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Slippery When Wet: The Case for More Conservative Wet Runway Braking Coefficient Models

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Over the past eight years, the NTSB has led or participated in the investigation of a number of runway overrun accidents and incidents that occurred after the airplanes involved landed on wet runways. An analysis of the airplane stopping performance during these events indicates that the wheel braking friction coefficient (μ_B) achieved during the landing roll was significantly less than the μ_B predicted by industry-accepted models, and less than the μ_B assumed in the wet-runway landing distance advisory data provided in the manufacturers' Airplane Flight Manuals. In recognition of this problem, the Federal Aviation Administration has issued a safety alert to operators warning them that the advisory data for wet runway landings may not provide a safe stopping margin under all conditions, and tasked an Aviation Rulemaking Advisory Committee with reviewing the wet runway stopping performance requirements contained in the *14 Code of Federal Regulations (CFR) Part 25* airworthiness standards and guidance (the μ_B that can be assumed on a wet runway during an aborted takeoff is specified by 14 CFR 25.109, and the 25.109 model has been proposed for computing landing distances on a wet runway). This paper presents six wet runway landing overrun events (all involving turbojet airplanes) and compares the μ_B achieved by the airplane in each event with the μ_B predicted by several models and inherent in advisory data. The results indicate that current models and advisory data can significantly overestimate the μ_B achievable on wet runways (and therefore underestimate the required runway length for landing on these runways). Consequently, these events underscore the need for more conservative models of μ_B, and more conservative use of existing advisory data and models in the meantime.

Nomenclature

Acronyms

AA	American Airlines
AC	Advisory Circular
AFM	Airplane Flight Manual
AIR	SAE Aerospace Information Report
AMC	Acceptable Means of Compliance (EASA)
AMJ	Advisory Material Joint (Europe)
ARAC	Aviation Rulemaking Advisory Committee
ASOS	Airport Surface Observation System
ATIS	Automatic Terminal Information Service
BA	Bombardier Aerospace
BCAR	British Civil Aviation Requirements
CFME	Continuous Friction Measurement Equipment
CFR	Code of Federal Regulations
CG	Center of Gravity
CMB	Combined μ_B model
CS	Certification Specification (EASA)
CVR	Cockpit Voice Recorder
CYMX	Montreal Mirabel Airport, Montreal, Canada
CYOW	Ottawa/MacDonald-Cartier International Airport, Ottawa, Ontario

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DFT	Neubert Aero Corporation Dynamic Friction Tester CFME device
EASA	European Aviation Safety Agency
EPB	Emergency / Parking Brake
ESDU	Engineering Science Data Unit
EU OPS	European operational regulation(s)
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
FTHWG	Flight Test Harmonization Working Group
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JAR	European Joint Aviation Regulations
JCAA	Civil Aviation Authority of Jamaica
KCXO	Lone Star Executive Airport, Conroe, Texas
KMDW	Chicago Midway Airport, Chicago, Illinois
KOWA	Owatonna Degner Regional Airport, Owatonna, Minnesota
KSGR	Sugar Land Regional Airport, Sugar Land, Texas
MAINT LEVEL	AC 150/5320-12C Maintenance Planning Friction Level
MIN LEVEL	AC 150/5320-12C Minimum Friction Level
MKJP	Norman Manley International Airport, Kingston, Jamaica
MM	Mu meter CFME device
NAC	Neubert Aero Corporation
NASA	National Aeronautics and Space Administration
NEW LEVEL	AC 150/5320-12C New Design/Construction Friction Level
NRC	National Resource Council of Canada
NTSB	National Transportation Safety Board
RCAM	Runway Condition Assessment Matrix
REP LEVEL	Average of AC 150/5320-12C MIN LEVEL and MAINT LEVEL
RNAV	Area Navigation (instrument approach)
SAE	Society of Automotive Engineers
SAFO	Safety Alert For Operators
SFT	Airport Surface Friction Tester CFME device
SW	Southwest Airlines
TALPA ARC	Takeoff/Landing Performance Assessment Aviation Rulemaking Committee
TAPHC	Transport Airplane Performance and Handling Characteristics
TC	Transport Canada
TSB	Transportation Safety Board of Canada
TTI	Texas Transportation Institute
UE	United Express Airlines
USA	United States of America
UTC	Universal Coordinated Time
WOW	Weight On Wheels

English symbols

d	Average water depth above the top of the runway macrotexture
F_N	Longitudinal reaction force at nose gear
F_M	Longitudinal reaction force at main gear
F_x	Force along body x-axis
F_z	Force along body z-axis
I	Rainfall intensity
k	Factor on η_{AS} to account for installation and undercarriage effects
k_B	$= (\mu_B\|_{CFME:50}) / (\mu_{max}\|_{25.109})$
k_{max}	$= (\mu_{max}\|_{CFME:50}) / (\mu_{max}\|_{25.109})$
L	Runway drainage path-length (distance from runway centerline)
M_y	Moment about body y-axis

n_x	Longitudinal load factor
N_N	Vertical reaction force at nose gear
N_M	Vertical reaction force at main gear
p	Tire pressure
r_{TIRE}	Effective tire radius
s	Wheel slip ratio
$s_{\mu,MAX}$	Wheel slip ratio for $\mu_{B,MAX}$
S	Runway cross slope
T	Average runway macrotexture depth
V	Airplane speed (airspeed or groundspeed depending on context)
V_1	Takeoff decision speed
V_G	Groundspeed
$\vec{V}_G$	Groundspeed vector
V_p	Hydroplaning speed (for dynamic hydroplaning)
$V_{p,spin\ down}$	Spin-down hydroplaning speed (rotating tire)
$V_{p,spin\ up}$	Spin-up hydroplaning speed (nonrotating tire)
V_{WHEEL}	Tangential speed of tire
$\mathrm{V_{REF}}$	Landing reference speed
W	Airplane weight
W_x	Component of airplane weight along body x-axis
W_z	Component of airplane weight along body z-axis
x_b	Airplane body coordinate system x (longitudinal) axis; see Fig. 1
z_b	Airplane body coordinate system z (vertical) axis; see Fig. 1

Greek symbols

α	Angle of attack
γ	Flight path angle
η_{AS}	Anti-skid braking system efficiency
θ	Pitch angle
μ	Friction coefficient
μ_B	Wheel braking friction coefficient
$\mu_{B,av}$	Average μ_B in the range of $0.1 \leq s \leq 0.5$
$\mu_B\vert_{CFME:50}$	CFME μ values at 50 mph transformed into airplane μ_B by NASA model
$\mu_{B,MAX}$	Maximum wheel braking friction coefficient (at $s_{\mu,MAX}$)
$\mu_{B,SKID}$	Wheel braking friction coefficient with locked wheels (i.e., at s =1)
$\mu_{cd,airplane}$	Characteristic dry μ_{cd} of an airplane
$\mu_{cd,CFME}$	Characteristic dry μ_{cd} of a CFME device
$\mu_{cd,DFT}$	Characteristic dry μ_{cd} of the NAC DFT CFME device
$\mu_{cd,Griptester}$	Characteristic dry μ_{cd} of the Findlay Griptester CFME device
$\mu_{cd,SFT}$	Characteristic dry μ_{cd} of the SFT CFME device
μ_{CFME}	Runway μ measured by a CFME device
μ_{DFT}	Runway μ measured by the NAC DFT CFME device
μ_{dry}, μ_{cd}	Dry-runway (or “characteristic dry”) friction coefficient
μ_N	Rolling friction coefficient at nose gear
μ_{max}, $\mu_{t/gMAX}$	Maximum μ available on runway
$\mu_{max}\vert_{25.109}$	μ_{max} specified by §25.109(c), at the airplane V_G corresponding to the CFME device speed of 50 mph, and the airplane p
$\mu_{max}\vert_{CFME:50}$	CFME μ at 50 mph transformed into runway μ_{max} by NASA model
μ_{SFT}	Runway μ measured by the SFT CFME device
μ_{wet}	Wet-runway friction coefficient
ω_{WHEEL}	Wheel angular velocity

I. Introduction

OVER the past eight years, the National Transportation Safety Board (NTSB) has led or participated in the investigation of a number of runway overrun accidents and incidents that occurred after the airplanes involved landed on wet runways. An analysis of the airplane stopping performance during these events indicates that the wheel braking friction coefficient (μ_B) achieved during the landing roll was significantly less than the μ_B predicted by industry-accepted models, and less than the μ_B assumed in the wet-runway landing distance advisory data provided in the manufacturers' Airplane Flight Manuals (AFMs). In recognition of this problem, the Federal Aviation Administration (FAA) has issued a safety alert for operators (SAFO) warning them that the advisory data for wet runway landings may not provide a safe stopping margin under all conditions, and tasked an Aviation Rulemaking Advisory Committee (ARAC) with reviewing the wet runway stopping performance requirements contained in the 14 Code of Federal Regulations (CFR) Part 25 airworthiness standards[2] and guidance (the μ_B that can be assumed on a wet runway during an aborted takeoff is specified by §25.109, and the §25.109 model has been proposed for computing landing distances on a wet runway). This paper presents six wet runway landing overrun events[3] (all involving turbojet airplanes) and compares the μ_B achieved by the airplane in each event with the μ_B predicted by several models and inherent in AFM advisory data. The results indicate that current models and advisory data can significantly overestimate the μ_B achievable on wet runways (and therefore underestimate the required runway length for landing on these runways). Consequently, these events underscore the need for more conservative models of μ_B, and more conservative use of existing advisory data and models in the meantime.

The landing overrun events considered in this paper are:

1. The BAe 125-800A accident in Owatonna, MN (NTSB #DCA08MA085);
2. The American Airlines flight 331 accident in Kingston, Jamaica (NTSB #DCA10RA017);
3. The United Express flight 8050 accident in Ottawa, Ontario (NTSB # DCA10RA069);
4. The Southwest Airlines flight 1919 incident in Chicago, IL (NTSB #DCA11SA047);
5. The EMB-505 accident in Conroe, TX (NTSB #CEN14FA505); and
6. The EMB-500 accident in Sugar Land, TX (NTSB #CEN15LA057).

Before the details of each of these events are discussed, it will be helpful to review the mechanics of wheel braking, the critical importance of μ_B on braking performance, and the effect of runway texture and wetness on μ_B. Accordingly, Section II of this paper outlines the physics of braking performance, including a method for computing μ_B during an actual landing based on recorded flight data. Section III presents several models for estimating μ_B on a wet runway, including the §25.109 model, and a National Aeronautics and Space Administration (NASA) model based on friction measurements taken by ground vehicles that better matches the μ_B actually attained during the overrun events considered here. Section III also discusses dynamic hydroplaning, and describes a model prepared by the Texas Transportation Institute (TTI) for estimating the depth of water on a runway, given the rainfall rate and details about the runway construction. With this foundation in place, Section IV describes the circumstances and outcomes of the six wet-runway overrun events considered in this paper. Section V then compares the μ_B achieved during these six events to the μ_B models presented in Section III, and with the models implicit in the wet-runway landing distances provided in the corresponding airplane AFMs. Section VI proposes an additional model, based on a combination of existing models, that matches both the accident/incident results and flight test data collected on a number of wet runways, and that accounts for the increasing slipperiness of runways in-between runway maintenance actions. Finally, Section VII discusses NTSB recommendations and FAA actions relevant to the wet-runway stopping performance problem.

[2] Hereafter, paragraphs in 14 CFR Part 25 are designated with the "§" symbol; e.g., §25.109 refers to 14 CFR Part 25, paragraph 25.109.

[3] The events include 5 "accidents" and 1 "incident." Per 49 CFR Part 830.2, an "*aircraft accident* means an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage." An "*incident* means an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations."

II. The mechanics of wheel braking and the calculation of μ_B

A. Calculating the μ_B achieved during a landing ground roll

Fig. 1 is a free-body diagram showing the forces and moments acting on an airplane during the braking portion of the ground roll following a landing. Applying Newton's second law in the body-axis system shown in Fig. 1 yields the following system of equations:

$$F_N = \mu_N N_N \tag{1}$$

$$F_M = \mu_B N_M \tag{2}$$

$$\sum F_x = W n_x + W_x = W(n_x - \sin\theta) \tag{3}$$

$$\sum F_z = W n_z + W_z = W(n_z + \cos\theta) \tag{4}$$

$$\sum M_y = 0 \tag{5}$$

Where:

N_N = vertical reaction at nose gear
μ_N = rolling friction coefficient at nose gear
F_N = longitudinal reaction at nose gear (rolling friction on nose gear)
N_M = vertical reaction at main gear
μ_B = wheel braking friction coefficient at main gear
F_M = longitudinal reaction at main gear (braking force on main gear)
$\sum F_x$ = sum of forces along body x-axis
W = airplane weight
W_x= component of airplane weight along body x-axis
n_x = longitudinal load factor
θ = airplane pitch angle
$\sum F_z$= sum of forces along body z-axis
W_z= component of airplane weight along body z-axis
n_z = vertical load factor (= normal load factor multiplied by -1)
$\sum M_y$ = sum of moments about body y-axis

Note from Eq. (2) that the retarding force provided by the main gear tires during braking (F_M) is equal to the normal force on the gear, N_M (acting perpendicular to the runway surface), multiplied by μ_B. N_M is approximately equal to the weight of the airplane, minus the lift provided by the wings (see Fig. 1). The lift depends on the flap setting, angle of attack (α), dynamic pressure (airspeed and air density), and the position of the spoilers or speedbrakes (if the airplane is so equipped). Deploying the spoilers or speedbrakes after landing greatly improves braking by reducing the airplane's lift, thereby increasing N_M (and F_M).

The factors that affect μ_B are discussed at length below.

For the overrun events considered in this paper, the μ_B developed during the ground roll can be computed from θ, n_x and engine N1 data recorded on the Flight Data Recorder (FDR), and knowledge of the airplane's aerodynamic and thrust characteristics. The vertical and longitudinal reaction forces at the main and nose gear (N_N, F_N, N_M, and F_M) are unknown, but can be computed by solving Eqs. (1)-(5). Assuming a typical value for rolling friction on the nose gear (μ_N),[4] Equations (1)-(5) can be reduced to three equations for the three unknowns N_N, N_M, and μ_B. As is evident in Fig. 1, the geometry of the landing gear, thrust line, center of gravity (CG) location, and aerodynamic reference point of the airplane must be known. This geometry, as well as aerodynamic coefficient and thrust data, is generally available from the manufacturers of the airplanes involved in the events being investigated. The runway gradient, which on the ground is equivalent to the flight path angle (γ), is needed along with the recorded θ to compute α, and can be obtained from airport survey data.

The results of solving Eqs. (1)-(5) for μ_B in several overrun cases are presented in Section V.

[4] The rolling friction coefficient is typically 0.02 to 0.03.

B. Physical parameters affecting μ_B

The physical parameters affecting μ_B have been the object of much study over the last 50 years. A convenient summary of much of this research can be found in the Engineering Science Data Unit (ESDU) Items 71025 and 71026, *Frictional and retarding forces on aircraft tires,* Parts I and II, respectively (Refs. 1 and 2).

References 1 and 2 indicate that μ_B increases above the rolling (unbraked) coefficient of friction (μ_N in Eq.(1)) when the slip ratio (s) of the main gear tires increases above 0, where s is given by:

$$s = 1 - \frac{V_{WHEEL}}{V_G} \tag{6}$$

Where V_G is the airplane's ground speed, and V_{WHEEL} is the tangential speed of the tire:

$$V_{WHEEL} = \omega_{WHEEL} r_{TIRE} \tag{7}$$

Where ω_{WHEEL} is the angular velocity of the wheel, and r_{TIRE} is the effective radius of the tire (the distance from the center of rotation of the wheel to the point where the tire contacts the runway). Per Eq. (6), when the tires are free-rolling and $V_{WHEEL} = V_G$, then $s = 0$. Conversely, when the tires are locked and $V_{WHEEL} = 0$, then $s = 1$.

μ_B increases to a maximum $\mu_{B,MAX}$ at a slip ratio $s_{\mu,MAX}$, and then decreases to the locked-wheel skidding coefficient of friction ($\mu_{B,SKID}$) at s = 1, as shown in Fig. (2). Reference 2 notes that "the shape of the curve of μ_B against s is affected by surface texture and tire tread pattern and is particularly variable in the region between $\mu_{B,MAX}$ and $\mu_{B,SKID}$." Reference 1 adds that "in practice, curves of μ_B against s vary considerably depending on many factors," and cites a number of references to this point. Reference 1 also lists a number of physical parameters that affect the values of $\mu_{B,MAX}$ and $\mu_{B,SKID}$:

- Tire factors:
    - Tire design and construction;
    - Tire tread material;
    - Tire tread pattern (particularly important on wet runways): "the primary function of a tread pattern is to improve the tire frictional properties on wet surfaces";
    - Inflation pressure: on dry and wet runways, μ_B tends to decrease with increasing inflation pressure; however, higher inflation pressure will increase the hydroplaning speed in standing water (see below)
- Runway surface factors:
    - Surface material and texture (see Fig. 3, which is taken directly from Ref. 2):
        - Large or macro-scale texture (macrotexture): "this depends on the sizes and relative quantities of the aggregates used. This scale of texture may be judged approximately by the eye."
        - Small or micro-scale texture (microtexture): "this is the texture of the individual stones of which the runway is constructed and depends on the shape of the stones and how they wear. It may not, in general, be judged by the eye but differences may be apparent to the touch."
    - Fluid depth on runway: on wet runways, μ_B is a strong function of forward speed, as shown in Fig. 3. When, in addition, the runway is flooded (water deeper than 3 mm or 0.1 inches above the top of the surface asperities), then hydroplaning is possible (see below). On flooded runways at high speeds, fluid drag on the tire and spray impingement can provide additional retarding forces.
    - Surface deposits:
        - Loose surface deposits such as sand, grit or dust: these decrease μ_B on a dry surface, and may increase or decrease μ_B on a wet surface depending on the surface texture and water depth.
        - Rubber deposits, hardened smears of asphalt binder, and paint: these deposits "can cover large areas of busy runways, particularly near the touch-down region … in dry conditions no appreciable effects are observed. In wet conditions, large reductions may occur in both $\mu_{B,MAX}$ and $\mu_{B,SKID}$ - depending in part on the initial texture of the underlying surface."

- Aircraft design and operational factors:
    - Forward speed: “In general, $\mu_{B,MAX}$ and $\mu_{B,SKID}$ decrease with increase in forward speed,” though this effect is much more pronounced on wet runways than on dry ones (see Fig. 3). The effect of speed on μ_B on a wet runway is described further below.
    - Tire wear: “For the aircraft operator, tire wear is a most important factor … the available μ_B in wet conditions decreases as a tire wears. For a typical aircraft-type, rib-tread tire, when groove depths have been reduced to about 20% or less of the unworn value, the remaining tread may be ‘flattened out’ under load and the tire may then behave as if smooth.”

Reference 3 (published in 1962) states the following regarding typical values of $s_{\mu,MAX}$:

> The relationship between friction coefficient μ_B and slip ratio s has considerable significance with regard to wheel braking. For example, to obtain maximum effectiveness, automatic braking systems must be designed to operate near peak μ_B ($\mu_{B,MAX}$ usually occurs at a slip ratio between 0.1 and 0.2). If operation occurs at a slip ratio greater than that required for peak friction, tire tread life is reduced by skidding and braking effectiveness is reduced. Operation at a slip ratio below that required for peak friction simply results in reduced braking action.
>
> Because of the transient nature of the tire- slip phenomenon, operation by the pilot or antiskid unit at $\mu_{B,MAX}$ is not generally realized without some overshooting or undershooting of the slip ratio for $\mu_{B,MAX}$. For this reason, the average friction coefficient $\mu_{B,av}$ developed between slip ratios of 0.1 and 0.5 …, rather than $\mu_{B,MAX}$ was arbitrarily chosen in [Ref. 3] as more nearly representative of the friction coefficient attainable with present- day braking systems.

