Safety Science 102 (2018) 14–25

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Effects of flare operation on landing safety: A study based on ANOVA of real flight data

Lei Wang[a,*], Yong Ren[a], Changxu Wu[b]

[a] *Flight Technology College, Civil Aviation University of China, Tianjin 300300, China*
[b] *Department of Systems and Industrial Engineering, University of Arizona, USA*

ARTICLE INFO

Keywords:
Flight safety
Flare operations
Landing incidents and accidents
Flight data
ANOVA
Regression model

ABSTRACT

Final approach and landing are generally defined as the two riskiest stages of flight due to their much higher accident rates than other phases. Long landings and hard landings are two kinds of abnormal events frequently occurring during the landing phase and also significantly increase the risk of landing accidents. The aim of this study was to examine the effects of pilot's critical flare operation on long and hard landing events based on real flight Quick Access Recorder (QAR) data. 293 flight QAR data samples were collected from airlines and 21 flight parameters from each sample were selected and calculated by programing. Then, an analysis of variance was carried out for finding flight parameter characteristics of abnormal landing at a flare initial point and in the whole flare process. Lastly, two regression models were developed to analyze the potential correlations between flare operations and landing performance. The study found that flare operation would greatly influence touchdown distance and touchdown vertical acceleration, the control column and throttle operation in flare would affect landing performance conjointly and pilots' quick and steady pulling up of the columns and softer throttle reduction are helpful for a better flare performance. These findings could be the basis of developing a mathematical and quantitative model for further revealing the relationships between pilot operations and landing performance, which can also be applied in practice to prevent landing incidents and even accidents.

1. Introduction

Pilots' operation performance can affect flight safety directly (Reason, 1990; Ebbatson et al., 2010). Many studies have reported that pilot error is the primary cause of over 60% of flight accidents (Shappell and Wiegmann, 1996; Shappell et al., 2007; Jarvis and Harris, 2010). The statistics on commercial flight accidents in China from 2007 to 2016 indicated that flight crew factors contributed to 63.64% of accidents (Civil Aviation Administration of China, 2017). Particularly in the final approach and landing stage, the occurrence rate of pilot error is significantly higher than other phases because pilots need to deal with more situational change, greater decision-making and higher operational activity (Wickens and Hollands, 2000; Stanton et al., 2009; Rosa et al., 2011). Statistics released by Boeing have also indicated that landing phase alone accounted for 24% of total fatal accidents occurring from 2007 to 2016, despite the fact that the landing phase accounts for just 1% of average flight time (Boeing, 2017). Long landings and hard landings are two kinds of abnormal events frequently occurring during the landing phase. A long landing is defined as when an aircraft's touchdown distance on runway exceeds the standard area and a hard landing is when the touchdown vertical load exceeds limited value (The standard values are generally regulated by air carriers and aviation administrators). These two kinds of abnormal events remarkably increase the probability of aircraft damage and even flight accidents such as Runway Excursions (RE) and Controlled Flight Into Terrain (CFIT) (Wang et al., 2014).

Currently, most commercial aircraft have been equipped with an advanced autopilot system and automatic Instrument Landing System (ILS). These systems have great effects in most of cruise and gliding stage, especially if there is a low Runway Visual Range (RVR), but they are not fully utilized in common visual landing operation of flight below 60 m (Suzuki et al., 2006) because pilots often take over aircrafts after visually finding a runway and passing the Decision Height (DH) point. In fact, 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 is achieved by performing the landing flare operation, which involves lifting of the nose to both land the aircraft on the main gear first and decrease the descent rate and vertical load at touchdown. If performed correctly, the flare maneuver would reduce the aircraft's descent rate to acceptable levels so

---

[*] Corresponding author.
E-mail address: wanglei0564@hotmail.com (L. Wang).

http://dx.doi.org/10.1016/j.ssci.2017.09.027
Received 30 November 2016; Received in revised form 20 September 2017; Accepted 29 September 2017

that it settles gently on the main landing gear (Grosz et al., 1995; Benbassat et al., 2002). However, the landing flare operation is considered one of the most technically demanding aspects of piloting. Both novice and expert pilots consistently rate the landing flare as one of the most difficult flight maneuvers (Benbassat et al., 2002; Ebbatson et al., 2008). It has been conservatively estimated that 18% of all landing accidents in the U.S. between 1995 and 1998 were due to problems with the landing flare (Benbassat et al., 2002, 2005). It can be seen that flare operation is related with landing performance and safety closely.

In the field of landing safety, previous studies more specifically focused on accidents such as runway overruns and excursions. Kirland et al. (2004) found that 20% of the overruns touched down more than 850 m from the threshold compared with none of the normal flight sample. Rosa et al. (2011) proposed a series of probabilistic models to estimate accident risk (due to runway overrun and landing undershoot). Multiple factors related to environments such as wind, runway surface conditions and runway distance available were involved in these models and studies (Khatwa and Helmreich, 1999; Kirland et al., 2003), but pilot's operation has seldom been mentioned. Some other studies (Grosslight et al., 1978; Wewerinke, 1980; Galanis et al., 2001) addressed the effect of visual perception on pilot's manual operation in landing. Grosslight et al. (1978) found that those landings with monocular approaches tended to be longer and harder. Galanis et al. (2001) also pointed out that changes in the aspect ratio of the runway would affect the perceived glide-slope. Palmisano and Gillam (2005) examined the accuracy of visual touchdown point perception during oblique descents (1.5–15°) through experiments in simulators, the results showed that optic flow per se did not appear to be sufficient for a pilot to land an airplane. Both Mori et al. (2007) and Jorg and Suzuki (2010) used simulator experiments to analyze visual cues and human-pilot control inputs during the landing phase. Their research results showed that the change of the apparent angle between the runway edges was identified as the main cue for flare timing. Meanwhile, the importance of flare operation was also addressed (Mori and Suzuki, 2010).

In fact, fewer studies paid attention to the crucial flare operation in landing. Benbassat et al. (2002, 2005) examined flare operation and depth perception based on 6676 aircraft accident reports and a 21-item perception questionnaire. Results revealed that pilots believed the flare to be more difficult than nine other standard flight maneuvers and most of them used visual cues to time the initiation of flare. Results also showed that experience and instruction were the most important factors for proper flares. Mulder et al. (2000) implemented an experiment to study the effects of pictorial detail on the timing of landing flare where results indicated that landing performance is improved when ground texture is added to the display. Palmisano et al. (2008) also examined three visual strategies for timing the initiation of the landing flare and demonstrated a significant effect of flight experience on flare timing accuracy. Wang et al. (2014) applied a new method for landing safety research by using real flight QAR data to analyze performance features of long landing incidents, the results indicated that significant differences of flight performance existed in the flare phase between normal landing and long landing. In summary, current research consistently demonstrated the importance of flare operation and most has tried to discover factors leading to a perfect flare in a qualitative way. At present, the outcome with regards to flare based on real flight data has rarely been found.

The aim of this study was to examine the effects of pilots' flare operation on landing incidents based on real flight Quick Access Recorder (QAR) data, especially its influences on landing touchdown distance and touchdown vertical load, which are two parameters judging long landing and hard landing.

2. Methods

2.1. QAR data processing

The QAR is a system that can acquire aircraft operational data easily. It includes airborne equipment for recording data and a ground software station for storing and analyzing data. A QAR record all kinds of aircraft parameters, pilot operation parameters, environmental features, and alarm information during a whole flight. The QAR data sampling frequency can reach as high as 16 Hz in modern aircraft. Based on related operational rules and regulations, commercial airlines always use flight data (such as QAR data) to monitor and analyze the whole aircraft and pilot operation performance in flight. When there is a flight parameter that exceeded the prescriptive normal range, it is called a QAR Exceedance Event. In most of time, exceedance events would not lead to severe results, but they can increase the probability of an accident and bring potential damages to aircraft and even passengers. Long landing and hard landing are two kinds of most frequent happened exceedance events, which were classified as abnormal landing events in this study.

QAR data used in this study were collected from three Boeing 737–800 aircrafts operated by local commercial airlines of Tianjin. 293 flights with visual landing operation in daytime and less influence of weather were selected out as samples in this study. The basic selecting principles of samples are described as follows: The man operation or auto operation was checked by switch variable 'auto pilot (A/P)' in QAR recorded data. The meteorological conditions were also considered when selecting samples. First, the data of wind speed and wind direction below 200 feet of each sample flight were calculated for verifying if there was wind shear or turbulence present. Moreover, the threshold of wind speed for choosing sample flight was 10 m/s. Second, those flights with severe landing weather conditions such as storm were not entered in sample group. Third, the landing airports for all flight samples were Category 4E and 4F which means the length of runways were greater than 1800 m. Fourth, those flights with landing at high-altitude aerodromes were excluded and the gross weight of sample flights was also considered. Finally, 293 flight samples were selected and their QAR data were processed. Each original data sample was a CSV (Comma Separated Value) file with thousands of rows and columns. Because it is time-consuming to deal with these unprocessed data manually, a program based on VBA (Visual Basic for Applications) was written and applied to minimize file volume and mine target information from massive QAR data.

