AIRCRAFT BRAKING FRICTION PREDICTION FROM FLIGHT DATA RECORDER DATA

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Abstract

In Nordic countries and in-fact all countries with winter conditions limits and weight penalties for aircraft takeoffs have been established and are rigorously exercised. These limits depend on the weather conditions and the runway conditions, which are established by visual inspection and the measurement of runway friction coefficient using ground friction measurement equipment.

It is expected and indeed is proven that the aircraft braking friction coefficients of contaminated runways are different for aircraft than that reported by the ground equipment from which the penalties and limits are based.

A system directly capable of determining the aircraft braking friction coefficient would represent a direct and substantial benefit for the aviation industry.

To address these issues a research project with two main objectives has been established.

- Research and development of a physical model and mathematical procedure to utilize already available data from the flight data recorder of a modern Boeing 737-700 aircraft and calculate true aircraft braking friction generated by the main gear brakes.
- Test and verify the developed model on real in-flight data provided by Braathens for a number of landings on winter-contaminated surfaces.

This paper presents a brief summary and outline of the outcome of the research, development and data analysis work performed by CDRM and TICS of the above two objectives. The scope of the work by CDRM and TICS was to research and develop the underlying base model, to provide the necessary background information and complete the data analysis and proof of concept for the aircraft effective brake friction coefficient calculation from flight data recorder data.

1. Introduction

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The current report is the outcome of the research, development and data analysis work performed by CDRM and TICS of the above two objectives. The scope of the work by CDRM and TICS was to research and develop the underlying base model, to provide the necessary background information and complete the data analysis and proof of concept for the aircraft effective brake friction coefficient calculation from flight data recorder data.

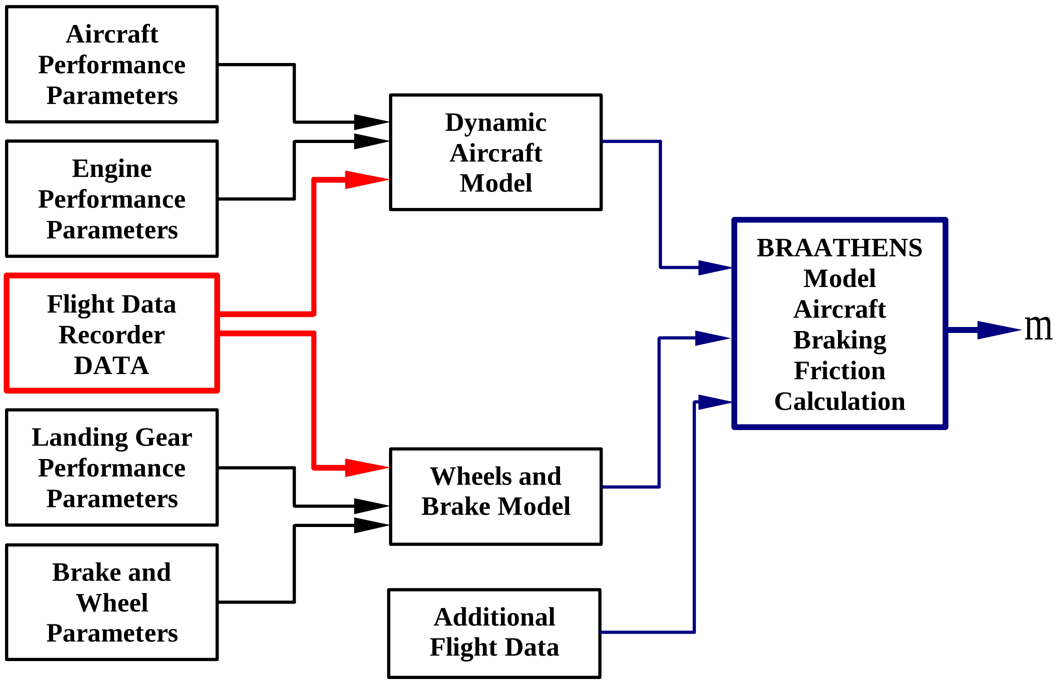
2. Background

The basis of the data processing and calculation of the effective aircraft brake friction achieved by an aircraft on a specific runway is a concept developed by the research work of CDRM and TICS with the co-operation of NASA and Boeing. The logic of the procedures applicable to the present study can be observed in Figure 1.

The figure depicts the flow of data from the flight data recorder to the dynamic model of the aircraft and landing gear system. The performance parameters of the aircraft, engine, and landing gear-brake assembly can be obtained from the manufacturer of the respective equipment and can be included in the dynamic models or can be programmed as constant input data and handled in the model procedures accordingly.

The dynamic models of the aircraft and wheels-brake-landing gear assembly are the representative physical models of the mechanical systems. The models have been constructed for the purpose of this study and therefore do not represent a complete and comprehensive description of the corresponding systems. Thus, they are capable of describing the behavior of the corresponding mechanical system with respect of the required inputs and outputs neglecting other none relevant aspects of aircraft operation.

