PRECIPITATION DRAG OF SNOW AND STANDING WATER

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Keywords: *contamination, contaminated runway, precipitation spray, precipitation drag, snow, standing water, water spray model, CONTAMRUNWAY, AMJ 25X1591*

Abstract

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

NLR's Cessna Citation II, a Dassault Falcon 2000 and a SAAB 2000 research aircraft were tested on a runway contaminated with either standing water or loose snow as part of CONTAMRUNWAY study. Unbraked rolling tests were performed through precipitation in order to obtain data on the precipitation drag. Hydroplaning phenomena were investigated during the tests in standing water.

For both water and snow conditions the results indicate that the total precipitation drag for commuter and business type of aircraft is higher than the drag predicted by the theory in the AMJ 25X1591. Spray patterns observed during the water tests contacted the airframe considerably more than the AMJ 25X1591 assumed due to the smaller type of aircraft used..

Analysis of the snow results showed that the AMJ 25X1591 has a physically incorrect model for snow drag prediction. A new model is presented to replace the existing theory on snow drag prediction in the AMJ.

This paper will discuss the preparation and execution of the flight tests, the results from the data collected and the theory developed.

1 Introduction

The CONTAMRUNWAY project is the 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 unbraked runway tests.

The test runs were conducted on runways covered with either standing water or loose snow. Each partner in the project conducted tests independent of each other.

Tests in standing water were performed by both Dassault and NLR at the Cranfield facilities in the UK.

Tests in snow were performed by SAAB using their SAAB 2000 at a military base near Linköping. NLR tested in snow at Skavsta Airport (Sweden) and Dassault went to Ivalo Airport (North Finland).

The results of the water- and snow tests are discussed separately.

Data obtained during the CONTAMRUNWAY project were used to update ESDU publication (see ref. [3]) and additionally future changes to the AMJ 25X1591 are prepared and proposed in flight working paper (FWP) 661 [4]. These changes proposed in the preliminary draft of FWP 661 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 (see ref. [1]) contains supplementary advisory information to the JAR 25 regulation. The procedures in the AMJ are advisory, meaning that a manufacturer may use the information to predict aircraft performance on contaminated runways, or: when the manufacturer chooses not to use the AMJ 25X1591 guidelines, then an alternate procedure (e.g. actual testing) may be used (if judged acceptable by the certifying authority).

The information used in this section is taken from the AMJ 25X1591 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]). For spray pattern information the AMJ25X1591 refers to information from a study by Engineering Sciences Data Unit (ESDU) [2].

Data obtained during the CONTAMRUNWAY were used by ESDU to update their publication (see ref. [3]). However the currently used AMJ still refers to the old ESDU publications. As such, the results of the CONTAMRUNWAY project are not yet incorporated in the AMJ. Further changes to the AMJ 25X1591 are prepared and are proposed in flight working paper (FWP) 661 [4]. The changes proposed in the preliminary draft of FWP 661 are not in effect at this moment so the AMJ 25X1591 as described in the next sections is still active.

2.2 Hydroplaning according to AMJ 25 X 1591

In the case of absence of testing data on the hydroplaning of an aircraft the AMJ provides the following formula to predict the hydroplaning speed (Vp):

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

Where Vp is ground speed in knots, p is tire pressure in lb/sq inch and σ is the specific gravity of the precipitation.

At speeds at or above Vp the precipitation drag decreases as the tires loses ground contact. The tire is not able to process all the water and a water layer remains under the tire. This can also be seen as the tire "rising" out of the contaminant and start skimming over the surface. When hydroplaning occurs the tire loses the ability to relay forces to the ground other than vertical forces. Braking and lateral course stability will become difficult. The decrease in displaced water volume will cause a decrease of the volume and angle the spray plume. Both the decrease in displacement and the change the spray plume characteristics 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:

- <u>displacement drag</u>
  (Drag caused by displacement of precipitation)
- <u>impingement drag</u>
  (Drag caused by precipitation hitting airframe)

2.3.1 Displacement drag

The displacement drag on a tire is given by:

$$Ddis = C_{Ddis} \; ½ \, \rho \; V^2 \, S \qquad (2)$$

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 tire width (see [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.

2.3.2 Spray impingement drag

Spray thrown up by the wheels may strike the airframe and cause further drag. The AMJ 25X1951 refers to [2] for information on the development of the spray. Although it is noted that aircraft configuration, speed and precipitation depth are factors in the development of the spray it is generally assumed in the AMJ 25X1591 that the spray plume stays between 10° and 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.