Advances in anti-skid braking systems since 1962 have improved their ability to detect and operate near $s_{\mu,MAX}$, but they still cannot do so perfectly. The ability of these systems to operate at $s_{\mu,MAX}$ is a measure of their efficiency (η_{AS}), and is discussed further below.

C. μ_B on wet runways

As shown in Fig. 3, on a wet runway μ_B decreases precipitously with forward speed, particularly on runways with relatively low macrotexture and / or microtexture. Reference 1 explains this phenomenon as follows:

> The presence of a fluid, which is usually water, on a runway decreases the available tire-ground coefficient of friction.
>
> The tire-ground contact area in wet conditions can be divided into three zones ….
>
> *Zone1* is the region where impact of the tire with the surface fluid generates sufficient pressure to overcome the inertia of the fluid. Much of the fluid is either ejected as spray or forced beneath the tire into the tread grooves (if present) or into the drainage paths provided by the surface texture. Throughout Zone 1 a continuous, relatively thick fluid layer exists between the tire and the runway surface and the only retarding force developed is that due to fluid drag ….
>
> *Zone 2* is a transition region. After the bulk of the fluid is displaced, a thin film remains between the tire and the surface. At the rear of Zone 1, and in Zone 2, a rapid outflow of fluid is prevented, and fluid pressures are maintained, by viscous effects. The thin film first breaks down at points where the local bearing pressure is high, e.g. at sharp surface asperities. In the presence of a lubricant such as water, the coefficient of friction of rubber on hard surfaces is greatly reduced from the dry surface value and varies little with changes in sliding speed and temperature …. Thus, in general, very little frictional force is generated wherever a thin film of fluid persists.
>
> *Zone 3* is the region of predominantly dry contact and, although obviously smaller than the contact area in dry conditions, it is here that most of the braking force is generated ….
>
> In wet conditions, the tire-ground coefficient of friction depends on the relative sizes of Zones 1, 2 and 3. These are determined by the surface texture, the depth, density and viscosity of the fluid, the tread pattern and inflation pressure of the tire and the time … for a tread element to pass through the contact area ….

Reference 1 goes on to explain that as forward speed increases on a wet runway, “Zone 1 extends farther back into the contact area and Zones 2 and 3 occupy a horseshoe-shaped region at the rear,” until at a sufficiently high speed, “contact with the ground is all but lost. In this condition the tire develops very little braking force.” At a still higher speed, “Zone 1 extends throughout the contact area. (When dry contact with the ground ceases, the tire is said to be ‘planing’.)”

D. Viscous and dynamic hydroplaning

The “planing” referred to in Ref. 1 is also called “dynamic hydroplaning,” and is one of three types of hydroplaning. As described in Ref. 4, the other two types are viscous hydroplaning, and reverted-rubber hydroplaning. Reverted-rubber hydroplaning will be discussed below. Reference 4 describes dynamic and viscous hydroplaning as follows:

> Water pressures developed on the surface of the tire footprint and on the ground surface beneath the footprint have been measured during a recent investigation …. This research showed that it was possible for this water-pressure buildup under the tire footprint to originate from the effects of either fluid density or fluid viscosity, depending upon conditions; hence the classification of hydroplaning into two types, namely dynamic or viscous.

Accordingly, "viscous hydroplaning" is associated with the buildup of water pressure due to viscosity, and corresponds to the situation in "Zone 2" described by Ref. 1. This kind of hydroplaning inferred when a surface is described as "slippery when wet," e.g., a wet bathtub. "Dynamic hydroplaning" is associated with the buildup of water pressure due to water density, and corresponds to the situation described in Ref. 1 where "Zone 1 extends throughout the contact area." Dynamic hydroplaning is commonly referred to simply as "hydroplaning," and can be experienced by driving a car through a deep puddle at high speed.

Both a minimum water depth above the runway macrotexture asperities, and a minimum airplane ground speed, are required to support dynamic hydroplaning. Reference 5 addresses the minimum water depth required to support dynamic hydroplaning, and the factors that affect water depth on the runway:

> An optimum runway design is one that delays surface flooding during natural rain until less frequent high rainfall rates are reached, such as the grooved runway shown in [Fig. 4]. In general, runway water depths increase with increasing rainfall intensity and drainage path lengths, and decrease with increasing runway transverse slope and surface macrotexture ([Ref. 6]). Surface winds do not affect runway water drainage appreciably until surface flooding occurs, and water then flows as a sheet along the runway surface. At this point, surface winds tend to increase drainage path lengths and can greatly increase water depths on the runway, depending upon the wind magnitude and direction as shown in [Fig. 4]. The horizontal lines drawn in [Fig. 4] qualitatively indicate the critical water depths required for dynamic tire hydroplaning to occur when the aircraft on the runway is traveling at speeds greater than the tire hydroplaning speed. During this speed and water depth regime, the aircraft is like a sailboat without a keel, and is hard to steer and stop without lateral drift (in crosswinds), due to absence of tire cornering and braking forces. It should be noted that on crowned runways, minimum water depths are encountered by aircraft tires when the pilot lands and maintains a course directly down the runway centerline. (Minimum drainage path lengths for aircraft tires are obtained.)

Reference 5 also addresses the minimum aircraft ground speed required to support dynamic hydroplaning (i.e., the hydroplaning speed, V_p). The V_p depends on both the tire inflation pressure, p, and on whether the tire is rolling (as on a takeoff roll), or nonrotating (as just before touchdown during landing):

$$V_{p,spin\,down} = 9\sqrt{p} \quad \text{(rotating tire)} \tag{8a}$$

$$V_{p,spin\,up} = 7.7\sqrt{p} \quad \text{(nonrotating tire)} \tag{8b}$$

Where p is in pounds per square inch (psi), and V_p is in knots. Reference 5 cites Ref. 6 as a source for determining the water depths illustrated in Fig. 4.[5] Reference 6 will be used below to determine the likely water depth on the runways during several of the overrun events considered in this paper. The potential for dynamic hydroplaning during these events, based on the computed water depth and the $V_{p,spin\,up}$ in each case, is evaluated below.

As noted in Reference 1, during dynamic hydroplaning, tire "contact with the ground is all but lost" and "the tire develops very little braking force." Similarly, Ref. 4 states that tests on flooded runways indicate "a total traction loss at … the predicted hydroplaning speed." A flooded runway model specified in European guidance material for showing methods of compliance with transport airplane certification requirements (described further below) specifies that, above the hydroplaning speed, μ_B = 0.05 constant, which is slightly above the unbraked rolling friction coefficient μ_N (typically modeled as 0.02 to 0.03).

Reference 7 describes another interesting effect of dynamic hydroplaning – the spin-down of unbraked hydroplaning tires:

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[5] Figure 4 does not indicate the pavement macrotexture depth used to construct the curves in the Figure; at a given rainfall rate, the water depth will be higher for lower macrotexture depths, and lower for higher macrotexture depths. Reference 6 provides a model for computing water depths including the macrotexture depth as a variable, and is discussed below.

Perhaps the most striking manifestation of tire hydroplaning is the now well substantiated condition in which free rolling (unbraked) wheels slow down or stop completely on wet runways …. Unbraked-wheel spin-down arises from two hydrodynamic lift effects which combine to produce a total wheel spindown moment in excess of the wheel spin-up moment due to all tire drag sources. First, as ground speed increases, the hydrodynamic lift progressively detaches the tire footprint from the pavement surface … and makes the tire-ground frictional spin-up moment … tend toward zero values. Secondly, the center of pressure of the hydrodynamic pressure and resulting lift developed between the tire footprint and ground surface shifts increasingly forward of the axle as the ground speed increases … and produces the wheel spin-down moment …. At some high forward speed near the total hydroplaning speed of the tire, this wheel spin-down moment overcomes the wheel spin-up moment from all the drag sources and wheel spin-down commences.

E. Reverted-rubber hydroplaning

Reference 4 describes reverted-rubber hydroplaning (which it calls "reverted rubber skidding"):[6]

> Evidence from skidding accidents.- A recent survey of conditions that prevailed during landing accidents on wet runways showed a very interesting correlation. In numerous documented cases on wet runways involving aircraft departure off the side of the runway or in an overrun (both types of accidents indicate drastic loss of tire traction), the runway surface was found to have developed white streaks in the tire paths. The aircraft tires showed evidences of prolonged locked wheel skids with indications that the rubber in the skid patches had reverted to an uncured state. … In [a photograph] where effects of an overrun accident are shown, the white streaks persisted down to the point that the aircraft stopped.
>
> In contrast, if the wheels lock on dry runways at speed, black streaks from molten rubber eroding from the tire are immediately deposited in the tire paths. Although friction decreases under this condition, at least one-third of the maximum dry friction coefficient is still available for stopping the aircraft …. It thus appears that some mechanism other than viscous or dynamic hydroplaning must be at work to prevent the skidding tire from developing traction on wet textured pavements even at very low ground speeds ….
>
> …
>
> A series of tests was made … with tires locked to prevent rotation on dry, wet, and flooded runways at speeds ranging from about 25 to 100 knots. … Under all conditions of the tests, if reverted rubber developed in the footprint, the traction values fell to very low values in comparison with those obtained with the tire under normal rubber tread conditions ... the reverted rubber condition tends to make all runway surfaces smooth acting. Pavement surface texture, which (as discussed previously) has such a large effect on traction losses from dynamic and viscous hydroplaning (normal rubber curves), has but little effect for the reverted rubber condition for the texture-depth range [tested].

Reference 4 includes several photographs of aircraft tires with patches of reverted rubber resulting from locked-wheel skids on wet runways. The tires from the EMB-505 and EMB-500 airplanes involved in the Conroe, TX (KCXO) and Sugarland, TX (KSGR) events (N322QS and N584JS, respectively) show similar patches (see Figs. 10b and 11b). These photos, and the white scrub marks observed on the KCXO and KSGR runways (similar to the "white streaks" mentioned by Ref. 4), indicate that N322QS and N584JS likely experienced reverted-rubber hydroplaning during the landing roll (the details of these events are discussed below).

III. Modeling μ_B on wet runways

A. Estimating the depth of water on wet runways

As described above, if a landing airplane touches down at a groundspeed greater than $V_{p,spin\,up}$, and if the depth of water on the runway is sufficient to support dynamic hydroplaning (see Fig. 4), then between touchdown and the time that the airplane decelerates through $V_{p,spin\,up}$, conditions that can support dynamic hydroplaning are present. Consequently, it is of interest to determine the possible depth of water on the runway when investigating an overrun event.

In steady-state equilibrium conditions during a rain event over a runway, the water depth at a given point from the runway centerline is constant (neither increasing nor decreasing). In this condition, the amount of water flowing towards that point from the crown (centerline) of the runway equals the amount of water flowing away from the point towards the runway edge. The volume of water per unit runway length flowing past a given point from the centerline is proportional to the speed of the water times the water depth. The water volume will increase with

[6] Reference 8 states, "the three presently known types of hydroplaning were first defined in [Ref. 4], that is, dynamic, viscous, and 'reverted' rubber hydroplaning," even though Ref. 4 uses the term "reverted rubber skidding." This paper uses the "reverted rubber hydroplaning" term of Ref. 8.

rainfall rate and distance from the centerline (the further from the centerline, the more runway area is available for collecting water that flows towards the point in question), and the water speed will increase with the runway cross-slope (the steeper the slope, the faster the flow). Thus, for a given slope, the water depth will increase with distance from the runway centerline (to accommodate the increasing volume of water) and with rainfall rate. At a given rainfall rate and distance from the centerline, the water depth will decrease as the runway cross-slope increases, since the increased speed of the water accommodates the same volume of water flow at a lesser water depth.

The runway macrotexture depth is the average depth of irregularities in the surface of the runway, produced by the coarseness of the surface texture (see Fig. 3). The greater the number and magnitude of these irregularities, the more "channels" are provided for water to flow through, and the higher the rainfall rate required to submerge the "peaks" of the irregularities.

Under some conditions, the required water depth to accommodate the volume of water flow will be less than the average macrotexture depth of the runway; in this case, the tips of the macrotexture irregularities will be above the water. If the required water depth is greater than the macrotexture depth, then the tips of the macrotexture irregularities will be below the water.

Reference 6 documents the results of experiments performed at the Texas Transportation Institute (TTI) that quantified the water depths resulting from various combinations of rainfall intensity, pavement cross slope, surface texture, and drainage length. The TTI report provides the following equation to describe the experimental results:

$$d = (0.00338)\left(\frac{1}{T}\right)^{-0.11}(L)^{0.43}(I)^{0.59}\left(\frac{1}{S}\right)^{0.42} - T \tag{9}$$

where:

d = average water depth above the top of the macrotexture irregularities (inches);
T = average macrotexture depth, inches;
L = drainage path-length (i.e., distance from runway centerline), feet;
I = rainfall intensity (inches / hour)
S = runway cross slope, ft/ft (= slope in % divided by 100)

The results of using Eq. (9) to evaluate the depth of water on several of the overrun events considered in this paper are discussed below.

B. Definition of 14 CFR §25.109 wet runway braking friction coefficients

14 CFR §25.109 defines the accelerate-stop distance for transport-category airplanes, and describes how this distance is to be determined. The accelerate-stop distance is the distance required to accelerate from a stop to V_1,[7] and then bring the airplane back to a stop in the remaining runway length.[8] §25.109(a) defines the accelerate-stop distance on a dry runway, and §25.109(b) defines the accelerate-stop distance on a wet runway. §25.109(c) defines the μ_B to be assumed in the calculation of the accelerate-stop distance for a smooth, wet runway (the μ_B for wet runways that are grooved or treated with porous friction coarse material are defined in §25.109(d)).

For a smooth, wet runway, §25.109(c) defines the μ_B as follows:

> The wet runway braking coefficient of friction for a smooth wet runway is defined as a curve of friction coefficient versus ground speed and must be computed as follows:
>
> (1) The maximum tire-to-ground wet runway braking coefficient of friction is defined as:

---

[7] Per 14 CFR 1.2, V_1 "means the maximum speed in the takeoff at which the pilot must take the first action (e.g., apply brakes, reduce thrust, deploy speed brakes) to stop the airplane within the accelerate-stop distance. V_1 also means the minimum speed in the takeoff, following a failure of the critical engine at V_{EF}, at which the pilot can continue the takeoff and achieve the required height above the takeoff surface within the takeoff distance."

[8] This simplified definition suffices for the intent of this paper; §25.109 defines additional details regarding how this maneuver is to be accomplished, that account for engine failures and pilot reaction times.

Tire Pressure (psi)	Maximum Braking Coefficient (tire-to-ground)
50	$\mu_{t/g_{MAX}} = -0.0350\left(\frac{V}{100}\right)^3 + 0.306\left(\frac{V}{100}\right)^2 - 0.851\left(\frac{V}{100}\right) + 0.883$
100	$\mu_{t/g_{MAX}} = -0.0437\left(\frac{V}{100}\right)^3 + 0.320\left(\frac{V}{100}\right)^2 - 0.805\left(\frac{V}{100}\right) + 0.804$
200	$\mu_{t/g_{MAX}} = -0.0331\left(\frac{V}{100}\right)^3 + 0.252\left(\frac{V}{100}\right)^2 - 0.658\left(\frac{V}{100}\right) + 0.692$
300	$\mu_{t/g_{MAX}} = -0.0401\left(\frac{V}{100}\right)^3 + 0.263\left(\frac{V}{100}\right)^2 - 0.611\left(\frac{V}{100}\right) + 0.614$

Where—

Tire Pressure = maximum airplane operating tire pressure (psi);
$\mu_{t/gMAX}$ = maximum tire-to-ground braking coefficient;
V = airplane true ground speed (knots); and

Linear interpolation may be used for tire pressures other than those listed.

(2) The maximum tire-to-ground wet runway braking coefficient of friction must be adjusted to take into account the efficiency of the anti-skid system on a wet runway. Anti-skid system operation must be demonstrated by flight testing on a smooth wet runway, and its efficiency must be determined. Unless a specific anti-skid system efficiency is determined from a quantitative analysis of the flight testing on a smooth wet runway, the maximum tire-to-ground wet runway braking coefficient of friction determined in paragraph (c)(1) of this section must be multiplied by the efficiency value associated with the type of anti-skid system installed on the airplane:

Type of anti-skid system	Efficiency value [η_{AS}]
On-Off	0.30
Quasi-Modulating	0.50
Fully Modulating	0.80

Consequently, §25.109(c) defines the wet runway braking coefficient as

$$\mu_B = (\mu_{t/gMAX})(\eta_{AS}) \tag{10}$$

Where $\mu_{t/gMAX}$ (or μ_{max})[9] and the anti-skid efficiency η_{AS} are defined in the rule as shown above.

FAA AC 25-7C, *Flight Test Guide for Certification of Transport Category Airplanes*, dated 10/16/2012 (Ref. 9), describes the three types of anti-skid braking systems identified in §25.109 as follows:[10]

(aa) The efficiency values specified in §25.109(c)(2) are a function of the type of anti-skid system installed on the airplane. Three broad system types are identified in the rule: on/off, quasi-modulating, and fully modulating. These classifications represent evolving levels of technology and differing performance capabilities on dry and wet runways. The classification of anti-skid system types and the assigned efficiency values are based on information contained in Society of Automotive Engineers (SAE) Aerospace Information Report (AIR) 1739, titled "Information on Anti-Skid Systems."

(bb) On/off systems are the simplest of the three types of anti-skid systems. For these systems, full-metered brake pressure (as commanded by the pilot) is applied until wheel locking is sensed. Brake pressure is then released to allow the wheel to spin back up. When the system senses that the wheel is accelerating back to synchronous speed (i.e., ground

[9] Throughout this paper, $\mu_{t/gMAX}$ and μ_{max} are used equivalently.
[10] See AC-25 7C, paragraph 11(c)(4)(b)(1), "Classification of Types of Anti-Skid Systems."

speed), full-metered pressure is again applied. The cycle of full pressure application/complete pressure release is repeated throughout the stop (or until the wheel ceases to skid with pressure applied).

(cc) Quasi-modulating systems attempt to continuously regulate brake pressure as a function of wheel speed. Typically, brake pressure is released when the wheel deceleration rate exceeds a preselected value. Brake pressure is re-applied at a lower level after a length of time appropriate to the depth of the skid. Brake pressure is then gradually increased until another incipient skid condition is sensed. In general, the corrective actions taken by these systems to exit the skid condition are based on a pre-programmed sequence rather than the wheel speed time history.

(dd) Fully modulating systems are a further refinement of the quasi-modulating systems. The major difference between these two types of anti-skid systems is in the implementation of the skid control logic. During a skid, corrective action is based on the sensed wheel speed signal, rather than a pre-programmed response. Specifically, the amount of pressure reduction or reapplication is based on the rate at which the wheel is going into or recovering from a skid.

C. Range of μ_{max} defined in ESDU 71026

The development of the μ_B calculation method in §25.109(c) is described in Ref. 10, which explains that the method is based on wet runway friction data from the Engineering Sciences Data Unit (ESDU), NASA, and the aerospace industry. In particular, ESDU 71026 (Ref. 2) contains extensive information about the maximum μ (μ_{max}), as a function of ground speed, obtainable on wet and dry runways of various textures, with different tire tread depths and at various tire inflation pressures. ESDU 71026 introduces the μ_{max} data it presents as follows:

> Curves of μ_{max} for unyawed tires are plotted against forward speed … for five prepared, hard runway surfaces: A, B, C, D and E, in both dry and wet conditions. Each of these surfaces typifies a class of runways having surface macro-texture depths lying within a specified range (see [Table 1] for classification of surfaces). Data are presented at four values of inflation pressure and, for wet conditions, include curves for rib tread ([tread depth] > 5 mm, 0.2 in) and smooth tread tires.
>
> In [the data plots], the thick lines are average values of μ_{max} drawn through the available data for each class of surface. The thin lines enclose most of the available data and thereby include the scatter due to the effects of variation in surface texture (within the stated class of surface), runway wetness, tire characteristics and experimental method. To complete the curves, the available data are extrapolated where necessary, particularly at speeds above 100 kt.

