Take-Off performance incidents: do we need to accept them or can we avoid them?

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History

On 27 November 1970, a DC-8-63 operated by Capitol International Airways, crashed following an unsuccessful takeoff attempt at Anchorage International Airport. The takeoff was rejected, but the aircraft overran the departure end of the runway and burst in flames. Forty-six passengers and one flight attendant received fatal injuries in the post-crash fire. The accident was caused by the failure of the aircraft to attain the necessary airspeed to effect lift-off during the attempted takeoff, due to a lack of acceleration.[1]

In their report on the Capitol crash the NTSB recommended to "Determine and implement takeoff procedures that will provide the flight crew with time or distance reference to appraise the aircraft's acceleration to V1 speed."

This recommendation was reiterated in an investigation report involving a PanAm Boeing 747, which on May 24, 1971, struck the approach lights structure for runway 19L while taking off from runway 01R at San Francisco International Airport. The aircraft returned to the airport with only one of its four hydraulic systems left. The accident is best known for its landing and emergency evacuation, during which the aircraft tailtipped, were captured on film, footage of which is available on Youtube (nearly 1.9 million views).

Nearly 34 years after the accident at Anchorage, on 14 October 2004, a Boeing 747 Freighter collided with an earthen berm supporting an ILS localizer antenna at Halifax International during a failed takeoff attempt. All seven crew members were killed and the aircraft was destroyed. The investigation determined that the aircraft's takeoff speed and thrust setting were too low to enable the aircraft to take off safely for the actual weight of the aircraft. One of the recommendations called for the establishment of a requirement for transport category aircraft to be equipped with a Take-off Performance Monitoring System that would provide flight crews with an accurate and timely indication of inadequate take-off performance.
Today, 15 years after Halifax accident, still no operational system exists that can warn the flight crew in the event that takeoff performance is degraded.

Takeoff performance incidents are a special group within the take-off incident and accident occurrences. They are not limited to specific aircraft types or flight operations. They stand out because of the absence of a proper warning system and because the outcome of the majority of these incidents is without damage or loss of life. The outcome of a performance incident can be catastrophic though, but luckily until now most incidents and accidents resulted in the airplane just getting airborne before the end of the runway. Even so, the rate of these incidents happening is alarming, but as the outcome is often without consequence one might tend to believe that the problem is not that serious.

This paper analyses the topic of take-off performance incidents and emphasizes their threat to safety. These incidents therefore require swift action from the regulators and the aviation industry. The paper also proposes a practical warning system.

[1] The lack of acceleration was the result of high frictional drag, caused by a failure of all main landing gear wheels to rotate on a runway covered with a light coating of ice.

Definition of take-off performance incidents

Take-off incidents and accidents take many forms, and may be related to improper weight and balance or aircraft configuration (e.g. an improper flap or stabilizer setting). However, within the scope of this article takeoff performance occurrences are defined as incidents and accidents in which, as a result of a flight crew data input or lack thereof, takeoff is started with:

- takeoff speeds lower than required (V1, Vr and V2);
- a takeoff thrust setting lower than required;
- Takeoff from an intersection with takeoff data assuming more runway length than is available for that intersection.

Review of incident and accident reports

Table 1 to 3 lists 49 incident and accident reports involving erroneous takeoff data.[2] The reports, covering the period 1998-2018, have been published by State Accident Investigation Authorities (AIAs) and nearly all are available on the internet. Table 1 lists reports in which the aircraft's takeoff data was calculated for a weight that was significantly lower than the actual TOW. Table 2 lists reports in which the takeoff thrust setting was lower than required, and table 3 lists reports in which aircraft took off from an intersection with takeoff data assuming more runway length than was available for that intersection.

Although the main focus of the industry is on incidents and accidents of the type listed in tables 1 and 2, the incidents and accidents listed in table 3 also have the potential to end in a catastrophic accident.

The reports vary in detail, but the majority provide an accurate account of what happened. The reports listed in table 1 through 3 detail a variety of operational consequences:

- Rejected takeoff due observation abnormal aircraft behaviour during rotation (27);
- Catastrophic accident (20);
- Damaged beyond economic repair (6, 16);
- Tail strike during rotation (1, <u>6</u>, 7, <u>10</u>, 12, <u>13</u>, 14, <u>16</u>, 17, <u>19</u>, <u>2</u>0, <u>21</u>, <u>23</u>, <u>24</u>, <u>25</u>, <u>26</u>, 27, 28). Damage was substantial for the underlined case numbers;
- Flight continued to destination with damage to pressure hull (7, 40);
- One inflight return due to cabin altitude warning (6);
- Debris on runway which remains operational following a heavy tail strike (with one subsequent aircraft taking off experiencing tire damage) (6);
- APU fire warning following APU damage (24);
- Stick shaker during rotation (6, 10, 14, 16, 24) or initial climb (23);
- Runway overrun (13, 30, 31, 32, 40, 46);
- Aircraft colliding with localizer antenna structure and/or approach lights structure (13, 30, 31, 40, 46);
- Many inflight returns following a tail strike;
- Flap retraction at flap retraction speeds based on the erroneous FMS weight, providing reduced margins to the stall speed;
- Reduced obstacle clearance during takeoff.

[2] The tables were completed early July 2019. Reports published after July 15, 2019, have not been included.

Table 1, case 6: Boeing 767, Madrid, 16 April, 2013 (Photo from CIAIAC report A-010/2013)

Adverse consequences of erroneous takeoff data were not limited to the takeoff phase, but may also manifest themselves during approach and landing:

- Stick shaker activation during approach (9);
- Tail strike during landing (28).

For table 1 the following factors were involved in more than one occurrence:

- the takeoff data were based on the ZFW (1, 2, 6, 8, 14, 16, 17, 19, 23, 25, 27, 28) or the LW (10, 11). The weight error ranges from 12 to 42.5 % of the actual TOW;
- the weight error was 10 tons, 100 tons or 100.000 lbs (3, 4, 5, 12, 13, 16, 21, 24, 26, 28);
- the takeoff data were calculated by dispatch instead of the flight crew (6, 15, 22).

In nearly all incidents derated/flexible thrust was used.
In only a few incidents thrust was increased when it became apparent that takeoff performance was degraded.[3]
None of the incidents/accidents involved a contaminated runway.
In several occurrences the flight crew were unaware that a tail strike occurred.

[3] One of the reports (table 2, case no. 30) includes Human Factors analysis that explains why this is not a natural to do.

Notes to the tables:

All weights mentioned are in metric tons.

