Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-217

Safety aspects of aircraft operations in crosswind

G.W.H. van Es, P.J. van der Geest and T. M.H. Nieuwpoort

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This report is based on a presentation held at the Flight Safety Foundation FSF, 11th Annual European Aviation Safety Seminar, Amsterdam on March 8-10, 1999.

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Summary

In the next decades, airline operations will continue to grow. It is expected that the number of departures will almost double by 2016. This increase in departures requires an increase of the capacity of many airports worldwide. An important aspect, which affects the potential growth of airport capacity, as well as the optimal layout of new airports, is the crosswind limit imposed on runway availability.
In order to assess the safety margins inherent to current operational crosswind limitations, and to get an impression of the impact on safety margins, if crosswind limitations would be relaxed, this reports gives a broad overview of all safety aspects related to operations in crosswind conditions.

The report presents first some background on the flight mechanics involved in crosswind operations. Further the wind climate around airports, as well as the measurement and reporting procedures of wind conditions are discussed.
Next an inventory is given of certification rules and operational guidelines for crosswind operations. Results of a survey among a large number of operators, concerning applied operational limitations for the aircraft types in use are presented. Also current crosswind limitations used by particular airports for runway assignment are provided.
Subsequently an analysis of historical accident and incident data is presented, focusing on quantification of the risk associated with crosswind operations.
Finally, based on the results of this report, a number of conclusions and recommendations are given.

One of the main conclusions drawn, is that crosswind operations in general are surrounded with substantial uncertainty, warranting substantial margins relative to theoretical limitations when operating in crosswind conditions.
Supported by statistical analysis of historical data it is concluded, that general crosswind limitation recommended by ICAO (15 Kt. incl. gust), cannot be relaxed without compromising safety unless additional measures are taken.

Contents

(46 pages in total)

1 Introduction

In the next decades, airline operations will continue to grow. It is expected that the number of departures will almost double by 2015. This increase in departures requires an increase of the capacity of many airports worldwide. An important aspect, which affects the potential growth of airport capacity, as well as the optimal layout of new airports, is the use of the maximum crosswind criteria for runway selection and it's effect on runway availability. It is therefore opportune to raise the question whether it is possible to increase maximum crosswind values for runway selection without compromising safety.

In about 10% off all accidents weather is identified as a causal factor[1]. These weather related aviation accidents are most often caused by wind (Ref. 1). A literature review showed that there are no studies available which systematically analyse these safety aspects. The present study will focus on the safety aspects of takeoff and landing operations in crosswind.

The objective of this current study is to explore the safety aspects of aircraft operations in crosswinds. Wind reporting practice, certification aspects, operational aspects and historical accident/incident data will be analysed in this study[2].

This paper is outlined as follows. In section 2 the basic flight mechanical aspects of crosswind operations are discussed. Wind climate and measurement are discussed in section 3. In section 4 certification rules and operational guidelines are presented. A systematic analysis of historical accident and incident data regarding crosswind is given in section 5. Finally conclusions and recommendations are given in section 6.

[1] Based on data from the NLR Air Safety Database.

[2] During the time between the initial presentation of the study and the publication of the NLR Technical Paper, a number of airports and operators have revised their crosswind policy as a result of the presented facts and findings. These facts and findings are still considered up-to-date by the time of publishing it in the present form of a NLR Technical Paper.

2 Background on flight mechanics of crosswind operations

2.1 Airborne part

A successful landing in crosswind conditions begins with a carefully flown final approach with the aircraft established on the glide path and the aircraft ground speed vector lined up with the centreline of the runway before the initiation of the flare.

Two procedures are possible to compensate for crosswind during an approach. First there is the "drift" or "crab" technique in which the aircraft is headed slightly into the wind and second the "wing-down" technique in which the aircraft is put into a steady sideslip such that it compensates the drift caused by the crosswind. Both techniques are illustrated in Figure 1 and Figure 2. In practice usually a composite approach pattern is adopted which combines both drift and sideslip in degrees which may vary during the course of the approach[3]. However with conventional aircraft this compromise usually is a close approximation to the idealised "crab" or "drift" technique.

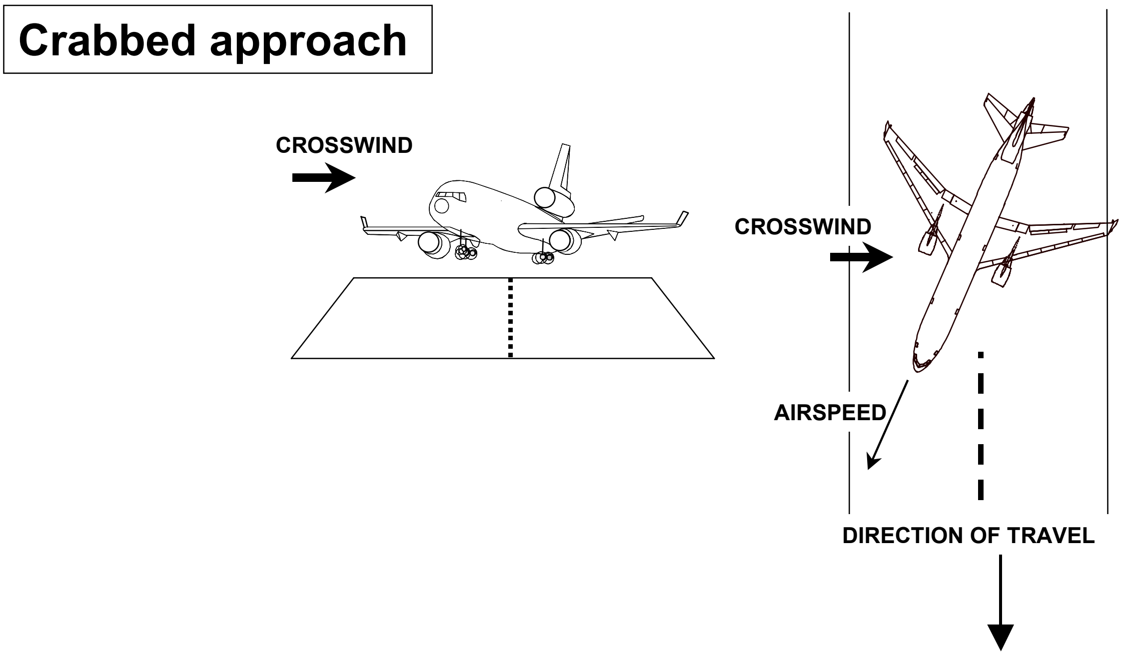

Figure 1:Crabbed approach for a crosswind landing.

[3] Generally pilots prefer the crabbed technique to the wing-down technique as it relieves them of flight with crossed controls. However it may be necessary to combine crab and sideslip during strong crosswinds. For crosswinds in excess of say 20 Kt. sideslip only landings are not recommended due to limited aileron capacity and bank angle limits.

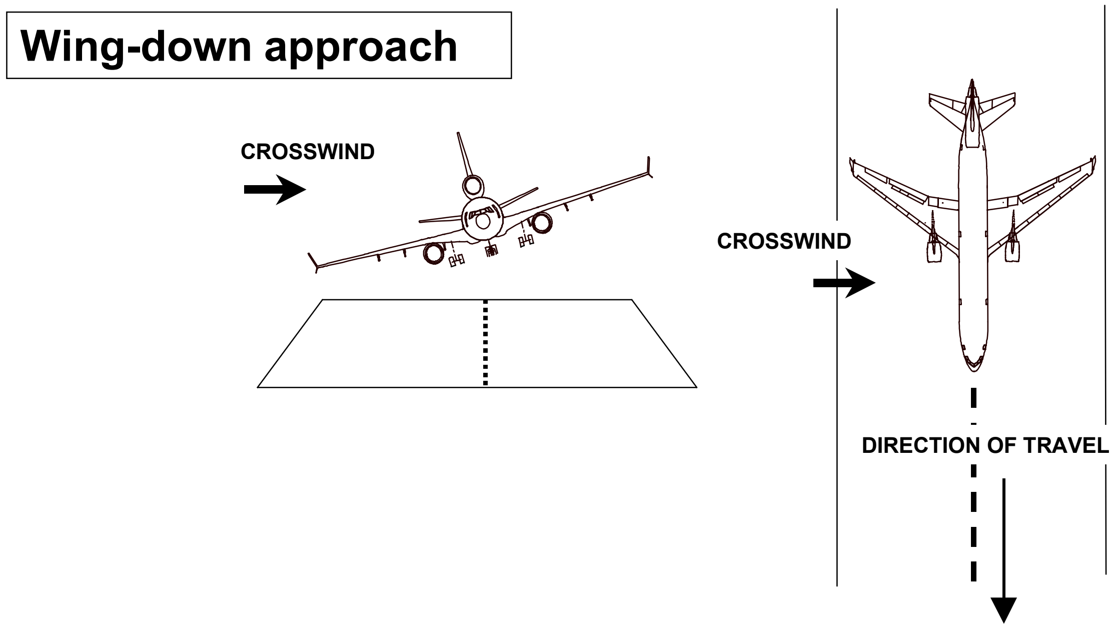

Figure 2: Wind-down approach for crosswind landing.

Usually before the landing the aircraft is “decrabbed” which yields a transition from the “drift” technique to the “wing-down” technique. This means that at a certain height above ground level selected by the pilot or programmed in the autoland computer a rudder input is given which yaws the aircraft towards the runway heading. In addition a roll input is given such that the aircraft banks into the wind. In the ideal situation the aircraft is aligned accurately with the runway centreline to touchdown with negligible lateral drift. However in practice aircraft are frequently landed with an appreciable residual drift, in particular when high crosswind components are present and when roll angle becomes the limiting factor. The latter is the case for large aircraft with wing mounted engines where wing tip and/or engine pods strikes are already possible at relatively small roll angles. Certain of these aircraft therefore are landed in the “drift” technique without “decrabbing” at all. Certain modern aircraft are now equipped with a GPWS mode that generates a roll angle audio warning when exceeding a combination of a pre-programmed roll angle and a roll rate at low height to limit the chances of tip or pod strikes.

The reduction in the accuracy of the “decrab” manoeuvre lessens the demands on the control capacity at the expense of the undercarriage, which must absorb the resulting side loads. Although frequently steady crosswinds are considered it is clear that in day to day operations aircraft also have to cope with vertical wind gradients and random gusts superimposed on the steady conditions. Turbulence intensities usually are related to the strength of the total wind. Because crosswind is only a component of the total wind vector the gust effects may be even stronger than the crosswind component itself. Also during strong crosswinds the wind direction veers. In particular these effects substantially contribute to the control effort in the final stage of the approach. It may force the pilot to use quick and large control deflections. This in return may lead to less controlled landings and increased risk of a hard landing and/or tip/pod strikes.

2.2 Ground roll part

Following the crosswind approach the touch down and the landing ground roll ensues. General considerations indicate three factors, which may limit the sustainable crosswind on the ground. First there is the tendency to drift side ways with the wind across the runway. Second the possibility of the aircraft turning of the runway by weather cocking into the wind as a result of inadequate directional control and finally the danger of overturning. Although the latter is small for larger aircraft in particular aircraft with wing mounted engines are limited in roll angle (pod or tip strike danger).
Crosswinds have their maximum effect on the aircraft just after touchdown when the aircraft is still flyable. Directional control can be maintained with rudder inputs, which in many aircraft also steer the nose wheel to a maximum of approximately 7 to 10 degrees. To cope with severe turbulence and gusts also on the ground pilots will give sometimes large and abrupt steering inputs with the pedals. However if possible they must be avoided because this may lead to over control and/or skidding of the nose wheel resulting in less grip on the runway.

Equilibrium conditions during a crosswind ground roll are determined by a complex balance between the aerodynamic forces acting on the aircraft and the mechanical forces generated by its undercarriage and tires (see Figure 3). The magnitude of the reaction sideforces acting on the tires are a function of yaw angle, ground speed and runway condition. On wet and contaminated runways, the magnitude of the sideforces of the tires are reduced significantly. Compared to a dry runway the sideforces can be reduced by 50-90%. Therefore wet and contaminated runway conditions will limit the sustainable crosswind during the ground roll.

The use of reverse thrust in crosswind conditions on wet and contaminated runways can aggravate directional control problems during the ground roll. Whenever the aircraft is allowed to weathervane into the wind, the reverse thrust force component perpendicular to the runway centreline adds to the crosswind force component. The reverse thrust will then pull the aircraft to the downwind side of the runway. The tire sideforces are too low to counteract this drift for the existing runway conditions. The only way for the pilot to overcome this situation is to release the brakes, deselect reverse thrust or even apply some forward thrust and steer the aircraft back onto the runway centreline before reapplying any braking force.

