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Metrics and Method for Measuring Commercial Aviation Safety Progress

Huasheng Li

January 2013

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16. Abstract

This report summarizes the research progress in fiscal year 2012 in the development of metrics and method for measuring, monitoring, and predicting the trend of commercial aviation toward the safety goal—a two-thirds reduction in the rate of aerospace-related fatalities and significant injuries by the year 2025, specified in the Federal Aviation Administration National Aviation Research Plan 2011.

This report proposes 28 safety metrics, which are defined as a set of precursors (factors or events) that have a strong correlation with fatalities, serious injuries, or both, to measure, monitor, and predict potential fatalities and serious injuries in commercial aviation.

Each safety metrics is quantified, in terms of the number of occurrences and the number of fatalities and serious injuries associated with a safety metrics through accidents, to establish the quantitative relation between the safety metrics and the fatalities and serious injuries, which is used to predict potential fatalities and serious injuries by measuring the occurrence of safety metrics.

A three-step method was developed to predict the rate of fatalities and serious injuries toward the year 2025. The initial results indicated that there is a good possibility that the two-thirds reduction goal of fatality and serious injury rates can be achieved by the year 2025. With the ongoing efforts of Next Generation Air Transportation System implementation and other safety improvement efforts, such as the Safety Management System and new technologies, the results of the reduction of fatality and serious injury rates would be promising.

The metrics and method developed and the results predicted in this research should be further validated when additional safety data from recent years become available.

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LIST OF ACRONYMS

AIDS	FAA Accident and Incident Data System
CAST	Commercial Aviation Safety Team
CFIT	Controlled Flight Into Terrain
CFR	Code of Federal Regulations
CICTT	CAST/ICAO Common Taxonomy Team
FAA	Federal Aviation Administration
FY	Fiscal Year
GA	General aviation
GPWS	Ground Proximity Warning System
ICAO	International Civil Aviation Organization
NARP	National Aviation Research Plan
NextGen	Next Generation Air Transportation System
NMACS	Near Midair Collision System
NTSB	National Transportation Safety Board
SCF-NP	System/Component Failure or Malfunction (Non-Powerplant)
SDR	Service Difficulty Reports
SMS	Safety Management System
TAWS	Terrain Awareness Warning System
TCAS RA	Traffic Collision Avoidance System Resolution Advisory

EXECUTIVE SUMMARY

This report summarizes the research progress in fiscal year 2012 in the development of metrics and method for measuring, monitoring, and predicting the trend of commercial aviation toward the safety goal—a two-thirds reduction in the rate of aerospace-related fatalities and significant injuries by the year 2025, specified in the Federal Aviation Administration (FAA) National Aviation Research Plan 2011.

The safety performance of commercial aviation is measured in the FAA by the fatality rate, which is defined as the number of fatalities per 100 million persons onboard. The fatality rate of commercial aviation steadily decreased through the past 20 years.

This report proposes 28 safety metrics, which are defined as a set of precursors (factors or events) that have a strong correlation with fatalities, serious injuries, or both, to measure, monitor, and predict potential fatalities and serious injuries in commercial aviation.

Each safety metrics is quantified, in terms of the number of occurrences and the number of fatalities and serious injuries associated with a safety metrics through accidents, to establish the quantitative relation between the safety metrics and the fatalities and serious injuries, which is used to predict potential fatalities and serious injuries by measuring the occurrence of safety metrics.

A three-step method was developed to predict the rate of fatalities and serious injuries toward the year 2025. The initial results indicated that there is a good possibility that the two-thirds reduction goal of fatality and serious injury rates can be achieved by the year 2025. With the ongoing efforts of Next Generation Air Transportation System implementation and other safety improvement efforts, such as the Safety Management System and new technologies, the results of the reduction of fatality and serious injury rates would be promising.

The metrics and method developed and the results predicted in this research should be further validated when additional safety data from recent years become available.

METRICS AND METHOD FOR MEASURING COMMERCIAL AVIATION SAFETY PROGRESS

BACKGROUND.

The Federal Aviation Administration (FAA) National Aviation Research Plan (NARP) 2011 set up a goal of human protection—a two-thirds reduction in the rate of aerospace-related fatalities and significant injuries by the year 2025.

To ensure that U.S. aviation is on the right track toward this goal, the NARP initiated a safety evaluation project to develop methods and metrics to measure progress in reducing the rate of fatalities and significant injuries by two-thirds.

The milestones specified in the NARP for this project include:

- By the year 2012, demonstrate a one-half reduction in the rate of fatalities and injuries.
- By the year 2016, demonstrate a two-thirds reduction in the rate of fatalities and injuries.

This report summarizes the research progress in fiscal year (FY) 2012 in the development of metrics and methods for measuring, monitoring, and predicting aviation safety trends.

AVIATION SAFETY.

