

Final Report for Publication

CONTAMRUNWAY *Contract N° AI-96-SC-170*

Project

Coordinator : DASSAULT AVIATION

Partners : SAAB

NLR

Project Duration :

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1 - PARTNERSHIP

Dassault Aviation, SAAB AB and NLR are participating as equal partners in the programme and each partner takes the full responsibility for its own work and cost.

Overview of the consortium

Organisation	Type	Size	Role	Country	Activity
Dassault Aviation	IND	9800	C	FR	Tests, tests analysis, synthesis of the work, project coordination
SAAB AB	IND	8100	P	SE	Tests, tests analysis, synthesis of the work
NLR	ROR	900	P	NL	Tests, tests analysis, synthesis of the work, modelisation

Notations for the type : IND : Industry
 ROR : Research organization

Notations for the role : C : Coordinator
 P : Contractor

There are neither financial nor legal links between partners.

Profile of the individual partners

1. *Dassault Aviation is an industrial group with numerous constituent parts, whose varied activities cover several areas of high technology. With 9000 people, the Dassault Aviation primary vocation is the design, development, production, sale and maintenance of aircraft. The Dassault Aviation Group's civil aviation division currently represents 50 % of overall turnover.*

The executive jet market has expanded greatly over the last few years, becoming a truly international market. This is due in part to the rise of several new and rapidly growing markets centred around recently emerging poles of economic development and in part of the product itself which brings every continent within flying distance of its neighbours. Mainly concentrated on the North American continent where the market absorbs 69 % of the world production, 25 % of this fleet have been manufactured by the European industry. Dassault Aviation is now the only remaining European executive jet manufacturer. And yet, the executive jet is winning increasing acceptance in Europe as a genuine productivity tool available to companies on much the same basis as information technology and telecommunications.

In USA, airliners have access to approximately 500 airports when business jets have access to 5000 airports. The same ratio exists in Europe (200 / 2000). The executive jet will undoubtedly come to play an ever larger part in economic life in the world of the 21st century.

In total, more than 1300 FALCONS of all types have been delivered in 65 countries (and 1400 sold) over the last 35 years. 90 % have gone for export (2/3 of which to the USA). They represent 16 % of the world's business airfleet and 34 % of the selective market. One FALCON takes-off or lands each minute around the world.

The FALCON family contributes enormously both the reputation of European executive aircraft and to the European economy. It contributes to maintaining the industrial base of a European high technology sector. The 212 FALCON 10 were produced in co-operation with CASA (wings) and ALENIA (fuselage and fin). Today the FALCON 2000 are developed and produced in European co-operation with ALENIA - PIAGGIO. Dassault launched the FALCON 900EX with partners from Belgium (SABCA), Italy (ALENIA) and Greece (Hellenic Aircraft Industries).

The Dassault firm is a leader in advanced technologies. It has developed the integrated CAO/CAM software package CATIA, now marketed (Dassault Systèmes) and even used by its major competitors. The FALCON 2000 has been the first civil aircraft designed with a digital mock-up. The fly-by-wire controls, the new materials and structural technologies, the laminar flow technology, have been implemented on its FALCON.

The Research and Development sector has an annual budget equivalent to 20 % of the turnover and employs 2150 people, approximately one quarter of the Group's workforce.

Dassault Aviation is facing a tough competition with a growing number of aircraft offered to customers knowing who provides the best price-value relationship. The technical innovations are accepted only when they provides the customers with more value at a reduced cost and better reliability for a flawless availability of their airplane. The firm has to drive costs down. It has to innovate with new industrial processes, further automated and to use materials taking into account the absolute necessity to shorten the production cycles. Leading-edge technological development programs are essential to maintain a design capacity of the very highest level.

In Dassault Aviation, the Direction Technique Aeronefs is in charge of business jets development. Experience on aircraft certification covers the whole Falcon family : Falcon 10, 20, 200, 50, 900, 2000, the most recent being the Falcon 2000 (JAA : November 1994, FAA : February 1995).

Employees of Dassault are members of several committees of JAA and AECMA.

Responsible for the project within Dassault :

Jean-Marie Wolff : Senior engineer, thirty years of experience with Dassault Aviation in R&D on executive aircraft (design, aerodynamics, performance, flight test analysis and airworthiness). Mr. Wolff has been involved in the Regulation Study on "Performance on flooded runways", funded by french DGAC in 1991. After being in charge of advanced studies, now concentrating on general airworthiness.

In this respect, acting as AECMA member in the JAA Flight Study Group and in several ARAC Harmonisation Working Groups (USA, Canada, Europe).

2. SAAB AB is a company with 8100 people specialized in transport technology with the capacity to carry out long-term projects involving spearhead technology. The product range includes civil and military aircraft, missiles, space products and avionics.

As regards aircraft products, SAAB is the market leader for commuter aircraft in the 30 to 40 passenger range and has presently developed and certified an advanced commuter aircraft in the 50 passenger range. Development and production of the first fighter aircraft of the fourth generation is also on-going. These aircraft comprise many of the new technologies such as carbon fibre composites and fly-by-wire systems.

In the SAAB AB unit responsible for civil aircraft, Saab Aircraft AB, one department, Aerodynamics Flight Operations Engineering, has the responsibility for Aerodynamics, Flying Qualities, Performance (aircraft and engine) and External Noise. This responsibility covers prediction, calculations, design of external geometry and planning, performing and reporting of flight test.

Responsible for the project within SAAB :

Jan Widmark, BS, Twenty years of experience in flight test from SAABs military projects (J35 Draken, JA37 Viggen and JAS39 Gripen) as manager on different levels. Joined the civil programme SAAB 340 from the beginning as responsible for performance testing 1980 and continued with the SAAB 2000 until May 1994. From June 1994 until his retirement December 1998 in a position managing development and cooperation programmes. AECMA member in the JAA Flight Study Group until his retirement.

Anders Andersson, Senior Engineer, Performance.

Ten years of experience in performance engineering including flight test planning performing and analysing. Joined Saab in 1987 as responsible for internal computer software. Involved in several certifications of variants of the Saab 340 and in the development and certification of the Saab 2000.

3. NLR (National Aerospace Laboratory) is the central institute in the Netherlands for aerospace research. Its principal mission is to provide expert contributions to activities in aerospace and related fields. NLR independently renders services to government agencies, private companies and other organisations.

NLR is a customer-oriented research organisation, mainly working under national and international contracts concerning aircraft development, aircraft operations and space technology. NLR's basic research programme is funded by the government of the Netherlands.

NLR employs a staff of about 900 in two establishments, one in Amsterdam, one in the Noordoostpolder. NLR operates several wind tunnels, two research aircraft, two research flight simulators, an ATC research simulator, equipment for testing structures and materials, for the development of spacecraft components and for environmental testing, as well as a computer network that incorporates a supercomputer. A quality organisation based on the ISO-9001/ AQAP-110 standards has been implemented ; accreditation and quality assurance certificates have been obtained.