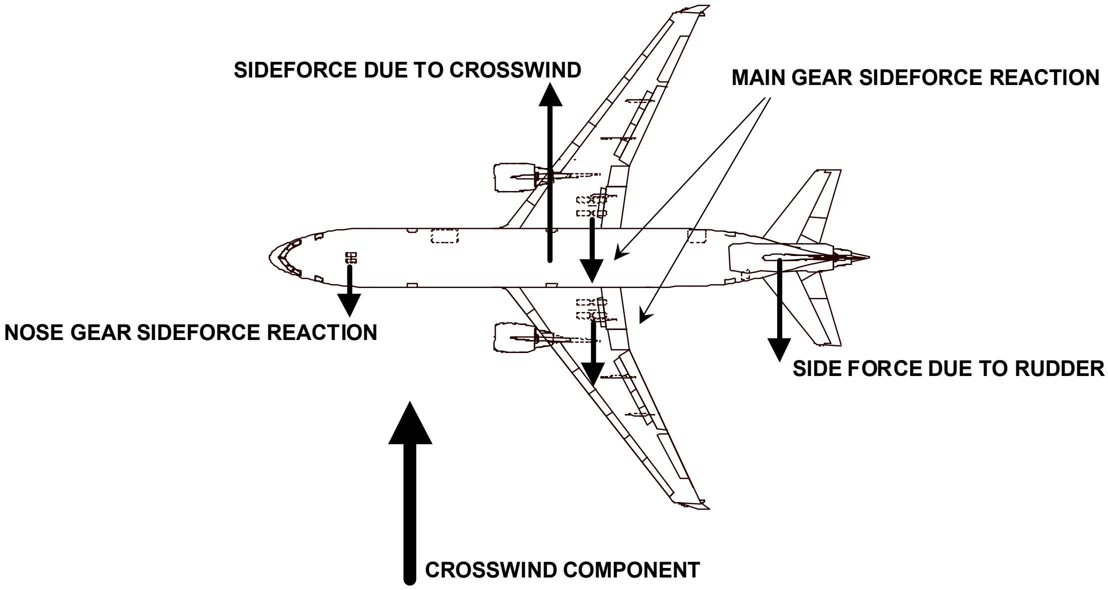

Figure 3: Forces acting on an aircraft during the ground run in crosswind.

3 Wind climate and measurement of wind conditions

3.1 Factors affecting the wind speed around an airport

At the Earth's surface, ground forces induced by obstacles, are exerted on the wind causing it to slow down. The effects of these ground forces decrease with increasing altitude up to a height of 500-3000 meters where there is no influence anymore. This height is called the gradient height. The region between the Earth's surface and the gradient height is known as the atmospheric boundary layer. The typical parameters, which affect the wind speed in this boundary layer at an airport, are:

- Surface roughness
- Geographical location
- Surrounding topography (e.g. hills and mountains)

For instance an airport surrounded by open fields will have a different wind climate than an airport surrounded by mountains.

3.2 Observing and reporting of surface wind

3.2.1 ICAO ANNEX 3 recommendations

International standards and recommended practices for observing and reporting of surface wind characteristics have been laid down in ICAO Annex 3, “Meteorological service for international air navigation”. Section 4.5 of Annex 3 states the following: "*The mean direction and the mean speed of the surface wind should be measured, as well as significant variations in speed and direction"*.

In general, there are a number of devices for measuring the surface wind. Normally a cup anemometer is used for measuring the wind speed. The wind direction can be measured using a weather vane. In practice, the surface winds cannot be measured directly on the runway. Therefore, Annex 3 recommends that the wind sensors should be located at those sites, which best represent the surface winds along the runway. If there are significant differences in wind along the different runways or landing paths (e.g. when due to terrain they are significantly different from that along the runway), additional wind sensors should be used. Annex 3 further states that "*the wind should be measured at a height of 6 to 10 meters"*. The average period for wind observations used for reports at the airport for takeoff and landing, and for wind indicators for air traffic services, should be 2 minutes according to Annex 3.

Significant variations in wind speed and direction should only be considered when:

- The total variation in wind direction is 60° or more with a mean speed of 3 Kt. or more, and/or
- The variation in wind speed is more than 10 Kt. relative to the mean wind speed
- When actual winds are reported as part of the takeoff and landing clearance by the tower.

Such variations should be expressed as the two extreme directions for the wind direction and as minimum and maximum speeds attained for the wind speed. Note that these variations are usually based on a 10-minute report. There are also weather reports used in which the mean wind and direction are also based on a 10-minute period, rather than a 2-minute period.

The attainable accuracy of the surface wind measurements is according to ICAO Annex 3:

- Wind direction: ± 5°
- Wind speed: ± 1 Kt up to wind speeds of 20 Kt., above 20 Kt. the accuracy is ±5%

3.2.2 Weather reports

Basically the following types of aviation weather reports, giving pertinent information concerning the governing wind-speed and –direction, are used:

- Actual reports, consisting of
    1. En-route METAR reports
    2. Take-off and landing (Tower and ATIS) reports
- Forecast reports

METAR reports

The METAR reports are normally compiled each half-hour for an airport, or at shorter intervals when the weather is changing rapidly. METAR reports contain information about wind, visibility, temperature etc. The mean surface wind speed given in the METAR reports, is measured over a ten-minute period preceding the given observation time.
Gusts are computed using a 3 seconds moving average window. Gusts are included when the maximum wind speed within the preceding ten-minute period exceeds the mean speed by 10 Kt.
Depending on the capabilities of the meteorological staff on the airport, the METARs may be supplemented by a 2-hour trend forecast, the validity period of which starts at the end of the observation time.
Special reports are supplemented to the METAR reports when certain abrupt changes occur in the weather.

Take-off and landing reports

For takeoff and landing operations pilots use actual weather reports. Before landing the pilot can obtain the weather information for the airport from the Automatic Terminal Information Service (ATIS). The ATIS message is updated every half-hour unless significant changes occur (See ICAO Annex 3). It contains information on: wind, ceiling, visibility, altimeter setting, runways in use, and other important airport information. The wind data in the ATIS is similar to that reported in the METAR. The wind data given in the ATIS are used to calculate the cross- and tailwind for the runway on which the pilot will land. On short final the pilot may obtain a final wind report from the tower. This wind report is more accurate than the ATIS report since it is based on the two-minute period preceding his contact with the tower. This wind reported by the tower is known as the "tower wind". Gust is included in the tower wind when it exceeds the mean wind by 10 Kt. or more. This gust speed is based on a ten-minute sample period. Note that this wind is not measured at the tower itself! The same measuring devices are used as for any other wind report. For takeoff it is normal to use initially the wind information obtained from the ATIS. Before actual takeoff the tower will normally provide the pilot with the tower wind. However, in some occasions the pilots use only the ATIS. ICAO Annex 3 states that for both takeoff, and landing the wind should be based on a two minutes sample period. This recommendation therefore implies that the ATIS wind data, which is based on a 10 minute sample period, should not be used for takeoff and landing. Some current cockpit procedures however may require some calculations to be performed before commencing the take-off, in which the wind is used from the ATIS. To avoid delay at the runway holding position, these are carried out while the aircraft is still parked at the gate.

The wind reported in the ATIS report is valid for the main runway in use. The tower wind is valid for the runway on which the pilot is cleared to land or to takeoff. If only the ATIS is used to calculate the crosswind and another runway than the main runway is used, the calculated crosswind may differ from the actual crosswind during takeoff.

Forecast Reports

Forecast reports are known as TAF reports. TAF reports contain the forecast of the weather conditions at an airport for a period from 9 or 24 hours.

3.3 Mean wind speed and gust

The instantaneous wind speed, V(t) is given by

$$V(t) = V_m + u(t)$$

In which V_m is the mean wind speed over time period T and u(t) is the amount of turbulence around the mean speed. An example of the variation of the wind speed over a time period T is given in Figure 4.

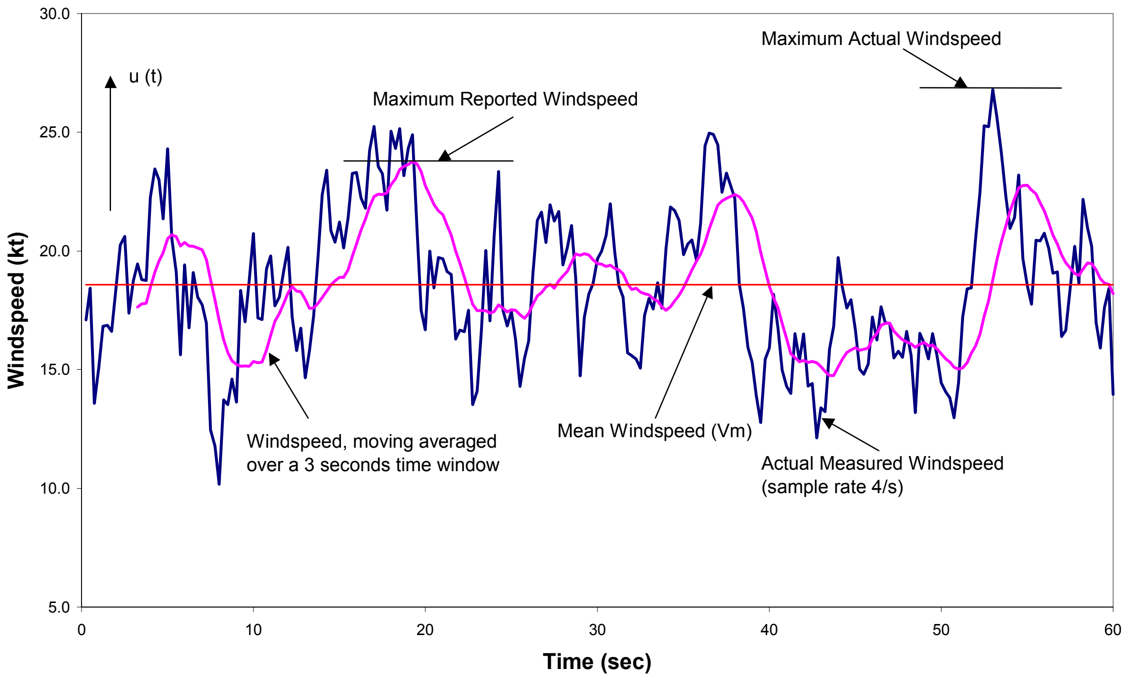

Figure 4: Wind speed versus time.

Substantial deviations of the mean wind speed over a time period T, are called gusts. The gust speed itself is usually the instantaneous maximum wind speed that occurred in the period T. In order to filter out the higher frequency components of turbulence, which are less relevant for aircraft performance, in general gust reports are based on the maximum value of a moving average of the wind measurements within a given time period T.

As mentioned in the previous section, ICAO Annex 3 recommends to use for this purpose a 3 seconds moving average window over a time period of 2 or 10 minutes.
Figure 4 also illustrates the effects of using such a moving average on wind measurements. Clearly substantial differences can occur between the instantaneous maximum wind speed in a given time period and the moving averaged maximum wind speed. .

In general, the ratio of the maximum gust speed and the mean speed is called the gust factor G. This factor is given as:

$$G = \frac{V_{gust}}{V_m}$$

A simple statistical model has been developed by Wieringa (Ref. 2) to calculate the expected gust factor G as function of e.g. surface roughness and height. For an airport this factor is typically about 1.3-1.6 at a height of 10 meters. As a rule-of-thumb a gust factor of 1.5 can be used. Note that gusts that occur in thunderstorms cannot be calculated using the gust factor presented in Ref. 2. Further details about thunderstorms and gusts can be found in Ref. 2.

3.4 Sources for uncertainty in wind reports

Amongst others, wind reports are used by pilots to assess whether crosswind conditions for the intended take-off and landing runway are within the operational limits for the aircraft at hand. In general there can be several sources for uncertainty in the wind reports, as conveyed to the pilot. One of the main sources is obviously the stochastic character of the wind phenomenon, due to which the wind may change since the last report to the pilot. Other sources are, as stipulated in the previous two sections, the way the wind measurements are processed and the reporting procedures to the pilot, according ICAO Annex 3.

The most crucial report to the pilot, on which he has to base his decision, to commence his takeoff or to continue/abort his landing, is obviously the wind report from the Tower. However due to the mentioned sources of uncertainty, the actual crosswind encountered during landing or take-off can substantially deviate from the latest Tower report.