Figure 1. Aircraft Braking Friction Coefficient Calculation System



The physics and the required mathematical procedures describing the dynamic aircraft model and the wheel and brake model are not within the scope of the present study and therefore will not be discussed.

The "BRAATHENS MODEL" aircraft braking friction calculation procedures with the necessary background information are discussed in detail in Chapter 6. Data Analysis.

The following modifications were done on the base data in order to make it suitable for the present study.

1. The obtained flight data recorder data was conditioned and the different data sets originally available on different sample frequencies were treated and re-sampled so that they represent the same time scale data sequence for all measured data. (see Chapter 4. Data Base for detailed description)
2. The acquired flight data was then converted to the SI unit base for ease of processing.
3. A tab delimited column based ASCII data file was produced for each set of landing data to form the input data to the full simulation and calculation model.
4. A basic crosscheck of the base data was performed to assure the integrity of the input data to the calculation program.

A full digital simulation and calculation program was generated to process the base data obtained from the received raw data sets by the above-described procedure. The output of the digital simulation program is the calculated effective aircraft braking friction for the available data sets.

3. Scopes and Objectives

The four objectives of the friction calculation project that was assigned to CDRM and TICS are the following:

1. The creation of the preliminary database for the project.
2. The Conversion and transformation of the data for the necessary analysis.
3. Digital simulation to obtain the effective aircraft braking friction.
4. Write a comprehensive report containing the base data and draw conclusion on the achieved results.

To achieve the objectives of the study, work has been proposed and completed according to the scope and description of the work as follows.

1. Database compilation and data validation.
   The provided set of data was compiled into a unified database and arranged in a logical order to be the project's foundation (RAW) database. No alteration or transformation in this database has taken place. Braathens provided eleven different sets for processing from which two representative sets will be presented.

2. Data conversion, transformation and analysis.
   The data from the preliminary database was moved into separate data sets and the necessary conversions and transformations were performed. The data sets were then conditioned with the necessary procedures and basic cross-checking for the validation was performed.
3. The data sets created in step 2 were then used in a digital simulation to perform the following calculations:
   - Determine aircraft dynamic behavior from measured data and performance parameters to compensate measured data for the calculation of wheel brake deceleration due to braking friction.
   - Determine aircraft and undercarriage dynamic behavior from measured data and performance parameters to compensate measured data for the calculation of main wheel loads.
   - Determine the $\mu_{Aircraft}$ – Time relationship.
   - Simulation of aircraft braking.
4. Report writing.

For the presentation of the major intermediate and final results the present report was created.

4. Data Base

In this chapter the description of the received data and the composition of the base data set are outlined.

The RAW database, which contains the original data, is a Microsoft Excel 97 workbook with several worksheets. Each of these worksheets contains information or data sent by Braathens and the whole workbook embodies the full database that serves as a foundation for the project.

The project database contains several sets of Excel workbooks. Each workbook contains the conditioned and validated data for a landing. The workbooks for the different landing data also are the means and tools for the preliminary data transformation and cross check.

4.1 Received Data

For the report Braathens airline provided eleven different data sets. The original data files were provided in Microsoft Excel © format. The worksheets contained the extracted data from the flight data recorder. The workbook filenames were constructed from the aircraft registration number; date time and flight number and the same information were included in the worksheets. The data had a time base of 1 sec per data for relatively low priority data and 0.25 sec for high priority data points.

In order to prevent possible identification and matching of the original flight with the data and analysis results the information of aircraft registration number, date of flight, time of flight and flight number were removed from the data sets used in the report and replaced with code names.

To establish the initial database 11 sets of flight data were received from Braathens. An example is given below in figure 2.

Figure 2. LN-TN0 ddmmyy ENSB.xls

AIRCRAFT BRAKE Mu VERIFICATION							
AC REG:	LN-___	**DATE:**		**TIME:**		**FLIGHT:**	
AIRPORT:	ENSB	**RUNWAY:**	10	**AUTOBRAKE SETTING:**		3	
GIVEN B/A:	41-40-38	**W/W:**	120/31	**QNH:**	993		
TEMP./DEVIATION POINT:		-1/-3		**LANDING WEIGHT:**		56.000	
REMARKS:							

In data set number 6 LN-TN0 ddmmyy ENBR.xls there is a discrepancy between the data set name and the corresponding header data. The data set nevertheless was processed according to the described procedures with the rest of the data. A complete set of all figures is given in the report “Braathens Aircraft Data Analysis” Vertic Corporation.

4.2 Conditioning of the Project Data Sets

The aircraft flight data received from Braathens was of a very good quality and free of detectable errors or discrepancies except for the problem in data set 6.

The measurement data concerning the ground speed, airspeed and deceleration contained some inadequacy that was assumed to be from dynamic effects of runway roughness during the landing and was thus compensated for and therefore disregarded.

In order to remove the effects of the vehicle dynamics from the landing flight data a basic filtering of the data proved to be necessary.

