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An analysis of flight Quick Access Recorder (QAR) data and its applications in preventing landing incidents

Lei Wang [a,c,d], Changxu Wu [b,*], Ruishan Sun [d]

[a] Institute of Psychology, Chinese Academy of Sciences, 16 Lincui Road, Beijing 100101, China
[b] State University of New York at Buffalo, USA
[c] University of Chinese Academy of Sciences, 19 A, Yuquan Road, Beijing 100049, China
[d] Civil Aviation University of China, 2898 Jinbei Road, Tianjin 300300, China

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ABSTRACT

A long landing is one type of flight incident that will multiply the risk of a runway excursion. It occurs frequently but receives little attention in research due to difficulty in obtaining the real flight data. The aim of this paper is to discover key flight parameter features of long landing incidents by analyzing Quick Access Recorder (QAR) data and put forward prevention measures from the perspective of pilot operation at the same time. First, 73 flight performance parameter variables and 4 operation parameter variables were defined, covering major landing stages from 1500 ft to touchdown. Then 128 cases of selected QAR data were divided into two groups according to the threshold of identifying normal and long landing. Second, each flight parameter variable of these 128 flights was compared between groups and then the logistic and linear regression models were developed respectively to further examine the links between touchdown distance and these flight parameter variables. Third, potential flight operation causing performance difference of long landing incidents was also analyzed. Finally results indicate that the period of 200 ft to touchdown is the key stage of landing and flare is the most critical operation affecting touchdown distance. It is suggested that the pilot should inspect the ratio of descent rate and groundspeed carefully at the height of 50 ft and pilot's faster and steady pulling up columns is probably helpful for an excellent flare and landing. The findings are expected to be applied into flight operation practice for further preventing long landing incidents and even the runway excursion accidents.

1. Introduction

1.1. Long landing incident and QAR

A long landing, which is one type of flight incident, is defined as an aircraft's contact with the runway over the normal touchdown area. Touchdown distance is generally used as a standard baseline for judging whether a landing is long or not. Long landing itself would not lead to major loss of life directly but will increase the occurrence probability of runway excursion accident greatly. A National Aerospace Laboratory of The Netherlands (NLR) study revealed that if the landing is long, the landing overrun accident risk is 55 times greater than when it is not long [17]. Meanwhile, the runway taxiing time of aircraft will be prolonged if the landing is long and this will decrease efficiency of runway utilization and increase probability of runway conflict.

Quick Access Recorder (QAR) is a system which can acquire aircraft operational data easily and quickly. It includes an airborne equipment for recording data and a ground software station for storing and analyzing data. QAR could record all kinds of position parameters, movement parameters, operation and control parameters, and alarm information in the whole flight phase.

Generally long landing incident is monitored by using QAR data in most commercial airlines, but these data are also confidential for them. Meanwhile, it is not all aviation administrators who have enforced their carriers to install QAR equipment on every commercial jet. Therefore, QAR data have been rarely utilized into research. Civil Aviation Administration of China (CAAC) has implemented the program of Flight Operations Quality Assurance (FOQA) since 1997, with all commercial airplanes of Chinese airlines obliged to install QAR or a similar equipment. The practice has proved that QAR data were helpful for improving flight safety management and quality control. The real flight QAR data also provides us with a new way of analyzing landing incidents and further studying on landing safety.

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* Corresponding author.
E-mail address: changxu.wu@gmail.com (C. Wu).

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1.2. Landing safety issues

The final approach and landing is cited as the most important flight stage where the human pilot needs to deal with more operations, decision-making, and workloads than other stages [19,37]. Accident statistics have indicated that the approach and landing was the most dangerous phase of flight, in particular, the landing phase alone accounted for 23% of total fatal accidents occurring from 2003 to 2012, despite the fact that the landing phase accounts for just 1% of average flight time [7]. Although lots of new safety measures have been implemented throughout the last decade worldwide, landing accidents have not only continued, but have increased slowly, as shown in Fig. 1 [15].

Runway excursion, including runway overrun and runway veer-off, is the second most frequent type of fatal Approach and Landing Accidents (ALAs). Runway excursions have been considered as a major threat to aviation safety, as they always lead to major damage of aircraft and even loss of life. According to the Flight Safety Foundation [14], over the 14-year period from 1995 to 2008, 431 accidents (30%) of commercial transport aircrafts were runway-related, 417 of which (97%) were runway excursion and 712 people died in runway excursion accidents.

Runway excursions generally were caused by multilevel factors, such as a pilot's operations, the weather or runway conditions, and so on [2,22]. However, a large number of runways excursion accidents in landing phase shared a same feature of long landing [17,23,32]. Long landing is one of the most important contribution factors to runway excursion accidents [14]. Meanwhile referring to the Iceberg Theory and the Heinrich Accident Triangle [20,21], a runway excursion accident is the smallest visible part of ice above the surface of water, while long landing incidents are the large invisible part of ice beneath the surface of water which is always omitted. Statistics also showed that long landing incidents regularly accounted for the largest part of QAR exceedance incidents [34]. Long landing incidents should be afforded more concerns from aviation carriers and safety researchers. Research findings on long landings would be helpful not only for preventing incidents but also for runway excursion accidents.

Regarding landing safety issues, there have been much more researches focusing on visual factors affecting analysis [16,26,29,36], landing operation analysis [4,5,27,28], runway overrun risk modeling [24,32,38] and so on. However, special research on long landing incidents was relatively less. In particular, the literatures with performance and operation analysis based on real flight data were not found.

1.3. Aim and structure of this study

Aiming to find differences of flight parameters between normal landing and long landing, the real flight QAR data were collected and used to analyze performance feature of long landing incidents in this study. Meanwhile, the critical flight operation leading to these differences was also analyzed in further and related prevention measures on long landing incidents were put forward from the perspective of flight operation. The whole work of this study is made up of three parts with Sections 2–4.

2. Methods

The core task of this study is using QAR data to examine flight performance and flight operation characteristics of long landing incidents. For achieving this aim, methods of statistical analysis and modeling were introduced in Sections 2.3 and 2.4. Section 2.3 focuses on the analysis of flight performance parameters such as groundspeed, descent rate and so on. For further finding potential human factors causing flight performance parameter change, the flight operation and human performance variables would be analyzed in Section 2.4. Before analyzing, flight parameter variables of landing were defined and selected in Section 2.1 and collected QAR data were also processed with programing in Section 2.2.