2.2. Flight parameter selection

An aircraft in flight is affected by many factors such as external atmospheric environments, the aircraft itself, pilots' basic capabilities and skills, pilots' mental state, and so on. Regardless of how these factors change, however, their effects ultimately are reflected in the change of aircraft attitude and kinematic parameters (Fang, 2005; Chen, 2007). General kinematic analysis of flight is shown in Fig. 1.

In final landing stage, aircrafts always fly within the profile of a landing glide path; their position changes in lateral axis are limited. The aim of landing is to let the aircraft touchdown with a proper groundspeed, sink rate, vertical load, and attitude. Meanwhile, the flare operation directly causes the change of pitch angle. Therefore, we focused on analyzing longitudinal and vertical parameters in this study. Finally, 19 columns of relevant original QAR data of each file were refined. Then 21 flight parameter variables were selected and calculated as shown in Table 1 based on VBA programs. These parameter variables cover all flight and operational parameters in the critical visual and manual landing stages from flare initial height to touchdown point.

The flare initial point in this study is higher than standard 30 feet indicated in most flight operation manuals. This is because any slight backward pulling of the control column could be recorded by a Quick Access Recorder, causing that the time and height of flare are earlier than the theoretical value. The variables of *Touchdown Distance* and *Vertical Acceleration* at touchdown point are two parameters used to determine a long landing and hard landing, respectively. The flare and touchdown process is as shown in Fig. 2. The *Touchdown Distance* is defined as the horizontal distance from the radio altitude of 50 feet to

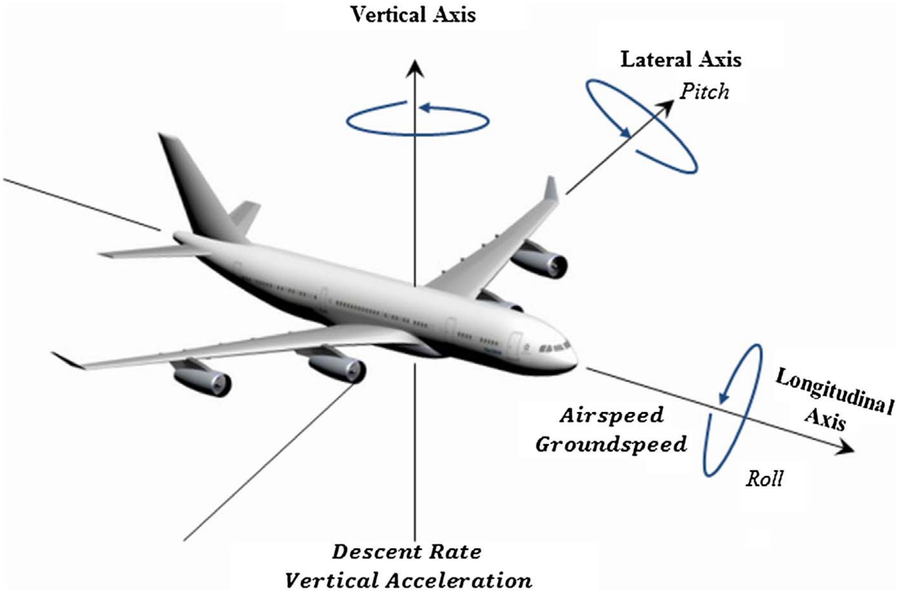

Fig. 1. General kinematic analysis of flight.

touchdown point in landing process (Civil Aviation Administration of China, 2012). The *Vertical Acceleration Touchdown* is the maximum value of vertical acceleration when the main landing gears touch the ground (Civil Aviation Administration of China, 2012).

Based on the common statistical results of QAR data and monitoring criteria of commercial airlines (Qi et al., 2011; Sun and Han, 2011), the two thresholds of determining long landing and hard landing events for this aircraft type was set as 2600 feet and 1.4 g in this study.

2.3. Statistical analysis and modeling

Aiming to find the flare operation characteristics of abnormal landing events and their correlations with landing performance, the statistical methods of analysis of variance (ANOVA) and regression modeling were applied in this study. The logical flowchart of methods is as shown in Fig. 3. Analysis of variance was used to look for differences of flare operations between normal and abnormal landings, including their parameter differences at the initial flare point and throughout the flare process. A multiple linear regression model was developed for analyzing the initial flare operation's effect on touchdown distance. The logistic regression model was built for examining contributions of flare operation on the occurrence probability of hard landings.

2.3.1. Analysis of variance

21 variables in four categories as shown in Table 1 were involved in the analysis of variance. *Touchdown Distance* and *Vertical Acceleration Touchdown,* which are parameters judging long landing and hard landing, were set as dependent variables (DVs) respectively. The other parameters regarding flare operation were independent variables (IVs) to examine. First, the variables of *Flare Height* and *Flare Time* between

Table 1
Selection of parameters.

Classification	Name	Description	Parameter name in QAR data	Units
Kinematics & performance	Flare height	The height of starting flare operation	RADIO HEIGHT	Feet
	Flare time	The total time from flare initial point to touchdown point	/	Second
	Groundspeed	The horizontal speed of an aircraft relative to the ground	GROUND SPEED	Knot
	Descent rate	The vertical speed of an aircraft	VERT SPD	Feet/minute
	Airspeed	The speed of the aircraft relative to the air	AIR SPD	Knot
	Vertical acceleration	The acceleration of aircraft on vertical axis	VERT ACCEL	g
	Touchdown distance	The horizontal distance from the radio altitude of 50 feet to touchdown point in landing	/	Feet
Operational parameter	Throttle resolver angle	The angle adjacent to the corresponding engine's thrust lever	SELTD TRA FILTERED	Degree
	Control column position	The angle of control column deviated from original point	CONTRL COLUMN POSN	Degree
	Control wheel position	The angle of control wheel deviated from original point	CONTRL WHEEL POSN	Degree
	Control column force	The external force loaded on control column	CONTRL COLUMN FORCE	LBS
	Control wheel force	The external force loaded on control wheel	CONTRL WHEEL FORCE	LBS
	Flap handle position	The setting position of flap handle	FLAP HANDLE POSN	Degree
	Speed brake handle position	The setting position of speed brake handle	SPD BRAKE HANDLE POSN	Degree
	Rudder pedal position	The setting position of rudder pedal	RUDD PEDAL POSN	Degree
Configuration & attitude	Flap	The control surfaces which are at the trailing edge of the wings are used to increase the lift of an aircraft	FLAP	Degree
	Aileron	The control surfaces which are used to roll the aircraft	AILERON POSN	Degree
	Elevator	The control surfaces which are used for the pitching moment of the aircraft	ELEV POSN	Degree
	Rudder	The control surfaces which are used to yaw the aircraft	RUDD POSN	Degree
	Pitch angle	Rotation angel around the aircraft side-to-side axis	CAP DISP PITCH ATT	Degree
	Roll angle	Rotation angel around the front-to-back axis	CAP DISP ROLL ATT	Degree

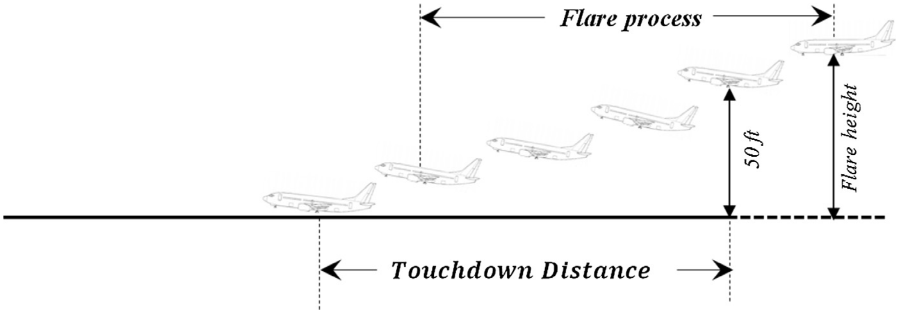

Fig. 2. Flare process and touchdown distance.

different groups were compared. Second, a repeated measures ANOVA was used to analyze the final landing track of different groups. Third, the other 18 parameter variables at the initial flare point were compared. The normal distribution test was carried out. Then, for the aim of difference analysis, a one-way ANOVA was used to examine variables that were subjected to a normal distribution and non-parametric K-W tests for others.

2.3.2. Regression modeling

Before developing the regression models, the correlations between flare operation time and the landing performance were analyzed.

