Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-490

Test and evaluation of precipitation drag on an aircraft caused by snow and standing water on a runway

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This report is based on a paper presented by NLR at the 22nd International Congress of Aeronautical Sciences (ICAS 2000), Harrogate (UK), August 2000.

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Summary

This report is based on a paper presented by NLR on the 22nd International Congress of Aeronautical Sciences (ICAS 2000) hosted by the Royal Aeronautical Society (Raes) from August 27th to September 1st 2000 in Harrogate (UK).

This presentation contained the results of the CONTAMRUNWAY project which started in 1997 when the European Commission (EC) Directorate General Transport (DG –VII) awarded a contract to a consortium of Dassault Aviation, SAAB Civil Aircraft and the National Aerospace Laboratory NLR to advice on the validity of the precipitation drag calculations in Joint Aviation Regulations (JAR) Advisory Material Joint (AMJ) 25X1591. The resulting project consisted of a theoretical study as well as the execution and analysis of flight test runs.

To obtain flight test data the NLR Cessna Citation II, a Dassault Falcon 2000 and a SAAB 2000 research aircraft performed tests on runways contaminated with either standing water or loose snow. Unbraked rolling tests were executed through the precipitation in order to obtain information on hydroplaning characteristics (in standing water) and precipitation drag (in fresh natural snow and standing water conditions).

The tests in standing water showed that hydroplaning phenomena occurred at lower speeds than predicted by the AMJ 25X1591. Observation of the spray patterns during the water tests showed considerably more contact with the airframe than the AMJ 25X1591 assumes, resulting in more total precipitation drag for commuter and business type aircraft than predicted by the method currently provided in the AMJ 25X1591 regulations.

Analysis of the snow results showed that the AMJ 25X1591 applies a physically incorrect model for snow drag prediction. The observed increase of the precipitation drag with the speed during the tests in fresh natural snow is substantially different from the theoretical drag predicted by the AMJ regulation. A new model is presented by NLR to replace the existing theory on snow drag prediction.

This paper discuses the execution and analysis of the flight tests and the theory developed.

Contents

(25 pages in total)

List of symbols and abbreviations

AMJ	Advisory Material Joint
D	Drag
$C_{D\ dis}$	Displacement coefficient
$C_{D\ imp}$	Impingement coefficient
$C_{D\ skin}$	Skin friction coefficient
D_{dis}	Displacement drag
D_{imp}	Impingement drag
$D_{rolling}$	Precipitation drag caused by dry natural snow on runway
D_c	Compression drag due to compression of snow
D_d	Displacement drag in snow
D_r	Rolling drag of a wheel on dry runway
EC	European Community
ESDU	Engineering Science Data Unit
FWP	Flight Working Paper
ICAS	International Congress of Aeronautical Sciences
JAA	Joint Aviation Authorities
JAR	Joint Aviation Regulations
NLR	National Aerospace Laboratory (“Nationaal Lucht- en Ruimtevaart Laboratorium”)
p	Tire pressure
Raes	Royal aeronautical society
S	Displacement area
SG	Specific Gravity
UK	United Kingdom
V_p	Hydroplaning speed
ρ	Specific gravity unit

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1 Introduction

This report is based on a paper presented by NLR on the 22nd International Congress of Aeronautical Sciences (ICAS 2000) hosted by the Royal Aeronautical Society (Raes) from August 27th to September 1st 2000 in Harrogate (UK). The presentation concerns the results of the CONTAMRUNWAY project in which NLR was a major partner. Due to the organisational constraints of the congress (a maximum 20 minutes lecture and an associated paper of 10 pages or less) the information presented had to be concise. As a result this report contains concentrated information concerning the project results. For more detailed information is referred to the NLR publications mentioned in the reference list.

The CONTAMRUNWAY project itself is a result of a contract between the European Commission (EC) Directorate General Transport (DG –VII) and a consortium consisting of Dassault Aviation, SAAB Civil Aircraft and the National Aerospace Laboratory NLR. The objective of the project is to advice on the validity of the precipitation drag calculations in the Joint Aviation Regulations (JAR) Advisory Material Joint (AMJ) 25X1591. The CONTAMRUNWAY program comprised both theoretical work as well as the execution and analysis of flight tests.

Test runs were conducted on runways covered with either standing water or fresh natural snow. Each partner in the project conducted these tests independently of each other. Tests in standing water were performed by both Dassault and NLR at the Cranfield University facilities in the UK. SAAB was the first to perform flight tests in snow, using their SAAB 2000 test aircraft at the military base of Linköping Malmen (Sweden). NLR tested in snow at the Skavsta Airport in Sweden and Dassault went to the Ivalo Airport in North Finland. The water- and snow tests are evaluated separately in this report.

The results of the CONTAMRUNWAY project were used both to update the relevant ESDU publications (see ref. [3]) and to prepare changes to the AMJ 25X1591. These chances are proposed in the preliminary draft of the Flight Working Paper (FWP) 661 [4]. The changes are not in effect at this moment so the AMJ 25X1591 as described is still active. As such, the results of the CONTAMRUNWAY project are not yet incorporated in the AMJ 25X1591.