2.1. Flight parameter definition and selection

Generally, aircraft in flight is affected by many factors such as external atmospheric environment (wind direction, wind speed, temperature, etc.), the aircraft itself (the position of all control surfaces, engine status, etc.), the pilot's basic capabilities and skills (cognitive reliability, flight operations skills, etc.) and the pilot mental state (fatigue, emotional status, etc.). These factors continue changing over time and bring an extremely complex influence on whole flight activity. Regardless of how these factors change, however, their effects ultimately are reflected in the change of aircraft attitude and kinematic parameters, including attitude angle, speed, and acceleration in three dimensions of longitudinal, vertical and lateral [12]. The kinematic analysis of flight is shown in Fig. 2. For studying flight performance of civil aircrafts, usually the linear motion along with longitudinal and vertical axes and rotation around longitudinal and lateral axes are concerned [8]. Particularly the flight phase of this study is the final landing stage, where, aircrafts always fly within a profile of landing glide path, and position change on the lateral axis is quite limited.

Fig. 1. Trend analysis plot for airlines fatal hull loss in landing phase [Data from Ref. [15]].

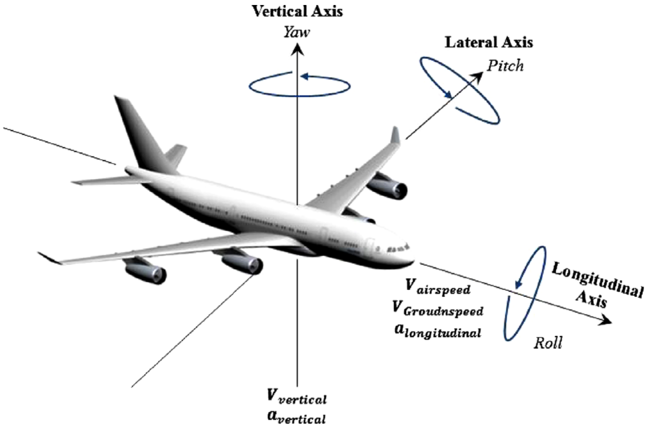

Fig. 2. Kinematic analysis of flight.

Table 1
Flight parameter variables.

Flight phases and points (ft)	Flight performance parameter variables			
	Attitude (average and StDev.)	Speed (average and StDev.)	Acceleration (average AND StDev.)	Velocity Ratio (Average)
1500–500	Roll angle, pitch angle	Descent rate, airspeed, groundspeed	Longitudinal acceleration, vertical acceleration	V Ratio (descent rate/groundspeed)
500–200	Roll angle, pitch angle	Descent rate, airspeed, groundspeed	Longitudinal acceleration, vertical acceleration	V Ratio (descent rate/groundspeed)
200–50	Roll angle, pitch angle	Descent rate, airspeed, groundspeed	Longitudinal acceleration, vertical acceleration	V Ratio (descent rate/groundspeed)
50	Roll angle, pitch angle	Descent rate, airspeed, groundspeed	Longitudinal acceleration, vertical acceleration	V Ratio (descent rate/groundspeed)
50–0	Roll angle, pitch angle	Descent rate, airspeed, groundspeed	Longitudinal acceleration, vertical acceleration	V Ratio (descent rate/groundspeed)
0	Roll angle, pitch angle	Groundspeed	Longitudinal acceleration, vertical acceleration	

Therefore we focused on analyzing longitudinal and vertical kinematic parameters in this study.

Meanwhile, aircraft flying can be seen as a centroid motion of a rigid body. According to the rule of velocity, a vector can be decomposed, where

$$dh = dv_{vertical}\,dt \tag{1}$$

$$ds = dv_{longitudinal}\,dt \tag{2}$$

And

$$\frac{dh}{ds} = \frac{dv_{vertical}}{dv_{longitudinal}} \tag{3}$$

In the above equations, longitudinal displacement *s* is correlated with the ratio of vertical and longitudinal velocity when height *h* is given. Therefore, another variable called Velocity Ratio (*V Ratio*) which represented the ratio of descent rate and groundspeed was defined in this study. Finally, the types of attitude and kinematic parameters we chose include roll angle, pitch angle, descent rate, airspeed, groundspeed, longitudinal acceleration, vertical acceleration, and velocity ratio.

According to the accident chain theory [6,20,31], in most cases, accidents are the consequence of an interlocking series of events; as long as the event of one link had been effectively controlled, the accident would not happen. As far as long landing incidents are concerned, the final consequence is touchdown distance exceeding the threshold; however, it might be caused by inappropriate operation or other factors at a previous flight phase. The flight operation of final approach and landing always initiated from the height of stabilized approach point. This height is generally set between 500 and 1500 ft [9,13]. Therefore, we chose the flight process from 1500 ft (radio height) to touchdown point for analyzing. This process was divided into four phases and two critical points, and statistical variables (average and standard deviation) of flight attitude and kinematic parameters in these phases and points were selected for further analysis. The 0 ft point referred to the touchdown point of one landing. The final selected flight performance parameter variables, a total of 73, are shown in Table 1. The units of these variables are listed in Table A1 of Appendix A1.

Lots of researches have indicated that pilot error is the primary cause of over 60% flight accidents. Pilots' operation performance is one of the most important factors in directly affecting flight safety [11,18]. Particularly in the final landing process, pilots often take over aircrafts after visually finding runway and passing the Decision Height (DH) point. The final visual landing is generally finished by human control and pilots are required to change the aircraft attitude in a few seconds for a safe and smooth landing. This critical maneuver operation is called flare, which involves lifting of the nose to both land the aircraft on the main gear first by pulling up control column and decrease sink rate and vertical load by closing throttle at landing. Flare operation would make large influences on final landing performance and also is one of the most skilled operations in flight [3]. Therefore, the pilot operation below 200 ft, especially the flare operation was selected as the main subject for further analysis in this study. The selected operation parameter variables are shown in Table 2.

Table 2
Flight operation parameter variables.

Name	Parameter name in QAR data	Units
Flare height	RADIO HEIGHT	ft
Flare time	–	s
Throttle resolver angle	SELTD TRA FILTERED	deg
Control column position	CONTRL COLUMN POSN	deg

Among that the *Flare Height* meant the height of initiating flare operation and *Flare Time* means the total time of aircraft flying from flare initial point to touchdown point. *Throttle Resolver Angle* and *Control Column Position* are two parameters reflecting flare operation process directly.

2.2. QAR data collection and processing

The data sampling frequency can reach as high as 16 Hz in a modern QAR equipment. Airlines monitor QAR data based on requirements of different aircraft types and regulations. It is called a QAR exceedance incident if there is a parameter exceeding normal range. Exceedance incidents would not lead to severe accidents in all cases, but the risk they bring existed all the time. Long landing and hard landing are two examples of the most common exceedance incidents.