To further find correlations between touchdown distance and the flight parameter variables, a multiple linear regression model was developed. The *Touchdown Distance* was set as the dependent variable (DV) in this model. As shown in Table 2, flare height, flare time and other parameters at flare initial point and were selected as initial independent variables (IVs). Considering the probable collinearity between independent variables, the stepwise regression method was used for eliminating collinearity and the stepping criteria were based on the probability of F ($F \leq 0.05$ 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 the regression, and explanatory variables were continuously added 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.

Logistic regression is a type of predictive model that can be used when the target variable is a categorical variable with two categories (Agresti, 2007). Aiming to find key flight parameters causing hard landings, a logistic regression model on hard landings was developed. In this study, the occurrence of a hard landing was defined as a binary and dependent variable (DVs), where the value was 1 if it happened and 0 if it did not happen. The hard landing was judged by the parameter of vertical acceleration. Then, 17 flight parameters from Table 1 were selected as original covariates in this logistical model, including all operational parameters, configuration and attitude parameters, and three kinematics parameters of groundspeed, airspeed and descent rate. Because the flare is a continuous operation from its initial point to touchdown, the parameter values both at the initial flare point and touchdown point were sampled, and there were 34 independent variables (IVs) in total and as shown in Table 3.

The name and definition of each flight parameter is as shown in Table 1. 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 which variables to add or drop from the model. The final predictor variables and coefficients of the model were obtained in the stepwise process. Meanwhile, the effectiveness of the model was checked and will be discussed further.

3. Results

3.1. Difference analysis of flare operation

3.1.1. Difference of flare height and time

For the selected 293 samples, the Mean (M) and Standard Deviation (SD) of *Touchdown Distance* and *Vertical Acceleration Touchdown* respectively was 2744.00 ± 518.381 and 1.385 ± 0.083. As seen in Fig. 4, these two landing performance parameters of touchdown

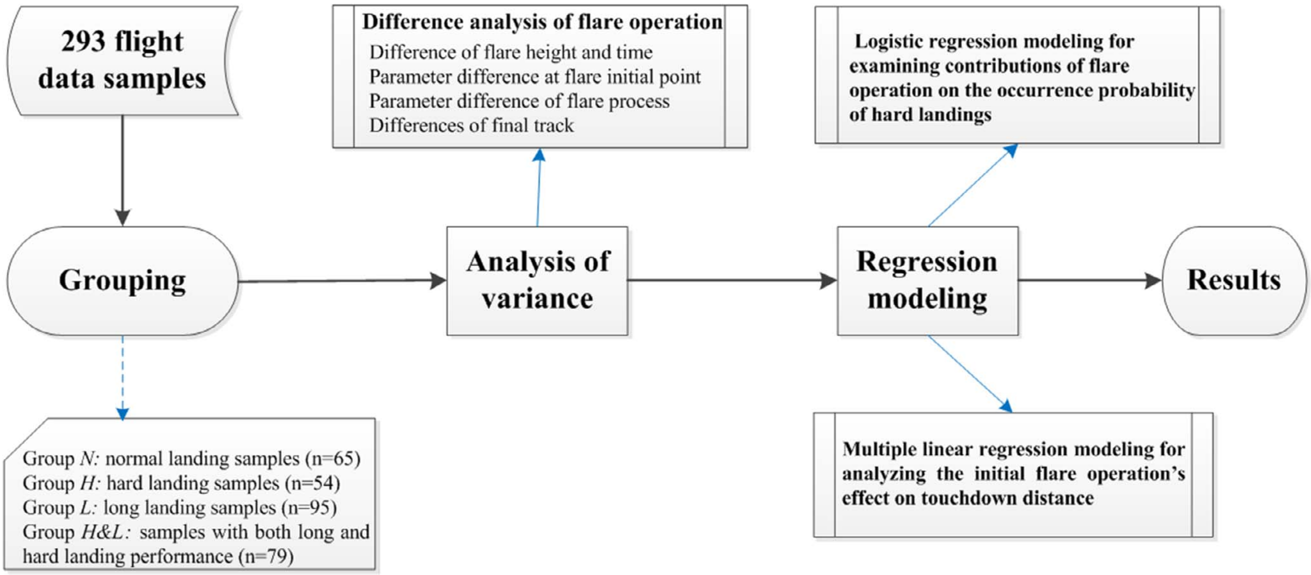

Fig. 3. Flowchart of methods.

Table 2
Dependent and independent variables in multiple linear regression model.

Classification	Name
Dependent variable	Touchdown distance
Independent variables	Flare height, Flare time, 18 parameters at flare initial point: Groundspeed, Descent rate, Airspeed, Vertical acceleration, Throttle resolver angle, Control column position, Control wheel position, Control column force, Control wheel force, Flap handle position, Speed brake handle position, Rudder pedal position, Flap, Aileron, Elevator, Rudder, Pitch angle, Roll angle

distance and vertical acceleration were essentially both subjected to a normal distribution and the results of Anderson-Daling test confirmed this ($p > .05$).

Then, there were 65 normal landing samples without long or hard characteristics (Group *N*), 54 hard landing samples (Group *H*), 95 long landing samples (Group *L*) and an additional 79 samples with both long and hard landing performance (Group *H* & *L*). The descriptive statistic on flare initial height and operation time of four groups is as follows.

As seen in Table 4, there was no significant difference observed between the initial flare height of the four groups, which are all around 50 feet ($F(3, 289) = 0.973, p = .406$). However, their flare times show that these two groups with long landing features are clearly significantly longer than the other groups ($F(3, 289) = 32.752, p < .001$).

Scaling with the time before aircraft touchdown and the height mean of each group, the final track of each of the four kinds of landings is as shown in Fig. 5. The first second on the horizontal axis is the time point of touchdown.

According to Fig. 5 and the results of a repeated measures ANOVA, the following points were found.

1. The total group effect was significant ($F(3, 289) = 48.569, p < .001$), indicating that the final tracks of the four kinds of landings were statistically different. The further posthoc comparisons (LSD) indicated that the differences between Group *N* and Group *L*, Group *N* and Group *H* & *L*, and Group *H* and Group *H* & *L* is remarkable ($p < .001$) and also as seen in Fig. 5.
2. The average heights of normal landing and hard landing are both higher than the other two groups at each second before touchdown. However, the changes in height among the four groups are basically linear before the time point of flare operation, and their slopes were also approximately equal.
3. The change in height indicates a difference after the flare operation. The most remarkable difference is the time of flare commencement as well as the flare operation time, where the normal landing group and hard landing group are shorter than the other two groups.

3.1.2. Parameter difference at flare initial point

The results of difference analysis on variables at flare initial point are as shown in Table A-1 in appendix. As seen in Table A-1, for the long landing and non-long landing groups, there are six variables showing the difference at a significance level of 0.05, which are *Throttle Resolver Angle, Flap Handle Position, Flap, Air Speed, Groundspeed* and *Vertical Acceleration*. However, only two variables, *Air Speed* and *Groundspeed,* represent the significant difference at the level of 0.001. This point means that the major difference between the two groups is reflected in longitudinal speed, including airspeed and groundspeed. In fact, the three variables *Throttle Resolver Angle, Flap Handle Position,* and *Flap* would directly affect longitudinal speed. For the hard landing and non-hard landing groups, there are only three variables indicating a significant difference at the level of 0.05, which are *Flap Handle Position*, *Flap* and *Pitch Angle*.

3.1.3. Parameter difference of flare process

The differences of variables in Table 1 from 200 feet to touchdown were analyzed using a repeated measures ANOVA and a one-way ANOVA. A summary table ANOVA results is as shown in Table 5.

Several important meaningful results regarding parameters of groundspeed, descent rate, control column, throttle and pitch angle are presented as below.

As shown in Fig. 6, the significant difference of variable *Groundspeed* exists in the whole stage of 200–0 feet ($F(2, 211) = 12.644, p < .001$), the groundspeed of long landing group was higher than the normal group and hard landing group. Results of the repeated measures ANOVA showed that the group effect of variable *Descent Rate* was significant ($F(2, 211) = 3.843, p = .023$). The descent rate of a long landing was larger than the normal group before 50 feet, also the initial flare point, which changes greatly past 50 feet and is more significantly different between groups ($F(1, 291) = 234.373, p < .001$).

In Fig. 7, the control column and throttle change greatly after passing 50 feet (initial flare operation point). There was no observed difference between the control column of the two groups ($F(2, 211) = 0.285, p = .752$). There was also no difference found for throttle operation before 50 feet. The main difference is reflected after the flare started when the pilot began to decrease thrust. Compared with a normal landing, the throttle change of the long landing group was much higher and the result of the one-way ANOVA was $F(1, 291) = 46.351, p < .001$. However, the difference of throttle operation between hard landing and normal landing was not found to be significant.