Commercial aviation and general aviation (GA) are two major sources of aviation fatalities and serious injuries that contribute about 10% and 90% of total aviation fatalities and serious injuries since 1991, respectively.

Commercial aviation includes both scheduled and nonscheduled flights of U.S. passenger and cargo air carriers (FAA Title 14 Code of Federal Regulations (CFR) Part 121) and scheduled passenger flights of commuter operators (14 CFR Part 135).

GA includes on-demand (nonscheduled 14 CFR Part 135) and GA flights (14 CFR Parts 91, 103, 125, 133, and 137) that comprise a diverse range of aviation activities, from single-seat, home-built aircraft; helicopters; balloons; single- and multiple-engine land and seaplanes; to highly sophisticated, extended-range turbojets.

Figures 1 and 2 show the annual numbers of fatalities and serious injuries associated with commercial aviation and GA, respectively. The number of fatalities and serious injuries in commercial aviation changes dramatically each year compared to GA, due to larger enplanement and lower rate of fatal accidents in commercial aviation.

Although commercial aviation is involved in about 10% of aerospace-related fatalities and serious injuries, its impact on public confidence is much higher than GA. Any fatal accident in commercial aviation will become the headlines of newspapers. This report focuses on the development of metrics and methods for commercial aviation.

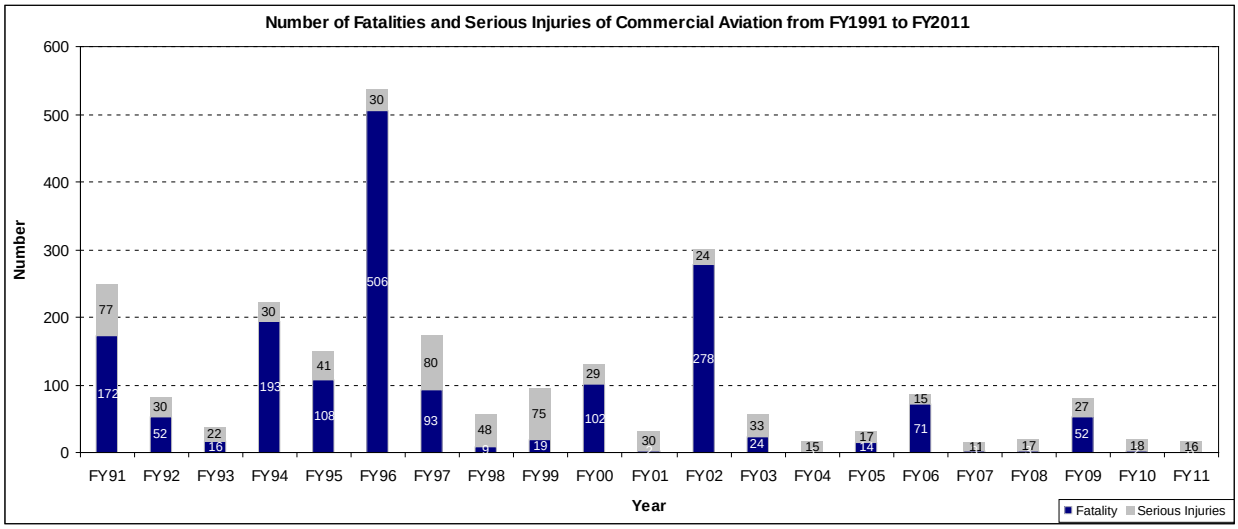

Figure 1. Safety Trend of Commercial Aviation from FY 1991 to FY 2011

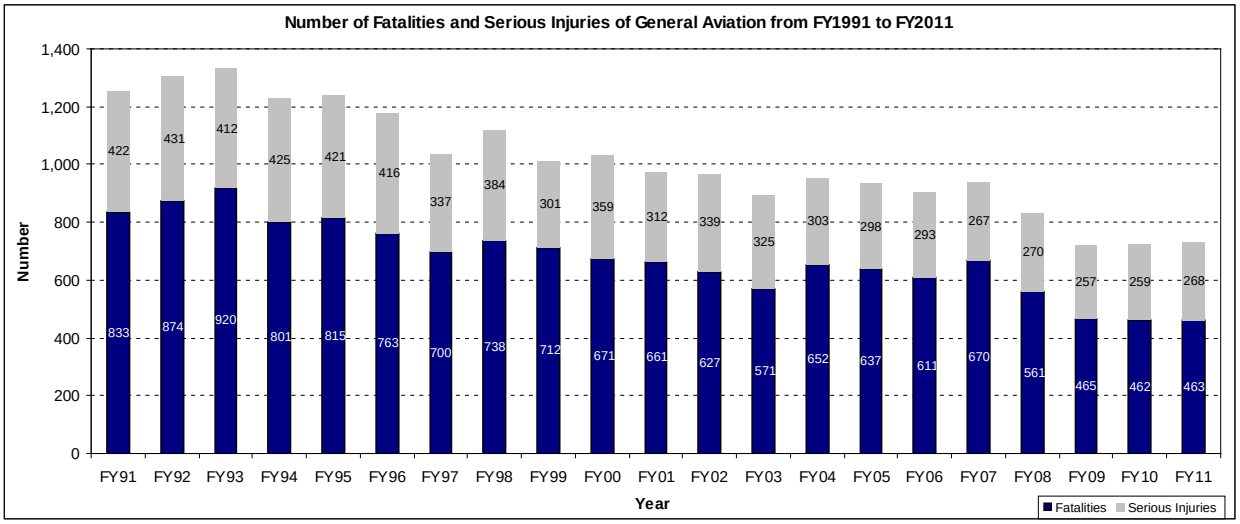

Figure 2. Safety Trend of General Aviation from FY 1991 to FY 2011

SAFETY PERFORMANCE.

The safety performance of commercial aviation is measured in the FAA by the fatality rate, which is defined as the number of fatalities per 100 million persons onboard. The fatalities resulting from aircraft accidents include passengers, crew, ground personnel, and the uninvolved public.

The fatality rate trend of commercial aviation in the U.S. is displayed in figure 3.

As shown in figure 3, the fatality rate of commercial aviation steadily decreased through the past 20 years.

