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Value of an Overload Indication System Assessed Through Analysis of Aviation Occurrences

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This paper identifies the value of an aircraft landing gear overload indication system by comparing vertical descent velocity landing data extrapolated from a statistical analysis of the Federal Aviation Administration's Video Landing Parameter Survey data, with reported occurrence data. Data suggest that there should be between 455–848 narrow-body aircraft and between 236–1279 heavy-wide-body aircraft per million departures, with a vertical descent velocity above the hard-landing threshold of 10 ft/s, and that flight crews declare hard landings at a frequency even higher than predicted by the Federal Aviation Administration data. Analysis of aviation authority and landing gear manufacturer data show that occurrences are reported at a much lower frequency than the 10 ft/s vertical descent velocity threshold or flight-crew declaration rates. This could be interpreted as suggesting that more hard landings occur than are reported. However, the discrepancy between the vertical descent velocity data and the reported occurrence data can be attributed to 1) Federal Aviation Administration data being based solely on vertical descent velocity without taking into account the other critical enveloping flight parameters required to calculate the loads in the landing gear structure and 2) reported occurrences being filtered in an authorized occurrence assessment process. Having reviewed the occurrence assessment process, it is argued that an overload indication system offers potential benefits through 1) improved aircraft operational availability; 2) reduced costs for the operator, aircraft manufacturer, and landing gear manufacturer; and 3) reduced risk to the aircraft and operator.

Nomenclature

$f(x)$	=	probability density function
$F(x)$	=	cumulative density function
α	=	shape parameter
β	=	scale parameter
γ	=	location parameter
Δn_z	=	incremental vertical acceleration
μ	=	mean
σ	=	standard deviation

I. Introduction

THE landing gear is the sole structure supporting the aircraft on the ground and, because it generally has no structural redundancy, static structural overloads are of interest to operators, aircraft manufacturers, and landing gear manufacturers [1,2]. A static structural overload occurs when the landing gear has exceeded its material yield point at some location. A structure that has exceeded its yield point may be left with a crack or residual stress, which can lead to a stress corrosion cracking failure or a fatigue-initiated landing gear failure at a load less than the static limit load.

An occurrence is defined as an accident or an incident [3]. An accident is defined as "an event associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage" [4]. An incident is defined as "an event other than an accident that affects or could affect the safety of operations" [4].

The Commercial Aviation Safety Team and International Civil Aviation Organization (ICAO) Common Taxonomy Team have identified 28 occurrence categories for powered, fixed-wing, land-operated aircraft. Nine common occurrences that may result in a landing gear overload are due to abnormal runway contact (hard landings, overweight landings, lateral load landings, and nose-wheel-first touchdown), abrupt maneuvers (rejected takeoff), ground handling (picketing, towing, and aircraft recovery), ground collision, runway excursion, runway incursion, overshoot/undershoot, in-flight impact (bird strike), or improper servicing [3].

The loads on a landing gear are dependent on the combination of a number of flight parameters; including aircraft gross weight; aircraft center of gravity; payload and fuel distributions; aircraft orientation (pitch, roll, and yaw); rates of motion (pitch rate, roll rate, and yaw rate); vertical descent velocity; longitudinal, lateral and vertical acceleration; shock-absorber servicing state; and tire-friction characteristics. Although hard landings, for example, are defined by the regulatory authorities in European Aviation Safety Agency Certification Specification (CS)-25¶ [5] and Federal Aviation

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¶Certification specifications govern civil European aircraft programs. For large aircraft, CS-25 governs the landing gear certification loads.

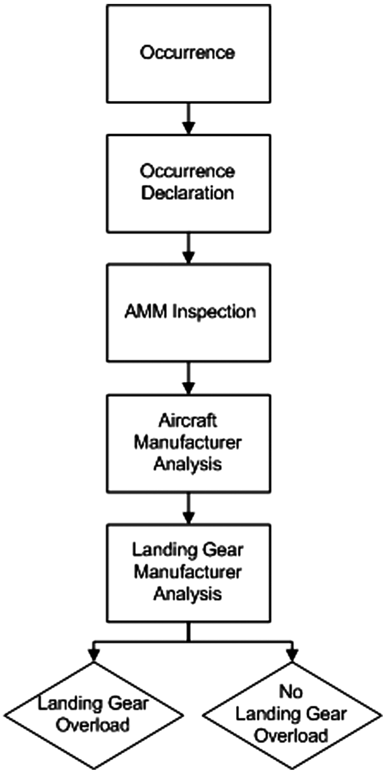

Fig. 1 Occurrence assessment process flowchart.

Regulation (FAR) 25** [6] as a landing with a limit vertical descent velocity of 10 ft/s or greater, in fact, the vertical descent velocity threshold must be combined with other critical enveloping flight parameters, as described previously, to overload the landing gear.

Presently, when there is an occurrence, the flight crew makes an occurrence declaration, and visual and nondestructive test inspections are performed on the landing gear by the operator's maintenance crew, based on the aircraft maintenance manual (AMM); flight data recorder information is downloaded and reported to the airframe and landing gear manufacturers, who use dynamic aircraft and landing gear models to calculate the loads during the occurrence [2]. It is only after the occurrence is analyzed by the aircraft and landing gear manufacturers that it can be determined if the landing gear has been overloaded and is considered unserviceable. This occurrence assessment process is illustrated in Fig. 1.

Although some aircraft are fitted with systems that are able to indicate landing gear overloads [1,7], most commercial aircraft are not. Therefore, the initial reporting of the occurrence is dependent on a subjective flight-crew declaration and visual inspections by the operator maintenance crew. This means that the aircraft may be grounded unnecessarily, which has a great economic impact, or the aircraft may be considered serviceable, when it has, in fact, exceeded its structural capability, which has safety implications [8]. Therefore, there is a motivation for implementing structural health monitoring to detect static structural overloads (and, equally, to detect when overloads did not occur) to maximize operational availability, minimize costs, and reduce risk [2,9].

In this paper, the value of a landing gear overload indication system is presented using reported occurrence data sampled from the aviation industry, including the U.K. Civil Aviation Authority (CAA), the U.S. National Transportation Safety Board (NTSB), the Society of Automotive Engineers (SAE), a landing gear manufacturer, and operational vertical descent velocity data from the Federal Aviation Administration's (FAA) Video Landing Parameter Survey. Data from narrow-body, wide-body, heavy-wide-body, and commuter aircraft types were investigated. Table 1 lists the aircraft models within each aircraft type. Figure 2 illustrates the samples of data, the timeline of each data set, and the aircraft models within each data set. When there are overlapping samples, it is possible that data are represented in each data set. Although occurrence data have been investigated in [7], there is no other known literature on this subject. In Sec. II of this paper, reported occurrence data from the aviation authorities (CAA and NTSB), flight-crew declarations (SAE), and a landing gear manufacturer are presented. In Sec. III, operational vertical descent velocity data from FAA video landing parameter surveys are analyzed, including data from surveys conducted at John F. Kennedy International (JFK), Ronald Reagan Washington National (DCA), Honolulu International (HNL), London City (LCY), Philadelphia International (PHL), London Heathrow (LHR), and Atlantic City International (ACY). In Sec. IV, the reported occurrence data versus the operational data are discussed. Finally, in Sec. V, conclusions are drawn from the data.

**Federal aviation regulations govern North American aircraft programs. For transport-category aircraft, FAR 25 governs landing gear certification loads.

II. Reported Occurrence Data

A. Reported Occurrences to the U.K. Civil Aviation Authority

The U.K. CAA's Aviation Safety Review [10] described the major types of reported occurrences up to 2004. From data gathered from ICAO, the reported accidents worldwide were classified by occurrence category [3]. Although 28 occurrence categories exist, the top 10 in terms of percentage of accidents are shown in Table 2. This table shows that within a period from 1995–2004, runway excursions accounted for 19% of reported accidents to the aviation

Table 1 Summary of FAA Video Landing Parameter Survey data, after [7]

Aircraft type and model	Total landings	Airports
Narrow body	1143	——
B727	106	DCA [a]
B737	197	JFK, DCA, LHR
B757	291	JFK, DCA, LHR
MD-80	208	JFK, DCA, LHR
MD-90	7	LHR
DC-9	86	JFK, DCA
A319	38	LHR
A320	123	DCA, LHR
A321	70	LHR
Fokker F-28	3	DCA
Fokker F-100	14	DCA
Wide body	340	——
B767	212	JFK, HNL, LHR
A300	83	JFK, LHR
A310	45	LHR [a]
Heavy wide body	758	——
B747	367	JFK, HNL, LHR
B777	85	LHR
L-1011	73	JFK, HNL, LHR
DC-10	163	JFK, HNL, LHR
MD-11	26	JFK, HNL, LHR
A330	19	LHR
A340	25	LHR
Commuter	658	——
Dash 7	26	JFK
Dash 8	160	JFK, LCY, PHL
ATR 42	42	JFK
SAAB 2000	5	LCY
Dornier 328	5	LCY
Fokker 50	72	LCY
Falcon	5	LCY
BAE 146	141	LCY
SAAB 340	46	JFK, PHL
Beech 1900D	139	PHL, ACY
Jetstream 41	10	PHL
Canadair Regional Jet	7	DCA
Supersonic	7	——
Concorde	7	JFK

[a]Although the JFK report suggests that A310 and B727 data were recorded, there are no data provided in the report.