The pitch angle changes of the three groups are as seen in Fig. 8. The subject effect among three groups was not remarkable ($F(2, 211) = 2.269, p = .106$). However, the results of pairwise comparisons between long landing and normal landing, and hard landing and normal landing represent the significant differences respectively ($F(1, 291) = 10.690, p = .001$ and $F(1, 291) = 8.233, p = .005$).

3.2. Regression model of landing performance

3.2.1. Flare operation and landing performance

The correlations between flare operation time and landing

Table 3
Dependent and independent variables in logistic regression model.

Classification	Name
Dependent variable	The occurrence of a hard landing
Independent variables	17 parameters at flare initial point: Groundspeed, Descent rate, Airspeed, Throttle resolver angle, Control column position, Control wheel position, Control column force, Control wheel force, Flap handle position, Speed brake handle position, Rudder pedal position, Flap, Aileron, Elevator, Rudder, Pitch angle, Roll angle 17 parameters at touchdown point: Groundspeed, Descent rate, Airspeed, Throttle resolver angle, Control column position, Control wheel position, Control column force, Control wheel force, Flap handle position, Speed brake handle position, Rudder pedal position, Flap, Aileron, Elevator, Rudder, Pitch angle, Roll angle

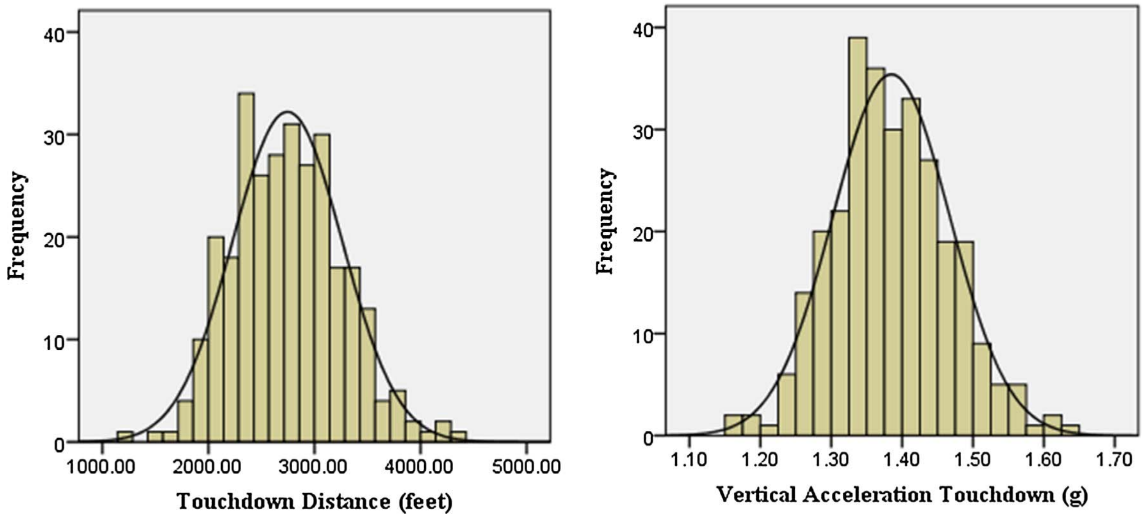

Fig. 4. The distribution of landing performance parameters.

performance can be found in Fig. 9. The *Flare time* correlates to *Touchdown distance* positively and V*ertical Acceleration* negatively, their correlation coefficients reaching 0.659 and −0.304, respectively.

Meanwhile, the correlation between touchdown distance and vertical acceleration was found as shown in Fig. 10.

The correlation coefficient between touchdown distance and vertical acceleration can reach as high as −0.548 which means that the longer the landing is, the less hard it is.

3.2.2. Flare operation and long landing incidents

The result of a stepwise linear regression showed that five significant predictors were included in the final regression model, which are *Flare Time, Flare Height, Groundspeed, Descent Rate* and *Vertical Acceleration.*

The *R* square of the final model was 0.974, which indicates that there is relatively good fitness of this linear model ($F(5, 287) = 1074.868, p < .001$). The linear regression model is expressed as following equation:

$$TD = -1823.106 + 235.295x_1 - 18.940x_2 + 19.111x_3 + 0.204x_4 + 566.668x_5 \tag{1}$$

The standardized regression model, which showing this correlation directly, is introduced and written as following equation:

$$Z_{TD} = 1.255Zx_1 - 0.869Zx_2 + 0.292Zx_3 + 0.057Zx_4 + 0.043Zx_5 \tag{2}$$

In Table 6, all of coefficients are highly statistically significant ($p < .01$). The variable x_1 (*Flare Time*) carries the largest coefficient (1.255) and has the greatest impact on *Touchdown distance*. This result is consistent with the results of difference analyses. It should be pointed out that the variable x_2 (*Flare Height*) also appears to greatly contribute to *Touchdown distance* despite the lack of a significant difference between normal and long landing groups.

The Durbin-Watson test showed that there are no autocorrelations existing among predictors (Durbin-Watson = 1.884). All VIF coefficients of these five predictors were less than 3, which indicates that the collinearity level of independent variables is acceptable. The P-P plot analysis demonstrated that the regression standardized residual is basically subjected to normal distribution. From this, it is reasonable to suggest that the normality assumption of regression was not violated.

3.2.3. Flare operation and hard landing incidents

Three predictors of *Flap Handle Touchdown*, *Pitch Angle Touchdown* and *Roll Angle Touchdown* are included in the final logistic regression model. Table 7 shows the estimated parameters of logistic model to predict landing incident type (hard landing or normal landing).

As shown in Table 7, the Wald criteria indicates that *Flap Handle Touchdown*, *Pitch Angle Touchdown* and *Roll Angle Touchdown* significantly contributes to the occurrence of hard landings ($p < .01$). The occurrence probability of a hard landing incident could be calculated out by Eqs. (3) and (4).

$$p = \frac{e^{\mathrm{logit}(p)}}{1 + e^{\mathrm{logit}(p)}} \tag{3}$$

$$\mathrm{logit}(p) = -2.814 + 0.157x_1 - 0.642x_2 + 0.804x_3 \tag{4}$$

The overall predictive percentage of model is 70.3%, the sensitivity is 0.684 and the specificity is 0.737.

Table 4
Statistics on flare height and time.

Group	N	Flare height ($M \pm SD$, *feet*)	Significant difference between each group	Flare time ($M \pm SD$, *s*)	Significant difference between each group
Normal landing	65	52.169 ± 23.521	Group (Hard), $p = .730$ Group (Long), $p = .962$ Group (Hard & Long), $p = .245$	8.031 ± 2.076	Group (Hard), $p = .730$ Group (Long), $p = .962$ Group (Hard & Long), $p = .245$
Hard landing	54	51.963 ± 20.175	Group (Normal), $p = .730$ Group (Long), $p = .706$ Group (Hard & Long), $p = .101$	7.722 ± 2.141	Group (Normal), $p = .730$ Group (Long), $p = .706$ Group (Hard & Long), $p = .101$
Long landing	95	53.495 ± 25.578	Group (Normal), $p = .962$ Group (Hard), $p = .706$ Group (Hard & Long), $p = .292$	10.926 ± 2.702	Group (Normal), $p = .962$ Group (Hard), $p = .706$ Group (Hard & Long), $p = .292$
Hard & long landing	79	47.532 ± 24.056	Group (Normal), $p = .245$ Group (Hard), $p = .101$ Group (Long), $p = .292$	10.392 ± 2.431	Group (Normal), $p = .245$ Group (Hard), $p = .101$ Group (Long), $p = .292$
Total	293	51.311 ± 23.791	/	9.550 ± 2.765	/