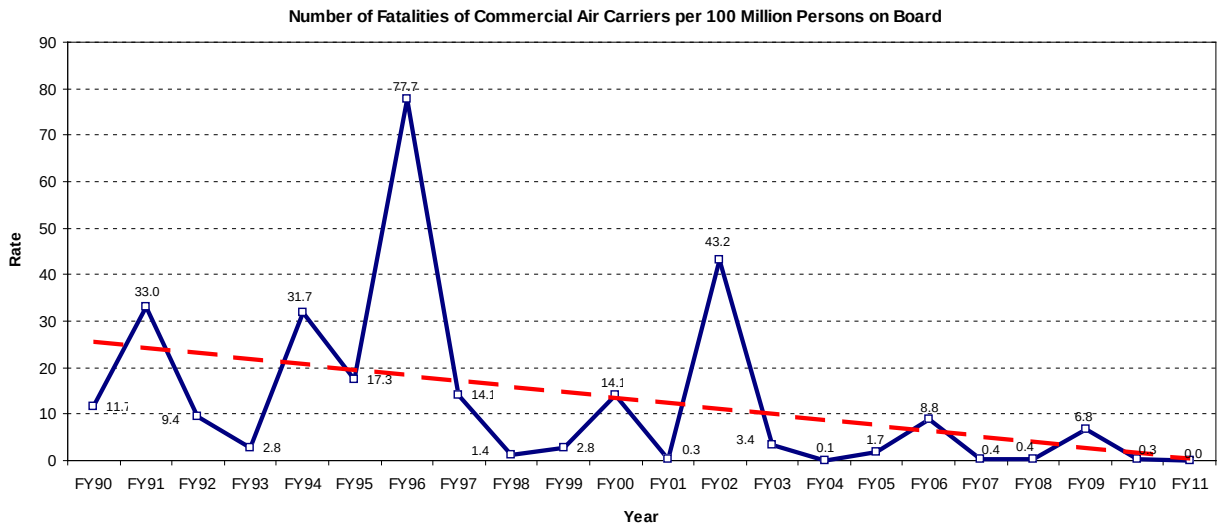

Figure 3. Fatality Rate Trend of Commercial Aviation from FY 1990 to FY 2011

SAFETY METRICS.

Safety metrics are defined in this research as a set of precursors (factors or events) that have a strong correlation with fatalities, serious injuries, or both, and can be used to measure, monitor, and predict potential fatalities and serious injuries. In other words, a precursor is an event or condition that precedes an accident leading to fatalities or serious injuries.

To be used for measuring and monitoring the progress in reducing the rate of fatalities and serious injuries, a precursor should meet the following criteria:

- Must be linked with accidents causing fatalities, serious injuries, or both
- Must have a sufficiently large number of occurrences available for trend analysis
- There must not be overlaps and gaps of precursors to overall types of accidents, fatalities, and serious injuries associated with commercial aviation

Through the extensive analysis of commercial aviation accidents, the 28 precursors shown in table 1 are proposed to measure, monitor, and predict potential fatalities and serious injuries. Note that these 28 precursors are 14 CFR Part 121 operations-oriented and are not adequate for Part 135 operations. Therefore, only 14 CFR Part 121 operations are considered for this research.

This list of precursors covers almost all the accident categories identified by the Commercial Aviation Safety Team (CAST)/International Civil Aviation Organization (ICAO) Common Taxonomy Team (CICTT) that cause fatalities, serious injuries, or both. For example, Controlled Flight Into/Toward Terrain (CFIT) accidents are associated with a precursor Ground Proximity Warning System (GPWS)/Terrain Awareness Warning System (TAWS) warning during flight; System/Component Failure or Malfunction (Non-Powerplant) (SCF-NP) accidents are associated

with more than one precursor, such as landing gear failure during takeoff or landing, ice accretion on airframe during flight, incorrect airspeed or altitude display, and separation of items from airplane during flight.