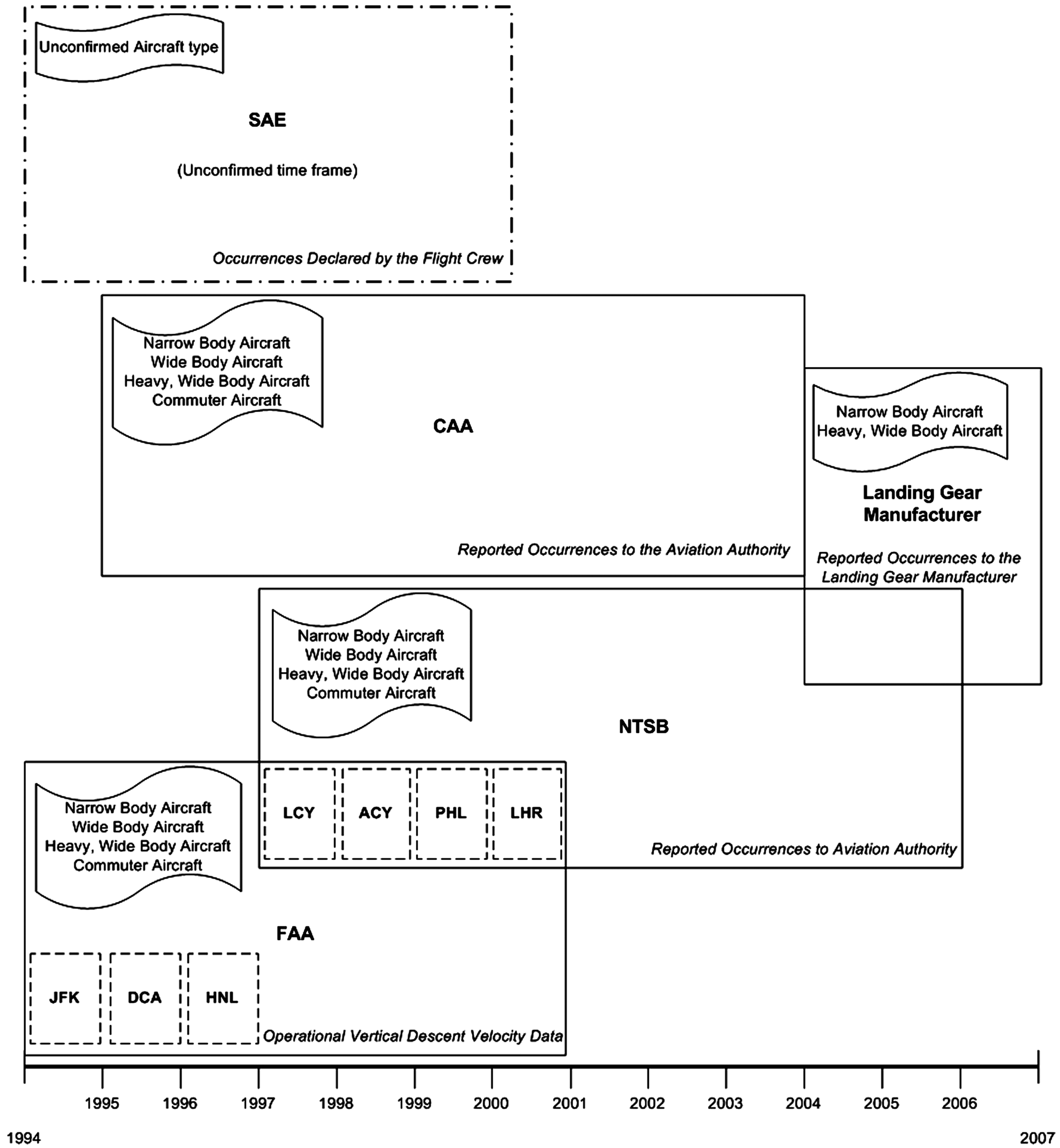

Fig. 2 Overview of sampled reported occurrence data and operational data.

authority, abnormal runway contact accounted for 16% of reported accidents to the aviation authority, and ground handling accounted for 10% of the reported accidents to the aviation authority [10]. These specific occurrences are identified because they are likely to result in a landing gear overload.

Data on United Kingdom registered or operated large transport aircraft,[††] presented in Table 3, show that ground collisions accounted for 35%, hard landings accounted for 9%, landing-gear-related accidents accounted for 9%, and offrunway excursions (departed runway accidents) accounted for 6% of all of the major types of reported aircraft accidents to the aviation authority from 1995–2004 [10]. As a result of these accidents, the landing gear could have been overloaded. Although ground collisions account for a high percentage of accidents, some accidents may not necessarily result in a landing gear overload. For example, a ground collision could include a collision between aircraft wings. However, hard landings, landing-gear-related accidents, and offrunway excursions account for 24% of the reported accidents to the aviation authority over a 10-year period.

[††]Large aircraft are defined here as having a maximum takeoff weight of over 5700 kg on public transport flights [10].

B. Reported Occurrences to the U.S. National Transportation Safety Board

Although the CAA's Aviation Safety Review indicates that the percentage of aircraft occurrences in which a landing gear could be overloaded is quite significant when all of the reported accidents over a 10-year period are analyzed, the authors gathered data from the NTSB database to provide a secondary source of occurrence data reported to an aviation authority.

Although [7] reported on hard landings, overweight landings, and runway excursion occurrences for type 121 common carriers, which include air carriers operating large transport-category aircraft, the data presented in Tables 4 and 5 include other types of abnormal runway contact, as well as abrupt maneuvers, ground handling, ground collision, runway excursion, runway incursion, overshoot/undershoot, in-flight impact, and improper servicing. A total of 724 type 121 occurrences reported to the aviation authority were examined over a 10-year period, from 1997–2006. This time frame

Table 2 Percentage of CAA-reported accidents within top 10 occurrence category from 1995–2004, after [10]

Accident category	Percent of reported aviation authority accidents within occurrence category
Runway excursion	19
System/component failure or malfunction (non-power-plant)	16
Abnormal runway contact	16
Turbulence encounter	11
Ground handling	10
In-flight loss of control	8
Controlled flight into or toward terrain	7.5
Power plant failure or malfunction	7
Unknown or undetermined	6
Ground loss of control	6

Table 3 Percentage of CAA-reported accidents from 1995–2004, after [10]

Accident category	Percent of reported aviation authority accidents
Ground collision	35
Tail scrape	12
Hard landing	9
landing-gear-related	9
Departed runway	6
Engine-related	6

Table 4 Percentage of NTSB type 121 reported occurrences from 1997–2006

Occurrence category	Percent of reported aviation authority occurrences
Abnormal runway contact	
Hard landing	1.93
Overweight landing	0.28
Bounce landing	1.80
Lateral load landing	3.18
Nose-wheel-first touchdown	0
Abrupt maneuver	
Rejected takeoff	2.21
Ground handling	
Towing occurrences	3.04
Aircraft recovery	0.14
Ground collision	0.97
Runway incursion	0.97
Runway excursion	3.04
Overshoot/undershoot	0.69
In-flight collision	0.28
Improper servicing	2.21

was considered due to the availability of yearly departure data from the NTSB.

When researching NTSB reports, only occurrences in which one could reasonably assume that the landing gear could have been overloaded were documented. For example, in the case of ground collisions, occurrences in which aircraft wings were damaged by other aircraft wings, occurrences of tail planes damaged by aircraft wings, or occurrences of vehicles damaging the aircraft fuselage were not documented. Lateral load landings were documented as occurrences in which there were asymmetric or lateral drift landings or when the aircraft veered off the side of the runway. Occurrences in which the aircraft taxied off the taxiway were considered to be runway excursions. In the case of runway incursions, aborted landings in which the landing gear did not contact the ground were not recorded, and when runway incursions resulted in rejected takeoffs, the occurrence was documented as a rejected takeoff. An overrun on takeoff was considered to be a runway excursion, unless there was braking involved, in which case the occurrence was documented as a rejected takeoff. Towing occurrences in which the landing gear could have been overloaded were recorded, and improper servicing occurrences related to landing gear shock-absorber misservicing as well as landing gear components not being assembled correctly were also recorded. In NTSB reports in which there may have been multiple occurrences (for example, a hard landing and subsequent runway excursion), the data are reported as the primary occurrence that initiated the chain of events.

Table 4 shows the percentage of reported occurrences to the aviation authority from the 724 occurrence reports examined over the 10-year period. Of all the occurrences, approximately 20% could result in a landing gear overload. Abnormal runway contact occurrences accounted for approximately 7% of the occurrences reported to the aviation authority, in which hard landings accounted for approximately 2%, bounce landings accounted for approximately 2%, and lateral load landings accounted for approximately 3%. Although the U.K. Civil Aviation Authority's Aviation Safety Review cites that hard landings accounted for 9% of the reported accidents over a 10-year period, if bounce landings were categorized as hard landings, the NTSB data would indicate that approximately 4% of occurrences were hard-landing-related.

Runway excursions accounted for approximately 23% of the NTSB occurrences, compared with 6% that the Aviation Safety Review cites. Towing occurrences in which the landing gear could be overloaded, rejected takeoffs, and improper servicing were also significant occurrences in the NTSB database. Ground collision occurrences were also found to be lower than those in Aviation Safety Review, because, as mentioned previously, only occurrences reported to the aviation authority in which landing gear could be overloaded were documented.

Table 5 indicates the frequency of reported occurrences to the aviation authority per million departures. Of the NTSB data collected, abnormal runway contact (specifically, lateral load landings) had the highest frequency of occurrence. Runway excursions and towing occurrences also had high frequencies of occurrence.

Although the frequencies of occurrence have, on average, a magnitude in the range of 10^{-7}, it must be kept in mind that for occurrences to be reported to the NTSB, they had to be significant enough to warrant reporting to the aviation authority [7]: for example, the occurrence caused substantial damage to the aircraft, resulted in injury, or somehow affected the safety of operations. The number of landing gear occurrences not reported to the aviation authority because there is no visible damage or injury is therefore unknown.