The QAR data in this study were collected from six commercial aircrafts which are belong to the same type of common commercial aircrafts with more than 100 seats.[1] The data covered all normal and exceedance flights of these six aircrafts from the 1st of January to the 30th of June in 2010. First, descriptive statistics on total flights were finished and 128 flight samples with visual landing operation and less influence of weather were selected. Then, QAR data files of these 128 flights were downloaded from QAR ground station. The original data is a Comma Separated Value (CSV) file with thousands of rows and columns. Therefore, Visual Basic for Applications (VBA) programing functions in Microsoft Excel was applied and eleven columns of original QAR data of every file were refined as Table A1 in Appendix A1. Finally we also compiled the VBA program to calculate 77 parameter variables and touchdown distance of each flight sample.

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[1] For legal concern, the information of the exact type of aircrafts is not able to be released in this paper.

2.3. Flight performance analysis

2.3.1. Difference analysis between normal and long landing

128 Sample flights were divided into two groups with 66 cases of normal landing (Group 1) and 62 cases of long landing (Group 2). QAR data of 66 normal landing events and 62 long landing incidents were regarded as two groups of independent samples. For the aim of observing dynamic change of flight performance parameter variables in landing phase and their differences between two groups, the altitude of 1500–0 ft was divided into four flight levels (1500–500–200–50–0 ft) and selected flight parameter was measured in every level. This could be seen as a repeated measuring process. The usual method of one way ANOVA, such as a t test, is not applicable in this case because the correlation existed in flight parameter variables that always change with height and time. Therefore, the multivariate analysis process of the general linear model was introduced to compare the differences in the two groups. Firstly the sphericity test was carried out for checking whether one category of repeated measuring data satisfied the condition of the Huynh–Feldt sphericity test. According to the results, the correlation of variables did not exist when there was a $p > 0.5$. In this case, the one way ANOVA in repeated measurement was used. When $p < 0.5$, the multiple variance analysis was carried out and the post hoc test was finished at the same time. The difference of flight performance parameters could be found in the final results of this process.

2.3.2. Logistic regression analysis of landing event type

Logistic regression is a type of a predictive model that can be used when the target variable is a categorical variable with two categories ([1]). Aiming to find out key flight performance parameters causing long landing incidents, the logistic regression model on long landing incidents was developed. In this study, the occurrence of long landing was defined as a binary variable, where the value is 1 if it happened and 0 if it did not happen. Based on results of difference analysis in Section 2.3.1, 32 flight performance parameter variables of two groups in difference level of sig. 0.05 were included in the model as original covariates. The forward stepwise method was then performed. The likelihood ratio test (χ^2 difference) testing the change in -2LL (*log likelihood*) between steps was utilized to determine automatically which variables to add or drop from the model. The final predictor variables and coefficients of the model were obtained in the stepwise process. Simultaneously, the effectiveness of the model was also checked and discussed.

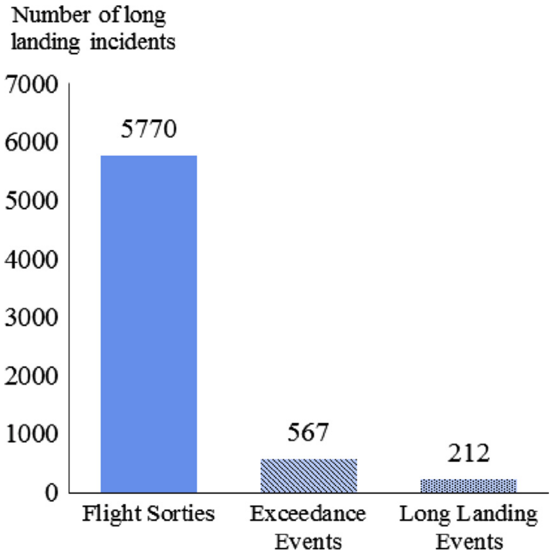

Fig. 3. Frequency statistics of long landing incidents.

2.3.3. Multiple linear regression of touchdown distance

The multiple linear regression attempts to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to observed data. In order to further analyze the correlations between touchdown distance and the other 73 performance variables, a multiple linear regression model was developed. Considering the probable collinearity between independent variables, the stepwise regression method was used for eliminating and the stepping criteria were based on probability of F ($F \leq 0.5$ for entering and $F \geq 0.10$ for removal). First, the variable most closely correlated with the dependent variable entered into the model. Then, the next most correlated variable was entered into regression, and explanatory variables were kept adding until no further variables were significant. In this approach, it is possible to delete a variable that has been included at an earlier step; however, after doing so, it is no longer significant, given the explanatory variables that were added later. Finally, the effectiveness of the model was analyzed.

2.4. Flight operation analysis

For the aim of studying the flight operation characteristics of long landing incidents and their correlations with landing performance, the method of variance analysis was used to find the difference of flare operation between normal landing and long landing, including their parameter differences at flare initial point and in the whole flare process. Then the correlation analysis was carried on between flare time and touchdown distance. The altitude of 200–0 ft was divided into four flight levels (200–150–100–50–0 ft) and two selected flare operation variables were measured at each level. The multivariate analysis process of the general linear model was introduced to compare the differences in the two groups. Especially, the variables *Control Column* and *Throttle Resolver Angle* were analyzed in detail and presented in this study.

3. Results

Three parts of results were presented in this section. First, results of descriptive statistics on long landings would make us know more about the basic feature of long landing incidents. Then, results of flight performance and human operation analysis would indicate the further parameter characteristics and potential causing factors of long landing.

Table 3
Statistics on touchdown distance.

Type	N	Mean	SD	Percentiles							p (AD)
				5	10	25	50	75	90	95	
Normal landing	66	1992.27	356.65	1378.46	1522.83	1739.50	2045.41	2248.27	2444.62	2523.68	0.204(0.498)
Long landing	62	3149.51	329.67	2659.38	2724.72	2867.69	3108.52	3417.39	3579.80	3741.24	0.072(0.682)

3.1. Descriptive statistics

3.1.1. Frequency statistics of long landing incidents

The six aircrafts flew 5770 flights in six months. Of this, there were 567 exceedance incidents, accounting for 9.8% of all flight sorties, as shown in Fig. 3. Among this, long landing incidents occurred 212 times and were the most frequent exceedance incidents, a proportion as high as 37.4%.