Table 1. Precursors (or Safety Metrics) for Measuring and Monitoring Progress

1. High-speed rejected takeoff	15. Severe turbulence encounter
2. Landing gear failure during takeoff or landing	16. Tail strike during landing
3. Aircraft commences takeoff with incorrect configuration	17. Tail strike during takeoff
4. Aircraft commences takeoff with contaminated wings	18. Thrust reverser failure during landing roll
5. Flight control problems from initial climb to final approach	19. Landing with a >20-knot crosswind
6. Wind shear encountered during flight	20. TCAS RA during initial climb to final approach
7. Hard landing	21. Runway incursion by vehicle or aircraft
8. Engine failure from initial climb to final approach	22. GPWS/TAWS warning from initial climb to final approach
9. Aircraft fire; including smoke, odor, or fumes during flight	23. Wake vortex encounter from initial climb to final approach
10. Flammable fluid leakage during flight	24. Separation of items from the airplane during flight
11. Incapacitation of the pilot from initial climb to final approach	25. Emergency evacuation
12. Cabin decompression or failure to pressurize from initial climb to final approach	26. Reported taxi or ramp incidents
13. Ice accretion on airframe from initial climb to final approach	27. Runway excursion during landing
14. Airspeed, altitude or attitude system failure from initial climb to final approach	28. Stall warning from initial climb to final approach

TCAS RA = Traffic Collision Avoidance System Resolution Advisory

QUANTIFICATION OF METRICS.

The purpose of quantifying precursors (or safety metrics) is to establish the quantitative relation between the precursors and the fatalities and serious injuries so potential fatalities and serious injuries can be predicted by measuring the occurrences of precursors.

Two items are quantified for each precursor:

1. The number of occurrences of a precursor
2. The number of fatalities and serious injuries caused by accidents associated with a precursor

The National Transportation Safety Board (NTSB) Aviation Accident Database is used for quantifying the correlation between accidents and precursors. The FAA Accident and Incident Data System (AIDS), Service Difficulty Reports (SDR), Near Midair Collision System (NMACS), and the information obtained from the Netherlands National Aerospace Laboratory are respectively used to quantify the occurrences of precursors.

Nine hundred and nine accidents associated with 14 CFR Part 121 operations occurred in the U.S. between January 1, 1995 and December 31, 2009. These accidents are manually reviewed and analyzed, and a precursor is assigned to each accident. Cases in which more than one precursor is associated with an accident, the first precursor in the event chain is assigned to the accident.

Table 2. Number of Accidents and Occurrences per Precursor

No.	Precursor	Accident	Occurrence
1	High-speed rejected takeoff	10	96
2	Landing gear failure during takeoff or landing	85	13,368
3	Aircraft commences takeoff with incorrect configuration	2	5
4	Aircraft takeoff with contaminated wings	1	1
5	Flight control problems from initial climb to final approach	71	313
6	Wind shear encounter during flight	2	12
7	Hard landing	16	36
8	Engine failure from initial climb to final approach	64	11,939
9	Aircraft fire; including smoke, odor, and fumes	57	705
10	Flammable fluid leakage	15	112
11	Incapacitation of pilot from initial climb to final approach	9	38
12	Cabin decompression or failure to pressurize from initial climb to final approach	7	138
13	Ice accretion on airframe from initial climb to final approach	8	14
14	Airspeed, altitude, or attitude system failure from initial climb to final approach	3	2,169
15	Severe turbulence encounter	170	248
16	Tail strike during landing	13	47
17	Tail strike during takeoff	6	18
18	Thrust reverser failure during landing roll	4	85
19	Landing with a >20-knot crosswind	4	16
20	TCAS RA during initial climb to final approach	12	71
21	Runway incursion by vehicle or aircraft	31	2,374
22	GPWS/TAWS warning from initial climb to final approach	12	9
23	Wake vortex encounter from initial climb to final approach	11	12

Table 2. Number of Accidents and Occurrences per Precursor (continued)

No.	Precursor	Accident	Occurrence
24	Separation of items from the airplane	31	589
25	Emergency evacuation	7	270
26	Reported taxi or ramp incident	220	803
27	Runway excursion during landing	29	117
28	Stall warning from initial climb to the final approach	7	11

PREDICTION METHOD.

To predict the rate of fatalities and serious injuries toward the year 2025, the following three-step method was proposed:

1. Determine the ratio of accident to occurrence ($R_{accident/occurence}$), the ratio of fatality to accident ($R_{fatality/accident}$), and the ratio of serious injury to accident ($R_{injury/accident}$).

