NASA/CR—2001-210905

Market Assessment of Forward-Looking Turbulence Sensing Systems

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Prepared under Contract C–71522–K

National Aeronautics and
Space Administration

Glenn Research Center

May 2001

Available from

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7121 Standard Drive
Hanover, MD 21076

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1 Executive Summary

This study examined the feasibility of the next generation of forward sensing turbulence systems for the Part 121 market segment: enhanced X band radar, LIDAR, and a product that combines these first two technologies. Highlights of the findings include:

- On an annual basis, Part 121 carriers experience at least 567.8 turbulence related injury events that result in 687.4 minor flight attendant injuries, 38.4 serious flight attendant injuries, 119.5 minor passenger injuries, and 17.1 serious passenger injuries.
- The expected cost of turbulence injuries to airlines is $164,286 for a serious flight attendant injury, $25,000 for a minor flight attendant injury, $170,000 for a serious passenger injury, and $33,333 for a minor passenger injury.
- Based on these estimated injury levels and costs, turbulence injuries have at least a $30 M annual impact on Part 121 carriers.
- The FAA values serious injuries at $521,800 and minor injuries at $38,500. If these injury costs are used, the industry impact of turbulence is near $60M annually.
- Approximately 67% of turbulence incidents are related to convective turbulence with clear air and wake /other causes roughly splitting the remainder.
- The impact of turbulence incidents in excessive flight time, aircraft damage, and diversions / delays does not appear to be a significant cost factor for consideration in a technology adoption decision.
- The business case for enhanced X band radar is positive if the nonrecurring investment cost is less than $21,966.
- The business cases for LIDAR and the combined product do not appear favorable under most foreseeable circumstances. These products will have to find market success based on safety, competitive advantage, free - flight requirement or other market or system pressures.
- The combined product appears to have the best market potential as a free flight requirement for large capacity aircraft involved in long duration flights.
- Enhanced X band radar will lead the market penetration of these products and will achieve a maximum of 43% of the market in approximately 11 years. It appears the

combined product may gain 31% of the market but will take about 14 years to achieve this level.

- The most important market success criteria for these technologies can be summarized as integration of the turbulence sensing technology into a cockpit weather information system that provides value added decision data during the en route portion of the flight while minimizing the pilot training required for use.
- In general, the warning threshold for severe turbulence should be greater than three minutes, for moderate turbulence two to three minutes, and less than two minutes for light turbulence.
- Forward sensing systems should detect severe turbulence with accuracy between 90%-100% and moderate turbulence with accuracy between 85% and 90%. Light turbulence should be detected with accuracy between 80% and 90% although there is significant opinion that light turbulence accuracy can be below 80%.
- From an airline viewpoint, reduction of injuries will be the primary reason to purchase turbulence sensing technology. Another important decision factor involves the possible use of this technology as a requirement for the free flight environment.

2 Introduction and Study Objectives

In the last 40 years, major strides have been made to make flying the safest of all major modes of transportation. However, more technological advances are needed in the next 20 years to prevent a rise in accidents if air traffic increases significantly as predicted. In response to this need, the Aviation Safety Program is a key element of the "Three Pillars for Success" initiative that describes NASA's plan to achieve national priorities in aeronautics and space transportation technology. The goal of the NASA Aviation Safety Program is to reduce the fatal aircraft accident rate by 80 percent in 10 years, and by 90 percent in 25 years. The program emphasizes not only accident reduction, but also a decrease in injuries when accidents occur. Program research targets reduction of human-error-caused accidents and incidents, prediction and prevention of mechanical and software malfunctions, and elimination of accidents involving hazardous weather.

This aggressive program involves a partnership that includes NASA, the Federal Aviation Administration (FAA), the aviation industry, and the Department of Defense (DoD). NASA's activities involve several research centers with NASA Langley Research Center in the lead. Critical roles also are being played by three other NASA centers including Ames Research Center, Dryden Flight Research Center, and Glenn Research Center. The FAA support involves definition of requirements and support for development and implementation of safety standards. The DoD will share in technology development as well as apply safety advances to military aircraft. The next section discusses the impact of turbulence on aircraft safety.

2.1 The Turbulence Issue and Study Objectives

Turbulence is a leading issue in aviation safety. The FAA reports that between 1981 and 1997, there were 342 reports of turbulence affecting flights of major air carriers (FAA, 2000a) that resulted in three deaths, eighty serious injuries, and 769 minor injuries. Lindsey (1998) indicates that encounters with turbulence account for 62% of all US air carrier accidents when weather is a factor and another FAA report (FAA, 2000b) indicates this number may be as high as 79%.

In recognition of the importance of turbulence mitigation as a tool to improve aviation safety, NASA's Aviation Safety Program developed a Turbulence Detection and Mitigation Sub-element. The objective of this effort is to develop highly reliable turbulence detection technologies for commercial transport aircraft to sense dangerous turbulence with sufficient time warning so that defensive measures can be implemented and prevent passenger and crew injuries. Current research involves three forward sensing products to improve the cockpit awareness of possible turbulence hazards. X band radar enhancements will improve the capabilities of current weather radar to detect turbulence associated with convective activity. LIDAR (Light Detection and Ranging) is a laser-based technology that is capable of detecting turbulence in clear air. Finally, a possible Radar-LIDAR hybrid sensor is envisioned to detect the full range of convective and clear air turbulence.

To support decisions relating to the development of these three forward–looking turbulence sensor technologies, the objective of this study was defined as examination of cost and implementation metrics. Five tasks were identified to achieve this goal:

- Identify cost factors for the turbulence sensor/software installation.
- Identify certification issues for each sensor/software installation and operation.
- Develop a model for implementation of the turbulence sensor/software into the commercial transport fleet.
- Provide cost budgets/targets for installing the turbulence sensor and associated software devices into the commercial transport fleet.
- Forecast implementation rate using the model developed for each turbulence sensor and associated software.

The next section provides a brief overview of the current state of technical development of these products.

2.2 Turbulence Sensing Product Overview

To provide background for the following chapters, this section briefly discusses the current technical issues and characteristics of the three products that are the focus of this study.

2.2.1 Enhanced X Band Radar Overview

The only current technology is the X Band radar product and there are currently two competitive weather radar systems that target the commercial aircraft sector: The Rockwell – Collins WXR-700 Series and the Honeywell RDR-4 A/B Series. The primary focus of these systems is to identify wind shear but they both have a convective turbulence detection mode that is available for selection by pilots. During telephone interviews related to data gathering for this study, several pilots indicated that this turbulence indication is often ignored and used only for awareness since it is often inaccurate.

Each of these systems has a base price of approximately $100,000 plus installation and upgrades to the current state of the art from previous versions cost about $50,000. More detailed product descriptions are contained in Appendix A.

2.2.2 LIDAR

The second forward turbulence sensing product is the LIDAR (Light Detection and Ranging) system. This technology employs a laser beam to detect clear air turbulence (CAT). At the time of this report, LIDAR product development is under way and no commercial products are available for CAT detection. Technology challenges for this product include:

- Power levels: Current lasers have a range of five miles with a 4-20 milli joule power output and there is concern that this does not provides adequate lead time for safety response actions. Current technology requires four times the power to double the sensing distance. This increased power requirements leads to the next issue.
- System weight and packaging: LIDAR systems include an array of hardware that must be packaged and fitted into aircraft compartments. The complexity of this technology leads to concern with both weight and space requirements.
- Reliability: With a complex system, there is concern with its reliability and maintainability under flight conditions.

2.2.2.1 Concerns Regarding LIDAR Feasibility

Several participants expressed a belief that a stand-alone LIDAR product is not a competitive market alternative and indicated that a feasible LIDAR product must be integrated into existing cockpit weather sensing systems. This is essentially the combined product- the third alternative that will be discussed in the next section. The origin of this view involved the availability of cockpit space and the demands of pilot interface with another source of information and data.

A representative of a firm that develops software for LIDAR systems expressed a different perspective with similar implications. This person provided a general view of the LIDAR market and indicated that his firm views the total LIDAR market as very limited. Without the military applications, his firm believes that the total worldwide market for LIDAR hardware and software is probably less than $10M with another $10M in components sold to organizations doing in house system development. His firm believes this is an insufficient product volume to support a stable private sector product base. In his organization, for example LIDAR related revenues stay constant but drop as a percentage of total firm revenues.

Although these points are beyond the scope of this study and are not factored into the decision model, they are issues for strategic evaluation of the LIDAR market product.

2.2.3 Combined LIDAR + X Band Radar System

The third forward turbulence sensing system combines the enhanced X band radar for detection of convective turbulence with LIDAR to detect clear air turbulence. The business case for this technology is that it should positively impact both of these turbulence categories. The feasibility issue for this product involves whether this impact is sufficient to offset the increased costs of LIDAR.

The next section describes the study methodology that was employed to gather information for this study.

2.3 Study Methodology

This study faced two challenges. First there is a limited population of individuals and organizations involved in forward sensing turbulence systems. In spite of this limitation, it was essential to find a representative group of subject matter experts willing to participate in and provide information for the study. The second issue involves the sensitive nature of the injury rate and cost information that this study required. Although firms see the need to provide information for studies such as this, the perceived confidentiality risks limit the details that are provided in many cases.

To address these challenges, a three - phase data gathering approach was employed. The first step targeted identification of issues and data sources. Over thirty telephone interviews were conducted with individuals representing all elements of turbulence sensing technology development, certification, and implementation including the views of turbulence sensing system developers, major airlines, airframe manufacturers, government, and industry organizations.

The second phase of the study integrated the results of the phone interviews with a thorough literature search to identify the basic decision elements, build conceptual decision models, and frame areas for additional study.

The final step employed a structured data - gathering survey to augment information obtained in the earlier phases. This survey provided an opportunity for selected participants to provide more detailed information on market and product factors. Considering confidentiality concerns, the survey allowed participants to respond to questions in a more anonymous and risk neutral context without providing direct company - confidential information. The next section describes the survey and its goals.

2.3.1 Survey Overview

The survey was developed to meet four objectives.

- To identify the current industry views on the commercial viability of the new advanced turbulence sensing radar systems ("the product") in the transport market.
- To estimate the costs and benefits of these advanced turbulence-sensing products.
- To estimate the technology adoption timing (market penetration curve) for the three versions of turbulence sensing products.
- To estimate the reduction in turbulence injuries that may be achieved by the new forward sensing technologies.
- To estimate of the future impact of cockpit weather systems in reducing weather - related accidents.

To achieve these objectives, the survey was organized in six sections.

- Section I- Participant Characterization: The first section of the survey requested participant contact information and categorized the participant's industry involvement.
- Section II- IV Description of "Forward Sensing Turbulence Systems:" The second, third and fourth sections asked specific questions about the participant's views of the product characteristics of the three forward sensing turbulence systems that are anticipated to enter the market and achieve possible success.

- Section V - Estimates of Market Penetration Curve: The fifth section asked the participants to estimate critical timing points for the market penetration of the three sensing systems. These values were used to develop a regression-based estimate of the penetration curves for these technical alternatives.
- Section VI Frequency and Cost of Injuries: The last section of the survey asked participants to estimate the frequency and cost of serious and minor injuries to passengers and crew due to turbulence events.

The survey data represents responses from key participants in the forward turbulence sensing industry including turbulence sensing system designers, airframe manufacturers, airlines, and industry / government groups. Participants were asked to respond to questions only in areas of their expertise. As a result of these factors, the smallest sample size for a survey question was ten responses and the largest was sixteen. Appendix B contains a sample survey.

2.3.2 Source Identification

To assure source confidentiality, the report narrative does not identify specific firms or individuals unless the referenced information is from a published document.

2.4 Report Organization

There are four remaining chapters in this report. Chapter 3 contains the detailed analysis of the business case. Chapter 4 estimates the rate of technology adoption of these technologies. Chapter 5 discusses the technical product descriptions of the three advanced turbulence - sensing products and Chapter 6 summarizes results and conclusions from the study.

3 Business Decision Model

Forward turbulence sensing technology improves flight safety but also presents investment and cost implications. This section examines that trade off by quantifying the business case for improvements in turbulence sensing. As a starting point for this discussion, the following bullets summarize several possible benchmarks for the financial impact of turbulence on the aviation industry:

- A report in Aviation Week and Space Technology (AW&ST, 1998) indicated that the cost to the aviation industry from turbulence events was approximately $100 M annually. However, Lindsey (2000) indicates that discussion with an FAA source of this figure revealed that $90M of this amount was related to general aviation and only $10M to commercial operations.
- At an address delivered at a NASA conference (NASA, 1998), a vice president of a major airline indicated that in 1997 his airline sustained turbulence related costs in the double digit millions of dollars. These costs involved 200 passenger claims, 235 workers compensation claims, and 2200 days of lost time.
- A recent study reviewed turbulence cost data from a major airline and indicated that a comprehensive figure for annual turbulence cost for Part 121 carriers may be as high as $175M (Search, 2000).

These points illustrate that a range of views and costs have been proposed for the financial impact of turbulence on the aviation industry. This section benchmarks a specific range of values and integrates these estimates into a financial business case model to evaluate the feasibility of a capital investment in forward sensing turbulence technology by a Part 121 carrier.

3.1 Business Model Description

In broad terms, this study uses the following general business model for adoption of forward sensing turbulence systems:

Net benefit of Turbulence System = - Investment –operating costs + savings from reduced turbulence accidents and incidents + savings from flight operations improvements (damage, diversions and flight time) + intangible benefits

The terms in this equation are briefly discussed below and will be developed in more detail in the following sections of the report:

Net System Benefit: The present value of the annual cash flows resulting from system implementation.

Investment: The non- recurring cost to purchase and install the necessary sensing hardware and software for the turbulence technology.

Operating cost: The annual cost to maintain and operate the sensing system.

Savings: Savings include two areas of financial benefit. The first addresses reduction of annual costs related to passenger and flight attendant injuries by mitigating the impact of unanticipated turbulence. The second area involves annual savings related to operational factors such as additional diversions and increased flying time that result from the inability to sense turbulence.

Intangible Benefits: Intangible benefits describe strategic or market based benefits that are not easily "monetized" using standard methods. Intangible benefits are inconsequential if net system benefits are positive without inclusion of intangible benefits. On the other hand, negative system benefits imply that intangible benefits may be important criteria in a decision to adopt turbulence sensing technology. As a result, this study values intangible benefits indirectly by identifying the financial value that they must represent to develop a positive net system benefit value. Study participants suggested the following examples of intangible benefits:

- Competitive advantage in marketing customer satisfaction or safety / comfort may accrue to firms that adopt forward sensing turbulence technology.
- In the future, ultra long distance flights (19-20 hours) may require that passengers safely enjoy extended out of seat periods. This may require forward turbulence sensing since more passengers will be out of their seats for longer periods.
- Free flight will change the current turbulence sensing paradigm: The current air system results in a "first - plane - at- risk" concept with following aircraft subsequently warned of turbulence in the flight path. This will not be the case in a free flight environment since each aircraft may be a potential first plane into a turbulence area.

The next section begins development of critical data for the business model by examining the rate of turbulence accidents, incidents, and injuries.

3.2 Turbulence Accident, Incident, and Injury Rates

The number of annual injuries related to turbulence is a critical benchmark for the business model and a starting point in developing this data is identification of the number of turbulence accidents and incidents. The National Transportation Safety Board (NTSB) defines an accident as an event that results in serious injury or substantial damage to aircraft occurring from the time of aircraft boarding till the last person leaves. A serious injury is one that involves one or more of the following: hospitalization for more than 48 hours, a major bone fracture, severe hemorrhage, nerve, muscle, or tendon damage, involvement of an internal organ, or second or third degree burns on more than 5% of the body.

On the other hand, an incident (or event) is more broadly defined as anything reported that threatens or may threaten safety. Incidents may include both accidents with major injuries and lesser events with either minor injuries or no injuries at all. Minor injuries are those that do not meet the previous criteria. Several general estimates of the frequency of turbulence events (accidents plus incidents) are provided below:

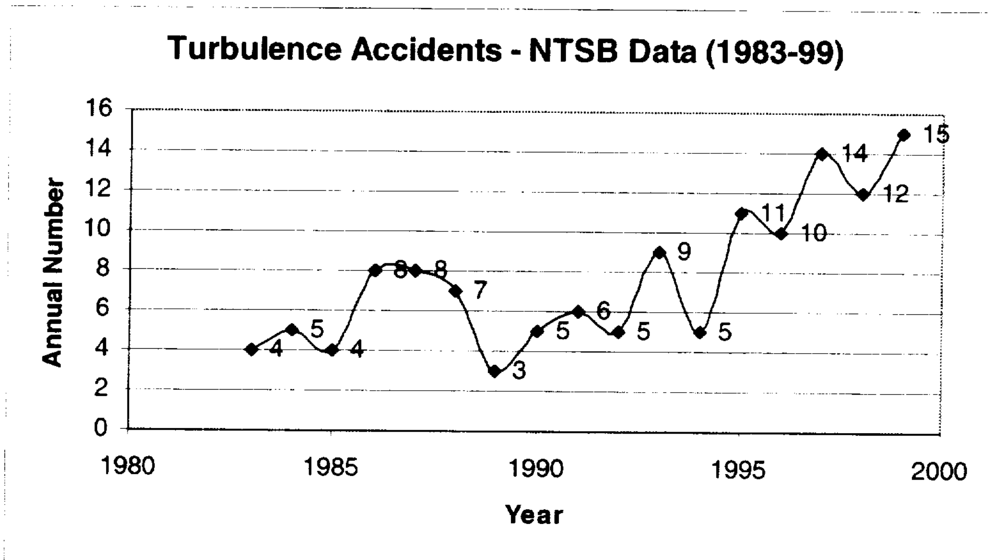
- AW&ST (1998) reported that federal weather researchers estimate a commercial aircraft encounters significant turbulence 180 days per year. This article also indicated that Part 121 air carriers experienced 386 events in a three - year period from 1994-96 for a resulting average of approximately 130 events per year.
- A survey participant who works closely with a number of airlines in weather avionics technology issues estimated that there are 750 turbulence related events per year for Part 121 carriers.
- As previously mentioned, a FAA report (2000a) indicated that from 1981-1997 there were 342 reports of turbulence affecting major air carriers for an annual average of twenty turbulence events.

This range of data points (20 to 750 annual events) indicates great uncertainty regarding the number of turbulence events that a forward sensing system may potentially mitigate. If forward sensing technology can avoid turbulence incidents and accidents, injuries and related costs can be reduced. The next sections examine specific data sources to more closely identify the annual rate of turbulence incidents.