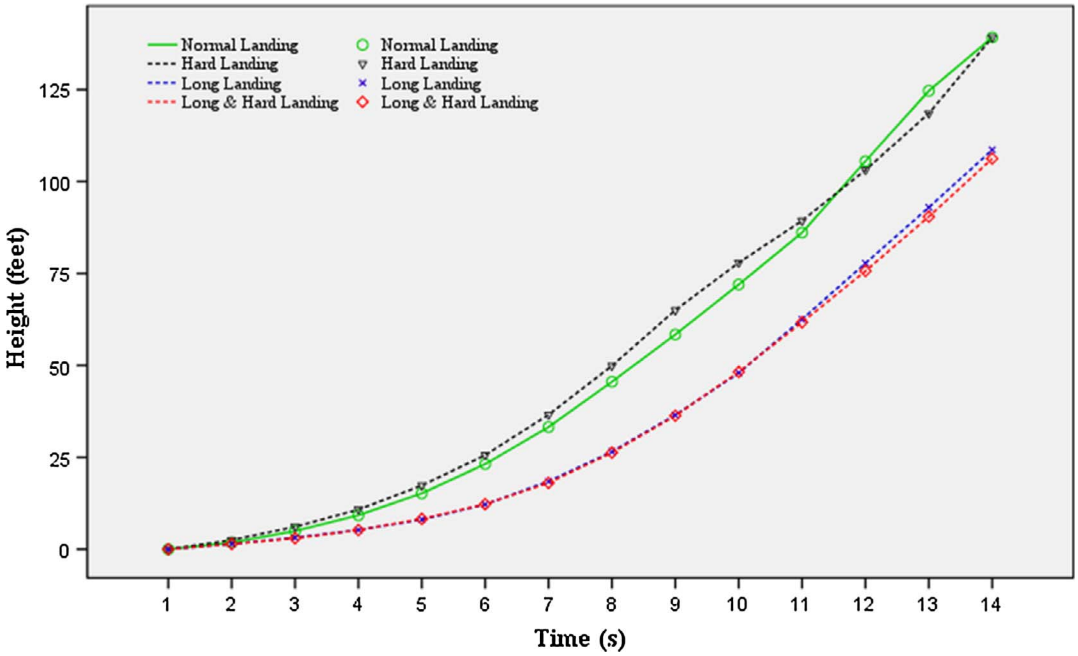

Fig. 5. Final track of different landing.

4. Discussion

The final approach and landing phase is been demonstrated to be the most critical stage of the whole flight process, which is consistent with existing literature (Shappell et al., 2007; Boeing, 2017). Though many studies regarding landing safety have been conducted, little research on pivotal flare operation has been conducted. Meanwhile, much landing safety research has been based on methods of accident investigations, models, or experiments rather than actual flight data. Benbassat's et al. (2002, 2005) studies on flare are creative and fruitful, but lots of their findings came from accident statistics and pilot survey. Based on real flight data, the predecessor to this research study analyzed the exterior flight performance and critical flare operation features of long landing events (Wang et al., 2014), but the underlying reason and formation mechanism that led to these operations was not referred to exactly. In this current study, a different and more innovative way to analyze the effects of flare operation on final landing performance and safety was explored.

4.1. *Effects of flare operation on landing safety*

4.1.1. *Discussion on flare initiation*

Through comparing the final flight track of a normal landing with abnormal landing, we found that the flare initial height of the four groups remained constant at 50 feet around. As a matter of fact, the height of 50 feet is a critical reference point in most flight operation rules (Civil Aviation Administration of China, 2012), requiring that an aircraft flies across the runway threshold with proper speed at this height. Theoretically the flare operation also starts at this height. Based on this finding, we can extrapolate that pilots tend to decide to flare according to height or the flight rule of crossing runway threshold at 50 feet, rather than other flight performance parameters. However, the flare time of a long landing is much longer than other groups, which means that this variable greatly contributed to touchdown distance and the occurrence of long landing. This result was also identified in the multiple linear regression model where the correlation coefficient between flare time and touchdown distance is as high as 0.659.

At the initial flare point, most parameters did not represent significant differences between groups except for flap setting, longitudinal speed and vertical acceleration (see Table A-1). The flap value of long landing was smaller than normal group (non-long group); by contrast this value of hard landing was bigger than normal group (non-hard group). Flaps are the control surfaces which are at the trailing edge of the wings are used to increase the lift of an airplane. In fact, the flap setting operation was often finished before final landing and the value would not change from when the aircraft was at 200 feet through touchdown. Therefore, although the flap setting has a great effect on landing performance, it is not included in flare operation. Meanwhile, flare operation variables, such as *Control Column* and *Throttle Resolver Angle,* do not indicate a significant difference at the flare point. This is probably because flare operations are consequent movements with differences existing in a period or a stage, rather than at a single point. Therefore, the difference analysis along with flight height change was also expected to conduct.

Table 5
Summary of ANOVA results.

Variable name	Groups analyzed	Name
Groundspeed	Group (Normal), Group (Hard), Group (Long)	$F(2, 211) = 12.644, p < .001$
Descent rate	Group (Normal), Group (Hard), Group (Long)	$F(2, 211) = 3.843, p = .023$
Descent rate	Group (Normal), Group (Long)	$F(1, 291) = 234.373, p < .001$
Control column	Group (Normal), Group (Hard), Group (Long)	$F(2, 211) = 0.285, p = .752$
Throttle resolver angle	Group (Normal), Group (Long)	$F(1, 291) = 46.351, p < .001$
Pitch angle	Group (Normal), Group (Hard), Group (Long)	$F(2, 211) = 2.269, p = .106$
Pitch angle	Group (Normal), Group (Long)	$F(1, 291) = 10.690, p = .001$
Pitch angle	Group (Normal), Group (Hard)	$F(1, 291) = 8.233, p = .005$

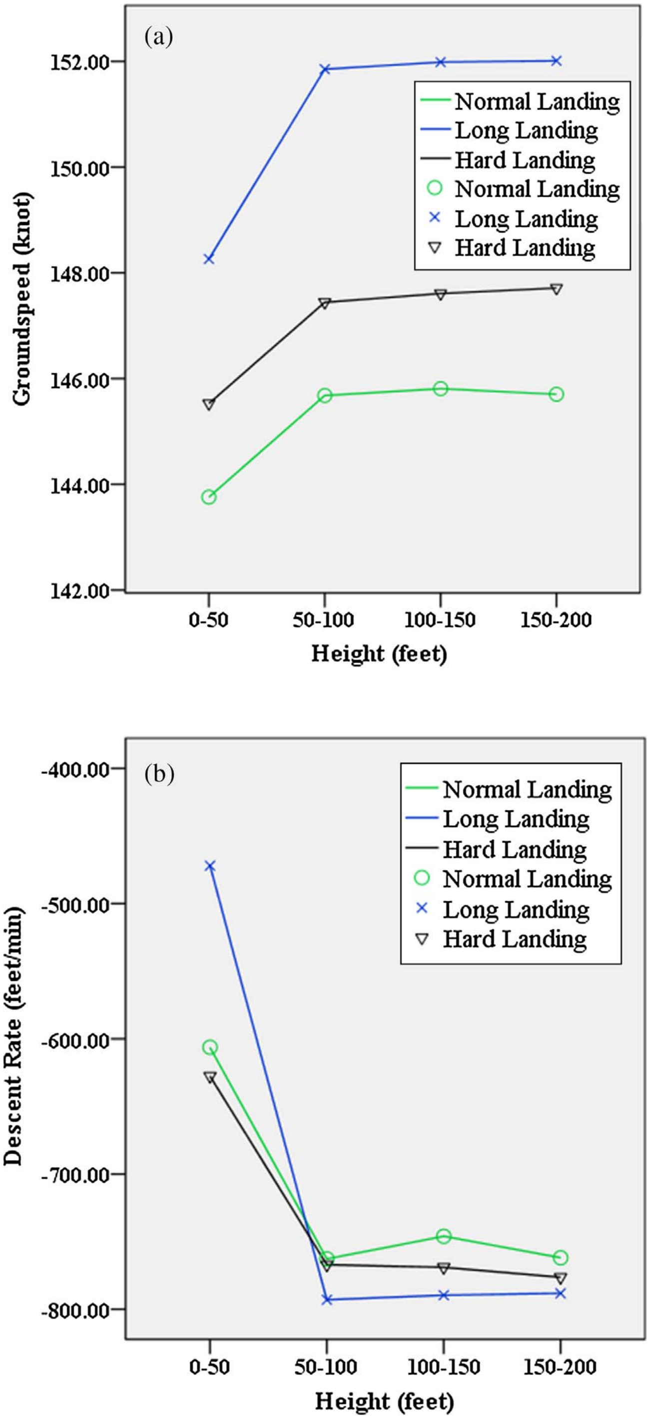

Fig. 6. Difference analysis of groundspeed and descent rate.