In order to illustrate to which deviations this can lead, in the following a representative example is given. For this purpose wind measurements have been simulated, according to a turbulence model as specified in the JAR-AWO (All Weather Operations), and which is used in the process of certification of auto-land systems. This turbulence model yields wind-velocities, with a Gaussian distribution, according to a so-called Dryden model. Parameters of this model have been set to provide wind measurements at 10 meters height above the ground and for a mean wind speed of 18 Kt, with a mean wind-direction of 50 degrees relative to the runway centre-line. Nominally this would lead to 14 Kt crosswind for the runway in use, which is in general within the operational limitations for a dry runway, and well within the operational crosswind capabilities of aircraft.

The simulated wind velocity and wind directions have been processed to generate METAR as well as Tower reports, according the procedures of ICAO Annex 3.
In general results show that METAR reports and Tower reports are well in agreement.

Two METAR reports, taken over an hour of simulated wind measurements, show a mean wind velocity of 18 Kt. No gusts are reported, because they did not exceed 10 Kt difference with the mean speed. Wind-direction showed a mean of 50 degrees, with variations between 20 and 80 degrees.
Thirty Tower reports, with 2 minutes time interval, show for the same data set reports of wind speed between 18 and 20 Kt. For the majority of time no gusts were reported, although some reports included gusts up to 30 Kt incidentally. Wind-direction showed a mean of 50 degrees, with variations between 20 and 90 degrees.

The agreement between METAR and Tower reports is not surprising, because the wind measurements were simulated with invariant parameters.

The real statistic properties of the simulated wind measurements over a one-hour period are summarised in Table 1.

Table 1: Statistic properties of simulated wind measurements over a one-hour period.

	Mean	**Min**	**Max**	**Stand. Dev.**	**Exceedance Time**	
Actual wind speed (Kt)	18.4	3.4	35.5	4.2	>25 Kt: 228 s	>30 Kt: 15 s
Moving averaged wind speed (Kt)	18.4	7.4	31.1	3.4	>25 Kt: 106 s	>30 Kt: 2 s
Wind direction (deg)	50	-5	114	14	>80 dg 73 s	<20 dg 69 s
Crosswind	13.8	-1.3	30.4	4.2	>20 Kt: 262 s	>25 Kt 16 s

From Table 1 it is clear that substantial deviations from the reported wind characteristics can occur due to the stochastic nature of wind phenomena. It is anticipated that in reality discrepancies may be even larger than illustrated here, because the simulation was carried out with time-invariant parameters, while in practice mean wind velocity and direction may vary over time, decreasing the accuracy of the wind reports. Moreover, the simulated measurements were modelled according to a Gaussian process, while in practice wind measurements will have a non-Gaussian (patchy) character, increasing the probabilities of substantial deviations from the mean.

Overall it can be concluded from the example, as presented here, that a reasonable probability does exist, that while wind reports to the pilot do indicate that crosswind is not exceeding 15 Kt,

in reality the actual encountered crosswind during the landing phase can deviate 10 Kt or even more from the reported wind.
For even higher reported crosswinds, deviations may increase accordingly.

To which situations this uncertainty may lead is illustrated in Figure 5. A part of the simulated wind measurement is taken, as an example for an aircraft during final approach. It is shown how wind speed and direction behaves, and which Tower report is given to the pilot some 1.5 minutes before landing. Based on this report the pilot would expect a crosswind of around 15 Kt during the landing phase. In reality it is shown that during the landing a patch of crosswind is encountered of around 22 Kt over a period of 10 seconds, with a peak crosswind of 28 Kt.

The situation described in this section clearly illustrates that a substantial margin has to be adopted with respect to the maximum demonstrated crosswind during the certification process.

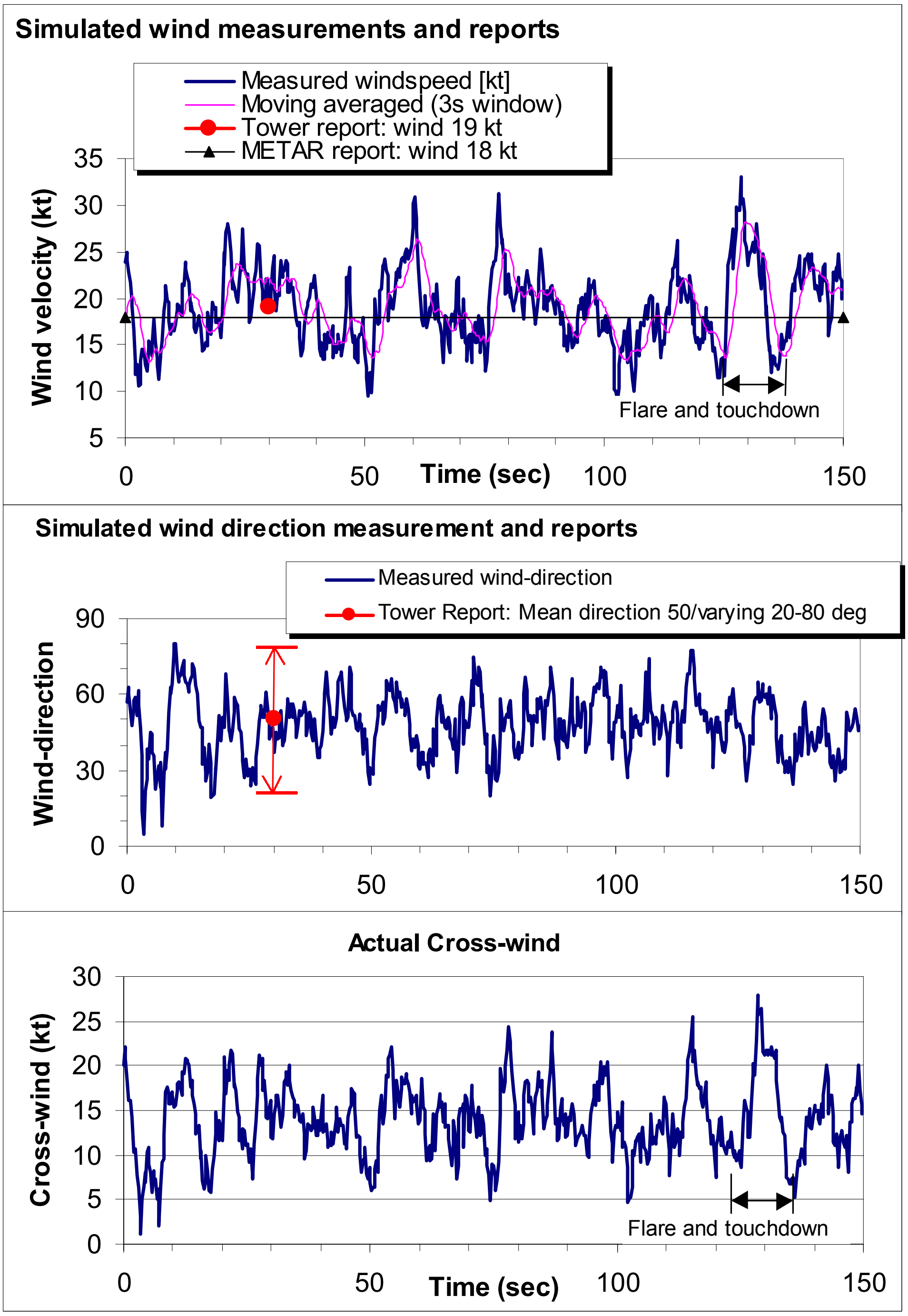

Figure 5: Illustration of wind reported and actually encountered during the landing

4 Inventory of certification rules and operational guidelines

4.1 Certification rules

The type of aircraft considered in this study are certified according to JAR 25 or FAR 25. Both FAR and JAR state the following regarding crosswind:

> *JAR/FAR 25.237 Wind velocities.*
> *For landplanes and amphibians, a 90-degree cross component of wind velocity, demonstrated to be safe for takeoff and landing, must be established for dry runways and must be at least 20 knots or 0.2 V_{S0}, whichever is greater, except that it need not exceed 25 knots*[4].

It is also stated that the wind velocity must be measured at a height of 10 meters above the surface, or corrected for the difference between the height at which the wind velocity is measured and the 10-meter height. An additional rule is that there also may be no uncontrollable ground-looping tendency in 90º crosswinds (JAR/FAR 25.233). When JAR/FAR 25.237 is examined carefully, the following can be noticed:

- Only dry runways have to be considered.
- It is not clear if the wind speed includes gusts or not.
- No crosswind limits have to be established, only demonstrated values.

The maximum demonstrated crosswind is the value that was demonstrated to the certifying authority during the certification flight test trials. Pilot judgement based on flight handling then is included in order to establish if this value is also the limiting crosswind for that aircraft.
An overview of demonstrated crosswinds of western-built passenger transport aircraft is given in Table 2. The overall average demonstrated crosswind of these aircraft is 30 Kt. For some aircraft different crosswinds are demonstrated for takeoff and landing.

[4] In which V_{SO} means the stall speed or the minimum steady flight speed in the landing configuration.

Table 2: Overview of demonstrated crosswinds of western-built aircraft.

Manufacturer	Model	Demonstrated Crosswind knots	Manufacturer	Model	Demonstrated Crosswind knots	Manufacturer	Model	Demonstrated Crosswind knots
Aerospatiale	ATR-42	45 (Takeoff)	British Aerospace	BAe146-100	25 (Takeoff)	Douglas	DC-10-10/30	29
Aerospatiale	ATR-42	38 (Landing)	British Aerospace	BAe146-100	30 (Landing)	Douglas	DC-10-40	23.5
Aerospatiale	ATR-72	35	British Aerospace	BAe146-200	30 (Takeoff)	Douglas	MD-11	35
Airbus	A300-600	32	British Aerospace	BAe146-200	35 (Landing)	Douglas	MD-80	28
Airbus	A310-200/300	28	British Aerospace	Jetstream 4100	35	Douglas	MD-87	28
Airbus	A320-100/200	29 (Takeoff)	Canadair	CL-65 RJ	24	Douglas	MD-90	30
Airbus	A320-100/200	33 (Landing)	Canadair	CL-600/601/604	24	Embraer	EMB-120	30
Airbus	A321	27 (Takeoff)	Cessna	500	25	Embraer	EMB-145	30
Airbus	A321	28 (Landing)	Cessna	550	23	Fokker	F28-all series	30
Airbus	A330-300	17 (Takeoff)	Cessna	560	20	Fokker	F100	30
Airbus	A330-300	22 (Landing)	Cessna	650	25	Fokker	F70	35
Airbus	A340-200/300	27	Cessna	750	21	Fokker	F50	33
Boeing	707-300B ADV/C	33	Dassault	Falcon 20	23.5	Fokker	F27-all series	25
Boeing	727-100/200	29	Dassault	Falcon 50	24.7	Gulfstream	II	24.5
Boeing	737-100/200	29	Dassault	Falcon 900	30	Gulfstream	III	21
Boeing	737-300/400/500	35	Dassault	Falcon 2000	35	Gulfstream	IV	24
Boeing	747-100/200	28	deHavilland	DHC-8-100/200/300	36	Learjet	24	26
Boeing	747 SP	34 (Takeoff)	Dornier	Do 328-100	21	Learjet	25	33
Boeing	747 SP	32 (Landing)	Douglas	DC-8-61	17	Learjet	31	30
Boeing	747-400	30	Douglas	DC-8-62	32	Learjet	35/36	26.5
Boeing	757-200	30	Douglas	DC-8-63	23.5	Learjet	55	27
Boeing	767-200	29	Douglas	DC-8-71/72/73	28	Learjet	60	29
Boeing	767-300	33	Douglas	DC-9-30/34/40	36	Lockheed	L1011-1	33
Boeing	777-200	38	Douglas	DC-9-50	28	Lockheed	L1011-500	28
						SAAB	340	35

SourceFaaand manufacturers

4.2 Crosswind demonstration according to FAA AC 25-7A

JAR/FAR 25.237 does not give details on the actual crosswind demonstration itself. The FAA has published a flight test guide for the certification of transport category aircraft in the form of an Advisory Circular (AC 25-7A). This Advisory Circular contains guidelines about the crosswind demonstration flight tests. These guidelines are:

25.237 - Wind Velocities.

Explanation.

- *There must be a 90-degree crosswind component established that is shown to be safe for takeoff and landing on dry runways.*
- *The airplane must exhibit satisfactory controllability and handling characteristics in 90-degree crosswinds at any ground speed at which the airplane is expected to operate.*

Crosswind Demonstration.