The following takeoff incidents and accidents were not included in the tables:

- *occurrences in which in aircraft acceleration and available runway length were sufficient, but the aircraft was rotated at an improper* V_R *;*
- *occurrences in which a NOTAM was active concerning a runway shortening ahead of the aircraft have not been included:*
- *Takeoffs from the wrong runway.*

Table 1: Takeoff with takeoff data based on a lower TOW than the actual TOW				
Case No.	**Date**	**Model**	**Safety Board / Report No. / Incident or accident**	**Description**
1	28Jul18	Boeing 737-800	AAIB EW/G2018/07/35	• Takeoff data based on ZFW (Δ 12.3 ton / 17.3 % of TOW) • Tail strike causing damage. Aircraft continued to destination.
2	29Mar18	Boeing 787-9	AAII Israel 33/08 Serious Incident	• Takeoff data based on ZFW (Δ 40 ton / 16.6 % of TOW) • Sluggish response upon rotation, takeoff otherwise uneventful
3	22May15	Boeing 777-200F	BEA F-GUOC report Serious incident	• Takeoff data based on improper weight (Δ 100 ton / 29 % of TOW). • Aircraft took off without further incident.
4	18Sep14	Boeing 737-800	DSB Insufficient thrust setting for takeoff - Serious incident	• Takeoff data based on improper weight (Δ10 ton / 15.9 % of TOW) • Aircraft became airborne 60 m before the runway end.
5	7Jul13	Boeing 777-300	DSB Summary First quarter 2016 - Serious incident	• Takeoff data based on improper weight (Δ 100 ton / 30.4 % of TOW). • Aircraft took off without further incident.
6	16Apr13	Boeing 767-200	CIAIAC A-010/2013 Accident	• Takeoff data based on ZFW (Δ 66.6 ton / 38.8 % of TOW) • Stick shaker activated during rotation. • Fuselage suffered substantial damage and cabin altitude warning activated before aircraft was returned to departure airport. • Aircraft was written off.
7	14Apr12	Boeing 737-300	AAIB EW/C2012/04/03 Accident	• Takeoff data based on TOW previous flight (Δ 6.8 ton / 12.5 % of TOW) • Tail strike, causing damage to pressure hull. Flight continued to destination.
8	29Apr11	Airbus A321	AAIB EW/G2011/04/29 Serious incident	• Takeoff data based on ZFW (Δ 16.9 ton / 19.5 % of TOW) • Takeoff path flight adapted to accelerate, further uneventful.
9	13Oct10	Boeing 717-200	ATSB AO-2010-081 Serious incident	• Takeoff data based on improper weight (Δ 9.4 ton / 20 % of TOW). • Takeoff was uneventful and discrepancy apparently went undetected. Stick shaker activated during approach.
10	4Mar10	Boeing 747-400F	ASC ASC-ASR-11-05 Accident	• Takeoff data based on LW. Weights not mentioned. • Stick shaker activated during takeoff, thrust was increased. • Tail strike, substantial damage.
11	12Dec09	Airbus A340-600	AAIB EW/G2009/12/04 Serious incident	• Takeoff data based on LW (Δ 86.5 tons / 26.8 % of TOW). • Aircraft took off without further incident.
12	31Aug09	Boeing 777-300	DSB (refer to report 7Jul13) Serious incident	• Takeoff data based on improper weight (Δ 100 ton / 28.8 % of TOW). • Tail strike, minor damage.
13	20Mar09	Airbus A340-500	ATSB AO-2009-012 Accident	• Takeoff data based on improper weight (Δ 100 tons / 27.6 % of TOW). • Tail strike, hit loc antenna and approach lights structure, suffering substantial damage. Full thrust was applied.
14	13Dec08	Boeing 767-300	AAIB EW/G2008/12/05 Accident	• Takeoff data based on ZFW (Δ 54.4 tons / 31.6 % of TOW). • Aircraft suffered tail strike, superficial damage to tail skid. • Full thrust was applied, stick shaker activated momentarily.
15	28Oct08	Airbus A330-300	AAIB EW/G2008/10/08 Serious incident	• Takeoff data based on improper TOW (Δ 90 tons / 42.5 % of TOW). • Full thrust selected during rotation, AC lifted off within confines of runway.
16	27Oct08	Boeing 747-200F	AAIU Belgium AAIU-2008-18- EBBR Accident	• Takeoff data based on ZFW (Δ 100 ton / 27 % of TOW). • Tail strike, causing substantial damage. Stick shaker during rotation. • Aircraft was written off.
17	10Dec06	Boeing 747-400	BEA f-ov061210 Accident	• Takeoff data based on ZFW (Δ 99 tons lower / 29 % of TOW). • Tail strike, damage to the lower aft fuselage.
18	12Jul06	Embraer 190	TSB A06A0069 Serious incident	• Takeoff data based on improper TOW (Δ 5.9 tons / 12 % of TOW) • Aircraft took off without further incident.
19	24Aug05	Airbus A340-300	CAA China / Scandinavian Airlines Accident report	• Takeoff data based on ZFW (Δ 80 tons / 31 % of TOW) • Tail strike, substantial damage lower aft fuselage.
20	14Oct04	Boeing 747-200F	TSB A04H0004 Accident	• Takeoff data based on improper weight (Δ 114 tons / 32.2 % of TOW) • Tail strike, followed by collision with terrain. • All seven crew members suffered fatal injuries. Aircraft was destroyed.
21	14Jul04	Airbus A340-313	BEA Bulletin No.4 - July 2006, Accident	• Takeoff data based on improper weight (Δ 100 tons / 37.7 % of TOW). • Aircraft suffered a tail strike at take-off, substantial damage lower aft fuselage.
22	04Sep03	Airbus A321	AIBN 40/2004 Incident	• Takeoff data based on improper weight (Δ 16.4 tons / 21.5 % of TOW) • Aircraft took off without further incident.
23	22Oct03	Boeing 747-200F	JTSB AA2004-2 Accident	• Takeoff data based on ZFW (Δ 90 tons / 26.2 % of TOW). • Aircraft suffered tail strike at take-off, substantial damage lower aft fuselage. • Stick shaker activated during initial climb.

24	03Mar03	Boeing 747-400	TAIC 03-003 Accident	• Takeoff data based on improper weight (Δ 100 tons / 28.8 % of TOW). • Tail strike, causing substantial damage and false APU fire warning. • Stick shaker activation.
25	11Mar03	Boeing 747-300	SACAA Ref. 0263 Accident	• Takeoff data based on ZFW (Δ 124 tons / 37.3 % of TOW). • Aircraft suffered tailstrike at take-off, substantial damage lower aft fuselage.
26	28Dec01	Boeing 747-100	NTSB ANC02LA008 Accident	• Takeoff data based on improper weight (45.4 ton / 100.000 lbs / ? % of TOW). • Tail strike causing substantial damage to the lower aft fuselage.
27	24Aug99	Boeing 767-300	Havarikommissionen HCL 49/99 Incident	• Takeoff data based on ZFW (Δ 63 300 kg / 33.9 % of TOW). • Takeoff was rejected at a speed of 158 knots. • Tailstrike causing minor damage.
28	11Nov98	MD11	NTSB SEA99LA014 Accident	• Takeoff data based on ZFW (45.4 ton / 100.000 lbs / 21.5 % of TOW). • Tail strike during landing due Vref 15 kt too low.