3.1.2. Statistics on flight parameter variables

73 Flight performance parameter variables of these 128 flights were calculated and the descriptive statistics results are as shown in Table A2 in Appendix A2. Differences of some variables could be found directly from the table, such as *Descent Rate Average* 50–0 ft and *V Ratio* 50–0 ft.

3.1.3. Statistics on touchdown distance

The *Touchdown Distance* was defined as the horizontal distance from the radio altitude of 50 ft to touchdown point in landing process [10]. Because QAR could not record the height point when passing runway end, it is easier to calculate touchdown distance from the height of 50 ft. It is always used as a standard baseline for judging whether a landing was long or not. Based on common statistical results of QAR data and monitoring criterion of aviation operators [30,34], the threshold of determining long landing for this aircraft type in this study was set as 2600 ft. Statistics on *TD* of these two groups of samples were made and results are shown in Table 3. *TD* mean of normal landing samples is 1992.27, while *TD* mean is 3149.51 for long landing samples. The difference between the two groups is significant ($t = -19.029$, $p < 0.001$). The *TD* for 75% of normal landing is in the limitation of 2248.27 ft and for 75% of long landing is shorter than 3417.39 ft.

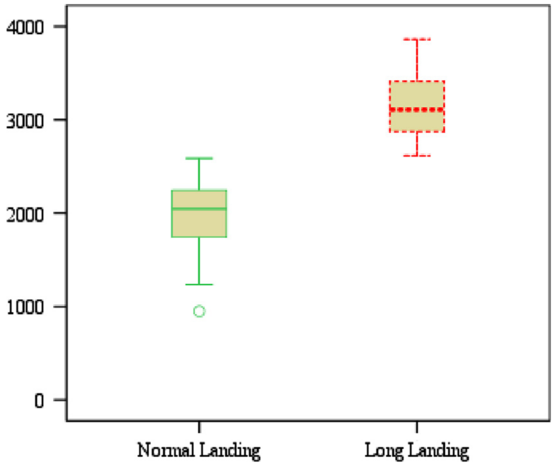

Fig. 4. Boxplot of touchdown distance.

Results of the Anderson Darling test indicated that the variable *TD* was basically subjected to normal distribution and boxplots of this variable are shown in Fig. 4.

3.2. Results of flight performance analysis

3.2.1. Results of difference analysis

Results of all sphericity tests showed that the significant correlations existed in all categories of flight parameter variables (all $p < 0.01$). For more details of these results, see Table A3 in Appendix A3. The next step of multivariate analysis results showed that 32 significantly different pairs of variables were at the level of sig. 0.05, 23 variables were at the level of sig. 0.0, and 13 variables at sig. 0.001. The significantly different variables at the level of sig 0.001 are shown in Table 4.

Based on the final 13 significant variables in Table 4, we can conclude that descent rate (P_1, P_2 and groundspeed (P_4, P_5, P_6, P_7 and P_8) are the two most important factors affecting landing distance. In particular, the difference of the variable groundspeed is very obvious and covering the whole landing stage from 500 ft to ground. It is shown in Fig. 5. This result is also supported by the previous kinematic analysis in methodologies.

In particular, it is noted that there are two flight attitude variables (P_9 and P_{10}) showing significant differences in Table 4. One is *Roll Angle StDev*. 1500–500 ft reflecting the differences of roll standard deviation in 1500–500 ft. In fact, in the whole process of 1500 ft to touchdown, both the roll (average value) and roll change (standard deviation value) of normal landings are greater than those in long landings (see Fig. 6). Another important variable is *Pitch Angle* 0 ft: its value is 0.973 ± 0.387 for normal landing and 1.172 ± 0.284 for long landing.

3.2.2. Results of logistic regression

Table 5 shows the estimated parameters of the logistic model in predicting landing type (long landing or normal landing). Seven predictors were included in the final logistic regression model. The overall predictive percentage of the model was 87.7%. The sensitivity was 89.9% and specificity was 86.6%.

As shown in Table 5, the Wald criteria indicates that *Descent Rate Average* 50–0 ft, *Groundspeed StDev.* 50–0 ft and *Longitudinal Acceleration StDev.* 200–50 ft significantly contribute to the occurrence of long landings ($p < 0.01$).

A test of the full model against a constant-only model was significant ($\chi^2(7, N = 128) = 127.944$, $p > 0.001$), indicating that the predictors as a set reliably distinguished between normal and long landing. Nagelkerke's R^2 of 0.835 indicated a relatively strong relationship between predicting variables and landing event type.

3.2.3. Results of linear regression

The stepwise linear regression was also performed and there were six significant predictors included in the final regression model. The R^2 of the final model achieved 0.746, which indicated

Table 4
Means comparing between normal events and exceedance events.

No.	Parameter variables	p	No.	Parameter variables	p
P_1	Descent Rate Average 50–0 ft	0.000	P_8	Groundspeed StDev. 50–0 ft	0.000
P_2	Descent Rate StDev. 50–0 ft	0.000	P_9	Roll Angle StDev. 1500–500 ft	0.001
P_3	Airspeed StDev. 50–0 ft	0.000	P_{10}	Pitch Angle 0 ft	0.001
P_4	Groundspeed Average 500–200 ft	0.000	P_{11}	Longitudinal Acceleration 50 ft	0.000
P_5	Groundspeed Average 200–50 ft	0.000	P_{12}	V Ratio 50 ft	0.001
P_6	Groundspeed 50 ft	0.000	P_{13}	V Ratio 50–0 ft	0.000
P_7	Groundspeed Average 50–0 ft	0.000			

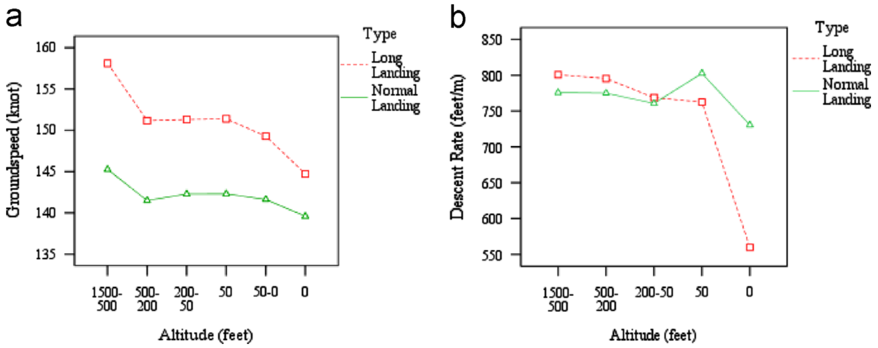

Fig. 5. The descent rate and groundspeed at different attitudes.