The two research aircraft of NLR are a Cessna Citation II and a Fairchild Metro II : the first one has been selected for the program.

Citation II : PH-LAB, is a low wing, twin jet aircraft. With a ceiling of 13km (43,000ft) and a maximum cruising speed of 710km/h (385 KTAS). Its flight envelope allows a wide range of operations. Provisions, modifications and special equipment include :

- dedicated test equipment and electrical power supply
- provisions for installation of special equipment under the forward fuselage
- provisions for installation of multiple antennas on top of the fuselage
- numerous facilities for accommodating test equipment
- EFIS (Electronic Flight Instrument System), FMS (Flight Management System), GPS (Global Positioning System), MLS (Microwave Landing System)
- provisions for additional programmable EFIS
- data measuring and recording system (standard 100 MBps, 240 MBps is possible)

NLR departments involved in the work :

Flight testing and Safety Department

Specification of responsibilities and related work :

Operation and maintenance of NLR research aircraft, Aircraft operations related studies, Development of flighttest methods, Systems safety assessment, Accident investigation, Airport risk assessment.

Experimental Aerodynamics Department

The department is charged with the execution of tests in the NLR windtunnels and engine calibration facility. If necessary work is done in close cooperation with other departments of the Fluid Dynamics Division. In general :

Testing of aircraft, launcher, and spacecraft models, Propulsion simulation, Support for various study and research projects.

In NLR, key personnel to be involved are :

Responsible for the project within NLR :

Name : Marijn K.H. Giesberts Position : Research Engineer

Telephone : +31 20 5113649, Fax : +31 20 5113210

Education and employment: Haarlem Polytechnic, Aeronautical Engineering including working projects with Dornier and Sécurité Civile (1986 - 1990). Airforce Officer (Air Defence) (1990 - 1992). NLR 1992 until now. Working Experience: Operational studies, Aircraft accident investigation, Risk analysis on aircraft operations.

WP 1 responsible :

Name : J.H.M. Gooden

Function: Senior Research Scientist

Education : University of Technology Delft, Aerospace Technology, "ingenieur" 1978.

Relevant experience :

- 1978-1981 : Application of boundary layer calculation methods to windtunnel experiments*
- 1981- : Fundamental experiments in boundary layers and wakes with pressure probes and hot-wire anemometry, mainly to create experimental databases for turbulence modelling in 2D and 3D viscous flows*
- 1981- : Regular contract work for the RLD (Civil Aviation Authority of the Netherlands) : literature surveys on heavy-rain, ice-accretion on wings and effects of wind-shear.*

2 - EXECUTIVE SUMMARY

The aim of CONTAMRUNWAY project is to support the JAA needs in reviewing the validity of existing methodology (AMJ 25 x 1591) for performance computations on runway contaminated by standing water slush or snow for small and commuter aircraft.

The 3 partners Consortium comprises two manufacturers of such aircraft and a National Research Laboratory, expertised in aerodynamics calculations.

After a review of literature and of existing data obtained as by-product of certification of aircraft on flooded runways, specific tests have been conducted :

- on water pond, with a CITATION II, aircraft assumed to be the best example to demonstrate any scale effect, and with a FALCON 2000, aircraft assumed to be representative of executive jets and of smallest transport jets.*
- on natural dry snow, with the same aircraft plus a SAAB 2000, aircraft assumed to be representative of commuter fleet.*

During these tests, particular attention has been paid to several components of hydrodynamic drag, to different parameters influencing the drag, and aquaplaning phenomena.

In addition, a theoretical study of drag produced by water thrown by the wheels and hitting the airframe has been undertaken to calculate droplets trajectories and estimate the drag due to reflection of friction on the airframe.

The general conclusion of the study is that AMJ 25 x 1591 is not applicable as it is to small and commuter aircraft.

The results have to be classified in two categories :

- standing water and slush down to a specific gravity around 0.5*
- natural dry snow having specific gravity lower than 0.2*

On standing water and slush, the current AMJ underestimates the drag at low speed, but overestimates the drag at high speed, thanks to a maximum drag speed lower than predicted.

A better estimation of the drag can be obtained with up-dated documents established by ESDU (UK), taking into account, among others, the CONTAMRUNWAY tests results, or with the theoretical model for spray impingement drag (WP1).

Another important result is that the drag increase with speed has a similar behaviour for slush with specific gravity down to 0.5 as for water, which means that the aquaplaning speed / maximum drag speed is not a function of the specific gravity. Also the current equivalent water depth concept using the specific gravity to recalculate the drag from water to slush is applicable down to a specific gravity of 0.5.

On dry snow of low specific gravity (lower than 0.2), no aquaplaning phenomena occurs and no drag is produced by contaminant thrown against the airframe. In such conditions, there is a significative drag at low speed, due to compression of the snow, and the evolution with speed is less important than that on standing water.

A specific methodology for this kind of contaminant has been developed by NLR, based on contaminant drag composed of drag due to compression and drag due to displacement of the snow.

The results of the project are communicated to the JAA Flight Study Group which will be responsible of evolution of AMJ 25 x 1591.

In respect of their decision, the two aircraft manufacturers will use the results to improve the information given to their customers.

NLR thinks that the theoretical model of spray impingement drag (WP1) can be improved and is seeking further collaboration with aircraft manufacturers to extend the test data base.

The new methodology for computation in dry snow will be published in the AIAA Journal by the end of 1999.

Contacts will be maintained with other on-going projects all around the world : Five year winter runway friction measurement program (North-America) and ASTM E 17.

3 - OBJECTIVES OF THE PROJECT

After a review of the commercial jet accidents (world-wide operations), towards the end of 1989, all the Airworthiness Authorities and Industries admitted the need of reconsidering the requirements about take-off and landing performance to take into account the runway conditions. Obviously, such information existed already in some Airplane Flight Manuals or Operations Manuals, but not all of them, and there was no guidance to standardize the presentation, and even to require the use of these data.

In this area, Europe took the lead : the Joint Aviation Authorities (JAA) included in change 13 of JAR25 regulations a new requirement 25 x 1591 and an Advisory Material Joint (AMJ) 25 x 1591, "Supplementary Performance Information for take-off from wet runways and for operation on runways contaminated by standing water, slush, loose snow, compacted snow or ice".

All the aircraft JAA certified after application of this change have to comply with these regulations and the eventuality of retroactive application for other certifications is not unlikely. The JAR-OPS1 states that take-off and landing should take in consideration any runway condition, dry, wet or contaminated : these operating requirements are coming in force at different dates, following the decision of each national Airworthiness Authority. Therefore, some aircraft manufacturers have explored this item, and some doubts arose, related to applicability to small aircraft like executive jets or commuters: it is mainly a safety concern, because the AMJ gives a method to determine take-off and accelerate stop distances on contaminated runways and they have to be accurate or on the conservative side.

For two projects recently certified, namely SAAB 2000 (Turboprop) and Falcon 2000 (Jet) the AMJ theoretical method does not adequately correlate with the test results.