2. Estimate the rate of occurrence ($R_{occurence}$) of each precursor from the year 2025 through extrapolation.

3. Predict the rate of fatality ($R_{fatality}$) and the rate of serious injury (R_{injury}) in the year 2025 by $R_{occurence}$ x $R_{accident/occurrence}$ x $R_{fatality/accident}$ and by $R_{occurence}$ x $R_{accident/occurrence}$ x $R_{injury/accident}$, respectively.

$R_{fatality/accident}$ and $R_{injury/accident}$ are determined for eight groups of precursors, not for each precursor. A group of precursors is assumed to share similar accident severities to smooth the random effect of a precursor. The groups of precursors and corresponding fatality/serious injury-to-accident ratios are shown in table 3.

Table 3. Groups of Precursors and Associated Fatality/Serious Injury-to-Accident Ratios

Group	Precursor	Fatalities per Accident	Serious Injuries per Accident
Accident On or Near the Runway (RA)	High-speed rejected takeoff	0.30	0.09
	Landing gear failure during takeoff or landing		
	Hard landing		
	Tail strike during landing		
	Tail strike during takeoff		
	Thrust reverser failure during landing roll		
	Landing with a >20-knot crosswind		
	Runway excursion during landing		

Table 3. Groups of Precursors and Associated Fatality/Serious Injury-to-Accident Ratios (continued)

Group	Precursor	Fatalities per Accident	Serious Injuries per Accident
Collision with the Ground (CG)	Flight control problems from initial climb to final approach	2.13	0.36
	Engine failure from initial climb to final approach		
	Aircraft fire; including smoke, odor, or fumes		
	Flammable fluid leakage		
	Incapacitation of the pilot from initial climb to final approach		
	Cabin decompression or failure to pressurize from initial climb to final approach		
	Ice accretion on airframe from initial climb to final approach		
	Airspeed, altitude, or attitude system failure from initial climb to final approach		
	GPWS/TAWS warning from initial climb to final approach		
	Stall warning from initial climb to final approach		
Aircraft Upset Inflight (AU)	Wake vortex encounter from initial climb to final approach	1.45	0.98
	Wind shear encounter during flight		
	Severe turbulence encounter		
Aircraft Collision (AC)	TCAS RA from initial climb to final approach	0	0.19
	Runway incursion by vehicle or aircraft		
SEP	Separation of items from the airplane	0.71	0.13
EVAC	Emergency evacuation	0	0.29
GA	Reported taxi or ramp incident	0.04	0.18
RA/CG	Aircraft commences takeoff with incorrect configuration	0	0
	Aircraft takeoff with contaminated wings		

PREDICTION RESULTS.

The rate of occurrence for each precursor toward the year 2025 is extrapolated by using the exponential trend function of the 5-year moving average. The moving average is used to balance out large differences between arbitrary years, and the exponential-trend extrapolation is chosen because, in the case of a descending trend, additional improvements over the years will become harder to achieve. The occurrence rate is expressed as the number of precursor occurrences per 100 million enplanements.

Two examples of the estimated occurrence rate are shown in figures 4 and 5.