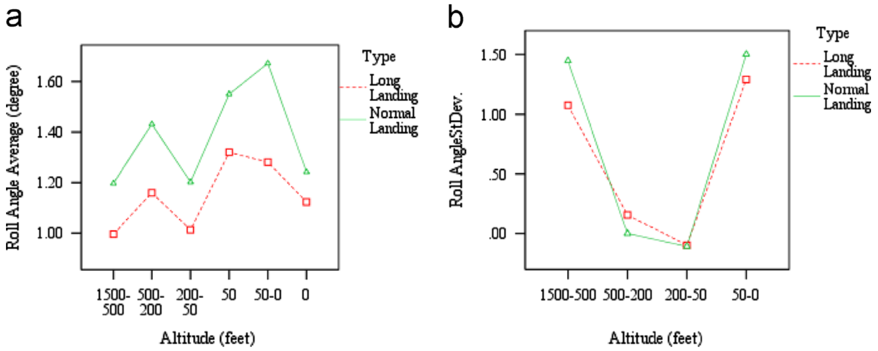

Fig. 6. Difference comparison of flight parameters (roll angle average and standard deviation).

Table 5
Logistic regression values of the predicting variables.

Predicting variables	Wald (χ^2)	Adjust OR[a]	95% C.I. for OR[b]
Descent Rate Average 50–0 ft	9.035**	0.978	0.964–0.992
Groundspeed Average 200–50 ft	0.7611;#	1.055	0.935–1.192
Groundspeed StDev. 50–0 ft	8.973**	7.414	1.999–27.500
Groundspeed 0 ft	5.381*	1.250	1.035–1.510
Pitch Angle 0 ft	5.479*	17.121	1.587–184.688
Longitudinal Acceleration StDev.200–50 ft	9.775**	0.000	0.000–0.000
V Ratio 500–200 ft	4.154*	0.127	0.018–0.924
Constant	5.324*	0.000	

* $p < 0.05$.
** $p < 0.01$.
\# $05 < p < 0.10$ and otherwise $p \geq 0.10$.
[a] Adjust ORs (odds ratio) predicted long landing.
[b] Confidence interval.

Table 6
Coefficients of model.

No.	Variables	Unstandardized coefficients		Standardized coefficients	Sig.	Collinearity statistics	
		B	Std. error	Beta		Tolerance	VIF
	Constant	2439.234	599.628		0.000		
x_1	V Ratio 50–0 ft	−285.788	41.683	−0.485	0.000	0.420	2.382
x_2	Descent Rate StDev. 50–0 ft	1.767	0.363	0.270	0.000	0.714	1.401
x_3	Groundspeed StDev. 50–0 ft	153.398	38.370	0.269	0.000	0.837	1.194
x_5	Pitch Angle Average 200–50 ft	−196.322	48.635	−0.219	0.000	0.684	1.461
x_1	Roll Angle Average 200–50 ft	−214.211	67.865	−0.158	0.002	0.463	2.158
x_1	Groundspeed Average 200–50 ft	9.111	3.453	0.134	0.009	0.809	1.235

that the relatively good fitness of this linear model ($F(6,121)=59.304$, $p<0.001$). The linear regression model was expressed as the following equation:

$$\mathrm{TD}=2439.234-285.788x_1+1.767x_2+153.398x_3 \\ -196.322x_4-214.211x_5+9.111x_6 \quad (4)$$

The standardized regression model, which could present this correlation directly, was introduced and written as the following equation:

$$Z_{TD}=-485Zx_1+0.27Zx_2+0.269Zx_3-0.219Zx_4-0.158Zx_5 \\ +0.134Zx_6 \quad (5)$$

In Table 6, all of the coefficients are highly statistically significant ($p<0.01$). The variable x_1 (*V Ratio* 50–0 ft) carries the biggest one (0.485) and has the greatest impact on touchdown distance. This point is consistent with the results of difference analysis.

Finally, the model diagnostics were performed. The Durbin–Watson test showed that there were no autocorrelations existing among predictors (Durbin–Watson=2.005). All VIF coefficients of these six predictors were less than three which meant that collinearity level of independent variables was acceptable. A *P–P* plot demonstrated that the regression standardized residual was basically subjected to a normal distribution. It meant that the normality assumption of regression was not violated.

Table 7
Statistics on flare height and time

Group	*N*	**Flare height** (*M* ± *SD*, ft)	**Flare time** (*M* ± *SD*, s)
Normal landing	66	53.394 ± 21.853	7.894 ± 1.882
Long landing	62	51.097 ± 25.099	10.708 ± 2.550

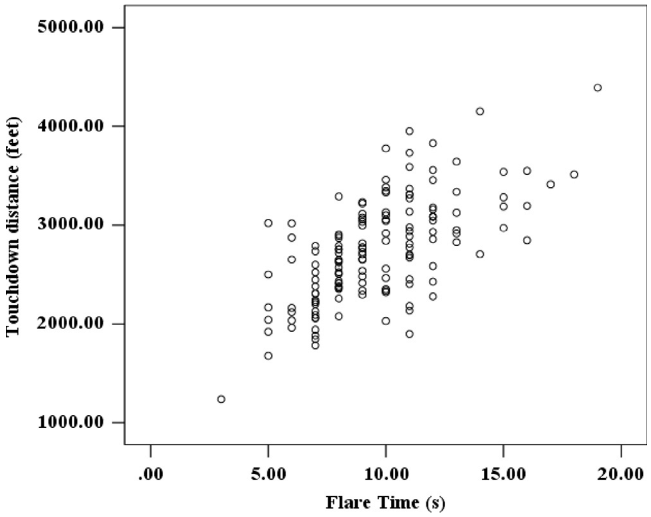

Fig. 7. Correlations between flare operation time and touchdown distance.

3.3. *Results of flight operation analysis*

The descriptive statistic on flare initial height and operation time of the two groups is shown in Table 7.

As seen in Table 7, there is no significant difference between the flare initial height of two groups, which are both around 51 ft ($F(1,126)=0.036$, $p=0.581$). However, their flare time shows that the long landing group is clearly significantly longer than normal group ($F(1,126)=50.932$, $p<0.001$).

The correlations between flare operation time and touchdown distance can be found in Fig. 7. The flare time affects touchdown distance positively and the correlation coefficients could reach to 0.659.