The Flight Study Group (FSG) of the JAA recognized the problem and asked the Research Committee of JAA to initiate a programme on this subject. This led to item 4.2.3/38 in the "Transport" specific programme of the 4th Framework Programme.

In fact the subject described in item 4.2.3/38 of the work programme is too wide to be fully investigated within reasonable time and funding. In the present project, as a first step, it was decided to concentrate on take-off performance, i.e. on the precipitation drag encountered by an aircraft on a runway covered by standing water, slush or snow :

- identify the most important parameters acting in the drag*
- review the validity of AMJ 25 x 1591 for small and commuter aircraft*
- establish elements to reformulate theoretical extra drag on contaminated runway with wheels free to roll (no braking)*
- propose elements to relevant authorities in order to modify if necessary the current regulations.*

4 - MEANS USED TO ACHIEVE THE OBJECTIVES

Initially, the work concentrated on operation on runway contaminated by standing water :

- *An extensive review of existing data done by the two aircraft manufacturers partners in the programme (SAAB and DASSAULT), enabled to make the comparison of aquaplaning speeds and hydrodynamic drag with the AMJ 25 x 1591 methodology.*
- *In the same time, the third partner (NLR) undertook the elaboration of a mathematical model to reproduce the water / spray field around the aircraft and to estimate the supplementary drag produced by the spray acting on the wing and fuselage.*
- *Specific test were conducted on the facilities of CRANFIELD Institute with a CITATION II (spring 1997) and a FALCON 2000 (summer 1998).*

By the end of the first year of the program, it was decided to perform additional tests on runway contaminated by natural snow in order to verify the equivalent water depth concept proposed by the same AMJ.

Specific tests were conducted in SWEDEN and FINLAND with SAAB 2000, CITATION II (winter 1998) and FALCON 2000 (winter 1999).

Since the beginning, the Consortium has been maintaining permanent contact and exchange of information with two other projects also addressing operation on contaminated runway :

- *Five-year Winter Runway Friction Measurement Programme conducted in North America by Transport CANADA, FAA, NASA and National Research Council CANADA*
- *CAA funded research done by ESDU, the first result being an up-date of ESDU reports already referenced in AMJ 25 x 1591.*

In addition, the JAA expert designated for the programme (G. SKILLEN – CAA), Chairman of a specific contaminated runway sub-group of JAA-FSG, has attended several CONTAMRUNWAY meetings as well as the Consortium has been represented in each meeting of this sub-group.

5 - SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE PROJECT

5.1. Research approach and methodology

The AMJ 25 x 1591 gives formulae to determine the aquaplaning speed and the precipitation drag from basic or geometric data (tire pressure, density of the contaminant, size of the tires, length of the fuselage ...).

The precipitation drag, or hydrodynamic drag, is a function of aircraft speed and is the sum of displacement drag and impingement drag.

The displacement drag corresponds to the force necessary to clear the precipitation in front of the wheels.

The impingement drag corresponds to contaminant thrown-up by the wheels and striking the airframe: in this case the configuration of the airplane might be a factor to consider.

The aquaplaning speed is assumed to correspond to the maximum value of the drag. A more accurate approach would be the determination of the speed at which the wheels begin to spin-down.

The purpose of the project is to check the applicability of such formulae to small and commuter aircraft, on the basis of specific tests and theoretical study.

In these tests, the drag is to be determined either by difference between available acceleration outside and in the pond, or by direct calculation from the aircraft aerodynamic model (lift and drag), the thrust during the test and the aircraft acceleration.

5.2. DESCRIPTION OF THE WORK PACKAGES

WP1 Theoretical study of spray impingement drag

Purpose :

The observed scale effect on airplane drag can possibly be contributed to aerodynamic effects, notably spray impingement (spray thrown-up by the wheels striking the airframe). For the spray-impingement drag an empirical relation is described in AMJ 25 x 1591 and there is some doubt if this relation still applies to smaller scale aircraft. In this work package a theoretical study will be made to identify possibly a theoretical model to quantify the spray impingement drag.

Split-up of activities :

NLR is fully responsible of this workpackage.

Sub-task 1.1 : Parameter identification.

- a. Literature study and compilation of information available to the partners (e.g. photos and video) on the spray pattern caused by a commonly used tire on a wet runway.*
- b. Identification of possible aerodynamic causes of the observed problem (from literature and information derived from work package 2 (analysis of existing data reports)).*
- c. Inclusion of test data obtained in third work package (Citation tests).*

Sub-task 1.2 : Spray pattern modelization

- a. Definition of the basic elements and variables (tire size and pressure, water height) for the spray initiation.*
- b. Derivation of a model to describe the water/air spray field around the aircraft (if necessary for various flap settings) in terms of droplet trajectories and velocities and water/air concentration relative to the aircraft and the ground.*

Sub-task 1.3 : Drag augmentation due to spray encounter

Identification and estimation of possible drag contributions due to the spray acting on the wing and fuselage. Test data from Work Package 3 and 5 will be included.

Sub-task 1.4 : Synthesis of modelization

- a. Demonstrate in a quantitative way the success or failure of the modelization of the spray pattern in combination with its effect on aircraft drag including an explanation of a possible scale effect.*
- b. If possible, derive an "easy to use" approximate method for the estimation of the extra drag on runways contaminated by standing water.*

WP2 Existing data analysis

Purpose :

Available flight test data on contaminated runways from Falcon 900 and SAAB 340/2000 aircraft give rise to serious doubts about the validity of the empirical formulae for the estimation of drag increase and derived values for aqua-planing speeds (AMJ 25 x 1591) for business and commuter aircraft.

Aircraft size (scale effect) is suspected to be a major cause for observed anomalies as the validity for large size aircraft has been established 25 years ago and has been confirmed on several occasions.

Task for the industry partners :

- 1. Make an inventory of existing data and a review of the quality and validity for a further analysis programme.*
- 2. Choose the quantity of data to be developed and how to contribute to obtain comparable data (In co-operation within the Consortium).*
- 3. Investigation of aqua-planing and drag parameters*

Work specific to each partner :

*SAAB : Review of existing data available on the SAAB 340 and SAAB 2000 (turboprops)
Investigation of difference noted in the results when the aircraft is accelerating or decelerating.*

*Dassault : Review of existing data available on the FALCON 2000 (jet)
Comparison to the results established on the FALCON 900 (Regulation Study funded by French D.G.A.C. in 1991).*

WP3 Citation II tests

Purpose :

It is considered essential to supplement available data with relevant testdata from aircraft which are expected to be even more critical than the aircraft mentioned WP2 above.

Cessna Citation II : (see part 1 for further information)

The Citation is used at the National Aerospace Laboratory NLR for research and development flight test programmes : the aircraft is equipped with test instrumentation. Certain dimensions of the aircraft, i.e. the ratio of main wheel diameter to height of wing above the ground, renders this aircraft particularly suitable to expand measurements in respect to operations on contaminated runways.