3.2.1 National Transportation Safety Board Reports

The National Transportation Safety Board (NTSB) maintains records on flight safety. A survey participant examined these reports from January 1983 to November 1999 and summarized the results. The NTSB database documented 167 reports involving turbulence and 131 were classified as accidents. Figure 1 describes the annual number of turbulence accidents for Part 121 carriers per this analysis of NTSB reports and shows an increasing trend beginning in 1989.

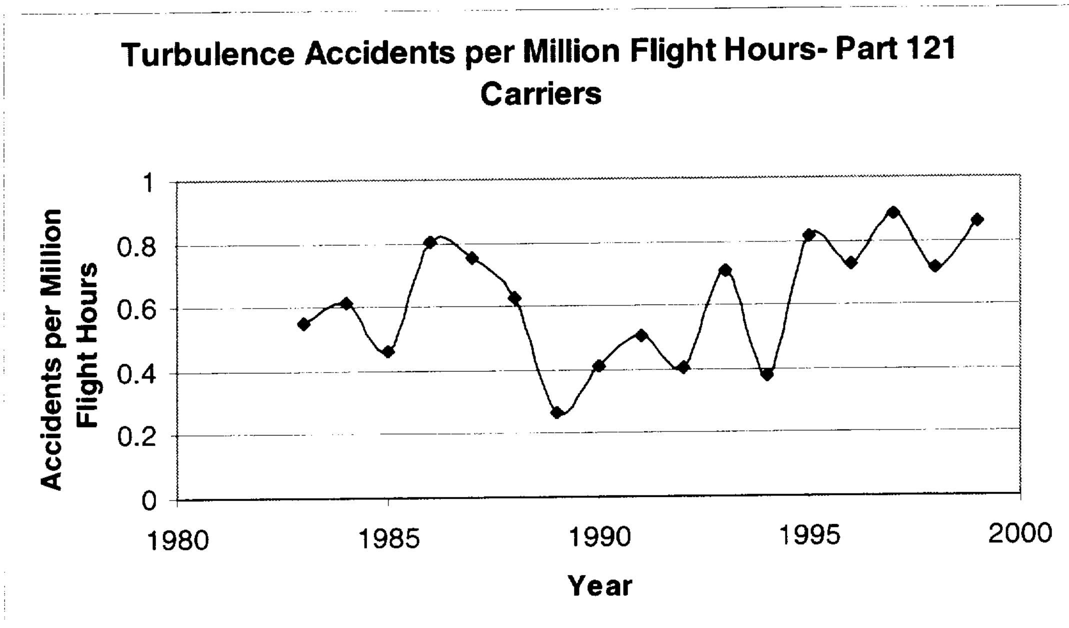
Figure 1 NTSB Annual Turbulence Accidents (1983-99)



To determine if the trend in Figure 1 is related to increasing Part 121 activity, Figure 2 presents the turbulence accidents as a rate per million hours of flight time for Part 121 carriers. Figure 2 indicates an increasing trend in turbulence related accident reports starting in 1989. Figure 2 also shows that this trend may have flattened out at 0.8 turbulence accidents per million flight hours since 1995.

The increasing trend shown by Figure 2 was discussed with several survey participants and they expressed a common opinion that this trend is more representative of the ease of computer based reporting rather than an actual increase in events.

Figure 2 Turbulence Accidents per Million Flight Hours



3.2.1.1 NTSB Injury Rate Summary

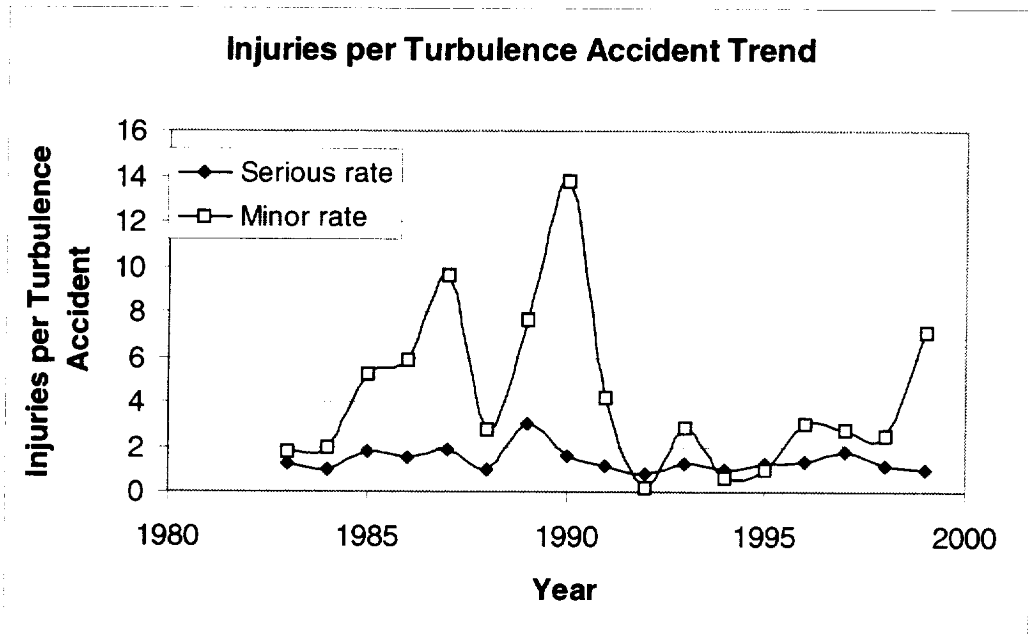
Table 1 summarizes the injury information related to the NTSB turbulence accidents described in Figures 1 and 2. To highlight recent data, Table 1 has been segmented into two time periods. The top half contains information on turbulence accidents from 1983-94 and the bottom portion covers 1995-99. Consistent with Figures 1 and 2, Table 1 shows that the number of turbulence related injuries increases from the 1983-94 period to the 1995-99 period. However, comparison of the mean injury rates of the two time periods ("average per event" line in Table 1) does not show a statistical difference at a 90% confidence level.

Table 1 Injury Rate Summary- Turbulence Accidents

		Passengers Injuries			Flight Attendant Injuries		Total	Total	Total
1983-94	Accidents	Fatal	Serious	Minor	Serious	Minor	Fatal	Serious	Minor
Period Total	69	2	45	256	50	72	2	95	328
Annual average	5.75	0.167	3.75	21.33	4.17	6	0.17	7.92	27.33
Average per event		0.029	0.65	3.71	0.72	1.043	0.029	1.38	4.75
1995-99									
Period Total	62	1	38	167	43	49	1	81	216
Annual average	12.4	0.2	7.6	33.4	8.6	9.8	0.2	16.2	43.2
Average per event		0.016	0.61	2.69	0.69	0.79	0.016	1.3	3.48
		Period rates not different at 90% confidence level							

To identify trends in injury rates over time, Figure 3 plots a time series of severe and minor injury rates for the NTSB data. For the serious injury rate, Figure 3 shows that a trend is not evident. The minor injury rate shows a marked improvement from 1990 - 92 but displays a possible increasing trend from 1992-99.

Figure 3 NTSB Injury Rate Trends



3.2.2 Airline Crew Reports

A major airline provided copies of turbulence related crew reports covering a recent thirteen- month period. These reports were examined, important information was extracted, and the results were normalized to represent a twelve - month period. Table 2 presents this data and shows that on an annual basis 170.9 turbulence related events occurred with 72% (122.9) resulting in an injury. On an annual basis, this data shows 149 minor flight attendant injuries, 8.3 serious flight attendant injuries, 25.9 minor passenger injuries and 3.7 serious passenger injuries. Table 2 also indicates that about 65% of these injury events related to convective turbulence and the remaining events are evenly divided between wake and clear air turbulence.

Table 2 Crew Report Summary - Turbulence Related Events

Annual Data				
	Clear Air	Wake	Convective	Total
Turbulence events	29.6	26.8	114.6	170.9
Percent events	17%	16%	67%	100%
Injury events	23.1	19.4	80.4	122.9
Percent injury events	19%	16%	65%	100%
Probability of injury in event	78%	72%	70%	72%
Minor FA injuries	26.8	28.6	93.3	148.8
Serious FA injuries	3.7	0.0	4.6	8.3
Minor PA injuries	3.7	2.8	19.4	25.9
Serious PA injuries	0.0	1.8	1.8	3.7

Table 3 converts the information in Table 2 into injury rates using only injury events. The right column in Table 3 compares the rates from this data with the NTSB injury rates for the 1995 - 1999 time period. With the exception of minor flight attendant injury rates, the crew report rates in Table 3 are lower than the NTSB data. This result is expected since the NTSB data reflects only accidents and the airline data reflects both incidents and accidents.

Table 3 Turbulence Injury Rate

	Crew report data injury rates based on injury events only				NTSB Turbulence Accidents
	Clear Air	Wake	Convective	Total	1995-99 Rates
Minor FA injuries	1.16	1.48	1.16	1.21	0.79
Serious FA injuries	0.16	0.00	0.06	0.07	0.69
Minor PA injuries	0.16	0.14	0.24	0.21	2.69
Serious PA injuries	0.00	0.10	0.02	0.03	0.61

To estimate the impact of turbulence on the Part 121 industry segment, the airline data was scaled to reflect the entire industry. Table 4 summarizes those results and indicates that a credible case exists that the number of turbulence events for the Part 121 carriers is nearly 800 per year with 567.8 injury events resulting in 687 minor flight attendant injuries, 38.4 serious flight attendant injuries, 119.5 minor passenger injuries, and 17.1 serious passenger injuries.

Table 4 Estimated Annual Turbulence Data for Part 121 Carriers

	Clear Air	Wake	Convective	Total	1999 NTSB Accidents
Turbulence events	136.6	123.8	529.4	789.8	NA
Injury events	106.7	89.7	371.4	567.8	15
Minor FA injuries	123.8	132.3	431.2	687.4	20
Serious FA injuries	17.1	0.0	21.3	38.4	10
Minor PA injuries	17.1	12.8	89.7	119.5	87
Serious PA injuries	0.0	8.5	8.5	17.1	5

Several sources corroborate the magnitude of the estimates in Table 4.

- Lindsey (2000) estimated 1000 turbulence events annually for Part 121 carriers with approximately 1500 flight attendant injuries (minor and serious combined) and about 560 combined passenger injuries.
- The previously referenced airline executive (NASA, 1998) indicated that his airline received 200 claims from passengers, and 235 workers compensation claims for turbulence related injuries in 1997. The Table 4 data represents (687.4 + 38.4) = 825.8 flight attendant injuries for the Part 121 segment. This level is consistent with 235 workers compensation claims related to a single major airline.
- Table 4 may under state the number of passenger injuries. For example, if the 200 passenger claims related by the airline executive are scaled to represent the entire Part 121 industry, a total passenger injury estimate is near 800 - over four times larger than the value for passenger injuries (119.5+17.1 = 136.6) in Table 4. This may indicate that many passenger injury claims are made after the passenger has departed the aircraft. In these cases, crew reports will not identify these occurrences since the crew is not aware of the passenger injury. This may be a similar phenomenon to whiplash injuries that do not manifest themselves for several days after the actual injury event.

3.2.3 Survey Results- Accident and Incident Rates

To assess the possibility that NTSB reports under estimate the impact of turbulence, the survey solicited participant opinion on this issue. Table 5 contains these results and indicates that participants believe that current accident rates and related injury rates are understated. Participants believe the largest area of under statement involves the annual accident rate and the rate of minor injuries to flight attendants. Nearly 90% of the respondents said that the rate of one minor flight attendant injury per accident was an understatement and 33% said this was low by more than 75%.

Table 5 Under Statement of Accident Rates and Injury Rates

Survey participant agreement with NTSB data:	Correct	Low by 0-25%	Low by 25-50%	Low by 50-75%	Low by more than 75%
Annual accident rate of 12-15	18%	18%	27%	9%	27%
One major passenger injury per accident	44%	44%	11%	0%	0%
Three minor Passenger injuries per accident	44%	44%	11%	0%	0%
One major flight attendant injury per accident	44%	33%	0%	22%	0%
One minor flight attendant injury per accident	11%	33%	22%	0%	33%

To provide another benchmark for the number of turbulence incidents, survey participants were asked to estimate the annual number of turbulence related incidents involving at least minor injuries. Table 6 presents those results and shows that participants believe that an average of over 200 incidents occur annually involving Part 121 carriers.

Table 6 Survey Participant Estimates for Annual Turbulence Events

Annual turbulence incidents for Part 121 Carriers		
Lower 90% interval	Most Likely	Upper 90% Interval
151	210	269

3.2.4 Summary of Turbulence Incident and Accident Data

This section examined a wide range of data sources to identify the rate of turbulence events and the injury levels that they produce. The information obtained from the crew reports and described in Table 4 is particularly compelling since it is based on original source data that is identical to the information that an airline would use to evaluate an investment decision in a turbulence sensing system. In addition, estimates in the vicinity of the number of turbulence events and injuries indicated in Table 4 were corroborated independently both by Lindsey (2000) and a survey participant. Consequently, this study uses the data in Table 4 as conservative values to develop the turbulence sensing technology business case.

The next section develops another critical data point for the business case: the annual cost of injuries.

3.3 Cost of Injuries

This section develops a cost framework to evaluate the financial impact of turbulence injuries for Part 121 carriers and begins with analysis of the Federal Aviation Administration (FAA) standards relating to injury cost.

3.3.1 FAA Injury Cost Standards

The FAA (1998) published a standard for economic evaluation of regulatory requirements and the second section of this document contains guidance on valuing the cost related to occurrence of fatality and injury. For a fatality, this standard uses a willingness to pay (WTP) approach to identify $2.7M as the cost benchmark.

Injury costs are developed using a combination of WTP costs and direct costs. The WTP value for an injury is based on evaluating the loss of quality or quantity of life incurred by the injury as a fraction of the fatality cost. For example, the WTP cost of a minor injury is evaluated as 0.2% of the loss of life cost. Since this WTP cost reflects only the value that a group of individuals places on avoiding injury, other direct costs are added to the WTP cost including out of pocket expenses such as legal and emergency medical costs. Table 7 summarizes the suggested minor and serious injury costs developed by the FAA along with the fatality cost. The FAA does not differentiate between flight attendants and passengers.

Table 7 FAA Average Injury Values Per Victim

Classification	Willingness to Pay	Emergency / Medical	Legal / court	Total Value
Death	$2.7M	Not a significant addition to WTP value		$2.7M
Minor injury	$34,000	$2,000	$2,500	$38,500
Serious Injury	$482,000	$27,600	$12,200	$521,800

The key issue with using the FAA values from Table 7 in a business case is determination of how airline decision makers value WTP costs in assessing the financial benefits of turbulence sensing systems. Basically, it is not clear how WTP relates to actual business costs and expenses. The next sections examine other data sources to provide additional benchmarks for the cost of injuries for flight attendants and passengers.

3.3.2 Cost of Flight Attendant Injuries

Several recent studies have estimated flight attendant injury costs:

- Lindsey (2000) indicated that the average flight attendant injury cost (minor and serious combined) is $10k-15k based on information he obtained from a Part 121 carrier. This figure includes lost work time, workers compensation, medical expenses, and additional expenses (such as travel and overtime) to fill the schedule vacancies created by unavailability of the injured employee. Using the mid point of this range ($12,500) and the number of serious and minor injuries in Table 4, an annual cost of flight attendant injuries of $9.1M is obtained.
- Search (2000) examined the costs of workers compensation claims and lost work- days related to flight attendant injuries resulting from turbulence accidents and incidents recorded by a major Part 121 carrier for 1998. To provide anonymity for the carrier, this data was scaled to reflect a commercial fleet of 3500 aircraft and identified flight attendant injury cost as $11,000,000 per year for the Part 121 segment. It is not possible to use this information to develop an estimate for the cost of a single injury.

3.3.3 Cost of Passenger Injuries

Passenger injury costs are the focus of much speculation since both airlines and insurance underwriters hold this information closely. Several published benchmarks were identified:

- Search (2000) assigned a direct payment cost of $600k for serious passenger injuries and $100k for minor injuries. Using these values and the Table 4 injury volumes for passengers, the annual passenger injury cost for Part 121 carriers is estimated at over $22.2 M.
- Lindsey (2000) estimated the average cost of a passenger injury (minor and serious combined) between $50,000 and $60,000. Using the average of this range ($55,000) and the passenger injury volumes in Table 4, an annual passenger injury cost of over $7.5M is identified.

The study survey asked participants to estimate costs of injuries for both passengers and flight attendants and the next section examines the responses.

3.3.4 Survey Injury Cost Data and Estimate of Part 121 Costs

The study survey solicited participant estimates of the total "out of pocket" costs of serious and minor injuries for both flight attendants and passengers. Table 8 shows the 90% confidence interval and expected value (mean) of the survey responses.

Table 8 Summary of Injury Cost Estimates

Values in dollars	Survey: 90% Confidence Interval for mean cost of injury		
Injury Category	**Lower**	**Expected**	**Upper**
Serious Flight Attendant	64,748	164,286	263,823
Minor Flight Attendant	9,292	25,000	40,708
Serious Passenger	76,587	170,000	263,413
Minor Passenger	3,256	33,333	63,411

Table 9 uses the cost estimates from the survey with the number of Part 121 turbulence injuries from Table 4 to develop an annual industry cost estimate. It should be noted that this is a conservative estimate. For example, these values do not reflect the passenger injuries that are not included in crew reports but may be identified after the flight.

Table 9 Annual Costs of Turbulence Injuries for Part 121 Carriers

Injury Category	Annual Injuries (Table 4)	Expected Cost $	Total Cost $
Minor Flight Attendant	687.4	25,000	17,184,125
Serious Flight Attendant	38.4	164,286	6,312,536
Minor Passenger	119.5	33,333	3,984,725
Serious Passenger	17.1	170,000	2,903,157
	Total Annual Part 121 Industry Injury Cost		30,384,542

To compare the total cost in Table 9 with other potential benchmarks for the total Part 121 industry cost, Table 10 provides estimates for turbulence costs by comparing the survey data with results using data from Lindsey, Search, and the FAA injury costs / methods. Table 10 indicates that the data from this analysis is very close in total to the estimate from Search (2000). Lindsey (2000) in fact estimated higher costs than Table 10 shows because he estimated a larger number of injuries than Table 4. Consequently, the estimate in Table 9 appears to be a conservative estimate of the total turbulence related injury costs.