Table 1 presents the runway macrotexture depths and surface descriptions for the five "classes" of runways identified in ESDU 71026 (classes A-E, in increasing order of roughness).

ESDU runway class	Minimum macrotexture depth, in. (mm)	Maximum macrotexture depth, in. (mm)	Surface description
A	0.004 (0.10)	0.006 (0.15)	Mainly very smooth concrete runways, some smooth asphalt runways
B	0.006 (0.15)	0.01 (0.25)	Typical of most lightly textured concrete and most small aggregate asphalt runways
C	0.01 (0.25)	0.02 (0.51)	Heavily textured concretes and the majority of harsher types of asphalt
D	0.02 (0.51)	0.04 (1.02)	Shallow grooving and scoring, some large aggregate asphalt
E	0.04 (1.02)	0.10 (2.54)	Deep grooved surfaces, "open textured" and "porous friction course" surfaces

Table 1. Classification of runway surfaces, per ESDU 71026 (Ref. 2).

All of the runways involved in the overrun events described in this paper would be classified as ESDU class "C" or rougher, based on measured macrotexture depths. As discussed further below, the μ_{max} defined by §25.109(c) reflects the average μ_{max} defined in Ref. 2 for an ESDU Class C runway reasonably well, though the actual μ_B achieved by the airplanes during the events were all well below that predicted by the 25.109(c) model.

It should be noted that the range of possible μ_{max} indicated by Ref. 2 for any particular runway class is quite large. For example, for a Class C runway, for p = 200 psi and a groundspeed (V_G) of 100 kt., Ref. 2 depicts a range of μ_{max} from 0.18 to 0.46, with an average of 0.28 (the average μ_{max} values in Ref. 2 are not simply the average of the maximum and minimum extents of the data range at each ground speed, but of all data points within the range at each groundspeed).

D. NASA μ_B model based on Continuous Friction Measurement Equipment data

Reference 11 describes a NASA method for computing μ_B for aircraft based on Continuous Friction Measuring Equipment (CFME) data. CFME are ground vehicles that measure surface friction, typically by measuring the forces exerted on a test tire that is driven or towed down the test surface at a set slip ratio (s). In addition, CFME vehicles apply a film of water ahead of the test tire (typically 1 mm deep) in order to measure wet surface friction. More details about CFME, including their qualification and use in monitoring runway friction, can be found in Ref. 12.

The NASA method for computing airplane μ_B values from the CFME data consists of computing the ratio of the wet-runway μ (μ_{wet}) to the dry-runway μ (μ_{dry}) based on the CFME μ (which measures μ_{wet}) and a "characteristic μ_{dry}" (μ_{cd}) for the test vehicle, and assuming that this ratio also applies to the μ_{wet}/μ_{cd} ratio of the braked airplane tires:

$$\left.\frac{\mu_{wet}}{\mu_{cd}}\right|_{CFME} = \left.\frac{\mu_{wet}}{\mu_{cd}}\right|_{airplane} \tag{11}$$

The μ_{cd} of each CFME device is determined experimentally; the μ_{cd} for four CFME devices are listed in Appendix B of Ref. 21. The μ_{cd} of the airplane tires is a function of the tire inflation pressure (see Ref. 11):

$$\mu_{cd}|_{airplane} = 0.93 - 0.0011p \tag{12}$$

With p in psi. The airplane ground speed associated with each μ_{wet} value is similarly based on computing the ratio of the ground speed (V_G) to the spin-down hydroplaning speed ($V_{p,spin\,down}$) of the test vehicle, and then applying that same ratio to the spin-down hydroplaning speed of the aircraft tires:

$$\left.\frac{V_G}{V_{p,spin\,down}}\right|_{CFME} = \left.\frac{V_G}{V_{p,spin\,down}}\right|_{airplane} \tag{13}$$

The $V_{p,spin\,down}$ of both the test vehicle and airplane tires are a function of each vehicle's tire inflation pressure (see Eq. (8a)).

One product of this method, which is based on similarity of the μ_{wet}/μ_{cd} and $V_G/V_{p,spin\,down}$ ratios between the friction test vehicle and an airplane, is the maximum wet friction coefficient that the runway can provide (μ_{max}), as a function of V_G, for an airplane. However, as described in §25.109(c), the actual μ_B achieved by an aircraft is less than μ_{max} because the braking systems of aircraft are not 100% efficient. In the NASA method, μ_B is computed from μ_{max} using the following equations:

$$\text{For } \mu_{max} < 0.7: \quad \mu_B = 0.2\mu_{max} + 0.7143{\mu_{max}}^2 \tag{14a}$$
$$\text{For } \mu_{max} \geq 0.7: \quad \mu_B = 0.7\mu_{max} \tag{14b}$$

The computation of μ_B from μ_{max} to account for the braking system efficiency of the airplane is similar to the method prescribed in §25.109 for the computation of μ_B by multiplying $\mu_{t/gMAX}$ by η_{AS} (see Eq. (10)). The η_{AS} implied in Eqs. (14a) and (14b) can be gleaned by dividing these equations by μ_{max}:

$$\text{For } \mu_{max} < 0.7: \quad \eta_{AS} = \mu_B/\mu_{max} = 0.2 + 0.7143\,\mu_{max} \tag{15a}$$
$$\text{For } \mu_{max} \geq 0.7: \quad \eta_{AS} = \mu_B/\mu_{max} = 0.7 \tag{15b}$$

Note that the η_{AS} defined by these equations is a function of μ_{max} (and is never greater than 0.7), and does not depend on the type of anti-skid braking system, as does the anti-skid efficiency value defined in §25.109. Significantly, Eq. (15a) indicates that η_{AS} deteriorates with μ_{max}; so, as the runway gets more slippery, the anti-skid system becomes less able to take advantage of the available friction that remains – in effect, a double penalty.

AC 25-7C (Ref. 9) also indicates that the η_{AS} of "quasi-modulating" anti-skid systems may deteriorate on wet runways, if the anti-skid system has not been properly "tuned" for such a runway:

> The effectiveness of quasi-modulating systems can vary significantly depending on the slipperiness of the runway and the design of the particular control system. On dry runways, these systems typically perform very well; however, on wet runways their performance is highly dependent on the design and tuning of the particular system.

Reference 10 indicates that η_{AS} may also deteriorate with decreasing μ_{max} even for "fully-modulating" anti-skid systems, such as that on the Boeing 737-200 ADV.[11] In analyzing the results of several wet-runway landing tests conducted at Roswell, NM, in 1973 with a Lockheed L-1011 airplane and a Boeing 737-200 ADV airplane (originally documented in Ref. 13), Ref. 10 concludes that the B737 landing data "indicate that the η_{AS} of even fully-modulating systems decreases as the runway becomes more slippery."

The authors of Ref. 13 arrived at a similar conclusion by examining the relationships between the μ measured by ground vehicles and the stopping performance of various aircraft during flight tests (including the L-1011 and 737 tested at Roswell):

> The theoretical aircraft braking efficiency, η, lines … are related to a μ_{max} value for a low friction wet surface and have been obtained from a current NASA/FAA digital computer simulation study. This comparison indicates a considerable reduction in braking efficiency of the aircraft as the wet runway surface exhibits lower friction values. This trend is confirmed by the data previously shown in [the Roswell B737-200 ADV μ_B data] wherein the aircraft effective braking friction coefficient was shown to be closer to the level of μ_{skid} than to μ_{max}.

The final airplane μ_B values predicted by the NASA method using CFME data measured on the runways involved in the overrun events considered in this paper are presented in Section V. In all but the Kingston case, the μ_B obtained from the NASA CFME model is lower than the μ_B predicted by the §25.109 model, and lower than the μ_B implied by the wet-runway landing distance data contained in the airplane AFMs. Furthermore, in 4 of the 6 overrun events considered in this paper, the NASA CFME model matches the actual μ_B achieved by the airplanes (as computed using Eqs. (1)-(5)) quite well. Consequently, the NASA CFME model will be the foundation for an alternative model, presented in Section VI, that combines elements of the NASA and §25.109 models.

As noted above, the μ_{max} defined in §25.109(c) is in relatively good agreement with the average ESDU μ_{max} for Class C runways. Moreover, the μ_{max} predicted by the NASA CFME model can be *higher* than the §25.109(c) μ_{max}, even though the final μ_B predicted by the NASA model is *lower* than the final μ_B predicted by the §25.109 model. These observations suggest that the μ_{max} specified in §25.109(c) is reasonable, but that the constant η_{AS} = 0.8 specified by §25.109 overestimates actual anti-skid system performance. The η_{AS} assumed in the NASA model, which is proportional to μ_{max}, results in better agreement with actual performance.

E. Anti-skid system efficiency information in ESDU 71026

ESDU 71026 also addresses anti-skid system efficiency, and includes the chart duplicated here as Fig. 5, which shows the range of η_{AS} values for "on-off" and "adaptive" type anti-skid systems. The chart indicates that, for values of μ_{max} from 0.25 – 0.30, "adaptive" systems have a "maximum likely value" of η_{AS} from 0.80 – 0.85, comparable to the η_{AS} specified by §25.109(c). However, these maximum values do "not allow for installation and undercarriage suspension effects." In discussing this chart, ESDU 71026 states that

> *Values of* μ_{eff} [equivalent to μ_B in this paper] *and* μ_{max} obtained or deduced from tests with a ground vehicle and aircraft are shown as the shaded areas in [Fig. 5]. The scatter indicated by these shaded areas reflects differences between types of brake system and also the differences resulting from the application of these systems to particular undercarriage and test vehicle configurations.
>
> *The efficiencies that may be expected* from current automatic braking systems are represented in [Fig. 5] by the curves labelled, "adaptive system" and "on-off system". These curves are derived principally from dynamometer tests and do not include any measure of the effects introduced when a brake system is incorporated as part of an aircraft undercarriage …. Where no further information is available, these curves should be used to estimate μ_{eff} once μ_{max} has been determined …. [emphasis in original].

ESDU 71026 goes on to include an equation for the effective braking force that is equivalent to modeling η_{AS} as follows:

$$\eta_{AS} = (k)(\eta_{AS,Fig.5}) \tag{16}$$

Where $\eta_{AS,Fig.5}$ is the η_{AS} determined from Fig. 5, and

[11] Per an email from Boeing to NTSB dated 12/08/2010, the B737-200 ADV is equipped with a Hydro-Aire Mark III anti-skid braking system, which is an analog, fully modulating system.

> The factor k is included in [Eq. (16)] to allow for possible reductions in braking efficiency due to, for example, normal load fluctuations, undercarriage vibration and suspension effects - none of which are usually simulated in dynamometer tests. Experience and the data presented as shaded areas in [Fig. 5], suggest that until values of η_{AS} based on aircraft trials are available, k should be assumed to lie in the range $0.8 \leq k < 1.0$ …. Where more precise information is available, either from aircraft braking trials or from brake manufacturers' tests, it should be used.

In allowing an η_{AS} of 0.80 for "fully-modulating" anti-skid systems, §25.109(c) effectively assumes that *both* terms in Eq. (16) ($\eta_{AS,Fig.5}$ and k) will achieve the maximum values contemplated in ESDU 71026, implying that these systems will always operate at the "maximum likely value" level shown in Fig. 5, and that there will be no reduction in efficiency due to "normal load fluctuations, undercarriage vibration and suspension effects." However, Fig. 5 indicates that when these effects are taken into account, the resulting η_{AS} can be as low as 0.50 at μ_{max} = 0.3. If the lower bound of k given in ESDU 71026 (0.8) is applied to the §25.109(c) η_{AS} of 0.80, the overall η_{AS} is $(0.8)^2$ = 0.64, closer to the η_{AS} values that make the §25.109(c) μ_B match the actual μ_B achieved during the overrun events discussed in Section V. This is further evidence that the η_{AS} = 0.80 value allowed by §25.109(c) may be unreasonably high.

Note that the η_{AS} = 0.80 value allowed by §25.109(c) is actually the *minimum* value allowed by the regulation, and applies in case an applicant for certification declines to demonstrate a higher value of η_{AS} through flight tests on a wet runway (though even in this case, flight tests are still required to demonstrate proper anti-skid system function). Two acceptable methods for determining a higher value of η_{AS} from flight tests are outlined in AC 25-7C (Ref. 9): the "torque method" and the "wheel slip method." Both of these methods rely on determining an instantaneous η_{AS} during a stop based on recorded wheel speed, acceleration, and slip ratio and brake pressure or torque parameters, and then integrating this instantaneous η_{AS} over the stopping distance to obtain an overall η_{AS}. There is no requirement to demonstrate that the resulting overall η_{AS}, in combination with the μ_{max} defined in §25.109(c), results in a computed stopping distance (through the solution of Eqs. (1)-(5)) consistent with the actual stopping distance achieved during the flight tests. This lack of a "closed loop" between the computed η_{AS} and measured stopping distance during flight tests leaves uncertainty as to whether the combination of μ_{max} and η_{AS} prescribed in §25.109 is actually consistent with the capabilities of the airplane.

In any case, AC-25 7C states that "an anti-skid efficiency of 92% (i.e., a factor of 0.92) is considered to be the maximum efficiency on a wet runway normally achievable with fully modulating digital anti-skid systems." As will be shown below, the η_{AS} implied by the wet-runway landing distances in some airplane AFMs is greater than 0.92, if the μ_{max} specified by §25.109(c) is assumed. Per AC-25 7C, these values of η_{AS} are unrealistic, and are evidence that the models of wet-runway braking underlying some AFM wet stopping distances are inadequate. The AFM wet runway stopping distances for certain overrun events are discussed further in Section V.

To correctly predict airplane stopping performance, a model must generate a product of μ_{max} and η_{AS} that matches the actual μ_B (see Eq. (10)). In the overrun events considered in this paper, the NASA CFME model satisfies this requirement much better than the §25.109 model; in every case, the latter overestimates the actual μ_B significantly. These results are consistent with findings from flight tests (see Refs. 10 and 13-16, and the discussion in Sections V and VI below). In addition, using the average μ_{max} for a Class C runway, the ESDU model best matches the μ_B obtained during the overrun events if the most conservative value of k (0.8) is used in Eq. (16).

F. Industry statements on correlating CFME μ values to airplane μ_B

As will be shown in Sections V and VI, there is relatively good agreement between the μ_B predicted by the NASA CFME model and the μ_B actually achieved during wet-runway overrun events and flight tests. However, at times doubt has been expressed as to whether CFME measurements can be reliably correlated to wet-runway airplane μ_B. For example, the final report on the United Express flight 8050 landing overrun in Ottawa, Canada in 2010 (Ref. 15)[12] states:

> It is widely acknowledged that a wet runway may be slippery and require additional landing distance over and above that required for a dry runway. National and international efforts to closely correlate surface-friction measurements on wet runways to aircraft braking effectiveness have not been successful.

Reference 15 does not provide a reference for this statement, but it may be repeating information found in International Civil Aviation Organization (ICAO) document 9137, *Airport Services Manual, Part 2: Pavement Surface Conditions* (Ref. 17):

[12] This accident is discussed further in Sections IV and V.

> 3.1.1 There is an operational need for information on paved runways that may become slippery when wet. To this end, there is a need to measure periodically the friction characteristics of a paved runway surface to ensure that they do not fall below an agreed level. An indication of the friction characteristics of a wet paved runway can be obtained by friction-measuring devices; however, further experience is required to correlate the results obtained by such devices with aeroplane braking performance due to the many variables involved, such as runway temperature, tire inflation pressure, test speed, tire-operating mode (locked wheel, braked slip), anti-skid system efficiency, and measuring speed and water depth.

However, a later section in Ref. 17 states that

> 5.4.2 In 1984, the United States undertook a five year programme to study the relationship between aeroplane tire braking performance and ground vehicle friction measurements. Several types of surface conditions were evaluated: dry, truck-wet, rain-wet and snow-, slush- and ice-covered …. The results of this investigation showed that the ground vehicle friction measurements did not directly correlate with the aeroplane tire effective braking friction on wet surfaces. However, agreement was achieved using the combined viscous/dynamic aquaplaning theory (see Appendix 1).

The "combined viscous/dynamic aquaplaning theory" presented in Appendix 1 of Ref. 17 is precisely the NASA CFME model described above, and presented in detail in Ref. 11. Consequently, while it is true that CFME μ values are not *directly* equivalent to wet-runway airplane μ_B, Ref. 17 appears to agree with the observations in this paper that the two can be correlated using the NASA CFME method.[13]

G. AMC 25.1591 flooded runway μ_B

The European Aviation Safety Agency (EASA) certification standards for transport category airplanes address operations from contaminated runways in EASA Certification Specification (CS) 25.1591, *Performance Information for Operations with Contaminated Runway Surface Conditions*. The EASA Acceptable Means of Compliance (AMC) document 25.1591, *The derivation and methodology of performance information for use when taking-off and landing with contaminated runway surface conditions* (AMC 25.1591), provides one acceptable means of compliance with the provisions of CS 25.1591. AMC 25.1591 paragraph 7.3.1 indicates that for runways contaminated with standing water, the "effective braking coefficient of an anti-skid controlled braked wheel/tyre" is given by

$$\mu_B = -0.0632\left(\frac{V}{100}\right)^3 + 0.2683\left(\frac{V}{100}\right)^2 - 0.4321\left(\frac{V}{100}\right) + 0.3485 \tag{17}$$

> Where V is the groundspeed in knots.
> Note: For V greater than the aquaplaning [hydroplaning] speed, use
> μ_B = 0.05 constant.

The hydroplaning speed is defined in AMC 25.1591 as the $V_{p,spin\,down}$ given by Eq. (8a). While this is appropriate for rejected-takeoffs, for landings it would be more appropriate to use the $V_{p,spin\,up}$ given by Eq. (8b).

Other paragraphs of AMC 25.1591 describe additional forces acting on the airplane during operations on contaminated runways, including contaminant drag (water displacement drag and water spray impingement drag).

European operational regulations (EU OPS 1.480(a)(2)) consider a runway "contaminated" with standing water (i.e., "flooded") when more than 25% of the runway surface is covered with surface water more than 3 mm (0.118 inches) deep. None of the runways involved in the overrun events considered in this paper would have met this definition, per water depth calculations using Eq. (9). However, the actual μ_B obtained in many of the overrun events discussed in Section V match the μ_B predicted by Eq. (17) relatively well, indicating that the μ_B attainable on some wet but *non-flooded* runways is comparable to the μ_B that is modeled for *flooded* runways.

[13] Note that the good correlation between the NASA CFME method and the actual airplane μ_B noted throughout this paper concerns only *wet* runways. No observations or conclusions regarding the correlation between CFME devices and μ_B for *frozen* contaminants (ice, slush, snow) are made here.

IV. Six wet-runway overrun events

The NTSB has led or participated in the investigation of a number of landing accidents or incidents on wet runways in which the airplane did not achieve the μ_B implied in the manufacturer's AFM landing distances, or that would be predicted by the §25.109 model. Six of these events are summarized below, along with relevant conclusions from the airplane performance studies or final reports of the investigations. In Section V, the μ_B achieved in these events is compared to the μ_B implied by the airplane AFMs, and to the μ_B predicted by the models described in Section III.

A. The BAe 125-800A accident in Owatonna, MN (NTSB #DCA08MA085)

On July 31, 2008, a Hawker Beechcraft BAe 125-800A, registration N818MV, crashed while attempting to go around after landing on runway 30 at Owatonna Degner Regional Airport (KOWA). The two pilots and six passengers died, and the airplane was destroyed (see Fig. 6, and Refs. 10 and 18). The NTSB determined that the probable cause of this accident was

> the captain's decision to attempt a go-around late in the landing roll with insufficient runway remaining. Contributing to the accident were (1) the pilots' poor crew coordination and lack of cockpit discipline; (2) fatigue, which likely impaired both pilots' performance; and (3) the failure of the Federal Aviation Administration (FAA) to require crew resource management (CRM) training and standard operating procedures (SOPs) for 14 CFR Part 135 operators (Ref. 18).