2 AMJ 25 X 1591

2.1 Introduction to AMJ 25X1591

The AMJ 25X1591 is a part of the JAA JAR 25.1591 regulations used for certification of aircraft with a maximum take-off weight above 12.500 lb. The AMJ 25X1591 is titled: "Supplementary Performance information for Take-off from wet runways and for Operations on Runways Contaminated by standing water, Slush, Loose Snow, Compacted Snow or Ice" amend.88 eff. 18.10.88 Change 14 1993 (see ref. [1]). It contains supplementary advisory information concerning certification of aircraft performance for take-off and landing on runways contaminated by standing water, slush, loose snow, compacted snow or ice. The procedures in the AMJ 25X1591 are advisory, meaning that a manufacturer *may* use the information to predict aircraft performance for certification purposes. When the manufacturer chooses *not* to use the AMJ 25X1591 guidelines, then an alternate procedure must be used: e.g. actual testing (if judged acceptable by the certifying authority).

This report uses information concerning theoretical prediction of precipitation drag from the AMJ 25X1591, however the AMJ 25X1591 uses references for specific details, such as spray pattern development. For information on this subject the AMJ 25X1591 refers to a study by Engineering Sciences Data Unit (ESDU), see ref. [2].

The test results obtained during the CONTAMRUNWAY project were used by ESDU to update their publication (see ref. [3]). However, the current version of AMJ 25X1591 still refers to the old ESDU publications.

2.2 Hydroplaning according to AMJ 25 X 1591

In case of absence of actual testing data on the hydroplaning characteristics of an aircraft the AMJ 25X1591 provides the following formula to predict the hydroplaning speed (V_{pp}):

$$V_p = 9 \sqrt{(p / \sigma)} \qquad (1)$$

Where V_p represents the minimal ground speed in knots were hydroplaning should occur, p is the tire pressure in lb/sq inch and σ represents the specific gravity unit of the precipitation. Above V_p the tire is not able to process all the water and a water layer will remain under the tire. This can also be seen as the tire "rising" out of the contaminant and start skimming over the surface. When the aircraft tires are hydroplaning a change in the spray pattern will occur, generally the "new" spray plume stays lower to the ground and less water is displaced).

When hydroplaning occurs the tire loses the ability to relay forces to the ground other than vertical forces. Braking and directional course stability will become difficult. The decrease in displaced water volume will cause a decrease in volume and angle of the spray plume. Both the reduction of the displaced water volume and the change of the spray plume will influence the precipitation drag (in general the drag will decrease when hydroplaning occurs). The current AMJ 25X1591 assumes the hydroplaning formula (1) to be valid for specific densities (SG) from 1.0 (water) to 0.4 (slush/snow).

2.3 Precipitation drag according to AMJ 25X1591

The AMJ (Change 14) divides the precipitation drag into two elements:

- displacement drag
  (Drag caused by displacement of precipitation)
- impingement drag
  (Drag caused by precipitation striking the airframe)

2.3.1 Displacement drag

The displacement drag on a tire is given by:

$$D_{dis} = C_{Ddis}\ \tfrac{1}{2}\,\rho\ V^2 S \qquad (2)$$

Where ρ is the density of the precipitation and S represents the displacement area. S is defined as being the product of the precipitation depth and the width of the tire at the precipitation height (see ref. [1]).

AMJ 25X1591 (ref. [4]) states that the value of C_{Ddis} may be taken as 0.75 for an isolated tire. Trailing tires close to each other (less than two tire width apart) will have overlapping cleared paths. Factors are used to represent bogie gear layout and trailing arm wheel arrangements, although there is still discussion about the validity of these factors.

2.3.2 Spray impingement drag

Contamination thrown up by the wheels may strike the airframe and cause further drag. AMJ 25X1951 refers to an ESDU study (see ref. [2]) for information on the development of the spray. Although it is noted that aircraft configuration, the ground speed and the precipitation depth influence the development of the spray plume, the AMJ 25X1591 assumes that the spray plume always has an angle of 10° to 20° relative to the ground. By using this assumption the AMJ 25X1591 concludes that for most aircraft the nose gear will be the major origin of the impingement drag as the spray of the main gear will stay clear of the airframe.

Conclusively AMJ 25X1591 determines the impingement drag coefficient to be:

$$C_{D\,spray} = 8\,L\,C_{D\,skin} \qquad (3)$$

Where $C_{D\ skin}$ represents the skin friction drag coefficient, which is assumed to be 0.0025. L represents the length (in feet) of the fuselage behind the point were the top of the plume reaches the height of the bottom of the fuselage. C_{Dspray} is to be applied to the total nose-wheel displacement area (S). The density of the contamination is represented by ρ. V is the ground speed.

$$D_{imp} = C_{D\,spray}\ ½\,\rho\ V^2\,S \qquad (4)$$

2.4 Precipitation drag of snow according to AMJ 25X1591

All formulae provided in section 2.3 (being no.1, 2, 3 and 4) do incorporate a density factor. In case of snow precipitation the specific gravity (SG) will be lower than 0.5. The AMJ assumes that the same formulae (2), (3) and (4) will be valid for the drag prediction. This theory leads to the assumption that a contaminant of 100 mm depth with SG = 0.1 can be represented by 10 mm of contaminant with SG = 1 (this is called the equivalent water depth theory).