Table 10 Summary of Part 121 Annual Turbulence Injury Cost Estimates

	Survey	Lindsey	Search	FAA
	Table 9	Average flight attendant injury: $12,500	Flight attendant injury cost not estimated	Serious injury: $521,800
	Table 9	Average passenger injury: $55,000	Serious passenger injury: $600,000 Minor passenger injury: $100,000	Minor injury: $38,500
Minor Flight Attendant	17,184,125	9,072,364	$11,000,000 estimated as total flight attendant cost	Total serious injury cost: $28,960,694
Serious Flight Attendant	6,312,536			
Minor Passenger	3,984,725	7,514,052	11,954,174	Total minor injury cost: $31,065,910
Serious Passenger	2,903,157		10,246,435	
Total Part 121 Cost Estimate	**30,384,542**	**16,586,416**	**33,200,609**	**60,026,604**

The next section examines data on the ratio of convective and clear air turbulence events to allocate the potential improvement in annual costs to the appropriate forward sensing technology.

3.4 Ratio of Convective and Clear Air Turbulence Events

This section examines the proportion of turbulence events that are related to convective and clear air turbulence (CAT). This segmentation is necessary to identify the specific injury avoidance impact of the enhanced X band radar and the LIDAR based products. The crew report data in Table 2 indicated that 65% of turbulence injury events are related to convective turbulence and 19% are clear air related. Other benchmarks are detailed in the following studies:

- Clark (1997) studied turbulence related accidents from 1980-1997 and found that one third were reported to involve CAT and half involved active weather cells or occurred in areas conducive to convective turbulence. The remaining turbulence events were related to mountains, wake vortex or other sources.
- Lindsey (2000) reviewed the NTSB database and found that CAT accounts for 26% of turbulence events but only 18% of injuries. He further indicated that if unspecified weather conditions are distributed proportionally to the specified events, then convection

accounts for 50% of turbulence events and 70% of injuries and CAT causes 34% of events and 23% of injuries.

Table 11 summarizes these alternative views on the proportion of turbulence events related to clear air and convective weather activity.

Table 11 Proportions of Turbulence Events and Weather Condition

	Convective	Clear Air	Wake / Other
Table 4- Crew Reports	67%	17%	16%
Clark (1997)	50%	33%	17%
Lindsey (2000)	50%	34%	16%

Discussions with survey participants identified several factors that may impact classification of causal weather and these points are presented below without judgment or evaluation:

- Some clear air turbulence reports may, in fact, be related to convective turbulence. Although the air may appear clear to the crew, the incident may have occurred in a space between convective cells that is a high potential turbulence area.
- Flight crews and controllers may be prone to report clear air turbulence since this is considered a more random event that is not easily anticipated or prevented by in cabin seat belt warnings or similar steps. This classification may have a less detrimental performance impact both on crews and flight controllers.

Several sources have quantified an estimate for this potential overstatement of CAT events:

- An analyst with the FAA who was involved in this study indicated that he believes that as many of half of the 33% clear air events indicated in the Clark study may in fact be related to clear air turbulence. This would result in proportions close to the values identified in Table 4.
- Lindsey (2000) believes that 20% of CAT events are misclassified and are related to other causal factors. This would shift his estimate to 57% convective turbulence related events and 28% CAT related.

Considering these points, this study utilizes the ratio of convective and clear air events identified in the crew reports detailed in Table 4 since it is consistent with other sources and represents a data base derived from a large sample size.

3.5 Non Recurring Investment for Turbulence Systems

The survey asked participants to estimate the non- recurring investment required by the three forward sensing technologies. This investment could occur in two possible ways. First, the investment could be made as a part of new aircraft purchase. Second, the investment could be made as a part of an upgrade to the fleet during an annual maintenance action. The retrofit approach, using the annual maintenance plan, has been employed to update fleet equipment with technologies such as predictive wind shear radar, and other radar upgrade programs. Table 12 summarizes the survey results for the 90% confidence interval for the mean investment estimate by survey participants for these two approaches.

Table 12 Non-recurring Cost Estimates for Forward Sensing Technologies

	OEM Purchase Cost			**Retrofit Cost**		
	-90%	Expected	+90%	-90%	Expected	+90%
X Band	25728	44643	63558	29865	43750	57635
LIDAR	48193	72500	96807	66182	87500	108818
Combined	59147	82500	105853	85823	97500	109177

Two other cost benchmarks should be mentioned:

- Lindsey (2000) estimated the current cost of LIDAR systems as approximately $150,000. The data in Table 12 reflects survey participant estimates for the price of a successful system in the future and so represents a different perspective.
- Some study participants believe that competition between major radar producers to protect current market share will result in significantly lower costs for X band radar improvements. Proponents of this view see this technology as a competitive upgrade by radar producers to maintain their current market position and consequently possible costs may be as low as $10,000 per unit.

3.6 Other Indirect Benefits

Forward sensing turbulence systems may yield other indirect benefits. This section summarizes the financial impact of these factors.

3.6.1 Fuel Savings

Search (2000) examined the impact of turbulence on flight operations. Using the projected fleet aircraft complement in ten years and the number of flights per day of each fleet aircraft type, this analysis estimated that 5% of flights will be prevented from flying at the optimum elevation by turbulence. This results in a total Part 121 industry loss related to flight at non-optimal elevations of $16,000,000 annually. This study estimated that 15% of this loss is avoidable with improved turbulence detection for a possible industry saving of $595 per aircraft for the Part 121 segment.

3.6.2 Aircraft damage:

Lindsey (2000) studied aircraft damage in turbulence events and indicated that no aircraft damage occurred in 83% of turbulence events. In 13%, minor interior damage occurred such as cart, galley, or cabin items. In 4% of cases, substantial damage occurred and in all cases but one this was due to hard landings that damaged the undercarriage or tail of the aircraft. The other case involved hail damage to the windscreen and radar dome. It appears from this study that aircraft damage related to turbulence is inconsequential.

3.6.3 Diversions

Lindsey (1998) found that diversions occurred in 14% of the NTSB turbulence events and were probably related to removing injured passengers or crew. In nearly all cases the aircraft continued on its course with the only costs being extra fuel and delay costs. The crew report data showed four cases of diversion in 122.9 injury events but did not indicate any additional details. It does not appear that diversions are a significant turbulence related cost factor.

3.6.4 Conclusions on Indirect Benefits

In summary, the information discussed in this section indicates that indirect financial benefits are not significant decision factors for turbulence sensing technology adoption decisions. This data agrees with survey findings that are discussed in Chapter 5.

3.7 Integrated Business Case

This section integrates the previous financial information to develop and evaluate an integrated business case for each of the three forward turbulence-sensing technologies. The basic decision model was briefly described earlier in this chapter and employs a pre tax investment analysis method described by the equation below where net benefits are described in terms of present worth:

Net benefit of Turbulence System = - Nonrecurring Investment – annual operating costs + annual savings from reduced turbulence accidents and incidents + annual savings from flight operations improvements (damage, diversions and flight time) + annual value of intangible benefits

There are two alternative decision scenarios in which to apply the business case model. In the first, turbulence - sensing systems are purchased as a part of new aircraft procurement. The second scenario views the business decision as involving an upgrade to the fleet over several years conducted in conjunction with annual maintenance activities. Implementation of predictive wind shear technology demonstrates these two approaches. This technology was certified in 1994 and since that time there has been a gradual implementation process of aircraft upgrade that has involved both purchase with new aircraft and retrofit conversion of 15-20% of the fleet annually.

The base business case focuses on the analysis of the retrofit decision for three reasons. First, the non - recurring cost is higher for this option and this results in the more demanding business case justification. Second, study participants believe that the decision to retrofit a new technology on an existing aircraft is a more closely analyzed decision than new purchase. Finally, for turbulence sensing technology to impact NASA's safety goals, timely market penetration will require retrofit to occur.

3.7.1 Overview of Base Business Case Factors

The following points detail key factors in the base business model:

- Rate of return: Since this technology has safety, cost, and business strategy implications, it is not a pure return based decision. Therefore a relatively low pre tax rate of 12% was selected as the discount rate.
- Project Life: Although many aviation projects are considered under very short life constraints, due to the safety and strategy implications of this technology, a life of five years is used in the base business case.
- Decision maker: The business model decision maker is a theoretical airline that has a fleet of 600 aircraft and flies 20% of the Part 121 passenger miles. Consequently 20% of the annual turbulence accident cost in Table 9 is assigned to this airline. Table 13 shows the annual turbulence costs for this airline and splits the cost in Table 9 between the types of turbulence based on the percentage of injury events in Table 2.

- Annual operating cost: New technologies may require annual increases in operating and maintenance costs. For X band radar, this cost is assumed to be no different than current systems. LIDAR and the combined product represent new technology and the business case charges annual operating costs to these technologies at 5% of initial investment per year.
- Injury Reduction: Survey participants consistently indicated that the successful turbulence sensing technology would provide accurate, timely warning to allow injury prevention measures. As a result the business case assumes an 80% reduction in injury cost related to the type of turbulence sensed. For example, X band radar will reduce convective related injury costs by 80% and LIDAR will reduce 80% of clear air related costs. The model does not assume cost reduction of wake turbulence injuries since these can be avoided by procedural means.

Table 13 Annual Turbulence Costs for Base Business Case

	Total	Clear Air	Wake	Convective
Fatality events @ 0.2 /yr for industry	$108,000	$20,301	$17,053	$70,647
Minor Flight Attendant	$3,719,304	$669,937	$716,139	$2,333,228
Serious Flight Attendant	$1,366,277	$607,234	$0	$759,043
Minor Passenger	$862,439	$123,206	$92,404	$646,829
Serious Passenger	$628,354	$0	$314,177	$314,177
Total	$6,684,374	$1,420,677	$1,139,773	$4,123,924
Annual cost per aircraft	$11,141	$2,368	$1,900	$6,873

Note: Based on theoretical airline with 600 aircraft fleet and 20% of Part 121 passenger miles

Although not significant, Table 13 also includes the cost of turbulence related fatalities using the FAA cost from Table 7 and an annual fatality rate of 0.2 per year. The next sections apply this business case to the three turbulence-sensing technologies. These business cases are developed based on an individual aircraft for simplicity.

3.7.2 X Band Radar Business Case

Table 14 shows that based on an initial investment of $43,750 (Table 12), annual injury savings of $5,499 (80% of Table 13 individual aircraft losses) and operating savings of $595 due to reduced flight time (Search, 2000), the present value of the business case for X band radar is –$21,784. As a result, this is an unfavorable investment at a 12% discount rate and a five-year project horizon.

Table 14 Enhanced X Band Radar - Base Case and Decision Reversal

Percent injury cost reduction	80%	
Business decision based on single aircraft model	X Band Base Case	Value to Reverse Decision
Non Recurring Investment	$43,750	$21,966
Annual injury savings	$5,499	$11,542
Annual operating savings	$595	$6,638
Annual intangible benefits	NA	$6,043
Increased annual maintenance	0	NA
Project life	5	NA
Rate of return	12%	NA
Net present value	-$21,784	

The decision reversal column describes the necessary change in model factors (one at a time) to reverse the outcome to a favorable investment (positive present value):

- Non - recurring investment: If this is reduced from $43,750 to $21,966, X band radar has a positive business case. As mentioned earlier, several study participants believe that there will be significant price competition in the enhanced X band product since system producers will protect their market share. As a result, significant reduction in non – recurring cost is possible.
- Annual injury savings: Other factors held constant at base case values, annual savings from injury reduction must increase from $5,499 to $11,542 to produce a positive present value. Considering Table 10, this would require the airlines to use the FAA cost data and this is not likely.
- Annual operating savings or intangible benefits: If either operating savings increase from $595 to $6,638 or intangible benefits increase from zero in the base case to a value of $6,043 per year per aircraft, the present value becomes positive. This does not appear likely based on the previous analysis.
- Project life or rate of return: Due to the size of the negative present value in Table 14, reasonable changes in life or rate of return cannot make the business case positive.

3.7.3 LIDAR Business Case

Table 15 shows that, based on an initial investment of $87,500 (Table 12), annual injury savings of $1,894 (80% of CAT costs in Table 13), operating savings of $595 due to reduced flight time, and annual operating costs of $4,375, the present value of the business case for

LIDAR is –$94,298. As a result, this is an unfavorable investment at a 12% discount rate for five years.

Table 15 LIDAR Base Case and Decision Reversal

Percent injury cost reduction	80%	
Business decision based on single aircraft model	LIDAR Base Case	Value to Reverse Decision
Non Recurring Investment	$87,500	$7,600
Annual injury savings	$1,894	$28,053
Annual operating savings	$595	$26,754
Annual intangible benefits	NA	$26,159
Increased annual maintenance	$4,375	NA
Project life	5	NA
Rate of return	12%	NA
Net present value	-$94,298	

The decision reversal column describes the necessary "one at a time" changes in base case factors to reverse the outcome to a favorable investment (positive present value):

- Non - recurring investment: The non-recurring investment for LIDAR must be reduced to $7,600 to achieve a positive business case. As mentioned earlier, Lindsey (2000) estimated the current cost of LIDAR units at $150,000 each.
- Annual injury savings: Other factors held constant at base case values, annual savings from injury reduction must increase from $1,894 to $28,053 to produce a positive present value. This does not appear possible based on CAT injury levels and costs.
- Annual operating savings or intangible benefits: If either operating savings increase from $595 to $26,754 or intangible benefits increase from zero to $26,189 per year, the present value becomes positive. This does not appear likely based on the previous analysis.
- Maintenance costs, life or rate of return: Due to the size of the negative present value of the base case, changes in these factors cannot reverse the decision and achieve a positive present value.

3.7.4 Combined Enhanced X Band + LIDAR Business Case

Table 16 shows that the based on an initial investment of $97,500, annual injury savings of $7,393 and operating savings of $595 due to reduced flight time, and annual maintenance costs of $4,875 the present value of the business case for the combined product is –$86,279. As a result, this is an unfavorable investment at a 12% discount rate for five years.

Table 16 Combined Product Business Case and Decision Reversal

Percent injury cost reduction	80%	
Business decision based on single aircraft model	Combined Base Case	Value to Reverse Decision
Non Recurring Investment	$97,500	$11,221
Annual injury savings	$7,393	$31,327
Annual operating savings	$595	$24,529
Annual intangible benefits	NA	$23,934
Increased annual maintenance	$4,875	NA
Project life	5	NA
Rate of return	12%	NA
Net present value	-$86,279	

The decision reversal column describes the necessary change in model factors (one at a time) to reverse the outcome to a favorable investment (positive present value):

- Non-recurring investment: If non-recurring investment is reduced from $97,500 to $11,221, the business case for the combined product becomes positive.
- Annual injury savings: Other factors held constant at base case values, annual savings from injury reduction must increase from $7,393 to $31,327 to produce a positive present value. This is more than a 400% increase and does not appear possible.
- Annual operating savings or intangible benefits: If either operating savings increase from $595 to $24,529 or intangible benefits are valued at $23,934 per year, the present value becomes positive. This does not appear likely based on the previous analysis.
- Maintenance costs, life or rate of return: Due to the size of the negative present value of the base case, changes in these factors cannot reverse the decision to achieve a positive present value.

3.8 Business Case Summary

This chapter has examined the business case for the three turbulence - sensing products. In summary:

- On an annual basis, Part 121 carriers experience at least 567.8 turbulence related injury events that result in 687.4 minor flight attendant injuries, 38.4 serious flight attendant injuries, 119.5 minor passenger injuries, and 17.1 serious passenger injuries.
- There is substantial corroboration that these numbers are conservative.
- These injuries cost Part 121 carriers over $30M annually.

- About 2/3 of turbulence events appear to be related to convective turbulence and the remaining third is split between clear air and wake / other causes.
- The cost impact of turbulence incidents in flight time, aircraft damage, diversions and delays does not appear to be a significant decision factor.
- The business case for enhanced X band radar is positive if the nonrecurring cost is less than $21,966.
- The business cases for LIDAR and the combined product do not appear favorable and reasonable changes to the parameters in the business model do not alter this outcome. These products may have to find market success based on other considerations such as safety, competitive pressures, free flight requirement or other market needs.

The next chapter examines the issue of market penetration for these technologies.

4 Penetration Rate Estimates

To assess the possible impact of turbulence sensing technologies on NASA goals for reducing aviation related accidents and injuries, it is essential to forecast how quickly and to what extent these products may penetrate the market place. To estimate this data, participants were asked to identify several market penetration benchmarks for the three turbulence-sensing technologies:

- The maximum proportion of the market that will adopt the technology.
- The points in the future at which the product will achieve 10%, 50%, and 90% of the maximum estimated market penetration

This section analyzes these responses both as point estimates and as data for a regression model using the approach developed by Fisher and Pry (1971) to estimate an adoption curve.

4.1 Point Estimates for Market Penetration Timing

This section examines survey responses as point estimates of the market penetration points. Table 17 summarizes the average of the survey responses and shows that X Band radar will achieve the greatest market penetration at over 43% but will require 10.7 years to reach 90% of this maximum. The combined product will require over 14 years from the present to achieve a maximum market penetration slightly over 30%. Participants estimate that an average of 26.3% of the Part 121 market will not adopt any turbulence sensing technology. Participants estimated the maximum market penetration of the stand- alone LIDAR product at 17.9% and over 12 years to reach 90% of this level. The percent maximum penetration values in Table 17 represent average responses and add to more than 100%.

Table 17 Mean Point Estimates for Market Penetration Timing

	Percent maximum penetration	Years until 10% of maximum	Years until 50% of maximum	Years until 90% of maximum
Enhanced X Band	43.3	3.3	6.7	10.7
LIDAR	17.9	5.0	8.3	12.3
Combined	31.1	6.7	10.3	13.8
% of market that will not adopt turbulence sensing technology	26.3			

4.2 Fisher –Pry Penetration Curve Estimates

Fisher and Pry (1971) developed an approach to use logarithmic regression to develop estimates for the S- shaped logistic curve that describes market penetration for many products. Figure 4 shows the resulting curves developed using this method and data provided by survey participants. A description of the complete mathematical steps used in developing Figure 4 along with a more detailed set of references can be found in Kauffmann and Pothanun (2000).