Table 1, case 20: Boeing 747-200F, Halifax, 14 October, 2004
(Photo from TSB report A04H0004)

Table 2: Takeoff with thrust setting being too low

Case	Date	Model	Safety Board / Report No./ Incident or accident	Description
29	11Dec18	Embraer 190	AAIB EW/G2018/12/05 Serious incident	• Takeoff with too low thrust setting. • Rotation was delayed, takeoff otherwise uneventful.
30	16Nov17	Boeing 737-700	TSIB AIB/AAI/CAS.154 Serious incident	• Takeoff with too low FMS thrust setting. • Aircraft struck approach lights beyond end of runway.
31	21Jul17	Boeing 737-800	AAIB 2/2018 Serious incident	• Takeoff with too low FMS thrust setting. • Aircraft struck eight approach lights beyond end of runway.
32	15Jul17	Boeing 747-8F	JTSB AI2019-2 Serious incident	• Takeoff with too low thrust setting. • Case regarded as equivalent to runway overrun.
33	20Apr16	Boeing 717	ATSB AO-2016-065 Incident	• Takeoff with too low thrust setting. • Adjusted thrust setting was reduced by auto-throttle. Takeoff uneventful.
34	21Nov10	Boeing 737-700	AAIB EW/C2010/11/06 Incident	• Runway change during taxi-out. A too high assumed temperature was inserted. • Aircraft became airborne before the end of the runway.

Table 3: Takeoff from an intersection providing less Takeoff Run Available (TORA) than TORA used for calculation of takeoff data				
Case	**Date**	**Model**	**Safety Board / Report No./ Incident or accident**	**Description**
35	21Jan17	Airbus A320	ATSB AO-2017-008 Incident	• ATC prevented A/C from departing from intersection providing less runway than intersection used for takeoff data calculation. (∆ 403 m)
36	30Aug16	Boeing 777-300	CAA India VT-JEK inquiry Serious incident	• AC departed RWY27L INT S4E, with takeoff data full RWY (∆ 1069 m). • AC airborne with approx. 97 m runway left. No thrust was increased.
37	9May16	Airbus A319	AAIB EW/G2016/03/07 Serious incident	• AC departed INT, with takeoff data assuming full RWY length (∆ 560 m). • Aircraft lifted off closer to runway end than expected.
38	3Dec15	Boeing 737-800	DSB Insufficient thrust setting for takeoff - Serious incident	• Takeoff data were based on runway 03 instead of runway 21 (∆ 1120 m) • Although the flight crew observed there was less runway than expected, thrust was not increased.
39	16Oct15	Airbus A319	AAIB EW/G2015/10/08 Serious incident	• AC departed RWY21 INT U5, with takeoff data for RWY 03 INT N2 (∆ 1120 m). • AC airborne with approx. 213 m runway left.
40	16Sep15	Boeing 777-300	QCAA 001/2015 Accident	• AC departed INT with takeoff data full RWY length (∆ 1000 m). • AC collided with app light structure, puncturing pressure hull. • Unaware of collision flight was continued to its destination.
41	16Jul15	Airbus A319	AAIB EW/G2015/07/11 Serious incident	• AC departed via INT with takeoff data full RWY length (∆ 474 m) • AC airborne with approx. 180 m runway left. No thrust was increased.
42	6Oct14	Airbus A320-200	SUST No.2256 Serious incident	• AC departed RWY15 INT with takeoff data full RWY length (∆ 1530 m). • AC passed runway end at height of 50 ft. Thrust was increased.
43	14Oct13	Boeing 737-800	ATSB AO-2013-195 Incident	• AC departed INT with takeoff data full RWY length (∆ 1116 m). • Takeoff was uneventful.
44	1Oct 13	Airbus A320-200	SUST No.2246 Serious incident	• AC departed RWY17 INT with takeoff data full RWY length (∆ 1580 m). • AC passed runway end at height of 104 ft. Thrust was not increased.
45	21Jun13	Embraer 190	ATSB AO-2013-112 Incident	• Takeoff from intersection providing less runway than required. • Aircraft lifted off within confines of runway.
46	8Dec11	Airbus A340-300	Cenipa IG-556/Cenipa/ A/2018, Serious incident	• AC departed RWY10 INT BB, with takeoff data INT AA (∆ 600 m). • AC collided with app light structure and localizer antenna, damaging gear. • Unaware of collision flight was continued to its destination.
47	22Nov11	Boeing 737-400	ATSB AO-2012-020 Incident	• AC departed intersection with takeoff data full RWY (∆ approx. 1300 m). • AC was rotated early. Takeoff otherwise uneventful.
48	12Jun11	Airbus A321	ATSB AO-2011-073 Incident	• AC departed intersection with takeoff data full RWY (∆ approx. 1090 m). • AC airborne with approx. 450 m runway left.
49	26Sep09	Boeing 777-200	AAIB 4/2010 Serious incident	• AC departed RWY07 INT B, with takeoff data INT A (∆ 695 m). • AC passed runway end at height of 80 ft. Thrust was not increased.

Takeoff performance related accident scenarios

Table 1:

Table 2:

Table 3:

Under-reporting

The incidents and accidents listed in the tables were investigated by State AIAs. But there is a larger group of incidents involving erroneous takeoff data which have not been subject to investigation by a State AIA. The authors are familiar with about 50 reports between 2000 and 2019 involving erroneous takeoff data. Most of them were reported and filed in a database, while the more serious ones –some of which involve more serious performance deficiencies than is described in some of the reports listed in the tables above- were subject to an internal company investigation.
Another group of these incidents never gets reported to the operator. There are several reasons that can explain this:

Flight crew may simply be unaware that an incident has occurred. For flight crew to file a report on an erroneous takeoff data event, the flight crew needs to be aware that an incident has occurred in the first place. This awareness does not necessarily exist, as there may still be sufficient runway available at lift-off, thus depriving the flight crew from a salient clue that takeoff data are compromised.
As a derated take-off is nearly always performed, the acceleration can be slow, even for relatively low aircraft weights. Also a greater portion of the take-off runway is used before the aircraft becomes airborne. Therefore slow acceleration and a long take-off roll may not be interpreted are not likely to be recognized as a take-off performance incident. It is also not unusual to lift off near the end of the runway, especially not when takeoff performance is known to be critical.

Even when the flight crew is aware that an incident has occurred, they may deliberately choose not to file a report, depending on factors like outcome and reporting culture. Likewise, operators may decide not to report incidents to State AIAs for the same reasons.
Another factor involves risk assessment of an incident, which may be based on its outcome instead of its potential for an accident to occur. This may result in a potentially catastrophic incident not being reported to the authorities.
Under-reporting (by the flight crew to the operator and/or by the operator to the authorities) thus masks the size of the problem and the actual exposure to what potentially may be a catastrophic accident.