In Fig. 8, the control column and throttle change greatly after passing 50 ft (flare operation initial point). There was no difference between the control column of the two groups ($F(1,126)=0.298$, $p=0.672$). There was also no difference found for throttle operation before 50 ft. The main difference was reflected after a flare starting when the pilot begins to decrease thrust. Compared with normal landing, the throttle change of the long landing group was much higher and the result of the one-way ANOVA is $F(1,126)=48.382$, $p<0.001$.

4. Discussion

In this section, results of flight performance analysis (Section 3.2) is discussed in Section 4.1 and results of flight operation analysis (Section 3.1) is discussed in Section 4.2. Then all findings of two parts are discussed together in Section 4.3. Meanwhile the potential contributions and limitations of this study are also concluded in Section 4.3.

4.1. *Discussion on flight performance analysis*

Long landing incidents make up the largest percentage of all exceedance incidents at 34.7% and would greatly increase the risk of runway excursion accident in landing phase. The first part of work we finished was to examine flight performance feature of long landing incidents. The results indicated that most of flight performance parameter variables with differences appeared in the stage of 50 ft to touchdown (10 variables except for P_4, P_5 and P_9). Theoretically speaking, many flight landing operations, including flares, need to be finished by pilots just in a few seconds [25]. Currently, most commercial aircrafts have been equipped with an advanced autopilot system and automatic Instrument Landing

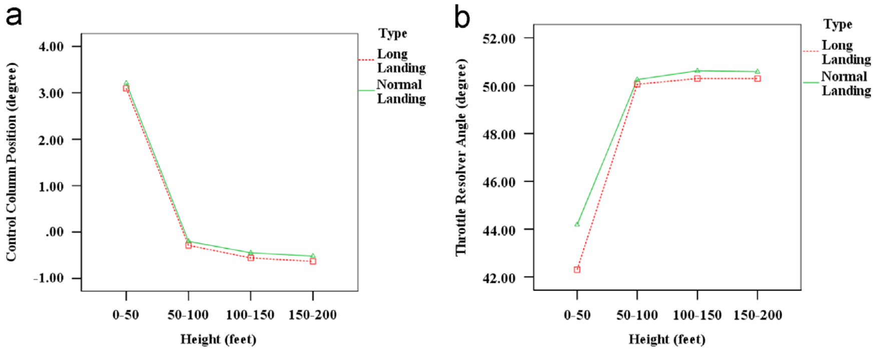

Fig. 8. Difference analysis of control column and throttle resolver angle.

System (ILS). These systems are making great effects in most of level off and gliding flight stage, especially there is a low runway visual range, but they were not fully used in common visual landing operation of flight below 60 m [35]. While aircraft in low speed flight is sensitive to wind and other weather factors, any small configuration changes during this stage could easily complicate the decision of the proper action to take at the decision point. Therefore, this phase is the most important operation stage for controlling touchdown distance or other landing performance variables. And there is no doubt that both descent rate and groundspeed (P_1, P_2, P_4, P_5, P_6, P_7 and P_8) are the crucial parameter variables. This point was confirmed by feedback from pilots (Appendix A4). They pointed out that pilots generally take over aircrafts after visually finding runway below 500 ft in the final landing phase.

There were two flight attitude variables showing significant differences, one is *Roll Angle StDev.* 1500–500 ft and the other is *Pitch Angle* 0 ft. The difference of roll angle between normal and long landing groups could be explained by the tracking performance theory [37]; aircrafts should fly with the smallest route deviation in low airspace and pilots generally operate aircrafts with highly augmented control. This meant that pilots should amend roll angle continuously and do their best to maintain the glideslope profile. Contrarily, our results indicated that the roll angle changed only a little for long landing. The difference of pitch angle between the two groups was not significant when only considering the mean of angle at touchdown point (0 ft). It is probably because pilots always want to increase the pitch angle for decreasing vertical load at touchdown, but this operation probably would increase risk of tail rubbing to some extent. Meanwhile, we noted that these pitch angles at touchdown point in our samples were around 1°, which is less than theoretical value and was always in the range of $3–6^\circ$. The possible reason is that the pitch angle we used here is an average value at touchdown second point rather than an instantaneous value (QAR on this type of aircraft could record 4 pitch angle values in 1 s).

In final regression results, the logistic regression model indicated the three most important factors were *Descent Rate Average* 50–0 ft, *Groundspeed StDev.* 50–0 ft and *Longitudinal Acceleration StDev.* 200–50 ft. The multiple linear regression model showed that the variable x_1 (*V Ratio* 50–0 ft) carried the largest weight (0.485) and had the greatest impact on touchdown distance. These results are consistent with the previous flight kinematics analysis and the difference analysis. The flight kinematics analysis has indicated that longitudinal distance was correlated with the ratio of vertical and longitudinal velocity when height was given. The results of variance analysis also proved that descent rate and groundspeed were the two most important parameters controlling long landing. Of the remaining predictive variables in the regression model, we found that there were several from the phase of 200–50 ft, including *Roll Angle Average* 200–50 ft, *Pitch Angle Average* 200–50 ft and *Groundspeed Average* 200–50 ft. These variables covered attitude change and speed change. It illustrated that 200–50 ft was also an important operation phase and that pilots should pay close attention to each of these flight parameters, especially the vertical acceleration and attitude parameters.

Combined with results of the difference analysis and regression analysis in this study, the period of 200 ft to touchdown is considered as the critical stage of landing. It is strongly suggested that pilots should focus on the control of attitude (roll and pitch angle), groundspeed, and descent rate, especially inspecting the variable of *V Ratio* at the final 50 ft. This *V Ratio* of normal landing and long landing were significantly different, one being 5.150 ± 1.093 (normal landing) and the other 3.748 ± 0.645. This meant that the long landing would probably happen if the *V Ratio* was smaller than 4.

4.2. Discussion on flight operation analysis

Even though other factors like weather will affect flight performance, pilot's operation always plays the decisive role on controlling aircraft. The correlation between touchdown distance and flare operation time was found in the correlation analysis. This meant that the flights with longer flare time have a longer touchdown distance. From this, we can infer that pilots probably prefer to prolong flare time for avoiding hard landing. Because hard landing is attracting more attention from passengers who normally require a more comfortable touchdown feeling and airlines also highlight more on hard landing monitoring and punishment. Pilots therefore prefer to land more softly. However, we have demonstrated that the risk of runway overrun is increased with prolonged flare time and the occurrence of long landing.