Test environment :

Within the European region two runways with test pond are known to be operational, one at Brétigny-sur-Orge, France (LFPY) and the other at Cranfield, UK (EGTC). The second one has been selected for the tests.

Split-up of activities :

2 two day tests are foreseen in this work package under the responsibility of NLR.

Sub-task 3.1 : Test preparation.

- a. Design of specific instrumentation system in Citation and installation in aircraft.*
- b. Review and, if required, upgrade of available, external, observation methods.*
- c. Definition of thrust and drag.*
- d. Validation of a model to determine engine thrust at relevant test speeds.*
- e. Preparing "quick look" method for "on-line" qualification of test runs.*
- f. Determination of test programme to enable quantification of the effect of flapsetting and height of contaminant on drag and aqua-planing speed.*

Sub-task 3.2 : Tests.

- a. Positioning of aircraft and measurement crew to and from test airfield.*
- b. Execute the test programme.*
- c. Evaluation of preliminary results during the tests to limit or expand the programme, as deemed necessary.*

Sub-task 3.3 : Data processing and analyses.

- a. Processing of measured data.
- b. Evaluation of externally recorded spray patterns and cross referencing to the study in Work Package 1.
- c. Analyses of results in a format to enable comparisons with results from other programmes in Work Package 4.

WP4 Intermediate synthesis and complementary tests definition

Purpose :

At this point of time in the study the results of Work Packages 2 and 3 as well as the interim report of Work Package 1 sub-task 1.1. were available. An evaluation took place, leading, among others, to the definition of complementary tests: it was decided to perform tests in natural snow (all partners) and that further results in standing water have to be provided (DASSAULT).

Split-up of activities :

Sub-task 4.1 : Evaluation of interim results.

Comparison of results from analysis of existing data (Work Package 2) and the results of the Citation trials (Work Package 3).

Sub-task 4.2 : Definition of complementary tests. (turbo prop)

Definition of a test programme for the SAAB 2000 on natural snow.

Sub-task 4.3 : Definition of complementary tests. (jets)

- a. Definition of test programme(s) for Cessna Citation II and Dassault Falcon 2000 on natural snow.
- b. Definition of test programme for Dassault Falcon 2000 on standing water to assess breakdown, of hydrodynamic drag.

WP5 Complementary tests programme

Purpose :

Implement the data base obtained from WP 2 and 3 on standing water. Establish hydrodynamic drag on runway contaminated by snow.

Split-up of activities :

5 two day tests are foreseen in this work package. The three partners are involved in natural snow test. The DASSAULT FALCON 2000 tests on standing water are conducted in CRANFIELD (U.K.).

Sub-task 5.1 : Tests (all selected aircraft).

- a. Positioning of aircraft and measurement crew to and from test airfield.
- b. Execute the test programme.
- c. Evaluation of preliminary results during the tests to limit or expand the programme, as deemed necessary.

Sub-task 5.2 : Data processing and analyses (all selected aircraft)

- a. Processing of measured data.
- b. Evaluation of externally recorded spray patterns and cross - referencing to the study in Work Package 1.
- c. Analyses of results.

WP6 Final Synthesis

Purpose :

Review all the results and give consideration to inputs from other on-going activities on the same subject.

Split up of activities :

Each partner is participating in this workpackage and the proposed conclusions reflect the general consensus established inside the Consortium.

5.3. THEORETICAL MODEL (WP1)

5.3.1 Method

The calculation of the airplane drag on a water-contaminated runway consists of two parts :

- ♦ *the calculation of the spray around the aircraft*
- ♦ *and the calculation of the increase in aircraft drag due to this spray.*

The heart of the spray calculation is formed by a droplet trajectory routine. This routine determines the trajectory of a spray droplet, given the initial conditions. These are determined from an comprehensive model, which is described in detail in Deliverable 9 (NLR CR 99199). This model uses ESDU data as a basis. Empirical constants, present in the model, are determined from NASA experiments, flight test results on the Dassault Falcon 2000 and Cessna Citation II, as well as Bristol University tests. This has been a very complicated and laborious task. And, although very satisfying results have been obtained, further experimental data, especially concerning the water flow distributions in realistic sprays, are desired to further support and improve the modeling.

The droplet trajectory calculation determines whether the droplet reaches an aircraft surface and continues the calculation of the trajectory of a (partially) reflected droplet. For this purpose a simple representation of the aircraft geometry has been included in the method. Upon impact the impact velocity vector of each particle as well as the flow rate, represented by the particle are determined. Both are required for a reliable drag calculation. At present the drag calculation is still kept rather simple. For future applications it would be advisable to implement a more sophisticated drag calculation method. The method includes the effects of the bow wave, the side waves and the centre wave (for side-by-side tyres).

The advantage of the approach followed is not only that the full spray is modeled, but also that reflections on the aircraft surface are taken into account and the drag force

resulting from the impingement velocity normal to the surface can be taken into account. The latter sometimes is quite significant.

5.3.2. Results

Figure 5.3/1 shows a comparison of the calculated and measured spray in side view. In this case the nose wheel spray of the Falcon 2000 is considered at a speed of 80 kts (include figures 14a and 15a from Deliverable 9). It is seen that the measured spray is reproduced very well by the calculation method, including the reflections on the fuselage and wing. As in the experiment, a small part of the spray is seen to move over the wing, outside of the engines (if ingestion would occur, these trajectories would end at the engine inlet).

Figures 5.3/2 and 3 show a comparison between the measured contaminated runway drag of both the Citation II (pool depth 10 mm) and Falcon 2000 (pool depth 20 mm) and the results from the drag calculation for each aircraft. A more detailed analysis of this result will be found in Deliverable D12. It is shown here that the present simple drag calculation method results in an under-prediction of the main gear drag and an over-prediction of the nose gear drag. Further refinement of the drag calculation module therefore is required. Up till now the method has only been used to calculate the sprays around the two aircraft mentioned and the Saab 2000. It is desirable to validate the method on large(r) aircraft as well.

5.4. EXISTING DATA ANALYSIS (WP2)

5.4.1 Method of analysis

During it's certification process, an aircraft has to conduct tests in a pond full of water : the primary purpose is to demonstrate that the engines are free of water ingestion, and in that respect the height of this contaminant is recorded, as well as the speed, acceleration, thrust setting and other interesting parameters on-board.

As a by-product of these tests, the comparison of the performance in the pond, and outside the pond, enables to establish the extradrag encountered, because there is no braking action inside the pond.

The AMJ 25 x 1591 gives a mathematical method to compute this precipitation drag which is the sum of the displacement drag (wheels running in standing water, slush or snow) and the impingement drag (water thrown-up by the wheels and striking the airframe). In fact there is also a split between nose gear and main gear, that means that the total contaminant drag has four components.

Such break down in drag is difficult to obtain from the certification tests : separating nose from main gear drag needs significant difference in water depth. The best is to have only one gear rolling in a water pond.