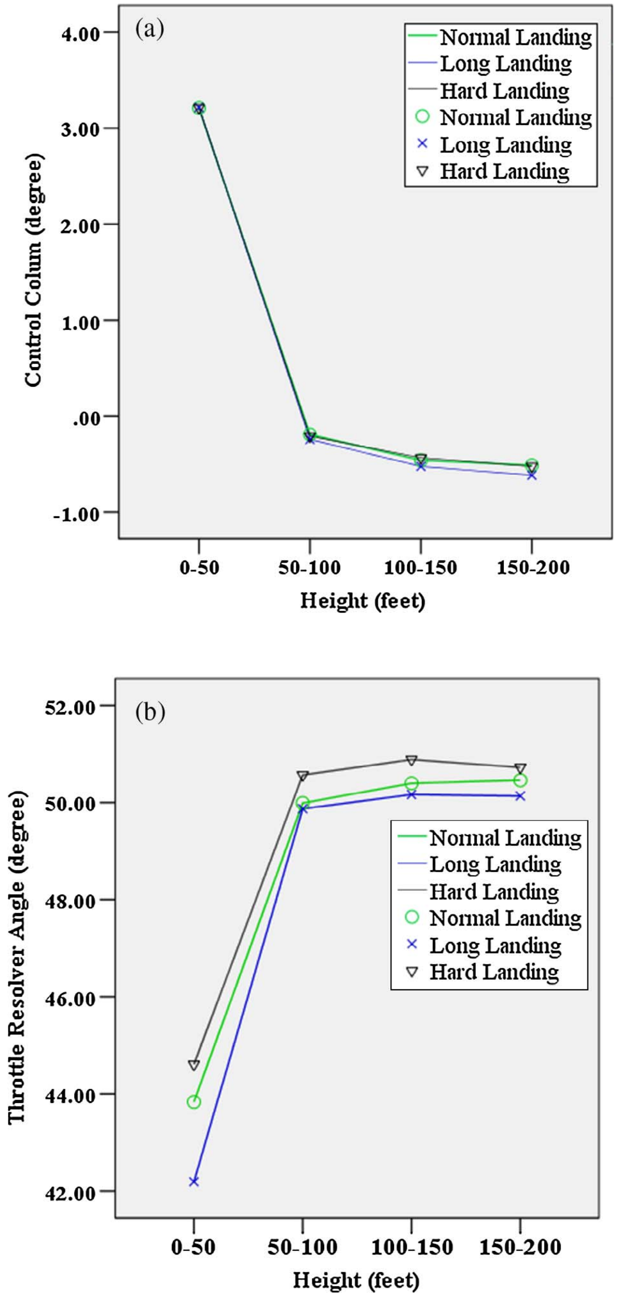

Fig. 7. Difference analysis of control column and throttle resolver angle.

4.1.2. Discussion on flare process

Through analyzing the parameter differences in the process of descending from 200 feet to ground, the change trend of variables was expected to be detected. As far as the two flare operation variables (control column and throttle) were concerned, the column change degrees and trend of the three landing groups both remained constant in this whole flight stage (see Fig. 7a). It needs to be noted that their time of operating column is definitely different, which means that the speed of pulling on the column is significantly different. The normal landing and hard landing group is faster than long landing group. Meanwhile, the throttle operation between long landing and contrast group represented the difference in flare process (50–0 feet) (see Fig. 7b). The value change of long landing is greater than the normal landing, which means that the throttle of normal operation was closed more steadily and softly.

The correlation between touchdown distance and touchdown vertical acceleration was not found in correlation analysis, but this kind of correlation existed between touchdown distance and the average of vertical acceleration from 50 to 0 feet (see Fig. 10). This indicates that the flights with longer touchdown distance have a lighter vertical load in landing. From this, it can be inferred that pilots probably prolong the flare time to avoid a hard landing. One piece of evidence supporting this viewpoint is that the vertical acceleration of a long landing at the initial flare point is higher than the non-long landing group (see Table A-1). In addition, a hard landing attracts more attention from passengers who are normally more sensitive to a comfortable touchdown feeling, and airlines subsequently tend to emphasize hard landing monitoring and punishment more than that for long landings. Pilots therefore prefer to land more softly. However, the risk of runway

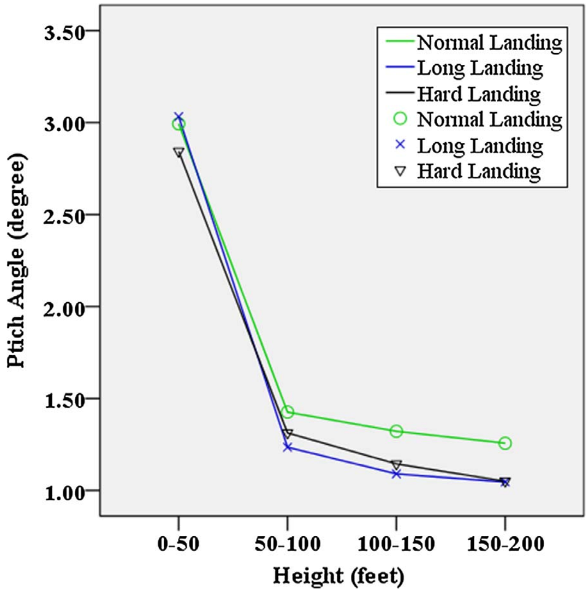

Fig. 8. Difference analysis of pitch angle.

overrun is increased with prolonged flare time and the occurrence of long landing.

The multiple linear regression model indicated that the initial flare height would also affect touchdown distance, with a lower flare height causing longer touchdown distance. The logistic model showed that the vertical load of touching ground was actually linked with touchdown attitude and configuration closely, including three variables of pitch angle, roll angle and flap degree. Among these, the pitch angle of the aircraft was correlated to control column operation directly and therefore is a strong external indication of flare. In fact, the correlations between pitch angle and vertical acceleration are strong at every stage from 200 to 0 feet.

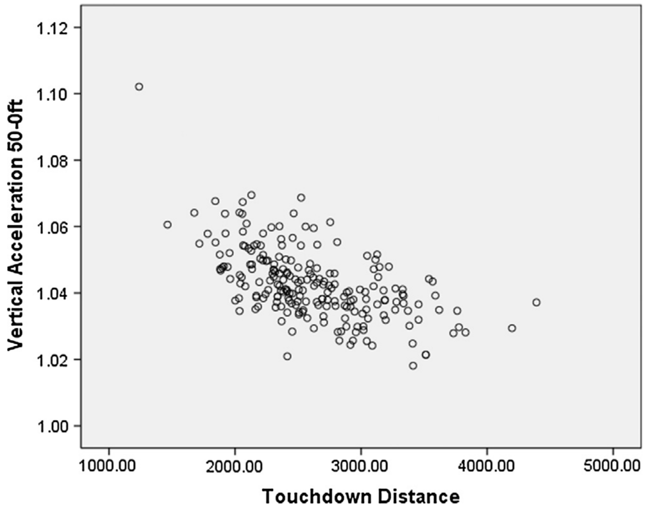

Fig. 10. Correlations between touchdown distance and vertical acceleration.

4.2. Future work

Even though pilots' flare operation was analyzed in detail and a couple of operational characteristics and patterns of abnormal landing were found, the underlying reason and formation mechanism leading to these operations was not referred often due to the limitation of statistical models in this study. Instead, a more general and mathematical model is expected to be developed to further illustrate the interactions between flare and landing performance in future work. The quantitative relationship of flight operation and flight performance could be expressed in this model and the landing incidents also could be predicted through this model.

Meanwhile, the cognitive mechanism of flare operation is also worth studying in future. While this study found that pilots typically chose to start flare operation at a height of around 50 feet, (the same as in a normal or abnormal landing), a crucial question is what kinds of factors contribute to pilots' decision on initiating flare operation. Bolton and Bass (2009) pointed that spatial awareness is important in a human pilot's ability to keep track of the relative locations of objects in the environment. Benbassat and Abramson (2002a) reported that depth perception plays an important role in this decision-making process. Depth perception is affected by an observer's self-motion speed (Watamaniuk et al., 1993). So a reasonable hypothesis may suggest that speed perception is perhaps also a contributing factor supporting flare

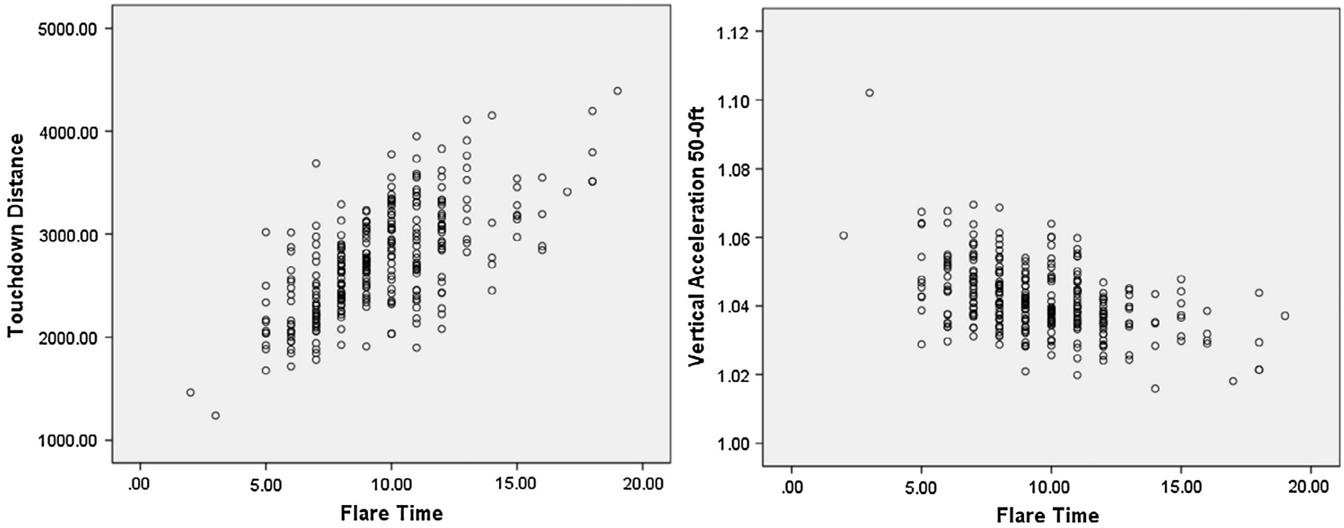

Fig. 9. Correlations between flare operation time and landing performance.