Through analyzing the operation parameter differences in the process of 200 ft to ground, the change trend of variables was expected to be found. As far as the two flare operation variables (control column and throttle) are concerned, the column change degrees and trend of the two landing groups both remained constant in this whole flight stage. However we need to note that their time of operating the column was definitely different, which means that the speed of pulling on column was significantly different. The normal landing group was faster than long landing group. Meanwhile, the throttle operation between long landing and contrast group represented the difference in flare process (50–0 ft). The value change of long landing was greater than normal landing, which meant that the throttle of normal operation was closed more softly. The feedback from pilots also confirmed the importance of flare operation (Appendix A4).

Based on the findings of flight operation analysis, following landing operation suggestions were summarized and expected to have some positive implications on improving flight training and operation. Firstly, pilots should establish a stabilized approach if they want a stabilized landing in 200 ft to touchdown. This requires that the aircraft must be in an approved landing configuration (including circling configuration, if appropriate), must maintain the proper approach speed, and must be established on proper flight path. Then, aircrafts should keep flying with 3° of glideslope, appropriate speed and trimming, and stable descent rate. The flaps and landing gear should be in the right position. Pilots are suggested to use throttle to revise reference speed and need to keep the feeling of a slight push on the control stick before entering 50 ft height. At a height of 50 ft, pilots should confirm the altitude, groundspeed, and *V Ratio* and start to pull control stick slowly and slightly. The descent rate would be decreased and aircraft would pitch up. The touchdown attitude would be required to be finished at final flare point (approximately at 1 m) and the throttle be pulled back to idle softly after level off. Finally, the aircraft is expected to touchdown with a pitch angle of $3–6^\circ$.

4.3. Discussion in general

In current aviation safety research, there have been lots of products focusing on aviation accidents where their occurrence rate has been decreased to quite a low level in most regions of the world. However, unsafe incidents have often been ignored probably due to their severity is not as high as accidents. Runway excursion is a typical accident in the landing phase. Though many studies regarding the runway excursion have been conducted, most of them were based on accident investigations, models, or experiments rather than flight data [32]. Long landing incident could increase the risk of runway excursion accidents greatly. It occurred frequently and sometimes led to runway excursion accidents. However, it has rarely been analyzed in detail because real flight data is hard to be obtained from air operators [34]. Our research on related statistics revealed that the occurrence rate of QAR exceedance incidents was quite high and nearly reached 10% of total flight sorties. Among that, long landings were the most frequent exceedance incidents and accounted for one-third of the total incidents. Coincidently, runway excursion accidents are the third most frequent type of all aviation accidents. The latent interrelations between them verified the Heinrich Accident Triangle rule and theory [20]. Based on flight QAR data, this study provided a new way to analyze flight incidents in the landing phase by considering a history of individual instances recorded during flight as being a set of interrelated variables, which could together, over time, be the cause of such unsafe incidents, as is the concept of the event chain theory.

This study examined the flight performance and operation characteristics of long landing incidents by analyzing QAR data. Results showed that significant differences existed in 32 defined flight parameter variables between normal landing and long landing ($p < 0.05$). In particular, descent rate and groundspeed were two most significant factors ($p < 0.001$). The regression analysis results illustrated that the period of 200 ft to touchdown is the key stage of landing and suggested that the pilot needs to inspect the ratio of descent rate and groundspeed carefully at the height of 50 ft. Meanwhile flare is the most critical operation affecting touchdown distance and pilot's faster pulling up columns and softer throttle closing are helpful for improving landing performance and safety. Lots of studies also have indicated that pilots' operation performance is one of the most important factors in directly affecting flight safety [18]. In the final landing and touchdown phase, the aircraft is generally operated by pilots themselves. An experienced pilot with sufficient training will definitely perform better than other ones when there is an emergency in flight. These findings in this study are expected to make some positive implications for improving pilot training, operation and landing safety in further.

The probability of landing accidents is increased with the occurrence of landing incidents. The findings of this study would be meaningful for predicting the risk of landing overrun. Current probabilistic models to estimate accident risk (due to runway overrun and landing undershoot) have been built on historical accident data, including several factors such as runway surface conditions, runway distance availability and so on [32]. The precision and predictability of this model would be greatly improved if the flight parameter and pilots' operation characteristics of long landings could be considered in. A more applicable tool for predicting the risk of abnormal landings is expected to be developed for supporting pilots' decision-making and actions and preventing landing incidents and accidents in future.

Human performance and reliability in flight deck plays and will continue to play a critical role in improving aviation safety [33,35]. The exterior flight performance and critical flare operation features of long landing incidents were analyzed in this study. However, the underlying reason and formation mechanism that led to these operations were not referred exactly. In the coming future work, a more qualitative mathematical model is expected to be developed for explaining interrelationships between human operation variables and exterior performance variables. The quantitative relationship of control column change and flight performance will be expressed in this model and the landing incidents also could be predicted through this model. Meanwhile, cognitive mechanism of flare operation will be studied in our future experiment research. Then more suggestions on optimizing flight operation and improving pilot reliability for avoiding unsafe incidents in landing phase will be found.

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Appendix A1. Names and units of QAR parameters.

See Table A1.

Appendix A2. Descriptive statistics of all flight performance variables.

See Table A2.

Appendix A3. Results of the sphericity test.

See Table A3.

Appendix A4. Results of interview with pilots.

For further confirming the rationality of these analysis results in this study, we interviewed 6 commercial pilots who both have flight experience over 2000 h. Generally following 5 questions were designed for them:

A. Which stage do you need to pay more attention resources in the whole flight process?
B. Which time point is the most important for a good landing?
C. Which flight parameter is the most important for controlling long landing?
D. Do you think the flare operation will make influences on final landing performance?
E. How do you make a successful flare?

Their feedbacks for Question A basically focused on approach and landing stage (5 pilots). There were 3 answers for Question B, which respectively were time point at height of 500 ft, 50 ft and flare maneuver. For Question C, descent rate and groundspeed were uniformly regarded as two most important flight parameters of avoiding long landings. For Question D, both of their answers were positive and the importance of flare operation was also confirmed by them. For Question E, most of them pointed out that a stabilized and matched operation on control column and throttle is very helpful for a perfect flare.

Table A1
Names and units of QAR parameters.

No.	Name of QAR parameters	Abbr.	Unit
1	Time	–	s
2	Air/ground	AGND	–
3	Altitude (1013.25 Mb)	ALT	ft
4	Radio height Deu-x	RALT	ft
5	Pitch att	PITCH	deg
6	Roll	ROLL	deg
7	Captdisplay groundspeed	GS	Knot
8	Computed airspeed	CAS	Knot
9	Longitudinal acceleration	LONG	g
10	Vertical acceleration	VRTG	g
11	Descent rate		ft/min

Table A2
Descriptive statistics of all flight performance variables.