This can be done with separate ponds or with a sharp study of the time history because there is roughly 0.1 second between nose and main gear entering or leaving the pond.

The AMJ 25 x 1591 addresses also other parameters and the more interesting to check is the aquaplaning speed. This speed is assumed to be in correlation with the maximum drag because the wheel, borne by the contaminant, is rotating with a lower speed, and the displacement of contaminant as well as impingement on the airframe is significantly decreased.

The analysis of the tests are made on a case by case basis because the conditions are different for each aircraft, and sometimes for each run.

5.4.2. Presentation of results

As the contaminant drag is supposed to be a parabolic function of the speed, up to the aquaplaning speed V_p , it was decided to present :

- ♦ a table giving the total drag, when possible splitted in elementary components, at a speed of 80 kt, in a water height of 10 mm (0.4 inches).*
- ♦ a chart showing the evolution of total drag versus speed in the same 10 mm water height.*

Tests results and theoretical data have been provided in each case with appropriate comments.

Since 1994 there are discussions around up-dating the AMJ 25 x 1591, mainly considering the coefficients applied to multiple wheels undercarriages : the current status of the proposed evolution, FWP 478, is also presented (see annex 2).

5.4.3. SAAB aircraft analysis

The task for SAAB is the review of data obtained on the facilities of CRANFIELD Institute (U.K.), during the certification tests of SAAB 340 and SAAB 2000 which are two turbopropeller aircraft operated by many commuter airlines all around the world.

Figures 5.4/1, 2 and 3, extracted from deliverable D3 of the project, give aircraft geometry, hydrodynamic drag break-down at 80 kts / 0.5 inch water depth and evolution of drag versus speed in 0.5 inch water depth for the SAAB 2000.

The results, also valid for SAAB 340, are the following :

- Propeller efficiency is not influenced by the spray plume from the nose wheels.*
- Acceleration or deceleration of the aircraft have no significant effect on hydrodynamic drag.*
- Aircraft configuration (flaps deflection) has no influence on hydrodynamic drag.*
- The hydrodynamic drag is not a linear function of water depth.*
- Flight tests show higher value (10 to 30%) than that determined by AMJ 25 x 1591.*
- Aquaplaning speed determined by the measured wheel speed is approximately 7% lower than the value corresponding to maximum drag ; this value is itself 10% lower than the theoretical aquaplaning speed from AMJ.*

Since the existing data analysis was conducted, the theoretical analysis by ESDU has been revised according to documents 83042 and 98001 according to the reference list. To verify the accuracy of this proposed methodology, a comparison with the flight tested data for the Saab 2000 has been based on the ESDU 83042 and 98001 and the displacement drag has been based on the ESDU 90035. Also the V_p in this analysis is based on applicable ESDU methods. The results for ½ inch water depth are shown in figure 5.4/4.

As can be seen there is a good agreement up to 70 kts as well while above that speed there is a speed range which ends up to be unconservative and then up to 20% too conservative.

The difference above 70 kts is further increased at higher water depth : still this method improves the accuracy of impingement drag calculation compared to current AMJ formula.

A major part of the differences at high speed between the flight tested drag and the calculated drag according to the ESDU method is due to the difference in ESDU derived speed and flight tested speed for maximum drag. As stated in other parts of this report, these speeds can differ significantly.

The results obtained in using the ESDU 83042 for analysis of the spray plumes show some differences compared to WP1 results as well as flight test results.

Hence the spray may counteract with the aircraft in a different way using the model compared to the reality. Depending on the specific aircraft geometry, the resulting error in drag may vary. Also the ESDU method assumes that the resulting spray plumes from each of the wheels will have the same impact on the aircraft drag independant of where on the airframe the water hits. In reality, the relative speed of the water droplets changes as well as the density of the water hitting the airframe changes significantly with the distance from the wheels. This is somewhat compensated for by using more narrow spray plumes compared to the reality. These assumptions and differences in spray plumes are believed to introduce errors that may vary significantly between different aircraft sizes as well as configurations. Actually it may be fully acceptable for one aircraft at a certain depth, while in another condition for the same aircraft significant errors may be introduced.

Even though the ESDU model seems to provide a reasonably good estimation of the drag for the Saab 2000, it is deemed hard to recommend that model in the current state for operational purposes without change in reference speed : this change can be made either by up-date of the formula, or by relevant flight testing.”

5.4.4. DASSAULT aircraft analysis

The tests conducted to gain certification of operation on flooded runway for all aircraft built by DASSAULT AVAITION have been done on the facilities of C.E.V Brétigny (FR).

The study covers five business jets :

FALCON 10

FALCON 20

FALCON 50

FALCON 900

FALCON 2000

All these 5 aircraft have the same general geometry : low wing, engines located at the rearpart of the fuselage, main gear extended under the wing and retracting insides the fuselage and the wing fairing.

Nevertheless, there are changes in dimensions (diameter and fuselage length, height above the ground...) and the engine inlets are above or behind the wing : see fig. 5.4/5 FALCON 900.

A larger aircraft, the only transport airplane build by DASSAULT, the MERCURE is added. This bigger aircraft has a similar geometry, the main difference being that the engines are located under and forward the wing.

Figures 5.4/6 and 7 extracted from deliverable D4 of the program give hydrodynamic drag breakdown at 80 kts / 10 mm water depth and evolution of drag versus speed in the same 10 mm water depth for the FALCON 900.

It is important to remind that in 1991, a regulation study conducted by French Airworthiness Authority (DGAC) with a FALCON 900 in the facilities of BRETIGNY has concluded that aircraft configuration, tyre pressure and center of gravity have no significant effect on the hydrodynamic drag. On the other hand, the tests demonstrate that this drag is a linear function of water depth up to 20 mm.

Despite the difficulty of getting accurate and stabilized aircraft performance, and water depth, there are some general conclusions for the whole DASSAULT fleet :

1-) For all FALCONS at low speed (below 100 kt), the drag developed by the aircraft running in water pond is significantly higher than that calculated following the AMJ 25 x 1591 formula.

For the MERCURE, the level of test drag could be reproduced by some theoretical amendment (FWP 478).

- 2-) *The aquaplaning speed corresponds to the maximum drag developed in the tests. This speed is 20 to 30% lower than that calculated following the AMJ formula.*

The FALCON 10 is perhaps an exception : with the assumption of water ingestion correlated with speed below aquaplaning speed, the theoretical formula may be acceptable.

5.5. CITATION II TESTS (WP3)

5.5.1. Objectives of the tests

CITATION II being the smaller business jet certified under FAR/JAR 25 requirements, is supposed to be a good example to demonstrate any scale effect of AMJ 25 x 1591 formula (see fig. 5.5/1 and 2 extracted from Deliverable D6).