Impingement drag coefficient is determined by:

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

Where C_{Dskin} is the skin friction drag coefficient which is assumed to be 0.0025. L represents the length in feet of the fuselage behind which 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.

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

2.4 Precipitation drag of snow according to AMJ 25X1591

All formulae provided in section 2.3 (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 The tests

Both NLR and Dassault tested at the Cranfield facilities in the UK. 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. Additionally this allows separate testing of the nose or main gear by selectively filling respectively the middle or outer lanes.

NLR conducted tests by accelerating the 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 are in both cases used to calculate the drag caused by the standing water.

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. Accordingly the decrease in wheel speed indicates the occurrence of hydroplaning.

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

For small variations in water depth the precipitation drag is considered to vary linear with the change in water depth. This allows transformation of the results of a test series to one water depth to make comparison of the data points possible. NLR converted all their results to 10 mm water depth while Dassault used 20 mm.

The test were performed with different aircraft configurations and pond set-ups:

- with all wheels in water, 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)
- zero flaps (NLR)
- closed main gear wheel wells (NLR)
- variation in tire pressure (Dassault)

3.2 Results from water tests

NLR and Dassault water test runs are made using acceleration to determine the precipitation drag and wheel rotation speeds to investigate the occurrence of hydroplaning.

3.2.1 NLR standing water results

Picture 1: Citation II in water pond

The following results for the Citation II in standing water are obtained from reference no.[5].

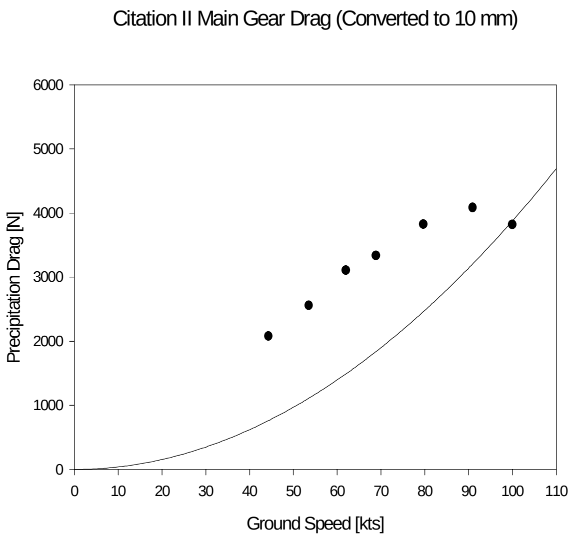

Figure 1: Citation II main gear precipitation drag in 10 mm standing water.(The Solid line represents the AMJ prediction. The points are the measured values).

Figure 1 shows the measured drag from the main wheels (black dots) compared to the calculated precipitation drag of the main wheel for the Citation II according to the AMJ 25X1591 (solid line). The test data are obtained by testing with the centre lane of the pond empty of water, giving the nose gear a dry run. The AMJ line is calculated using information (depth contaminant, speed, wetted area etc..) from the tests and the AMJ formulae (1) to (4) .

Clearly can be seen that the AMJ under-estimates the drag caused by the main gear.

Figure 2 shows the drag for the Citation II with all tires in water. Results from tests in different configurations are included in the figure. The solid line represents the calculated drag according to the AMJ for a complete aircraft. From the figure 2 can be concluded that the different configurations have no significant effect on the precipitation drag.

Additionally the figure shows that maximum drag is encountered at a speed lower than the hydroplaning speed obtained with the formula (1).

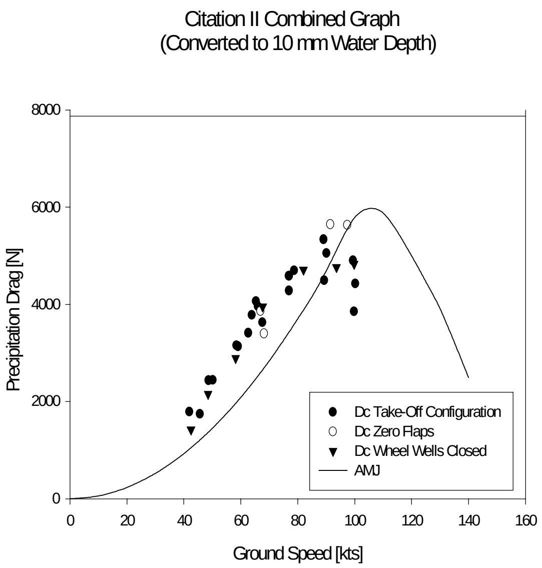

Figure 2: Citation II precipitation drag in 10 mm standing water (combined graph).