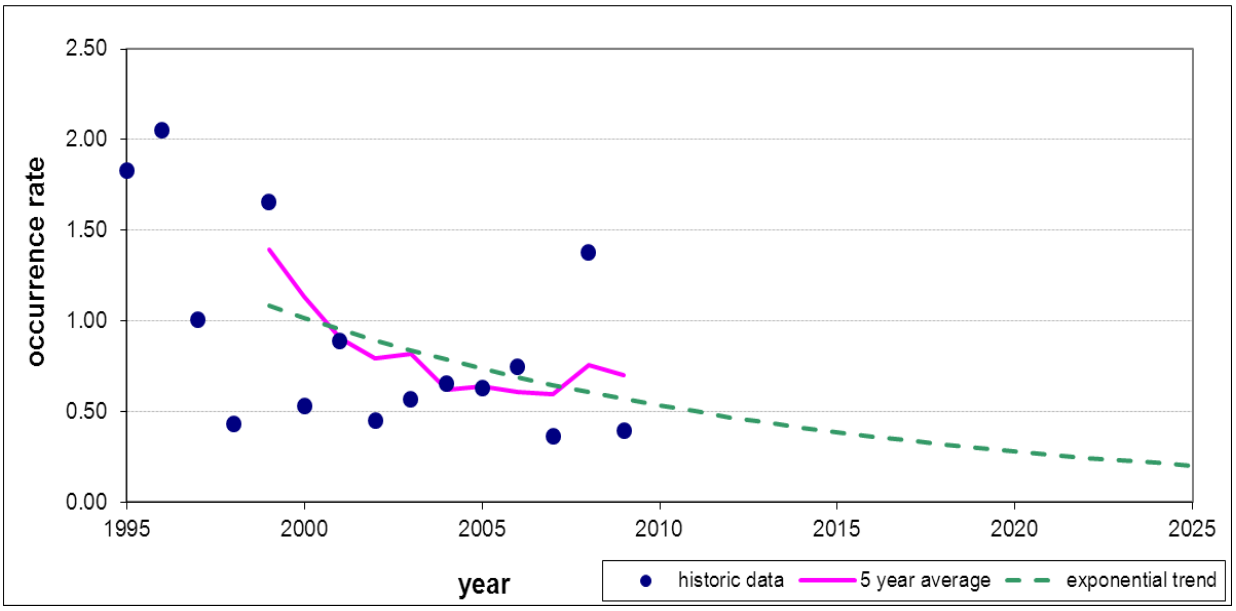

Figure 4. Trend of Occurrence of Precursor 1—High-Speed Rejected Takeoff

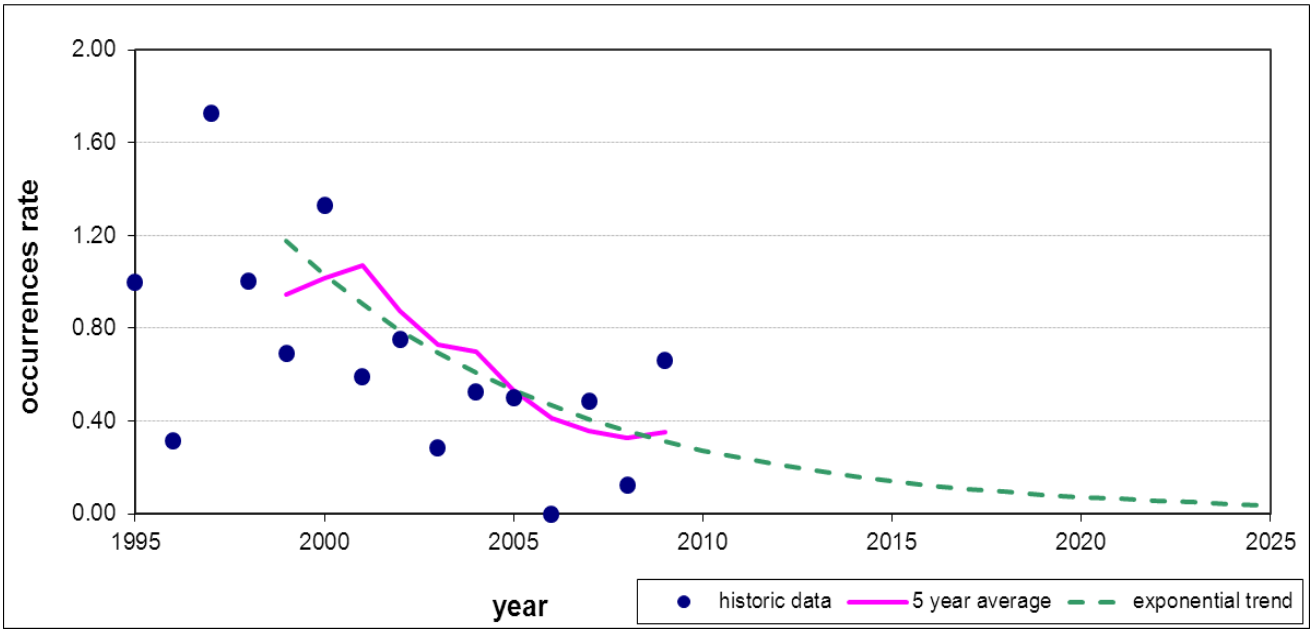

Figure 5. Trend of Occurrence of Precursor 20—TCAS RA During Initial Climb to Final Approach

The accident rate trend associated with each precursor is obtained by multiplying the predicted occurrence rate by the accident-to-occurrence ratio of each precursor. The accident rate is then multiplied by the fatality/serious injury-to-accident ratios in the appropriate group to obtain the fatality and serious injury rates per precursor. The total accident, fatality, and serious injury rates

are obtained through the corresponding rate summations of all precursors, as shown in figures 6, 7, and 8.