C. Reported Occurrences to the Landing Gear Manufacturer

Although occurrences are reported to aviation authorities directly by the aircraft operator, they are only reported to the landing gear manufacturer when the operator has reported the occurrence to the aircraft manufacturer, and an analysis of the landing gear is required by the aircraft manufacturer to determine whether it has been overloaded.

Landing gear occurrences reported to a landing gear manufacturer for narrow-body and heavy-wide-body aircraft were investigated by the authors to determine the types of occurrences that are reported and the frequency of occurrence per million departures. The percentage of landing gear determined to have been overloaded during

Table 5 NTSB type 121 frequency of reported occurrences per million departures from 1997–2006, after [7]

Occurrence category		Abnormal runway contact					Abrupt maneuver	Ground handling							
Date	Departures	Hard landings	Overweight landings	Bounce landing	Lateral load landings	Nose-wheel-first touchdown	Rejected takeoffs	Towing occurrences	Aircraft recovery	Ground collision	Runway incursion	Runway excursion	Overshoot/ undershoot	In-flight collision	Improper servicing
1997	9,925,058	0.202	0	0.302	0.202	0	0.101	0.000	0	0.202	0	0.302	0	0	0.202
1998	10,535,196	0.095	0	0.095	0.475	0	0.380	0.475	0	0.095	0	0.190	0.095	0	0.095
1999	10,860,692	0.276	0	0.092	0.184	0	0.000	0.092	0	0.000	0	0.184	0.000	0	0.460
2000	11,053,826	0.271	0	0.090	0.181	0	0.271	0.090	0	0.000	0.090	0.271	0.090	0.090	0.181
2001	10,632,880	0.188	0.094	0.094	0.188	0	0.188	0.188	0	0.094	0.188	0.094	0.094	0	0.188
2002	10,276,107	0.097	0.097	0.097	0.097	0	0.097	0.195	0	0.000	0.097	0.097	0.097	0	0.292
2003	10,227,924	0.000	0	0.000	0.391	0	0.098	0.293	0	0.000	0.098	0.293	0	0	0
2004	10,782,989	0.000	0	0.278	0.093	0	0.093	0.185	0.093	0.000	0	0.185	0.093	0.093	0
2005	10,910,460	0.092	0	0.183	0.275	0	0.092	0.275	0	0.275	0.183	0.183	0	0	0.092
2006	10,627,481	0.094	0	0.000	0.094	0	0.188	0.282	0	0.000	0	0.282	0	0	0
	Average	0.132	0.019	0.123	0.218	0	0.151	0.208	0.009	0.067	0.066	0.208	0.047	0.018	0.151

an occurrence, following analysis by the landing gear manufacturer, was also investigated. Data was available from 2004 to 2007, and although the sample size is not large, the data are still able to give an indication of those occurrences that are reported to the landing gear manufacturer.

1. *Narrow-Body-Aircraft Landing Gear Occurrences*

The average frequency per million departures of the reported occurrences to the landing gear manufacturer is of the same approximate magnitude (10^{-7}) as the NTSB data. The landing gear manufacturer data also follows the same trend as the NTSB data in that occurrences involving abnormal runway contact (hard landings, overweight landings, bounce landings, and lateral load landings) account for the highest frequency of occurrences, compared with other occurrence categories. Towing occurrences, runway excursions, and rejected takeoffs also had high frequencies of occurrence, which is similar to the NTSB data. From the reported occurrences to the landing gear manufacturer, it was found that 30% of the narrow-body family of landing gear analyzed following a hard-landing occurrence reported to the landing gear manufacturer had at least one component that was found to have been overloaded.

2. *Heavy-Wide-Body-Aircraft Main Landing Gear Occurrences*

The reported occurrence data available from the heavy-wide-body-aircraft main landing gear (MLG) was limited to only abnormal runway contact occurrences, because it was not possible to determine which occurrences were due to hard landings, bounce landings, lateral load landings, or nose-wheel-first touchdown. The frequency per million departures of the reported abnormal runway contact occurrences to the landing gear manufacturer were found to be a magnitude of 10 times higher than the frequencies of occurrence that the narrow-body aircraft family experiences. Anecdotal evidence suggests that because of the greater weight of the heavy-wide-body family of aircraft compared with the narrow-body family of aircraft (as well as the placement of the pilot in the heavy-wide-body family of aircraft at a greater distance from the MLG, which makes it difficult to detect intuitively when to touchdown the landing gear), the heavy-wide-body family of aircraft experiences a higher frequency of abnormal runway contact occurrences per million departures. The FAA Video Landing Parameter Survey, which will be discussed in Sec. III, also found that the Airbus heavy-wide-body family of aircraft tended to have higher vertical descent velocities than comparable Boeing aircraft [11].

It was also found that 39% of the heavy-wide-body family of main landing gear analyzed by the landing gear manufacturer following an abnormal runway contact occurrence had at least one component that was found to have been overloaded.

D. Occurrences Declared by the Flight Crew

It is the responsibility of the flight crew to report a landing gear occurrence to the aircraft operator, and therefore a subjective assessment is made by the flight crew based on their experience and perception of the occurrence. The SAE reported on data obtained from pilot hard-landing reports. Although the data are from an unidentified commercial carrier over a five-year period, the SAE indicates there were 1850 hard-landing-occurrence declarations per one million departures from pilots when there was a suspected hard landing [7].

What is unknown from the pilot hard-landing declaration data is the type of aircraft that the commercial carrier used. As mentioned in the previous section, the heavy-wide-body family of aircraft tend to have a higher number of abnormal runway occurrences than the narrow-body family. Therefore, the type of aircraft may have an effect on the hard-landing declarations. Also, the data do not indicate how many hard landings reported by the flight crew were actual landing gear overloads.

III. Operational Data

The FAA's Operational Loads Monitoring Program conducts studies to give insight into the operational loads that aircraft actually experience, to validate original design criteria and fatigue-life estimates for aircraft landing gear and also so that these data can be used to develop design requirements for future aircraft [12,13]. Through the FAA's Operational Loads Monitoring Program, video landing parameter surveys have been conducted to calculate the kinematic flight parameters of aircraft landings to document operational data of aircraft landing conditions. Flight parameters such as vertical descent velocity, longitudinal velocity, aircraft attitude, rate of change of those attitudes, offcenter distance, and distance from the runway threshold at touchdown were calculated based on detailed analysis of the time-tracked video images as well as wind and weather conditions [14].

Since the 1940s, the U.S. Navy has conducted video landing parameter surveys to collect operational usage data on aircraft flown by their pilots in the normal operating environment [14]. In the 1950s, NASA conducted various landing parameter surveys on piston-engine, turboprop, and turbojet aircraft [15–18]. One of the significant results of the surveys was that although piston-engine, turboprop, and turbojet aircraft were designed to the same vertical descent velocity (10 ft/s), the development of larger, heavier, and faster turbojet aircraft was resulting in higher vertical descent velocities on landing than piston-engine and turboprop aircraft were experiencing [16,18].

Recently, video landing parameter surveys were conducted by installing an adaptation of the Naval Aircraft Approach and Landing Acquisition System (NAALAS) on runways at high-activity airports such as JFK, DCA, HNL, LCY, PHL, LHR, ACY, and Cincinnati International Airport. Descriptions of the adaptation of the NAALAS used to record the video images as well as the procedure used by the FAA to calculate the landing parameters can be found in [13,14]. Aircraft types captured in the survey include narrow-body aircraft, wide-body aircraft, heavy-wide-body aircraft, commuter aircraft, and a very limited number of supersonic aircraft. To date, Video Landing Parameter Survey data reports have been published for JFK [19], DCA [20], and HNL [21]; a summary report has been published for LCY, PHL, and ACY [22]; and most recently, a report has been published for LHR [11]. Table 1 provides a summary of all FAA Video Landing Parameter Survey data, including aircraft models, total landings, and airports. In the FAA Video Landing Parameter Survey reports, the vertical descent velocity data are compared with MIL-SPECs MIL-A-8866 [23] and MIL-A-8863 [24].

A. Military Specifications

Although CS-25 [5] and FAR 25 [6] state that the design-limit vertical descent velocity for commercial transports is 10 ft/s and consider this a once-per-lifetime event, MIL-SPECs are often considered by civil aircraft manufacturers to estimate aircraft usage during the design phase, because no equivalent commercial specification exists [25].

In the JFK, DCA, and HNL surveys, the recorded vertical descent velocity spectra were compared with the vertical-descent-velocity-life frequency distribution described in MIL-A-8866 [23], a U.S. MIL-SPEC. However, in the LCY, PHL, LHR, and ACY surveys, the recorded vertical descent velocity spectra were compared with the Pearson type III frequency distribution. The Pearson type III distribution is defined by the parameters for flared field landings on prepared runways described in MIL-A-8863 [24], a ground-loads specification. The authors of the FAA Video Landing Parameter Survey reports determined that it would be more appropriate to use MIL-A-8863, because this specification contains a frequency distribution and the data from the surveys are in a distribution form. MIL-A-8866 [23], on the other hand, is not a distribution, but is provided in a table, and is used for fatigue-lifing. However, a comparison of the MIL-SPEC distributions, shown in Fig. 3, illustrates the similarity between them. Both MIL-A-8866 and MIL-A-8863 [24] indicate that landings normally occur with a vertical descent velocity of 3–4 ft/s and both state that a landing exceeding 10 ft/s will occur approximately once in every 2000 departures.