Flight Data Monitoring filters

Flight Data Monitoring (FDM) filters able to capture takeoff performance incidents take many forms, and range from filters detecting a large in-flight weight change, resulting from a flight crew changing the FMS aircraft Gross Weight (GW), to filters detecting aircraft acceleration or height above threshold. Depending on the filter used, the use of various databases may be required. But in general, the use of sophisticated filters is rare, as it requires expertise not normally available within the average airline. Also there is no formal requirement to have filters sensing erroneous takeoff data events.
Most FDM programmes are limited, if not incapable, in reliably sensing erroneous takeoff data events. Incident reporting, with all its limitations, therefore remains a vital tool in detecting erroneous takeoff data incidents.

Takeoff incidents and accidents - causal factors

A large variety of factors can result in a takeoff with erroneous takeoff data. These factors include -but are not limited to- simple calculation errors, loadsheet design, EFB design, FMS page design, and operating procedures. When taking into regard the plethora of systems to calculate takeoff data, variant flying (leaving pilots blind to recognizing abnormal takeoff data), operational pressure, and human factors like distraction and fatigue, it is inevitable that incidents and accidents will continue to occur, no matter how robust the procedures are. As concluded by the Air Accidents Investigation Branch (AAIB) in their report on an Airbus A340 taking off using takeoff date based on the LW (table 1, case no. 11):

> *The loadsheet and TODC SOPs developed by the airline were robust and contained numerous crosschecks to ensure takeoff performance data was calculated correctly. Despite this, the crew used incorrect information to calculate takeoff performance and, even though the pilots noticed the high FLEX temperature, it did not prompt them to investigate whether they had made an error.*

This clearly indicates the need for an independent warning system.

Initiatives

In the past several recommendations have been made to develop a Take Off Performance Management System. Both the Dutch NLR and NASA developed a TOPMS prototype. Nevertheless, these systems were never operationally introduced.

To address the take-off performance issue EASA established two working groups (WGs). WG-88 focussed on the specification and standardization of On-Board Weight and Balance Systems (OBWBS). WG-88 considered this to be a feasible option and is still working on the standards for such a system.
WG-94 focussed on developing standards and operational conditions for a TOPMS. WG-94 considered that developing a TOPMS was not feasible due to various factors, including limitations in technology and data availability. WG-94 was concluded early 2017.

Why is it so difficult to develop a TOPMS? Past initiatives for a TOPMS took into account many variables and aimed at an accuracy level which had the potential for many nuisance warning to activate. This only introduces new risks.
Table 1 shows that many of the incidents involving a relatively minor weight error did not have serious consequences. The same is true for many of the unreported incidents. These smaller errors were absorbed by the existing take-off performance margins, even in the case of maximum thrust deration. The authors therefore believe that detecting small errors should presently not be the aim of a TOPMS, as such systems require a significant larger effort and time to develop. Instead, the focus should be on a system that only warns flight crew in the event of a gross errors.

Unlike an OBWBS, which on many aircraft would require hardware changes for installation, a gross error TOPMS could make use of the existing avionics architecture and thus become available for a large range of aircraft types currently in use.
Another advantage of a gross error TOPMS over an OBWBS is that it is independent: it does not require any flight crew action during the pre-flight phase.

All gross take-off performance errors could have been easily detected with a TOPMS. With Dutch airlines having had their fair share in take-off performance incidents, KLM, Martinair and the NLR looked at the feasibility of a *gross error* TOPMS system that provides an alert during the low speed part of the take-off run.

The authors believe that the introduction of such a gross error TOPMS is feasible in the near future, and propose a system that warns the pilots at the start or early during the takeoff roll (at speeds below 80 kt for a safe reject to be made). The system is not limited to the detection of improper weight inputs or improper FMS speeds, but also issues a warning when takeoff is made from an intersection affording less runway length ahead than required by the takeoff data used.

TOPAP - a simple TOPMS system

The authors propose the following system, hereafter referred to as Takeoff Performance Alerting Program (TOPAP). The system comprises three major steps:

Step 1: Checking FMS Weight vs V2

Take-off performance entry errors can already be detected while the aircraft is still at the parking bay. However, in order to prevent nuisance warnings following last minute changes it is advisable to do this check when the takeoff is actually started. For a given aircraft weight and flap setting performance tables can be used to determine minimum Vr and V2 speeds. For reasons of simplicity only the minimum V2 value is used for comparison. If the correct aircraft weight is entered into the FMS, but improper takeoff speeds have been entered (thus including an improper V2) TOPAP can already perform a first check by comparing the FMS V2 speed with the V2 taken from the performance tables. Minimum V2 is independent from the thrust setting used (thus taking into account both full and derated thrust settings). The V2 check therefore provides a valuable means to detect a gross weight performance error. Several of the incidents in table 1 could have been avoided if this check had been performed.

Step 2: The algorithm estimating the actual TOW

The idea is to have a simple algorithm that is not necessarily capable to take into account special conditions like contaminated runways but which is still robust enough to be effective as a warning system for detecting large errors in the takeoff weight used for performance calculations under such conditions. The feasibility of a simple algorithm that can determine if the takeoff weight as entered into the FMS by the pilots differs much with the actual takeoff weight was explored by NLR. Some of the results are discussed in this paper. In this approach the actual takeoff weight is estimated from the on-board recorded longitudinal acceleration, an engine thrust model, an aerodynamic model, estimated slope and assumed rolling resistance. Using the following equation for the longitudinal acceleration of an aircraft during the takeoff run:

$$a=g/W\,[(T-\mu W)-(C_D-\mu C_L)Sq-W\sin\emptyset]$$

With W the weight of the aircraft, S the wing reference area, q the dynamic pressure, CD the drag coefficient, CL the lift coefficient, μ the rolling friction coefficient, and Ø the runway slope angle (positive for upslope)[4]. A large difference between both weights (FMS and actual weight) should trigger an alarm warning the pilots. This is like a Type I TOPM system as defined by SAE. A type I system compares the achieved aircraft takeoff performance to the aircraft reference performance and indicates to the crew deviations from this reference. It does not have any predictive capability which makes it much simpler and robust than many of the TOPM systems studied in the past. The approach is demonstrated here using recorded takeoff flight data of a wide body jet aircraft under wide variation of conditions.