Among the conclusions of the *Aircraft Performance Study Addendum #1* to the KOWA accident (Ref. 10) are:

- Given the measured rainfall on the day of the accident, the KOWA runway cross-slope gradient and surface macrotexture do not support a conclusion that the runway could have been flooded at the time of the accident, or that the airplane could have experienced dynamic hydroplaning during the landing roll.
- As indicated in the *Performance Study* [of the KOWA accident], simulations of the accident landing using the [BAe 125-800A landing performance computer] program required flooded runway conditions to match the performance data available for this accident, assuming sufficient braking to take full advantage of the available friction on the runway. Flooded runway conditions are inconsistent with the weather and runway evidence.
- The wet runway landing distances published in the BAe 125-800A AFM and computed by the … performance program are based on μ_B wet / μ_B dry ratios specified in [European Joint Aviation Regulations (JAR)] [Advisory Material Joint (AMJ)] 25X1591. The wet – runway μ_B values that result from these ratios correspond roughly to half the value of the braking coefficients obtained on a dry runway, and do not decrease significantly with increasing groundspeed.
- §25.109, which considers the accelerate-stop distance during rejected takeoffs, indicates that the μ_B on a wet runway is a strong function of both ground speed and the efficiency of the anti-skid braking system (η_{AS}). A wet-runway μ_B corresponding to about half of a dry-runway μ_B can only be obtained with anti-skid systems with efficiencies of 0.8 or higher, and at relatively low groundspeeds.
- The Dunlop Maxaret anti-skid braking system used on the BAe 125-800A is an "on-off" type system, which can have an η_{AS} in the range of 0.3 to 0.75, though §25.109 requires an assumption of 0.3 for this type of system unless higher values can be demonstrated. Assuming sufficient braking effort on a wet runway, the braking performance of N818MV during the accident is consistent with an η_{AS} of about 0.475.
- The wet – runway μ_B values based on the §25.109 μ_B model and an η_{AS} of 0.475 are significantly lower at high groundspeeds than the wet – runway μ_B values based on the JAR AMJ 25X1591 μ_B wet / μ_B dry ratios.
- Landing distance flight tests of a Boeing 737-200ADV airplane on a wet runway at Roswell, NM, in 1973 indicate that the η_{AS} of even fully-modulating systems decreases as the runway becomes more slippery. This finding is consistent with the behavior of η_{AS} used in the NASA prediction of the effective braking coefficient available on the KOWA runway, based on CFME tests performed after the accident. These observations suggest that models of braking performance may be improved by modeling η_{AS} as a function of the maximum available friction coefficient (μ_{max}), rather than as a constant, as currently specified in §25.109.
- The Roswell B737 tests also indicate that the actual braking performance achieved on some ungrooved, wet runways may be below that produced by the combination of μ_{max} and η_{AS} specified in §25.109. These results underscore the importance of testing the actual η_{AS} achieved on a wet, ungrooved runway during certification, and ensuring that the values of μ_{max} and η_{AS} determined from the tests are consistent with the actual landing distances achieved by the airplane during the tests.
- Given that the §25.109 μ_B model provides a better representation of N818MV's performance during the accident (as indicated by the simulations), the [performance] program (and the AFM) under-predict the actual, unfactored

landing distances on some wet, ungrooved runways by a significant amount. The difference between the AFM and §25.109 μ_B – based distances examined in this Addendum are much greater than the minimum 15% safety factor to be applied to AFM advisory data when performing the en-route landing distance assessments envisioned by FAA SAFO 06012 and NTSB recommendation A-07-057 [See Section VII]. Consequently, for this airplane (and potentially all aircraft with wet landing distances based on the AMJ 25X1591 μ_B model) the use of the AFM data for en-route landing distance assessments on wet runways may not be advisable, unless additional correction and / or safety factors are applied to the data.

These conclusions are consistent with findings in the other five overrun events considered in this paper. Specifically:

- AFM data can underestimate the landing distance required on wet runways.
- A constant η_{AS} = 0.8 is specified in §25.109(c) for fully-modulating anti-skid systems, when research and flight test data indicate that η_{AS} decreases with μ_{max}, even for these systems.
- The §25.109(c) model can overestimate μ_B on wet runways.
- There is no requirement to demonstrate consistency between the μ_B model used to develop AFM wet-runway performance data, and actual wet-runway stopping performance.

Strictly speaking, the deficiency of the §25.109(c) μ_B model is the result of the *combination* of the modeled μ_{max} and η_{AS}, and a deficiency in either term (or both) will result in a deficiency in μ_B (see Eq. (10)). It can be difficult to identify which term is more in error (μ_{max} or η_{AS}) when a shortfall in μ_B is identified. While the range of ESDU data for Class C runways includes values of μ_{max} lower than those specified in §25.109(c), the use of a constant η_{AS} = 0.8 in §25.109(c) demands the closest scrutiny. AC 25-7C, the NASA CFME model, ESDU 71026, and the flight test results cited in Ref. 13 agree that η_{AS} deteriorates with μ_{max}, even for adaptive anti-skid systems. Consequently, the η_{AS} = 0.8 assumption in §25.109(c) must remain suspect until it is demonstrated that the μ_B resulting from this value is consistent with the μ_B computed from flight tests on a wet runway, per the method described in Eqs. (1)-(5).

B. The American Airlines flight 331 accident in Kingston, Jamaica (NTSB #DCA10RA017)

On December 22, 2009, American Airlines Flight 331 (AA331), a Boeing 737-823, overran runway 12 after landing at Norman Manley International Airport in Kingston, Jamaica (MKJP) (see Fig. 7). According to the final report issued by the Civil Aviation Authority of Jamaica (JCAA) (Ref. 16),

> The aircraft landed … on runway 12 in the hours of darkness at 22:22 EST (03:22 UTC) in Instrument Meteorological Conditions (IMC) following an Instrument Landing System (ILS) approach flown using the heads up display (HUD) and becoming visual at approximately two miles from the runway. The aircraft touched down at approximately 4,100 feet on the 8,911 foot long runway in heavy rain and with a 14 knot left quartering tailwind.
>
> The crew was unable to stop the aircraft on the remaining 4,811 feet of runway and it overran the end of the runway at 62 knots ground speed. The aircraft broke through a fence, crossed above a road below the runway level and came to an abrupt stop on the sand dunes and rocks between the road and the waterline of the Caribbean Sea.
>
> There was no post-crash fire. The aircraft was destroyed, its fuselage broken into three sections, while the left landing gear collapsed. The right engine and landing gear were torn off, the left wingtip was badly damaged and the right wing fuel tanks were ruptured, leaking jet fuel onto the beach sand.
>
> One hundred and thirty four (134) passengers suffered minor or no injury, while 14 were seriously injured, though there were no life-threatening injuries. None of the flight crew and cabin crew was seriously injured, and they were able to assist the passengers during the evacuation.

Section 1.18.6 of the JCAA report, titled "Estimated Water Depth and Braking Action," states:

> The depth of water on MKJP runway 12 during the flight 331 ground roll can be estimated using empirically-based models to calculate water depth as a function of rainfall intensity and the runway 12/30 width, transverse slope, and pavement macro-texture characteristics. Based on the NASA rainfall rate/flooding exposure model and the Texas Transportation Institute (TTI) accumulated water depth model data presented to the JCAA at the Aircraft Performance Group Briefing in August 2010, no evidence supports a runway 12/30 water depth accumulation close to 3 millimeters (mm) of water.
>
> These models indicate that, depending on the pavement macro-texture and airplane lateral position, there was at most a 0.5 to 1.0 mm water depth in the calculated main gear braked wheel path. A similar conclusion holds (at most 0.75 to 1.5 mm water depth) for all possible pavement macro-textures, even if the measured rainfall rate at the time of the

accident is doubled to 1.0 inch/hour and the calculated airplane lateral position is artificially and significantly biased toward the runway shoulder.

An independent Boeing analysis of the existing rainfall precipitation and runway 12/30 factual data is consistent with the TTI model results described here.

…

The estimated depth of water in the airplane braked wheel paths during the runway 12 ground roll was less than 3 mm (less than .125 in.), which corresponds to an equivalent stopping performance level better than that expected for either a runway covered with standing water or a flooded runway ….

Independent of the above models for estimating water depth, the airplane deceleration observed during the flight 331 ground roll is consistent with B737NG (-700/900) flight test data on an artificially wet (no active rainfall; water applied to pavement prior to airplane touchdown using a fleet of tanker trucks), un-grooved runway with pavement macro-texture characteristics similar to or better than MKJP runway 12. These Boeing flight test data benefit from explicit knowledge that less than 25 percent of the runway surface was subject to standing water 1/8 inch deep or greater. In other words, the AA 331 braking performance level has been achieved on a wet, un-grooved runway with no active rainfall and less than 1/8 inch depth of water.

Analysis of the AA flight 331 event indicates the achieved airplane braking coefficient value was less than that traditionally considered to be associated with a wet runway (0.2), but better than what Boeing associates with a flooded runway (0.05). The factual evidence indicates that the airplane/ runway stopping performance interaction for AA flight 331 was essentially consistent with AA Fair/Medium braking action.

In other words, the AA flight 331 stopping performance level is inconsistent with the Boeing model for standing water or flooded runway.

Quoted performance is based on Wet/Good braking action, maximum manual braking, without reverse thrust and landing at about 1,000 feet from the threshold.

Section 1.11.2.2 of the JCAA report, titled "Information from Flight Data Recorder," includes the following bullets resulting from an examination of the FDR data:

- Boeing FDR graphs showed aircraft ground speed at end of runway was 62 knots, in accordance with runway condition between Wet Smooth and Standing Water.
- Boeing FDR graphs showed actual rate of deceleration from braking on the wet runway to be less than defined by §25.109 for a Wet-Smooth runway, but more than defined by the NASA Standing Water Runway model.

The JCAA report refers to the μ_B computed by Boeing in order to match the deceleration recorded on the FDR.[14] Boeing provided the results of these calculations to the NTSB in Ref. 19, and indicated that the required μ_B was equal to a 27% factor between the Boeing wet-smooth μ_B and the Boeing standing-water μ_B, where 0% = wet-smooth, and 100% = standing-water. The resulting μ_B is plotted in Fig. 14 and discussed further below.

The JCAA report contains findings similar to those reported in the KOWA *Aircraft Performance Study Addendum*, and in other cases considered in this paper: an evaluation of the water depth on the runway indicates that the runway could not have been flooded or have supported dynamic hydroplaning; yet the μ_B achieved during the landing roll was less than assumed in the AFM for a wet runway, and less than that predicted by the §25.109(c) model. Moreover, the JCAA indicates that these same observations follow from B737-700/900 flight test data on an *artificially wetted runway*, with no active rainfall. This is additional evidence of the inadequacy of the §25.109(c) model for predicting μ_B reliably on smooth, wet runways.

C. The United Express flight 8050 accident in Ottawa, Ontario (NTSB # DCA10RA069)

On June 16, 2010, United Express flight 8050 (UE8050), an Embraer EMB-145LR operated by Trans States Airlines LLC, overran runway 07 after landing at the Ottawa/MacDonald-Cartier International Airport in Ottawa, Ontario (CYOW) (see Fig. 8). According to the final report issued by the Transportation Safety Board of Canada (TSB) (Ref. 15),

The aircraft came to rest 550 feet off the end of Runway 07 and 220 feet to the left of the runway centreline. The nose and cockpit area were damaged when the nose wheel collapsed. There were 33 passengers and 3 crew members aboard. Two of the flight crew and 1 passenger sustained minor injuries.

…

[14] The Boeing μ is actually expressed in terms of the total airplane μ, which is less than the wheel-braking μ_B used throughout this paper. The difference between these terms is explained below. The Boeing airplane μ has been converted to μ_B for the purposes of this discussion, and in the plot in Fig. 14.

When the aircraft descended through approach minimums, 200 feet agl and 0.3 nm from the threshold, the airspeed was 144 KIAS. The aircraft crossed the threshold of Runway 07 at 49 feet agl, at a speed of 139 KIAS. The aircraft did a very smooth touchdown, and the weight on wheels (WOW) switch momentarily activated at 1430:15, 1740 feet from threshold. At that point, the nose was still in the air, and the aircraft floated. Two seconds later, 2270 feet from the threshold and at a speed of 132 KIAS, the second WOW activated and the nose wheel came down …. Video recordings at the time of landing showed that the runway was wet.

The first officer was depressing the brake pedals during the second WOW activation; all spoilers automatically deployed after the nose wheel was lowered to the ground. The first officer continued to apply brakes until maximum braking was commanded. Sensing a lack of deceleration, the first officer informed the captain, who then took control of the aircraft and applied maximum braking as well. The aircraft could not be slowed during brake application.

The aircraft was on the centreline until approximately 200 feet before the end of the runway, where it veered left. The aircraft exited the paved surface of the runway at approximately 62 KIAS. It continued through the grass for approximately 120 feet, at which point there was a sharp downward change in elevation of about 2 feet. The nose gear collapsed rearward, but the aircraft continued to skid. It came to a rest 550 feet from the end of the runway and 220 feet left of centreline. The flight attendant initiated the evacuation procedure for the passengers.

Section 1.6.6 of the TSB report, titled "Aircraft Braking Coefficient," states

For the occurrence landing, the brake-pedal position went from 0% to 95%, while the braking coefficient and brake pressure remained constant at 0.07 and 200 psi, respectively ….

The aircraft braking coefficient of friction calculated for the occurrence ground roll was compared with the wet runway braking coefficient of friction (adjusted for a fully modulated antiskid system) used by Embraer as per §25.109(c). The comparison showed that the occurrence aircraft had a braking coefficient significantly lower than that predicted by the smooth wet runway equations in §25.109(c)(1).

Another comparison was made between the FDR data from the occurrence ground roll and brake-system test data obtained from Honeywell for the ground-roll phase of wet runway landing. The test was conducted in an aircraft under the same conditions and with the same configuration as the occurrence aircraft. The test showed that braking performance by the occurrence aircraft was as expected, and that the brake system on the occurrence aircraft performed as designed. The test also indicated that the braking coefficients of friction for both landings were similar and significantly lower than that predicted by the smooth wet runway equations in §25.109(c)(1).

Section 2.6 of the TSB report, titled "Hydroplaning," states

In this particular occurrence, the factors exhibited during the landing roll are indicative of viscous and not dynamic hydroplaning. These factors were smooth touchdown, slower-than-normal wheel spin-up with no lockup, and supply of very low brake pressures by the brake control unit (BCU) until very low speeds. The friction between the tire and runway was reduced, but not to a level that impeded the wheel rotation. Dynamic hydroplaning did not occur, as wheel rotation did not stop, and the water depth was calculated to be less than the 3 mm normally associated with the onset of dynamic hydroplaning. Once hydroplaning begins, it will continue to speeds well below that required to initiate hydroplaning. Although the pedals of both pilots were deflected to the right during the latter part of the landing roll, the aircraft veered to the left, indicating the lack of friction and lack of directional control that are associated with hydroplaning.

During a post-accident examination, no reverted-rubber burns were found on the aircraft's main landing-gear tires. The aircraft exited the runway before the rubber reached reversion temperature; hence there was no reverted-rubber hydroplaning. However, there were steam-cleaned marks at the end of the runway, indicating the temperature had reached that at which steam is formed.

Notably, the TSB report concludes that the μ_B achieved on this wet (but not flooded) runway is "significantly lower" than that predicted by §25.109(c); and that the same result was observed during a flight test "under the same conditions and with the same configuration as the occurrence aircraft."

D. The Southwest Airlines flight 1919 incident in Chicago, IL (NTSB #DCA11IA047)

On April 26, 2011, Southwest Airlines flight 1919 (SW1919), a Boeing 737-7Q8, exited the left side near the end of runway 13C after landing at Chicago Midway International Airport, Chicago IL (KMDW) (see Fig. 9). The airplane had minor damage and there were no injuries (see Refs. 14 and 20).

The NTSB determined that the probable cause of this incident was

the flight crew's delayed deployment of the speedbrakes and thrust reversers, resulting in insufficient runway remaining to bring the airplane to a stop.

Contributing to the delay in deployment of these stopping devices was the flight crew's inadequate monitoring of the airplane's configuration after touchdown, likely as a result of being distracted by a perceived lack of wheel braking effectiveness.

Contributing to the incident was the flight crew's omission of the Before Landing checklist, which includes an item to verify speedbrake arming before touchdown, as a result of workload and operational distractions during the approach phase of flight (Ref. 20).

The crew of a Southwest Airlines B737 that had landed prior to the incident flight reported that the runway was "wet with fair braking action." Reference 20 states that

The [incident] airplane touched down within 500 feet of the runway threshold. After touchdown, the captain perceived a lack of braking effectiveness and quickly applied full manual brakes. Speedbrakes did not deploy upon touchdown, nor were thrust reversers deployed. About 16 seconds after touchdown, thrust reversers were manually deployed, which also resulted in speedbrake deployment per system design, when the airplane had about 1,500 feet of runway remaining. As the airplane neared the end of the pavement, the captain attempted to turn onto the connecting taxiway but was unable. The airplane struck a taxiway light and rolled about 200 feet into the grass.

FDR data and component examination revealed that all airplane systems operated as expected. The automatic speedbrakes were not armed and, therefore, would not deploy upon touchdown without crew action. Extending the speedbrakes after landing increases aerodynamic drag and reduces lift, which increases the load applied to the main gear tires and makes the wheel brakes more effective. A lack of speedbrake deployment results in severely degraded stopping ability. According to the flight operations manual, braking effectiveness is reduced by as much as 60 percent. The flight crew's delay in applying reverse thrust also contributed to the amount of runway used.

Simulation studies concluded that the airplane would have stopped with about 900 feet of runway remaining if the speedbrakes had been deployed at touchdown (without reverse thrust) or with about 1,950 feet remaining if both speedbrakes and reverse thrust had been deployed at touchdown, per standard procedures. The calculated braking coefficient of the incident airplane was consistent with a "fair" braking action report, as given by the preceding Southwest Airlines 737 arrival. The braking coefficient is also in accordance with the [Onboard Performance Computer] calculations.

Reference 20 makes it clear that the flight 1919 incident resulted from a number of serious operational mistakes; nonetheless, the "fair" braking action reported by the previous Southwest crew, and the simulation studies performed during the investigation, indicate that the §25.109 μ_B model can over-predict the μ_B available on wet *grooved* runways (such as those at KMDW), as well as on wet *smooth* runways.

The *Aircraft Performance Study* for this incident (Ref. 14) states:

To simulate the combination of runway friction and anti-skid system effectiveness that best matched the airplane stopping performance observed during the incident landing, Boeing created a curve defining the wheel braking coefficient as a function of ground speed. Boeing created this curve by taking the NASA Convair 880 Standing Water curve and adding 60% of the difference between the it and the §25.109 Wet Smooth Runway curve (0% corresponds to NASA Convair 880 and 100% corresponds to §25.109 Wet, Smooth). The resulting simulation airplane braking coefficient is representative of the average levels of the airplane braking coefficient calculated from the FDR data …. Furthermore, the resulting simulation ground speed agrees with the incident deceleration ….

Note that the KMDW *Study* refers to both the "wheel braking coefficient" and the "airplane braking coefficient." The KMDW *Study*, following Boeing convention, primarily uses the latter quantity, and describes the difference between these coefficients as follows:

Another measure of the friction between the tires and the runway is the wheel braking coefficient, which is the ratio of the frictional retarding force on the main gear tires alone to the weight borne by the main gear tires alone. The wheel braking coefficient differs from the airplane braking coefficient in that it does not include the rolling friction on the nose gear or the weight borne by the nose gear. For a given frictional retarding force on the main gear and (relatively small) rolling friction force on the nose gear, the airplane braking coefficient is usually less than the wheel braking coefficient, since the sum of the frictional forces on both the main and nose gear divided by the sum of the weight borne by both the main and nose gear is usually less than the frictional force on the main gear alone divided by the weight borne by the main gear alone. The results of research into runway friction are usually presented in terms of the wheel braking coefficient, but the Boeing simulator study (and this aircraft performance study) present results in terms of the airplane braking coefficient.

