory wear requirement would be difficult to enforce and would divert limited enforcement resources from potentially more dangerous boating activities. Forum participants wished to proceed cautiously on untested policy solutions and not divert attention from targeted law enforcement, boater education, and an emphasis on personal responsibility.

Presentations of PFD technology by the Coast Guard and the Personal Flotation Device Manufacturers Association (PFDMA) illustrated the wide range of PFDs and the work being done to improve the comfort and style of PFDs. Options range widely—from the traditional "lifejacket" style to float coats and suits, and a variety of water sports-related designs for specific applications. Of particular interest was the new line of inflatable PFDs that, according to the presenters, are more comfortable and wearable (but are not approved for all recreational boating activities, such as riding a personal watercraft). Forum participants agreed that most boaters are not aware of the extensive range of PFD technology that is available.

Although the BOAT/US survey provided some insight into why boaters do not wear PFDs, there apparently has been no comprehensive research to date that specifically considers boater attitudes towards PFD wear or attempts to uncover factors that would lead to increased PFD wear, especially among boaters in small boats on calm waters where the risks are not apparent. The personal watercraft experience does provide some anecdotal evidence showing that, when a mandatory PFD wear requirement is combined with a concerted effort by industry to integrate PFDs into all aspects of recreational boating, resistance to PFD use by adults can be reduced and compliance increased. The Personal Watercraft Industry Association (PWIA) presentation illustrated the use of a marketing model to integrate PFD use into personal watercraft recreational boating. In that approach, PFD use was promoted by manufacturers, retailers, and personal watercraft media, and PFD design and fashion were integrated into the sale of boats and accessories. Before personal watercraft legislation was introduced requiring everyone aboard personal watercraft to wear PFDs, they accounted for a disproportionate number of recreational boating deaths and injuries. By 2003, all States had enacted legislation requiring everyone aboard personal watercraft to wear PFDs. As a result, despite a more than 50 percent increase in the number of registered personal watercraft from 1997–2003, the number of injuries and the number of deaths due to drowning and other causes declined (table 5). Further, the rates for drowning, other types of fatalities, and injuries in accidents per 100,000 registered personal watercraft in 2003 were less than half those of 1997. The Coast Guard's observational study during 1998–2002 found PFD wear among adults on personal watercraft to be the highest among all boaters, ranging between 93 to 97 percent.

Forum discussions revealed that much more can be done by the recreational boating industry. Boat shows often do not prominently display PFDs, and manufacturers, retailers, and recreational boating organizations rarely make available boating safety literature that addresses or advocates PFD use. Only the personal watercraft industry, and to some extent the paddle sports industry, have successfully integrated PFD use into the recreational boating experience.

TAKING ACTION TO IMPROVE ADULT PFD USE

A mandatory PFD wear requirement was not opposed by all of the forum participants. In its presentation, the Coast Guard's National Boating Safety Advisory Council (NBSAC) stated its concern that the proportion of fatalities resulting from drowning had not changed. Initially, NBSAC believed that boater education efforts would positively affect PFD use, and requested that the Coast Guard coordinate with NASBLA to develop a program to encourage mandatory safe boating education. NBSAC also recommended that the Coast Guard engage in PFD public awareness campaigns targeting specific risk groups such as hunters, anglers, paddlers, and personal watercraft operators. Unfortunately, data continue to show that PFD use has not increased despite these public safety campaigns. At the forum, NBSAC reiterated its 2003 resolution that NASBLA develop a model act requiring boaters to wear PFDs while underway on all recreational boats 21 feet or less in length. The National Safe Boating Council concurred, and stated in its presentation at the forum that putting a jacket on everyone in the small boat category would be the single most effective way to reduce deaths due to drowning.

How such legislation might be enacted in the United States was described in the Canadian Safe Boating Council's (CSBC) presentation *Will It Float?* CSBC had commissioned a study to examine the feasibility of legislating mandatory PFD wear for all people in small recreational boats in Canada. After considering the potential costs and benefits of such legislation, the study concluded that a mandatory PFD requirement was appropriate, and CSBC is now working on a strategy to legislate mandatory PFD wear requirements in Canada. It is interesting to note that the study found support for such legislation among boaters and non-boaters alike—the vast majority (70-87 percent) supported the idea of mandatory wear legislation, and almost all (84-93 percent) would comply with the law under all circumstances.