Furthermore the AMJ 25X1591 assumes there will be hydroplaning in certain snow conditions as the hydroplaning formula is valid down to SG's of 0.4.

3 Precipitation drag testing in standing water

3.1 Flight tests

Both NLR and Dassault tested at the Cranfield University facilities in the UK. The university provides an runway with an artificial pond located 600m from the beginning of the runway. The 70 m x 12 m (length by width) pond is divided in three adjacent lanes. Each lane is divided into four consecutive sections in the direction of the runway heading. The division of the pond into 12 sections allows better control of the water-depth and separate testing of the nose or main gear by selectively filling the middle or outer lanes.

NLR conducted tests by accelerating their Citation II to a desired speed, retarding the throttles and crossing the pond at idle thrust, while Dassault tested their Falcon 2000 using different distances to the pond and "accelerating" the aircraft through the pond at take-off thrust. The difference in acceleration before, during and after the pond is in both cases used to calculate the drag caused by the standing water. The occurrence of hydroplaning is investigated by looking at the wheel rotation speeds.

NLR tested in an average of 12 mm water depth (being the maximum water depth allowed for the Citation II). Dassault tested in approximately 20 mm average depth.

The test were performed using the following aircraft configurations and pond set-ups:

- all wheels in water and the aircraft in take-off configuration (Dassault 20° flaps. NLR 15° flaps)
- nose wheel only in water (outer lanes of the pond empty) (Dassault - NLR)
- main gear only in water (inner lane of the pond empty) (Dassault - NLR)
- all wheels in water with zero flaps (NLR)
- all wheels in water with closed main gear wheel wells (NLR)
- all wheels in water with variations in tire pressure (Dassault)

3.2 Results from water tests

The results of the NLR and Dassault water test runs are presented in the next sections. In order to be able to compare results of different tests it is assumed that for small variations in water depth the precipitation drag is considered to vary linear with the change in water depth. This allows transformation of all results of the test series to one water depth to make comparison possible. NLR converted all their results to 10 mm water depth while Dassault converted their results to 20 mm water depth.

3.2.1 NLR standing water results

Picture 1: Citation II in water pond

One of the objectives of the project is to determine at what conditions hydroplaning does occur. Hydroplaning effects are studied by recording the rotation speed of each wheel. In case of hydroplaning the water pressure under the tire will create a vertical force in front of the wheel axis. This results in a momentum contrary to the wheel rotation, slowing down the wheel. Therefore the decrease in wheel rotation speed indicates the occurrence of hydroplaning. In the analysis the actual wheel rotation speed is compared with the wheel speed corresponding with the measured ground speed (the dry wheel speed). The ratio between the actual wheel rotation speed (wet wheel speed) and the corresponding dry wheel speed is used as an indication of the occurrence of hydroplaning. Figure 1 below gives a good example of hydroplaning of the Citation II in standing water (see ref. [5]).

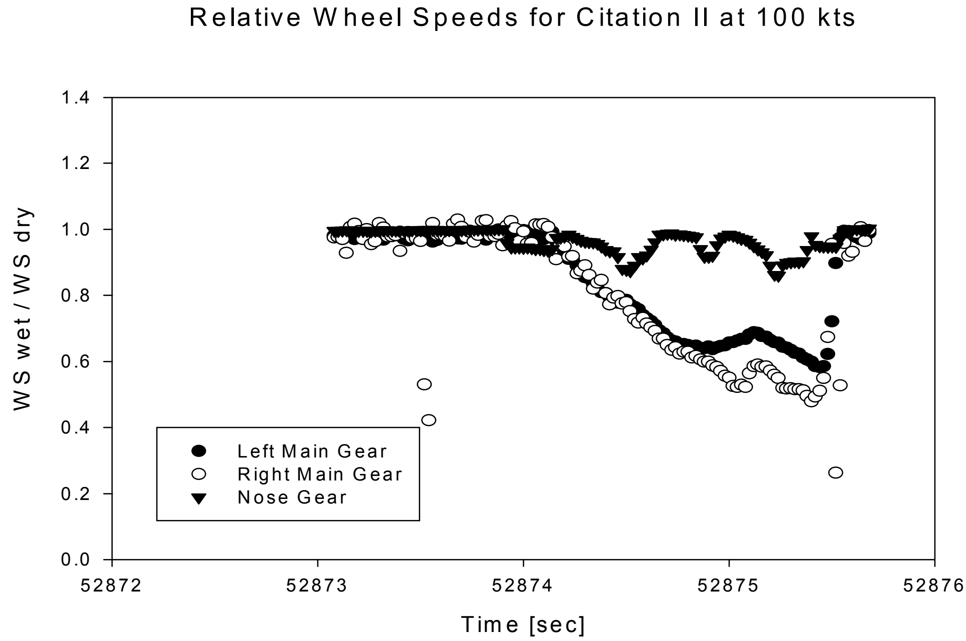

Figure 1: Citation Wheel speed wet / Wheel speed dry vs time for 90 kts

As can be seen from the figure above the Citation main gear clearly show a reduction of the main gear wheel speed compared to the dry wheel speed. Why the recording of the nose wheel does not show any decrease in the nose wheel speed could not be established.