Therefore, specific tests have been conducted on the CRANFIELD facilities to investigate :

- effect of flaps and wheels wells*
- break down in-between nose gear and main gear*
- spray patterns*
- aquaplaning speed*
- evolution vs speed in 10 mm water depth*

5.5.2. Conclusions of the tests

- No difference appears with flaps configuration, nor with open/closing wheel wells.*
- Aquaplaning is encountered above 90 kt, i.e. : at 20% lower speed than that computed by AMJ, and after this speed, there is a significant drop in the drag.*
- Total precipitation drag is higher than that predicted by AMJ by 15 to 40% : this is due only to main gear contribution (more than 50% above prediction), because the nose wheel drag is 30% lower than predicted (see fig. 5.5/3 from deliverable D6).*

5.6. INTERMEDIATE SYNTHESIS (WP4)

5.6.1. Operation on standing water

All the tests show significant increase in precipitation drag as compared to that calculated following AMJ 25 x 1591 even if the difference varies from one aircraft to another as shown figure 5.6/1 extracted from deliverable D8 : the CITATION II overall drag is closer to the theory than SAAB or DASSAULT aircraft, mainly because the contribution of nose gear of the NLR aircraft is very low.

The maximum spray plume angles seen in the test are always at least twice that determined by the ESDU document referenced in the AMJ 25 x 1591.

The aquaplaning speed and the speed corresponding to maximum drag are lower than that predicted by the AMJ formula, yielding test drag coming under predicted drag at high speed, as shown figure 5.6/2.

In order to improve the validity of ESDU reports referenced in the AMJ, all the information collected about test drag and spray plume are communicated to ESDU, in agreement with European Commission and with the JAA expert.

At this point of the study, there is clearly a need to perform further tests to assess more precisely the break-down in nose gear and main gear, as well as aquaplaning speed and speed corresponding to maximum drag.

With that in mind, the Consortium decided that DASSAULT will conduct these complementary tests with the FALCON 2000 on the CRANFIELD facilities.

5.6.2. Operation on runway covered with snow

From contacts outside of the consortium (see sub-chapter 5.9), it appears that the results obtained on snow are confusing.

The drag seems to be less affected by the speed, but there is some drag at low speed which is not in agreement with the parabolic function predicted by AMJ formulae.

On the proposal of SAAB AB, the Consortium decided to perform tests on natural snow, which corresponds to an operational runway condition.

The purpose is to determine contaminant drag with wheels free to roll (no braking) and to compare with AMJ 25 x 1591 (equivalent water depth concept).

5.7. COMPLEMENTARY TESTS (WP5)

5.7.1. Falcon 2000 tests in water

Dassault has conducted a two-days testing session in 20 mm water depth (CRANFIELD, September 1998) : the results are detailed in Deliverable D13.

Fig. 5.7/1 is a picture showing main gear only in water, with over sized tyre pressure.

The evaluation of total precipitation drag, as well as isolated drag of nose gear and main gear high lights the need to elaborate a new hydrodynamic drag model, different from that contained in current AMJ 25 x 1591 (see Annex 1).

Main gear hydrodynamic drag

Fig. 5.7/2 presents measured drag versus aircraft speed compared to the theoretical displacement drag. The theoretical displacement drag is calculated from ESDU 90035, which is a refinement of AMJ methodology (see Annex 2) :

- drag coefficient due to fluid displacement function of speed and of the ratio tyre width at fluid surface over tyre width at ground contact (instead of 0.75).
- typical dual wheel trailing arm drag two times single wheel drag (instead of 1.6).

The difference between test data and computation indicates clearly that there is significative impingement drag produced by the main gear spray plume.

ESDU 83042 Amendment A and ESDU 98001 enable to calculate additional drag due to impingement on rear fuselage, but the value obtained is not enough, i.e. : 20% to 50% of the difference. The remaining is assumed to come from forward spray hitting directly the wing.

Nose gear hydrodynamic drag

Figure 5.7/3 presents measured drag versus aircraft speed, compared to the theoretical displacement drag (calculated from ESDU 90035) plus the spray impingement drag (calculated from ESDU 83042 Amendment A and ESDU 98001).

In addition to refinement of displacement drag this methodology improves the accuracy of impingement drag which is calculated in current AMJ by a very simple formula.

The accuracy of theoretical computation is $\pm 30\%$ around test results.

Total hydrodynamic drag

The tests with all gears in the pond give roughly the same amount of drag as the sum of the drag obtained with respectively nose gear and main gear alone in water : this is correct because it is likely that there is just little interference.

Therefore fig.5.7/4 gives the total precipitation drag established by test, compared to the sum of theoretical nose gear and main gear drag computed above.

The accuracy is within $\pm 20\%$.

Tyre pressure and aquaplaning speed

During the tests, all the characteristics associated to aquaplaning phenomena have not been clearly identified :

- ♦ nose wheel rotation speed decelerating down to 10kt, but without effect on the associated drag.*
- ♦ deceleration of main wheel rotation speed limited to 50%, but a significative decrease in associated drag was seen.*
- ♦ effect of main gear tyre pressure (10, 13 and 16 bars) was unclear for wheel rotation speeds, and was not seen on the hydrodynamic drag : whichever the tyre pressure, the total drag reaches the same maximum above 93 kt.*

5.7.2. Citation II tests in natural snow

NLR has conducted a session of tests runs in natural snow reported in Deliverable D15, showing that the snow causes significative drag at low speed.

These results are the background for the development of a new methodology applicable to operation on low density snow.

The new concept incorporates the compressibility of the snow : the computed drag is less increasing with aircraft speed than computation on standing water (fig. 5.7/5).

5.7.3. SAAB 2000 tests in natural snow

SAAB has conducted two sessions of test runs in natural snow, detailed in Deliverable D16.

The first session was performed in snow with low specific gravity (0.11) and the results from that test indicate that the total precipitation drag of natural dry snow for the SAAB 2000 aircraft is higher than the prediction by AMJ 25 x 1591 at speeds up to 60 kts and significantly lower at scheduled lift-off speeds. The NLR model shows a better agreement with flight tested data although it calculates a higher drag level than the flight tested results for the SAAB 2000 aircraft shows in this case (figure 5.7/6).

The second session was performed in wet snow/slush with higher specific gravity (0.5 to 0.8) and the results from that test indicate that the total precipitation drag of natural wet snow/slush for the SAAB 2000 aircraft is higher than the prediction by AMJ 25 x 1591. Results of calculations with the water tested drag level, using the AMJ proposed method of the wet snow/slush, shows a good agreement with the flight tested data for the SAAB 2000 aircraft in natural wet snow/slush.

The aquaplaning speed on the main wheels caused by wet snow/slush seems from this test data to be the same as on standing water. This is not in line with the theoretical formulae in the AMJ, which state that the aquaplaning speed should increase with decreasing specific gravity.

The conclusion is that the concept of equivalent water depth seems to be applicable down to a specific gravity around 0.5.

5.7.4. FALCON 2000 tests in natural snow

Dassault has conducted a session of tests runs in natural snow reported in Deliverable D14.