The takeoff roll is started by advancing the thrust levers to an initial setting as per operating procedures at a low taxi speed. The engines should be stabilised momentarily before pressing the TO/GA switch.[5] This provides uniform engine acceleration to takeoff thrust and minimises directional control problems caused by asymmetric thrust. Right after pressing the TO/GA switch the longitudinal acceleration increases rapidly until the target fan speed is reached. After that the longitudinal acceleration stabilises and slowly decreases with speed due to the increase

[4] The thrust T developed by the engines depends on the atmospheric conditions (e.g. temperature), the individual engine fan speeds (expressed in N1 or in EPR depending on engine manufacturer), and Mach number (hence true airspeed and temperature). If the engine is at an inclination angle with the airframe body the thrust should be corrected. However for small inclination angles less than 3 degrees the influence on the longitudinal acceleration can be ignored. The lift and drag coefficients in the ground roll depend on the flap configuration. The rolling friction coefficient can vary with ground speed but is usually taken as a constant. During the ground roll the runway slope can be approximated by the measured pitch angle.

[5] When on Boeing aircraft TO/GA is selected, the autothrottle will advance the thrust levers to either the reduced or full takeoff thrust setting. On Airbus aircraft the thrust levers are selected to the FLEX/MCT detent to obtain flexible takeoff thrust or the TO/GA detent to obtain full takeoff thrust. Irrespective of the aircraft type involved, this paper will refer to TO/GA selection when referring to the selection of reduced or full takeoff thrust.

in aerodynamic drag and decrease in thrust. An example of the variation of the longitudinal acceleration with time during the takeoff roll of a jet aircraft is shown in Figure 1.

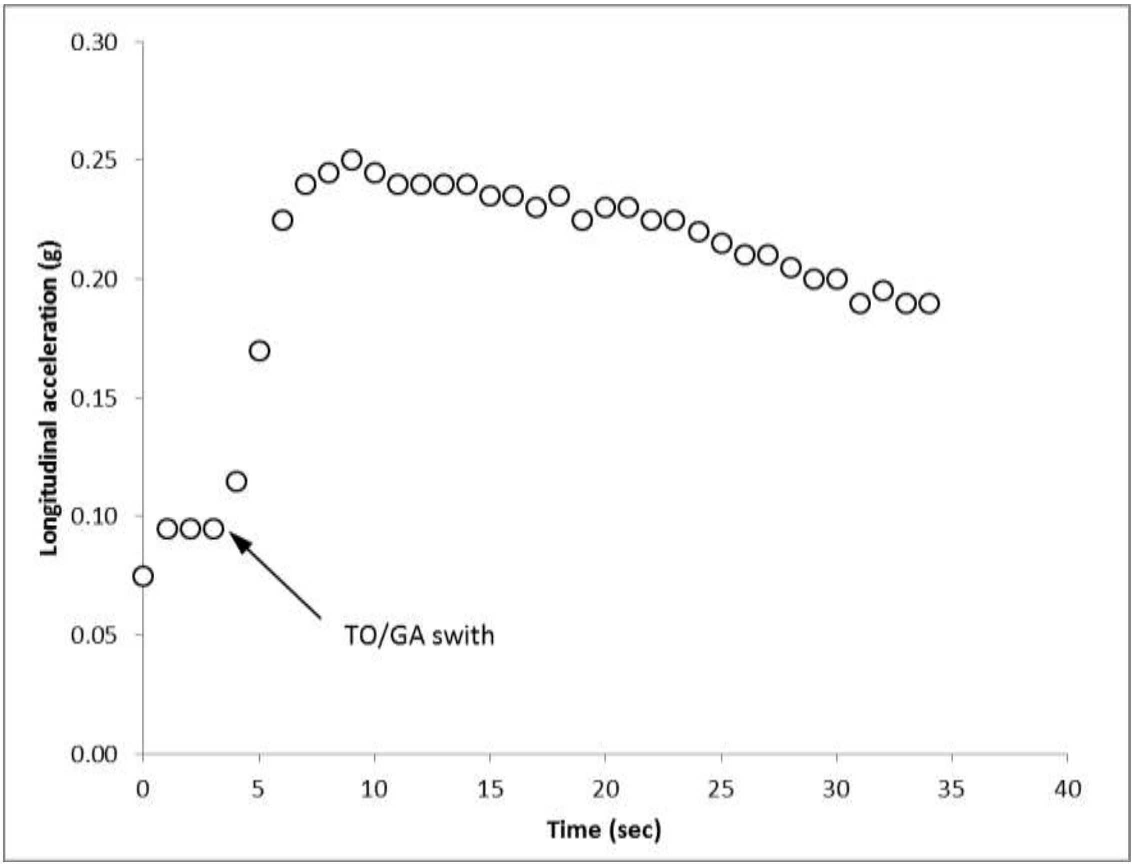

Figure 1: Example of longitudinal acceleration variation with time during the takeoff roll of a jet aircraft.

To avoid warnings of improper takeoff weights to be triggered at high speeds, the algorithm should work at the lowest speeds possible. The taxi roll is not really useable to calculate the weight of the aircraft as the acceleration levels are very low and strongly fluctuate making it difficult to accurately derive the weight of the aircraft. During the takeoff roll higher and more stable values of the longitudinal acceleration can be found as shown in Figure 1. The data recorded right after pressing the TO/GA switch could be used to calculate the weight of the aircraft. A practical problem is that for calculating the engine thrust and aerodynamics forces the airspeed must be known. At very low speeds there are no accurate measurements of the airspeed possible.
Typically from 35-50 knots the airspeed is being measured accurately depending on the aircraft type. This limitation does not apply to the ground speed which is always recorded even at very low speeds. To obtain airspeeds at low speeds the measured ground speed could be corrected using an estimate of the wind speed. A soon as airspeed is being recorded it can be compared to the ground speed. The difference between the true air speed and ground speed can be used as the wind speed. The true airspeed can then be calculated for much lower speeds. Before reaching say 60 knots IAS the algorithm should have calculated the actual weight (best fit) and made a comparison with the FMS weight. When a large difference is detected the pilots should be warned and the takeoff can be aborted safely at speeds less than around 70 knots. Aborts at higher speeds could be acceptable, although it is desirable to avoid this if possible.

The algorithm compares the calculated longitudinal acceleration to the on-board measured values up to a speed of say 55 kt. IAS and tries to find a best fit by varying the weight. The effect of fuel burn is ignored as this will only have a very small influence on the results.

The algorithm was applied to a wide-body jet aircraft. For this aircraft detailed data on thrust and aerodynamics were available. Also recordings of flight data during several takeoffs were available for this aircraft. The takeoffs were conducted at a wide range of airports located at different altitudes and with a wide range of temperatures. Also the takeoff weight varied from being close to the maximum to very low weights due to short flights between nearby airports. These flight data came from the Quick Access Recorder (QAR). Compared to on-board measurements the sample rates are much lower for QAR data. However, for the demonstration purposes these data are still useful. If the algorithm works for the low sample rate data it will definitely also work with data recorded at higher frequencies.
Before testing the algorithm, it was first tried using the recorded QAR data of some 50 takeoffs with the time traces starting from the application of TO/GA switch until rotation. This gave insight in how well the method would work using data from a complete takeoff run. An example is given in Figure 2. This shows the recorded (smoothed) longitudinal acceleration for a wide-body jet aircraft during the takeoff run until the start of the rotation. Also shown is the calculated acceleration using the FMS weight and the calculated acceleration using a weight that gave the best fit. In both cases the simple model for the longitudinal acceleration as presented earlier was used. The recorded N1 of each engine was used to calculate the thrust. In this example the FMS weight and the best fit weight compare very well, with a difference of less than 1%. For most of the analysed takeoffs the difference was less than ±3%.