An aspect not considered in the FAA's MIL-SPEC comparison was that the design-limit vertical descent velocity at maximum landing weight for military and navy aircraft tends to be higher than the 10 ft/s design-limit vertical descent velocity for commercial aircraft. For land-based military trainers, for example, the limit vertical descent velocity is 13 ft/s at design gross weight [7]. The MIL-SPEC then provides a frequency for 10 ft/s landings, which is higher than most commercial aircraft would experience in a lifetime. Therefore, for commercial applications, the MIL-A-8863 [24] distribution should have a lower frequency. This would ultimately show an even greater discrepancy between the design requirements and the operational usage.

The United Kingdom defense standard for combat aircraft also uses MIL-A-8866 [23] as the basis for its main landing gear design. A future defense standard for large-type aircraft may also provide a vertical descent velocity spectrum [26].

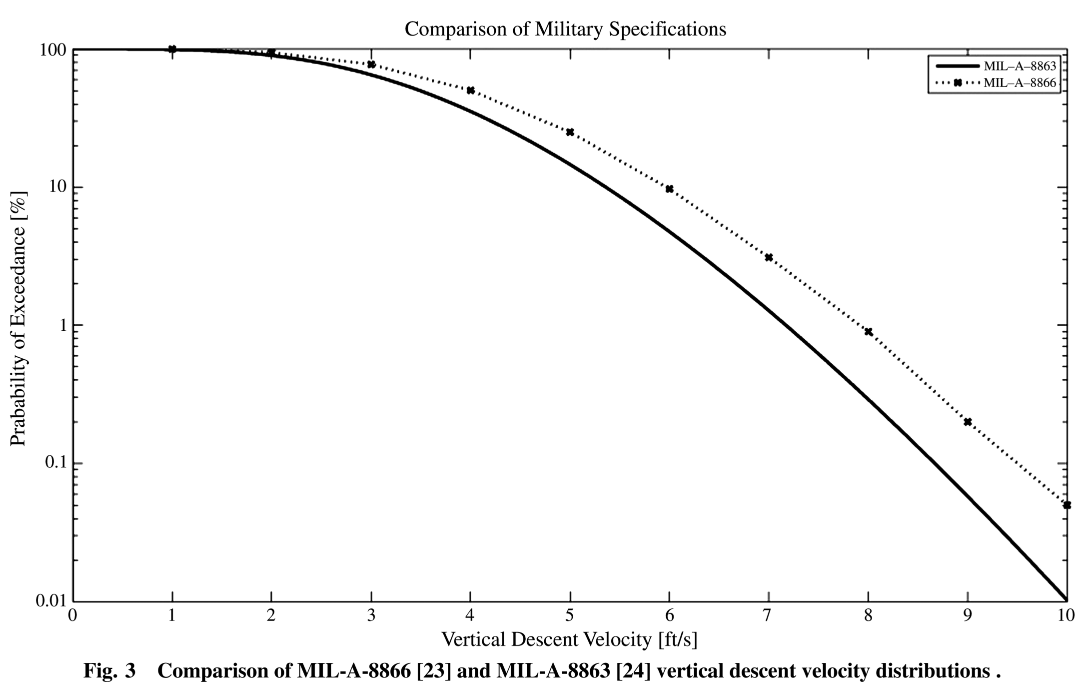

Fig. 3 Comparison of MIL-A-8866 [23] and MIL-A-8863 [24] vertical descent velocity distributions .

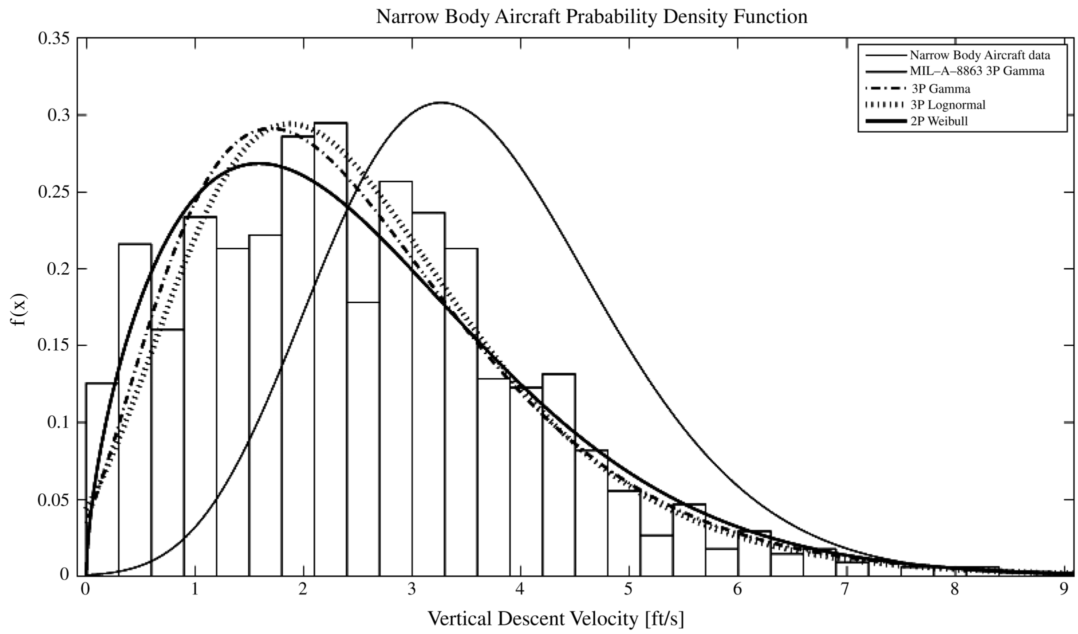

Fig. 4 Narrow-body-aircraft vertical descent velocity probability density function, FAA Video Landing Parameter Survey data.

B. Vertical Descent Velocity Frequency Distributions

The data from the published FAA video landing parameter surveys was analyzed by the authors to determine the vertical descent velocity frequency distributions for all narrow-body, wide-body, heavy-wide-body, and commuter aircraft. The FAA has found that for almost every civil aircraft model type, when the vertical descent velocity data collected is plotted as a histogram, there is asymmetry and the data are positively skewed [27]. To develop frequency distributions for these data, the Pearson type III statistical distribution has historically been used for the definition of landing vertical descent velocity in NASA reports [16], MIL-SPECs [24], and FAA video landing parameter surveys. The Pearson type III distribution, a reparameterized form of the three-parameter gamma statistical distribution, provides a good mathematical model because its parameters (shape, scale, and location) can be used to fit the data [27]. The probability density function (PDF) of the three-parameter gamma distribution is given by [27]

$$f(x) = \frac{(x-\gamma)^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} \exp\left(\frac{-(x-\gamma)}{\beta}\right) \qquad x > 0 \qquad (1)$$

where α is the shape parameter, β is the scale parameter, and γ is the location parameter.

The two-parameter Weibull statistical distribution can also be used to fit a variety of data shapes, and the Loads and Dynamic Harmonization Working Group (LDHWG)[‡‡] suggests that it may also be used if it is shown to better fit the FAA measured data [29]. The two-parameter Weibull PDF is given by [29]

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x}{\beta}\right)^{\alpha}\right) \qquad x \geq 0 \qquad (2)$$

where α is the shape parameter and β is the scale parameter.

However, any distribution that accurately fits the data may be used. The three-parameter lognormal distribution was plotted in addition to the three-parameter gamma and two-parameter Weibull distributions, because it also provided a good fit to the data. The three-parameter lognormal PDF is given by [29]

$$f(x) = \left[\exp\left(-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right)\right] \Big/ x\sigma\sqrt{2\pi} \qquad x > 0 \qquad (3)$$

where μ is the mean and σ is the standard deviation of the variable's natural logarithm.

As part of a review of the FAA Video Landing Parameter Survey results from JFK, DCA, HNL, LHR, and ACY, the LDHWG found that the data sample size, particularly at high vertical descent velocities, was inadequate to accurately fit a statistical distribution curve through the data , and therefore statistical extrapolation was required [28]. However, statistical extrapolation is unreliable and the data can be extrapolated to give a number of results [28].

To provide a more accurate extrapolation, the three-parameter (3P) gamma, two-parameter (2P) Weibull, and three-parameter (3P) lognormal distributions were fit to the data so that a range of high-vertical-descent-velocity probabilities could be achieved. Figures 4–7 show the probability density functions for the FAA narrow-body, wide-body, heavy-wide-body, and commuter-aircraft vertical descent velocity data, respectively, from the JFK, HNL, DCA, LCY, PHL, ACY, and LHR video landing parameter surveys. MIL-A-8863 [24] was plotted to provide a reference to the estimated aircraft usage. Table 6 provides the statistical distribution summary, including the distribution parameters and the chi-squared (χ^2) goodness-of-fit ranking using a significance level of 5%.

The 3P gamma, 2P Weibull, and 3P lognormal PDFs for each aircraft type are positively skewed and do not follow the MIL-A-8863 [24] distribution. The mean vertical descent velocities of the surveys ranged from 2.6 to 3.1 ft/s, depending on the aircraft type, and the maximum vertical descent velocity observed was 9.5 ft/s. The NAALAS system was designed to measure vertical descent velocity to within ± 0.1 ft/s [14]. To provide verification of the accuracy of the vertical descent velocity results, the FAA compared the results from the NAALAS system with a Boeing MD-90 that was equipped with an inertial navigation system (INS) [11]. There was a good correlation of results, and the NAALAS system was shown to have an accuracy of within ± 0.5 ft/s with the INS [11].