As pointed out in a number of forum presentations, PFDs are already required in certain recreational boating situations. All States require people onboard a personal watercraft to wear a PFD, and 41 States and territories require PFDs during tow-behind (for example, wake boarding and water skiing) boating activities. All but five States require children to wear a PFD while the boat is underway although there is considerable variability in age requirements. The Coast Guard enacted rules in 2004 requiring any child under 13 to wear a PFD while the boat is underway (unless the child is below decks or in an enclosed cabin) in Federal waters. Additionally, some States mandate PFDs be worn for "hazardous conditions/ locations" or specific vessels or events, and some organizations, like the American Canoe Association (ACA), require PFDs during all sponsored activities.

ALTERNATIVES TO MANDATORY PFD WEAR

Boater education combined with safe boating awareness programs was the single most often cited alternative to a mandatory PFD wear requirement. In its presentation at the forum, the National Marine Manufacturers Association (NMMA) stated that available resources should be focused on increasing voluntary PFD use through public awareness. Any efforts to enforce a new mandatory PFD wear law, NMMA went on to say, would only divert resources from other, more productive efforts, such as awareness campaigns and mandatory boater safety education. The Marine Retailers Association of America (MRAA) voiced the same concerns, and stated in its presentation that boaters need strong reasons to support a significant change to a long established lifestyle.

All opponents of a mandatory PFD wear requirement were in favor of mandatory safe boating education and industry-wide efforts to promote wear of PFDs while boating. The ACA presentation showed how the paddlesport community has established education and safety advocacy programs as part of the canoeing and kayaking experience. Forum presenters argued that much can be gained through increased boater education and better efforts by industry to promote PFD use through marketing materials, point of sale transactions, and outreach programs.

NASBLA's National Boating Education Standards provide States with the basis for all acceptable recreational boating safety courses; PFD use is specifically addressed in Standard 2.3. This standard recognizes the need to inform all boat operators that they should wear PFDs at all times, and that they need to be alert to high-risk conditions such as high boat traffic, severe weather, dangerous water conditions, night operations, and boating alone. The standard does not, however, specifically discuss high-risk boating populations, boats, or boating activities, nor does it provide detailed descriptions of PFD types, applications, and effectiveness. In its presentation at the forum, PFDMA described the variety of currently available PFD types, which address a wide range of comfort, performance, and effectiveness factors. Forum participants agreed that such information is a necessary part of any safe boating education course, and that the National Boating Education Standards need to discuss high-risk boating populations, boats, or boating activities and provide sufficient detail about the range of PFD technologies.

ASSESSING THE EFFECTIVENESS OF RISK REDUCTION STRATEGIES

The Coast Guard also presented evidence at the forum to show that safety programs that promote increased PFD wear, especially among adults, could substantially reduce the number of boaters who drown every year. However, data presented at the forum also indicated that the effectiveness of various intervention strategies can be difficult to determine. A case in point is the Coast Guard frequency data for 2003, which indicated that most drownings were associated with motorboats 21 feet or less in length. The difficulty with this finding is that most motorboats in the recreational fleet fall into this category.

This point can be illustrated further by considering two very similar boating activities: canoeing and kayaking. ACA presented fatality statistics for 2002 showing more canoeists (39) fatally injured in accidents than kayakers (28) (Snow-Jones and others, *Critical Judgment II: Understanding and Preventing Canoe and Kayak Fatalities, 1996–2003*). However, when those data are combined with estimates of participation from the U.S. Department of Agriculture Forest Service's *National Survey of Recreation and the Environment,* a different picture emerges. When NSRE estimates of the number of participants in each type of activity are used to calculate exposure measures, kayakers appear to be much more at risk than canoeists. NSRE 2002 estimates showed that kayakers suffered 3.5 fatalities per million participants while the fatality rate among canoeists was almost half that, at 1.9 per million participants.

Accident and injury data for canoeists and kayakers also illustrate the need for different risk mitigation actions. Data from the Coast Guard observational study found that, in general, more than 84 percent of kayakers wore PFDs, in contrast to only 27 percent of canoeists. These data imply that a requirement to wear PFDs would affect kayakers less than canoeists. In addition, the high rate of PFD wear among kayakers indicates that factors other than PFD use affect the outcome in such accidents. However, Coast Guard data also show that 48 percent of the kayakers who were fatally injured from 1996–2002 were not wearing PFDs,[1] indicating that the kayakers observed during the Coast Guard study may not have been representative of the kayakers involved in fatal accidents. Such discrepancies suggest that surveys and observational studies must be carefully designed to ensure that the data collected are representative of the participants most at risk. Such discrepancies also illustrate the potential to underestimate actual risk, which complicates any attempt to evaluate intervention strategies.