Figure 4 Estimated Penetration Curves for Turbulence Products

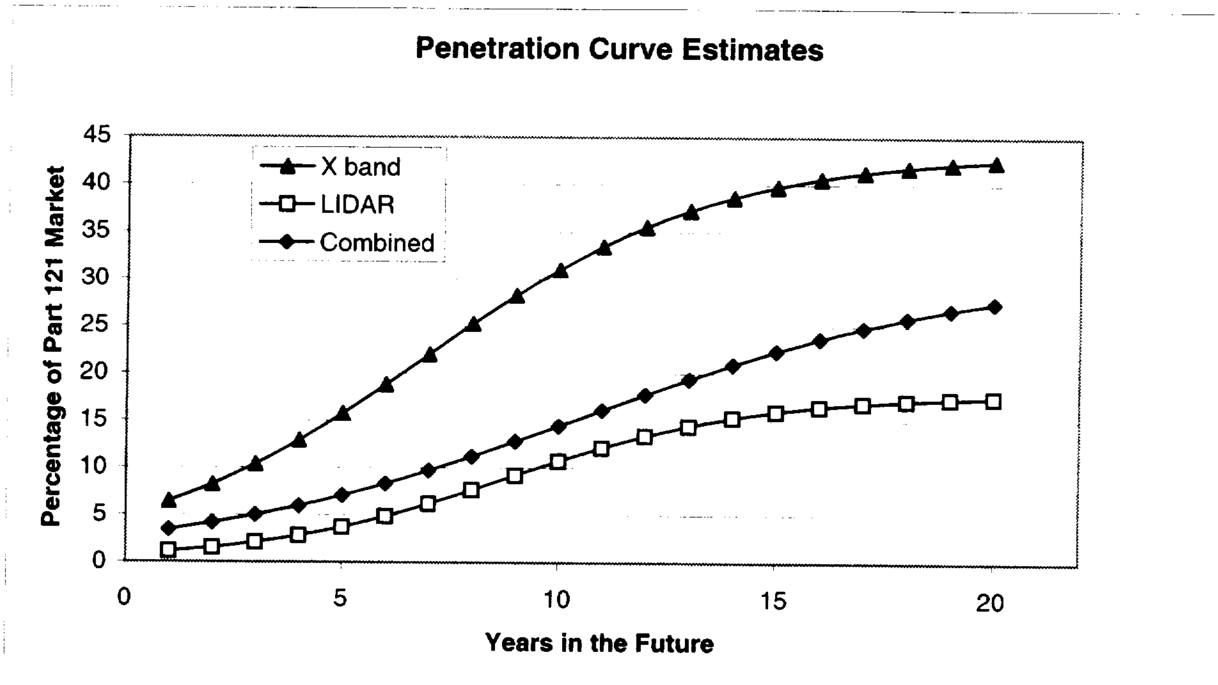


Figure 4 indicates that enhanced X band radar will lead market penetration for forward sensing turbulence systems and the combined product and LIDAR will lag behind. Figure 4 reflects a view that is consistent with the business cases discussed in the previous chapter. For example, the enhanced X band product had a less unfavorable business case than the other two products and thus leads the estimated market penetration.

Market penetration estimates describe a complex process involving industrial purchasing, marketing, market needs, and product characteristics among many other factors. The next chapter attempts to provide some additional insight into these important product characteristics and decision factors for these products.

5 Characteristics of Advanced Turbulence Sensing Systems

During the data gathering and telephone interview phases of this study, a number of issues were raised ranging from product characteristics to purchaser decision priorities. To help clarify these points, a series of survey questions asked participants to evaluate the characteristics and market success factors of the three forward sensing products. This chapter describes those responses.

5.1 Importance of Product Features for Market Success

It is important in evaluating market success potential to develop as much detail as possible regarding the product the survey participants envision. For each of the three products, participants rated a list of product features based on the perceived importance for achieving market success. A standard 1-5 rating scale was utilized with 1 as unimportant and 5 as very important. This section summarizes those results and contains a sub section relating the responses for each product. In interpreting the charts in this section, a difference of one unit in the average score typically indicates a statistically significant difference between two factors.

5.1.1 Importance of Product Features - X Band Radar Market Success

Figure 5 contains the importance ratings of the potential success factors for enhanced X band radar. Factors that scored higher than 4.0 include minimum pilot training (4.3), supply useful information during en route phase of flight (4.7), and integration of this product into a weather awareness system (4.4). Other highly rated factors include supply of information during descent and take off and detection of some forms of clear air turbulence (4.2). This last point must be emphasized since this capability could promote a positive business case for this product. Although participants did not rate any feature below 3.0, the lowest rated product features were that the product consist primarily of software changes and transmit turbulence data to other aircraft.

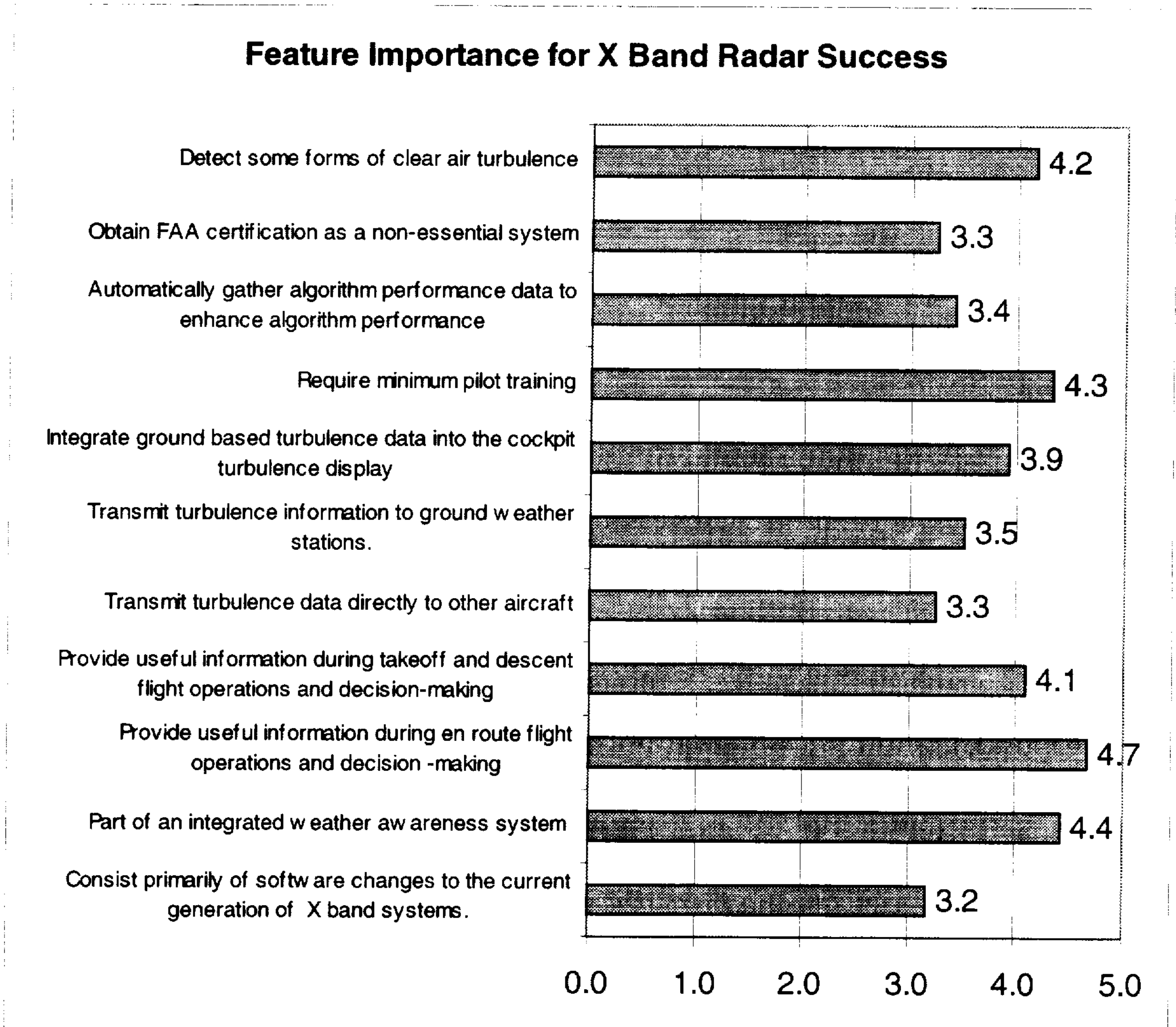


Figure 5 Importance Rating of Success Factors - X Band Radar

5.1.2 Importance of Product Features - LIDAR Market Success

Figure 6 contains the importance ratings for the potential success factors for LIDAR. Only three factors scored 4.0 or higher and these included a focus on useful information during en route flight operations (4.2), integration into a weather awareness system (4.0), and requirement for minimal pilot training (4.0). The next highest rated feature at 3.8 was the ability to provide useful information during take off and descent. Low rated items include the ability to transmit turbulence data directly to other aircraft (3.0), automatic gathering of algorithm performance enhancing data (3.2), and the ability to be a stand- alone weather information system (1.4).

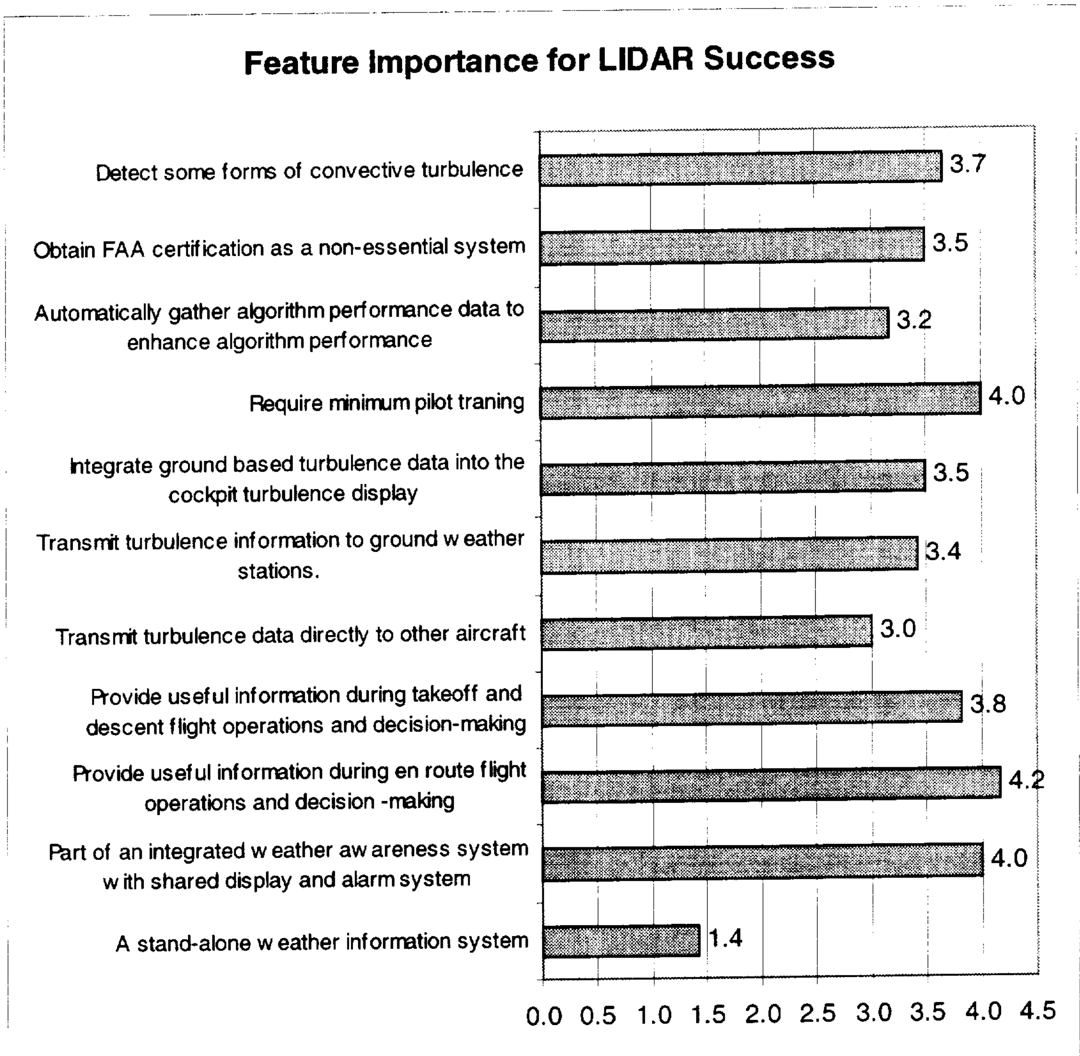


Figure 6 Importance Rating of Success Factors – LIDAR

5.1.3 Importance of Product Features - Combined Product Market Success

Figure 7 contains the importance ratings of the potential success factors for the combined enhanced X band plus LIDAR product. Only one factor scored 4.0 or higher: the ability to provide useful en route information (4.4). Two other factors that were highly rated at 3.9 include the requirement for minimal pilot training and the integration of ground based turbulence information into this system's display. Low rated items include the necessity for FAA certification as a non – essential system (2.7), data transmission to other aircraft (3.2), and the ability to be a stand-alone weather information system (2.0).

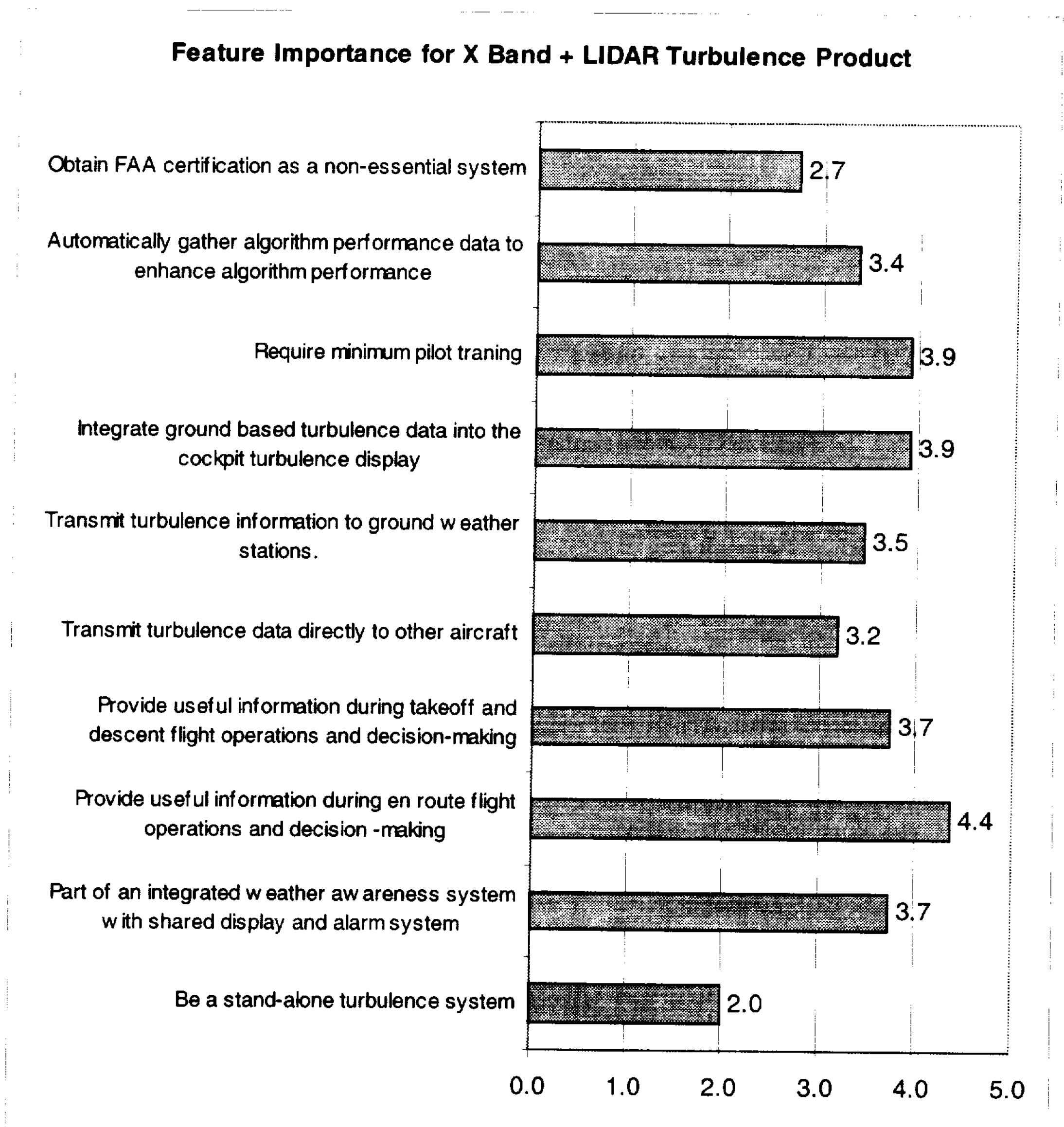


Figure 7 Importance Rating of Success Factors –Combined Product

5.2 Turbulence Warning Period

The survey asked participants to indicate the warning threshold that is necessary for the three sensing systems to succeed in the market. The survey questions in this area assumed that the new products would have varying degrees of forward sensing capability for severe, moderate and light levels of turbulence and the responses are organized based on these levels. As a starting point, Table 18 provides the expected values of the survey responses

Table 18 Expected Turbulence Warning in Minutes

	Expected Warning in Minutes		
	Severe Turbulence	Moderate Turbulence	Light Turbulence
X band	3.06	2.16	1.13
LIDAR	2.68	1.93	1.06
Combined	3.53	2.30	1.28

Figure 8, 9, and 10 provide histograms of the survey responses on warning time. For severe turbulence, Figure 9 shows that near 60% of responses for enhanced X band and 80% for the combined product indicated that the warning should exceed three minutes. On the other hand, about 25% of the X band responses indicated that less than one minute was acceptable warning for market success. Almost 65% of the LIDAR responses (clear air turbulence related) indicated an acceptable warning interval of three minutes or less for severe turbulence.