The design tire pressure for the Citation tires is 120 psi. During the testing the main gear tire pressure increased to values between 130 psi and 150 psi as a result of heating of the brakes, wheel rim and tires. The changes in pressure of the nose wheel are notably less, as it does not contain a braking unit.

Formula no. 1 predicts the hydroplaning speed (V_p) as follows:

Table 1: Citation II theoretical hydroplaning speeds

CITATION II	
Tire pressure (p)	V_p Theoretical
psi	kts
120	99
130	103
140	107
150	110

The results of the Citation tests (fig. 1) show that hydroplaning of the main gear occurred at 90 kts with an actual main gear tire pressure of 150 psi. This is approximately 20% lower than the theoretical hydroplaning speed of 110 knots as shown in the table 1. In general the tests showed that hydroplaning occurred at speeds 10% to 20% below the theoretical hydroplaning speed.

Additionally the test runs were analysed using video images of the aircraft while passing through the pond. These images showed at low speeds a considerable amount of vertical spray at both main and nose gear while the spray plume considerably decreased at higher speeds when hydroplaning occurred. The video also showed that spray angles vary far more than the 10° to 20° predicted by the AMJ 25X1591. Spray angles were observed to range from 0° to 110°.

For the Citation the following results are obtained for the precipitation drag in standing water. See figure 2 and ref. [5]. Figure 2 shows the measured drag from the main gear tires (black dots) compared to the calculated precipitation drag of the main gear for the Citation II according to the AMJ 25X1591 (solid line). The test data were obtained by testing with the centre lane of the pond emptied of water, giving the nose gear a dry run. The AMJ line was calculated using information (depth contaminant, speed, wetted area etc...) from the tests and the AMJ formulae no. 1 to 4 . It can be clearly seen that the AMJ 25X1591 underestimates the drag caused by the main gear.

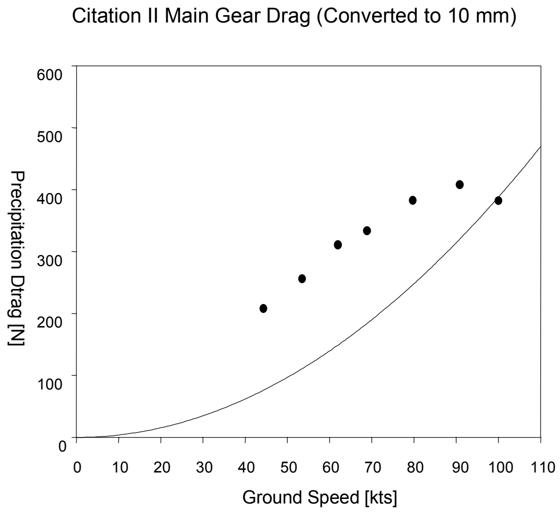

Figure 2: Citation II main gear precipitation drag in 10 mm standing water (Solid line represents the AMJ values, the dots are the measured values).

Fig. 3 shows results from tests in different configurations. The solid line represents the predicted drag according to the AMJ for the Citation in landing configuration with three wheels in the water and open wheel wells. It can be concluded that the different configurations have no significant effect on the precipitation drag. Fig. 3 also shows that maximum drag is encountered at a speed lower than the theoretical hydroplaning speed for the test (see table 1). This is also an indication that hydroplaning occurs at lower speeds than predicted by the AMJ.

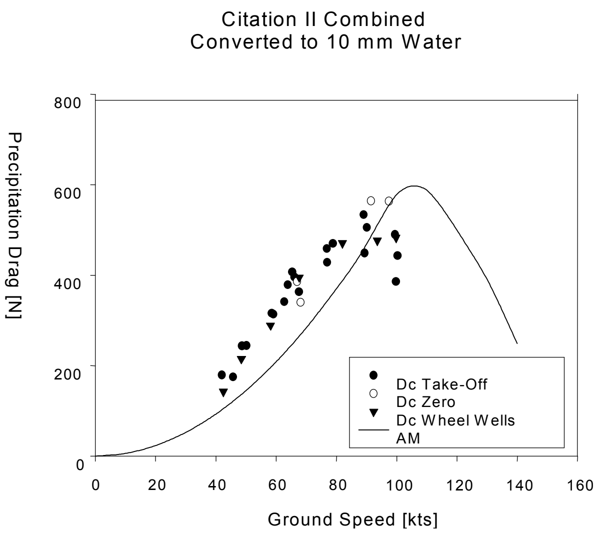

Figure 3: Citation II precipitation drag in 10 mm standing water (combined graph).

3.2.2 Dassault standing water results

Figure 4 below is obtained from the CONTAMRUNWAY deliverable D13 (see ref. [6]).The solid line in the figure represents the calculated AMJ drag for a Falcon 2000 using the AMJ 25X1591. The aircraft was tested in 20mm water with all wheels going through water and take-off configuration. The solid dots show the drag values calculated with the updated ESDU model (see ref. [3]). The measured points obtained during the CONTAMRUNWAY testing period are represented by the hollow square symbols.