The analysis of the deceleration and ground speed of the data showed a variation that presumably was due to a specific roughness of the runways and a simple low pass filter was used for the correction of the ground speed data. The aircraft deceleration was cumulatively integrated over the elapsed time and used to correct the aircraft ground speed.

5. Project Data Sets

The following three figures are examples of the project data sets after the initial data conditioning and alignment was performed. The complete set is given in the report.

The data plotted on the graphs are the following:

1. Va: Air Speed [m/s]
2. Vg: Ground Speed [m/s]
3. Ax Longitudinal Deceleration [m/s^2]
4. TRr Thrust Reversal Sleeve RIGHT [%]
5. TRl Thrust Reversal Sleeve LEFT [%]

The brake pressure for the left and right sides are not included in the presented figures because the scale of these data are different from what can be depicted in the graphs and still retain the comprehensibility of the picture.

Figure 3. Base data for set#4 (LN-TN0 ddmmyy ENGM)

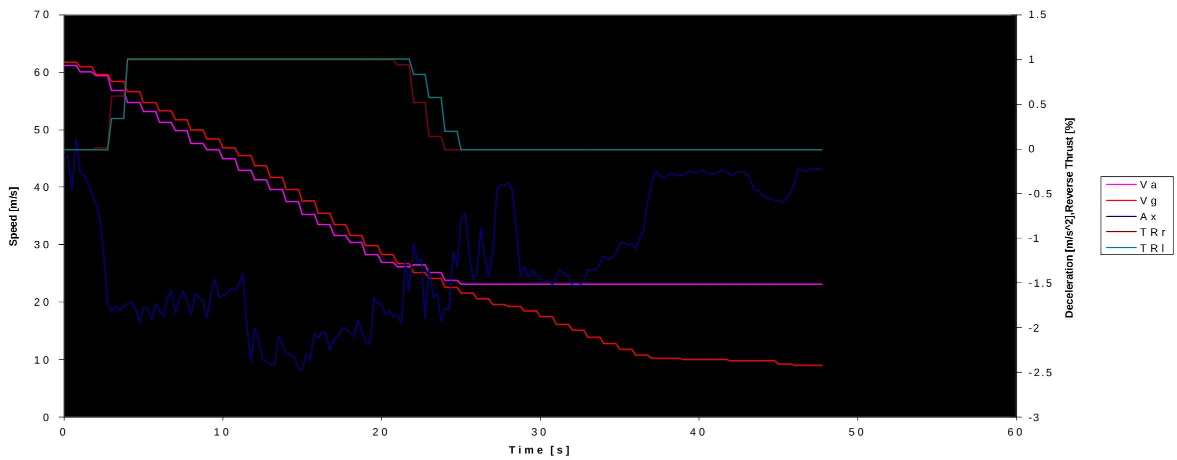


Figure 4. Base data for set#8 (LN-TN0 ddmmyy ENVA)

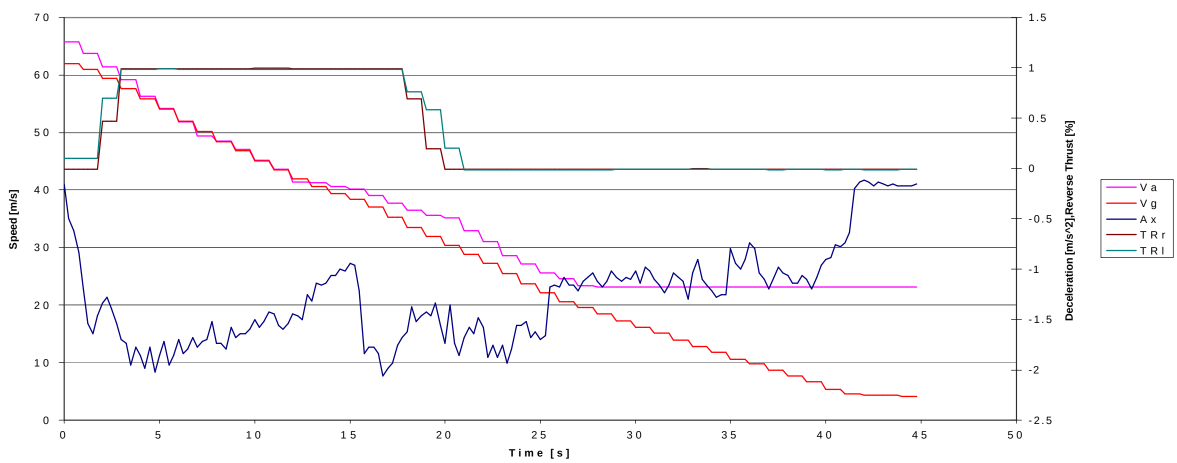
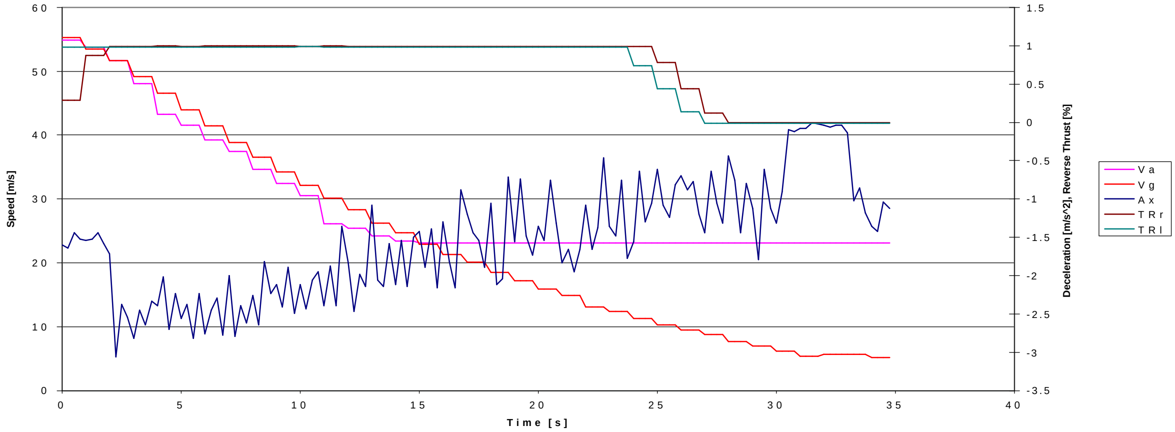