A 90-degree crosswind component at 10 meters of at least 20 knots or 0.2 V_{S0}*, whichever is greater, except that it need not exceed 25 knots, must be demonstrated during type certification tests. There are two results possible:*

- *A crosswind component value may be established which meets the minimum requirements but is not considered to be a limiting value for airplane handling characteristics. This "demonstrated" value should be included as information in the AFM.*

- *A crosswind component value may be established which is considered to be a maximum limiting value up to which it is safe to operate for takeoff and landing. This "limiting" value should be shown in the Operating Limitations section of the AFM.*

Procedures.

(i) Configuration. These tests should be conducted in the following configurations:

- *At light weight and aft CG (this is desirable; however, flexibility should be permitted).*
- *Normal takeoff and landing flap configurations using the recommended procedures.*
- *Normal usage of thrust reversers. Particular attention should be paid to any degradation of rudder effectiveness due to thrust reverser airflow effects.*
- *Yaw dampers/turn co-ordinator On, or Off, whichever is applicable.*

(ii) Test Procedure and Required Data. Three takeoffs and three landings, with at least one landing to a full stop, should be conducted in a 90-degree crosswind component of at least 20 knots or 0.2 V_{S0}*, whichever is greater, except that for Amendment 25-42 only it need not exceed 25 knots. For each test condition, a qualitative evaluation by the pilot of airplane control capability, forces, airplane dynamic reaction in gusty crosswinds (if available), and general handling characteristics should be conducted. The airplane must be satisfactorily controllable without requiring exceptional piloting skill or strength. Wind data from the INS systems, tower, or portable ground recording stations should be corrected to a 90-degree crosswind component and to a height of 10 meters.*

Regarding this AC the following comments can be made. First there are two possibilities on how to note crosswinds in the AFM. If the demonstrated crosswind is not considered to be a limiting value for aircraft handling characteristics, this demonstrated value can be placed as information in the AFM. Higher crosswinds are then allowed when the applicable operational requirements and the airline specification allow it. If the demonstrated crosswind is considered to be a maximum limiting value up to which it is safe to operate the aircraft, the demonstrated crosswind value will appear as a limiting value in the AFM. It is not allowed to operate the aircraft beyond this crosswind. For practically all aircraft certified by the FAA the demonstrated crosswind is not regarded as limiting by the FAA test pilots. Some other certification authorities always consider the demonstrated crosswind as limiting. For instance, for all Fokker aircraft certified by the Dutch Civil Aviation Authorities (RLD), the demonstrated crosswind is considered to be a limit. This last approach avoids any subjectivity on the fact whether or not the demonstrated crosswind is limiting. In fact, Fokker 100 flight testing at wind speeds up to 43 knots crosswind component during takeoff, manual and autolands showed that the airplane was not the limiting factor. However, because these flights were not part of an official test campaign these values never appeared in the AFM.
In the test procedure and required data section, it is stated that wind data can be obtained from the INS system, the tower or a portable ground station. The tower wind contains a mean wind based on a two minute sample and (if high enough) a gusting wind value. The AC does not clearly state which wind should be used. Crosswind derived from the INS system can include gust depending on for instance the way the data is analysed. Fokker tests showed that between the mean INS derived wind and the mean tower wind, differences of up to 10 Kt. or more are possible. Boeing (See Ref. 5) for instance uses the INS data to derive a crosswind by plotting the crosswind component as function of time. The crosswind at the time the aircraft is 10 meters above the ground is then read off the plot. Engineering judgement is used in fairing the data. Fokker Aircraft on the other hand has a different approach (See Ref. 4). During the test flights with Fokker aircraft the tower wind is requested when the aircraft is close to a height of 10 meters from the ground. The mean wind given is then used to compute the crosswind. From

information provided by Fokker, concerning the crosswind demonstration flight tests with the Fokker 70, it can be deduced that had Fokker chosen to apply the same methodology as Boeing, the demonstrated crosswind capability would have been at least 10 Kt higher than presently mentioned in the aircraft's AFM.

4.3 Use of crosswind limitations by operators

Operators normally have wind limitations noted in their Aircraft Operating Manuals (AOM). A survey was taken of a number of (large) operators worldwide. These operators were requested to send the crosswind limits for the aircraft they operated as published in their AOMs. The operators were also asked to provide information about any additional limitation posed on crosswind operations. From this survey the following facts are identified for the operators surveyed:

- Most of the operators include gusts in their crosswind limits.
- All operators adjust the crosswind limits for wet and contaminated runways.
- Some of the operators adjust the crosswind limits for visibility.
- Most of the operators have reduced crosswind limits for less experienced pilots.
  FAR part 121.438 demands that first officers that have less than 100 hrs currency on type are not allowed to make crosswind landing in excess of 15kts.
- Most operators use crosswind limits that do not exceed the demonstrated crosswinds.
- Most operators account for runway width.
- Most operators have a separate (lower) maximum crosswind for autoland operations.

Autoland certification under crosswind conditions is established primarily through "Monte-Carlo" simulations of automatic landings of that particular aircraft. The simulations must show that under varying conditions the touch down performance complies with the criteria set by the FAR/JAR requirements. By means of a specific set of flight tests it must be demonstrated that the actual touch down performance falls within the footprint of the performed simulations. Due to system constraints maximum crosswind values for autoland operations are less than the manually demonstrated crosswind landings. However, it is likely that most autoland systems can handle higher crosswinds. It is the opinion of the authors that when the visibility is good and the crosswind is high, preference should be given to conduct an autoland rather than a manual landing.
The adjustments of crosswinds on wet and contaminated runway conditions are normally based on advisory information obtained from the manufacturers. An example of the impact of runway condition on crosswind limits is presented in Table 3 for a number of Boeing aircraft (Ref. 5). The crosswind limits presented in Table 3, are recently revised values. Some operators use the older guidelines provided by Boeing. Boeing derives crosswind guidelines for wet and

contaminated runways using piloted simulations and engineering analyses. No flight tests are conducted. It appears that the majority of the development is based on piloted evaluations in the 757 engineering simulator in order to develop an analytical model that is then used as a basis for the other aircraft types (Ref. 6). In fact this is remarkable because (engineering) simulators are not a good tool to explore the ground part of a landing or takeoff, dry or wet/contaminated. This because the quality of the mathematical ground model in combination with the motion and visual ques of a simulator is usually not high enough to allow sufficient confidence in the evaluation results. Therefore limits based on pilot evaluations in a simulator may prove significantly different (optimistic in most cases) from realistic values. Also it is remarkable that Boeing has concluded in this process that turbulence is not a real factor for the determination the operational crosswind limitations. According to Boeing turbulence does increase workload to some extent, but is not the limiting factor for crosswind up to 40 Kt. The limiting factor appears to be mainly directional control capability. This is in sharp contrast with Fokker experience with crosswind demonstration flight tests with the Fokker 70, carried out on Keflavik, Iceland, where real crosswind up to 40 Kt. was encountered. Clearly during these tests it was shown, that the extreme turbulence associated with the heavy wind, caused specifically lateral-directional controllability problems, which limited the crosswind capability.

Note also that because the demonstrated crosswinds of the Boeing aircraft are not considered to be limiting, Boeing is allowed to advice higher crosswinds than demonstrated to the operators as shown in Table 3. Because the crosswind limits on wet and contaminated runways are advisory information only, the operators can use different crosswind limits for the same aircraft and runway condition. It can be noted that the interaction between aircraft tires and a non-dry runway varies between different runways. Some factors that play an important role here are surface texture, contamination, grooving and the ability to spill water. The result is that the measurements on one non-dry runway cannot be used to predict the behaviour on another non-dry runway. As the airframe manufacturer is responsible for valid legal certification data, it is usually their policy to provide only non-legal information.
Figure 6 shows an example of crosswind limits used by three different operators for the Boeing 747-400. Operator A uses the revised crosswind values which are significantly higher than those imposed by the other operators.

Table 3: Revised Operations Manual Landing Crosswind Guidelines for Boeing aircraft (Kt.).*

Runway Condition	**737**	**747**	**757**	**767**	**777**
Dry	40	36	40	40	45
Wet	40	32	40	40	40
Standing Water/Slush	20	20	20	20	20
Snow - No Melting	35	25	35	35	35
Ice - No Melting	17	15	17	17	17

* Note: These crosswinds are derived using piloted simulations and engineering analyses. These are not demonstrated values.

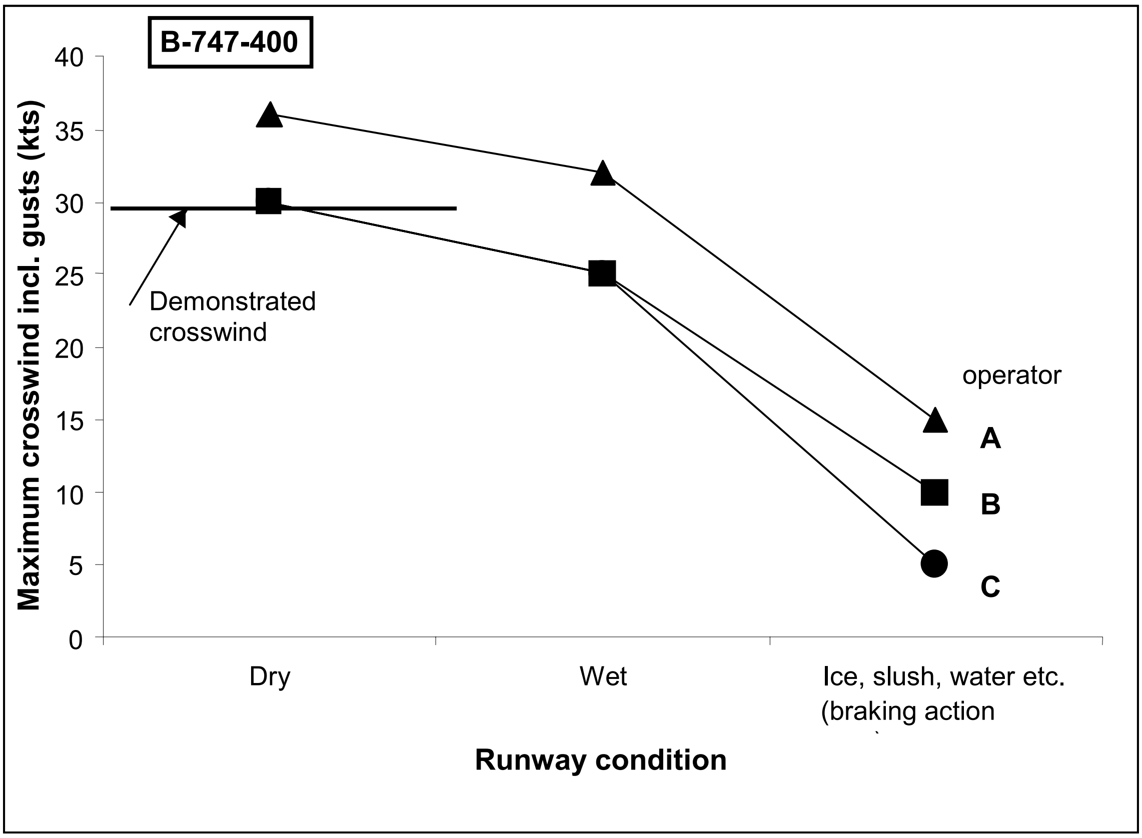

Figure 6: Maximum crosswind of a B-747-400 for landing as function of runway condition for three different operators.

4.4 Use of crosswind criteria for runway selection by airports

Airports can also set crosswind maxima. These are general maxima valid for all commercial aircraft, which use the airport. gives an overview of crosswind maxima used by a number of airports obtained from the relevant AIP's. When analysing table 4, the following can be noticed:

- Gusts are not included in the crosswind maxima except for one airport.
- There are differences in the actual crosswind maxima used varying from 10 to 25 Kt. One airport uses different crosswind maxima for day and night hours. The vast majority of airports use a maximum of 15 Kt. (according to ICAO recommendations but without gust included).
- Most airports consider the impact of runway surface condition on crosswind maxima.