The μ_B term used throughout the present paper is what the KMDW *Study* calls the "wheel braking coefficient" (see Eq. (2)). Note that the KMDW *Study* indicates that the *wheel* braking coefficient (i.e., μ_B) required to match the airplane performance in the KMDW event is less than the μ_B defined by §25.109(c) for a *smooth* (ungrooved) runway,[15] and that KMDW runway 13C is *grooved*. Per Table 1, a grooved runway is an ESDU class E runway, with the highest macrotexture depth and corresponding μ_{max}.

§25.109(d) specifies 5th-order polynomials defining μ_B as a function of V_G for a grooved or "porous friction course" runway, similar to the 3rd-order polynomials defined in §25.109(c) for a smooth runway. As in §25.109(c), the polynomial coefficients in §25.109(d) are functions of tire inflation pressure (p). For a given V_G and p, the μ_{max} defined in §25.109(d) is greater than that defined in §25.109(c). For example, for p = 200 psi and V_G=100 kt., §25.109(c) specifies μ_{max} = 0.2529 and §25.109(d) specifies μ_{max} = 0.3478, which is about 38% higher. As in §25.109(c), the μ_{max} defined in §25.109(d) must be multiplied by η_{AS} to obtain μ_B (see Eq. (10)).

The Boeing airplane braking coefficient required to match the deceleration on the FDR, provided in the KMDW *Study*, is converted into μ_B and presented in Section V.[16] Note that since this μ_B is lower than that defined in §25.109(c), it will be even lower than the larger μ_B defined in §25.109(d) corresponding to a grooved runway. Since the KMDW runway is grooved, this points to a significant discrepancy between the achieved performance and that assumed in §25.109(d). However, as will be shown in Section V, the achieved μ_B is consistent with the NASA CFME model based on CFME tests run at 40 mph.

E. The EMB-505 accident in Conroe, TX (NTSB #CEN14FA505)

The investigations of the four events described above are complete, and the final reports for each issued. The NTSB is currently investigating two other wet-runway landing overrun accidents involving Embraer Phenom airplanes, under circumstances very similar to each other. The first involved a Phenom 300 (Embraer model EMB-505) in Conroe, TX, in September 2014, and the second involved a Phenom 100 (Embraer model EMB-500) in Sugar Land, TX, in November 2014. Although these accidents are still under investigation, μ_B calculations based on each airplane's FDR data, and CFME μ measurements on the runways involved, are complete and can be discussed in this paper. The Conroe accident is described in this sub-section, and the Sugar Land accident is described in the next sub-section.

The *Aircraft Performance Study* for the Conroe accident (Ref. 21) has been completed, and describes that accident as follows:

> On September 19, 2014, about 08:47 central daylight time, an Embraer EMB-505 airplane, N322QS, encountered soft terrain and mud after overrunning the runway while landing at the Lone Star Executive Airport (KCXO), Conroe, Texas. Neither of the airline transport rated pilots on board were injured. The airplane was substantially damaged [see Fig. 10a]. The airplane was operated by NetJets Aviation, Inc. as a 14 Code of Federal Regulations Part 91 positioning flight. Instrument meteorological conditions (IMC) prevailed for the flight, which was operated on an instrument flight rules flight plan. The flight originated from the Nashville International Airport (KBNA), Nashville, Tennessee, at 07:10.
>
> According to the air traffic controller who witnessed the accident, the pilots flew the area navigation (RNAV) runway 1 approach and broke out of the clouds at the minimums for the approach. The controller stated the airplane touched down just past the 1,000 foot marker on the runway but did not appear to decelerate as it continued down the runway. The airplane traveled off the departure end of the runway and continued about 400 feet through soft/muddy terrain before coming to rest half way down a ditch. The controller stated there was moderate to heavy rain at the time of the accident.

Reference 21 summarizes its results as follows:

> The results of this *Study* indicate that the approach of N322QS to runway 1 complied with the operator's stabilized approach criteria, with the airplane tracking the RNAV final approach course and glide slope at an airspeed of about 130 kt. (within the +20/-0 kt. tolerance on the 112 kt. nominal landing reference speed (V_{REF}) corresponding to the airplane's landing weight and flap setting, and within the ±10 kt. tolerance of the V_{REF} + 10 kt. (122 kt.) final approach target speed). The airplane crossed the runway threshold at about 121 kt. (9 kt. faster than V_{REF}), and touched down about 903 ft. from the threshold, at a groundspeed of 118 kt. The headwind component at touchdown was negligible.
>
> After touchdown, the pilot's brake pedal deflections progressively increased to maximum braking over a period of about 11 seconds, and the airplane achieved a maximum deceleration (longitudinal load factor, n_x) of about -0.17 G's

[15] The NASA Convair 880 Standing Water μ_B referred to in the KMDW *Study* is less than the μ_B defined by §25.109(c), and the μ_B that matches the KMDW airplane performance lies *between* these two models.

[16] The conversion from airplane braking coefficient to μ_B involves an algebraic combination of the airplane braking coefficient, the nose wheel rolling friction coefficient, and airplane geometric terms.

> about 7 seconds after touchdown. The airplane maintained an n_x between -0.15 and -0.17 G's for about another 6 seconds, until the wheel speeds dropped to zero, consistent with the application of the emergency / parking brake (EPB) and the beginning of a full, locked-wheel skid. The wheel speeds reached zero 13.5 seconds after touchdown, and the wheels remained "locked" until the aircraft came to rest. During the skid, the n_x steadily increased[17] from -0.17 G's to about -0.09 G's, before dropping again to about -0.12 G's as the airplane passed the end of the runway. The airplane exited the runway about 27 seconds after touchdown, at a groundspeed of about 61 knots, and came to rest about 400 ft. past the end of the runway.
>
> During the landing roll, the Cockpit Voice Recorder (CVR) recorded the crew making several statements expressing concern about the airplane's speed and deceleration.
>
> This *Study* also presents an estimate of the braking friction coefficient (μ_B) developed by the airplane during the landing roll, using FDR data, and airplane thrust and aerodynamic data provided by Embraer. After the airplane touches down, the computed μ_B increases steadily as the brake pedals are depressed, reaching a peak of about 0.16 before decreasing steadily to about 0.06 after the EPB is applied and the airplane enters a full, locked-wheel skid. However, even before the EPB is applied, the computed μ_B is significantly lower than the μ_B that would be predicted using models prescribed in 14 Code of Federal Regulations (CFR) Part 25 for computing accelerate-stop distances on a wet runway.[18] The computed μ_B (before the EPB is applied) is also significantly lower than the μ_B implied by the unfactored, wet-runway landing distances published in the EMB-505 Pilot's Operating Handbook, which are computed as 25% greater than the unfactored (demonstrated) landing distances on a dry runway.
>
> However, the μ_B achieved during the accident *is* consistent with the μ_B predicted using a National Aeronautics and Space Administration (NASA) model that is based on runway friction measurements taken with a Continuous Friction Measurement Equipment (CFME) device. These results reflect NTSB findings in other accidents, and confirm that the actual μ_B that can be achieved on a wet runway may be significantly lower than the μ_B predicted by industry-standard models, or the μ_B required to match the manufacturer's published unfactored, wet-runway landing distances. The results also indicate that a more accurate estimate of the degraded stopping performance (and consequent longer landing distances) that are possible on wet runways may be obtained by applying the NASA μ_B model to the minimum CFME friction levels prescribed in Advisory Circular (AC) 150/5320-12C for airports certified per 14 CFR Part 139.
>
> The decrease in μ_B after the EPB is applied is consistent with research indicating that the braking friction achieved in a full locked-wheel skid (a braking slip ratio of 1.0) is significantly less than the maximum μ_B that can be achieved at lower slip ratios. Examination of N322QS's tires revealed evidence of reverted-rubber hydroplaning, which is also consistent with locked-wheel skids and a reduction in μ_B. The *Study* indicates that had the μ_B remained at the levels attained prior to the EPB being set, the airplane would have stopped on the runway.

Reference 21 also uses the TTI model to estimate the depth of water on the runway at the time of the accident, and concludes that

> the rainfall rate, runway macrotexture, and runway cross slope indicate that the water depth on the runway at the time of the accident was far below the [Ref. 5] "Hydroplaning Danger Zone" and "Caution Zone" levels, as well as far below the 3 mm (0.017 inches) that AMC 25.1591 considers a "flooded" runway. Therefore, it is unlikely that N322QS experienced dynamic hydroplaning during the landing, even when its ground speed was above the $V_{p,spin\ up}$ of 103 kt.

In Section V of this paper, the μ_B calculations for the Conroe case are compared with the μ_B predicted by the §25.109 and NASA CFME models, and with the μ_B implied by the EMB-505 AFM data. The application of the NASA μ_B model to CFME friction levels prescribed in AC 150/5320-12C, as introduced in Ref. 21, is discussed here in Section VI.

F. The EMB-500 accident in Sugar Land, TX (NTSB #CEN15LA057)

On November 21, 2014, an Embraer Phenom EMB-500 airplane, registration N584JS, overran the runway after landing at the Sugar Land Regional Airport (KSGR) in Sugar Land, Texas. The airline transport rated pilots were not injured but the airplane was substantially damaged (see Fig. 11a). The NTSB preliminary report for this event[19] states

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[17] I.e., the n_x value became less negative, indicating decreased deceleration. Positive values of n_x indicate acceleration (increasing speed), and negative values of n_x indicate deceleration (decreasing speed).

[18] Specifically, the μ_B model prescribed in 14 CFR 25.109(c).

[19] The preliminary NTSB report for this event can be found at http://www.ntsb.gov/_layouts/ntsb.aviation/brief.aspx?ev_id=20141123X91658&key=1&queryId=4da7f04a-b899-472e-b998-44e3228c7f41&pgno=1&pgsize=50.

> According to the crewmembers, the purpose of the flight was to reposition the airplane from [William P. Hobby Airport (KHOU)] to KSGR. After departing KHOU the flight received vectors from air traffic control, who also told the pilots to expect the ILS 35 approach at KSGR. The first officer reported that the KSGR tower controller cleared the flight to land and that there was no standing water on the runway. During the approach, the first officer noted that there was a tailwind of 15 knots that decreased to 9 knots on touch down.
>
> After landing, the captain, who was flying the airplane, applied the brakes which were unresponsive. She then pulled the emergency brakes twice, but the airplane continued past the end of the runway and onto a grassy area. The airplane then crossed a service road and came to rest in a drainage ditch. The airplane's empennage section was partially submerged by water and the airplane faced the opposite direction of travel.

The investigation of this accident is still ongoing, but an examination of the KSGR runway, and a computation of the μ_B achieved during the landing roll have been completed. The results are similar to those for the Conroe accident: the depth of water on the runway computed using the TTI model could not have supported dynamic hydroplaning, which is consistent with the spin-up and slip ratio of the tires after touchdown; and the μ_B developed during the ground roll is below that implied by the wet-runway landing distances in the AFM, and below that predicted by the §25.109(c) model. However, the maximum μ_B achieved is consistent with the predictions of the NASA CFME model.

V. Achieved vs. modeled μ_B for the six wet-runway overrun events

This section compares the μ_B achieved during the six wet-runway overrun events described above, as computed from Eqs. (1)-(5), with the μ_B that would be predicted by the §25.109(c) and NASA CFME models, and with the μ_B implied by the wet-runway landing distance data included in the airplane AFMs. The μ_B predicted by a combination of the §25.109(c) and NASA CFME models for each event is also presented; this "combined μ_B model" (CMB) is described in detail in Section VI, and consists of scaling the §25.109(c) μ_{max} to match the μ_B predicted by the NASA CFME model at the speeds for which CFME data is available (in essence, the CMB model uses the NASA CFME model to determine the appropriate value of η_{AS} in Eq. (10)).

A. Results for the BAe 125-800A accident in Owatonna, MN (NTSB #DCA08MA085)

As discussed in Ref. 10, N818MV was not equipped with an FDR, so Eqs. (1)-(5) could not be solved for μ_B directly. Instead, μ_B was modeled per Eq. (10), with μ_{max} defined by the §25.109(c) model, and η_{AS} selected so as to make the resulting μ_B provide the braking force required to make a simulation of the airplane's motion on the runway best match other available evidence. This alternative evidence included radar data, CVR data, Enhanced Ground Proximity Warning System (EGPWS) and Flight Management System (FMS) data, weather data, ground scars, and witness statements.

The red line in Fig. 12 plots μ_B vs. V_G from the §25.109(c) model, with η_{AS} = 0.475 and tire inflation pressure p = 142 psi. This μ_B makes the simulation of the airplane motion consistent with the computed performance of N818MV. The green diamonds in Fig. 12 are the μ_B points predicted by the NASA CFME model based on measurements of the KOWA runway using a Surface Friction Tester (SFT) CFME device, operated at 40 mph and 60 mph (the SFT results themselves are presented in Section VI). The 50 mph CFME point in Fig. 12 is based on an interpolation of the 40 mph and 60 mph points; as described in Section VI, the CMB model uses the 50 mph CFME point to determine the scale factor (or η_{AS}) that should be applied to the §25.109(c) μ_{max} to obtain the final μ_B estimate. Since the 50 mph point lies on the red line in Fig. 12, the η_{AS} predicted by the CMB model is the same η_{AS} used to construct the red line, i.e., η_{AS}= 0.475. Hence, in this case, the CMB model exactly matches the μ_B required by the simulation to duplicate the airplane performance observed in the accident.

The black line in Fig. 12 is the μ_B underlying the unfactored[20] wet runway landing distances in the BAe 125-800 AFM, and as cited above, is based on JAR AMJ 25X1591. This μ_B corresponds to a pre-defined, "standard" wet runway. This standard runway is the "Reference Wet Hard Surface" that was used to define wet stopping performance in historical versions of the British Civil Aviation Requirements (BCAR) and European Joint Airworthiness Regulations (JAR), and associated advisory material (see Ref. 10). The AFM μ_B is significantly higher than the CMB model μ_B at high speeds, resulting in much better stopping performance than that predicted by the CMB model (and observed during the KOWA accident).

The blue and magenta lines in Fig. 12 show the §25.109(c) model μ_B for η_{AS} values of 0.80 and 0.30, corresponding to "fully-modulating" and "on-off" anti-skid braking systems, respectively. As cited above, the

[20] The "unfactored" landing distance means the actual distance from the runway threshold required to land the airplane and bring it to a stop, without any safety factors applied.

Dunlop Maxaret system on the BAe 125-800A is considered an "on-off" system, which can have an η_{AS} in the range of 0.3 to 0.75, though §25.109 requires an assumption of 0.3 for this type of system unless higher values can be demonstrated.

The dark yellow line in Fig. 12 is the μ_B underlying the unfactored flooded runway landing distances in the BAe 125-800 AFM, and is based on the EASA AMC 25.1591 model (Eq. 17). The step in the line at V_G = 102 kt. corresponds to deceleration below $V_{p,spin\ down}$. Note that the flooded runway μ_B matches the achieved μ_B (the red line) relatively well. This observation, and similar circumstances present in other wet-runway overrun events, can lead observers to conclude (understandably) that the runways involved must in fact have been flooded. However, the NASA CFME model predicts that low μ_B levels can be obtained on merely wet (not necessarily flooded) runways; and more importantly, in every case considered in this paper, the TTI water-depth model does not support a conclusion that the runways involved could have been flooded, given the macrotexture and cross-slope characteristics of the runways, and the rainfall rates at the times of the events.

The water depth on the runway at the time of the KOWA accident, computed using the TTI model, is shown in Fig. 13. Note that even for the maximum rainfall recorded during the morning of the accident (about 0.7 in. / hour), the maximum depth of the water anywhere on the runway is only 0.044 in., which is a little more than a third of the 0.118 in. used by EU OPS 1.480(a)(2) and the BAe 125-800A AFM to define the runway as "flooded." Moreover, this maximum depth occurs at the edge of the runway – not near the center, where the airplane tires are more likely to be.

The BAe 125-800A main gear track width is 9 ft. 2 in., and so the track half-width is 4 ft. 7 in. Figure 13 depicts three vertical blue lines indicating the location of one of the main gear tires at one, two, and three times the track half-width from the runway centerline. If the nose gear were on the centerline, the main gears would be 4.6 ft. on either side of the centerline, coincident with the blue line labeled "Half of track width = 4.6 ft." If the airplane were sufficiently off the centerline to place one of the main gears on the centerline, the other main gear would be 9.2 ft. from the centerline, coincident with the blue line labeled "2 x Half of track width = 9.2 ft." The third blue line shows where one of the main tires would be at "3 x Half of track width = 13.8 ft." from the centerline. Even in this last case, the water depth for a rain intensity of 0.7 in. / hour is only about 0.017 in. – less than 15% of the water depth used in the "flooded" definitions noted above. Using the rain intensity value closest to the time of the accident (about 0.3 in. / hour), 13.8 ft. from the centerline the water depth is only 0.002 in. – barely above the surface irregularities, and less than 2% of the water depth used in the "flooded" definitions. If the airplane remained within about 6.5 ft. of the runway centerline, then at a rain intensity of 0.3 in. / hour, all the tires would be in areas where the water level would be below the peaks of the runway surface irregularities.

These observations indicate that at the time of the accident, the rainfall at any time during the previous hour would have been insufficient to produce the water depths on the runway necessary to consider the runway "flooded," or to support dynamic hydroplaning.

B. Results for the American Airlines flight 331 accident in Kingston, Jamaica (NTSB #DCA10RA017)

The airplane braking coefficient computed by Boeing based on AA331's FDR (see Ref. 19) is converted into μ_B and plotted here as the red line in Fig. 14. The airplane braking coefficient computed by Boeing in order to match the deceleration recorded on AA331's FDR is converted into μ_B and plotted as the dashed brown line in Fig. 14. As noted above, both the FDR-based and simulation μ_B lie between the Boeing wet-smooth μ_B and the Boeing standing-water water μ_B. Per Ref. 19, the Boeing wet-smooth μ_B is equivalent to the §25.109(c) model μ_B (for p = 200 psi), and is plotted as the blue line in Fig. 14.[21] The Boeing standing-water water μ_B is based on what Ref. 19 calls the "NASA Convair 880 data," and is plotted as the dark yellow line in Fig. 14.

CFME measurements at 40 and 60 mph on runway 12 at MKJP were performed on January 7, 2010 as part of the American Airlines flight 331 accident investigation, using a Findlay Irving Mark 2 Griptester Friction device (see Ref. 22). At 40 mph 10 ft. to the left of the runway centerline, the average (device) μ values measured were 0.66, 0.60, and 0.54 on the first, second, and third thirds of the runway, respectively. The corresponding values measured at 60 mph were 0.61, 0.63, and 0.54, respectively. The results of converting these measurements into airplane V_G and μ_B per the NASA CFME model (see Ref. 21) are plotted in Fig. 14 as the green diamonds. Curiously, except for the first third of the runway, the Griptester results do not show the reduction in μ with increased speed that would be expected based on the physics of wet-runway braking. Furthermore, the airplane μ_B resulting from the Griptester measurements is well above what was actually achieved (the red line in Fig. 14), and is even above the §25.109(c)

[21] The §25.109(c) μ_B shown in Figs. 14 and 16 use η_{AS} = 0.80, although for certification purposes, Boeing demonstrated a higher η_{AS} using the methods described in AC 25-7C (Ref. 9).

model μ_B. In this case, the NASA CFME model does not match the actual μ_B well at all; however, the puzzling Griptester results (little to no reduction in μ with increasing speed), and the fact that the NASA CFME model does match the actual μ_B well in many other cases, suggest that the CFME results in this case are an anomaly.

As noted above, the JCAA report (Ref. 16) states that per the TTI water depth model, the runway could not have been flooded or have supported dynamic hydroplaning; yet the μ_B achieved during the landing roll was less than assumed in the AFM for a wet runway, and less than that predicted by the §25.109(c) model. Interestingly, Boeing's letter to the NTSB (Ref. 19) notes that "the airplane would have stopped on the paved surface if the runway had performed equivalent to a Wet-Grooved or Wet-Smooth runway as defined by FAR 25.109, even with the long touchdown point."