Figure 5. Base data for set#11 (LN-TN0 ddmmyy KSU)



6. Data Analysis

6.1 Introduction

In this section of the report the basic friction analysis is presented. The methods and the mathematical procedures will be briefly described.

7. Dynamic Equations

The development of the braking model for the Boeing 737-700 aircraft was based in part on a model from the Boeing report: “**AN EXTENDED PREDICTION MODEL FOR AIRPLANE BRAKING DISTANCE AND A SPECIFICATION FOR TOTAL BRAKING PREDICTION SYSTEM**”

For a detailed description of the models and an in-depth explanation of the physical background we have to refer to the report mentioned above. The scope of the present study does not make it possible to include comprehensive and detailed information of the used physics and mathematics of aircraft braking maneuvers.

The research work of the present study have led to the formation of the model capable of taking the data collected by the flight data recorder and the performance parameters of the specific aircraft together with the parameters of the actual flight and calculate real time the braking friction forces.

The description of the developed physical model is outside of the scope of the present paper.

8. Brake Simulation

For the simulation of the braking process of the aircraft the data retrieved from the flight data recorders had to be processed through the created dynamic model. The model was formulated to be flexible and easy to adopt to other types of aircraft. The mathematical procedures implementing the physical model relies on three independent sources of data:

1. Sensor data from the aircraft (retrieved from the flight data recorder)
2. Parameters of the actual flight (Aircraft weight, OAT, etc.)
3. Aircraft performance parameters.

The necessary data for the first two points were provided by Braathens Airline and was used in the simulation. The aircraft performance parameters needed for the study were not readily available. During the preparation, research and implementation phase of the project every effort was made to obtain the necessary parameters from Boeing and from other sources with no positive results. The investigators therefore used two different approaches to overcome on the difficulties:

1. Some of the needed parameters of the Boeing 737-700 aircraft was found readily available and was downloaded from the Internet.
2. In order to obtain the remaining parameters for which no values could be found two choices were made:
   - Engineering estimation
   - Substitution of parameters from a different aircraft.

The parameters of the KC-185 aircraft were used in place of the B737-700 in a few cases.

8.1 Aircraft Performance Parameters

The following values were used in the simulation for the different aircraft performance parameters.

8.1.1 Engine parameters

Thrust=91633; % 20600 lb *4.44822162 [Newton]
RT=0.25; % Reverse thrust percentage maximum

8.1.2 Aircraft Parameters

AW=124.6; % Wing area m^2
CL(1)=0.42; % Lift with 80% efficient spoilers
CL(2)=0.53; % Lift with 60% efficient spoilers
CL(3)=0.64; % Lift with 40% efficient spoilers
CL(4)=0.75; % Lift with 20% efficient spoilers
CD(1)=0.1878; % Drag with 80% efficient spoilers
CD(2)=0.1736; % Drag with 60% efficient spoilers
CD(3)=0.1594; % Drag with 40% efficient spoilers
CD(4)=0.1452; % Drag with 20% efficient spoilers
L=12.4; % Wheel Base [m]
LA=12.03; % Nose gear to CG distance [m]
LB=0.37; % Main gear to CG distance [m]
HB=2.1; % Height of CG above ground [m]
IYY=6.4081171179e-7; % Mass moment of inertia, pitch [kg.m.s^2]

8.1.3 Wheel Parameters

D=1.016; % Tire diameter [m]
NBM=4; % Number of Main Gear Wheels
NBN=2; % Number of Nose Gear Wheels
Iw=16.052885; % Main wheel rotational moment of inertia [kg.m^2]