3.2.2 Dassault standing water results

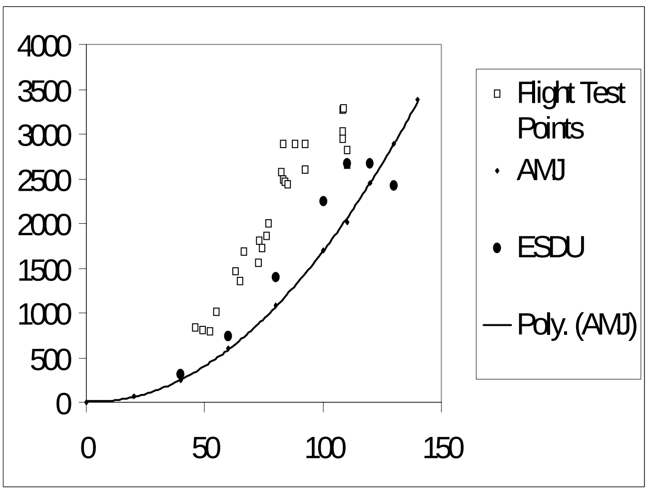

Figure 3: Falcon 2000 main and nose gear precipitation drag in 20 mm standing water.

Figure 6 is obtained from CONTAM-RUNWAY deliverable D13 (see reference [6]). The solid line in the figure represents the calculated AMJ drag for a Falcon 2000 using the AMJ 25X1591. The solid points 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.

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. The Citation II measurements are converted to 10 mm uniform water depth. Thereafter the data points showed less scattering, indicating that the scatter of data points is partially caused by the variations in average water depth. (Note: the figures shown concerning precipitation drag in standing water for the Citation II are all converted to 10 mm uniform water depth).

7. 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

After NLR and Dassault performed tests in standing water SAAB suggested it might be worth while to conduct test runs in 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. Contaminants are classified by specific gravity (SG) as following:

- 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 less forces due to its lower density. The AMJ assumes that:

- snow will create a spray plume
- high density snow will cause hydroplaning effects just like water.

4.2 The Tests

4.2.1 SAAB tests

SAAB conducted tests at the Linköping Malmen airport in Sweden. In two separate sessions SAAB tested in fresh natural snow (SG=0.11) and slush (SG between 0.5 to 0.8). Figure 4 shows the results in fresh natural snow (SG=0.11) (from ref [7]).

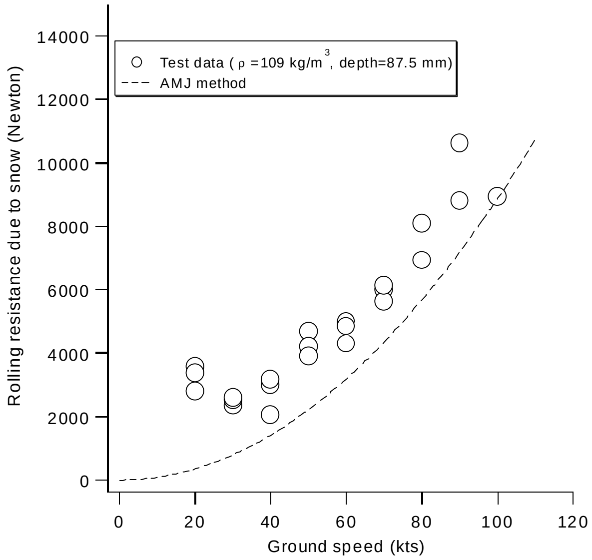

Figure 4: SAAB Snow precipitation drag in fresh natural snow with SD = 0.109.