The ability to assess risks to recreational boaters and determine the effectiveness of actions taken to reduce recreational boating accidents and fatalities requires accurate data. Without an effective data collection method, the Coast Guard's boating safety program cannot adequately determine the risks in boating nor effectively reduce the number of accidents, fatalities, injuries, property damage, and healthcare costs associated with boating accidents. Although some measures of participation, activity, and exposure are available for recreational boating, using those measures to make risk-based decisions can be difficult. For example, the Coast Guard calculates accident and fatality rates based on the number of registered boats. Unfortunately, boat registration requirements differ considerably among States. Some, like Ohio and South Carolina, require registration of all watercraft; others, like Vermont and Maryland, limit registration to motorboats only. Further, the Coast Guard's system for documenting and numbering boats is not comprehensive and does not necessarily correspond to State registration requirements. Consequently, accident or injury rates based on boat registration data may not adequately represent the size, composition, and use of the recreational boating fleet for risk assessment purposes.

1 Critical Judgment II, page 19.

THE SAFETY BOARD TAKES ACTION

The insights provided by the forum prompted the Safety Board to take action by issuing four safety recommendations in the following areas: implementing a more effective risk assessment program for recreational boating; collecting data on boaters, boats, and boating activities; improving boater education; and increasing industry efforts to promote PFD use.

The first recommendation focused on the Coast Guard's recreational boating risk assessment program. The Safety Board was concerned that the Coast Guard's risk-based approach to recreational boating was not consistent with standard practice in system safety,[2] and concluded that an effective risk assessment program with new survey and research methods, at both the national and State levels, was required to collect, analyze, and disseminate data and information on recreational boating participation and activity. Such survey and research methods, stated the Board, can also provide the basis for longitudinal studies of educational and licensing programs, identification of best practices at the State level, and ongoing observational studies of recreational boating activity and boater behavior. As a result, the Board recommended that the Coast Guard develop measures of recreational boating activities, boaters, and boats that can be used to identify and evaluate the risks in recreational boating. Once those measures have been developed, the Coast Guard should collect the appropriate data at the Federal and State levels and use it to evaluate the effectiveness of recreational boating safety programs. Furthermore, the data and the results of the evaluations should be provided to States for use in their own boating safety programs.

The second recommendation to the Coast Guard specifically emphasized the need to collect boater education data. In that recommendation, the Safety Board urged the Coast Guard to ensure that the measures of recreational boater characteristics include documentation of boater educational experience that can be used at both the Federal and State levels to plan, coordinate, and evaluate recreational boating education and licensing programs.

The Safety Board addressed the concerns about boater education in a recommendation to NASBLA. Citing deficiencies in the National Boating Education Standards, the Board recommended that NASBLA modify its standards to ensure that boating safety education courses adequately discuss high-risk boating populations, boats, and boating activities, and present sufficient detail about the range of PFD technologies available.

2 For example, U.S. Department of Defense MIL-STD-882D, *Standard Practice for System Safety* (2000).

Finally, the Safety Board concluded that the recreational boating industry could do more to promote PFD use in all aspects of recreational boating. Pointing to the success of the PWC and the paddlesports industries, the Board concluded that such marketing strategies can be effective in promoting the desirability and increased use of PFDs and can be a model for the rest of the recreational boating industry. The Board recommended that MRAA and NMMA develop a marketing strategy that promotes increased use of PFDs; increased activity in boating safety education by recreational boating manufacturers, retailers, and media; and integration of PFD use into the sale of boats and accessories. The Board suggested that the marketing strategy specifically target high-risk boating populations, boats, and boating activities, and include sufficient detail about the range of PFD technology, comfort, performance, and effectiveness.

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Positive Train Control Systems

Jana Price and Jim Southworth, National Transportation Safety Board

On March 2-3, 2005, the National Transportation Safety Board hosted the Positive Train Control (PTC) Systems Symposium at the NTSB Academy in Ashburn, Virginia. The goal of the symposium was to reinvigorate dialogue regarding issues relevant to the implementation of PTC systems. More than 150 people participated in the symposium, including representatives from the railroad industry, equipment manufacturers, and government regulators.

In her opening remarks, Safety Board Chairman Ellen Engleman Conners emphasized the need for PTC by noting that 145 head-on, rear-end, and side collision accidents had occurred in 2003, and that 91 percent of those accidents were attributed to human error. PTC systems are designed to employ automatic control systems to override mistakes made by human operators, thereby preventing train collisions and over-speed accidents.