8.1 4 Brake Parameters

TBG=4.420575e-4; % Torque Gain [N.m/Pa]

8.2 Intermediate Braking Simulation Results

In the following chapter some of the intermediate results of the braking simulation model will be presented. For each data set three different graphs will be shown:

1. Aircraft speeds with integrated ground speed:
   The graph contains three different speeds of the aircraft plotted as a function of time.
   (1) The black colored line depicts the aircraft's air speed as received from the flight data recorder.
   (2) The red line shows the ground speed of the airplane from the flight data recorder.
   (3) The blue line is the output of the simulation "Braathens model" and shows the simulated ground speed of the aircraft. It is a check for the simulation model's validity. The blue and red lines should show a good agreement in tendencies and absolute values.
2. Simulated main wheel load:
   The second graph of each data set plots the simulation model's calculated wheel load on the main wheels. It is showing the load of the individual tires in the main gears. The load is plotted in Newton as a function of time.
3. Calculated aircraft braking friction:
   The third graph depicts the computed aircraft braking friction coefficient. The graph shows the simulations output friction for the entire length of the available data received. Thus it is not limited to the time of the actual braking maneuver. The graph shows the friction plotted as a function of time.

8.2.1 Data set#4: LN-TN0 ddmmyy ENGM

Figure 6. Data set#4 Aircraft speeds with integrated ground speed.

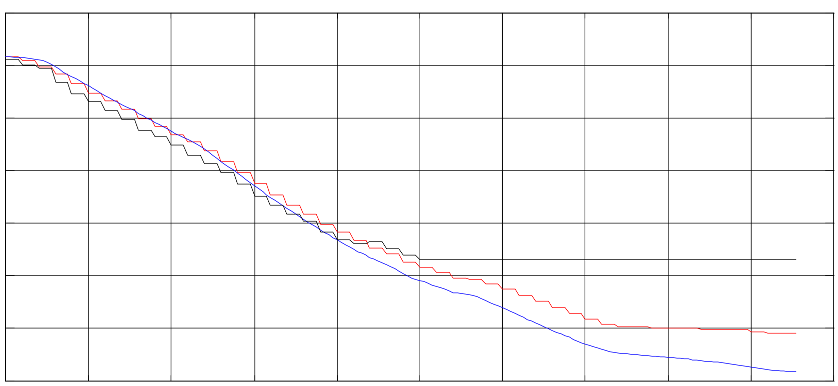


Figure 7. Data set#4 simulated main wheel load

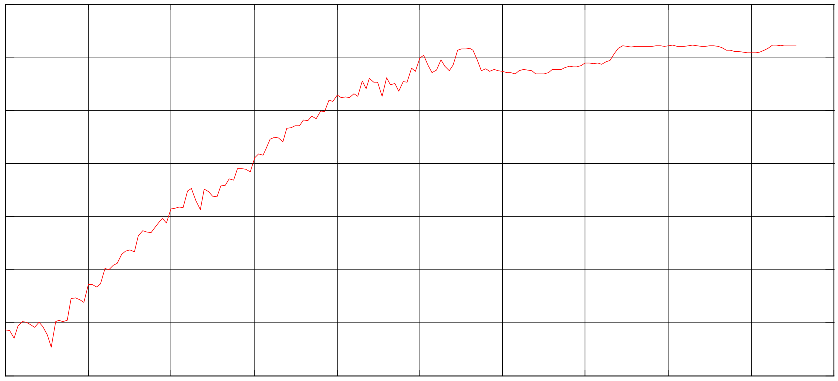
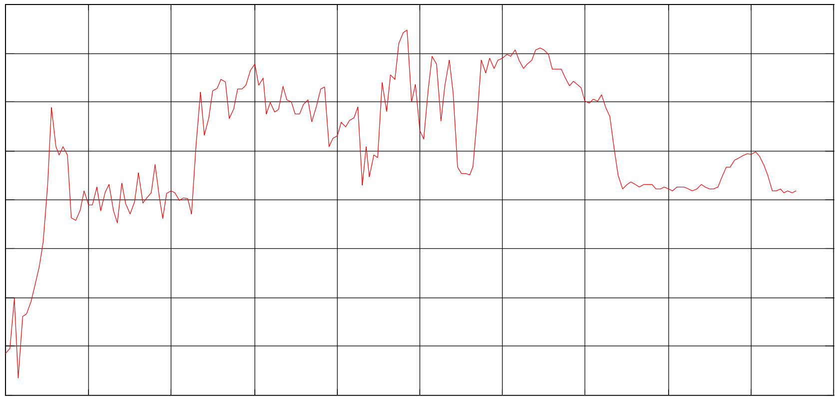


Figure 8. Data set#4 calculated aircraft braking friction.



8.2.2 Data set#8: LN-TN0 ddmmyy ENVA

Figure 9. Data set#8 Aircraft speeds with integrated ground speed.