Previous NASA data found that the mean vertical descent velocities of jet transports observed was 1.6 ft/s and the maximum vertical descent velocity observed was 4.2 ft/s [11]. The NASA system had an accuracy within ± 0.31 ft/s. Accounting for the accuracy of the each system, the FAA survey data show that there was an overall increase in vertical descent velocities observed when compared with previous NASA work documenting aircraft vertical descent velocities in the 1950s [21].

‡‡The Loads and Dynamic Harmonization Working Group (LDHWG) is a subgroup of the Aviation Rulemaking Advisory Committee, which is a rulemaking study group composed of regulatory and industry representatives [28].

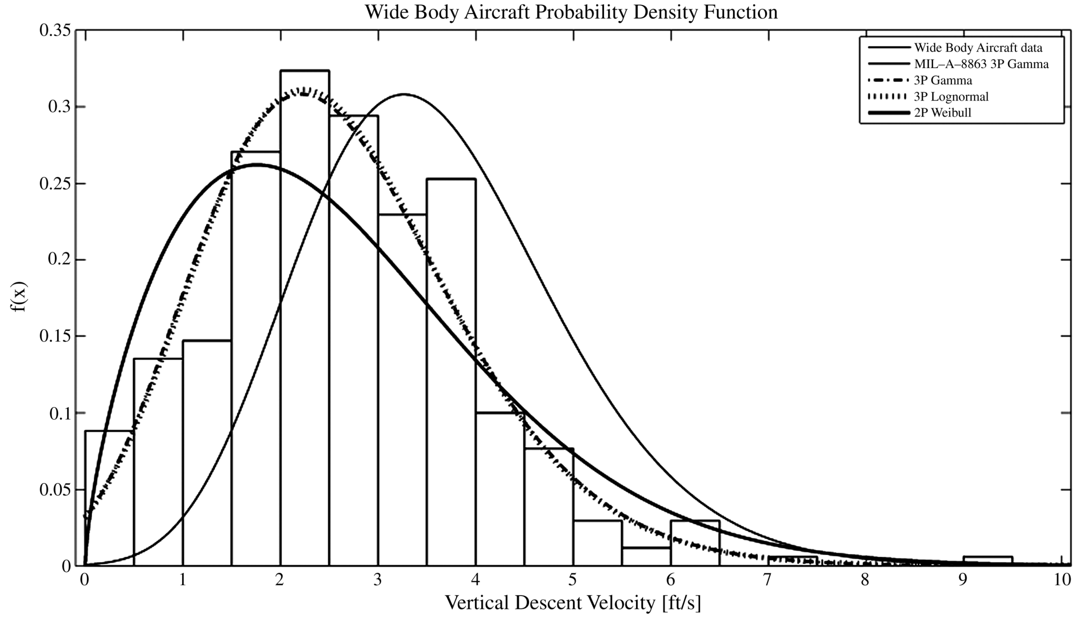

Fig. 5 Wide-body-aircraft vertical descent velocity probability density function, FAA Video Landing Parameter Survey data.

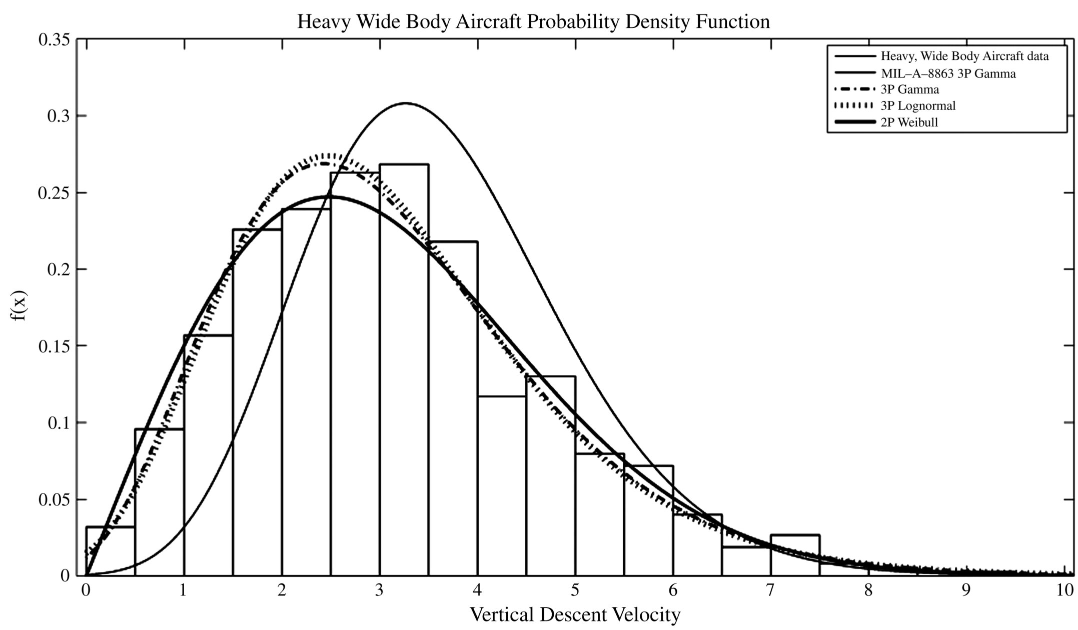

Fig. 6 Heavy-wide-body-aircraft vertical descent velocity probability density function, FAA Video Landing Parameter Survey data.

The cumulative distribution functions (CDF) for the 3P gamma, 2P Weibull, and 3P lognormal distributions are given by [30]

$$F(x) = \int_{-\infty}^{x} f(x)\mathrm{d}x \tag{4}$$

To determine the probability of exceeding a 10 ft/s vertical descent velocity, the CDF can be used such that [27]

$$\text{probability of exceedance}\,(x) = 1 - F(x) \tag{5}$$

Figures 8–11 show a comparison of the probability of exceeding the vertical descent velocity for narrow-body, wide-body, heavy-wide-body, and commuter aircraft, respectively, for all FAA Video Landing Parameter Survey data from JFK, HNL, DCA, LCY, PHL, ACY, and LHR. The vertical descent velocity data was compared with the MIL-A-8863 [24] curve. The 3P gamma, 2P Weibull, and 3P lognormal distributions were plotted. Table 7 provides the range of probability of exceeding a 10 ft/s vertical descent velocity based on the different distributions.

For narrow-body aircraft, the best-fitting distribution was the 2P Weibull distribution, which predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 455 per million departures. The 3P gamma distribution predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 808 per million departures, and the worst-fitting distribution, the 3P lognormal distribution, predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 848 per million departures. All distributions exceeded the MIL-A-8863 [24] distribution at a vertical descent velocity of approximately 7 ft/s.

For wide-body aircraft, the best-fitting distribution was the 3P gamma distribution, which predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 25 per million departures. The 3P lognormal distribution and the worst-fitting 2P Weibull distribution both predict that the frequency of exceeding a 10 ft/s vertical descent velocity is 411 per million departures. The 2P Weibull distribution

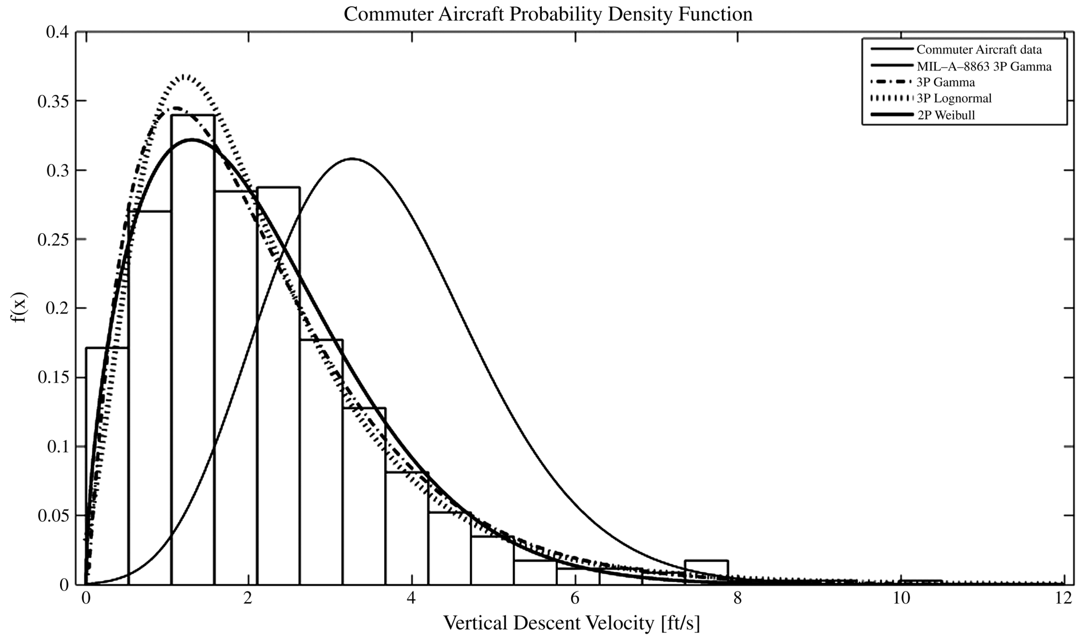

Fig. 7 Commuter aircraft vertical descent velocity probability density function, FAA Video Landing Parameter Survey data.

exceeded the MIL-A-8863 [24] distribution at a vertical descent velocity of approximately 7 ft/s; however, the 3P gamma and 3P lognormal distributions did not exceed the MIL-A-8863 distribution.

For heavy-wide-body aircraft, the best-fitting distribution was the 2P lognormal distribution, which predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 1279 per million departures. The 2P Weibull distribution predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 236 per million departures, and the worst-fitting distribution, the 3P gamma distribution, predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 923 per million departures. All distributions exceeded the MIL-A-8863 [24] distribution at a vertical descent velocity of approximately 5 ft/s.