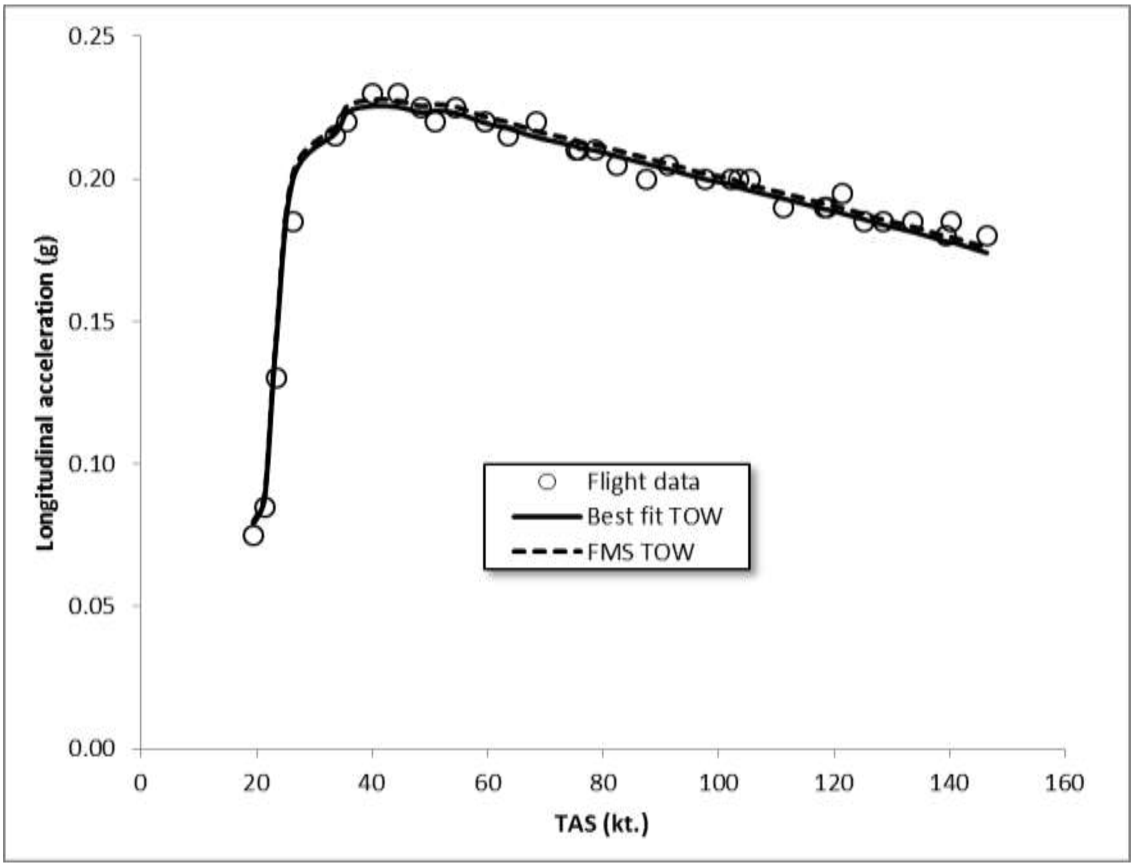

Figure 2: Comparison between recorded longitudinal acceleration, calculated acceleration using FMS TOW, and best fit TOW.

There can be several reasons for differences found between the FMS weight and the calculated weight from the longitudinal acceleration. First the actual passenger weights and the weight of their carryon luggage could be different from what was used to calculate the (FMS) weight (based on regulations). For instance passengers and there carry-on luggage could be heavier than assumed. The weight of the checked baggage is often measured during the check in process.

This means that the total weight of the checked-in luggage of all the passengers is fairly accurate. The same is true for any cargo on-board the aircraft. The engine performance can degrade over time e.g. thrust loss caused by compressor fouling. A recently washed jet engine can produce more thrust at the same throttle setting than an engine that has not been washed. Therefore the engine thrust calculated from the engine deck could be higher than actually achieved. The tire rolling resistance coefficient could be different from the assumed value due to differences in tire inflation pressure and effects of ground speed. It is assumed for simplicity that the accelerations at the aircraft CG and at the accelerometers location are equal. In reality this will not be the case. This could introduce some errors in the derived weight if the aircraft experiences a pitch rate or pitch acceleration during the ground roll[6]. Runways contaminated with standing water, slush or loose snow can induce an additional drag force on the aircraft. Information on the actual contaminant on the runway is not recorded on the QAR. METAR could be used instead however; this makes the algorithm more complex and more prone to errors. The takeoffs analysed were all conducted above outside temperatures of 5 deg. C, making it less likely that snow or slush was present on any of the runways. Standing water is possible but requires a large amount of rain and poor drainage characteristics of the runway. The sensitivity of the algorithm to contaminated runway conditions is tested and discussed later in this report. Differences in weight can also arise from errors in the used basic empty weight. Aircraft are normally weighed at intervals of 36 calendar months. Alternatively an operator may choose to weigh only a portion of the fleet every 36 months and apply the weight determined by these sample weighings to the remainder of the fleet. Both methods can introduce errors over time in the basic empty weight that is used to calculate the takeoff weight of a particular aircraft. Finally the aerodynamic lift and drag coefficients are conservatively based on the most forward CG limit of the aircraft. A more mid-range CG reduces trim drag and increases total lift because horizontal tail download required for aerodynamic balance is reduced.

The small differences in the actual and assumed takeoff weight are mostly covered by the margins taken into account in the performance calculations and should therefore not trigger an alarm. That should only occur for much higher differences in the takeoff weight, of say more than 10%. This represents the typical gross weight errors made by flight crew when computing takeoff speeds.

The first example of the algorithm is a case in which the crew used the zero fuel weight for their performance calculations. TO/GA was selected at low speed of around 10 knots in this example. At a speed of around 50 knots the algorithm estimated that the actual takeoff weight was more than 40% higher than assumed. Figure 3 shows longitudinal acceleration and speed as measured using the on-board IRS compared to the calculated relation using the crew entered takeoff weight, and the fit that the algorithm made. In this example the aircraft started its takeoff at a low speed. This gives the algorithm sufficient time and data to estimate the actual takeoff weight. If the aircraft is rolling at a higher speed when TO/GA is applied, there is less time to for the algorithm to estimate the actual takeoff weight as the aircraft will accelerate quicker to the target speed of around 60 knots at which the algorithm preferably should start warning the flight crew. An example of such a case is shown in Figure 4. In this example the crew selected TO/GA at 40 knots speed. Still the algorithm is able to accurately estimate the actual takeoff weight and warn the crew in time of a large difference between the entered weight and the actual takeoff weight (in this example there is a difference of 20%).