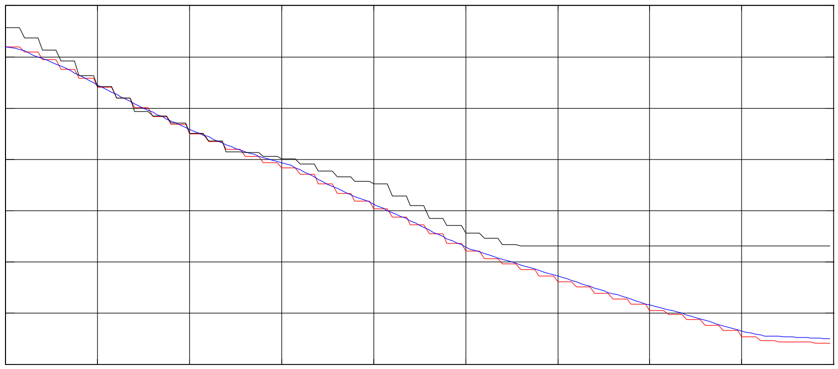


Figure 10. Data set#8 simulated main wheel load.

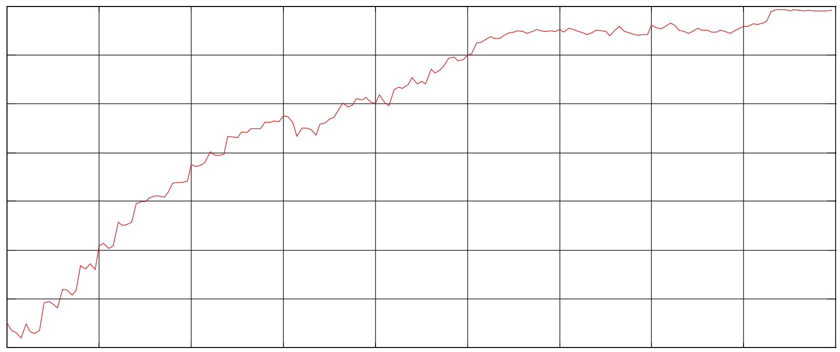
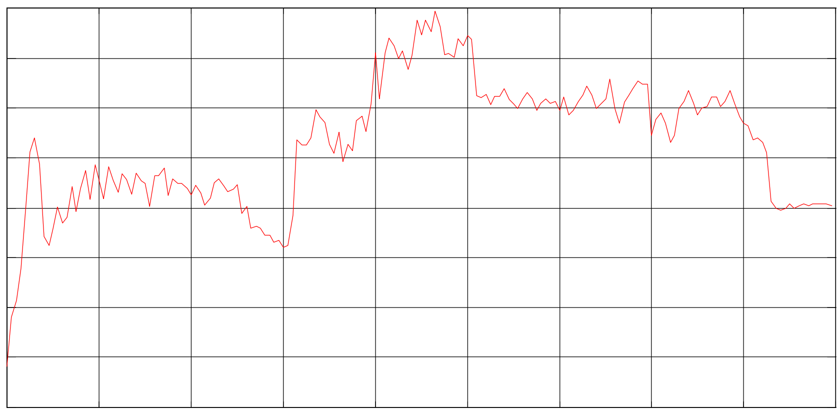


Figure 11. Data set#8 calculated aircraft braking friction.



8.2.3 **Data set#11: LN-TN0 ddmmyy KSU**

Figure 12. Data set#11 Aircraft speeds with integrated ground speed.

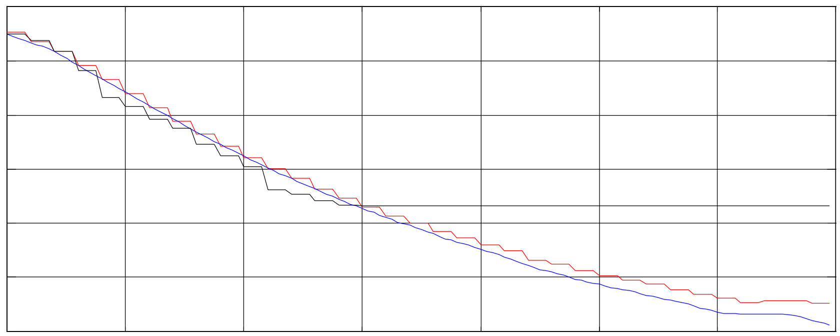


Figure 13. Data set#11 simulated main wheel load.