Flight parameter performance variables		Normal landing events ($n=66$)		Long landing incidents ($n=62$)	
		Mean	SD	Mean	SD
Descent Rate	Average 1500–500 ft	775.795	79.269	800.818	67.416
	Average 500–200 ft	774.978	101.943	795.465	64.423
	Average 200–50 ft	760.701	101.635	768.851	75.295
	50 ft	802.727	160.226	762.581	138.871
	Average 50–0 ft	730.659	170.230	559.804	100.979
	StDev. 1500–500 ft	151.685	109.073	130.536	137.081
	StDev. 500–200 ft	134.686	57.547	110.464	60.814
	StDev. 200–50 ft	135.616	65.106	113.767	61.224
	StDev. 50–0 ft	222.064	91.164	317.560	91.636
Airspeed	Average 1500–500 ft	149.703	13.846	151.335	19.683
	Average 500–200 ft	147.236	5.469	147.979	4.705
	Average 200–50 ft	147.495	5.475	148.197	5.074
	50 ft	146.318	5.596	148.319	4.960
	Average 50–0 ft	144.644	5.761	145.190	5.361
	StDev.1500–500 ft	3.433	3.846	3.242	6.502
	StDev.500–200 ft	1.809	0.874	1.600	1.248
	StDev.200–50 ft	1.902	1.067	1.491	1.009
	StDev. 50–0 ft	2.698	1.170	3.450	0.948
Groundspeed	Average 1500–500 ft	145.256	31.518	158.110	38.754
	Average 500–200 ft	141.495	10.778	151.156	8.118
	Average 200–50 ft	142.287	10.106	151.298	7.360
	50 ft	142.303	10.015	151.395	7.367
	Average 50–0 ft	141.627	9.936	149.287	7.598
	0 ft	139.591	10.256	144.726	7.872
	StDev. 1500–500 ft	4.338	9.047	4.650	13.169
	StDev. 500–200 ft	1.041	0.708	0.795	0.757
	StDev. 200–50 ft	0.644	0.444	0.624	0.668
	StDev. 50–0 ft	0.972	0.678	2.537	1.066
Roll Angle	Average 1500–500 ft	1.197	0.438	0.996	0.410
	Average 500–200 ft	1.431	0.761	1.160	0.635
	Average 200–50 ft	1.202	0.549	1.013	0.419
	50 ft	1.550	0.618	1.320	0.606
	Average 50–0 ft	1.672	0.738	1.282	0.687
	0 ft	1.242	0.622	1.123	0.543
	StDev. 1500–500 ft	1.448	0.652	1.075	0.586
	StDev. 500–200 ft	0.001	1.798	0.157	1.479
	StDev. 200–50 ft	−0.107	1.138	−0.097	1.207
	StDev. 50–0 ft	1.502	0.707	1.293	0.762
Pitch Angle	Average 1500–500 ft	1.124	0.412	0.990	0.379
	Average 500–200 ft	1.172	0.524	1.019	0.520
	Average 200–50 ft	2.158	0.782	2.399	0.703
	50 ft	0.815	0.387	0.617	0.346
	Average 50–0 ft	0.554	0.193	0.494	0.291
	0 ft	0.973	0.387	1.172	0.284
	StDev. 1500–500 ft	1.042	0.477	0.925	0.424
	StDev. 500–200 ft	0.987	0.922	0.755	0.958
	StDev. 200–50 ft	3.429	0.908	3.543	0.896
	StDev. 50–0 ft	0.522	0.244	0.468	0.305
Longitudinal Acceleration	Average 1500–500 ft	0.027	0.009	0.025	0.008
	Average 500–200 ft	0.027	0.013	0.026	0.016
	Average 200–50 ft	0.029	0.015	0.022	0.009
	50 ft	0.021	0.009	0.015	0.008
	Average 50–0 ft	0.013	0.006	0.012	0.011
	0 ft	0.016	0.006	0.017	0.007
	StDev. 1500–500 ft	0.027	0.013	0.023	0.011
	StDev.500–200 ft	0.024	0.021	0.017	0.021
	StDev. 200–50 ft	0.012	0.026	−0.002	0.023
	StDev. 50–0 ft	0.013	0.007	0.011	0.008
Vertical Acceleration	Average 1500–500 ft	2.356	0.017	2.351	0.017
	Average 500–200 ft	2.357	0.028	2.355	0.031
	Average 200–50 ft	2.441	0.040	2.423	0.027
	50 ft	0.043	0.019	0.033	0.021
	Average 50–0 ft	0.047	0.018	0.041	0.024
	0 ft	0.055	0.022	0.052	0.019
	StDev. 1500–500 ft	2.356	0.018	2.354	0.020
	StDev. 500–200 ft	1.008	0.052	1.001	0.044
	StDev. 200–50 ft	1.046	0.060	1.017	0.042
	StDev. 50–0 ft	0.048	0.022	0.041	0.023
V Ratio	1500–500 ft	5.441	0.621	5.213	0.674
	500–200 ft	5.479	0.581	5.265	0.361

Table A2 (*continued*)

Flight parameter performance variables		Normal landing events (n=66)		Long landing incidents (n=62)	
		Mean	SD	Mean	SD
	200–50 ft	5.343	0.549	5.083	0.452
	50 ft	5.644	1.079	5.050	0.950
	50–0 ft	5.150	1.093	3.748	0.645

Table A3
Results of the sphericity test.

Within subjects effect	Mauchly *W*	Approx. χ^2	*df*	*p*
Descent Rate Average	0.361	126.603	9	0.000
Descent Rate StDev.	0.397	115.215	5	0.000
Airspeed Average	0.001	923.266	9	0.000
Airspeed StDev.	0.020	490.727	5	0.000
Groundspeed Average	0.000	2070.062	14	0.000
Groundspeed StDev.	0.124	258.788	14	0.000
Roll Angle Average	0.001	909.353	5	0.000
Roll Angle StDev.	0.195	202.628	14	0.000
Pitch Angle Average	0.277	160.078	5	0.000
Pitch Angle StDev.	0.407	111.549	14	0.000
Longitudinal Acceleration Average	0.498	86.866	5	0.000
Longitudinal Acceleration StDev.	0.106	278.907	14	0.000
Vertical Acceleration Average	0.538	77.384	5	0.000
Vertical Acceleration StDev.	0.354	129.462	5	0.000
V Ratio	0.437	103.061	9	0.000

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