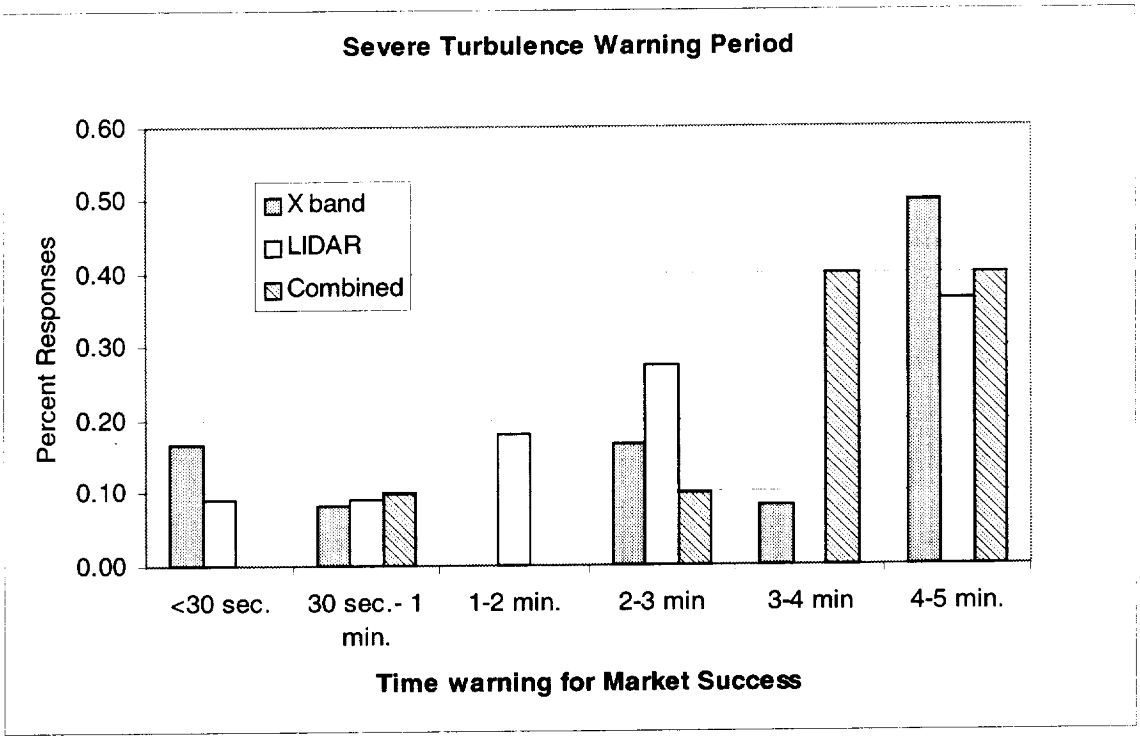


Figure 8 Severe Turbulence Warning Period

Figure 9 describes the responses for the warning interval required for moderate turbulence. 60% for the combined product and 45% for enhanced X band responded that the 2-3 minute interval was desirable. Over 50% responded that between one and three minutes was an acceptable moderate turbulence warning for all products.

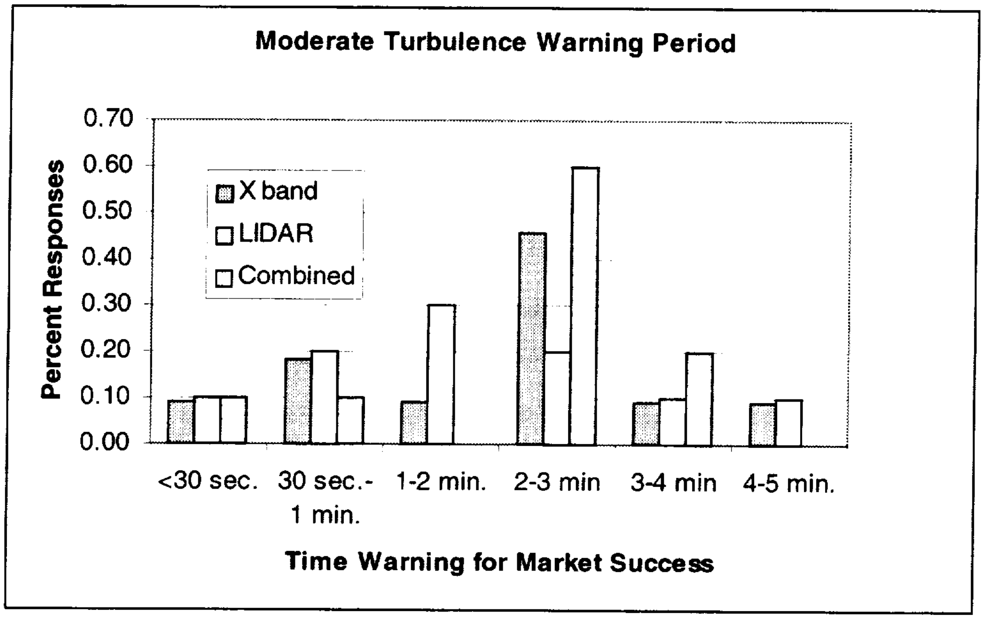


Figure 9 Moderate Turbulence Warning Period

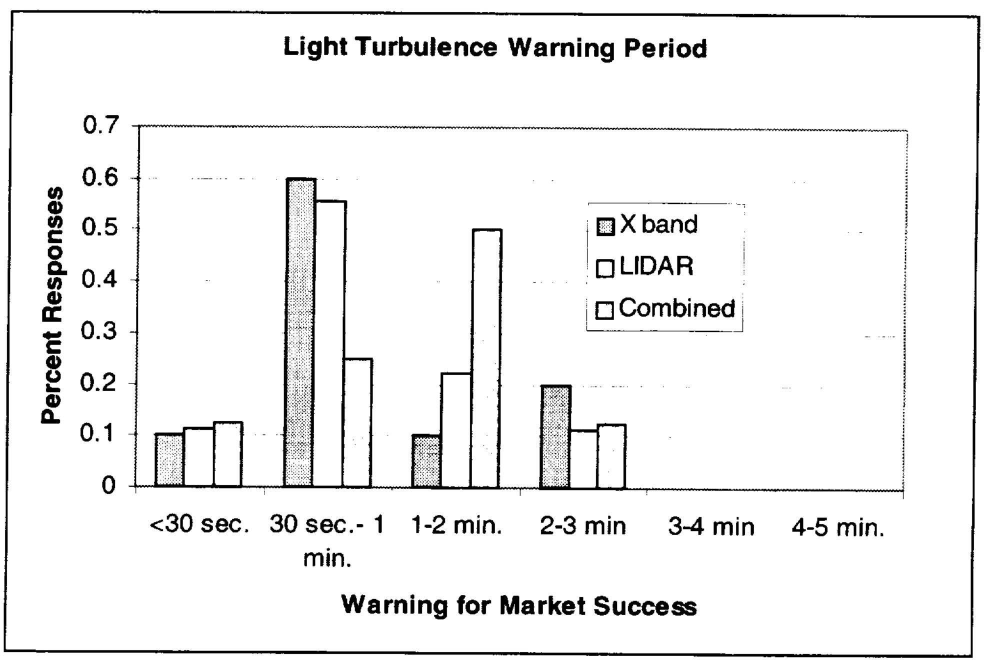


Figure 10 Light Turbulence Warning Period

Figure 10 provides the responses for light turbulence warning and shows a general shift to a shorter warning interval. Over 50 % of the X band and LIDAR responses were in the 30 second to one - minute interval. 50% of the combined product responses were in the 1-2 minute interval.

5.3 Detection Accuracy

The next generation of turbulence sensing systems will detect certain levels of turbulence with different accuracy. The survey asked participants to estimate the detection accuracy that would be required for market success. Table 19 summarizes the expected value of those responses.

Table 19 Estimated Detection Accuracy

	Expected Accuracy		
	Severe Turbulence	Moderate Turbulence	Light Turbulence
X band	90%	88%	83%
LIDAR	91%	88%	84%
Combined	93%	90%	85%

Figure 11,12, and 13 provide histograms of the data in Table 19. Figure 11 shows that over 60% of respondents believe that severe turbulence must be detected with accuracy over 90% for all three technologies. In particular, the hurdle for the combined system is above 95% in the opinion of 50% of the respondents.

Figure 12 shows that there may be a lower accuracy expectation for moderate turbulence with over 60% of responses for all technologies between 85% and 95% accuracy. Figure 13 indicates that light turbulence should be detected with accuracy between 80% and 90%. Consistently, there is a significant group of responses in Figure 11, 12, and 13 that believe less than 80% accuracy is acceptable. For example, this group is between 10% and 20% for severe and moderate turbulence but grows to above 30% for light turbulence.

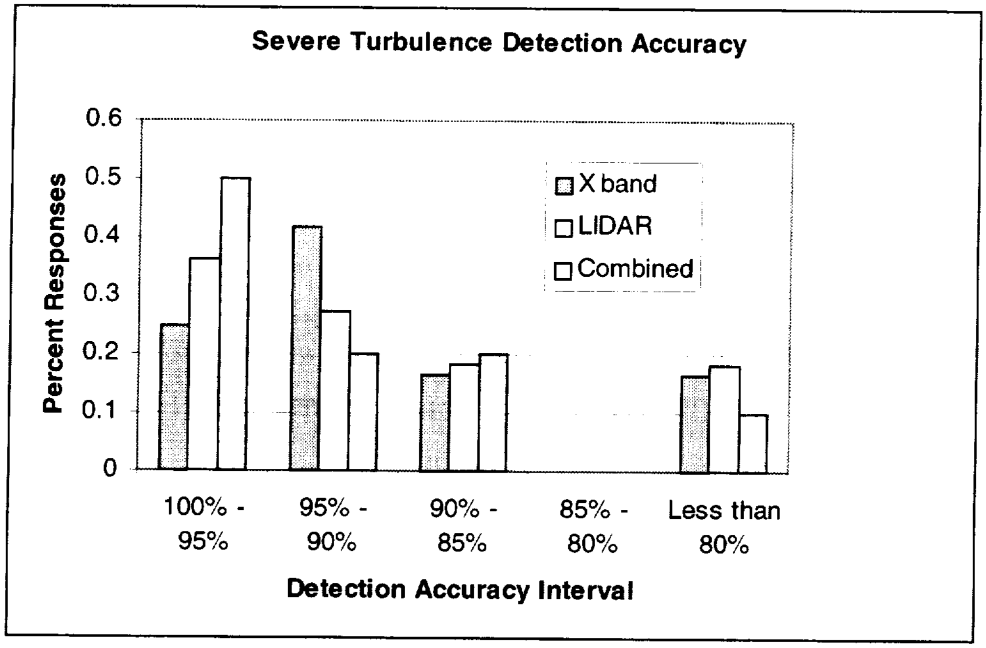


Figure 11 Severe Turbulence Detection Accuracy

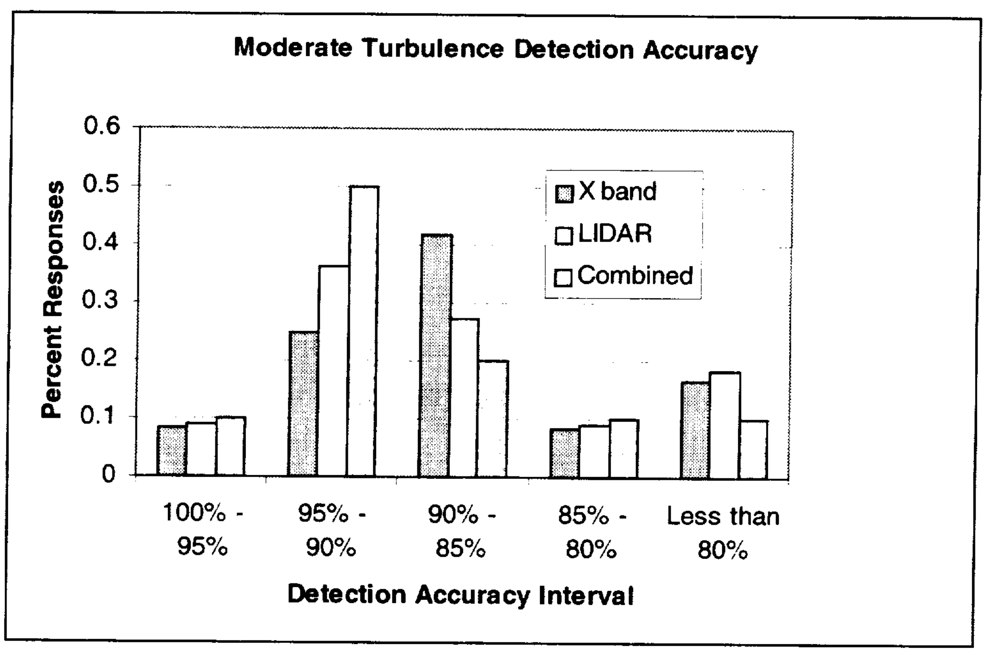


Figure 12 Moderate Turbulence Detection Accuracy

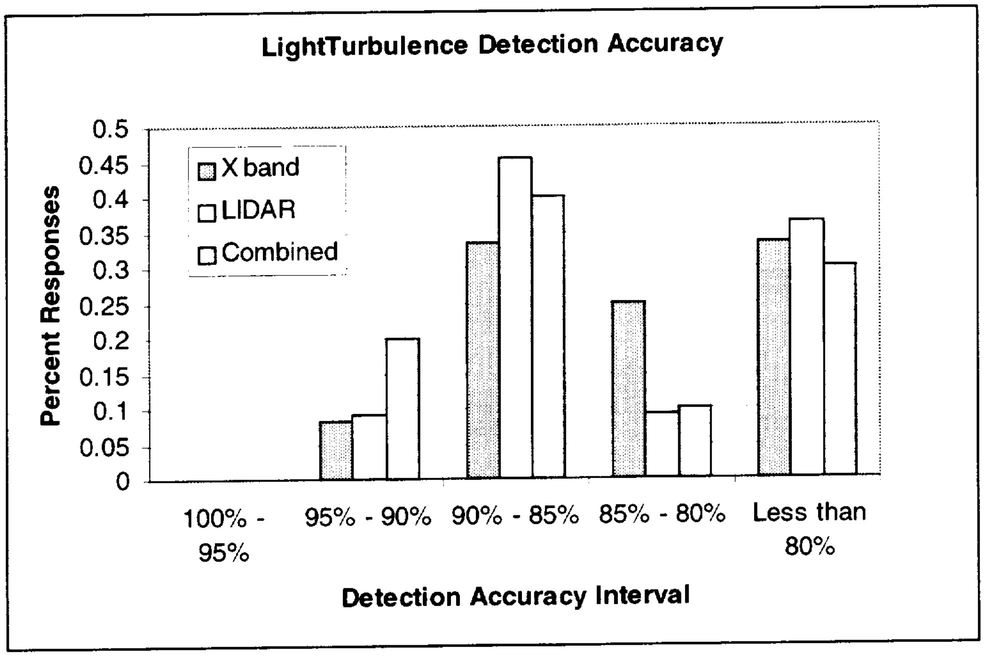


Figure 13 Light Turbulence Detection Accuracy

5.4 Alarm Errors

Different types of errors are possible in sensing turbulence and these errors impact the usefulness of the detection system in improving safety. Survey participants were asked to rate the importance of these errors from the viewpoint of impact in diminishing system effectiveness in reducing passenger, flight attendant and aircraft safety using 1 (not important) to 5 (very important). Figure 14 indicates that respondents believe false alerts (alarm given and turbulence does not exist) and failures to alert (turbulence exists and no alarm provided) will diminish system safety effectiveness more than nuisance alarms (overstatement of the degree of turbulence).

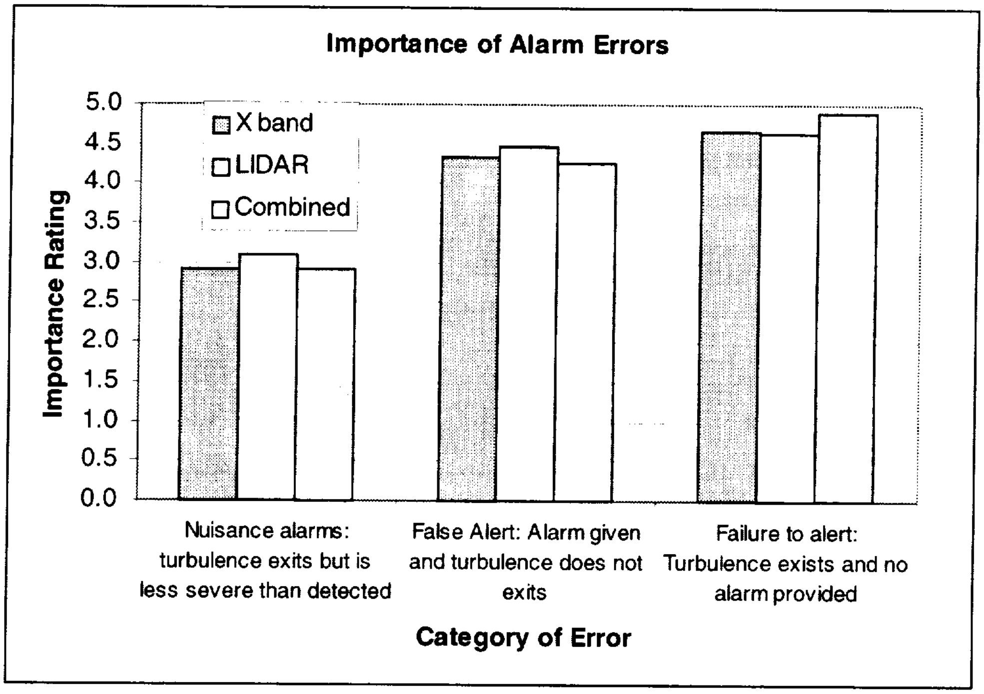


Figure 14 Importance of Type of Error

5.5 Method of Market Penetration

As discussed in the business case chapter, the next generation of turbulence sensing technology may penetrate the market in two ways. It may be installed on new aircraft as original equipment and / or it may be installed as an upgrade (retrofit) to the current fleet. The survey examined the strength of these two options for each of the three technologies. Figure 15 indicates that respondents strongly agree that these new technologies will be purchased on new aircraft. Figure 16 may indicate that retrofit is not as strong an option for system implementation as purchase on new aircraft since the "strongly agree" group is smaller than in Figure 15. In addition, Figure 16 shows 20% of survey respondents disagree or strongly disagree that retrofit is a market penetration option for these technologies.