C. Results for the United Express flight 8050 accident in Ottawa, Ontario (NTSB # DCA10RA069)

The airplane braking coefficient computed by the TSB based on UE8050's FDR (see Ref. 23) is converted into μ_B and plotted here as the red line in Fig. 15. The §25.109(c) model μ_B (for the EMB-145 p of 160 psi and η_{AS} = 0.80) is plotted as the blue line in Fig. 15. As noted above, the μ_B achieved on this wet (but not flooded) runway is significantly lower than that predicted by §25.109(c); the computed μ_B remains approximately constant at around 0.08 until the airplane decelerates below about 87 kt., at which point it increases noticeably and even has two temporary peaks that reach the §25.109(c) level. Per Ref. 15, the airplane departed the runway at about 70 kt., and so the μ_B comparisons end at this point.

CFME measurements with a SFT device at 40 mph were taken on CYOW runway 7 in April 2010 and on June 25, 2010 (the accident occurred on June 16; see Ref. 15). The average μ values measured were 0.55 and 0.63, respectively. The 0.55 value is below the runway maintenance level for the SFT (0.60), while the 0.63 value is above it (required runway maintenance actions based on CFME measurements are discussed in Section VI). However, for CYOW tests the SFT device was run with 0.5 mm of water applied in front of the measuring tire, as opposed to the 1 mm specified by the FAA for CFME measurements in the USA, and as recommended by International Civil Aviation Organization (ICAO). Reference 15 notes that

> The results of [post-accident] coefficient-of-friction testing conducted from April to August 2011 indicate that, when using 0.5 mm, the friction values are above the specified [Transport Canada (TC)] guidelines for programming corrective action. However, when using 1.0 mm, the friction values are below those specified in ICAO Airport Services Manual (DOC 9137) Part 2, and immediate corrective action would have to be taken. The investigation was unable to determine the reason for the differences in published minimum friction values and testing methodology between TC and ICAO/FAA …. This difference may result in reduced runway friction levels at Canadian airports.

Consequently, it is likely that if the SFT device had been run with 1 mm of water during the April and June 2010 tests, the results would have been lower (and possibly below the runway maintenance level for *both* runs).

The results of converting the CYOW SFT measurements into airplane V_G and μ_B per the NASA CFME model (see Ref. 21) are plotted in Fig. 15 as the green diamonds. The airplane V_G corresponding to the SFT speed of 40 mph is about 80 kt., for an airplane p of 160 psi; as shown in Fig. 15, at this speed the FDR-based μ_B has increased from the 0.08 level present for much of the ground roll, and matches the CFME-based μ_B reasonably well. The results of using the CFME points in Fig. 15 to determine the scaling that should be applied to the §25.109(c) μ_{max} in the CMB model are shown in Fig. 15 as the dashed- and dash-dotted black lines (the CMB model is described in Section VI). As noted above, the CMB scales the §25.109(c) μ_{max} to match the μ_B predicted by the NASA CFME model; the scale factors required to match the two CYOW points are the two k_B factors for the black lines in Fig. 15. These k_B factors are equivalent to η_{AS} in the §25.109 model, and can be compared directly to η_{AS}. The $k_B = \eta_{AS}$ = 0.55 factor in Fig. 15, based on the April 2010 SFT test, approaches the peaks of the oscillations of the FDR-based μ_B at the higher V_G, but still overestimates the achieved braking performance (though it is much closer to the actual performance than the §25.109 model, which assumes η_{AS} = 0.8). If the SFT μ were lower (as might have been the case had the device been run with 1 mm of water), then the resulting k_B would also be lower, and the CMB model would match the actual μ_B better.

D. Results for the Southwest Airlines flight 1919 incident in Chicago, IL (NTSB #DCA11IA047)

The airplane braking coefficient computed by Boeing based on SA1919's FDR (see Ref. 14) is converted into μ_B and plotted here as the red line in Fig. 16. The airplane braking coefficient computed by Boeing in order to match the deceleration recorded on SA1919's FDR is converted into μ_B and plotted as the dashed brown line in Fig. 16. The Boeing wet-smooth μ_B is equivalent to the §25.109(c) model μ_B (for p = 200 psi and η_{AS} = 0.80), and is plotted as the solid blue line in Fig. 16. The Boeing wet-grooved μ_B is equivalent to the §25.109(d) model μ_B (for p = 200 psi and η_{AS} = 0.80), and is plotted as the dashed blue line in Fig. 16 (KMDW runway 13C is grooved). The Boeing standing-water water μ_B (based on the NASA Convair 880 data) is plotted as the dark yellow line in Fig. 16.

As noted above, CFME tests at 40 mph were conducted on KMDW runway 13C after the SW1919 incident. The results of the tests conducted 10 ft. left and right of the runway centerline show considerable variation in μ over the length of the runway (see Figs. 17a-b, taken from Ref. 21; two runs were performed to the left of the runway centerline, though only the first of these is presented here). A CFME μ value of 0.54, corresponding to about the average μ measured in the first 3000 ft. of the runway, is used to compute the "NASA CFME point" plotted in Fig. 16 as the green diamond (see Ref 21). The result of using this CFME point to determine the scaling that should be applied to the §25.109(c) μ_{max} in the CMB model is shown in Fig. 16 as the black line. A scale factor of $k_B = \eta_{AS}$ = 0.55 matches the CFME point, and also matches the FDR-based μ_B and the simulation μ_B quite well. Interestingly, the 0.55 value is the same as that resulting from the SFT runs on CYOW runway 7.

A point-by-point estimate of the airplane μ_B over the length of the runway, using the CMB model and the CFME data in Figs. 17a-b, is presented in Ref. 21. Regarding these estimates, Ref. 21 states:

> … between 1000 and 2700 ft. from the threshold, the μ_B from the combined μ_B model for all three SFT runs matches the μ_B required in the simulation to duplicate the airplane's deceleration very well ….
>
> Between 2700 and 3400 ft. from the threshold, both the μ_B computed from the airplane data, and the measured SFT μ, show a large rise. The airplane μ_B increases above the §25.109(d) level for a grooved runway (assuming η_{AS} = 0.8), while the μ_B computed from the SFT data and the combined μ_B model increases to about the §25.109(d) level. Following this peak, both the actual and modeled μ_B drop significantly, though the modeled μ_B drops further and indicates worse performance than both the actual μ_B and the Boeing simulation μ_B. The modeled μ_B remains below the actual and simulation μ_B until about 5300 ft. from the threshold, when the modeled μ_B climbs back up to the actual and simulation μ_B levels.
>
> The large drop in the modeled μ_B starting at 3400 ft. from the threshold reflects the drop in the SFT μ measured in the same area; the SFT μ drops to about 0.25, or half of the [minimum friction level] defined in AC 150/5320-12C for the SFT device at 40 mph …. The airplane μ_B, on the other hand, generally follows the trend indicated by the simulation μ_B, which is based on monotonic functions of V_G (i.e., the simulation μ_B increases monotonically as V_G decreases). In other words, in this area the airplane μ_B trend appears to be driven primarily by decreasing V_G, without significant influences from other factors (such as a dramatic change in the runway surface condition). Since the actual μ_B does not decrease notably below the simulation μ_B, it appears that (for unknown reasons) the airplane did not experience the increased runway "slipperiness" between 3400 and 5300 ft. from the threshold measured by the SFT device.

Figure 16 indicates that the combination of μ_{max} and η_{AS} assumed in §25.109(c) (for a *smooth* runway) can greatly overestimate the actual μ_B achievable on some wet runways, even *grooved* runways at large commercial airports certified under 14 CFR Part 139. On the other hand, the good agreement between the achieved μ_B and the CMB model is further evidence that the CMB model, and the NASA CFME model it employs, are reliable predictors of the actual μ_B that can be achieved on a wet runway, if the CFME characteristics of that runway are known or can be estimated.

E. Results for the EMB-505 accident in Conroe, TX (NTSB #CEN14FA505)

The findings from Ref. 21 regarding μ_B for the accident involving N322QS at KCXO, cited above, are presented graphically in Fig. 18. The μ_B computed per Eqs. (1)-(5), using FDR data from N322QS, is plotted as the red line in Fig. 18. During the landing roll, the crew engaged the Emergency / Parking Brake (EPB), which locked the main gear tires at a groundspeed of about 87 kt.; this point is depicted by the black arrow in Fig. 18. Following this point, the μ_B decreased, consistent with the behavior shown in Fig. 2.

During the investigations of the KCXO and KSGR accidents, the NTSB conducted CFME and other measurements on the accident runways. The CFME measurements were made using a Neubert Aero Corporation Dynamic Friction Tester (DFT) device, operated at speeds of 30, 40, 50, and 60 mph (see Figs. 23 and 24). The results of converting the (averaged) KCXO DFT measurements into airplane V_G and μ_B per the NASA CFME model (see Ref. 21) are plotted in Fig. 18 as the green diamonds. The result of using the 50 mph CFME point to determine the scaling that should be applied to the §25.109(c) μ_{max} in the CMB model is shown in Fig. 18 as the black line. A scale factor of $k_B = \eta_{AS}$ = 0.64 matches the 50 mph CFME point, and also matches the FDR-based μ_B (between 109 and 100 kt.) and the other CFME μ_B points quite well.

The §25.109(c) model μ_B (for p = 180 psi and η_{AS} = 0.80), is plotted as the solid blue line in Fig. 18. The AMC 25.1591 μ_B for a flooded runway (Eq. 17) is plotted as the dark yellow line in Fig. 18.

The EMB-500 and -505 AFMs contain tables of unfactored (i.e., no safety factor applied) landing distances on wet runways; however, these distances are not physics-based, but are based on a scale factor applied to the demonstrated dry landing distances. As explained in Ref. 21, the EMB-500 and -505 AFM unfactored wet landing distances are equal to the unfactored dry distances multiplied by 1.25, per an agreement between Embraer and EASA during the certification of these airplanes. Nonetheless, Ref. 21 presents a method for deriving a μ_B model that is consistent with the wet-runway landing distances in the AFM:

> Even though the [AFM] unfactored wet distances are not the result of computations grounded in a μ_B model, an "equivalent" μ_B model can be inferred from the AFM distances, and expressed in terms of the same variables that define the §25.109 model. For a given set of landing conditions, this approach seeks to determine the η_{AS} (called $\eta_{AS,AFM}$) that would have to be applied to the μ_{max} specified in §25.109(c) in order to generate a μ_B that results in a wet-runway stopping distance identical to that published in the AFM ….
>
> The landing distance is the sum of the air, transition, and ground roll distances. The air distance is the distance from a point 50 ft. above the threshold to touchdown; the transition distance is the distance from touchdown to the point where all three gear are on the ground and all the deceleration devices are activated; and the ground roll distance is the distance travelled from the end of the transition distance to the point where the airplane stops. The AFM provides total landing distance for specified conditions, but does not break this distance into the air / transition and ground roll distances.
>
> For this *Study*, the sum of the air and transition distances was estimated by subtracting the computed ground roll distance on a dry runway from the AFM total landing distance on a dry runway, for the accident weight and ambient conditions ….
>
> …
>
> From this initial condition, the η_{AS} required to match the AFM unfactored, wet landing distance using the μ_{max} defined by [§25.109(c)] was determined by trial and error. … η_{AS} = 0.95 resulted in a match of the AFM wet landing distance for the accident conditions.

Hence, the μ_B model that is "equivalent" to the AFM unfactored wet-runway landing distance for the KCXO conditions is the §25.109(c) μ_{max}, multiplied by an η_{AS} of 0.95. This μ_B is plotted in Fig. 18 as the dashed blue line. Reference 21 notes that an η_{AS} of 0.95 is "even higher than the η_{AS} = 0.8 specified in §25.109(c) that, as shown [by the overrun events considered in this paper], is already too high."

The water depth on the runway at the time of the Conroe accident, computed using the TTI model, is shown in Fig. 19. As noted above, Fig. 19 does not support a conclusion that the runway could have been flooded at the time of the accident, or that N322QS experienced dynamic hydroplaning.

F. Results for the EMB-500 accident in Sugar Land, TX (NTSB #CEN15LA057)

The μ_B computed per Eqs. (1)-(5), using FDR data from N584JS, is plotted as the red line in Fig. 20. Note that between 110 and 94 kt. the computed μ_B is very low, with large oscillations around an average of about 0.05. At 94 kt., the μ_B jumps to an average of about 0.14 before the EPB is set at 75 kt. After the EPB is set, the μ_B decreases, consistent with the behavior shown in Fig. 2.

The results of converting the averaged KSGR DFT measurements into airplane V_G and μ_B per the NASA CFME model (see Ref. 21) are plotted in Fig. 18 as the green diamonds joined by the solid green line. The NASA CFME μ_B values lie much closer to the FDR-based μ_B (particularly between 94 and 75 kt.) than the §25.109(c) model with η_{AS} = 0.8, depicted in Fig. 20 as the solid blue line. The AFM "equivalent" μ_B, determined by a method similar to that described above for the KCXO accident, is depicted in Fig. 20 as the dashed blue line, and is equivalent to the §25.109(c) model with η_{AS} = 0.94.

The result of using the 50 mph CFME point to determine the scaling that should be applied to the §25.109(c) μ_{max} in the CMB model is shown in Fig. 20 as the black line. A scale factor of $k_B = \eta_{AS}$ = 0.75 matches the 50 mph CFME point, is not much less than the §25.109(c) result with η_{AS} = 0.8, and does not match the FDR-based μ_B well.

The model plotted in Fig. 20 that matches the FDR-based μ_B best is the AMC 25.1591 model for a flooded runway (Eq. 17). Furthermore, the $V_{p,spin\,up}$ for the EMB-500, with p = 166 psi, is 99 kt. (Eq. 8b); and the jump in μ_B occurs at about 94 kt. So, while the jump in μ_B occurs later than the deceleration of the airplane through $V_{p,spin\,up}$, it does resemble what would be expected if the airplane had transitioned from a dynamic hydroplaning to a non-hydroplaning condition at about 94 kt.

Consequently, it is particularly important to determine whether the KSGR runway could have been flooded and supported dynamic hydroplaning at the time of the accident. As shown in Fig. 21, the TTI model indicates that it is very unlikely that the runway was in fact flooded, given the rainfall rate at the time,[22] and the runway macrotexture and cross-slope characteristics measured by the NTSB during the accident investigation. This finding is consistent

[22] The maximum rainfall rate recorded by the KSGR automated Airport Surface Observation System (ASOS) during the morning of the accident was 0.25 inches/hour.

with the report issued to N584JS by the KSGR air traffic control tower that “there was no standing water on the runway,” and with the spin-up and slip ratio of the tires after touchdown. The reasons for N584JS’s poor braking performance above 94 kt. are still under investigation. For the present, it suffices to note that the depth of water on the runway could not have supported dynamic hydroplaning, and that the μ_B developed during the ground roll is well below that implied by the wet-runway landing distances in the AFM, and below that predicted by the §25.109(c) model. Instead, the maximum μ_B achieved is (more) consistent with the predictions of the NASA CFME model.

VI. μ_B model combining §25.109, NASA CFME, and AC 150/5320-12C methods

A. Overview

This section presents an alternative “combined” μ_B model based on:

- The observation that the NASA method for correlating CFME measurements to actual airplane μ_B on wet runways best predicts the μ_B achieved in the KOWA, KMDW, KCXO, and KSGR events taken together, and is therefore the most reliable μ_B model of those examined in this paper;
- The CFME-measured μ_B values defined in existing FAA advisory material (Ref. 12) as the basis for runway maintenance practices; and
- The observation that the §25.109 μ_B model mirrors the non-linear shape of the μ_B vs. V_G curves in the ESDU 71026 data, and hence serves to extrapolate CFME-based data to V_G values outside of the range measured by a CFME device.

The alternative model (referred to in earlier sections, and hereafter, as the “combined μ_B” or “CMB” model) relies on CFME μ_B values that can be reasonably expected on actual runways, and converts these to airplane μ_B based on a proven method. As shown below, this model can accurately predict the μ_B achieved in the KOWA, KMDW, KCXO, and KSGR events, without the actual CFME data from the runways involved. In addition, the model is in relatively good agreement with the results of wet-runway flight and CFME tests conducted by Transport Canada using both a Falcon 20 jet and a De Havilland Dash 8 turboprop.

FAA Advisory Circular AC 150/5320-12C, *Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces* (Ref. 12) provides guidance to airport operators for evaluating and maintaining runway friction characteristics. The AC specifies minimum CFME μ values for newly constructed runways, and the μ values at which maintenance (such as rubber deposit removal) must be either planned for or taken immediately in order to improve the runway friction. These CFME μ values are used in the CMB model in lieu of actual CFME measurements on a particular runway.

Reference 12 specifies CFME μ values for different maintenance actions at two different CFME vehicle speeds: 40 mph and 60 mph. The two speeds are intended to determine the condition of the runway microtexture and macrotexture:

> All of the approved CFME … can be used at either 40 mph (65 km/h) or 60 mph (95 km/h). The lower speed determines the overall macrotexture/contaminant/drainage condition of the pavement surface. The higher speed provides an indication of the condition of the surface's microtexture. A complete survey should include tests at both speeds.

In the combined μ_B model, these vehicle speeds and associated μ values are converted into V_G and μ_B for a particular airplane (using the airplane tire inflation pressure p) per the NASA CFME method described in Section III. This provides the aircraft μ_B at two values of V_G.

Finally, the μ_B vs. V_G curve for the aircraft across the V_G range of interest is determined by finding the factor that should be applied to the μ_{max} specified in §25.109(c) in order to approximately match the μ_B at the two V_G speeds computed from the CFME μ values specified in Ref. 12. The factor accounts for the efficiency of the anti-skid braking system (η_{AS}), as well as any adjustment that must be made to the §25.109(c) μ_{max} in order to make it match the μ_{max} that results from applying the NASA conversion method to the Ref. 12 CFME μ values.

These steps are described in further detail below.

B. CFME μ values defined in AC 150/5320-12C

Reference 12 notes that the μ_{max} on a given runway will deteriorate over time, and recommends that airports that support turbojet traffic monitor the μ_{max} on the runways through the use of CFME:

> Over time, the skid-resistance of runway pavement deteriorates due to a number of factors, the primary ones being mechanical wear and polishing action from aircraft tires rolling or braking on the pavement and the accumulation of contaminants, chiefly rubber, on the pavement surface. The effect of these two factors is directly dependent upon the volume and type of aircraft traffic. Other influences on the rate of deterioration are local weather conditions, the type of pavement ([Hot Mix Asphalt or Portland Cement Concrete]), the materials used in original construction, any subsequent surface treatment, and airport maintenance practices.
>
> …
>
> All airports with turbojet traffic should own or have access to use of CFME. Not only is it an effective tool for scheduling runway maintenance, it can also be used in winter weather to enhance operational safety (see AC 150/5200-30). Airports that have few turbojet traffic operations may be able to borrow the CFME from nearby airports for maintenance use, share ownership with a pool of neighboring airports, or hire a qualified contractor.