The Consortium was seeking for a snow specific gravity between 0.2 and 0.5, because there is a lack of test results in this zone : unfortunately it was impossible to find such condition, and after several cancellations, DASSAULT decided to take the last opportunity to get snow in 1999 winter and had to go to IVALO (FINLAND).

The tests were conducted in 100 mm depth of fresh snow with low specific gravity (0.11) and the results confirm those obtained by the CITATION II and by the SAAB 2000 on dry snow :

- the three gears create each separate rail in the snow, and there is no evidence of "aquaplaning".*
- there is no impingement of snow on the airframe.*
- there is a significant compression drag at low speed and the new NLR methodology is closer to tests results than current AMJ (figure 5.7/7).*

5.8. FINAL SYNTHESIS (WP6)

The comparison between the results obtained for the different aircraft in this study shows some differences, but it appears clearly that AMJ 25 x 1591 is not applicable as it is to small and commuter aircraft.

Another important result is the fact that the contaminant drag in dry snow looks more independent of aircraft speed : there is a significant drag probably from 0 speed, and the variation with increase in speed is less important than that in standing water.

The preceding demonstrates that an equivalent water depth concept, like that shortly explained Annex 1, cannot be used for a low density contaminant. It seems that the regulations should define more precisely the contaminant : this is also assessed by discussions with operators who claim that the current AMJ does not reflect operational conditions.

Having that in mind, the results of the program have to be classified in two categories :

- standing water and slush, down to a specific gravity of 0.5*
- dry snow with specific gravity lower than 0.2.*

Unfortunately, there is a lack of results for specific gravity between 0.2 and 0.5, and associated conclusion should be reserved.

5.8.1. Standing water and slush

The general trend of the test drag is different from that obtained with current AMJ formulae : there is more contaminant drag at low speed, but at higher speed the AMJ seems too penalizing.

This is because the aquaplaning speed calculated by $9\sqrt{P/s}$ does not correspond clearly to a peaking of displacement drag.

We have to remember that beginning of the sixties the tyre pressure P and the density σ were identified as the most important parameters for hydroplaning phenomena and maximum drag. The results of the test infirm that statement :

- ♦ no significant change in drag for FALCON 2000 main gear with different tyre pressures*
- ♦ no change in aquaplaning speed / maximum drag speed shown by the SAAB 2000 in standing water / slush with specific gravity varying between 0.56 and 1.*

The explanation is perhaps the change in tyre design since 30 years, and therefore the first proposal of the Consortium is to consider $V_p = 9\sqrt{P}$ as a reference speed, and to provide information that aquaplaning phenomena, as well as decrease in contaminant drag, can start earlier : it is now time to initiate a work to reformulate V_p to a more proper description of modern tyres design.

In addition to the problem of evolution with speed, the accuracy of calculation at a given speed is also questionable.

The proposals of the Consortium, developed in Chapter 6 do not change the breakdown proposed by current AMJ, i.e. : landing gear displacement drag and spray impingement drag.

It is assumed that with the refinements proposed on C_D and on dual-wheel trailing arm arrangement, the displacement drag will be well predicted.

The problem lies with impingement drag : the spray envelope calculated by WP1 technical model seems different and more accurate than that defined by ESDU report 83042. Unfortunately it is impossible to be 100% confident in associated drag calculated by WP1 model ; on the other hand ESDU report 98001 demonstrates an acceptable level of computed drag as compared to test results.

Therefore, waiting for further development of WP1 model, the Consortium will recommend the use of up-dated ESDU documents for estimation of spray impingement drag.

In fact this methodology applied to CITATION II and FALCON 2000 shows that at low speed the drag is underpredicted, probably because of an extradrag produced by the main gear bow wave : on the basis of theoretical model WP1, an amount of 10 to 20% of total drag could be related to bow-wave.

5.8.2. Dry snow

No hydroplaning phenomena has been seen in the tests, and no drag was produced by contaminant thrown on the airframe.

NLR has developed a new methodology taking into account the compression of the snow and the displacement drag : this methodology is presented in report NLR. TR-98165, and will be published at the end of 1999 in the AIAA Journal of Aircraft (Method for predicting the rolling resistance of aircraft in dry snow).

In addition, the Consortium could propose a simplification of this methodology in the conclusion chapter : the use of this simplified calculation should be limited to aircraft having wheel load, tyre pressure and dimensions in the same range as the tested aircraft.

5.9. CONTACTS OUTSIDE OF THE CONSORTIUM

The fructuous contacts developed since the beginning of the program have been maintained with the JAA, ESDU and North American program partners.

All test results in water pond are provided to ESDU, with E.C. agreement, enabling update of report ESDU 83042, devoted to estimation of spray patterns generated from sides of aircraft tyres running in water or slush. These new data give important information on chines effect and on center-spray generated by side by side tyres.

The contaminated runway sub-group of JAA Flight Study Group, which is chaired by the designated JAA expert for CONTAMRUNWAY program, has been informed in real time of our work and is therefore able to discuss our conclusions.

Unfortunately, the contacts with the North American Winter Program were less productive. This program encounters some difficulties in issuing elaborated synthesis ; nevertheless the information exchanged with TRANSPORT CANADA support the new methodology elaborated by NLR for operation on low specific gravity snow.

6 - CONCLUSIONS

The general conclusion of the programme is the need to modify the methodology of precipitation drag contained in current AMJ 25 x 1591 :

- *For water and contaminant of specific gravity between 0.5 and 1, it is recommended to apply up-dated ESDU reports.*
- *For snow having specific gravity lower than 0.5, it is recommended to use the concept developed by NLR.*

6.1. PROPOSED MODIFICATIONS OF AMJ 25 x 1591

6.1.1. Definition of the contaminants

Need to develop definitions corresponding to operational conditions :

- *standing water*
- *slush (specific gravity between 0.5 and 1)*
- *wet snow (specific gravity between 0.2 and 0.5)*
- *dry snow (specific gravity below 0.2)*
- *compacted snow*
- *ice*

Note : during winters 1998 and 1999, the only condition encountered for the tests has been natural dry snow, which is probably the most frequent in ambient temperature below 0°C.

6.1.2. Aquaplaning speed (reference speed)

Need to explain that the speed V_P given by $9\sqrt{P}$ (V_P in knots, P tyre pressure in pounds per square inch) is a reference speed used in the calculations.

Deceleration of wheel rotation speeds and hydrodynamic drag peak may occurs at speed significantly lower (10 to 20%)

No change of the speed corresponding to hydrodynamic drag peak is expected for specific gravity between 0.5 and 1.

6.1.3. Precipitation drag calculation (standing water and slush)

The precipitation drag in standing water or slush is the sum of landing gear displacement drag and spray impingement drag created by all the wheels running through the contaminant.

A) Landing gear displacement drag

a) Basic tyre drag

$$D = C_D \times \frac{1}{2} \rho s v^2$$

where ρ is the density of the precipitation and S the frontal area

$S = b \times d$, where d is the depth of precipitation and b is the tyre width at the surface, derived from maximum width of the tyre and tyre deflection.