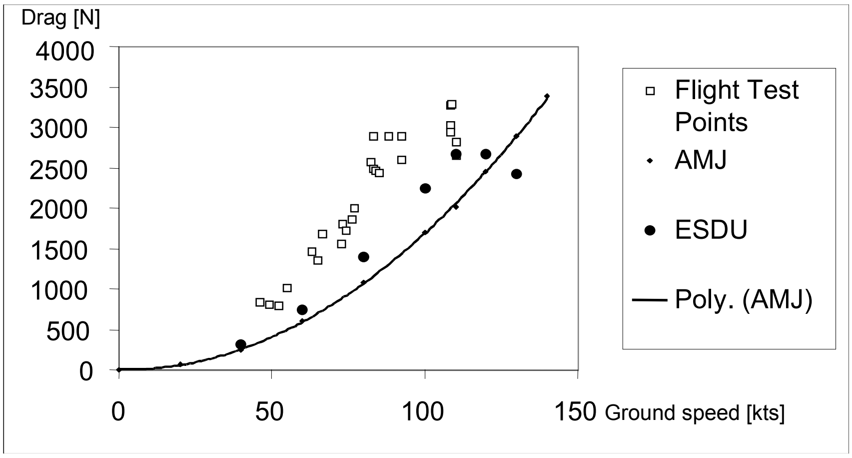

Figure 4: Falcon 2000 precipitation drag in 20 mm standing water.

3.3 Conclusions on drag caused by standing water.

Based on the tests, the following conclusions can be drawn:

1. During the tests hydroplaning is encountered at speeds up to 20 % lower than the calculated hydroplaning speed according to AMJ 25X1591 (formula 1).
2. For the aircraft tested (business and commuter type aircraft) the measured total precipitation drag for the complete aircraft is 15 to 40% higher (depending on ground speed) than the precipitation drag calculated according to AMJ 25X1591.
3. For the geometry of the Falcon and Citation it appeared that there is no significant difference in total precipitation drag for 0° and take-off position flap setting (20° respectively 15°).
4. Closing of the main wheel wells appears to have no significant effect on the total precipitation drag.
5. The measured precipitation drag for the main gear only is approximately 50 % higher (depending on ground speed) than the main gear precipitation drag calculated according to AMJ 25X1591.
6. Video analysis of the test runs showed at low speeds a considerable amount of vertical spray at both main and nose gear.

4 Precipitation drag in snow

While NLR and Dassault conducted flight tests in standing water, SAAB suggested conducting flight tests using contaminants with lower densities (e.g. fresh natural snow or slush). After discussion with EC it was decided that all partners would perform tests in snow or slush conditions.

As there are many definitions of slush and snow, the partners in the project decided to use the following classification of contaminants by specific gravity (SG):

- SG < 0.2 - Dry snow
- 0.2 < SG < 0.5 - Snow
- 0.5 < SG < 1 - Compacted snow, slush or ice
- SG = 1 - Water

4.1 The AMJ 25X1591 on snow

As stated in section 2.4 the AMJ 25X1591 "scales" the existing formulae on standing water drag using the specific density as factor. This implies the assumption that snow will physically behave as water only creating fewer forces due to its lower density. The AMJ assumes that snow will create a spray plume and that high-density snow will cause hydroplaning effects just like water.

4.2 The tests in snow

4.2.1 SAAB snow tests

SAAB conducted tests at the Linköping Malmen airport in Sweden. The tests were performed during two separate sessions. First SAAB tested their SAAB 2000 in fresh natural snow with a specific gravity (SG) of 0.11. Later a second test campaign was performed. During the preparations of the second test session the ambient temperature increased to a value just above zero degrees Celsius. This changed the fresh snow into slush with a specific gravity between 0.5 and 0.8. As the CONTAMRUNWAY study concentrated the precipitation drag of fresh natural snow it was decided to use the results of the first testing sessions for the data analysis to create a new theoretical model. The tests in slush indicated that for SG values above 0.5 the precipitation drag of the wet snow tends to develop according to the formula already provided in the AMJ. The results of the SAAB 2000 in fresh natural snow (SG = 0.11) are shown in figure 5 and are obtained from ref. [7].

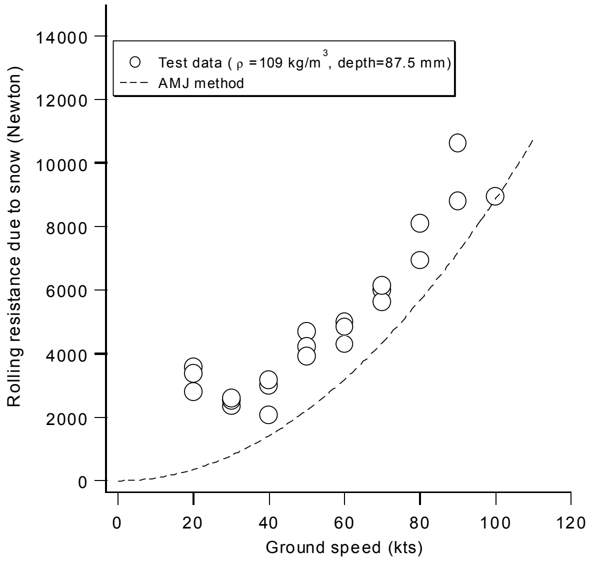

Figure 5: SAAB Snow precipitation drag in fresh natural snow with SG = 0.109.