[6] The accelerometers are also subjected to a bias error. Usually this error is very small, however, it will produce very large errors in speed and position calculations when integrated over time. The present algorithm does not integrate speed and position as it only uses the filtered longitudinal acceleration.

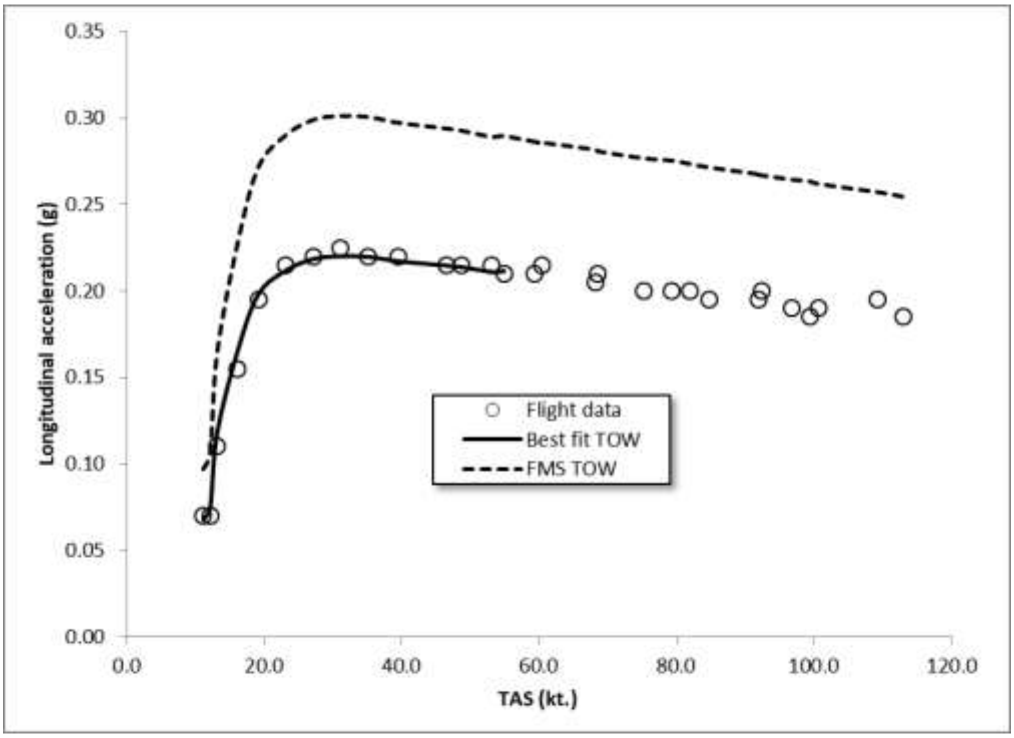

Figure 3: Example of the algorithm for a takeoff started at low speed.

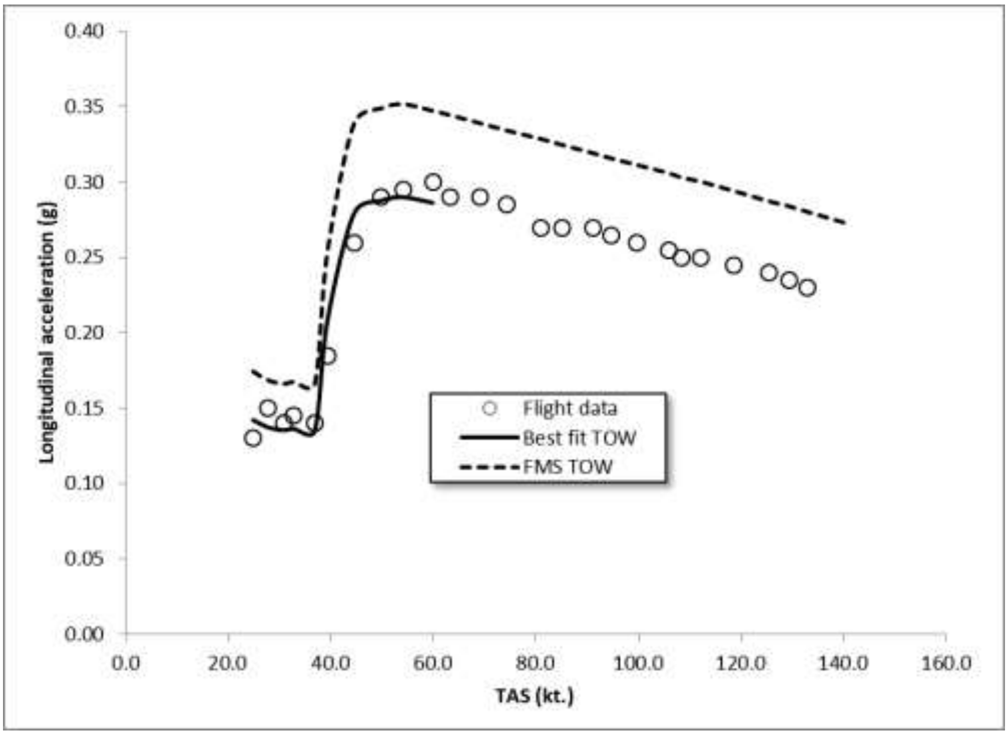

Figure 4: Example of the algorithm for a takeoff started at medium speed.

The examples show that a simple algorithm is capable of giving pilots critical warnings well below V1 in case the assumed takeoff weight is significantly different from the actual takeoff weight.

Step 3: The algorithm checking available runway length
The system discussed so far captures the incidents and accidents presented in table 1.
The second and third group of takeoff incidents, presented in table 2 and 3, concern occurrences in which takeoff is initiated with a thrust setting being too low or from an wrong entry point allowing less runway ahead than required.

After the pilot has selected TO/GA the calculated takeoff weight is checked and compared with the entered FMS weight. If no large differences are detected, the system can then check if the all engine dry runway takeoff distance for the given conditions (weight, flap and thrust setting) is sufficient by comparing it to the TO/GA GPS position with the end of the runway. This check will also capture those cases in which the thrust setting is too low e.g. due to erroneous OAT or incorrect assumed temperature entries during FMS programming.

The warning system as described here is specifically designed to detect gross errors and provide the flight crew with an alert before 80 kt. The system would have captured many of the incidents and accidents included in table 1 - 3 . The overall system is summarized in Figure 4.