Some additional notes should be made regarding table 4. Heathrow has the highest crosswind (25 Kt.) maximum of all airports considered in table 4[5]. However, if the wind climate around Heathrow is analysed it becomes clear that crosswinds of 25 Kt. or more, occur less than 0.2% of the time per year (17 hours per year). Most airports in table 4 use a crosswind maximum of 15 Kt. for the preferential runway(s). This rule is adopted from ICAO which states that *"Noise abatement should not be the determining factor in runway nomination when the crosswind component, including gusts exceeds 15 Kt."*. Note that ICAO clearly states that gusts are included. No additional information is available in which the 15 Kt. maximum is explained. It should be clear that ICAO only gives recommendations, and does not constitute regulations. When the 15 Kt. including gusts maximum is compared to the wind reporting methods recommended by ICAO (see section 3.2 and ANNEX 3), the following interesting fact can be found. With a typical gust factor of 1.5 (see section 3.3), the mean wind speed associated with a wind of 15 Kt. including gust, is 10 Kt. The difference between the mean wind and the maximum wind is then 5 Kt. According to ICAO ANNEX 3, gusts should only be reported when the difference between maximum wind and mean wind is 10 Kt. or more. This means that gust is only reported when the mean wind speed is about 20 Kt. (again assuming a gust factor of 1.5). So opposed to the guideline of ICAO regarding a crosswind maximum of 15 Kt. including gusts, in practice a crosswind limit of 15 Kt excluding gusts is used as a result of the recommended reporting procedures. It is likely that minimal reported gust values in general can only be reached whenever the mean wind speed is in excess of 15 Kt. In this case the wind speed including gust can be around 22.5 Kt. (see also section 3.3). This can be a hazardous situation since the pilot uses in this example, only the mean wind speed for evaluating the crosswind maximum stated in the AOM.

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[5] Note that Schiphol has the same crosswind limit of 25 kts during the night hours in combination with CAT I operations and good braking action.

The AIP Canada gives recommendations about the maximum crosswind in relation to the braking friction of a runway. Figure 7 gives the recommended crosswind maximum as function of the James brake index (JBI). This brake index is determined using a friction tester known as the James Brake Decelerometer. Typical JBI values for different runway conditions are:

- JBI >0.7 for dry runways
- JBI = 0.6-0.7 for damp runways
- JBI = 0.3-0.6 for wet runways
- JBI = 0.2-0.4 for snow covered runways
- JBI < 0.3 for water/slush (>1 in.) covered runways
- JBI <0.2 for icy runways

According to the AIP Canada approach runway conditions could occur on which crosswinds are not allowed at all. It is not clear from the AIP Canada if gusts are considered or not in the recommended maximum crosswind.

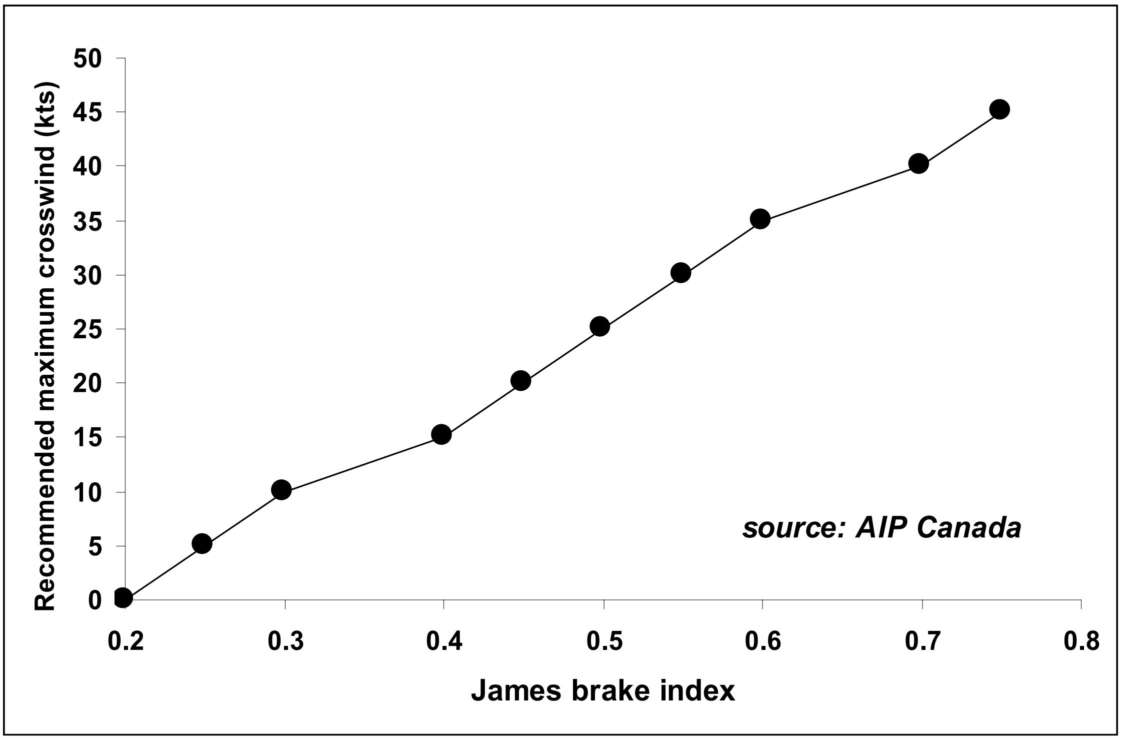

Figure 7: Maximum crosswind as function of the James brake index.

Table 4: Overview of crosswind limits used by a number of airports (survey of 1998).

ICAO CODE	Airport	Preferential runway and wind limitations
EGLL	London/Heathrow	a) When tailwind component is not greater than 5 kts on 27R/L these runways will be used in preference to 9R/L when surface is dry. b) When crosswind component on 27/09 exceeds **25 kts**, runway 23 will normally made available if there is a lesser crosswind component affecting it. Pilots asking permission to use the runway in the wind when 27L/R are in use should understand that their arrival or departure may be delayed.
EDDL	Dusseldorf	Jet and other aircraft of more than 8t AUW are not permitted to land/depart on runways 15/33. Permission may be granted for aircraft with higher AUW, if crosswind component on main runways 05R/23L does not allow safe landings, or when unavoidable due to traffic conditions.
LEBL	Barcelona/ElPrat	Whenever the runway is dry, or wet with braking action good, and the wind components do not exceed 8 kts tail and/or **20 kts** cross, use the following runway configuration: *See AIP for details.* Pilots could ask for the use of a runway other than the described system, but should assume possible delays.
EBBR	Brussels/National	When the runways 25L/R are dry and when meteorological conditions are such that the cross- and/or tailwind components do not exceed 15/8 kts surface wind, runways 25 L/R will be used for landing/takeoff. When these runways are wet, covered with snow or slush, the maximum cross- and/or tailwind components are **10 kts** and 5 kts. When the components exceed the values stated above, a runway more nearly into the wind will be assigned. However, 7L/R shall not be used for landing and 25L for takeoff except when no other suitable runway is available. ATC will on pilot's request assign another runway, runway-, traffic and weather conditions permitting.
EKCH	Copenhagen/Kastrup	All jets and prop > 11t MTOW: Runways 04/22 L/R are preferential and shall be used to the greatest possible extent. Between 0600-2300LT: Runway 12 & 30 may be used when: - crosswind component on preferential runway exceeds **15 kts**. - friction coefficient is below .3 on any part of the preferential runway. - preferential runway cannot be used due snow clearance, disabled aircraft, work on the runway, meteorological & runway conditions. When wind conditions permit, runway 12 shall be used for takeoff in preference to runway 30.

<table>
<tr><td></td><td></td><td>Between 2300-0600LT:
Runways 12 & 30 are closed for takeoff and landing. Runway 30 may, however, be used for landing when:
- crosswind component on preferential runway exceeds 15 kts.
- preferential runway cannot be used due snow clearance, disabled aircraft, work on the runway, meteorological & runway conditions.</td></tr>
<tr><td>EHAM</td><td>Amsterdam Schiphol</td><td>In selecting RWY combination, ATC will apply the following limits of wind components:

• If RWY is dry: tailwind 5 kts and crosswind 15 kts (gust included).
• If RWY is wet: no tailwind and 10 kts crosswind (gust included).

During the night hours wind criteria for the selection of RWYs will be 25 kts crosswind and 5 kts tailwind. In bad weather the selection will be made on the following table:

<table>
<tr><td>Operation:</td><td>CAT I</td><td>CAT II/III</td><td></td></tr>
<tr><td>RWY friction coefficient:</td><td>≥ 0.5</td><td>≥ 0.5</td><td>< 0.5</td></tr>
<tr><td>Crosswind:</td><td>25 kts</td><td>15 kts</td><td>5 kts</td></tr>
<tr><td>Tailwind:</td><td>5 kts</td><td>5 kts</td><td>0 kts</td></tr>
</table>
</td></tr>
<tr><td></td><td>Reykjavik</td><td>During the hours of 2330-0700 (2330-0730 Sat., Sun., and public holidays) runway 14/32 is designated noise as the preferential runway as far as practical. Takeoff from Runway 07 is not permitted, unless crosswind component on other runways exceeds 10 kts.</td></tr>
<tr><td>CYVR</td><td>Vancouver</td><td>Limiting Factors when selecting a preferential runway
a) physical condition of surface
b) effective crosswind component not to exceed 25 knots
c) effective tailwind component not to exceed 5 knots</td></tr>
<tr><td></td><td>Jandakot Airport, Perth</td><td>Jandakot Tower will select the duty runway on the basis of prevailing wind, with preference to 06/24 up to a crosswind maximum of 10 kts:</td></tr>
<tr><td></td><td>Ferihegy Budapest</td><td>According to the prevailing surface wind, normally runway 31R is used for landing and runway 31L for takeoff. Noise abatement should not be the determining factor in runway nomination when

• The runway is not clear and dry, i.e. it is adversely affected by snow, slush, ice or water, or by mud, rubber, oil or other substances.

• When the crosswind component, including gusts, exceed 15 kt</td></tr>
</table>

CYYC	Calgary International	Night Restrictions (2300-0700) local time Monday-Friday, 2300-0900, Saturday and Sunday: Taking into consideration the following conditions and except as authorised by Air Traffic Control, aircraft will depart on Runway 34 and land on Runway 16 or 28. 1. Physical condition of surface. 2. Effective crosswind component not to exceed **15 knots** for arrivals, **20 knots** for departures. 3. Effective tailwind component not to exceed **15 knots**. 4. Other Safety considerations declared by the Captain of the aircraft.

KANC	Anchorage International	Conditions that allow selection of next preferential runway:
		Selection of the next preferential runway based on the priorities established in Section A (*See AIP*). are allowed under the following conditions:
		
		• If the runway is not clear and dry, i.e. it is adversely affected by snow, slush, ice or water, or by mud, rubber, oil or other substances.
		
		• When winds, including gusts, as recorded by airport wind sensors, exceed:
		  • crosswind components of **28 km/hour (15 knots**), or
		  • tailwind components of 9KM/hour (5 knots)
		
		• When wind shear has been reported or forecast, or thunderstorms are expected to affect the departure or approach.
		
		• When the combined traffic levels at Elmendorf AFB and Anchorage International Airport result in excessive traffic congestion and cause unacceptable departure delays.
		
		• Consistent with Airport Bulletin 95-06, Runway 32 Extension Departure Policies, delay alone does not constitute a reason for heavy aircraft pilots to request a Runway 6R departure.

KMSN	Dane County Regional	Conditions for preferential use: Tailwind - 5 knots or less Crosswind - **15 knots** or less Runway Conditions - Clear and dry i.e. there is no ice, slush or other conditions in which the use of the preferential runway may compromise aircraft safety.
CYXD	Edmonton Municipal	Limiting factors for preferential runway : (affecting order of preference)* • Wet, snow covered or icy runway surface conditions. • Strong winds favouring non-preferential runways which are beyond safety limits of aircraft being operated with an effective crosswind exceeding **15 knots** for arrivals and departures or tailwind exceeding 5 knots. • Use of a less preferred runway is acceptable if a backlog of aircraft traffic builds up on the airport due to aircraft waiting for departure. For example when runway 30 is active, north and eastbound departures may be assigned runway 34. • Preferential runway out of service due to airfield maintenance reasons, or an aircraft halted on the runway due to mechanical problems, which preclude its immediate removal. • Medivac aircraft may deviate from the preferred runway system as circumstances require. *Note: These procedures shall not limit the decretion of either the air traffic controller or the pilot with respect to the full utilisation of the airport in the event of an unusual situation.
KOMA	Eppley Airport	Runway 32L is designated as the preferential use runway for turbojet aircraft under the following conditions: • Crosswind component within 90 degrees of runway heading and crosswind velocity not exceeding **15 knots**. • Tailwind component not exceeding 5 knots • Runway conditions clear and dry.