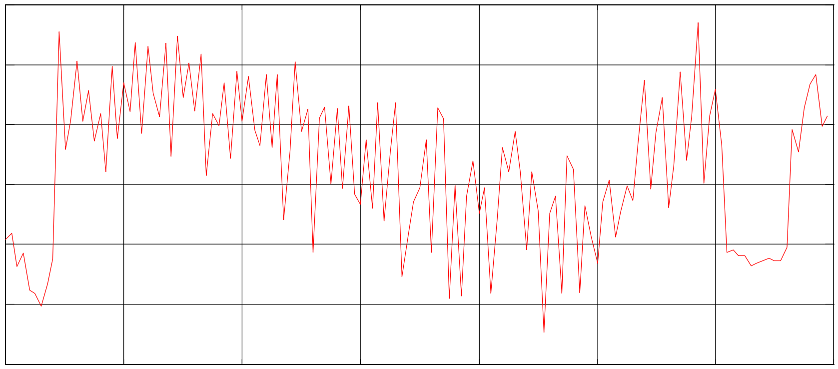
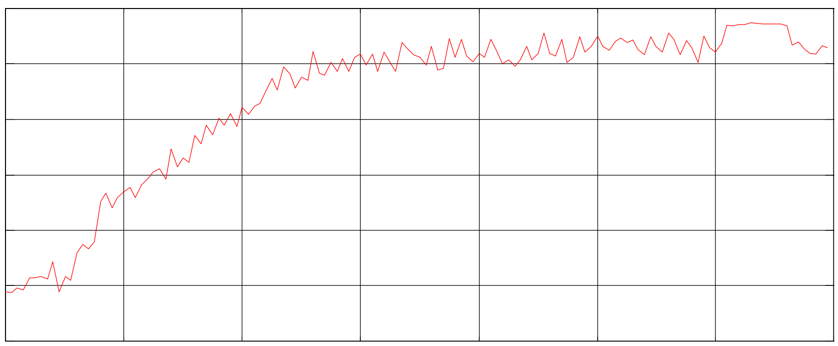


Figure 14. Data set#11 calculated aircraft braking friction.



9. Results

The results of the computations from the "Braathens model" are mapped into one chart per data set for better comprehensibility. The charts contain three different physical entities plotted on the same dimensionless scale. The different curves have been multiplied with a constant to enable the use of the same scale. The three different physical parameters are:

1. (BLUE LINE): Hydraulic brake pressure, the multiplication constant is 1 and the scale is "Pa".
2. (RED LINE): Aircraft braking friction, the multiplication factor is 10^7 and the scale is, of course, dimension less.
3. (BLACK LINE): Main wheel tire load, the multiplication factor for this plot is 30 and the dimension is Newton.

For each of the data set plots of the brake pressure and the generated braking friction provide an easy way to depict the following cases:

- The torque limited braking scenario: the case when the applied hydraulic pressure for the braking produces creates a torque less or equal than the surface friction can support.

- Friction limited braking scenario: the used brake pressure generates more braking torque than the surface friction can support. Thus in the friction limited case an increase in the hydraulic brake pressure does not result in the increase in the generated wheel friction.

On the resulting graph of data set #4 it can be observed that the increase of the braking pressure can result in the entering of a deep skid on the slippery surfaces from which the recovery takes a relatively long time.

The following data sets were identified as having parts or the whole braking maneuver as friction limited, data set #4 and data set #11 of these are shown in the following figures. On the graph the sections which have been identified as friction limited section have been enclosed by two red vertical lines for better observation.

The thick red vertical lines border those periods during the braking when the available friction of the surface tire-interface have limited the braking action. Thus, the aircraft auto-brake or in case of pilot braking the pilot himself tried to produce more deceleration of the aircraft by applying more braking power – torque, but the surface friction was not adequate to produce the required values. In some of the cases this resulted in frequent and deep skids of the aircraft tires reducing the braking action significantly.

The following data sets have been classified as friction limited:

1. Data set#1: LN-TN0 ddmmyy ENSB
2. Data set#2: LN-TN0 ddmmyy ENTC
3. Data set#4: LN-TN0 ddmmyy ENGM
4. Data set#10: LN-TN0 ddmmyy ENDU
5. Data set#11: LN-TN0 ddmmyy KSU