BACKGROUND

Over the last three decades, the Safety Board has investigated numerous accidents in which crewmembers failed to operate their trains effectively and in accordance with operating rules for a variety of reasons, including fatigue, medications use, or distractions within the operating cab. Because of the potential for such accidents, the Safety Board has advocated implementation of a system that compensates for human error and incorporates collision avoidance. The Safety Board believes that this system, known in the industry as positive train control, is particularly important where passenger trains and freight trains operate on the same tracks. Because of the Safety Board's longstanding interest in this issue, the issue has been on the Board's Most Wanted List since the list's inception in 1990. This safety issue was again highlighted when a freight train and a commuter train collided head-on in Placentia, California, in 2002. As a result of this accident, the Board reiterated the need for PTC systems, particularly on high-risk corridors where commuter and intercity passenger railroads operate.

In 1997, the Federal Railroad Administration's (FRA) Railroad Safety Advisory Committee established a working group to address PTC. In 2001, the FRA published a

Notice of Proposed Rulemaking titled, "Standards for Development and Use of Processor-Based Signal and Train Control Systems." The final rule, which became effective on June 6, 2005, established performance-based standards for processor-based signal and train control. Several organizations, including Amtrak, New Jersey Transit, Alaska Railroad, CSX, Burlington Northern Santa Fe Railway (BNSF), and the State of Illinois in partnership with FRA and the Association of American Railroads (AAR), have taken steps towards implementing PTC by sponsoring demonstration projects.

SYMPOSIUM OVERVIEW

The symposium was organized as a series of presentations followed by panel discussions and open question-and-answer sessions. Most of the presenters described their organizations' ongoing efforts to develop, test, and implement PTC systems, as summarized below. Other presenters included representatives from PTC manufacturers, industry consultants, and the FRA. For example, the FRA described its role in the development of PTC systems, provided an overview of the use of the Nationwide Differential Global Positioning System (NDGPS) in PTC systems, and summarized its ongoing research to understand PTC human performance issues.

FRA INITIATIVES AND ACTIVITIES

Tom McFarlin and Terry Tse of the FRA stated that FRA is a strong proponent of PTC systems and the benefits that they can provide, and provided an overview of the new rule, which was scheduled for release the week after the symposium (49 CFR 236, Subpart H). The rule was described as "performance-based" to accommodate advances in PTC technology. Effectively, the rule requires that any new system must be at least as safe as what was there before, and that the operator must demonstrate to FRA through system tests that risk has been reduced.

The speakers stated that rail lines with trains that run faster than 79 miles per hour require in-cab systems or PTC. The FRA has funded a project in Illinois and one in Michigan to equip high-speed corridor railways with PTC. The FRA stated that they would continue to support PTC demonstration projects, encourage interoperability among PTC systems, and promote the Illinois project as a way to provide a template for compliance with the PTC rule.

INDUSTRY PRESENTATIONS

Robert VanderClute of AAR led off the industry presentations by noting that the number of main-line train collisions and fatalities on Class 1 freight railroads has dropped significantly since 1980 while the number of ton-miles traveled has increased. He expressed concern that the currently implemented PTC systems may not be cost effective and that the current costs have exceeded the benefits gained—railroads have spent $225 million on PTC-related projects over the last 20 years. He further suggested that a key challenge for railroads would be developing systems that consider standardization, interoperability, and "migratability." According to VanderClute, the AAR's Rail Electronics Taskforce meets regularly to discuss these issues, and has made progress towards reaching agreement on industry standards.

New Jersey Transit

John Volger from New Jersey Transit described their Advanced Speed Enforcement System (ASES), which builds on existing wayside and on-board technologies. ASES provides speed authority enforcement, displays speed authorities, and functions as a speedometer. According to Volger, ASES operates over a range of territories with various signal systems and has software-based rollaway protection. Transponders at wayside signal locations are programmed with fixed and variable information. Installation of the ASES system is slated to include over 500 miles of track. To date, 23 miles have been installed on a single-track test area. The design for wayside equipment is approximately 60 percent complete and the on-board cab signal equipment is about 92 percent complete. According to Volger, implementation has been slower than anticipated.