For commuter aircraft, the best-fitting distribution was the 3P lognormal distribution, which predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 2560 per million departures. The 2P Weibull distribution predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 38 per million departures, and the worst-fitting distribution, the 3P gamma distribution, predicts that the frequency of exceeding a 10 ft/s vertical descent velocity is 876 per million departures. The 3P lognormal and 3P gamma distributions exceeded the MIL-A-8863 [24] distribution at a vertical descent velocity of approximately 7–8 ft/s. However, the 2P Weibull distribution did not exceed the MIL-A-8863 distribution.

C. Additional Considerations from the Video Landing Parameter Surveys

The video landing parameter surveys found that an aircraft's vertical descent velocity was influenced by two main factors: the velocity at which the aircraft flies the glide slope and the flare before touchdown. Under typical operating conditions, on approach, an aircraft typically flies a 3 deg glide slope at the manufacturer's specified approach speed, which is a function of aircraft weight, wind conditions (i.e., gusts), and weather conditions (i.e., thunderstorms) [11]. The aircraft flares, or pitches up, before touchdown, which increases the aircraft's lift and reduces the vertical descent velocity. The flare of the aircraft depends on the pilot's ability, but it can also be affected by other factors such as crosswinds or wet runways [11].

The video landing parameter surveys found that changing operating conditions alter the way aircraft are flown. For example, the higher volume and intensity of current flight operations compared with when NASA documented aircraft operations in the 1950s mean that aircraft are under additional pressure to land as quickly as possible and taxi off the runway, which results in higher vertical descent velocities [22].

Other issues to consider are the weather conditions and airport characteristics such as altitude, climate, and surrounding terrain [20], which could affect the vertical descent velocity results. Although the surveys were conducted in the summer months, when the weather is generally favorable, it was found that crosswind landings, which

Table 6 FAA Video Landing Parameter Survey statistical distribution parameter summary

		Parameters					Chi-squared (χ^2) goodness-of-fit summary
Aircraft type	Distribution	Mean μ	Standard deviation δ	Alpha α	Beta β	Gamma γ	Rank
Narrow body	3P lognormal	1.50	0.32	——	——	−2.17	2
	3P gamma	——	——	3.52	0.84	−0.40	3
	2P Weibull	——	——	1.63	2.86	0.00	1
Wide body	3P lognormal	1.98	0.18	——	——	−4.75	2
	3P gamma	——	——	13.01	0.37	−2.24	1
	2P Weibull	——	——	1.70	2.98	0.00	3
Heavy wide body	3P lognormal	1.70	0.28	——	——	−2.60	1
	3P gamma	——	——	5.94	0.66	−0.81	3
	2P Weibull	——	——	2.01	3.49	0.00	2
Commuter	3P lognormal	0.85	0.54	——	——	−0.53	1
	3P gamma	——	——	2.02	1.06	0.02	3
	2P Weibull	——	——	1.61	2.37	0.00	2

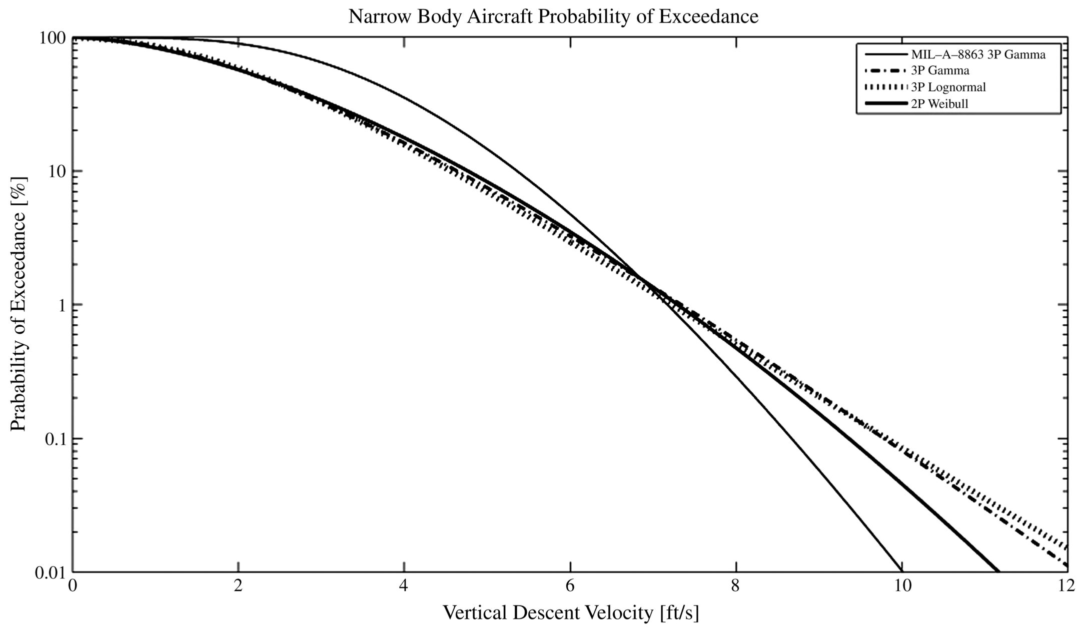

Fig. 8 Narrow-body-aircraft vertical descent velocity probability of exceedance, FAA Video Landing Parameter Survey data.

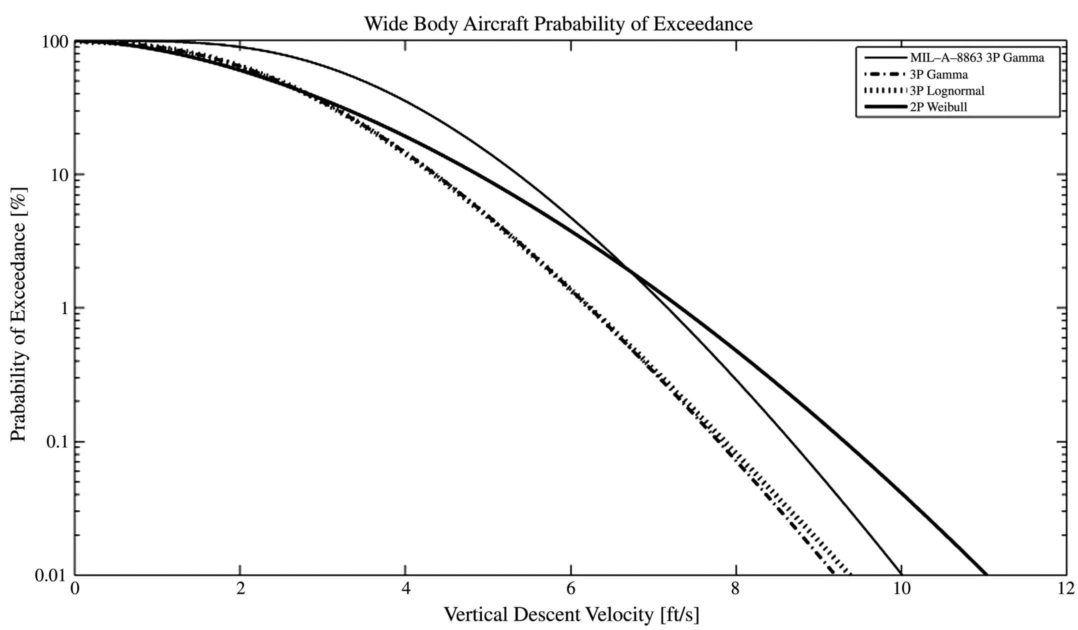

Fig. 9 Wide-body-aircraft vertical descent velocity probability of exceedance, FAA Video Landing Parameter Survey data.

allow less time for the pilot to flare, tended to have higher vertical descent velocities [21].

The operational characteristics of the particular airport, such as the runway configuration and terminal locations, must also be taken into consideration. For example, at DCA, aircraft attempted to touchdown as close as possible to the runway threshold to reduce their taxi time to the main terminal, which would have affected their vertical descent velocity [20]. At HNL, an operational requirement in effect at the time of the survey stated that due to the ill-maintained condition of the initial 4000 ft. of the runway, pilots should not touch down the nose landing gear in this area; therefore, the length of the runway was reduced [21]. Aircraft also trying to land on shorter runways could have an increased vertical descent velocity. Data from airports such as LCY, which has a steep glide slope of 5.5 deg, indicated that the steeper glide slope resulted in increased approach speed and increased vertical descent velocity [22].

Other considerations include the design differences between aircraft. The LHR survey showed that Airbus heavy-wide-body aircraft produced higher vertical descent velocities than comparable Boeing aircraft. The authors of the FAA Video Landing Parameter Survey report hypothesized that this was because the heavy-wide-body Airbus aircraft tend to flare less than comparable Boeing aircraft before touchdown [11].

The survey results challenged the aviation industry's understanding of aircraft usage. Based on the results of the JFK survey, the FAA and the Joint Aviation Administration questioned the adequacy of the current CS/FAR 25.473 ([5,6]) landing gear vertical descent velocity requirement when applied to the next generation of large transport aircraft: specifically, the A380.