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

4.2.2 Dassault 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 5 and 6 from reference [8].

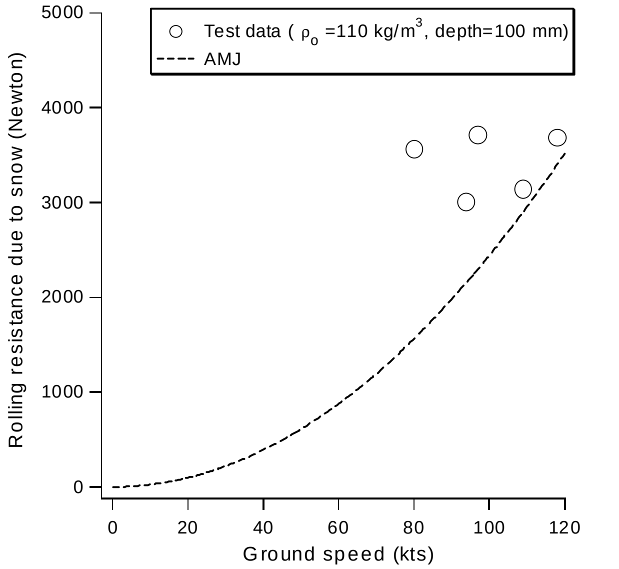

Figure 5: Falcon 2000 nose gear only precipitation drag in 100 mm fresh natural snow.

The dashed line in figure 5 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 6 gives results for snow drag of the Falcon 2000 with all tires in the snow.

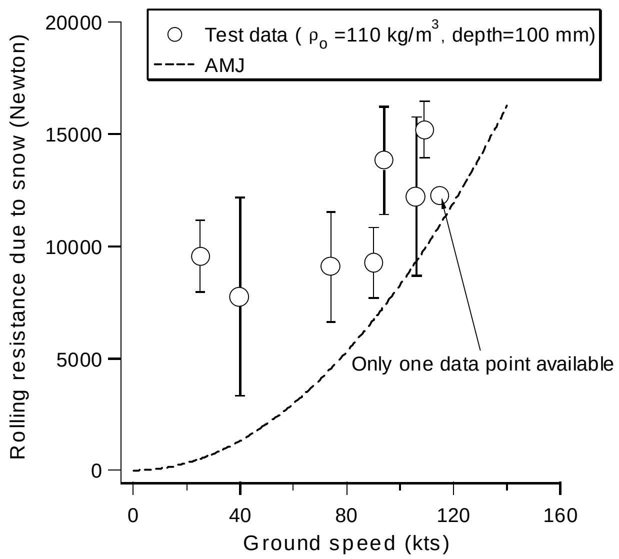

Figure 6: Falcon 2000 precipitation drag with all gears in 100 mm fresh natural snow

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 points 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 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.

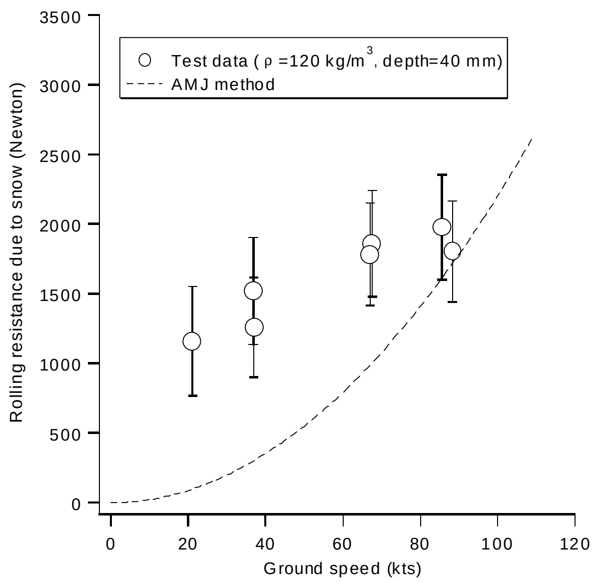

Figure 7: Citation II precipitation drag with all gears in fresh natural snow.

The solid vertical lines represent error bars which were calculated considering the data reduction method and inaccuracies of the measured variables. The dashed line represents the predicted precipitation drag calculated using the parameters of the Citations II tests.

4.2 Analysis on precipitation drag caused by snow

From the results of the testing it can be concluded that 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.

4.3 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 existing 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 which is present right from the 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 D_r is the rolling resistance on a dry hard surface. The equations presented in this paper for D_c and D_D are 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 simply 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 are 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.