North American Joint Positive Train Control

Terry Tse of FRA and Alan Polivka of the Transportation Technology Center, Inc., presented information about the North American Joint Positive Train Control (NAJPTC) project. The NAJPTC project involves the FRA, AAR, and the Illinois Department of Transportation, along with several operators and manufacturers. Its objectives are to demonstrate PTC safety and functionality, develop interoperability standards, produce cost-effective design, and develop a revenue-ready system for high-speed passenger trains intermixed with freight trains. NAJPTC uses modular vital train control, non-proprietary hardware and software, and a high performance location determination system. An additional goal of the project will be to serve as a test case or template for how industry can comply with the FRA's new PTC rule.

NAJPTC territory includes about 120 miles of track between Springfield and Mazonia, Illinois. Six Union Pacific locomotives and ten Amtrak locomotives have been equipped with PTC equipment and have been successfully tested over part of the territory. All wayside signal equipment has been installed and is currently being tested at 79 mph. At the time of the symposium, the project was conducting field tests on the system and the FRA stated that they expect that high-speed railway service would commence in 2006.

Amtrak

Bob Kollmar presented information about Amtrak's Incremental Train Control System (ITCS), which supports revenue service operating up to 90 mph on 45 track miles between Chicago and Detroit. The ITCS has a GPS location system and an on-board computer system that provide information about track restrictions, additions, curves, and temporary slow orders, as well as supervising movement and enforcement of the train. The on-board display shows track speed limit, actual train speed, target future speed, time until override, distance to home signal, milepost number, and train type.

The ITCS is designed to prevent trains from exceeding speed limits (permanent and temporary), encroaching into the work limits of roadway workers, and colliding with one another. The ITCS has developed braking algorithms based on "worst case scenarios." For example, Kollmar described a test in which a heavy Norfolk Southern freight train was run downhill with disabled dynamic brakes. The train engineer was instructed not to use the controls, and the ITCS overrode the controls and stopped the train as designed. Their testing has passed FRA standards for both passenger and freight and, based on their success, Amtrak has requested to increase train speeds to 95 and 100 mph.

Steve Alleman of Amtrak described another system they have implemented on the Northeast Corridor known as the Advanced Civil Speed Enforcement System (ACSES). Originally developed in Europe, ACSES is a "vital overlay" system that has been implemented incrementally using existing signals. ACSES has been used on the high-speed Amtrak Acela trains between New York City and Boston since 2000. Its current capabilities include positive train stop at interlocking signals and radio release of signals. Currently, Amtrak is working on enforcement of temporary speed restrictions using PTC. However, during testing of the phase-two system, they encountered difficulties, which led them to shut the system down. Alleman noted that they have learned to keep the system specifications as simple as possible, to standardize on-board equipment as much as possible, and to have precise location data at the outset of the project.

Alaska Railroad

Eileen Reilly and Andy Schiestl presented information about the Alaska Railroad's Collision Avoidance System (CAS). Development of CAS began in 1997 with the primary goal of train separation. Other goals included increasing train speed, capacity, and efficiency, and having a paperless system. Because Alaska Railroad has no power on much of its track, they felt it couldn't support a "big infrastructure" system.

The CAS system consists of a main computer, on-board displays, dispatcher displays, locomotive polls at waysides to provide on-board data, and speed/distance evaluation brakes. The system allows for remote control of siding switches to keep trains at a safe distance from each other using GPS technology. On-board computers in locomotives monitor the status of the switches and show train movement instructions to the crew. Alaska Railroad has also installed a computer-aided dispatch system and converted its analog microwave communication system to digital. Prototype CAS equipment is scheduled to be installed in the spring of 2006 on a test locomotive, and a braking test of the collision avoidance system is scheduled to begin in the fall of 2006.

CSX

Denise Lyle from CSX provided a freight rail perspective and discussed the CSX Communication Based Train Management (CBTM) system. According to Lyle, CSX has not set a goal of zero collisions, but has addressed areas of highest risk. CBTM is an overlay safety enhancement system, currently designed for nonsignalized territory. The system relies on existing signal technology to make sure that crews comply with authorities or speed restrictions that they have been given. The system will notify a crew as they approach work zones, speed restrictions, or the end of the train's authority. If the crew does not respond, the system will provide a penalty brake override. According to Lyle, if the CBTM system fails, it will return to its original level of operation, which places primary responsibility of train control on the crew.

Burlington Northern Santa Fe Railway

Rick Lederer from the BNSF presented information about the BNSF Electronic Train Management System (ETMS). This overlay system provides a "safety net" while other systems maintain primary control. Like other systems, the train receives communications from signals as it approaches them, and in-cab computers provide information about the upcoming signal. If the crew approaches a signal without slowing, the signal will send a message to the in-vehicle system to begin automatic braking. Currently, the system covers 22,000 track miles, with 8,000 to 10,000 thousand that remain to be covered, mostly in single train branch lines.