$C_D = 0.75$ for an isolated tyre.

A method for estimating with more accuracy this drag is given in ESDU data item 90035, "Frictional and retarding forces on aircraft tyre – Part V : estimation of fluid drag forces".

b) Multiple wheels

The drag of multiple wheels of the same gear is usually less than the sum of each basic tyre drag.

A typical dual wheel trailing arm arrangement shows a drag 2 times the single wheel drag.

B) Spray impingement drag

The spray thrown up by the wheels strikes the airframe and cause further drag : a method for estimating the plume angles in plan and elevation is given in ESDU data item 83042 with amendment A (May 1998) "Estimation of spray patterns generated from the sides of aircraft tyres running in water or slush".

These angles vary mainly with speed and depth of precipitation.

The acknowledge of plume angles enables to determine which parts of the airframe are attained.

Based on nose-wheel alone drag measurements on three aircraft, the skin friction drag is converted in an equivalent displacement drag as follows :

$$D_{\text{spray}} = C_{D_{\text{spray}}} \times \frac{1}{2} \rho s v^2$$

Where ρ is the density of the precipitation and s is the total nose-wheels displacement area.

$C_{D_{\text{spray}}} = 8 \times L \times 0,0025$ where L is the length in feet of fuselage behind the point at which the top of the plume strikes the fuselage.

This empirical relationship applies also in case of main-wheel spray striking the fuselage : for other parts of the airframe (wing, flaps or gears) special assumptions have to be made.

A method for estimating with more accuracy this drag is given in ESDU data item 98001 "Estimation of airframe skin-friction drag due to impingement of tyre spray".

6.1.4. Precipitation drag calculation (dry snow)

The precipitation drag for a tyre in dry snow, with a density lower than 0.2 is the sum of the drag due to the compression of the snow by the tyre and the drag due to the displacement of snow particles in vertical direction.

A) Single tyre drag calculation

A method for estimating these drags is given in NLR Technical Report 98165 "Rolling resistance of aircraft tyres in dry snow".

This method can be simplified as below for tyres having dimensions and pressure generally in use for business jets and commuters, i.e. :

- width 5 to 10 inches
- diameter 20 to 35 inches
- pressure 7 to 15 bars

a) Drag due to snow compression

$$D_{C \text{ (Newton)}} = 371 \times b \times h \times \rho$$

In which b is the effective tyre width at the snow surface (meters), h is the snow depth (meters) and ρ the specific mass of snow (kg/cubic meters).

b) Drag to displacement

$$D_{d \text{ (Newton)}} = 25 \times b \times h \times V^2$$

In which V is the aircraft ground speed (meters/second), b the effective tyre width at snow surface and h the snow depth (meters).

B) Total airplane drag calculation

For dual tyre landing gear, each tyre is supposed to act independently ; the drag is simply the sum of each tyre drag without any interference.

In case of bogie landing gear, only the leading tyres have to be considered : it is assumed that after initial compression, there is no supplemental loss of energy, and the drag is that of leading tyres only.

It is also assumed that the drag due to snow impingement on the airframe can be neglected.

6.2. OBJECTIVES FOR THE FUTURE

In fact the study has been limited to small and commuter aircraft, and there is a lack of test results with specific gravity of contaminant between 0.2 and 0.5.

In addition following actions are needed in the future :

- *Improve accuracy of ESDU methodology by taking into account the contribution of bow wave.*
- *Get a more elaborated drag modelling from WP1*
- *Correlate the conclusions with computation of stopping performance on contaminated runway in order to calculate balanced field length, as recommended by JAR OPS1.*
- *Reformulate reference speed V_p to a more proper description of modern tyre design (differences between radial and cross-ply tyres).*

ANNEX 1

METHODOLOGY FOR PRECIPITATION DRAG CALCULATION (current AMJ 25 x 1591)

The precipitation drag is the sum of landing gear displacement drag and spray impingement drag created by all the wheels running through the contaminant.

1) Landing gear displacement drag

a) Basic tyre drag

$$D = C_D \times \frac{1}{2} \rho s v^2$$

where ρ is the density of the precipitation and S the frontal area

$S = b \times d$, where d is the depth of precipitation and b is the tyre width at the surface, derived from maximum width of the tyre and tyre deflection.

$C_D = 0.75$ for an isolated tyre.

b) Multiple wheels

The drag of multiple wheels of the same gear is usually less than the sum of each basic tyre drag.

A typical dual wheel trailing arm arrangement shows a drag 1.6 times the single wheel drag.

2) Spray impingement drag

The spray thrown up by the wheels strikes the airframe and cause further drag : a method for estimating the plume angles in plan and elevation is given in ESDU data item 83042 "Estimation of spray patterns generated from the sides of aircraft tyres running in water or slush".

These angles vary mainly with speed and depth of precipitation.

The acknowledge of plume angles enables to determine which parts of the airframe are attained.

Based on nose-wheel alone drag measurements on three aircraft, the skin friction drag is converted in an equivalent displacement drag as follows :

$$D_{\text{spray}} = C_{D_{\text{spray}}} \times \frac{1}{2} \rho s v^2$$

Where ρ is the density of the precipitation and s is the total nose-wheels displacement area.

$C_{D_{\text{spray}}} = 8 \times L \times 0,0025$ where L is the length in feet of fuselage behind the point at which the top of the plume strikes the fuselage.

This empirical relationship applies also in case of main-wheel spray striking the fuselage : for other parts of the airframe (wing, flaps or gears) special assumptions have to be made.

3) Effect of aquaplaning speed

The aquaplaning speed V_P is given by the formula $V_P = 9 \sqrt{\frac{P}{s}}$, where V_P is the ground speed in knots, P tyre pressure in p.s.i and s is specific gravity of the precipitation.

Above this speed, the precipitation drag decreases as the tyres rise and the angle of spray plumes decreases : an acceptable method to calculate the drag above V_P is to reduce C_D and $C_{D_{\text{spray}}}$, in function of the ratio V/V_P , down to 0 for $V = 1.6 V_P$.

4) Equivalent water depth concept

The displacement drag (§1 above) can be given as a function of an equivalent water depth $= \rho \times d$. This simplification needs to ignore the change of tyre width at the surface for different contaminant depth : there is also a need of evaluation of the aquaplaning speed. Nevertheless, this concept is sometimes retained to present simplified data;

ANNEX 2

METHODOLOGY FOR PRECIPITATION DRAG CALCULATION (FWP 478, 582 and 583)

These Flight Working Papers, proposed by the JAA Flight Study Group introduce the following modifications to the current AMJ 25 x 1591 methodology :

- *Multiple wheels displacement drag : typical dual wheel trailing arm arrangement shows a drag 2 times the single wheel drag.*
- *Additional reference to ESDU data item 90035 "Friction and retarding Forces on aircraft tyres - Part V : Estimation of fluid drag forces".*

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