4.5 Use of crosswinds in relation to the design of an airport

ICAO Annex 14, "*Aerodrome Design and Operations*" provides guidelines for designing airports. One of its recommendations deals with the number and orientation of runways. It is stated in Annex 14 that the number and orientation of the runways should be such that the usability factor of the airport is not less than 95%. ICAO Annex 14 also provides guidelines for the maximum permissible crosswind components which should be used when analysing the usability of the airport. Table 5 presents the recommended maximum crosswinds as function of the reference field length. The reference field length is equal to the minimum required take-off field length. Most medium sized aircraft and larger aircraft have field lengths of 1500 meter and more. There are factors which may require that a reduction of the maximum crosswinds listed in Table 5 be taken into account. These factors are for instance runway surface conditions, handling characteristics among the different types of aircraft, width of runway etc.

Table 5: Maximum crosswind recommended for usability analysis.

Reference field length Meters	**Maximum crosswind** Kt. (mean wind, excl. gust)
1500 or more	20 (13 for poor braking condition)
1200 up to but not including 1500	13
less than 1200	10

5 Analysis of historical accident and incident data

In order to quantify the risk of crosswind operations and to get a better understanding of the contributing/causal factors, historical accident/incident data are analysed. The analysis is limited to aircraft operations of transport aircraft in the United States only. The main reason for this limitation is the availability of a virtually complete listing of all reported accidents and incidents that occurred in the US. Especially a complete listing of all incidents is very difficult to obtain for other regions in the world. The types of aircraft considered for this study are representative for most of the large commercial airports around the world. Also the different types of climate at the US airports are representative as an average for other non-US airports.

The following approach is applied:

- Identification of a sample of takeoff and landing accidents/incidents, including background information for each accident/incident (e.g. runway condition, crosswind, gusts etc.).

- Compilation of exposure data (e.g. number of flights).

- Analysis of the data.

5.1 Definitions

The following definitions are used in this study for an aircraft accident and an aircraft incident, which are based on the definitions used by the NTSB and FAA:

- Aircraft accident is an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage.

- Aircraft incident is an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations.

5.2 Accident data sources

Searches are conducted in the NLR Air Safety Database, which consists of several databases including those from the FAA, NTSB, ALPA and others. These sources provide sufficient data to enable compilation of a virtually complete listing of reported accidents and incidents fulfilling the selection criteria presented in section 5.3.

5.3 Accident selection criteria

The following selection criteria are used in selecting the accidents and incidents:

- Crosswind or gusting winds are contributing factors in the accidents/incidents.
- The accident/incident flights occurred in the U.S.
- Time period, in which the accident/ incident flights occurred, runs from 1983 through 1995.
- The accident/incident flights are conducted by U.S. Air Carriers, Operating under regulation 14 CFR 121, scheduled or non-scheduled service.
- Accidents/incidents occurred during takeoff or landing.
- Accidents/incidents due to sabotage, terrorism, and military action are excluded.

5.4 Exposure data

Exposure data are obtained from the FAA and are listed in Table 6. In the period 1983-1995 more than 96 million flights have been conducted under regulation 14 CFR 121.

Table 6: Exposure data for U.S. Air Carriers operating under regulation 14 CFR 121, Scheduled and Non-scheduled Service.

Year	*Flight Hours*	*Flights*
1983	7,298,799	5,444,374
1984	8,165,124	5,898,852
1985	8,709,894	6,306,759
1986	9,976,104	7,202,027
1987	10,645,192	7,601,373
1988	11,140,548	7,716,061
1989	11,274,543	7,645,494
1990	12,150,116	8,092,306
1991	11,780,610	7,814,875
1992	12,359,715	7,880,707
1993	12,706,206	8,073,173
1994	13,124,315	8,242,327
1995	13,510,066	8,465,203
TOTAL	**142,841,232**	**96,383,531**

5.5 Discussion and results

The total accident sample fulfilling the criteria stated in section 5.3 consists of 69 accidents and incidents of which 15 are classified as accidents. From the exposure data in Table 6 it follows that one crosswind related accident/incident occurs per 1.4 million flights. Of the 69 identified accidents/incidents, 58 (84%) occurred during landing and 11 (16%) during takeoff. Using the exposure data it follows that for landings 1 crosswind related accident/incident will occur per 1.7 million landings and for takeoffs 1 crosswind related accident/incident will occur per 8.8 million takeoffs. Standard statistical tests show that this difference between takeoff and landing rates is statistically significant.

Figure 8 shows the distribution of a number of factors in the accident/incident sample. For each accident/incident it is determined if the aircraft was on the ground or airborne during the event. Both phases have a different relation to crosswind performance (see section 2). Of all accidents/incidents, 52 % occurred during the ground roll and 48% occurred during the airborne phase (e.g. the landing flare). Of all the accidents/incidents that occurred during the airborne phase, 32 (97%) occurred during landing and only one during takeoff. In 70% of these accidents/incidents a wingtip or engine struck the ground and in 58% of the accidents/incidents in which a wingtip or engine strike occurred there was also a gusty wind present. Of all accidents/incidents that occurred during the ground run, 26 (72%) occurred during landing and 10 (28%) during takeoff.

Figure 9 shows the distribution of factors in those accidents/incidents, which occurred during the ground roll. Gusty wind in combination with a wet or contaminated runway is the most frequent combination that occurs. It is realised that the significance of these factors can only be established when the number of non-accident flights, under identical circumstances, is known. On average, about 24% of the takeoffs and landings are conducted on a wet or contaminated runway. Therefore the probability of a crosswind related accident/incident during the ground roll on a wet or contaminated runway is 3.5 times higher than on a dry runway, based on the current accident/incident sample. This clearly indicates that runway condition is a very important contributing factor. As discussed in section 4, operators correct the maximum allowable crosswind for runway condition using reports about the braking friction conditions on the runway. Braking friction devices or pilot reports are used to determine the braking conditions. As discussed in Ref. 3, good correlations cannot always be found between a braking friction device and an aircraft. This could be a factor causing the significantly higher probability of a crosswind-related accident on a wet or contaminated runway. However, also the fact that crosswind capability has to be demonstrated on dry runways only could be causing the higher incident/accident rate and higher probability of occurrence. Also there is the possibility that the method that was used to determine the crosswind limit on a wet or contaminated runway could be significantly wrong.

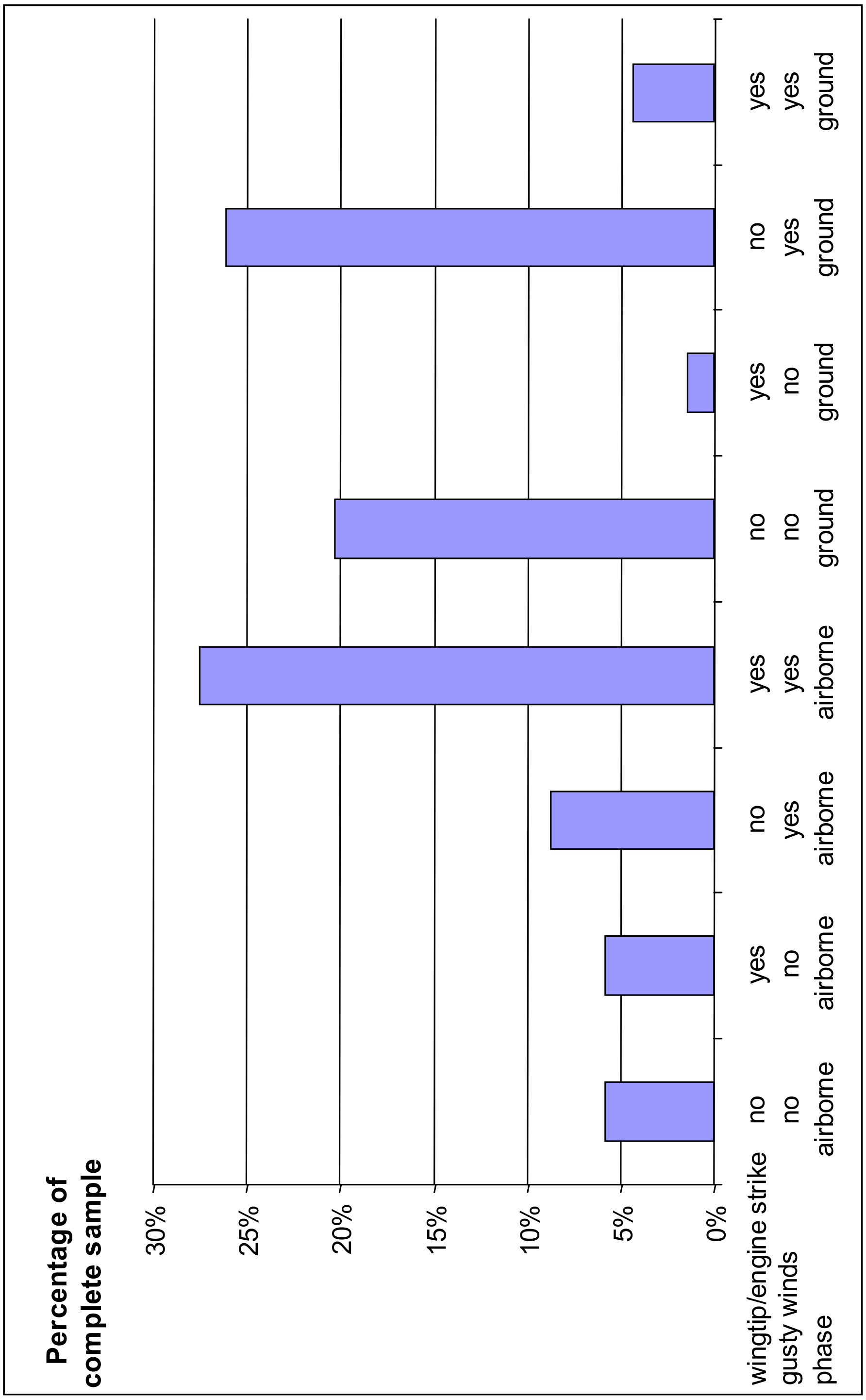

Figure 8: Distribution of a number of factors in the accident/incident sample.

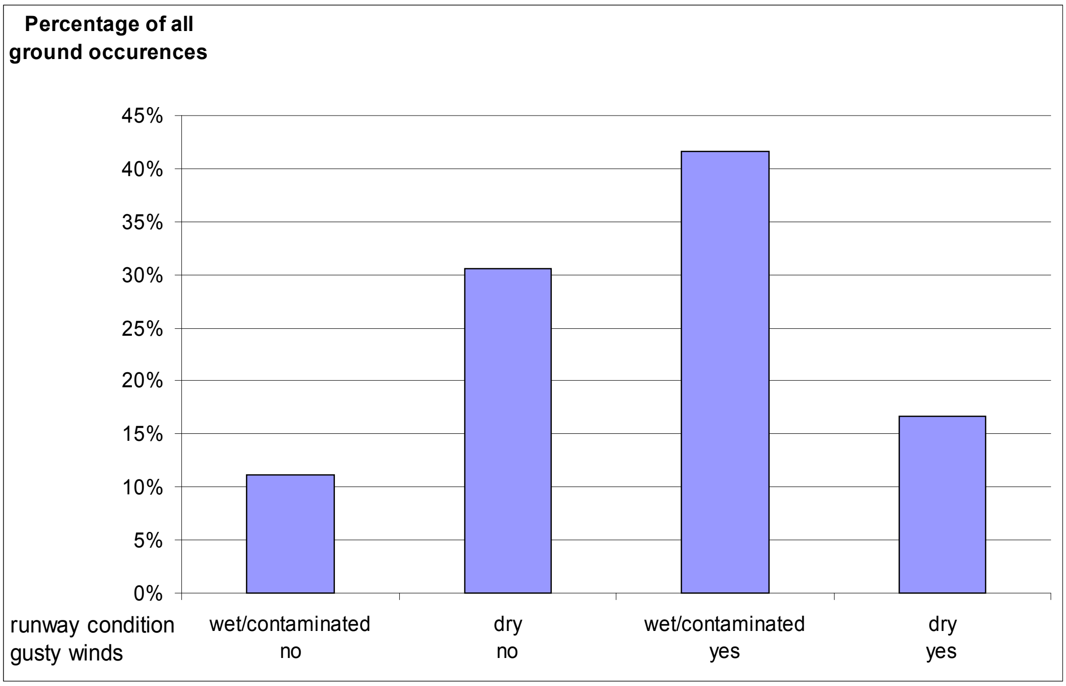

Figure 9: Distribution of factors for ground occurrences.