The dashed line in figure 5 represents the AMJ curve for the predicted precipitation drag for the conditions of the tests.

4.2.2 Dassault snow tests

Picture 2: Falcon 2000 in 100 mm fresh natural snow (Ivalo).

Dassault tested a Falcon 2000 in Finland at the airport of Ivalo. Conditions there were 100 mm of fresh natural snow with SG = 0.11. Results are presented in figures 6 and 7 obtained from reference [8].

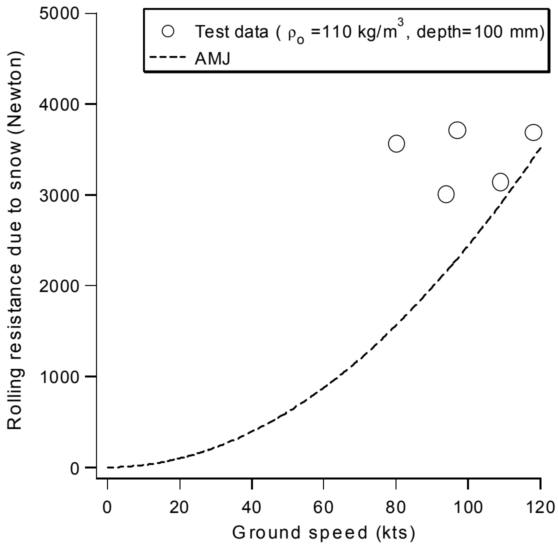

Figure 6: Falcon 2000 nose gear only precipitation drag in 100 mm fresh natural snow.

The dashed line in figure 6 represents the predicted precipitation drag derived from the AMJ 25X1591 using the parameters of the Dassault tests (ground speed, snow density and snow height). The points are the measured results of the runway tests.

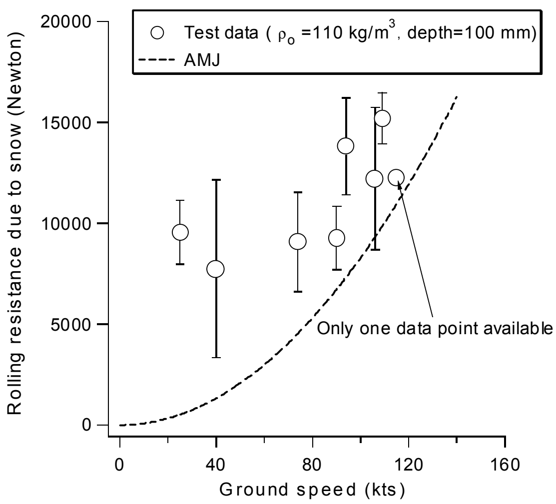

Figure 7: Falcon 2000 precipitation drag with all gears in 100 mm fresh natural snow.

Again the dashed line represents the predicted precipitation drag derived from the AMJ 25X1591 using the parameters of the tests (ground speed, snow density and snow height). The circles are the measured results of the runway tests with the vertical solid lines extending from the data points representing the standard deviation of each point. These are plotted in the figure to indicate the variation in experimentally derived rolling resistance. For more information on the snow model see ref. [12].

4.2.3 NLR snow tests

Picture 3: Citation II in 40 mm snow (Skavsta).

NLR tested a Citation II at Skavsta airport in Sweden. Tests runs were made in 40 mm fresh natural snow with SG = 0.12.

The solid vertical lines figure 8 on the next page represent error bars that were calculated considering the data reduction method and inaccuracies of the measured variables. The dashed line represents the predicted theoretical precipitation drag according to the AMJ 25X1591 for the Citation II in 40 mm fresh snow (SG = 0.12). The results clearly show that the current AMJ 25X1591 has difficulties in predicting the precipitation drag of fresh snow at low speeds. The assumption that snow does behave like a fluid causes the AMJ to omit the drag caused by compression of the snow in front of the tire. Additionally it can be questioned if the increase in drag predicted by the AMJ is valid for a fresh snow situation.

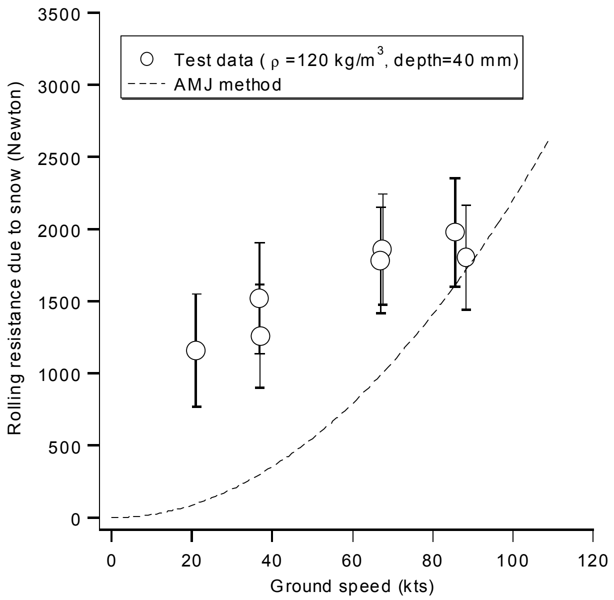

Figure 8: Citation II precipitation drag with all gears in fresh natural snow.