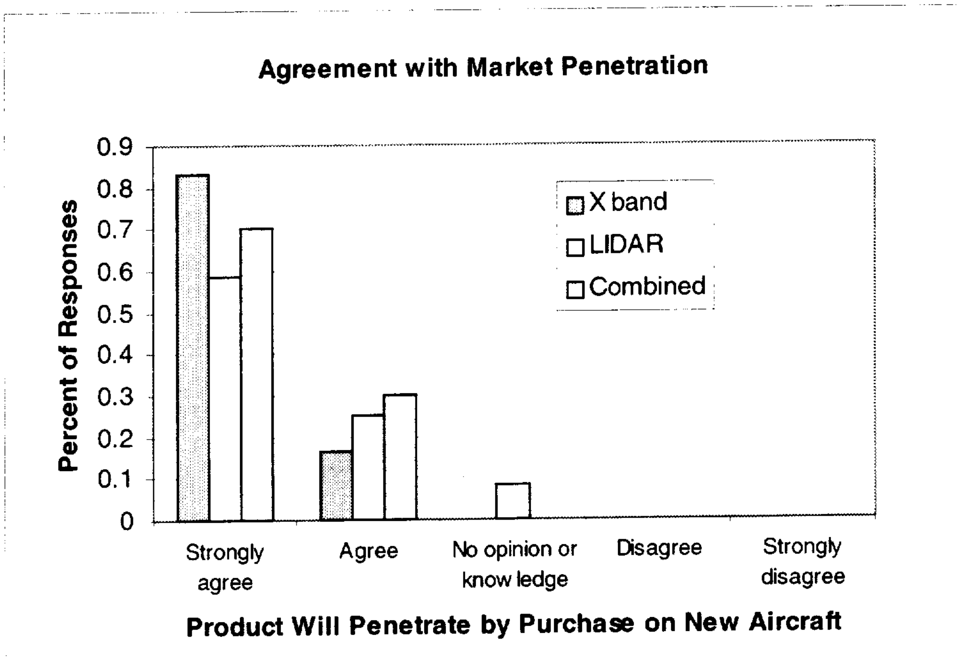


Figure 15 Market Penetration by New Aircraft Purchase

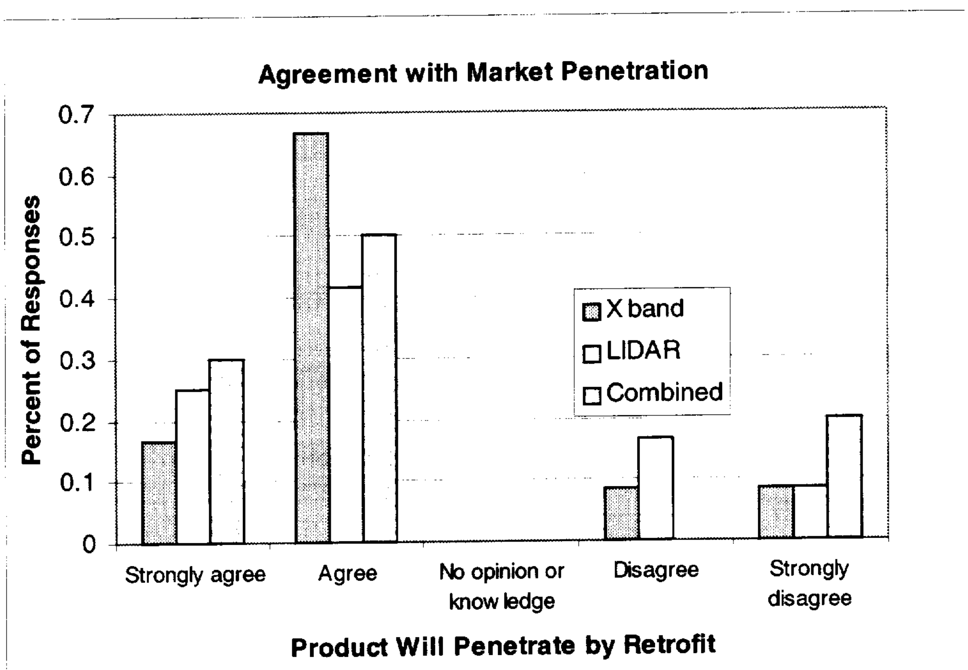


Figure 16 Market Penetration by Retrofit to Current Fleet

5.6 Importance of Decision Factors

Using a 1-5 scale with 1 (unimportant) and 5 (very important), survey participants were asked to rate the importance of key factors in the decision by airlines to upgrade the current fleet or purchase new aircraft equipped with turbulence sensing technology. Figure 17 shows those results.

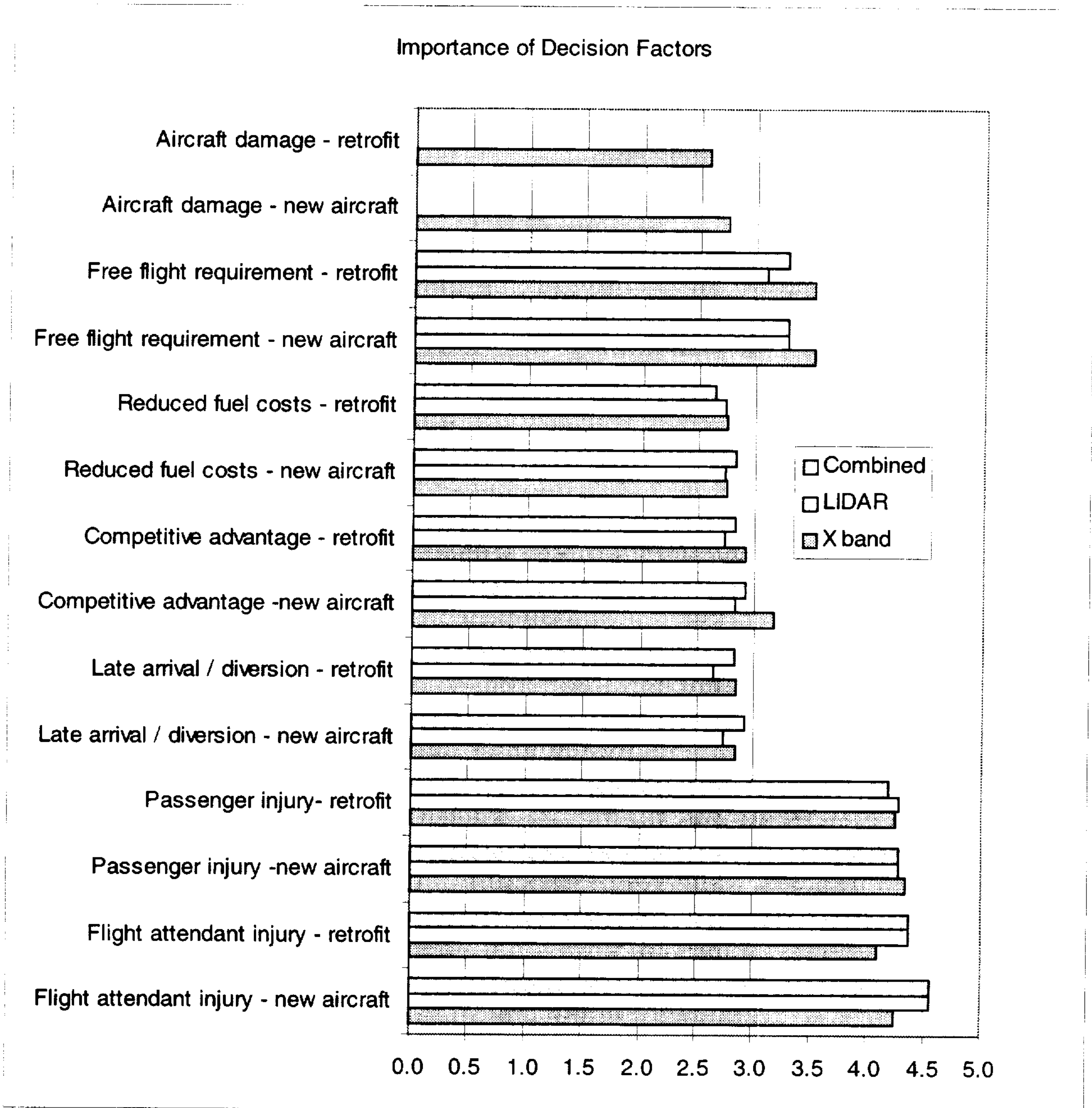


Figure 17 Importance of Factors in Technology Adoption Decision

In general the responses in Figure 17 are statistically different at a 90% confidence level if there is a difference in the mean importance rating of one unit. It is clear that participants believe the primary adoption motivation will be passenger and flight attendant injury reduction. The next tier of importance involves turbulence sensing as a tool to enable free flight. This factor may help to explain the penetration rate mechanisms for these technologies discussed in the previous sections. For example, based on the free flight issue, it is possible that the niche for turbulence sensing technology is large capacity aircraft involved in long duration flights.

Figure 17 also shows a picture that is consistent with the discussions in Chapter Three involving the minimal business case impact of factors such as fuel costs, diversions, and aircraft diversions. With regard to mechanisms of penetration, Figure 17 indicates that there is no difference in the decision motivations between retrofit and new purchase.

5.7 Certification Issues

Discussions with several certification experts within the FAA indicated that it is most probable that turbulence sensing systems will be categorized as non- essential or minor - function systems. As a result, these new products will not require the extensive testing that was a part of the certification process for predictive wind shear systems. Presuming that the target function of the turbulence systems is to enhance safety, primary certification considerations will include:

- Levels of false and nuisance alarms including alarm intrusiveness
- Pilot workload / usability evaluation. Since theses systems will be operational primarily in the cruise phase, this may mitigate pilot workload issues to some extent.

In determining benchmarks for performance accuracy, the FAA usually involves airlines and pilots to assure that the benefits to the traveling public are maximized.

From the airframe manufacturer's view, weather radar is a freedom of choice item so the system producers will bear the certification costs. LIDAR will entail a more complicated certification process since it requires additional systems (such as cooling) and may not fit completely into the radar dome.

5.8 Conclusions on System Product Characteristics

This chapter examined the characteristics of the successful turbulence sensing system and the details of the decision to adopt this technology. The following points summarize the results:

- Survey participants expect the turbulence sensing system to primarily furnish information that is useful for en route flight decisions. Take off and descent decision information appears to be less important but is still highly rated.
- Minimal pilot training is also a highly rated success issue so human factors considerations should be an important product development area.
- In general, the warning threshold for severe turbulence should be greater than three minutes, for moderate turbulence two to three minutes, and less than two minutes for light turbulence.
- Forward sensing systems should detect severe turbulence with accuracy between 90%-100%, moderate turbulence with accuracy between 85%-95%, and light turbulence with accuracy in the 80%-90% interval. 30% or more respondents believe light turbulence accuracy can be below 80%.
- False alerts and failures to alert will impact system effectiveness more than nuisance alarms.
- Survey responses indicate a strong agreement that turbulence sensing systems will penetrate by means of purchase on new aircraft. On the other hand, there is less agreement that retrofit will be a penetration method.
- From an airline viewpoint, reduction of injuries will be the primary reason to purchase turbulence sensing technology. The next important decision factor is as a requirement for a free flight environment. Issues such as aircraft damage, reduced fuel costs, and competitive advantage appear to be the least important decision factors.

6 Conclusions

This study examined the market potential of three versions of advanced forward sensing turbulence systems: enhanced X band radar, LIDAR, and a combined X band + LIDAR product. The base business case of these technologies is built upon the impact in cost reduction from reducing injuries to passengers and flight attendants. This business case is negative. In this analysis, the cost impact resulting from operational items such as flight time- savings and diversion avoidance was inconsequential. There are several important issues that may impact future product development goals:

- Enhanced X band radar has the greatest potential for a favorable business case. It is critical that the initial investment stay as low as possible and the detection accuracy stay high including some level of capability to detect clear air turbulence.
- Competition by sensing system manufacturers to protect cockpit system market share may help to keep enhanced X band radar investment costs low.
- LIDAR and the combined product have a very unfavorable business case. Penetration of these products appears most likely as an optional piece of equipment on new aircraft purchases. In addition, these products appear to be most likely to be purchased on aircraft that will be used for large numbers of passengers on long flights that will require significant out of seat time by passengers and service requirements by flight attendants.

This study did not examine competitive, alternative technologies but these do exist and new ones will enter the market over the interval of turbulence sensor market penetration. For example, improved ground based weather information developed using improved turbulence forecasting systems may be broadcast into an integrated cockpit weather system display. It is clear that this type of technology may impact these forward turbulence -sensing systems and this is an area for additional product development study.

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Appendix A: Technical Description of Current Weather Radars

As a starting point in the study, current weather radar products were identified and benchmarked. There are two primary weather radars in commercial use: the Rockwell Collins WXR 700 series and the Honeywell RDR-4A/B series. This appendix summarizes important details of these two products.

WXR-700 Wind shear radar (ARINC708)

Description:

The Collins WXR-700X Wind shear Radar System automatically alerts flight crews of potential wind shear and microburst event dangers both during take-off and landing. Wind shear detection is automatically activated anytime an aircraft is below 2,300 feet radio altitude. Alerts become active in the cockpit at 1,200 feet. All other selected radar information is continuously displayed during wind shear detection.

The flight crew is alerted to detected wind shear events occurring within five NM and ± 30 degrees of the aircraft heading. Depending on the location of the wind shear event, the crew will receive a caution to 'monitor radar' or a warning to 'go around' the event. All wind shear events within five NM and ± 30 degrees are displayed on the radar indicator or EFIS. Crew warnings are issued to 1.5 NM on landing and 3 NM on take-off. When wind shear detection is active, the radar antenna is time-shared between flight crew radar parameters and the automatic wind shear detection parameters.

Collins has recently added the FMR-200-X system for the military applications. The FMR-200-X Flight Multimode Radar system is a standard non-developmental item / commercial off the shelf (NDI/COTS) ARINC 708A X-band coherent Doppler color weather radar system. This system provides full precipitation detection, turbulence detection, wind shear detection, and an additional active skin paint mode capable of detecting tanker-size aircraft at ranges up to 15NM. New multimode radar software has been designed and certified to RTCA DO-178B level D standards. The system has been qualified to meet environmental standards described in RTCA DO-160C with a few exceptions. Operation at –40C is required only after warm-up period of 30 minutes for temperatures below –15C. Mil-STD-461D is used for radiated emissions, antenna spurious and harmonics. All operations other than the paint mode, sixteen-level mapping, minor display and control bus modifications are defined in accordance with ARINC 708A (Airborne Weather Radar with Forward Looking Wind shear detection capability).

Components:

Receiver and transmitter	WRT-701X
Size:	7.7"H x 10.1"W x 14"D
Weight:	31 pounds
Cooling:	Mount based fan
Power:	200 Watts nom @ 115VAC 400Hz
Mode Control Panel:	WCP-701
Size:	2.625"H x 5.75"W x 6"D
Weight:	1.7 pounds
Cooling:	Natural convection

Power:	5 Watts
Antenna Pedestal	WMA-701X
Size:	Per ARINC 708
Weight:	28 pounds
Cooling:	Natural convection
Power:	100 Watts nom @ 115VAC 400Hz
Flat plate Antenna	WFA-701X
Size:	28" x 34"
Weight:	6.8 pounds
Beam width	22.5° elevation x 3.5° azimuth
Side lobe Performance	>30 dB
Range and Cursor Control Panel:	CP-255
Size:	3.0"H x 5.75W x 6.5"D
Weight:	2.1 pounds
Cooling:	Natural convection
Power:	5 Watts

System Cost:

Component	Price Range (according to the aircraft)
WRT-701X	\$90,000 - \$131,644
WCP-701	\$7,644 - \$13,788
WMA-701X	\$32,868 - \$36,148
WFA-701X	\$8,464 - \$12,348

**Total WXR-700 wind shear radar system is $100,000.

Honeywell RDR-4B Wind shear Radar

Description:

The RDR-4B is the next generation of X-band radar systems used in the transport and large executive aircraft. The system provides weather avoidance with turbulence detection, wind shear detection and terrain mapping modes of operation. Solid-state circuit design and the use of state of art components enable the RDR-4B system to provide higher standards of performance and reliability than have ever been achieved in previous weather systems.

The RDR-4B radar system features a non-fading, high-resolution color display of storm conditions at selectable ranges up to 320 NM. The system also incorporates circuits that modify the receiver gain as a function of intervening rain attenuation. This function, called penetration compensation, allows more accurate presentation of storm cells.

The RDR-4B radar system's turbulence detection capability incorporates a sophisticated Doppler Turbulence Detection circuit that measures the variations in horizontal speed of precipitive particles. If particle horizontal speed variations (indicative of wind shift) exceed the threshold of moderate to heavy turbulence, a corresponding display id provided. The forward-looking wind shear feature detects the presence of wind shear, giving 10 to 60 seconds of warning before the encounter. Wind shear operates automatically below 2300" AGL with alerts given at 1500" AGL and below. The system scans ± 60° (± 40°windshear display), 5 NM ahead of the aircraft and automatically operates antenna tilt during the wind shear scans.

The turbulence detection system will not detect clear air turbulence because lack of precipitive particles. Turbulence information is limited to the first 40NM. Turbulence within this range will be displayed in magenta along the weather displayed in red, yellow and green. Some aircraft using EFIS display will indicate turbulence as additional areas id red rather than magenta. Only weather will be displayed beyond the 40NM turbulence limit when a range of more than 40NM is selected.

The turbulence detection circuitry utilizes the Doppler phenomenon, which causes an apparent echo-signal frequency shift due to relative motion between the aircraft and the target. No attempt is made to measure the velocity of the aircraft relative to the storm cell since the aircraft's velocity is independent of the amount of turbulence within the storm cell. Only the return velocity variance is measured, and this provides the indication of the amount of turbulence present in the weather. Weather turbulence causes relative random radial motion of raindrops. Wind shear can also cause similar relative radial target motions, and so will differences in fall speeds of various size drops. This random motion of droplets produces a spectrum spread of the radar's received signal. The radar detects the spectrum spread width parallel to the beam axis. A wide spectrum spread indicates the presence of heavy turbulence. When the spectrum width exceeds the threshold of moderate to heavy turbulence, the return is displayed as turbulent weather. The areas of turbulence associated with light to moderate rainfall should be avoided by 5NM.

Components:

Receiver and transmitter	RTA-4B
Size:	8 MCU per ARINC-708A
Weight:	29 pounds
Cooling:	ARINC 600

Power:	125 Watts nom @ 115VAC 400Hz
Certification:	TSO c63c, Class 7 RTCA DO-220
Pulse width:	6 and 18 microseconds
Pulse repetition rate:	380Hz Weather map Modes 1600 Hz Turbulence Mode 6000 Hz Wind shear Mode
Color Indicator	PPI-4B
Size:	Per ARINC-708A
Weight:	14.8 pounds
Cooling:	ARINC 600
Power:	115VAC 400Hz
Display Size:	3.3" x 4.3"
Antenna and Drive	DAA-4B
Radiator:	24" Flat plate
Gain:	33dB
Weight:	4 pounds
Beam width:	3.6 °
Scan Rate:	38 °/sec
Certification:	TSO c63b
Control Panel	CON-4B

Total RDR-4B Wind shear radar system costs $100,000. The upgrade from RDR-4A to RDR-4B is $50,000.