NATIONWIDE DIFFERENTIAL GLOBAL POSITIONING SYSTEM

Leonard Allen from the FRA provided an update on the status of the Nationwide Differential Global Positioning System (NDGPS), which will facilitate development and implementation of PTC. Originally developed for the U.S. Coast Guard near ocean and inland waterways, NDGPS comprises a series of reference stations throughout the United States that interact with satellites to provide location information. In 1997, Congress decided to expand the network nationwide, and it is now operational on single-station coverage over about 92 percent of the land area of the continental U.S. NDGPS provides 1- to 3-meter position accuracy to receivers capable of receiving the differential correction signal.

The NDGPS project is now in the process of converting a group of decommissioned U.S. Air Force ground network systems to provide additional coverage. Nine Federal agencies are involved, and the FRA has a lead role as the sponsoring agency within DOT to increase dual (redundant) coverage from 60 to 100 percent coverage of the continental U.S. According to the FRA, the NDGPS project has suffered from inadequate funding. For example, the funding received for the program in fiscal year 2004 was less than one-quarter of what was requested. This funding shortfall has led the DOT to reconsider its plan to pursue development of a high-accuracy NDGPS system, which would provide accuracy of approximately 10 to 15 centimeters and could be used to collect data concerning track problems using instrumented trains.

THE RELATIONSHIP BETWEEN PTC AND HUMAN PERFORMANCE

Jordan Multer from the Volpe National Transportation Systems Center opened his presentation by noting that the number of railroad accidents has gone down, but that the nature of accidents is changing. Although the proportion of accidents attributable to mechanical issues has declined, those attributable to human issues, such as fatigue, distraction, and medical disability, have increased. PTC creates an additional layer of defense to systems that are already in place to prevent human error, such as training and redundant staffing. However, introduction of PTC technology and features will undoubtedly add complexity to the system, which may introduce new sources of errors.

Multer identified a list of human performance factors to consider when implementing PTC systems. For example, he noted that some companies claim that when their systems fail, they revert to their basic non-PTC operational mode, which would not affect the operation of the system. However, if human operators are not aware of the system failure, they may commit errors by behaving as if the system were functional. Another area of concern Multer identified is interoperability. For example, when a train leaves one PTC territory and enters another, how will the in-cab display change? Should there be one common interface or different interfaces for each railroad? Multer suggested that involving human operators in the design process is the best way to address these concerns by fostering a system design that will accommodate human performance limitations and allow designers to identify new sources of risk. These issues have been addressed in multiple FRA research studies and are highlighted in the new rulemaking.

PANEL DISCUSSIONS

At the end of both days of the symposium, speakers assembled for a panel discussion with the attendees and throughout the symposium, audience members were encouraged to submit questions for the speakers. Multiple issues were raised during these discussions, including the following:

- Interoperability of various PTC systems
- Setting interoperability standards and designing for interoperability
- Effects of PTC on rail system capacity and efficiency
- Locomotive crew feedback on the usability and effectiveness of PTC systems
- Testing and preparing for software failures
- Protecting systems from tampering or sabotage
- Future of investments in railroad train control and enforcement
- Aging train authority systems
- Wayside-centric versus vehicle-centric PTC architectures
- Track integrity detection systems
- Energy conservation

CONCLUDING REMARKS

At the end of the symposium, Bob Chipkevich, Director of the Safety Board's Office of Railroad, Pipeline, and Hazardous Materials Investigations, reaffirmed the importance of PTC by noting that in the last 6 years, the Safety Board has launched on 38 accidents that could have been prevented by PTC type systems. Chipkevich concluded,

> PTC is a national issue, it's not a single railroad issue, it's not a regional issue. I think it's important for

> us to get together and talk about the issue, to share information about what's being studied and developed on different systems. It is very enlightening to see a lot of the work that is being done. I look forward to seeing the industry work together to solve the issue, and to come up with an interoperability standard that everyone can agree on.

Safety Board Member Debbie Hersman also thanked the group for its commitment and interest in the topic of PTC and stated, "I think PTC has come a long way since we first put it on our list in 1990. I think we've seen today that there's been great progress and I look forward to continuing the dialog."

For additional information on the National Transportation Safety Board Positive Train Control Systems Symposium, please visit the NTSB PTC Symposium website at http://www.ntsb.gov/events/symp_ptc/symp_ptc.htm.

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