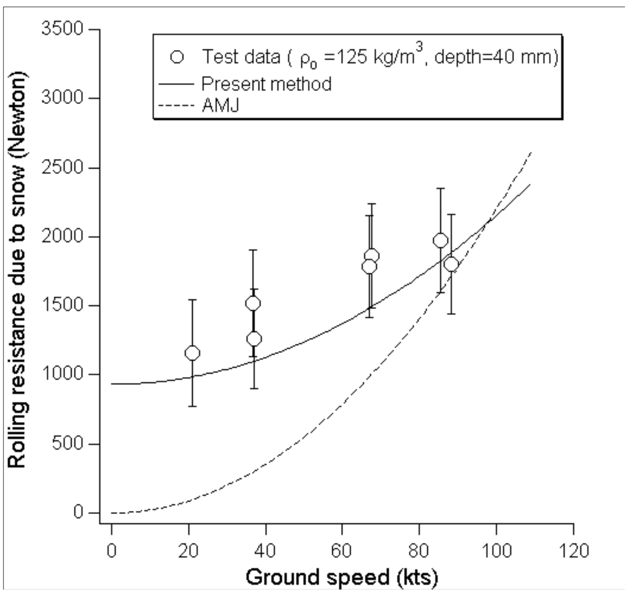

Figure 8: Citation II rolling resistance on a snow covered surface (snow depth =40 mm, snow density = 120 kg/m3).

When the precipitation drag according to the new model (see ref. [12]) is plotted into the test results the following results are obtained:

Where 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 which were calculated considering the data reduction method and inaccuracies of the measured variables.

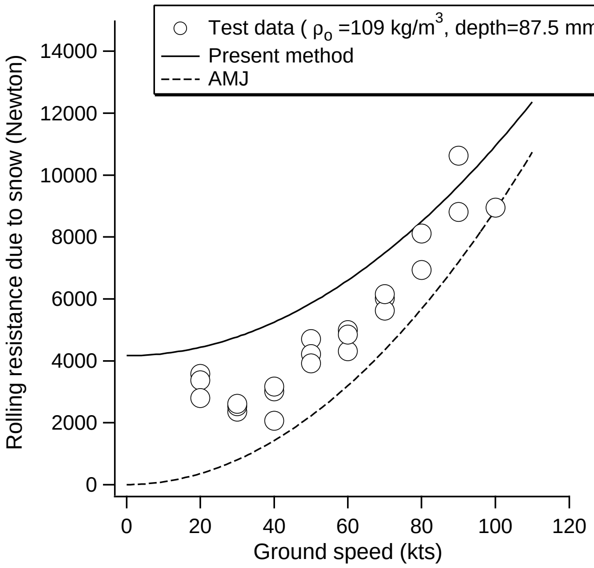

Figure 9: SAAB 2000 rolling resistance on a snow covered surface (snow depth =87.5 mm, snow density =109 kg/m3).

Again the solid line represents the prediction of the new NLR model and the dashed line represents the AMJ prediction. The dots are the measured values. It can be noted that the SAAB test points show are consistent below the prediction of the new model. This is mainly caused by differences in testing technique and data reduction between SAAB and the other partners.

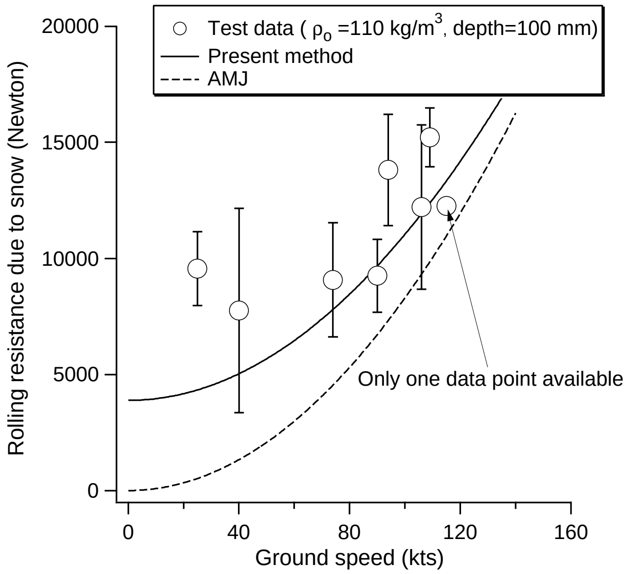

Figure 10: Falcon 2000 rolling resistance on a snow covered surface (snow depth =100 mm, snow density = 110 kg/m3).

The dashed line is derived using AMJ information and 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].

4.4 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.

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