In 2003, the LDHWG recommended revisions to the current FAR and CS ground-loads regulations. As part of this review of ground-loads requirements, the LDHWG looked at the results of the video landing parameter surveys that had been collected from JFK, DCA, HNL, LHR, and ACY, and the data were used to evaluate the current 10 ft/s vertical descent velocity requirement. The LDHWG concluded that in terms of static design, the vertical descent velocities

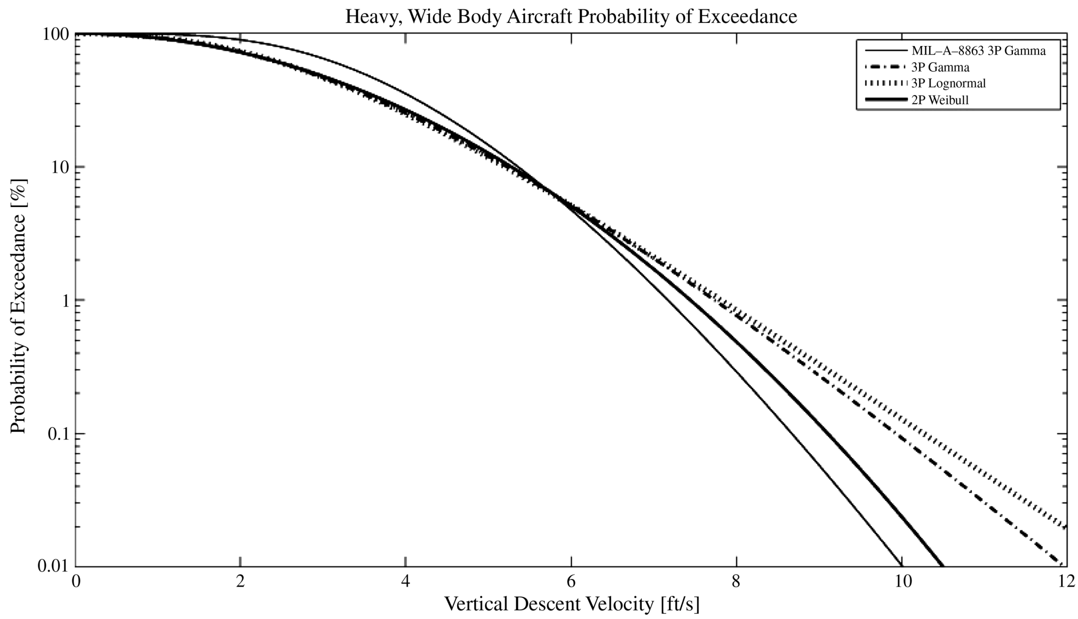

Fig. 10 Heavy-wide-body-aircraft vertical descent velocity probability of exceedance, FAA Video Landing Parameter Survey data.

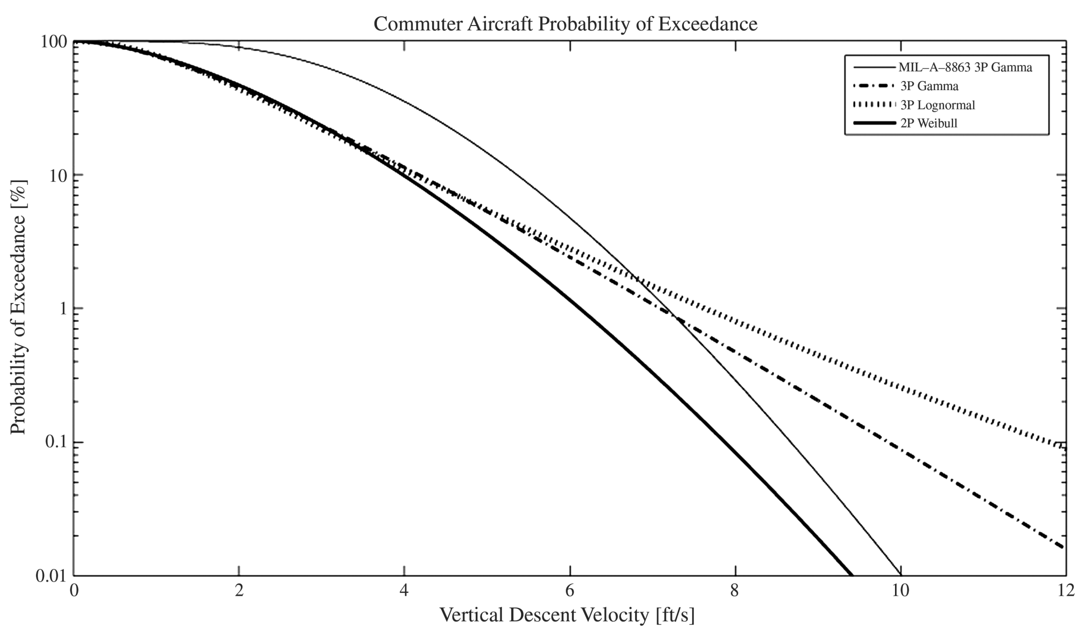

Fig. 11 Commuter-aircraft vertical descent velocity probability of exceedance, FAA Video Landing Parameter Survey data.

specified in the limit landing load conditions should be retained, because the current FAA data sample size, particularly at vertical descent velocities, was inadequate to fit a statistical distribution curve through the data [28].

In addition, there are other enveloping flight parameters, such as aircraft gross weight, center of gravity, payload and fuel distribution, aircraft orientation, acceleration, shock-absorber servicing state, and tire-friction characteristics that must be combined with the vertical descent velocity to determine the landing gear loads. These flight parameters were not taken into account when looking at the survey results for vertical descent velocity. Therefore, the LDHWG recommended that the FAA should continue the video landing parameter surveys to include the relevant flight parameters and to expand the database available [28]. Although some dynamic aircraft flight parameters can be directly measured (such as aircraft orientation, rate of motion, and acceleration), flight parameter measurements of aircraft gross weight, aircraft center of gravity, and tire-friction characteristics can only be estimated. In addition, the FAA video landing parameter surveys should be expanded to include other high-activity airports such as Hartsfield-Jackson Atlanta International, Los Angeles International, and Frankfurt International. The accuracy of the data collection could be improved by selecting airports based on traffic flow, runway length, and weather conditions.

Because the data from the video landing parameter surveys have higher average vertical descent velocities than data typically used by aircraft manufacturers, the LDHWG also suggested that the vertical descent velocity results could be used for fatigue design of the landing gear and aircraft structure [28].

IV. Discussion of Reported Occurrence Data Versus Operational Data

The occurrence assessment process, shown in Fig. 1, includes the occurrence declaration (flight-crew declaration or onboard system); the operator's analysis based on the AMM; the operator's report to the aircraft manufacturer and the aviation authority, as appropriate; and the aircraft manufacturer's report to the landing gear

Table 7 FAA Video Landing Parameter Survey statistical distribution summary

Aircraft type	Distribution	Probability of exceeding 10 ft/s vertical descent velocity (1 CDF)	Frequency of exceeding 10 ft/s vertical descent velocity per million departures
Narrow body	3P lognormal	8.48E − 04	848.2
	3P gamma	8.09E − 04	808.8
	2P Weibull	4.55E − 04	455.1
Wide body	3P lognormal	4.12E − 04	411.8
	3P gamma	2.52E − 05	25.2
	2P Weibull	4.12E − 04	411.8
Heavy wide body	3P lognormal	1.28E − 03	1279.3
	3P gamma	9.24E − 04	923.7
	2P Weibull	2.37E − 04	236.8
Commuter	3P lognormal	2.56E − 03	2560.6
	3P gamma	8.76E − 04	876.4
	2P Weibull	3.88E − 05	38.8

Table 8 Summary of average reported hard-landing-occurrence data versus vertical descent velocity data

	Database	Narrow-body family of frequency per million departures	Heavy-wide-body family of frequency per million departures
Reported hard-landing occurrences	NTSB	0.132	0.132
	Landing gear manufacturer	1.627	31.245[a]
	Airline pilot hard-landing declarations	1850	1850
Landings with a vertical descent velocity exceeding 10 ft/s	FAA Video Landing Parameter Survey	455–848	236–1279

[a]The heavy-wide-body family of landing gear manufacturer data represent the average for abnormal runway contact.

manufacturer. The aircraft and landing gear manufacturers then determine if the landing gear has been overloaded. A summary of the reported occurrence data and operational data in relation to actual landing gear overloads is presented in Table 8 and Fig. 12. Figure 12 draws together the data presented in Secs. II and III and illustrates the key points discussed in Sec. IV to show where an overload indication system may add value.

The flight-crew declaration is the first stage in the occurrence assessment process. Although the FAA Video Landing Parameter Survey data predict that the number of landings with a vertical descent velocity exceeding 10 ft/s should be in the range of 455–848 per million departures for the narrow-body family and 236–1279 per million departures for the heavy-wide-body family, flight crews are declaring 1850 hard landings per million departures, which is more than what is predicted. Reference [7] suggests that the flight crew typically makes a hard-landing declaration at a threshold of 7–8 ft/s, which is lower than the 10 ft/s limit vertical descent velocity defined in the CS/FAR regulations. A flight crew is not able to feel vertical descent velocity, and so they make a make a subjective judgement based on the deceleration they feel in the cockpit. The flight crew may be unable to determine the difference between the deceleration caused by an 8 ft/s vertical descent velocity and a 10 ft/s vertical descent velocity. If this were the case, then it would suggest that the flight crew were declaring hard landings when there were, in fact, no