Appendix B- Survey Sample

Next Generation of Forward Turbulence Sensing Systems Business Case Analysis and Market Penetration Survey

This document provides introductory information for participants in a survey to estimate the business case and market adoption (penetration) timing for the next generation of forward sensing turbulence radar systems.

Who is conducting this survey?
The survey is conducted by the Department of Engineering Management of Old Dominion University under the direction of the Weather Accident Prevention (WxAP) project involving a wide range of NASA researchers and industry partners.

What is the next generation of forward sensing turbulence radar systems that the survey is studying?
The survey is focusing on better understanding the business case and product features for the forward sensing turbulence radar system(s) that will eventually achieve market success over the next 5-10 years. This survey envisions three possible future products that participants are asked to consider:

1) The next generation of enhanced X band turbulence radar systems for convective turbulence.
2) LIDAR based turbulence systems to sense clear air turbulence.
3) A combined, hybrid system including both enhanced radar (X band) and LIDAR to sense both convective and clear air turbulence.

The survey will ask your opinion on the features and feasibility of these future turbulence-sensing technologies.

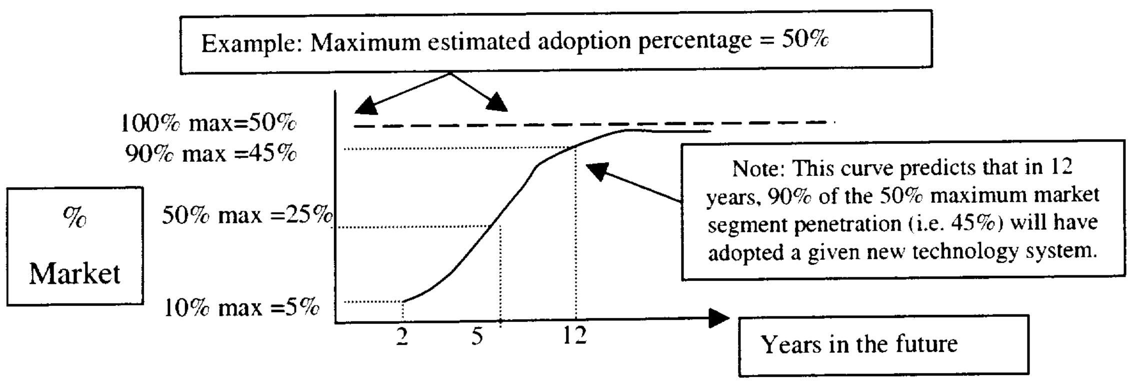
What are the objectives of the survey?
There are four related survey objectives. The first is to identify the current industry views on the commercial viability of these new, advanced turbulence sensing radar systems ("the product") in the transport market. The second objective is to estimate the costs and benefits of these advanced turbulence-sensing products. The third objective builds on this information by estimating the technology adoption timing (market penetration curve) for the three versions of turbulence radar. The final objective is to estimate the reduction in turbulence injuries. These survey results will provide an estimate of the future impact of cockpit weather systems in reducing weather - related accidents.

How is the Survey organized?
The survey is organized in the six sections described below.
Section I Participant characterization: The first section of the survey asks for information on the participant such as name, phone, email, and industry perspective.
Section II- IV Description of "forward sensing turbulence systems:" The second section has three parts and asks specific questions about the participant's opinions of the general characteristics of the three forward sensing turbulence systems the participants anticipate entering the market.
Section V Estimates of the market penetration curve: In this section, the participants estimate critical points for the penetration curves of the various sensing systems. These values will be used to develop a series of regression equations to estimate the penetration curves.
Section VI Frequency and cost of injuries: This last section estimates the frequency and cost of serious and minor injuries to passengers and crew due to turbulence.

Will the survey ask for information that my organization feels is confidential?
No. The survey was structured to prevent this. It attempts to capture enough information to understand the general characteristics and cost / benefit factors of the advanced weather information system that you envision in the marketplace. At the same time, the survey tries not to ask for technical details or specific information that is confidential to you. This is a preliminary survey and focuses on the general business case and market potential for forward sensing turbulence products. Please contact us if you feel any response will reveal confidential information.

Will specific estimates and responses from participants be identified?
No. For confidentiality purposes, individual participant responses will not be identified. The report will represent the results and responses from the participant group. However, we would like to list the names of the organizations that participated in the survey in the report. If you have special confidentiality needs, please contact us or indicate your wishes on the survey.
In general, please contact us if you have any concerns on confidentiality of your responses. We will work with you on your concerns.

What is a market penetration (adoption) curve?
These curves ("the S curve") estimate the percentage of the target market that will have adopted turbulence system technology at a given point in the future. Figure 1 provides an example of an adoption curve with critical points noted.



How will the survey identify the data to develop the market penetration curves?
Close examination of Figure 1 demonstrates the four critical benchmarks that survey participants will estimate for each of the three theorized, advanced products. These benchmarks are described below:

- *What is the maximum proportion of a given market that will eventually adopt the advanced turbulence sensing system?* For example in Figure 1, you may decide that the maximum possible penetration of one of the products is 50%. That value then becomes the "limit" that the adoption curve approaches.
- *How many years in the future (if ever) will it take for each of the advanced turbulence sensing systems to be adopted by 10%, 50%, and 90% of these potential adopters?* Three example points are shown in Figure 1. In this example, 10% of the maximum of 50% (5%) will be reached in two years, 50% of the maximum (25%) will be reached in five years, and 90% of the maximum (45%) will be reached in 12 years. Using curve - fitting tools (such as regression), we can define the equation and confidence intervals for the penetration curve. For example Figure 1 shows a curve fitted to the estimated maximum limit and the 10%, 50%, and 90% penetration points.

Will the survey ask for information that my organization feels is confidential?
No. The survey was structured to prevent this. It attempts to capture enough information to understand the general characteristics and cost / benefit factors of the advanced weather information system that you envision in the marketplace. At the same time, the survey tries not to ask for technical details or specific information that is confidential to you. This is a preliminary survey and focuses on the general business case and market potential for forward sensing turbulence products. Please contact us if you feel any response will reveal confidential information.

Should I involve others in my organization in completing the surveys?
The first question in each survey asks you to evaluate your expertise for each turbulence-sensing product. You should answer product questions only if you feel you have an understanding of that market. If another person in your organization has more experience with a particular technical area, please involve that individual in those survey questions. Some organizations plan to use a team to complete the surveys.

Who is participating in this survey?

A broad representation of the aviation industry is participating and represents the following industry sectors involved in forward sensing turbulence radar system technology: weather system and radar manufacturers, aviation industry organizations, airframe manufacturers, and airlines.

How quickly should I complete my survey and when will the report be completed?

Please plan on completing your survey and mailing it back to us within a week. The survey data should be compiled and the report completed by October 2000.

Will each participant receive a copy of the report?

Yes. The completed report will be sent to each participant.

For other questions, contact Paul Kauffmann, Old Dominion University, Department of Engineering Management, 129 Kaufman Hall, Norfolk VA 23529, 757-683-4946, pkauffma@odu.edu.

Market Assessment of Forward Looking Turbulence Sensing Systems

Primary Survey Participant: ______________________ **Title:** ____________

Telephone ______________________ **Email** ______________________

Job Duties:

____

If others participated in completing this survey, please complete the line(s) below
Additional Participant ______________ **Additional Participant** ______________

Job Duties: ______________ **Job Duties** ______________

Part I: Description of Survey Participant (Choose the Appropriate Response)

1. Participant / Organization Classification
My organization is involved in forward sensing turbulence radar systems primarily as: (circle one choice)

Airline	Industry or research Group	Turbulence system design / production	Airframe manufacturer	Other: ____________

Comments:

2. Permission is granted to list my organization in the final report as a participant in this survey. (It will not be possible to link specific data or responses to an individual organization or participant.)

Yes No

Comments:

3. Please send a copy of the final report to me at the following address:

Part II – Enhanced X Band Radar Turbulence Sensing System

INSTRUCTIONS: In answering the questions in this section, consider your view of the technical characteristics of the next generation of forward sensing turbulence X band radar. This system will primarily detect convective turbulence. As a professional in the aviation industry, you have opinions on the characteristics of the system that will achieve market success. This section targets identification of your view of the general features of this advanced forward sensing turbulence system. This successful system balances benefits, technology limits, information, and costs. Answer these questions based on the successful system you envision.

1. Product Knowledge: I rate my knowledge (or my organization's knowledge) of X band turbulence radar systems as:

Expert	**Very Good**	**Good**	**No knowledge of this product or technology**

(Note: If you do not have knowledge of a specific turbulence sensing product, please skip questions on that item or include input from others to augment your survey information).

2. Product Feature Importance for Advanced X Band Turbulence Radar: A new product may have many different features and the following table contains possible characteristics of the next generation of X band turbulence radar. Rate the importance of these product features for market success. (Evaluate each product feature)

Rate the importance of these features for market success of the next generation of Advanced X band Turbulence Radar:	**No opinion/ knowledge**		←		→	**Very Important**
Consist primarily of software changes to the current generation of X band systems.	☐	1	2	3	4	5
Part of an integrated weather awareness system with shared display and alarm system.	☐	1	2	3	4	5
Provide useful information during en route flight operations and decision- making.	☐	1	2	3	4	5
Provide useful information during takeoff and descent flight operations and decision- making.	☐	1	2	3	4	5
Transmit turbulence data directly to other aircraft.	☐	1	2	3	4	5
Transmit turbulence information to ground weather stations.	☐	1	2	3	4	5
Integrate ground based turbulence data into the cockpit turbulence display.	☐	1	2	3	4	5
Require minimum pilot training.	☐	1	2	3	4	5
Automatically gather algorithm performance data to enhance algorithm performance.	☐	1	2	3	4	5
Obtain FAA certification as a non- essential system.	☐	1	2	3	4	5
Detect some forms of clear air turbulence.	☐	1	2	3	4	5
Other critical features:	☐	1	2	3	4	5

Comments:

3. Turbulence Warning Period: The next generation of advanced X band turbulence radar will sense convective turbulence in the path of the aircraft and provide warning to the cockpit. The time warning threshold for market success of the next generation is: (Choose one interval for each turbulence type)

	No opinion	< 30 sec.	30 sec. - 1 min.	1-2 min.	2-3 min.	3-4 min.	4-5 min.
Detect severe turbulence with a warning of:	☐	☐	☐	☐	☐	☐	☐
Detect moderate turbulence with a warning of:	☐	☐	☐	☐	☐	☐	☐
Detect light turbulence with a warning of:	☐	☐	☐	☐	☐	☐	☐

Comments:

4. Detection Accuracy: The next generation of X band turbulence radar will be able to detect certain levels of turbulence with varying degrees of accuracy. What levels of accuracy will be necessary for market success? (Select an opinion for each detection alternative.)

The successful next generation of Advanced X band Turbulence Radar Will:	100%-95%	95%-90%	90%-85%	85%-80%	Less than 80%
Detect severe turbulence with an accuracy of:	☐	☐	☐	☐	☐
Detect moderate turbulence with an accuracy of:	☐	☐	☐	☐	☐
Detect light turbulence with an accuracy of:	☐	☐	☐	☐	☐

Comments:

5. Alarm Errors: Different types of errors are possible in sensing turbulence and they may impact the usefulness of the detection system in improving safety. Rate the importance of these errors from the viewpoint of their impact in diminishing system effectiveness on reducing passenger, flight attendant and aircraft safety using 1 (not important) to 5 (very important). Rate each choice for which you have knowledge.

Rate the importance of these types of errors in diminishing system impact on safety	No Knowledge or Opinion	Unimportant	←		→	Very Important
Nuisance alarms: Turbulence exists but is less severe than detected	☐	1	2	3	4	5
False Alert: Alarm given and turbulence does not exist	☐	1	2	3	4	5
Failure to alert: turbulence exists and no alarm provided	☐	1	2	3	4	5
Other:	☐	1	2	3	4	5

Comments:

6. Method of Market Penetration: The next generation of X band turbulence radar may penetrate the market in two ways. It may be installed on new aircraft (Original Equipment) and / or it may be an upgrade (retrofit) to the current systems. This question examines your views on these two options. (Indicate your opinion on each alternative.)

The next generation of Advanced X band Turbulence Radar Will:	Strongly agree	Agree	No opinion/ knowledge	Disagree	Strongly disagree
Be installed as original equipment on new aircraft purchases.	☐	☐	☐	☐	☐
Be installed as an upgrade to current weather radar systems in the existing fleet.	☐	☐	☐	☐	☐

Comments:

7. System Cost- Original Equipment: If an airline purchases new X band turbulence sensing systems as a part of new aircraft equipment, what is your estimate of the increased cost per aircraft in constant dollars that will be paid? This question assumes that there will be an option not to purchase advanced X band turbulence radar on new aircraft.
What is your estimate of the incremental cost for the enhanced X band turbulence radar if purchased on new aircraft? Circle your response:

Cost will not be a decision factor since this new product will be the industry standard	0-$25,000	25,000 - $50,000	$50,000- $75,000	$75,000- $100,000	More than $100,000 Estimate: ______	No Opinion or knowledge

Comments:

8. System Cost- Retrofit Option: If an airline purchases new X band turbulence sensing systems to upgrade the current fleet, what is your estimate of the cost per aircraft? Circle your response:

Cost will not be a decision factor since this product will be the industry standard	0-$25,000	25,000 - $50,000	$50,000- $75,000	$75,000- $100,000	More than $100,000 Estimate: ______	No Opinion or knowledge

Comments:

9. Importance of Decision Factors: In the decision by airlines to upgrade the current fleet or purchase new aircraft equipped with the next generation of X band radar, rate the importance of the following decision factors on a 1-5 scale with 1 (unimportant) and 5 (very important).

Rate the importance of these factors in the decision to purchase X band turbulence radar:	Importance on 1-5 scale for outfitting new aircraft	Importance on 1-5 scale for decision to retrofit existing fleet
Savings in flight attendant injury costs as a result of turbulence avoidance.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings in passenger injury costs as a result of turbulence avoidance.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings resulting from avoidance of late arrivals or diversion due to turbulence.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Competitive advantage or pressure from competitors.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings from reduced fuel usage.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Requirement for free flight environment.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Prevention of aircraft damage.	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Other: ______________________	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion

Comments:

10. Year of Product Introduction: When will the enhanced X band turbulence radar you described be introduced into the market as a commercial product?

2001	2002	2003	2004	2005	2006 or Beyond

Comments:

Additional Comments on the next generation of X-band turbulence radar:

Part III– LIDAR Based Turbulence Sensing System

INSTRUCTIONS: In answering the questions in this section, consider your view of the technical characteristics of a stand-alone LIDAR based forward sensing turbulence system for clear air turbulence (CAT) detection. This section attempts to identify the general features of this advanced forward sensing turbulence system. As a professional in the aviation industry, you have opinions on the characteristics of the LIDAR based system that may successfully penetrate the transport market. This successful system balances benefits, technology limits, information, and costs. Answer these questions with your successful system in mind.

1. Product Knowledge: I rate my knowledge (or my organization's knowledge) of LIDAR turbulence sensing systems as:

Expert	Very Good	Good	No knowledge of this product or technology

(Note: If you do not have knowledge of a specific turbulence sensing product, please skip questions on that item or include input from others to augment your survey responses).

2. Product Features of LIDAR based Turbulence systems: Rate the importance of the following product features for market success of the LIDAR based turbulence sensing product. (Evaluate each product feature)

For market success, a LIDAR turbulence sensing product will be:	No opinion/ knowledge		◄		►	Very Important
A stand- alone weather information system.	☐	1	2	3	4	5
Part of an integrated weather awareness system with shared display and alarm system.	☐	1	2	3	4	5
Provide useful information during en route flight operations and decision- making.	☐	1	2	3	4	5
Provide useful information during takeoff and descent flight operations and decision- making.	☐	1	2	3	4	5
Transmit turbulence data directly to other aircraft.	☐	1	2	3	4	5
Transmit turbulence information to ground weather stations.	☐	1	2	3	4	5
Integrate ground based turbulence data into the cockpit turbulence display.	☐	1	2	3	4	5
Require minimum pilot training.	☐	1	2	3	4	5
Automatically gather algorithm performance data to enhance algorithm performance.	☐	1	2	3	4	5
Obtain FAA certification as a non- essential system.	☐	1	2	3	4	5
Detect some forms of convective turbulence.	☐	1	2	3	4	5
Other critical features:	☐	1	2	3	4	5

Comments:

3. Turbulence Warning Period: LIDAR based turbulence products will accurately sense clear air turbulence in the path of the aircraft and provide warning to the cockpit. The time warning threshold for market success is: (Circle one choice)

	No opinion	< 30 sec.	30 sec. - 1 min.	1-2 min.	2-3 min.	3-4 min.	4-5 min.
Detect severe turbulence with a warning of:	☐	☐	☐	☐	☐	☐	☐
Detect moderate turbulence with a warning of:	☐	☐	☐	☐	☐	☐	☐
Detect light turbulence with a warning of:	☐	☐	☐	☐	☐	☐	☐

Comments:

4. Detection Accuracy: The LIDAR based turbulence system will be able to detect certain levels of turbulence with varying degrees of accuracy. What levels of accuracy will be necessary for market success? (Select an opinion for each detection alternative.)

The LIDAR based turbulence system will:	**100%-95%**	**90%-95%**	**90%-85%**	**85%-80%**	**Less than 80%**
Detect severe turbulence with an accuracy of:	☐	☐	☐	☐	☐
Detect moderate turbulence with an accuracy of:	☐	☐	☐	☐	☐
Detect light turbulence with an accuracy of:	☐	☐	☐	☐	☐

Comments:

5. Alarm Errors: Different types of errors are possible in sensing turbulence and they may impact the usefulness of the detection system in improving safety. Rate the importance of these errors from the viewpoint of their impact in diminishing system effectiveness on reducing passenger, flight attendant and aircraft safety using 1 (not important) to 5 (very important). Rate each choice for which you have knowledge.