The CFME μ values corresponding to runway friction levels that warrant specific maintenance actions are defined in Section 3 of Ref. 12. Three friction levels are defined:

> 3-20.EVALUATION AND MAINTENANCE GUIDELINES. The following evaluation and maintenance guidelines are recommended based on the friction levels classified in [Fig. 22]. These guidelines take into account that poor friction conditions for short distances on the runway do not pose a safety problem to aircraft, but long stretches of slippery pavement are of serious concern and require prompt remedial action.
>
> a. Friction Deterioration Below the Maintenance Planning Friction Level [MAINT LEVEL] (500 ft). When the average Mu value on the wet runway pavement surface is less than the Maintenance Planning Friction Level but above the Minimum Friction Level [MIN LEVEL] in [Fig. 22] for a distance of 500 feet (152 m), and the adjacent 500 foot (152 m) segments are at or above the Maintenance Planning Friction Level, no corrective action is required. These readings indicate that the pavement friction is deteriorating but the situation is still within an acceptable overall condition. The airport operator should monitor the situation closely by conducting periodic friction surveys to establish the rate and extent of the friction deterioration.
>
> b. Friction Deterioration Below the Maintenance Planning Friction Level (1000 ft). When the averaged Mu value on the wet runway pavement surface is less than the Maintenance Planning Friction Level in [Fig. 22] for a distance of 1000 feet (305 m) or more, the airport operator should conduct extensive evaluation into the cause(s) and extent of the friction deterioration and take appropriate corrective action.
>
> c. Friction Deterioration Below the Minimum Friction Level [MIN LEVEL]. When the averaged Mu value on the wet pavement surface is below the Minimum Friction Level in [Fig. 22] for a distance of 500 feet (152 m), and the adjacent 500 foot (152 m) segments are below the Maintenance Planning Friction Level, corrective action should be taken immediately after determining the cause(s) of the friction deterioration. Before undertaking corrective measures, the airport operator should investigate the overall condition of the entire runway pavement surface to determine if other deficiencies exist that may require additional corrective action.
>
> d. New Design/Construction Friction Level for Runways [NEW LEVEL]. For newly constructed runway pavement surfaces (that are either saw cut grooved or have a PFC overlay) serving turbojet aircraft operations, the averaged Mu value on the wet runway pavement surface for each 500 foot (152 m) segment should be no less than the New Design/Construction Friction Level in [Fig. 22].

The DFT trailer used during the CFME testing at KCXO and KSGR is represented by the “Mu meter” (MM) device entry in Fig. 22, and the Saab 9-5 vehicle used at KOWA, CYOW, and KMDW is represented by the “Airport Surface Friction Tester” (SFT) device entry. The DFT trailer and Saab vehicle have similar operational characteristics: a 30 psi measurement tire inflation pressure, operated at a slip ratio between 10% (for the Saab vehicle) and 12% (for the DFT trailer). However, the μ values in Fig. 22 for the MM and SFT devices are different, and therefore comparing the friction levels of different runways (e.g., KCXO runway 1 and KOWA runway 30), measured with different devices, is not straightforward.

The friction levels of different runways measured with different devices can be compared if the device measurements, and the μ values defined in Fig. 22, are converted into airplane μ_B using the NASA CFME method. As noted above, the method requires the “characteristic dry” μ_{cd} of each device. Appendix B of Ref. 21 lists the μ_{cd} for the SFT as 1.1, but does not have a specific entry for the DFT, though the entry for the MM is 0.9. Since the DFT vehicle shares the MM friction classification levels, it is reasonable to assume that it will also share the MM μ_{cd} value.

This assumption can be verified by estimating the DFT μ_{cd} based on the data in Fig. 22. For each friction classification level in Fig. 22, the resulting μ_B for an airplane should be the same, regardless of the CFME device used to measure μ. The μ_B is given by Eq. (10), with μ_{max} from the NASA CFME model given by

$$\mu_{max} = \frac{\mu_{CFME}}{\mu_{cd,CFME}} \mu_{cd,airplane} \tag{18}$$

Where:
μ_{CFME}= runway μ measured by the CFME device;
$\mu_{cd,CFME}$= characteristic dry μ_{cd} of the CFME device; and
$\mu_{cd,airplane}$= characteristic dry μ_{cd} of the airplane (Eq. (12)).

Since the μ_{max} computed from DFT and SFT measurements should be the same, we can write

$$\frac{\mu_{DFT}}{\mu_{cd,DFT}} \mu_{cd,airplane} = \frac{\mu_{SFT}}{\mu_{cd,SFT}} \mu_{cd,airplane} \tag{19}$$

Where:
μ_{DFT} = runway μ measured by the DFT device;
$\mu_{cd,DFT}$= characteristic dry μ_{cd} of the DFT device;
μ_{SFT} = runway μ measured by SFT device; and
$\mu_{cd,SFT}$= characteristic dry μ_{cd} of the SFT device.

From Eq. (19) it follows that

$$\mu_{cd,DFT} = \frac{\mu_{DFT}}{\mu_{SFT}} \mu_{cd,SFT} \tag{20}$$

Equation (20) can be used to compute $\mu_{cd,DFT}$ based on the μ_{DFT} and μ_{SFT} values in Fig. 22, and $\mu_{cd,SFT}$ = 1.1. The results vary from 0.84 to 0.98, with an average of 0.92. This paper uses $\mu_{cd,DFT}$ = 0.92, which compares well with the MM μ_{cd} of 0.9 listed in Appendix B of Ref. 21.

The average CFME μ measurements on the runways involved in the overrun events discussed in this paper are summarized in Table 2. Figures 17, 23, and 24 present point-by-point CFME μ measurements at KMDW, KCXO, and KSGR, respectively. The Ref. 12 friction classification levels based on these measurements are also shown in Table 2 and the Figures. For the KCXO runway, the average DFT μ 5 ft. to the left of the centerline is used in Ref. 21 (and this paper) to compute μ_B from the NASA CFME model, since this coordinate best matches the position of N322QS during the ground roll prior to the setting of the EPB. Similarly, the average DFT μ 5 ft. to the left of the centerline between 800 and 3200 ft. from the threshold is used to compute μ_B for the KSGR runway.

Based on the available CFME measurements from the KCXO, KSGR, KOWA, CYOW, and KMDW runways, a reasonable estimate for the μ values for a "representative" runway that could well be encountered in service is an average between the MIN LEVEL and MAINT LEVEL values specified in Fig. 22 (e.g., 0.47 at 40 mph and 0.33 at 60 mph, for the "Mu Meter" device). This "REP LEVEL" will be added to the three levels specified in Ref. 12 in the further development of the combined μ_B model discussed below.

Runway / CFME device	μ at 40 mph	μ at 60 mph
KOWA 30 / SFT: 10 ft. left of centerline 10 ft. right of centerline	 0.51 0.53	 0.38 0.40
MKJP 12 / Griptester: 1st third 2nd third 3rd third	 0.66 0.60 0.54	 0.61 0.63 0.54
CYOW 07 / SFT: April 2010 June 2010	 0.55 0.63	No data
KMDW 13C / SFT: Point-by-point measurements Average in 1st 3000 ft.	 See Fig. 17 0.54	No data
KCXO 1 / DFT: Point-by-point measurements Average, 5 ft. left of centerline	 See Fig. 23 0.50	 See Fig. 23 0.36
KSGR 35 / DFT: Point-by-point measurements Average, 5 ft. left of centerline	 See Fig. 24 0.50	 See Fig. 24 0.44

Table 2. Summary of CFME μ measurements on various runways. μ values are color-coded per the Ref. 12 friction classification levels, as follows: red < MIN LEVEL ≤ orange < MAINT LEVEL ≤ yellow < NEW LEVEL ≤ green. This color scheme is also reflected in Fig. 25.

C. Scaling the §25.109 μ to the AC 150/5320-12C μ using the NASA CFME model

Consideration of the μ values associated with the different runway friction levels specified in Ref. 12 yields four μ values at each of two CFME vehicle speeds: the MIN LEVEL, REP LEVEL, MAINT LEVEL, and NEW LEVEL μ values, at both 40 mph and 60 mph. We now seek to transform both the speeds and the μ values into corresponding parameters applicable to airplanes, that is, to V_G and μ_B, using the NASA CFME model presented in Section III (and described in detail in Appendix B of Ref. 21). The results of the transformation will define scale factors that must be applied to the §25.109(c) μ_{max} and μ_B in order to approximately match the μ_{max} and μ_B resulting from the transformed CFME μ values. For simplicity, these scale factors are determined for CFME measurements at a single CFME device speed: at 50 mph, with the corresponding μ taken as the average of the 40 and 60 mph μ values.

The NASA method uses the tire p of both the CFME device and the airplane as inputs, as well as the μ_{cd} of the CFME device. For both the DFT and SFT, p = 30 psi. As discussed above, for the DFT, $\mu_{cd,DFT}$ = 0.92, and for the SFT, $\mu_{cd,SFT}$ = 1.1. Values of the airplane p considered in §25.109(c) (i.e., 50, 100, 200, and 300 psi) are also considered here, as well as the EMB-505 p of 180 psi (the CMB model was originally developed in Ref. 21 as part of the KCXO EMB-505 accident investigation).

Tables 3a-3g present the CFME μ values at 50 mph transformed to airplane μ_{max} and μ_B, and the CFME speed of 50 mph transformed to airplane V_G, for the four runway friction levels and four airplane p values considered in this development. The μ_{max} specified by §25.109(c) at each V_G, and the factors required to scale the §25.109(c) μ_{max} to the CFME-based μ_{max} and CFME-based μ_B, are also listed. The scale factors are defined as follows:

$$\mu_{max}|_{CFME:50} = (k_{max})(\mu_{max}|_{25.109}) \tag{21}$$

$$\mu_B|_{CFME:50} = (k_B)(\mu_{max}|_{25.109}) \tag{22}$$

Where:

$\mu_{max}|_{CFME:50}$ = CFME μ at 50 mph transformed into runway μ_{max} by the NASA model;

$\mu_{max}|_{25.109}$ = μ_{max} specified by §25.109(c), at the airplane V_G corresponding to the CFME device speed of 50 mph, and the airplane p; and

$\mu_B|_{CFME:50}$ = CFME μ values at 50 mph transformed into airplane μ_B by the NASA model.

k_{max} indicates how closely the μ_{max} from the NASA and the §25.109(c) models compare, and k_B is equivalent to the anti-skid efficiency η_{AS} that should be applied to the §25.109(c) μ_{max} in order to match the final μ_B predicted by the NASA model. The η_{AS} corresponding to the NASA model itself (i.e., Eqs. (15a) and (15b)) is given by

$$\eta_{AS} = \frac{\mu_B|_{CFME:50}}{\mu_{max}|_{CFME:50}} = \frac{k_B}{k_{max}} \quad (23)$$

The η_{AS} computed using Eq. (23) is listed in Table 3g.

CFME μ		CFME speed, mph		
		40	50	60
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.42	0.34	0.26
	REP	0.47	0.40	0.32
	MAINT	0.52	0.45	0.38
	NEW	0.72	0.69	0.66

Table 3a. "Mu meter" μ values defined in AC 150/5320-12C for different friction level classifications. Shaded values are defined in the AC; others are interpolated. The 50 mph values are used in the development of the combined μ_B model.

$\mu_{max}\|_{CFME:50}$		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.323	0.303	0.271	0.262	0.222
	REP	0.376	0.352	0.314	0.305	0.258
	MAINT	0.428	0.401	0.358	0.347	0.293
	NEW	0.656	0.615	0.549	0.533	0.450

Table 3b. AC 150/5320-12C μ at 50 mph transformed into runway μ_{max} by the NASA CFME model.

$\mu_B\|_{CFME:50}$		Airplane tire pressure, psi				
		50	100	180	200	300
AC 150/5320-12C CLASSIFICATION LEVEL	MIN	0.139	0.126	0.106	0.102	0.079
	REP	0.176	0.159	0.133	0.127	0.099
	MAINT	0.216	0.195	0.163	0.156	0.120
	NEW	0.439	0.393	0.325	0.309	0.235

Table 3c. AC 150/5320-12C μ at 50 mph transformed into runway μ_B by the NASA CFME model.

	Airplane tire pressure, psi				
	50	100	180	200	300
Airplane spin-down V_p, kt.	63.6	90.0	120.7	127.3	155.9
V_G for CFME speed of 50 mph, kt.	56.1	79.3	106.4	112.2	137.4
$\mu_{max}\|_{25.109}$	0.496	0.345	0.241	0.224	0.167

Table 3d. Airplane spin-down hydroplaning speed (V_p), ground speed (V_G), and §25.109(c) μ_{max} corresponding to a CFME device speed of 50 mph, for various airplane tire inflation pressures.

k_{max}		Airplane tire pressure, psi				
		50	**100**	**180**	**200**	**300**
AC 150/5320-12C CLASSIFICATION LEVEL	**MIN**	0.652	0.878	1.122	1.170	1.328
	REP	0.758	1.021	1.303	1.359	1.543
	MAINT	0.863	1.163	1.484	1.549	1.758
	NEW	1.324	1.783	2.276	2.375	2.695

Table 3e. Factor k_{max} for scaling $\mu_{max}|_{25.109}$ to $\mu_{max}|_{CFME:50}$.

k_B		Airplane tire pressure, psi				
		50	**100**	**180**	**200**	**300**
AC 150/5320-12C CLASSIFICATION LEVEL	**MIN**	0.281	0.366	0.441	0.453	0.476
	REP	0.355	0.461	0.553	0.568	0.592
	MAINT	0.437	0.566	0.677	0.694	0.720
	NEW	0.885	1.140	1.348	1.378	1.405

Table 3f. Factor k_B for scaling $\mu_{max}|_{25.109}$ to $\mu_B|_{CFME:50}$.

η_{AS}		Airplane tire pressure, psi				
		50	**100**	**180**	**200**	**300**
AC 150/5320-12C CLASSIFICATION LEVEL	**MIN**	0.431	0.416	0.393	0.387	0.358
	REP	0.468	0.451	0.424	0.418	0.384
	MAINT	0.506	0.486	0.456	0.448	0.410
	NEW	0.669	0.639	0.592	0.580	0.521

Table 3g. NASA CFME model anti-skid braking system efficiency η_{AS} = k_B / k_{max}.

Figure 25 plots the μ_B resulting from multiplying $\mu_{max}|_{25.109}$ by the k_B from Table 3f, for p = 180 psi (corresponding to the EMB-505) and the four runway friction classification levels, as a function of airplane ground speed (V_G). The Figure also plots $\mu_{max}|_{25.109}$ multiplied by an η_{AS} of 0.80, corresponding to the value in §25.109(c) for fully-modulating anti-skid braking systems. Note that as scaling factors on the μ_{max} defined in §25.109(c), k_B and η_{AS} operate equivalently.

Figure 25 also plots the results of converting the CFME μ and speed measured in the accident investigations discussed above to airplane μ_B and V_G using the NASA CFME model. For the MKJP measurements with the Griptester, a $\mu_{cd,Griptester}$ = 0.91 was used, based on a method similar to that used above to determine $\mu_{cd,DFT}$. For a proper comparison with the μ_B runway classification levels plotted in Fig. 25, a k_B corresponding to each of the airplane p involved should be used, rather than the 180 psi used for the EMB-505 (though this value is appropriate for the KCXO comparison). The p of the CYOW EMB-145 was 160 psi, and the p of the MKJP B737 was 200 psi.[23] Nonetheless, Figure 35 places the resulting μ_B and V_G in the same runway pavement classifications that would result from comparing the original CFME μ measurements to the values in Fig. 22.

Figure 25 indicates that the μ_B predicted by the NASA CFME model based on the CFME measurements taken during several accident investigations are below that predicted by the §25.109(c) model, and below the MAINT LEVEL classification of Ref. 12. Further, the Figure indicates that the §25.109(c) μ_B lies between the Ref. 12 NEW and MAINT friction classification levels, when the μ values corresponding to those levels are converted to μ_B over a large range of V_G, per the combined model presented here.

[23] See Refs. 15 and 16, respectively. The tire pressure of the KMDW B737 is assumed to match the 200 psi measured on the MKJP B737.

It should be noted that while the μ_B actually achieved by the airplanes in the KOWA, KMDW, KCXO, and KSGR events match the μ_B predicted by the NASA CFME model relatively well, the airplanes in the CYOW and MKJP accidents achieved μ_B levels *lower* than those predicted by both the §25.109(c) *and* the NASA CFME models. The MKJP μ_B based on the Griptester measurements is above the §25.109(c) μ_B, but the Boeing simulation match indicates that the effective μ_B achieved was far below that level, and even less than the Ref. 12 MIN LEVEL, until V_G dropped below 44 kt. (see Figs. 14 and 25). Figure 15 indicates that the μ_B achieved over a large portion of the runway at CYOW oscillated about a constant value of approximately 0.08, much lower than the values based on the SFT measurements and NASA model.[24] Consequently, the μ_B predicted by the NASA CFME model should be considered *maximum* likely values for a given airplane and runway combination; other factors could make the actual μ_B achieved lower.

The results shown in Fig. 25 indicate that unfactored wet-runway stopping distances based on the §25.109(c) model μ_B values (or greater) likely overestimate the μ_B available on runways that do not achieve CFME μ values about 18% better than the MAINT LEVEL values in Fig. 22, and consequently underestimate the runway length required to stop on these runways. The μ_B values resulting from the REP LEVEL k_B factors in Table 3f (and illustrated in Fig. 25 for p = 180 psi), which are about 30% below the §25.109(c) values, are more representative of the airplane performance that may well be encountered on actual, operational wet runways.

D. Comparison of the combined μ_B model with wet-runway flight and CFME test results

In September 2006, the National Research Council of Canada (NRC-CNRC) published a report titled *Evaluation of Falcon 20 Turbojet and DHC-8 Series 100 and 400 Turbopropeller Aircraft Safety Margins for Landings on Wet Runway Surfaces* (Ref. 24). This report concludes that

> An analysis of Falcon 20 landing distances, using the braking coefficients obtained during the tests on wet surfaces, indicates that the current operational dispatch factor of 1.92 for turbojet aircraft does not provide an adequate safety margin for landings on wet runways, particularly those with low texture or rubber contamination. A similar analysis for the DHC-8-100 and DHC-8-400 aircraft indicates that the current operational dispatch factor of 1.43 for turbopropeller aircraft does not provide an adequate safety margin for landings on wet runways. These conclusions are identical to those made in a separate statistical study done by Transport Canada.[25]

The testing described in Ref. 24 included CFME measurements (with two SFT devices) of the runways involved. Reference 21 compares the μ_B computed from these measurements (per the CMB model) to the actual μ_B documented in the flight test reports. The results of these comparisons are summarized here.

The Falcon 20 tests are documented in Ref. 27, which concludes that the achieved μ_B "essentially overlays the ESDU 50% efficiency level for values of [μ_B] between about 30 knots and 120 knots, and is well below the certification requirement of 80% efficiency for a fully modulating anti-skid braking system." Hence, the flight tests indicate that, assuming the §25.109(c) μ_{max}, η_{AS} = 0.50 for the Falcon 20 tests. Equivalently, for these tests, k_B = 0.50 in the CMB model. We now seek to determine the k_B that would be predicted by the CMB model from the SFT measurements on the test runway.

Reference 27 indicates that the SFT μ achieved on the test runway was 0.54. The tire pressure p of the Falcon 20 is 136 psi (Ref. 27, p. 8). With this value of airplane p, and the CFME p and μ_{cd} for the SFT (30 psi and 1.1, respectively), the NASA CFME model predicts that an SFT μ reading of 0.54 at 40 mph represents an airplane μ_B of 0.18 at an airplane V_G of 74 kt.

At V_G = 74 kt. and p = 136 psi, the §25.109(c) μ_{max} is 0.35. From Eq. (22), the resulting k_B for the combined μ_B model is therefore

$$k_B = \frac{\mu_B|_{CFME:40}}{\mu_{max}|_{25.109}} = \frac{0.18}{0.35} = 0.51 \qquad (24)$$

Where $\mu_B|_{CFME:40}$ is the SFT μ measured at the vehicle speed of 40 mph (the only SFT speed used in the tests). The k_B= 0.51 value compares well with the k_B= 0.50 value determined from the flight test data. Since the combined

[24] The EMB-500 involved in the KSGR accident also achieved μ_B values much lower than those predicted by the NASA CFME model for a portion of its ground roll, though the μ_B subsequently increased to levels more consistent with the DFT measurements. The reasons for the lower μ_B are still under investigation.

[25] The Transport Canada statistical study is documented in Refs. 25 and 26.

μ_B model correctly predicts the Falcon 20 actual μ_B based on SFT runs alone, the tests described in Ref. 27 provide additional validation of the combined model (and of the NASA CFME model upon which it is based).