4.3 Analysis on precipitation drag caused by snow

From the results of the testing it can be concluded that frsh snow conditions do create drag at lower speeds. In water conditions the precipitation drag will decrease to zero with decreasing speed. However, due to the energy absorbed by compressing the snow the precipitation drag in snow conditions will be considerable even at low speeds.

4.4 Theory developed

In order to accommodate the drag caused by snow on the runway a new model was developed by NLR (see reference [11] and [12]).

The main difference between the AMJ model and the new NLR snow drag model is that the NLR model does incorporate the drag caused by snow compression. The compression forces create a drag component that is already present at low speeds.

The total rolling resistance of an aircraft rolling along a snow-covered runway is given by (see ref. [12]):

$$D_{rolling} = D_r + D_c + D_d \qquad (5)$$

In which Dr is the rolling resistance of a wheel on a dry hard surface. D_c represent the compression drag caused by the compression of the snow in front of the wheel. D_d is the displacement drag caused by the vertical movement of the snow to clear the track. The equations for D_c and D_d presented in ref. 12 are valid for single tires. A complete aircraft has at least 3 tires, one on each main landing gear and one on the nose landing gear. To obtain the total aircraft rolling resistance due to snow, the resistance D_c and D_d for each single tire have to be calculated and summed.

The rolling resistance on dual tire landing gears (found on both nose and main gears) is the resistance of both single tires added together. The interference effects between both tires as found on dual tire configurations running through slush or water, is not likely to be present when rolling over a snow covered surface. The rolling resistance originates from the vertical compression of the snow layer. Although there is some deformation perpendicular to the tire motion direction present, this deformation occurs mainly at or below the bottom of the rut and therefore does not affect the deformation in front of the adjacent tire. Hence interference effects can be ignored.

Another multiple-tire configuration is the bogie landing gear. After the initial compression of the snow by the leading tires, the snow in the rut becomes more solid and a higher pressure must be applied to compress the snow further. For the pressures used in aircraft tires it can be noted that the resistance on a bogie landing gear is equal to that of a dual tire configuration (see ref. [11] and [12]).

The results of the runway tests (see ref. [7], [8] and [9]) show that the snow spray coming from the tires is limited to small portions, which hardly strike the airframe. The speed and the density of the snow spray are much less than for instance water spray. Therefore, the resistance due to snow impingement on the airframe can be neglected.

When the precipitation drag according to the new model (see ref. [12]) is plotted together with the test result the following graph is obtained:

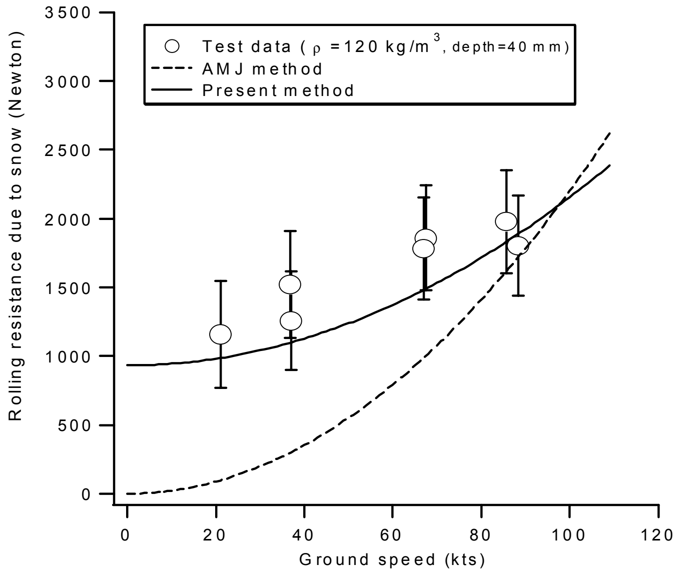

Figure 9: Citation II rolling resistance on a snow covered surface (snow depth =40 mm, snow density = 120 kg/m3).