Table 6
Coefficients of model.

No.	Variables	Unstandardized coefficients		Standardized coefficients	t	Sig.	Collinearity statistics	
		B	Std. error	Beta			Tolerance	VIF
	(Constant)	−1823.106	239.156		−7.623	0.000		
x_1	Flare time	235.295	3.606	1.255	65.257	0.000	0.478	2.094
x_2	Flare height	−18.940	0.442	−0.869	−42.863	0.000	0.430	2.328
x_3	Groundspeed	19.111	0.909	0.292	21.019	0.000	0.914	1.094
x_5	Descent rate	0.204	0.053	0.057	3.863	0.000	0.813	1.231
x_5	Vertical acceleration	566.668	204.316	0.043	2.773	0.006	0.735	1.361

Table 7
Logistic regression values of the predicting variables.

Predicting variables	Wald (χ^2)	Adjust OR[a]	95% C.I. for OR[b]
Flap handle touchdown (x_1)	10.888**	1.169	1.066–1.283
Pitch angle touchdown (x_2)	17.899**	0.526	0.391–0.709
Roll angle touchdown (x_3)	16.084**	2.235	1.509–3.311
Constant	3.557$^{\#}$	0.060	

$^{**}p < .01$, $^{*}p < .05$, $^{\#}.05 < p < .10$ and otherwise $p \geq .10$.

[a] Adjust ORs (odds ratio) predicted hard landing.

[b] Confidence interval.

decision-making. Furthermore, in most flight decks, pilots hear the audible message, "fifty" reminding them of when the aircraft is passing through a height of 50 feet. This auditory information also possibly has an influence on pilots' judgment on flare operation. Therefore, flare operation is a typical Perception-Decision-Action process that requires a pilot to integrate all kinds of visual and auditory perceptual information to make an accurate judgment of the situation and act accordingly. Future experimental study is needed to examine the effects of perception on flare timing and action. In addition, pilots' perception and operation might be affected by flight experience and training. An empirical study could be conducted for finding this transferring effect and it could be helpful for improving flight training.

The probability of landing accidents is increased with the occurrence of abnormal landing events such as long landing and hard landing. A NLR (National Aerospace Laboratory of Netherlands) study has revealed that if the landing is long, the landing overrun accident risk is 55 times greater than when it is not long (Gerard, 2006). The findings of this study could be meaningful for predicting the risk of landing overrun and overload accident. 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 (Rosa et al., 2011). The precision and predictability of this model would be greatly improved if flight parameters and pilots' operation characteristics of long landing were considered in. Similarly, a risk assessment model for hard landing incidents and accidents could be built based on statistical results from this study. Noyes (2007) proposed a new concept of an energy management system onboard civil aircraft and found that displays with predictive information elements produced the most accurate decisions concerning aircraft states. In the future, a more applicable tool for predicting the risk of landing incidents is also expected to be developed and integrated into predictive display for supporting pilots' decision-making and actions.

5. Conclusions

Based on real flight data, this study examined the effects of flare operation on touchdown distance and touchdown vertical acceleration, which were two parameters determining abnormal events of long landing and hard landing. Through difference analysis and statistical modeling, several main conclusions were made, and are summarized as follows:

1. Flare is a critical operation in landing, which can greatly influence touchdown distance and vertical acceleration through flare operation time and initial flare height.
2. Control column and throttle operation below 50 feet represents a difference between normal landings and abnormal landings, which together play a great role on the whole flare performance. Pilots' faster and steady backward pulling on columns and softer throttle reduction are helpful for a better flare and landing.
3. Pilots are advised to monitor and control aircraft to an appropriate longitudinal and vertical speed when entering into a manual operation phase in landing. Groundspeed and descent rate are two crucial parameters leading to excellent landing performance.
4. The pitch angle of aircraft can have effects on vertical acceleration in the flare process. The final landing altitude, including pitch and roll angle at touchdown point, is correlated to final vertical load.

In general, flare operation that is made up of control column pulling and throttle closing can have a great effect on aircraft landing performance and safety. The control column pulling is linked with pitch angle and attack angle directly, which ultimately affects the lift and the acceleration in the vertical axis of the aircraft. The throttle is clearly correlated with thrust, longitudinal acceleration, and speed. However, a potential interaction effect exists between the two actions. For example, the calculation formula of lift indicated the function relationship between ground speed and lift. Therefore, excellent flare operation is dependent on the coordination of these two actions and landing performance is the result of the two actions working in tandem. The results of this study revealed the human operation mechanism of two landing incidents and the findings would be helpful for achieving better landing performance and improving the landing safety level.

Acknowledgments

We want to thank Dr. Steven Leib of University of South Australia for his careful review and revision of this manuscript. We appreciate the valuable suggestions from the anonymous reviewers in improving this work. We also appreciate the support of this work from the National Natural Science Foundation of China (Grant No. U1733117, Grant No. 61304207) and the National Key Research and Development Program of China (Grant No. 2016YFB0502405).

Appendix A

Table A-1
Difference analysis on variables of flare initial point.

Parameter categories	Variable names	Group	N	Mean ± SD	p	Group	N	Mean ± SD	p
Operation parameter	Throttle resolver angle	Non-Long	119	49.570 ± 1.926	0.052	Non-Hard	160	49.055 ± 2.112	0.069
		Long	174	49.062 ± 2.355		Hard	133	49.525 ± 2.287	
	Control column	Non-Long	119	1.004 ± 0.773	0.818	Non-Hard	160	0.981 ± 0.750	0.128
		Long	174	1.023 ± 0.667		Hard	133	1.057 ± 0.661	
	Column force	Non-Long	119	2.072 ± 0.942	0.419	Non-Hard	160	2.040 ± 0.940	0.090
		Long	174	2.164 ± 0.978		Hard	133	2.231 ± 0.983	
	Control wheel	Non-Long	119	0.461 ± 8.938	0.330	Non-Hard	160	−0.297 ± 9.686	0.825
		Long	174	−0.628 ± 9.674		Hard	133	−0.053 ± 9.036	
	Wheel force	Non-Long	119	−0.017 ± 0.424	0.139	Non-Hard	160	0.032 ± 0.458	0.634
		Long	174	0.055 ± 0.466		Hard	133	0.019 ± 0.442	
	Flap handle position	Non-Long	119	31.597 ± 3.678	0.008	Non-Hard	160	30.438 ± 2.052	0.000
		Long	174	30.632 ± 2.441		Hard	133	31.729 ± 3.796	
	Speed brake position	Non-Long	119	2.949 ± 0.822	0.286	Non-Hard	160	2.880 ± 0.975	0.339
		Long	174	2.843 ± 0.912		Hard	133	2.893 ± 0.745	
	Rudder pedal	Non-Long	119	0.563 ± 0.250	0.564	Non-Hard	160	0.576 ± 0.221	0.441
		Long	174	0.579 ± 0.142		Hard	133	0.569 ± 0.153	
Configuration and attitude	Elevator	Non-Long	119	2.492 ± 0.938	0.547	Non-Hard	160	2.482 ± 0.917	0.199
		Long	174	2.431 ± 0.794		Hard	133	2.425 ± 0.774	
	Aileron	Non-Long	119	1.504 ± 1.864	0.307	Non-Hard	160	1.329 ± 2.018	0.743
		Long	174	1.267 ± 2.006		Hard	133	1.404 ± 1.872	
	Flap	Non-Long	119	31.597 ± 3.678	0.008	Non-Hard	160	30.438 ± 2.052	0.000
		Long	174	30.632 ± 2.441		Hard	133	31.729 ± 3.796	
	Rudder	Non-Long	119	−0.160 ± 0.605	0.189	Non-Hard	160	−0.232 ± 0.609	0.519
		Long	174	−0.248 ± 0.528		Hard	133	−0.189 ± 0.498	
	Pitch angle	Non-Long	119	1.464 ± 0.653	0.596	Non-Hard	160	1.516 ± 0.713	0.032
		Long	174	1.421 ± 0.704		Hard	133	1.345 ± 0.635	
	Roll angle	Non-Long	119	−0.345 ± 1.221	0.074	Non-Hard	160	−0.200 ± 1.282	0.936
		Long	174	−0.091 ± 1.173		Hard	133	−0.188 ± 1.091	
Flight performance	Air speed	Non-Long	119	148.462 ± 4.871	0	Non-Hard	160	149.669 ± 4.391	0.849
		Long	174	150.575 ± 4.402		Hard	133	149.774 ± 5.076	
	Groundspeed	Non-Long	119	146.277 ± 7.453	0.000	Non-Hard	160	149.244 ± 7.755	0.256
		Long	174	152.080 ± 7.375		Hard	133	150.301 ± 8.118	
	Descent rate	Non-Long	119	−813.849 ± 148.094	0.131	Non-Hard	160	−814.925 ± 131. 458	0.462
		Long	174	−825.448 ± 142.712		Hard	133	−822.316 ± 136.951	
	Vertical acceleration	Non-Long	119	1.047 ± 0.037	0.005	Non-Hard	160	1.054 ± 0.042	0.642
		Long	174	1.061 ± 0.040		Hard	133	1.057 ± 0.036	