Rate the importance of these types of errors in diminishing system impact on safety	**No Knowledge or Opinion**	**Unimportant**	◄		►	**Very Important**
Nuisance alarms: Turbulence exists but is less severe than detected	☐	1	2	3	4	5
False Alert: Alarm given and turbulence does not exist	☐	1	2	3	4	5
Failure to alert: turbulence exists and no alarm provided	☐	1	2	3	4	5
Other:	☐	1	2	3	4	5

Comments:

6. Method of Market Penetration: The LIDAR based turbulence system may penetrate the market in two ways. It may be installed on new aircraft (Original Equipment) and / or it may be an upgrade (retrofit) to the current systems. This question examines your views on these two options. (Indicate your opinion on each alternative.)

The LIDAR based turbulence system will:	**Strongly agree**	Agree	**No opinion/ knowledge**	**Disagree**	**Strongly disagree**
Be installed as original equipment on new aircraft purchases.	☐	☐	☐	☐	☐
Be installed as an upgrade to current weather radar systems in the existing fleet.	☐	☐	☐	☐	☐

Comments:

7. System Cost- Original Equipment: If an airline purchases LIDAR based turbulence system as a part of new aircraft equipment, what is your estimate of the increased cost per aircraft in constant dollars that will be paid? This question assumes that there will be an option not to purchase the LIDAR based turbulence system on new aircraft.
What is your estimate of the incremental cost for the LIDAR based turbulence system if purchased on new aircraft? Circle your response:

Cost will not be a decision factor since this new product will be the industry standard	0-$25,000	25,000 - $50,000	$50,000- $75,000	$75,000- $100,000	More than $100,000 Estimate: ____	No Opinion or knowledge

Comments:

8. System Cost- Retrofit Option: If an airline purchases the LIDAR based turbulence sensing product to upgrade the current fleet, what is your estimate of the cost per aircraft in constant dollars that will be paid? Circle your response:

Cost will not be a decision factor since this product will be the industry standard	0-$25,000	25,000 - $50,000	$50,000- $75,000	$75,000- $100,000	More than $100,000 Estimate: ______	No Opinion or knowledge

Comments:

9. Importance of Decision Factors: In the decision by airlines to upgrade the current fleet or purchase new aircraft equipped with the LIDAR based turbulence sensing product, rate the importance of the following decision factors on a 1-5 scale with 1 (unimportant) and 5 (very important).

Rate the importance of these factors in the airline decision to purchase the LIDAR based turbulence sensing product:	**Importance on 1-5 scale for outfitting new aircraft**	**Importance on 1-5 scale for decision to retrofit existing fleet**
Savings in flight attendant injury costs as a result of turbulence avoidance	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings in passenger injury costs as a result of turbulence avoidance	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings resulting from avoidance of late arrivals or diversion due to turbulence	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Competitive advantage or pressure from competitors	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings from reduced fuel usage	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Requirement for free flight environment	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Other: ______________________	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion

10. Year of Introduction: When will the LIDAR based turbulence-sensing product be introduced into the market as a commercial product?

2001	2002	2003	2004	2005	2006 or Beyond: Estimate: _____

Comments:

Additional Comments on the LIDAR based turbulence sensing product:

Part IV: Combined Product- Enhanced X Band Radar + LIDAR Turbulence Sensing System

INSTRUCTIONS: In answering the questions in this section, consider your view of the technical characteristics of a combined enhanced X band plus LIDAR turbulence product. This section attempts to identify the general features of this enhanced forward sensing turbulence system. As a professional in the aviation industry, you have opinions on the characteristics of the system that will successfully penetrate the markets. This successful system balances benefits, technology limits, information, and costs. Answer these questions with your successful system in mind.

1. Product Knowledge: I rate my knowledge (or my organization's knowledge) of combined enhanced X band plus LIDAR turbulence product as:

Expert	**Very Good**	**Good**	**No knowledge of this product or technology**

(Note: If you do not have knowledge of a specific turbulence sensing product, please skip questions on that item or include input from others to augment your survey information).

2. Product Features of combined enhanced X band plus LIDAR turbulence product: Rate the importance of the following product features for market success of the combined enhanced X band plus LIDAR turbulence product. (Evaluate each product feature)

For market success, the combined enhanced X band plus LIDAR turbulence product will:	**No opinion/ knowledge**	Unimportant	◄		►	**Very Important**
Be a stand-alone turbulence system.	⊡	1	2	3	4	5
Part of an integrated weather awareness system with shared display and alarm system.	⊡	1	2	3	4	5
Provide useful information during en route flight operations and decision- making.	⊡	1	2	3	4	5
Provide useful information during takeoff and descent flight operations and decision- making.	⊡	1	2	3	4	5
Transmit turbulence data directly to other aircraft.	⊡	1	2	3	4	5
Transmit turbulence information to ground weather stations.	⊡	1	2	3	4	5
Integrate ground based turbulence data into the cockpit turbulence display.	⊡	1	2	3	4	5
Require minimum pilot training.	⊡	1	2	3	4	5
Automatically gather algorithm performance data to enhance algorithm performance.	⊡	1	2	3	4	5
Obtain FAA certification as a non- essential system.	⊡	1	2	3	4	5
Detect some forms of clear air turbulence.	⊡	1	2	3	4	5

Comments:

3. Turbulence Warning Period: The combined enhanced X band plus LIDAR turbulence product will accurately sense turbulence in the path of the aircraft and provide warning to the cockpit. The time warning threshold for market success is: (Circle one choice)

	No opinion	< 30 sec.	30 sec. - 1 min.	1-2 min.	2-3 min.	3-4 min.	4-5 min.
Detect severe turbulence with a warning of:	⊡	⊡	⊡	⊡	⊡	⊡	⊡
Detect moderate turbulence with a warning of:	⊡	⊡	⊡	⊡	⊡	⊡	⊡
Detect light turbulence with a warning of:	⊡	⊡	⊡	⊡	⊡	⊡	⊡

Comments:

4. Detection Accuracy: The combined enhanced X band plus LIDAR turbulence system will be able to detect certain levels of turbulence with varying degrees of accuracy. What levels of accuracy will be necessary for market success? (Select an opinion for each detection alternative.)

The combined enhanced X band plus LIDAR turbulence product will:	**100%-95%**	95%-90%	**90%-85%**	**85%-80%**	**Less than 80%**
Detect severe turbulence with an accuracy of:	☐	☐	☐	☐	☐
Detect moderate turbulence with an accuracy of:	☐	☐	☐	☐	☐
Detect light turbulence with an accuracy of:	☐	☐	☐	☐	☐

Comments:

5. Alarm Errors: Different types of errors are possible in sensing turbulence and they may impact the usefulness of the detection system in improving safety. Rate the importance of these errors from the viewpoint of their impact in diminishing system effectiveness on reducing passenger, flight attendant and aircraft safety using 1 (not important) to 5 (very important). Rate each choice for which you have knowledge.

Rate the importance of these types of errors in diminishing system impact on safety	**No Knowledge or Opinion**	**Unimportant**	←		→	**Very Important**
Nuisance alarms: Turbulence exists but is less severe than detected	☐	1	2	3	4	5
False Alert: Alarm given and turbulence does not exist	☐	1	2	3	4	5
Failure to alert: turbulence exists and no alarm provided	☐	1	2	3	4	5
Other:	☐	1	2	3	4	5

Comments:

6. Method of Market Penetration: The combined enhanced X band plus LIDAR turbulence product may penetrate the market in two ways. It may be installed on new aircraft (Original Equipment) and / or it may be an upgrade (retrofit) to the current systems. This question examines your views on these two options. (Indicate your opinion on each alternative.)

The combined enhanced X band plus LIDAR turbulence product will:	**Strongly agree**	Agree	**No opinion/ knowledge**	**Disagree**	**Strongly disagree**
Be installed as original equipment on new aircraft purchases.	☐	☐	☐	☐	☐
Be installed as an upgrade to current weather radar systems in the existing fleet.	☐	☐	☐	☐	☐

Comments:

7. System Cost- Original Equipment: If an airline purchases the combined enhanced X band plus LIDAR turbulence product as a part of new aircraft equipment, what is your estimate of the increased cost per aircraft in constant dollars that will be paid? This question assumes that there will be an option not to purchase the LIDAR based turbulence system on new aircraft. What is your estimate of the incremental cost for the LIDAR based turbulence system if purchased on new aircraft? Circle your response:

Cost will not be a decision factor since this new product will be the industry standard	0-$25,000	25,000 - $50,000	$50,000-$75,000	$75,000-$100,000	More than $100,000 Estimate: ______	No Opinion or knowledge

Comments:

8. System Cost- Retrofit Option: If an airline purchases combined enhanced X band plus LIDAR turbulence product to upgrade the current fleet, what is your estimate of the cost per aircraft in constant dollars that will be paid? Circle your response:

Cost will not be a decision factor since this product will be the industry standard	0-$25,000	25,000 - $50,000	$50,000-$75,000	$75,000-$100,000	More than $100,000 Estimated: ______	No Opinion or knowledge

Comments:

9. Importance of Decision Factors: In the decision by airlines to upgrade the current fleet or purchase new aircraft equipped with the combined enhanced X band plus LIDAR turbulence product, rate the importance of the following decision factors on a 1-5 scale with 1 (unimportant) and 5 (very important).

Rate the importance of these factors in the airline decision to purchase the combined enhanced X band plus LIDAR turbulence product:	Importance on 1-5 scale for outfitting new aircraft	Importance on 1-5 scale for decision to retrofit existing fleet
Savings in flight attendant injury costs as a result of turbulence avoidance	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings in passenger injury costs as a result of turbulence avoidance	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings resulting from avoidance of late arrivals or diversion due to turbulence	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Competitive advantage or pressure from competitors	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Savings from reduced fuel usage	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Requirement for free flight environment	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion
Other: ______________________	1 2 3 4 5 no opinion	1 2 3 4 5 no opinion

10 Year of Introduction: When will the combined enhanced X band plus LIDAR turbulence product be introduced into the market as a commercial product?

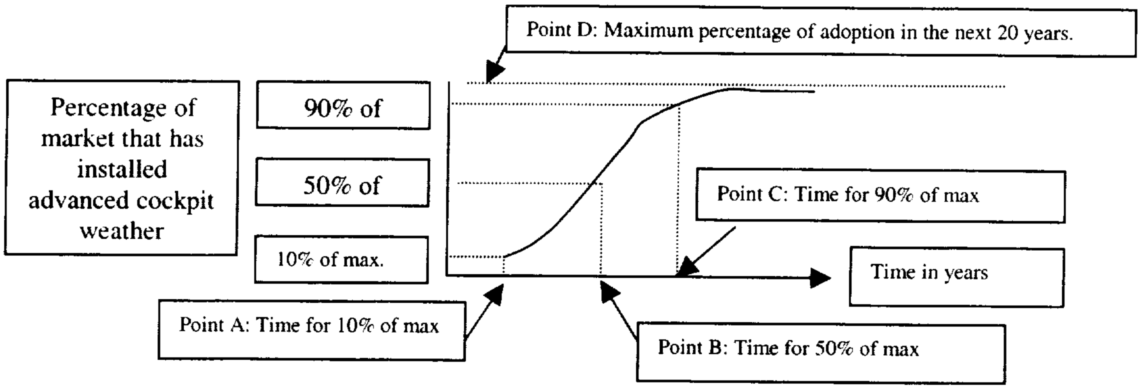
2001	2002	2003	2004	2005	2006 or Beyond Estimate: _____

Comments:

Additional Comments on the next generation of X-band turbulence radar:

Part V: Market Adoption Rate Estimate for Turbulence Sensing Products

The object of this section is to estimate the adoption rate of advanced turbulence sensing products by Part 121 aircraft. In this section you are asked to estimate important values to develop adoption curves for these turbulence- sensing products.



There are two market forces at work in this curve. The first is the impact of new aircraft, equipped from the factory with forward turbulence sensing systems, entering the transport market. The second force involves retrofit of existing aircraft with forward turbulence sensing systems. These two influences should be considered in your answer to the questions below.

What is your estimate for Part 121 aircraft?

Future Turbulence Sensing Product	Point D: Maximum market penetration for this product	Point A: Years from present to 10% of maximum penetration	Point B: Years from present to 50 % of maximum penetration	Point C: Years from present to 50 % of maximum penetration
Advanced X Band Radar Systems	_______%			
LIDAR Systems	_______%			
Combined Radar / LIDAR	_______%			
Percentage of transport market that will not equip with turbulence sensing systems.	_______% Total 100%			

Comments:

Part VI: Frequency and Cost Estimates for Turbulence Injuries

INSTRUCTIONS: The questions in this section ask you to estimate the financial impact of turbulence accidents / incidents and related injuries to passengers and crew- members. Here are some definitions for you to use:

Turbulence accident: an occurrence of in flight turbulence that results in either a death or a serious injury of a passenger or crewmember.

Turbulence incident: an occurrence of in flight turbulence that results in minor injury to a passenger or crewmember.

Serious injury: any injury that requires hospitalization for more than 48 hours, results in a fracture of any bone (except fingers, nose and toes), or causes nerve, muscle or tendon damage.

Minor injury: an injury that does not fit the serious category.

1. Annual number of Turbulence Accidents: NTSB reports from 1995-1999 indicate an annual average of 12-15 turbulence accidents involving Part 121 aircraft and serious injuries to passengers and crew. Based on the experience of and data from your organization, how do you evaluate this number? Please circle your view.

This annual rate is approximately correct	This rate is low by 0-25%	This rate is low by 25%-50%	This rate is low by 50%-75%	This rate is low by more than 75%. My estimate is: ________

If you feel this incident rate is low, please give a brief explanation of why:

2. Number of injuries per turbulence accident: This question targets the average number of serious and minor injuries that occur as a result of a turbulence accident. The NTSB data is given in the first column and indicates the average number of injuries per accident from 1995-99. Based on the experience of and data from your organization, how do you evaluate these averages?

1995-99 NTSB Data shows an average of:	Your opinion of the NTSB average injury rates				
One major injury to a passenger per turbulence accident	This injury rate is approximately correct	This rate is low by 0-25%	This rate is low by 25%-50%	This rate is low by 50%-75%	This rate is low by more than 75%. My estimate is: ________
Three minor passenger injuries per turbulence accident	This injury rate is approximately correct	This rate is low by 0-25%	This rate is low by 25%-50%	This rate is low by 50%-75%	This rate is low by more than 75%. My estimate is: ________
One major flight attendant injury per turbulence accident.	This injury rate is approximately correct	This rate is low by 0-25%	This rate is low by 25%-50%	This rate is low by 50%-75%	This rate is low by more than 75%. My estimate is: ________
One minor flight attendant injury per turbulence accident.	This injury rate is approximately correct	This rate is low by 0-25%	This rate is low by 25%-50%	This rate is low by 50%-75%	This rate is low by more than 75%. My estimate is: ________

Comments:

3. Average Cost of Serious Injuries: A serious injury is any injury that requires hospitalization for more than 48 hours, results in a fracture of any bone (except fingers, nose and toes), or causes nerve, muscle or tendon damage. Based on the records and experience of my organization, I estimate the average out of pocket expense for a serious injury including legal, medical, lost time, workers compensation, and similar expenses is: (Please consider all the expenses that an airline would include in a business case)						
Average Cost of a Serious Injury to a Flight Attendant	No Opinion	0-$100,000	$100,000-$200,000	$200,000 - $300,000	$300,000 - $400,000	More than $400,000: My estimate is: ________
Average Cost of a Serious Injury to a Passenger	No opinion	0-$100,000	$100,000-$200,000	$200,000 - $300,000	$300,000 - $400,000	More than $400,000: My estimate is: ________
Comments:						

4. Average Cost of Minor Injuries: For simplicity, please consider a minor injury is any injury that is not major. Based on the records and experience of my organization, I estimate the average out of pocket expense for a minor injury including legal, medical, lost time, workers compensation, and similar expenses is: (Please consider all the expenses that an airline would consider in a business case)						
Average Cost of a Minor Injury to a Flight Attendant	No Opinion	0-$25,000	$25,000-$50,000	$50,000 - $75,000	$75,000 - $100,000	More than $100,000: My estimate is: ________
Average Cost of a Minor Injury to a Passenger	No opinion	0-$25,000	$25,000-$50,000	$50,000 - $75,000	$75,000 - $100,000	More than $100,000: My Estimate is: ________
Comments:						

5. Annual number of Turbulence Incidents: Turbulence incidents involve minor injuries and legally do not require reporting. Based on data from your organization, what is your best guess of the annual number of turbulence incidents for Part 121 aircraft? Please circle your view.						
Less than 50 incidents per year	50-100 incidents per year	100-150 incidents per year	150-200 incidents per year	200-250 incidents per year	250-300 incidents per year	More than 300: My estimate is: ________
Comments:						

Other comments on frequency and / or valuation of turbulence injuries and related costs:

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
May 2001

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Market Assessment of Forward-Looking Turbulence Sensing Systems

5. FUNDING NUMBERS
WU-728-40-30-00
C-71522-K

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
E–12782

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR—2001-210905

11. SUPPLEMENTARY NOTES
Project Manager, Shari Nadell, Aeronautics Directorate, NASA Glenn Research Center, organization code 2500, 216–977–7035.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 03 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
In recognition of the importance of turbulence mitigation as a tool to improve aviation safety, NASA's Aviation Safety Program developed a Turbulence Detection and Mitigation Sub-element. The objective of this effort is to develop highly reliable turbulence detection technologies for commercial transport aircraft to sense dangerous turbulence with sufficient time warning so that defensive measures can be implemented and prevent passenger and crew injuries. Current research involves three forward sensing products to improve the cockpit awareness of possible turbulence hazards. X-band radar enhancements will improve the capabilities of current weather radar to detect turbulence associated with convective activity. LIDAR (Light Detection and Ranging) is a laser-based technology that is capable of detecting turbulence in clear air. Finally, a possible Radar-LIDAR hybrid sensor is envisioned to detect the full range of convective and clear air turbulence. To support decisions relating to the development of these three forward-looking turbulence sensor technologies, the objective of this study was defined as examination of cost and implementation metrics. Tasks performed included the identification of cost factors and certification issues, the development and application of an implementation model, and the development of cost budget/targets for installing the turbulence sensor and associated software devices into the commercial transport fleet.

14. SUBJECT TERMS
Market research; Aircraft safety; Atmospheric turbulence

15. NUMBER OF PAGES
79

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102