The general causes of the accident/incident sample as identified by the accident investigators are shown in Figure 10. The factor "improper level off" is identified as the most frequent occurring factor followed by "improper operation of brake or flight controls on the ground" and "improper alignment with the runway". Most of the factors identified in Figure 10 are pilot related. In only less than 21% of the crosswind related accidents and incidents other than pilot induced causes were identified. Such numbers are common for other types of accidents and incidents and thus not unique for crosswind-related accidents and incidents. What is unique to crosswind-related accidents and incidents identified for this study, is that most of the pilot related events are dealing with flight control or handling. Indeed crosswind operations can be quite demanding for the pilot at the controls. Certification flights conducted in heavy gusting crosswinds indeed showed a significant increase in the pilot workload (Ref. 4).

In all accidents/incidents in which an improper alignment with the runway was identified, visibility was poor. In general, visibility can be a factor in most of the crosswind-related accidents and incidents. Figure 11 shows the frequency distribution of the actual visibility in the crosswind related accidents and incidents compared to the distribution for all takeoff and landing accidents and incidents of aircraft operating under regulation 14 CFR 121. It becomes clear that a significant higher number of crosswind related accidents and incidents occurred in a visibility of less than 1 mile compared the overall number of accidents and incidents. About 4%

of the landings in the US are conducted with a visibility of less than 1 mile[6]. If this is combined with the accident and incident data during landing, it becomes clear that the probability of a crosswind related accident or incident is 6 times higher in visibility conditions of less than 1 mile than for visibility of 1 mile or higher. One of the contributing factors hereby may be the fact that although crews receive simulator training under crosswind conditions usually the on line experience with strong crosswinds is low. Consequently when a crew is confronted with maximum crosswind the margin for mistakes deteriorates fast certainly when low visual conditions prevail and runway contamination is present.

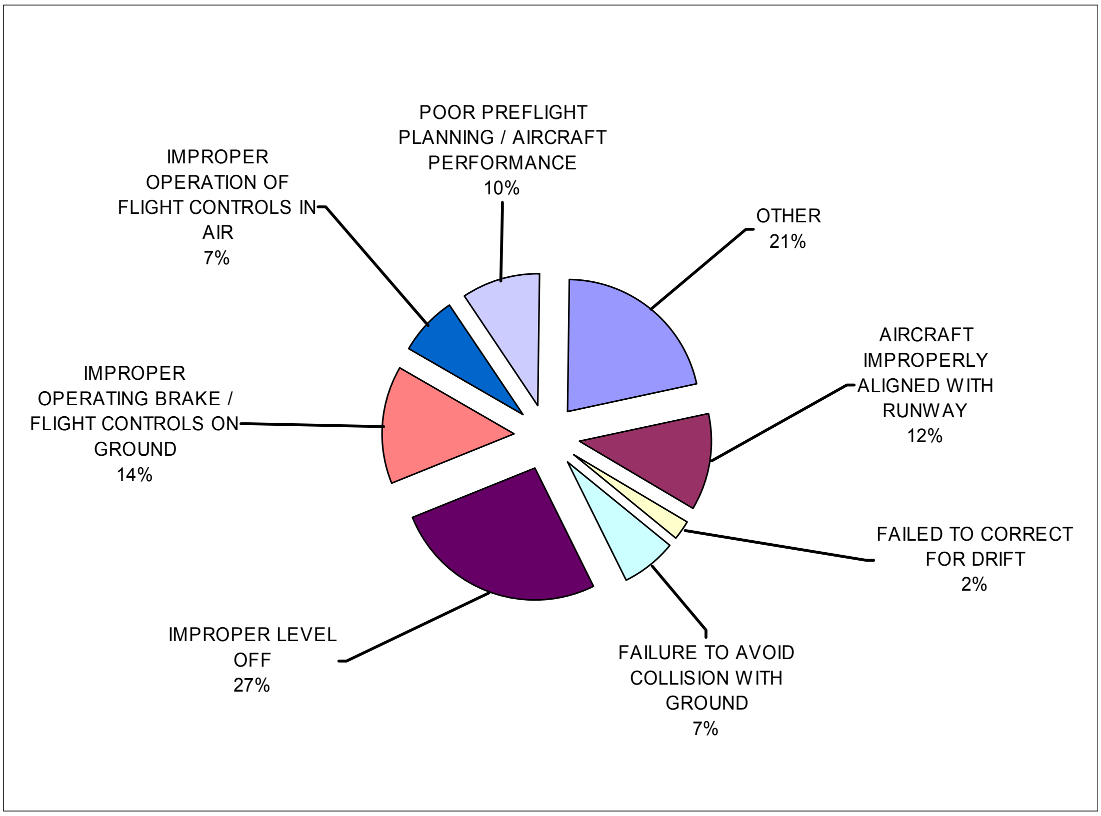

Figure 10: General causal factors.

[6] Based on climate data of airports in the US.

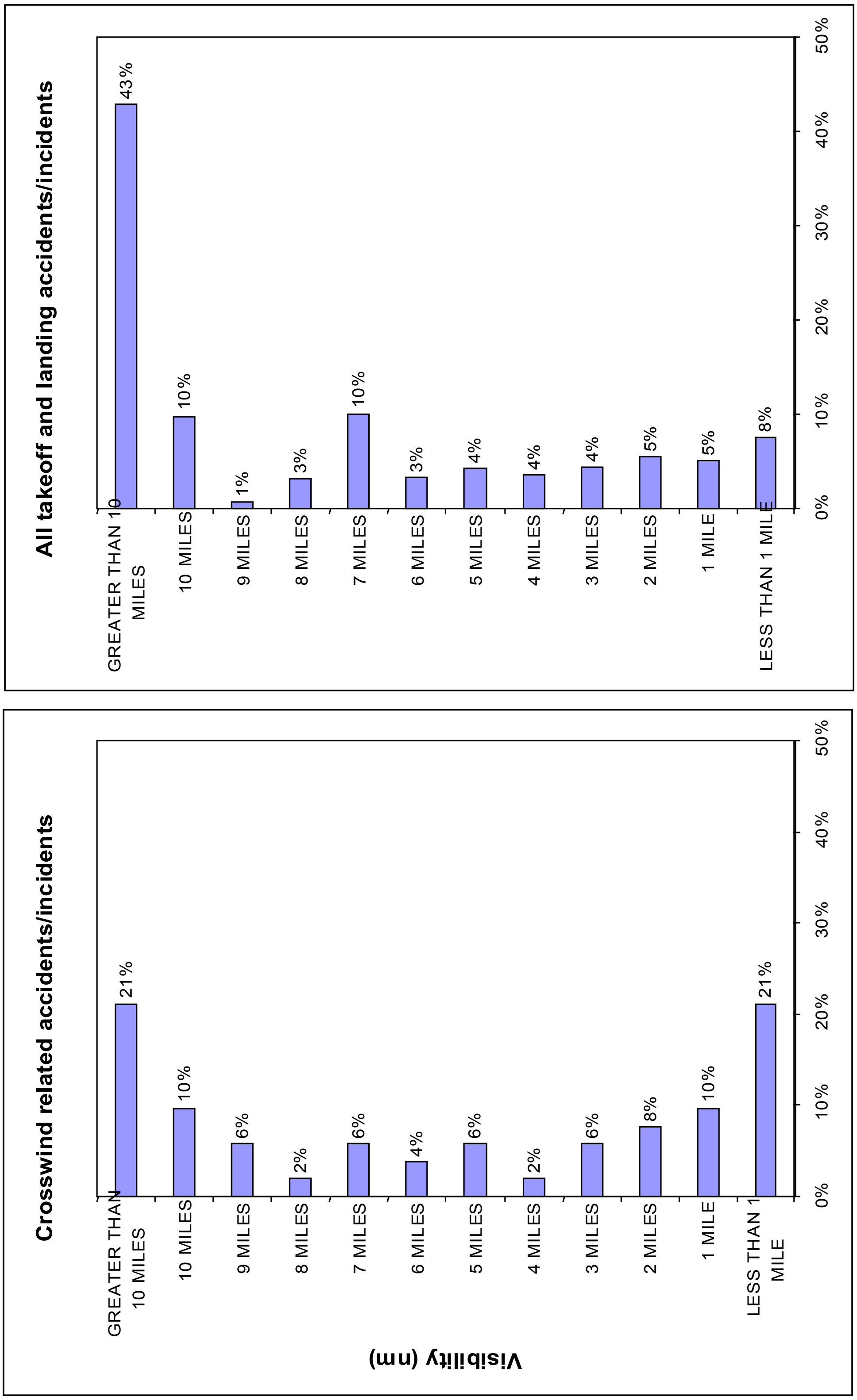

Figure 11: Visibility in crosswind related accidents/incidents compared to all takeoff and landing accidents/incidents.

In order to quantify the risk associated with crosswind operations, the number of takeoffs and landings in a particular crosswind condition must be known. An engineering approach is used in order to determine the number of takeoffs and landings conducted with a certain crosswind. In JAR ACJ AWO-131, probabilities of exceeding a mean crosswind condition are presented. These values are shown in Figure 12 and are based on historical data of UK airlines from airports worldwide. These values are assumed to be representative as an average for U.S. airports. It is further assumed that the probability of exceeding a particular crosswind is equal to the relative number of takeoff and landings conducted with this crosswind or higher. Of course this will result in some overestimation of the actual number of takeoffs and landings conducted, especially for very high crosswinds, resulting in an underestimation of the associated risk. However, the high gusts associated with high winds have a de-stabilising effect on the approach and landing and thus increase the risk. Therefore, it is believed that as a rough estimation of the associated risk, this approach will be accurate enough.

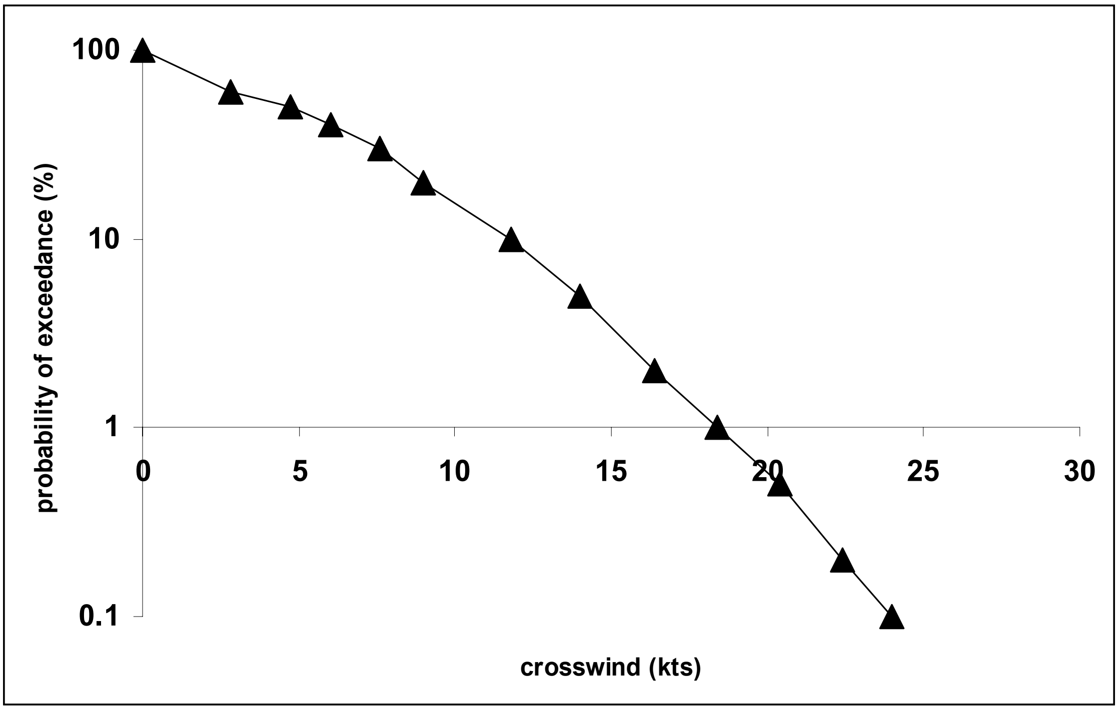

Figure 12: Percent probability of mean crosswinds equalling or exceeding given values.