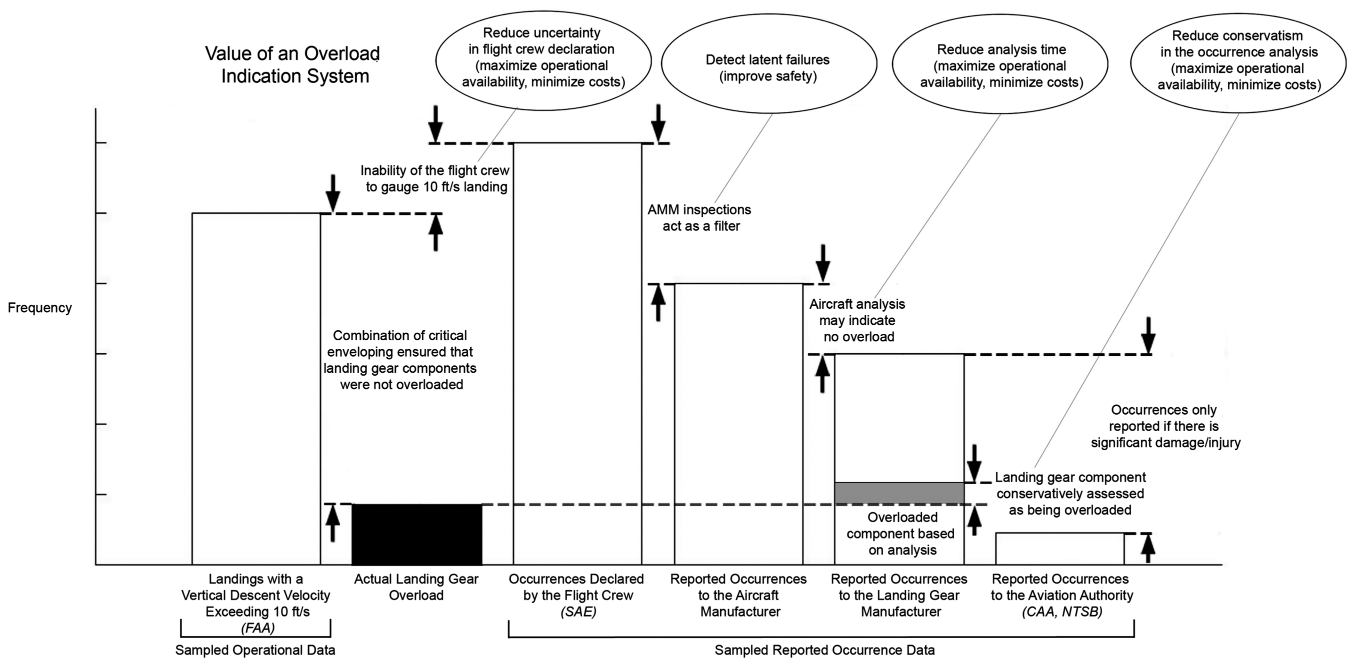

Fig. 12 Summary of sampled reported occurrence data and sampled operational data in relation to actual landing gear overloads.

hard landings. An overload indication system could reduce the uncertainty in the flight-crew declaration and make it possible to determine if there was or was not an overload. If flight crews are, in fact, overdeclaring hard landings, then aircraft may be grounded unnecessarily, and from the operator's perspective, there is an economic value in having an overload indication system that can increase the operational availability of the aircraft.

However, the reported occurrence data from the aviation authorities and the landing gear manufacturer indicates that hard landings are reported at a much lower frequency. The NTSB data suggest that those hard landings that are reported to the aviation authority as serious incidents or accidents occur at a frequency of 0.132 per million departures, and the CAA data tend to match the NTSB findings. The landing gear manufacturer narrow-body family of hard-landing data indicate that only approximately 1.627 hard-landing occurrences are reported per million departures, and the heavy-wide-body family of hard-landing data indicate that approximately 31.245 abnormal runway contact occurrences are reported per million departures. The SAE report suggests that virtually all hard landings reported by operators do not result in any structural damage. However, 30% of the narrow-body family of landing gear analyzed by the landing gear manufacturer following a reported hard-landing occurrence, and 39% of the heavy-wide-body family of main landing gear analyzed by the landing gear manufacturer following a reported abnormal runway contact occurrence had at least one component that was determined to have been overloaded.

If flight crews are overdeclaring hard-landing occurrences and there is a high frequency of landings above 10 ft/s as predicted by the Video Landing Parameter Survey, then there appears to be a discrepancy between the vertical descent velocity data and the reported occurrence data. If the frequency of hard-landing occurrences were higher than what is reported, the aviation industry would expect to see more in-service landing gear failures due to latent damage. However, the landing gear manufacturer's in-service failure data show that this is not the case. This discrepancy can be accounted for by two things: the first is that the data from the FAA Video Landing Parameter Survey are based solely on a vertical descent velocity threshold of 10 ft/s without taking into account the other critical enveloping flight parameters required to calculate the loads in the landing gear structure, and the second is that the occurrences reported to the CAA and NTSB and landing gear manufacturers have been filtered in the occurrence assessment process.

As discussed previously, a 10 ft/s vertical descent velocity defines the hard-landing threshold for an aircraft with other critical enveloping flight parameters such as aircraft gross weight, center of gravity, payload and fuel distribution, aircraft orientation, acceleration, shock-absorber servicing state, and tire-friction characteristics. If the critical enveloping flight parameters are reduced, the loads in the landing gear are reduced. For example, if the aircraft is landing with a 10 ft/s vertical descent velocity, but at a weight much less than its maximum landing weight (MLW), then the landing gear may not be overloaded. Reference [31], which reported on statistical data from 17 Boeing 737-400 (narrow-body) aircraft analyzed by the FAA's Operational Loads Monitoring Program for 11,721 flights, indicates the incremental vertical acceleration versus gross landing weight. Boeing correlated the incremental vertical acceleration with the 10 ft/s hard-landing threshold. The B737 hard-landing inspection threshold is an incremental vertical acceleration Δn_z of 1.1 g [32] at or below the MLW of 121,000 lb [31]. For this Δn_z, there was only one landing that exceeded the Δn_z threshold, and that was at a landing weight of approximately 10% less than the MLW. Therefore, although the FAA Video Landing Parameter Survey data predict that there are many landings above 10 ft/s, there may be other flight parameters that are not critical and that reduce the resulting landing gear loads. With the given FAA Video Landing Parameter Survey data, other critical enveloping flight parameters were not considered, and so it was not possible to determine if the landing gear was indeed overloaded at high vertical descent velocities.

Once the flight crew has made a hard-landing declaration, it is filtered through the occurrence assessment process, which aids in determining if the flight-crew declaration was warranted. Because the reported occurrence to the aviation authority and landing gear manufacturer has made it through this filtering, this may also explain why the reported occurrences have a lower frequency than that predicted by the FAA Video Landing Parameter Survey. However, there is some uncertainty and conservatism in the occurrence assessment process.

Following the hard-landing declaration, the aircraft operator maintenance crew consults the AMM to determine if the landing gear structural capability has been exceeded and initial visual inspections are carried out. However, the operator maintenance crew is only able to inspect for visible damage such as deformation, leaking fluid, and dents, and they are not able to determine if the landing gear structure had exceeded its structural capability and been left with a crack or residual stress. Therefore, an overload indication system would reduce risk if it was able to detect latent damage in the structure.

There is also uncertainty in the occurrence analysis performed by the aircraft and landing gear manufacturers. Vertical acceleration, one of the flight parameters used in the dynamic analysis of the occurrence, is sampled at 8 Hz. A landing, however, takes less than 125 ms. Therefore, it is possible that the peak vertical acceleration on the landing impact could be missed. To account for this uncertainty, factors of safety are added in the analysis. Because of these factors of safety, it is possible that the landing gear may be considered to be overloaded when it was not. Therefore, an overload indication system may reduce the number of landing gear considered to be unserviceable if the conservatism in the analysis process were reduced. There is an economic value if an overload indication system was able to reduce the conservatism in the occurrence analysis.

There is also a considerable amount of time spent by the aircraft and landing gear manufacturers performing the occurrence analysis to determine if the landing gear has been overloaded. During this time, the aircraft may be grounded, which has a significant economic impact on the aircraft operator. In addition, the aircraft and landing gear manufacturers must provide the resources to perform the analysis. Therefore, there is also value in an overload indication system if it is able to reduce the aircraft and landing gear manufacturers' analysis time.

The aviation industry data presented suggest that there is value in having an overload indication system that is able to detect static structural overloads and, equally, to detect when an overload did not occur, to maximize aircraft operational availability, minimize operator, airframe manufacturer and landing gear manufacturer costs, and reduce aircraft and landing gear risk.

V. Conclusions

The purpose of this paper was to investigate landing gear overloads based on available aircraft industry data. The reported occurrence data from the aviation authorities, the SAE, and a landing gear manufacturer and the operational data from the FAA provided the following conclusions:

1) The FAA Video Landing Parameter Survey data predict that there are between 455–848 landings with a vertical descent velocity greater than 10 ft/s per million departures in the narrow-body aircraft family and between 236–1279 landings with a vertical descent velocity greater than 10 ft/s per million departures in the heavy-wide-body aircraft family. These data do not take into account the other critical enveloping flight parameters that, along with the 10 ft/s vertical descent velocity threshold, result in a landing gear overload. Therefore, it is not possible to determine if there was a landing gear overload.

2) Flight crews are overdeclaring hard-landing occurrences.

3) The AMM inspections act as a filtering system in the occurrence assessment process to ensure that only occurrences in which the landing gear was actually overloaded are reported to the aircraft and landing gear manufacturers. However, there is uncertainty in the AMM inspections that could result in latent landing gear failures being undetected.

4) There is conservatism in the occurrence analysis performed by the aircraft and landing gear manufacturers, which may result in landing gear being considered unserviceable when they are, in fact, serviceable.

5) There is a significant amount of time spent performing the occurrence analysis by aircraft and landing gear manufacturers, which may result in an aircraft being grounded unnecessarily.

Based on these conclusions, there is a need for a landing gear overload indication system that is able to detect landing gear overloads and also to be able to detect when the landing gear has not been overloaded. An overload indication system would reduce risk, and may reduce costs and increase operational availability.

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