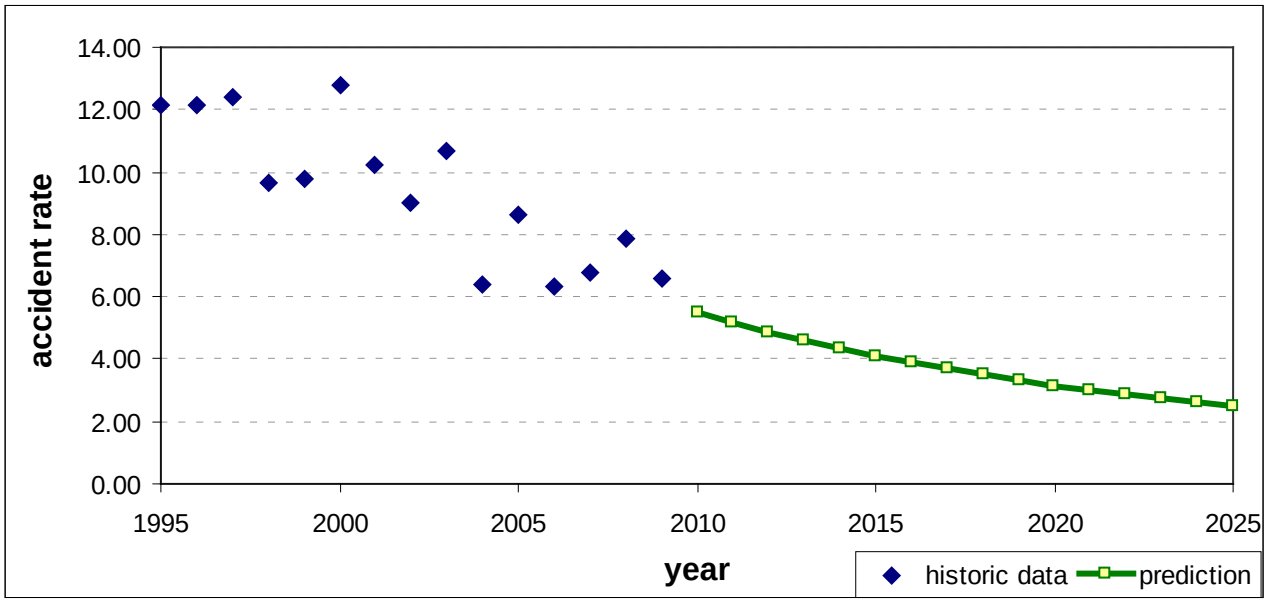

Figure 6. Trend of Accident Rate in Number of Accidents per 100 Million Enplanements

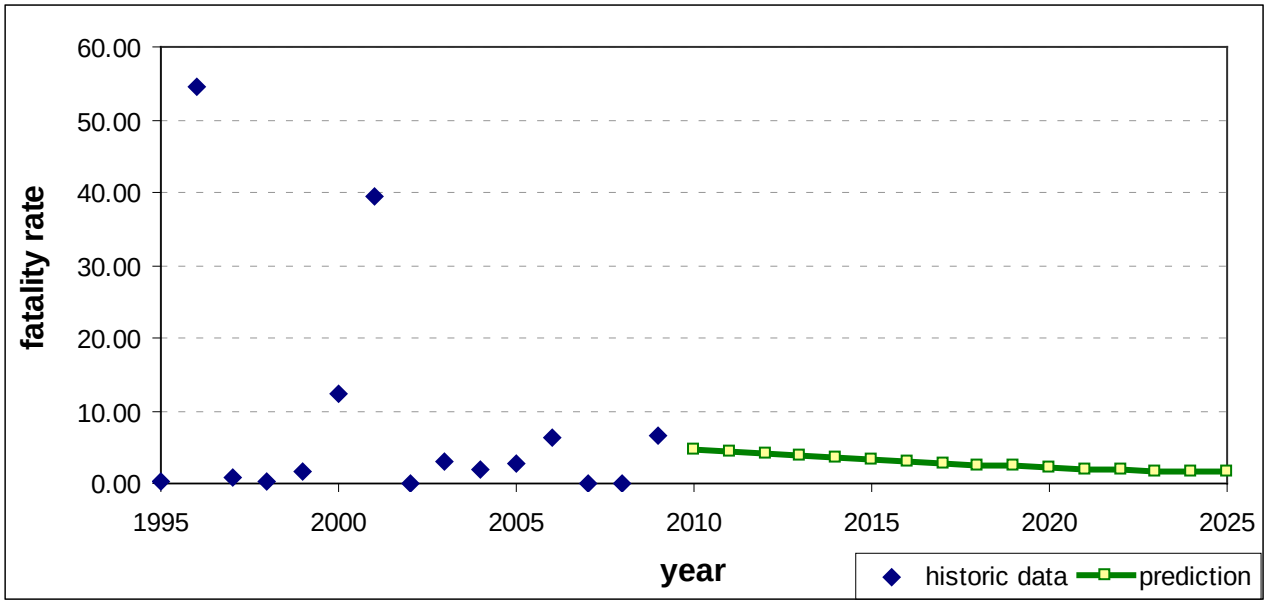

Figure 7. Trend of Fatality Rate in Number of Fatalities per 100 Million Enplanements