The bivariate analysis is limited to accidents only because there is not sufficient information available about the actual crosswind conditions for all the incidents in the sample. To compare the different crosswind conditions, a risk ratio is introduced defined as:

$$\text{Risk Ratio} = \frac{\left(\dfrac{\text{number of crosswind related accidents with } V_{cross} \geq V}{\text{number of flights with } V_{cross} \geq V}\right)}{\left(\dfrac{\text{number of crosswind related accidents with } V_{cross} < V}{\text{number of flights with } V_{cross} < V}\right)}$$

In which V is a chosen crosswind value. For instance if V=10 Kt., the risk ratio represents the associated risk of crosswind operations equal or above 10 Kt. compared to crosswind operations below 10 Kt. A risk ratio of 1 shows no increase in risk whereas a risk ratio above 1 shows a higher risk associated with the crosswind condition under consideration. Figure 13 shows for a number of crosswind values (incl. gust), the risk ratio for the current accident sample (incidents are excluded from the sample). To obtain the crosswind including gust, the mean values presented in Figure 12 are multiplied with a gust factor of 1.5 (see section 3.3).

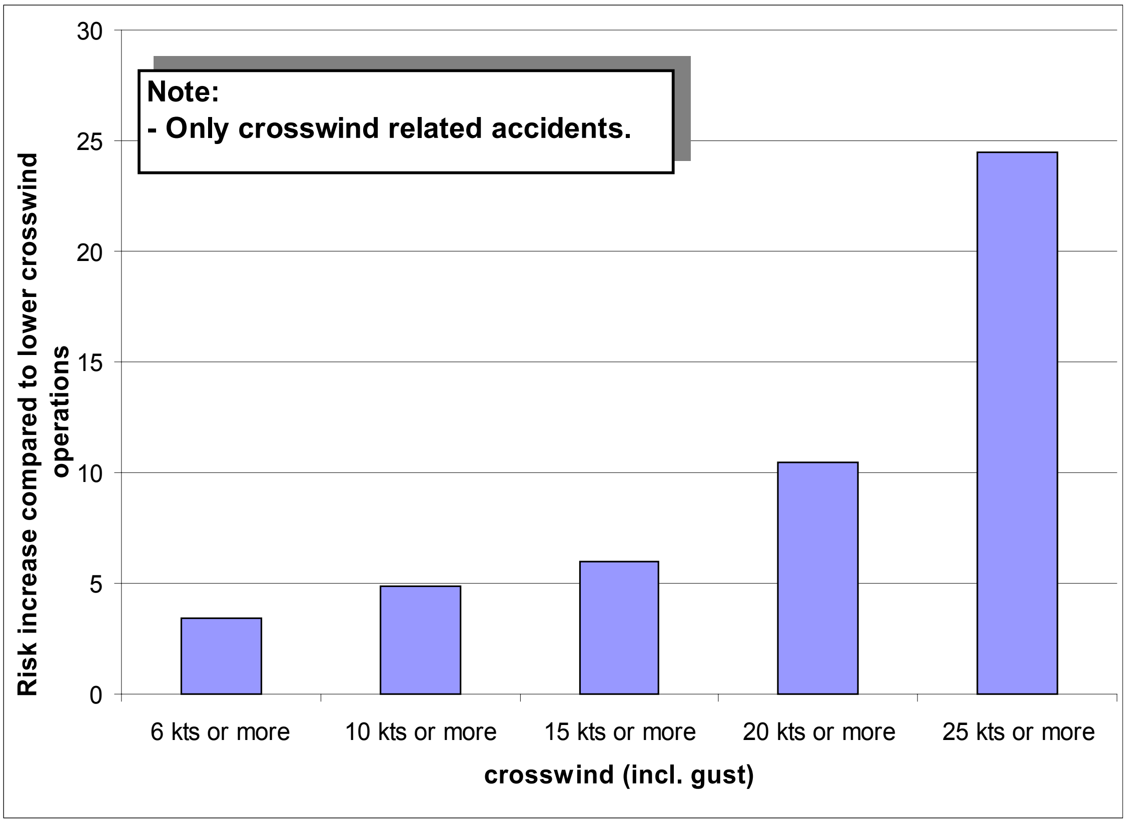

Figure 13: Risk ratio for different crosswind conditions.

As can be expected higher crosswind conditions show an increase in the probability of a crosswind-related accident compared to lower crosswind conditions. Especially operations with crosswinds equal or above 25 Kt. (incl. gusts) show a very significant increase in the probability of a crosswind related accident compared to operations below a crosswind of 25 Kt. (incl. gust).

It is important to realise that although the associate risk increases with higher crosswinds, the probability that such a crosswind condition exists decreases as shown in Figure 12. For instance the probability that the crosswind is equal to or exceeding 25 Kt. (incl. gust), is less than 2%.

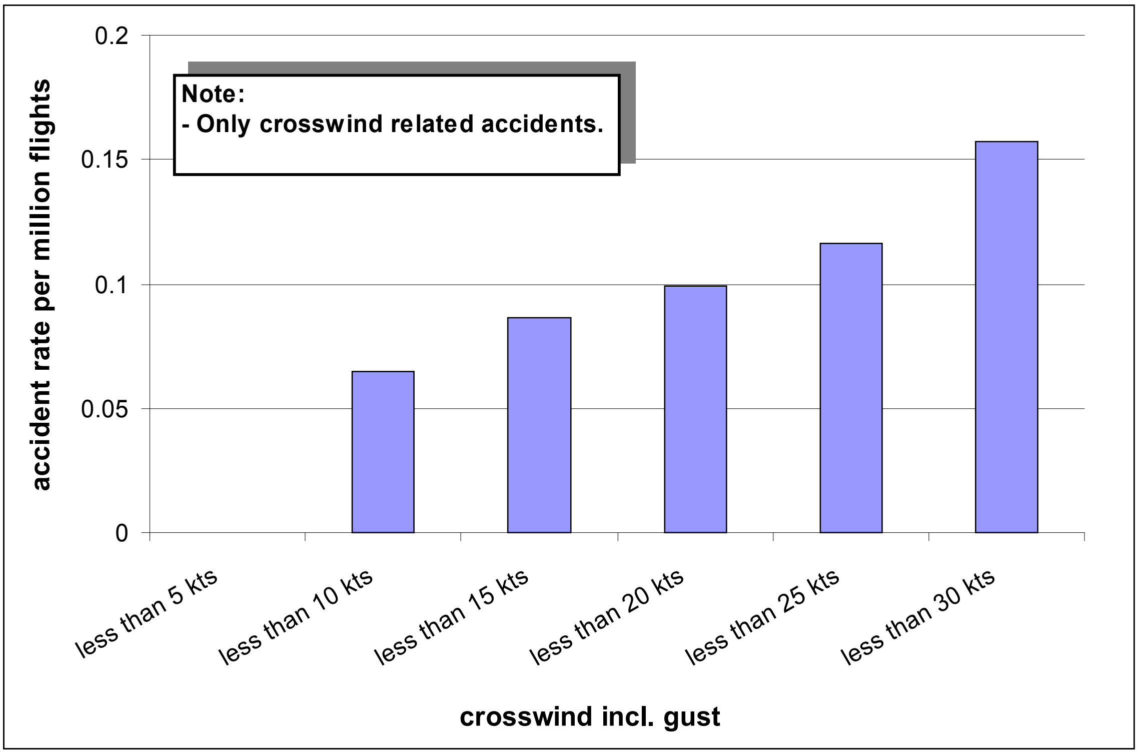

Figure 14: Rate of crosswind related accidents for given crosswind conditions.

Figure 14 shows the accident rate of crosswind related accidents for a number of crosswind conditions. It becomes clear that the probability of a crosswind related accident increases with increasing crosswind condition. For every 5 Kt. increase in the maximum crosswind (incl. gusts), the accident probability increases approximately with 0.025 per million flights. The accident rates presented in Figure 14 should be compared to the overall accident rate, which is about 2 accidents per million flights. This rate is computed using the selection criteria specified in section 5.3, except that all take-off and landing accidents are considered. Note that only the accidents from the sample are considered and not the incidents.

6 Conclusions and recommendations

6.1 Conclusions

Based on the results of this study the following conclusions are made:

- The current certification rules stated in FAR/JAR 25 regarding crosswinds are very limited and are only directed to satisfy a minimum requirement for demonstrating safe operation. Furthermore, it is not clear if and how gusts should be considered during the certification.

- FAR advisory material concerning the establishment of demonstrated crosswind capability describes two different procedures, which may lead to substantially different results.

- The demonstrated crosswinds for the currently operated transport aircraft certified under FAR/JAR 25, can be a limiting value or an advisory value, depending on whether the test pilot found it limiting or not and/or the certifying authority involved.
- In the current way of reporting wind speeds recommended by ICAO, gusts are not always given. This may result in substantial discrepancies between reported and actually encountered crosswind. Consequently, this may lead to reduced safety margins when operating under relatively benign crosswind conditions, as perceived by the pilot.

- The crosswind maximum of 15 Kt. including gusts as a criterion for the selection of a noise preferential runway as recommended by ICAO, can not always be properly used due to the recommended practices on the reporting of gusts, as given by ICAO Annex 3.

- Most operators have more or less the same policy regarding crosswind limits. However, some significant differences in the actual crosswind limits used, are found in this study.

- Landing is the flight phase in which most of the crosswind related accidents and incidents occur. In general it is a far more demanding task (high gain loop) to perform a landing out of the open space into a very small strip of the earth than it is leaving the small strip into the open space (low gain task).

- The probability of a crosswind related accident/incident during the ground roll on a wet or contaminated runway in both takeoff and landing, is 3.5 times higher than on a dry runway.

- A significant higher number of crosswind related accidents and incidents occurred in a visibility of less than 1 mile compared to non-crosswind-related accidents and incidents.

- Most crosswind related accidents and incidents are related to improper or incorrect aircraft control or handling. The reason for this has not been determined, but this can to a certain point be explained by the low currency of most pilots on strong crosswind landings.

- Gusty wind is the most important contributing factor in crosswind-related accidents and incidents. It can be noted that the strength of the gustiness depends mainly on the total wind, which can be much stronger than the crosswind component itself.

- The probability of the occurrence of a crosswind related accident increases with increasing crosswind conditions. Statistical evidence, based on historic accident data, shows that the accident risk increases exponentially when operating in conditions with crosswind exceeding 20 Kt, including gust.

6.2 Recommendations

- In light of the significant variations in wind speed that can exists between the reported wind and wind encountered during e.g. the landing flare and the fact that most aircraft are demonstrated for crosswinds of 30 Kt., the recommendation of 15 Kt. maximum crosswind including gusts stated by ICAO, cannot be increased without significant reductions in operational safety margins, unless additional measures are taken, which reduce the uncertainties inherent in the current wind measurement and reporting system.

- Reported wind velocities should include gust, if the gust velocity exceeds 5 Kt, as opposed to the current value of 10 Kt.

- Pilot assessment of the actual crosswind conditions in relation to the operational limits of the aircraft should always be based on the reported wind, including gust.
- Separate crosswind limits for takeoff and landing could be considered since this study shows that there is a significant difference between the accident/incident probabilities in both flight phases. At this moment the adjustment to a higher maximum crosswind for selection of a preferential runway for takeoff at an equivalent safety level as has been accepted for landing, has not yet been evaluated.

- Runway conditions such as wet and contaminated should be considered in a more formal way during the certification of crosswind operations of an aircraft. It is recommended to publish such information in the form of a FAA AC and JAA AMJ.

- The actual crosswind for a runway should be provided to the pilot in addition to the wind direction in combination with wind speed. This avoids miscalculation of the crosswind by the pilot.

- Establishment of demonstrated crosswind capability of an aircraft should always be based on actual reported wind by the control tower (according the procedures of ICAO Annex 3) during the flight test. This corresponds best to the way the aircraft is operated under practical crosswind conditions, and avoids discrepancies with alternative procedures, as currently allowed by FAR advisory material.

- Maximum demonstrated crosswind capability should always be considered as limiting and should therefore be placed in the Operations Limitations section of the AFM.

- It should not be allowed to advice operational crosswind limitations in excess of the demonstrated capability, based on simulator investigations. Simulators in general lack fidelity in modelling of turbulence phenomena near the ground, and modelling of lateral-directional control characteristics in ground-effect to provide sufficiently reliable results for this purpose. Furthermore the quality of the mathematical ground model in combination with the motion and visual ques of a simulator is usually not high enough to allow sufficient confidence in the evaluation results.

- It should be more clear in both FAR and JAR how the wind is defined, e.g. as mean wind based on a 2-minute period or wind including gust. In determining the maximum allowable crosswind for takeoff and landing, all airports should formally address runway friction coefficients and gusts.

- It is recommended to analyse crosswind limits in combination with low visibility conditions.

- It is recommended to analyse the possibilities of landing in strong crosswind conditions in combination with good visibility using an autoland system, to explore the use of higher crosswinds than normally defined by standard FAR/JAR autoland certification.

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