The solid line represents the snow precipitation drag as predicted by the new NLR snow model. The dashed line represents the AMJ prediction and the vertical solid lines are error bars that were calculated considering the data reduction method and inaccuracies of the measured variables. For the SAAB snow results the following graph was made:

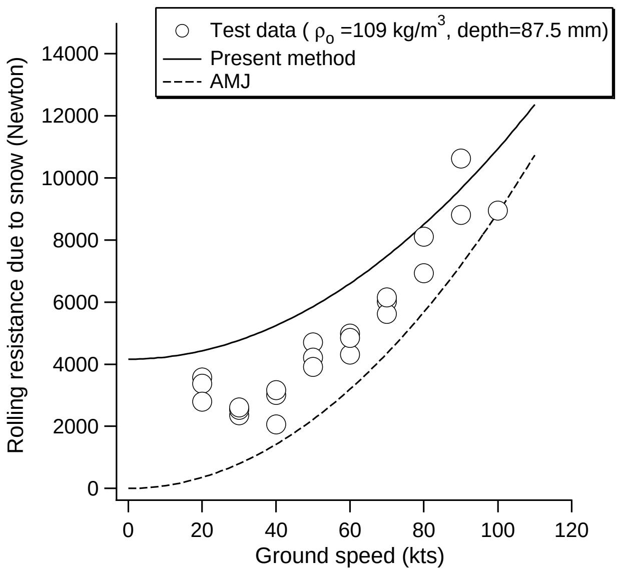

Figure 10: SAAB 2000 rolling resistance on a snow covered surface (snow depth =87.5 mm, snow density = 109 kg/m3).

Again the solid line represents the prediction of the new NLR model and the dashed line represents the AMJ prediction. It can be noted that the SAAB test points shown are consistently below the prediction of the new model. This is mainly caused by the limited way of testing and differences in data reduction techniques between SAAB and the other partners.

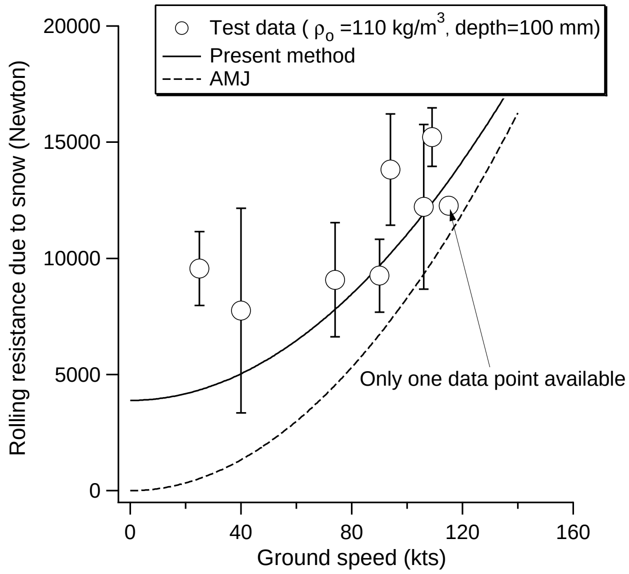

Figure 11: Falcon 2000 rolling resistance on a snow covered surface (snow depth =100 mm, snow density = 110 kg/m3).

The dashed line is derived using AMJ information and the test parameters. The solid line represents the results of the new NLR snow precipitation model. The vertical lines extending from the data points represent the standard deviation of each point. This is to indicate the variation in experimentally derived rolling resistance. For more information on the snow model see ref. [12].

4.5 Conclusions on snow drag

- Snow precipitation drag is substantial at low speeds
- The AMJ predicts a very low precipitation drag at low speeds as it omits the compression of snow. Consequently the AMJ predicts the precipitation drag of snow incorrectly at low speeds.
- Precipitation drag in snow increases with the speed, but less compared to water, because the contribution of the impingement drag is less significant
- No hydroplaning effects occur in dry snow
- Density and height of the snow influence the drag as function of the ground speed.
- The snow spray stays relatively close to the ground and does not hit the airframe in a substantial manner.

5 Conclusions and recommendations

5.1 Conclusions on drag caused by standing water.

Based on the tests, the following conclusions can be drawn:

1. During the tests hydroplaning is encountered at speeds up to 20 % lower than the calculated hydroplaning speed according to AMJ 25X1591 (formula 1).
2. For the aircraft tested (business and commuter type aircraft) the measured total precipitation drag for the complete aircraft is 15 to 40% higher (depending on ground speed) than the precipitation drag calculated according to AMJ 25X1591.
3. For the geometry of the Falcon and Citation it appeared that there is no significant difference in total precipitation drag for 0° and take-off position flap setting (20° respectively 15°).
4. Closing of the main wheel wells appears to have no significant effect on the total precipitation drag.
5. The measured precipitation drag for the main gear only is approximately 50 % higher (depending on ground speed) than the main gear precipitation drag calculated according to AMJ 25X1591.
6. Video analyses of the test runs showed at low speeds a considerable amount of vertical spray at both main and nose gear.

5.2 Conclusions on snow drag

- Snow precipitation drag is substantial at low speeds
- The AMJ predicts a very low precipitation drag at low speeds as it omits the compression of snow. Consequently the AMJ predicts the precipitation drag of snow incorrectly at low speeds.
- Precipitation drag in snow increases with the speed, but less compared to water, because the contribution of the impingement drag is less significant
- No hydroplaning effects occur in dry snow
- Density and height of the snow influence the drag as function of the ground speed.
- The snow spray stays relatively close to the ground and does not hit the airframe in a substantial manner.

5.3 Recommendations

- The current version of AMJ 25X1591 should be adjusted with the new results as soon as possible.
- Research into braking action of aircraft on contaminated runways is needed to provide complete information for take-off and landing performance calculations.

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