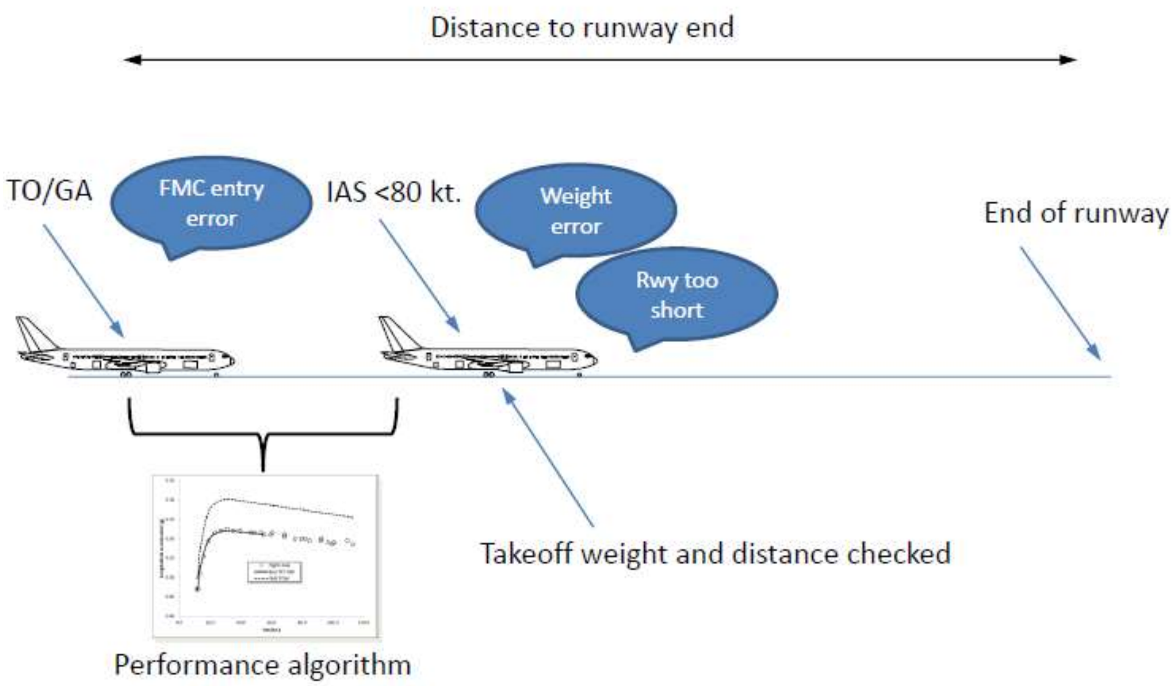

Figure 4: Overview of a simple takeoff performance warning tool.

TOPAP Limitations

The following limitations apply:

- The system only detects gross errors;
- Obstacles are not taken into account;
- The system only uses runway length based on a dry runway;
- NOTAM-ed Runway shortenings are not taken into account.

Not just erroneous takeoff data

Although the TOPAP concept was developed having in mind the erroneous takeoff data occurrences discussed above, there are also other types of occurrences it can prevent from escalating into accidents.
Let's look at two accidents which occurred in the past.

- On 27 November, 1970, a DC-8-63 operated by Capitol International Airways, crashed following an unsuccessful takeoff attempt at Anchorage. The aircraft did not accelerate on a runway coated with ice, as the brakes were providing high frictional drag throughout the takeoff roll. Forty-seven people perished.

- On 13 January 1982, a Boeing 737 operated by Air Florida, hit a bridge over the Potomac after experiencing a loss of control following takeoff from Washington National Airport. A major factor of this accident was that the engine inlet pressure probes on both engines were blocked with ice before initiation of the takeoff. This caused the engines to produce significantly less thrust than required, even though the Engine Pressure Ratios (EPR) presented to the flight crew indicated that the engines were producing the required EPR takeoff thrust setting. Eighty-seven people perished.

Although these two accidents are very different in nature, there are two major similarities: (1) during both takeoffs the EPR instruments showed the flight crew that takeoff thrust had been properly set; and (2) both aircraft accelerated at a significantly lower than normal rate during the take roll.

Now suppose that these aircraft would have been equipped with an FMC and a TOPAP. The TOPAP would have sensed the low acceleration and have calculated a corresponding TOW. This TOW would have been higher than the FMC GW and an alert would have been issued if the difference would have exceeded the weight alerting threshold.
For weight differences falling below the weight alerting threshold, the TOPAP can still issue an alert should the available runway length be insufficient to safely continue the takeoff.

Thus TOPAP is capable of providing alerts for accident scenarios other than those of FMCs programmed with improper takeoff data.

Conclusion

Take-off performance accidents involving loss of life have happened in the past. Apart from the crash involving the Capitol Airways DC-8 in 1970 and the 14 October 2004 all seven crew members were killed in the crash of an MK Airlines Boeing 747 Freighter at Halifax which started the takeoff with erroneous takeoff data. However, despite a large number of incidents and a few accidents, there have been no accidents involving loss of life since 2004.
However, the potential for another catastrophic accident involving a large passenger jet is clearly present. The authors believe that it is not a matter if this will occur, but when. A mid-air collision gave impetus to the development of Airborne Collision Avoidance System, a successful alerting system which is a far more complicated system than the system proposed in the paper. Do we need another major takeoff accident like in the case of TCAS to get things moving? It seems that the need for a TOPMS is not yet fully recognised. And it is questionable if the current movement into the direction of the recommendations for a TOPMS will prevent future accidents. We may just run out of luck. We hope that this seminar can focus the attention of aircraft manufacturers, authorities, airline companies and investigation agencies to jointly develop a TOPAP which can be installed in the majority of the airliners in service today.

Abbreviations

AC	Aircraft
AAIB	Air Accidents Investigation Branch
AAII	Air Accidents and Incidents Investigation
AAIU	Air Accident Investigation Unit
AIA	Accident Investigation Authorities
AIBN	Accident Investigation Board Norway
ATSB	Australian Transport Safety Bureau
BEA	Bureau d'Enquêtes et d'Analyses
CAA	Civil Aviation Authority
DSB	Dutch Safety Board
FDM	Flight Data Monitoring
FMS	Flight Management System
GW	Gross Weight
JTSB	Japan Transport Safety Board
NTSB	National Transportation Safety Board
OBWBS	On Board Weight and Balance System
QAR	Quick Access Recorder
QCAA	Qatar Civil Aviation Authority
SACAA	South African Civil Aviation Authority
TAIC	Transport Accident Investigation Commission
TAMS	Takeoff Acceleration Monitoring System
TO/GA	Takeoff/Go-around
TOPAP	Takeoff Performance Alerting Program
TOPMS	Takeoff Performance Management System
TORA	Takeoff Run Available
TOW	Takeoff Weight
TSB	Transportation Safety Board
TSIB	Transport Safety Investigation Bureau
ZFW	Zero Fuel Weight