References

Agresti, A., 2007. Building and applying logistic regression models. In: An Introduction to Categorical Data Analysis. Wiley, Hoboken, New Jersey.

Benbassat, D., Abramson, C.I., 2002a. Landing flare accident reports and pilot perception analysis. Int. J. Aviat. Psychol. 12 (2), 137–152.

Benbassat, D., Abramson, C.I., et al., 2002. Comparative approach to pilot error and effective landing flare instructions. Int. J. Comp. Psychol. 15 (2), 249–255.

Benbassat, D., Williams, K.W., Abramson, C.I., 2005. General aviation leveloff, roundout, and accident rate analysis. Int. J. Aviat. Psychol. 15, 189–203.

Boeing, 2017. Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations, 1959–2016. Boeing Commercial Airplanes, Seattle, WA.

Bolton, M.L., Bass, E.J., 2009. Comparing perceptual judgment and subjective measures of spatial awareness. Appl. Ergon. 40 (4), 597–607.

Chen, T., 2007. Aircraft Flight Performance Quality and Control. National Defense Industry Press, Beijing, China.

Civil Aviation Administration of China, 2017. Aviation Safety Report of CAAC. CAAC, Beijing, China.

Civil Aviation Administration of China, 2012. Implementation and Management of Flight Operation Quality Assurance. Advisory Circular: 121/135-FS-2012-45. CAAC, Beijing, China.

Ebbatson, M., Harris, D., Huddlestone, J., Sears, R., 2008. Combining control input with flight path data to evaluate pilot performance in transport aircraft. Aviat. Space Environ. Med. 79 (11), 1061–1064.

Ebbatson, M., Harris, D., Huddlestone, J., Sears, R., 2010. The relationship between manual handling performance and recent flying experience in air transport pilots. Ergonomics 53 (2), 268–277.

Fang, Z., 2005. Aircraft Flight Dynamics. Beihang University Press, Beijing, China.

Galanis, G., Jennings, A., Beckett, P., 2001. Runway width effects in the visual approach to landing. Int. J. Aviat. Psychol. 11 (3), 281–301.

Gerard, V.E., 2006. When a runway is not long enough to land on. Transport Canada. Aviat. Saf. Lett. (Issue 1/2006), 27–28.

Grosslight, J.H., Fletcher, H.J., Masterton, B., Hagen, R., 1978. Monocular vision and landing performance in general aviation pilots: cyclops revisited. Hum. Factors 20 (1), 27–33.

Grosz, J., Rysdyk, R.T., Bootsma, R.J., Mulder, J.A., Van der Vaart, J.C., Van der Wieringen, P.C.W., 1995. Perceptual support for timing of the flare in the landing of an aircraft. In: Flach, J.M., Hancock, P.A., Caird, J.K., Vicente, K.J. (Eds.), Local Applications of the Ecological Approach to Human-Machine Systems. Erlbaum, Hillsdale, NJ, pp. 104–121.

Jarvis, S., Harris, D., 2010. Development of bespoke human factors taxonomy for gliding accident analysis and its revelations about highly inexperienced UK glider pilots. Ergonomics 53 (2), 294–303.

Jorg, O.E., Suzuki, S., 2010. Modeling of the visual approach to landing using neural networks and fuzzy supervisory control. Aerosp. Sci. Technol. 14 (2), 118–125.

Khatwa, R., Helmreich, R.L., 1999. Analysis of critical factors during approach and landing in accidents and normal flight. Flight Saf. Dig. 17–18, 1–256.

Kirland, I.D.L., Caves, R.E., Hirst, M., Pitfield, D.E., 2003. The normalisation of aircraft overrun accident data. J. Air Transport Manage. 9 (6), 333–341.

Kirland, I.D.L., Caves, R.E., Humphreys, I.M., Pitfield, D.E., 2004. An improved methodology for assessing risk in aircraft operations at airports, applied to runway overruns. Saf. Sci. 42 (10), 891–905.

Mori, R., Suzuki, S., Sakamoto, Y., Takahara, H., 2007. Analysis of visual cues during landing phase by using neural network modeling. J. Aircraft 44 (6), 2006–2011.

Mori, R., Suzuki, S., 2010. Modeling of pilot landing approach control using stochastic switched linear regression model. J. Aircraft 47 (5), 1554–1558.

Mulder, M., Pleijsant, J., van der Vaart, H., van der Wieringen, P., 2000. The effects of pictorial detail on the timing of the landing flare: results of a visual simulation experiment. Int. J. Aviat. Psychol. 10 (3), 291–315.

Noyes, J., 2007. Energy management displays: a new concept for the civil flight deck. Appl. Ergon. 38 (4), 481–489.

Palmisano, S., Favelle, S., Sachtler, W.L., 2008. Effects of scenery, lighting, glideslope, and experience on timing the landing flare. J. Exp. Psychol.: Appl. 14 (3), 236–246.

Palmisano, S., Gillam, B., 2005. Visual perception of touchdown point during simulated landing. J. Exp. Psychol.: Appl. 11 (1), 19–32.

Qi, M., Shao, X., Chi, H., 2011. Flight operations risk diagnosis method on Quick Access Record exceedance. J. Beijing Univ. Aeronaut. Astronaut. 37 (10), 1207–1211.

Reason, J., 1990. Human Error. Cambridge University Press, New York, NY.

Rosa, M.A.V., Fernando, G.C., Gordún, L.M., Nieto, F.J.S., 2011. The development of probabilistic models to estimate accident risk (due to runway overrun and landing undershoot) applicable to the design and construction of runway safety areas. Saf. Sci. 49 (5), 633–650.

Shappell, S., Wiegmann, D., 1996. U.S. naval aviation mishaps 1977–92: differences between single- and dual-piloted aircraft. Aviat. Space Environ. Med. 67 (1), 65–69.

Shappell, S., Detwiler, C., Holcomb, K., Hackworth, C., Boquet, A., Wiegmann, D., 2007. Human error and commercial aviation accidents: an analysis using the human factors analysis and classification system. Hum. Factors 49 (2), 227–242.

Stanton, N.A., Salmon, P., Harris, D., Marshall, A., Demagalski, J., Young, M.S., Dekker, S., 2009. Predicting pilot error: testing a new methodology and a multi-methods and analysts approach. Appl. Ergon. 40 (3), 464–471.

Sun, R., Han, W., 2011. Analysis on parameters characteristics of flight exceedance events based on distinction test. Chinese J. Saf. Sci. Technol. 7 (2), 22–27.

Suzuki, S., Sakamoto, Y., Sanematsu, Y., Takahara, H., 2006. Analysis of human pilot control inputs using neural network. J. Aircraft 43 (3), 793–796.

Wang, L., Wu, C., Sun, R., 2014. An analysis of flight quick access recorder (qar) data and its applications in preventing landing incidents. Reliab. Eng. Syst. Saf. 127, 85–96.

Watamaniuk, S.N.J., Grzywacz, N.M., Yuille, A.L., 1993. Dependence of speed and direction perception on cinematogram dot density. Vision. Res. 33 (5–6), 849–859.

Wewerinke, P.H., 1980. The effect of visual information on the manual approach and landing. National Aerospace Laboratory Technical Report (No. 8005U). NLR, Amsterdam, Netherlands.

Wickens, C.D., Hollands, J.G., 2000. Engineering Psychology and Human Performance, third ed. Prentice Hall Press, Upper Saddle River, New Jersey.