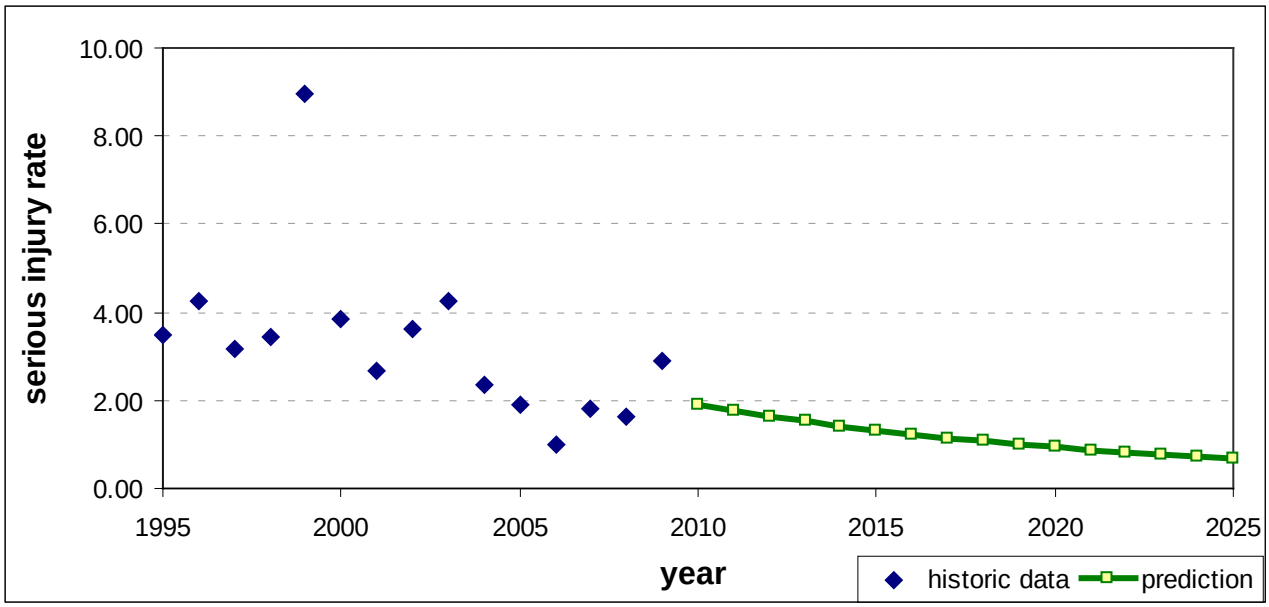

Figure 8. Trend of Serious Injury Rate in Number of Serious Injuries per 100 Million Enplanements

The predicted accident, fatality, and serious injury rates as well as the associated reduction rates in the years 2018 and 2025 are shown in table 4. The rates in the years 2018 and 2025 are two important targets specified in the FAA Destination 2025 and the NARP, respectively.

Table 4. Accident, Fatality, and Serious Injury Rates and Reductions in the Years 2018 and 2025

Baseline (year)	Rates (per 100 million enplanements) and Reductions					
	Accident		Fatality		Serious injury	
	9.54		6.67		3.48	
2018	3.49	-63.4%	2.54	-61.9%	1.07	-69.3%
2025	2.52	-73.6%	1.55	-76.8%	0.69	-80.2%

The baselines of accident, fatality, and serious injury rates are based on the number of accidents, fatalities, and serious injuries per 100 million enplanements for U.S. air carriers operating under 14 CFR Part 121 from 1997 through 2006.

There is a good possibility that the two-thirds (or 66.7%) reduction goal of fatality and serious injury rates can be achieved by the year 2025. With the ongoing efforts of Next Generation Air Transportation System implementation and other safety improvement efforts, such as the Safety Management System and new technologies, the results of the reduction of fatality and serious injury rates would be promising.

However, it is important to point out that the prediction of the future always comes with the risk of uncertainty. The accuracy of predicted results depends on a lot of factors, such as method used, data quality, assumptions made, unpredictable changes in the future. In this research, data quality is a major concern.

The metrics and method developed and the results predicted in this research should be further validated when additional safety data from recent years become available.

CONCLUSION

The safety metrics, consisting of 28 precursors, for Title 14 Code of Federal Regulations (CFR) Part 121 operations were proposed, covering almost all accident categories identified by the Commercial Aviation Safety Team/International Civil Aviation Organization (CAST/ICAO) Common Taxonomy Team (CICTT) that cause fatalities, serious injuries, or both. These metrics can be used to measure and monitor the progress of reducing the rate in fatalities and serious injuries toward the year 2025.

The method for predicting the trend of fatality and serious injury rates is developed, which is based on the historical accident-to-occurrence and fatality/serious injury-to-accident ratios. This method is simple, straightforward, and easy to understand.

The initial prediction result for the year 2025 demonstrates that it is possible to achieve the two-thirds reduction of fatality and serious injury rates for 14 CFR Part 121 operations.

The metrics and method should be further validated when new safety data become available.

Another research effort would be needed if a similar request for measuring, monitoring, and predicting the safety performance of general aviation (GA) was determined, because significant differences exist between commercial aviation and GA in terms of operations, rules, data quality, aircraft, safety goal, and so forth.