Figure 15 Data set #4 with Autobrake setting OFF

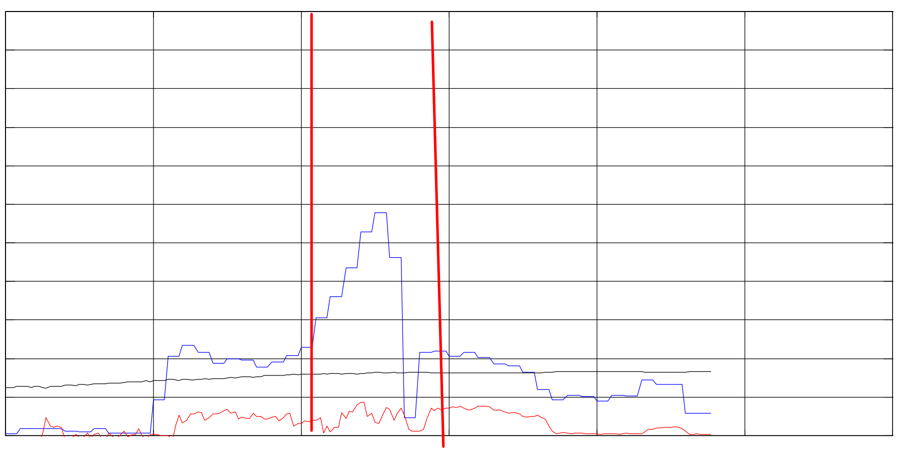


Figure 16 Data set #8 result with Autobrake setting OFF

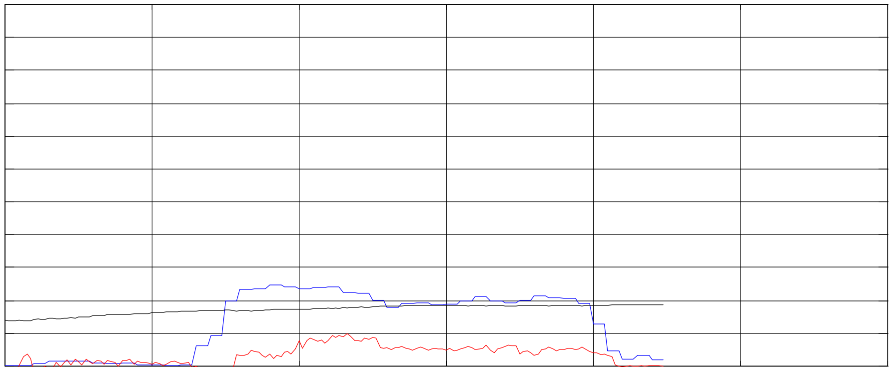
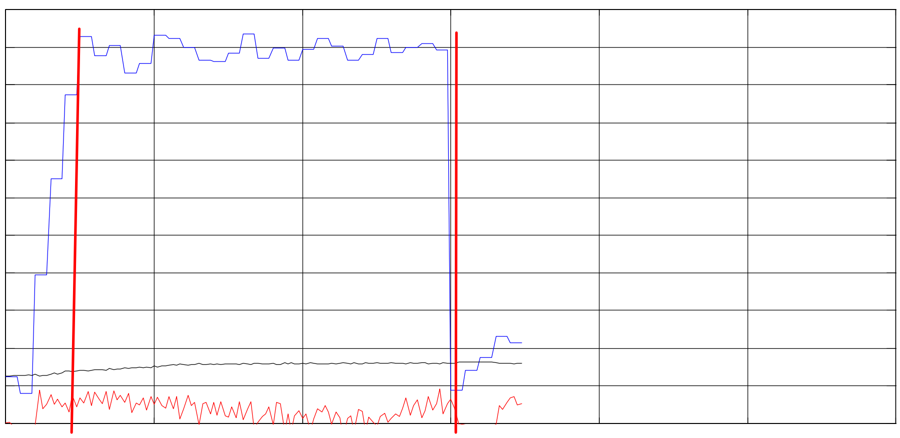


Figure 17 Data set #11 result with Autobrake setting MAX



As a comprehensive summary of the results, the following table has been filled out with the most important results of this study. For each data set, besides the auto-brake setting and the given B/A, the maximum value of the calculated wheel friction and the friction limit has been collected into this table. In the torque limited cases there is no friction limit value.

Data set #	AutoBrake setting	Given B/A	Max value of calculated wheel friction	Friction limit during braking action
4	OFF	56-51-50	0.17	0.1
8	OFF	GOOD, 65-47-35	0.2	-
11	MAX	35-37-41	0.15	0.08

10. Conclusion

The results of the present study lay a sound foundation for the following conclusions:

1. The study has shown that data of the flight data recorder can be used for the real time calculation of the aircraft wheel braking friction. The researched and developed model can be regarded as the proof of concept for the calculation of the braking friction coefficient for aircraft during landing.
2. The calculated braking wheel friction represents the generated friction by the aircraft wheel-brake-antiskid-autobrake system. Thus, it does not necessarily present the total available friction potential of the surface. It simply reports the generated friction.
3. In the special case of a detected friction limited braking action the calculated and reported friction can represent the actual available surface friction for the special aircraft and wheel-brake combination.
4. The friction and torque limited cases can be monitored and in real-time separated by the developed model and procedures. In the case of a detected friction limited braking, the available total surface friction can be calculated and reported.
5. Since the friction limited braking can be detected by this procedure, a warning system can be developed for the pilot to alert of potentially insufficient braking forces of the tire surface interface.
6. Data rates of 4Hz are sufficient for the model to properly determine the fiction.

The reported aircraft wheel friction is one part of all the available surface friction, the part used by the wheel and brake to reach the required deceleration set by the Autobrake setting or by the action of the pilot. Depending on the other different possible configurations of a landing aircraft (including the flaps, airbrakes, thrust reverse etc.), the required braking action or the demand for the contribution of the braking friction for the required deceleration may only be a fraction of the possible total braking friction available. In the case when the demand for the friction from the braking process is less that the total available friction, very little can be drawn from the braking process. However, in the case of an over demand (the case when the required braking friction is more than that of the tire-surface interaction can provide) the total available friction can be calculated. In the present study this scenario occurred in data sets 1, 2, 4, 10 and 11 and they can be used as a measure on the surface friction.