Reference 28 describes the tests conducted with the DHC-8-400 airplane at Montreal Mirabel airport (CYMX), and provides SFT and airplane μ_B data on a run-by-run basis. This information is more detailed than that provided for the Falcon 20, and allows a more thorough check of the NASA CFME and CMB models.

An equivalent way of comparing the CMB model prediction to the actual μ_B achieved is to compare the k_B at each point predicted by the model (computed from Eq. (22)) to the ratio of the actual μ_B to the §25.109(c) μ_{max}. These comparisons are made in Ref. 21; the results are included here as Figs. 26a and 26b. These Figures present, as a function of distance from the CYMX runway 11 threshold, the k_B computed from the actual μ_B (the red lines labeled "Based on airplane test data"), and k_B from the CMB model, based on the SFT runs before and after each airplane test point. Since all the SFT runs were conducted at 40 mph, the k_B was computed using Eq. (24), with $\mu_{max}|_{25.109}$ at each point equal to 0.356, corresponding to a tire p of 134 psi (the DHC-8-400 p cited in Ref. 28) and a V_G of 73.5 kt. (the airplane V_G corresponding to an SFT speed of 40 mph and an airplane p of 134 psi, per the NASA CFME model).

Figures 26a and 26b also note the type of test for each test point (landing or accelerate/stop), the runway used (CYMX runway 11 or 29), and the weather conditions before and after each SFT run. Note that for test points 5.1 and 5.5, only the SFT data for the run taken after the test point is presented; Ref. 28 explains that for these test points, "too much time had elapsed between the SFT runs before the aircraft test and the aircraft test."

Figures 26a and 26b indicate generally good agreement between the k_B computed from the airplane test data, and from the SFT data using the combined μ_B model, for the landing tests. The k_B based on the airplane data is lower than that based on the SFT data at the higher groundspeeds for test points 4.1 and 4.2 (nearer the runway threshold), indicating worse braking performance than that predicted by the combined μ_B model (this may be due to water depths in the neighborhood of 3 mm, as discussed in Ref. 28). For test point 4.1, the k_B lines based on the SFT runs are initially slightly higher than that based on the airplane data, but then bracket the airplane-based k_B for the majority of the length of the runway. For test point 4.2, the SFT-based k_B again is initially higher than the airplane-based result, but then shows slightly worse performance (though the black line based on the SFT run performed before the airplane test matches the airplane-based data fairly well). The degraded performance shown by the blue line for the SFT run after the airplane test may be due to the heavier rain and increased water depths during that run.

For the accelerate-stop tests, Figures 26a and 26b show that the actual braking performance is consistently worse than that predicted by the combined μ_B model, though the difference diminishes at lower groundspeeds (for test point 5.2, the solutions are essentially the same by the end of the test). The SFT-based k_B remains relatively constant at about 0.5, whereas the airplane-based data for test points 5.5 and 5.7 peak at about 0.40 to 0.45, or 10% to 20% lower. However, it should be noted that the CMB model approximates the actual performance much better than the §25.109(c) model, for which k_B = 0.8 constant. The actual maximum k_B of 0.40 to 0.45 is 43% to 50% lower.

VII. NTSB recommendations and FAA actions

This section discusses NTSB recommendations and FAA actions relevant to wet-runway stopping performance. The recommendations and actions focus on:

- The operational practice of re-evaluating the landing distance required when conditions at arrival have deteriorated from the assumed dispatch conditions (en-route landing distance assessments); and
- The development of reliable data with which to perform these landing distance assessments.

A. NTSB recommendations A-07-057, A-07-061 and A-11-029

As a result of its investigation of the Southwest Airlines landing overrun accident involving a Boeing 737-700 at Chicago Midway Airport (KMDW) in December 2005,[26] the NTSB issued two recommendations concerning landing distance assessments to the FAA:

> Immediately require all 14 *Code of Federal Regulations* Part 121, 135, and 91 subpart K operators to conduct arrival landing distance assessments before every landing based on existing performance data, actual conditions, and incorporating a minimum safety margin of 15 percent. (A-07-057) Urgent (Supersedes Safety Recommendation A-06-016 and classified "Open—Unacceptable Response").

[26] This a different event than the SW1919 event discussed above.

> Require all 14 *Code of Federal Regulations* Part 121, 135, and 91 subpart K operators to accomplish arrival landing distance assessments before every landing based on a standardized methodology involving approved performance data, actual arrival conditions, a means of correlating the airplane's braking ability with runway surface conditions using the most conservative interpretation available, and including a minimum safety margin of 15 percent. (A-07-061)

Recommendations A-07-057 and A-07-061 differ in that A-07-057 recommends that landing distance assessments be required *immediately* using existing performance data, while A-07-061 recommends that landing distance assessments be *eventually* required based on a "standardized methodology" that would have to be developed. Both recommendations include a minimum 15% safety margin.

The history of the correspondence between the NTSB and the FAA regarding these recommendations is documented in Refs. 21, 29, and 30. Recommendation A-06-057 is classified "Closed – Unacceptable Action," because "this urgent safety recommendation was issued as an interim solution because [the NTSB] recognized that the standardized methodology recommended in Safety Recommendation A-07-61 would take time to develop; however, to date, the FAA's actions have not been responsive" (Ref. 29). Recommendation A-06-061 is currently classified "Open – Unacceptable Response," because the FAA indicated that it would seek to fulfill the intent of the recommendation through voluntary guidance, as opposed to regulation, and the NTSB does "not believe that non-regulatory guidance is effective; therefore, [the NTSB does] not consider such action to be an acceptable response" (Ref. 30).

One of the recommendations issued by the NTSB as a result of the KOWA accident was A-11-029, to the FAA:

> Inform operators of airplanes that have wet runway landing distance data based on the British Civil Air Regulations Reference Wet Hard Surface or Advisory Material Joint 25X1591 that the data contained in the Aircraft Flight Manuals (and/or performance supplemental materials) may underestimate the landing distance required to land on wet, ungrooved runways and work with industry to provide guidance to these operators on how to conduct landing distance assessments when landing on such runways. (A-11-029)

A-11-029 is currently classified "Open – Unacceptable Response." The correspondence between the NTSB and the FAA concerning this recommendation is documented in Ref. 36 and summarized in Table 4. Note that the disagreement between the FAA and NTSB reflected in the correspondence mainly concerns the water depth on the runway, and whether the runway could have supported dynamic hydroplaning. The NTSB conclusion that the runway could not have been flooded (and that dynamic hydroplaning was not possible) is based on the TTI model described above (see Fig. 13).

Also note that the witness reports of a "rooster tail" of water behind the airplane, which the FAA takes as evidence of a flooded runway and hydroplaning, is in fact evidence of the opposite. As described above, in dynamic hydroplaning conditions, the tires would lose contact with the runway and spin down, reducing the spray behind the airplane. Because of this phenomenon, rooter tails are evidence *against* hydroplaning.

As shown in Fig. 12, in the KOWA accident the NASA CFME μ_B model matched the computed airplane performance, while the AFM data overestimated the performance.

Date From/To	Summary of actions re: A-11-029	Status
03/29/2011 NTSB/FAA	Original recommendation transmittal letter, issued after the conclusion of the KOWA investigation.	Open- Await Response
06/10/2011 FAA/NTSB	FAA is reviewing the *Aircraft Performance Study* [Ref. 10] and other reports for this accident, and plans to evaluate which airplanes base wet runway landing distance on AMJ 25X1591. Following the reviews, the FAA will determine how best to address the recommendation.	Open- Await Response
09/06/2011 NTSB/FAA	NTSB acknowledges; pending completion of recommended action classifies A-11-026 Open – Acceptable Response.	Open- Acceptable Response
08/21/2012 FAA/NTSB	FAA believes BAe 125-800A wet runway AFM data correct, because validated by flight tests in Hatfield, UK, and as evidenced by successful operation of the airplane for 50 years. FAA notes that the *Performance Study Addendum* indicates that while the limited information for the accident introduces elements of uncertainty in the analysis, the stopping performance was most consistent with the AFM data for a flooded runway. FAA points to a picture of a puddle in a parking lot a mile from the accident, the fact that there were thunderstorms in the area, and to witness reports of a "rooster tail" of water behind the airplane to reject the *Study* conclusion that the runway could not have been flooded. FAA did its own stopping calculations and also found that the AFM data for a flooded runway best fit the accident scenario, supporting the conclusion that the runway must indeed have been flooded. FAA concludes that there are too many uncertainties in the accident to justify questioning the AFM data, and states that more testing would be required to make the case that the distances are underestimated. FAA material, including the Airman's Information Manual and SAFO 09015, advise pilots how to evaluate landing on "less than ideal runway conditions," including wet runways. FAA considers its actions complete.	Open- Acceptable Response
11/13/2012 NTSB/FAA	NTSB and FAA agree that the airplane performance is most consistent with the AFM data for a flooded runway, and dynamic hydroplaning. Hence, whether or not the runway was flooded, leading to dynamic hydroplaning, is key to this recommendation. The *Addendum* examined this question, and rather than relying on a picture of a parking lot taken a mile from the runway, relied on measurements of the runway cross slope, macrotexture, and recorded rainfall rate, together with a model for runway drainage provided by the Texas Transportation Institute (TTI) to compute the likely depth of water on the runway. The maximum TTI water depth was only about 1 mm, significantly less than the 3 mm of water necessary for hydroplaning. Further, per a NASA expert, "rooster tails" are evidence *against* hydroplaning, because they indicate spinning tires in contact with the runway. Further, the *Addendum* indicates that the AMJ 25X1591 wet runway μ_B are substantially higher than those of the TALPA ARC's recommendations, which are based on § 25.109. NTSB agrees that more testing is needed; however, the FAA does not plan to perform testing, or otherwise to address the safety problem documented in the *Addendum*. NTSB asks the FAA to reconsider; in the meantime, A-11-029 is classified OPEN—UNACCEPTABLE RESPONSE. Mounting evidence suggests that the §25.109 standard may not be representative, and consequently NTSB may issue more recommendations.	Open- Unacceptable Response

Table 4. Summary of NTSB/FAA correspondence re: A-11-029. For full correspondence, see Ref. 36.

B. FAA actions, part 1: SAFO 06012, TALPA ARC recommendations, and Advisory Circular 25-32

Following the 2005 Southwest Airlines landing overrun accident at KMDW, the FAA performed an internal audit of regulations and guidance information concerning landing distance requirements, and on August 31, 2006 issued Safety Alert For Operators (SAFO) 06012, titled *Landing Performance Assessments at Time of Arrival (Turbojets)* (Ref. 31). While a SAFO is not regulatory, it "contains important safety information and may include recommended action. SAFO content should be especially valuable to air carriers in meeting their statutory duty to provide service with the highest possible degree of safety in the public interest." SAFO 06012

> urgently recommends that operators of turbojet airplanes develop procedures for flightcrews to assess landing performance based on conditions actually existing at time of arrival, as distinct from conditions presumed at time of dispatch. Those conditions include weather, runway conditions, the airplane's weight, and braking systems to be used. Once the actual landing distance is determined an additional safety margin of at least 15% should be added to that distance. Except under emergency conditions flightcrews should not attempt to land on runways that do not meet the assessment criteria and safety margins as specified in this SAFO.

The SAFO also notes that "the FAA has undertaken rulemaking that would explicitly require the practice described above."

In October 2007, FAA order 1110.149 established the "Takeoff/Landing Performance Assessment Aviation Rulemaking Committee" (TALPA ARC). According to the order, the objectives and scope of the TALPA ARC were to

> … provide a forum for the U.S. aviation community to discuss the landing performance assessment methods provided in SAFO 06012. Additionally, takeoff performance for contaminated runway operations and issues relevant to part 139, Certification of Airports, will be discussed. These discussions will be focused on turbine powered aircraft including both turbojet and turboprop airplanes operated under parts 121, 135, 125, and 91 subpart K.

In addition, the TALPA ARC "will provide advice and recommendations to the Associate Administrator for Aviation Safety. The committee will act solely in an advisory capacity."

The TALPA ARC presented landing performance recommendations to the FAA in April, 2009 (see Ref. 21 for a detailed discussion of these recommendations). The regulatory changes proposed by the TALPA ARC would codify many of the provisions of SAFO 06012, and introduce a new "Runway Condition and Braking Action Reports" table that would provide a mapping between a six-level runway "code" and corresponding runway contaminant type and depth, Continuous Friction Measuring Equipment (CFME) measured friction coefficient values, airplane wheel braking coefficient values, and pilot braking action reports. The runway codes range from "6," for a dry runway, to "0," for runways contaminated with various forms of wet ice, and for which braking action is "minimal to non-existent." Aircraft manufacturers would have to supply data from which "operational" landing distances could be calculated for runway codes 6 through 1; operations would be prohibited on code "0" runways. The methods and assumptions to be used for generating this data would be specified in new regulations added to 14 CFR Part 25, "airworthiness standards: transport category airplanes." Specifically, the new rules would require that the braking coefficients on wet, ungrooved runways be computed per the method described in 14 CFR §25.109 (see Section III of this paper).

In addition, pilots would be required to perform an en-route landing distance assessment prior to landing. This assessment would "consider the runway surface condition, aircraft landing configuration, and meteorological conditions, using approved operational landing performance data in the Airplane Flight Manual supplemented as necessary with other data acceptable to the Administrator." A 15% safety margin would be added to the computed operational landing distance to determine the runway length required for landing.

In its October 28, 2014 letter to the NTSB regarding NTSB safety recommendation A-07-061, the FAA stated that "we are no longer considering rulemaking related to TALPA or regulating performance data" (see Ref. 30). Instead, "as a result of the TALPA ARC recommendations, many document changes will be forth coming," including the incorporation of the information contained in SAFO 06012 into ACs and other documents. The FAA also indicated that it was developing the Runway Condition Assessment Matrix (RCAM) tool:

> The RCAM takes a known assessment criteria provided from the airport and provides the pilot with a downgrade assessment criterion. This downgrade assessment criterion is based on the reported runway conditions, such as the reported runway friction expressed in mu (μ) values and reported braking action. This information will provide the pilot with an expected braking ability to slow or stop the airplane during the landing roll. The RCAM is still under final development … (from FAA 10/28/2014 letter).

The RCAM is the outgrowth of the “Runway Condition and Braking Action Reports” table proposed by the TALPA ARC. The current version of the RCAM is contained in Table 2 of AC 25-32, “Landing Performance Data for Time-of-Arrival Landing Performance Assessments” (Ref. 32), and is presented here as Fig. 27. The FAA issued AC 25-32, and a companion AC (AC 25-31, “Takeoff Performance Data for Operations on Contaminated Runways”), on December 22, 2015. As of April 2016, there is no official correspondence between the NTSB and the FAA regarding these ACs and their effect (if any) on NTSB recommendation A-07-061.

Note in Fig. 27 that runway condition code 5 includes a runway surface that is “wet (includes damp ⅛″ (3 mm) depth or less of water),” and is associated with a pilot-reported braking action of “good.” This runway surface condition would describe the runways associated with the overrun events described in this paper, in the absence of pilot braking reports. The surface condition also describes the KMDW runway in the SW1919 event, although in that case, the previous Southwest crew reported a braking action of “fair” (which translates to “medium” in the RCAM), and so the associated runway condition code would be 3, corresponding to a “wet (‘Slippery When Wet’)” runway.

A flooded runway (i.e., greater than 1/8 inch (3 mm) of water), on which dynamic hydroplaning is possible, is an RCAM code 2, and is similar to the AMC 25.1591 flooded runway model given in Eq. (17).

For a code 5 runway, Figure 33 indicates that the μ_B should be computed “per [the] method defined in §25.109(c).” For the code 3 runway, the μ_B should be a constant 0.16.

A practical operational difficulty with the “slippery when wet” designation is determining whether a wet (but not flooded) runway corresponds to condition code 5 or 3, in the absence of a prior CFME test[27] or a current pilot braking report. This difficulty was addressed in the NTSB comments on the draft versions of ACs 25-31 and 25-32 (Ref. 33). The NTSB comments also express concern with the use of the §25.109(c) μ_B model for code 5 runways, given the evidence from multiple events that this model is insufficiently conservative:

> One technical problem that should be addressed within the ACs is their reliance, in part, on the wheel braking coefficient model codified in Section 25.109(c) for wet runway stopping performance calculations. However, the Section 25.109(c) model has never been validated by flight test data. To its credit, the FAA has recognized that the wheel braking coefficient model in Section 25.109(c) might be insufficiently conservative, as evidenced by the recent FAA Aviation Rulemaking Advisory Committee (ARAC) tasked to provide recommendations regarding new or updated standards for airplane performance and handling qualities. Under the subject area of Takeoff and Landing Performance, subtask (b) addresses wet runway stopping performance ….
>
> The NTSB encourages the FAA to perform flight tests on representative domestic and international runways that support turbine-powered airplane operations in order to validate the wet-ungrooved and wet-grooved wheel braking coefficient models in Section 25.109(c). The NTSB believes that issuing these draft ACs relying on the untested and potentially insufficiently conservative models in Section 25.109(c) is premature. The suggested ARAC flight test validation work should be used to update the wheel braking coefficients appropriate for wet runway operations.
>
> Another technical problem within the ACs arises for certain runway surface conditions characterized as Wet. The ACs define a Wet runway surface condition with good braking action and a wheel braking coefficient calculated by the method in Section 25.109(c), as well as a Wet (“Slippery When Wet”) runway surface condition with medium braking action and a wheel braking coefficient of 0.16. Designating a runway as “Slippery When Wet” requires that it be tested using a calibrated Continuous Friction Measuring Equipment (CFME) device, and the resulting friction coefficient found to be below some threshold value. However, because the wet runway friction coefficients specified in Section 25.109(c) have never been validated by flight test, the association of these coefficients with airplane stopping performance capability on runways with CFME friction measurements above a target threshold is unproven. Furthermore, many international runways and smaller domestic runways that support turbojet operations will not have a friction maintenance program, and might therefore not get tested. The NTSB believes that untested runways should be designated as “Slippery When Wet” until and unless (1) the runways have been tested and shown to meet the minimum CFME friction coefficient threshold, and (2) the CFME measurements have been shown to correlate to a minimum wheel braking coefficient developed by airplanes on wet runways deemed to be adequately maintained. This procedure would result in more conservative estimates of airplane stopping distance required on runways with undocumented friction characteristics until a proper CFME friction survey could be conducted and the results could be reliably correlated to airplane stopping performance.

The FAA’s response to these comments are contained in Ref. 34, as follows:

> The FAA tasked an ARAC working group to investigate wet runway issues.
>
> The FAA will react to the recommendations of this body when they have been formulated. However, we do not agree with delaying the implementation the TALPA ARC recommendations until that working group has completed its tasking.

[27] The CFME values used to designate a runway “slippery when wet” are discussed below.

As to the inclusion of "Slippery when Wet," the FAA agrees with many of the NTSB's specific points. However, the TALPA ARC felt, and the FAA concurs, that it is better at a minimum to supply some guidance that has the potential of identifying a worse than nominal wet runway and, therefore, have operators take actions to mitigate the possible worse than expected wheel braking on a wet runway. We recognize the tools to do this are less than optimal and are optimistic the ARAC working group will be able to determine a better course of action for the future.

FAA Flight Standards (AFS-200) has also addressed this topic to some degree in SAFO 15009, dated 8/11/15.

The NTSB comments note the difficulty, in the absence of test data, of identifying the minimum CFME-measured μ required to achieve the μ_B level specified in 25.109(c). The CMB model presented in Section VI is an alternative μ_B model that can more reliably predict the minimum μ_B that can be reasonably expected from a wet runway, even in the absence of CFME data for that particular runway.

Figure 25 suggests that the μ_B that can be expected on many runways will likely be between the μ_B values specified by the RCAM runway condition codes 5 (wet) and 3 (slippery when wet) shown in Fig. 27. AC 25-32 (Ref. 32) defines "slippery when wet" as follows:

A wet runway where the surface friction characteristics would indicate diminished braking action as compared to a normal wet runway.

This definition is less specific than the one that was contained in the draft version of AC 25-32, for which the NTSB provided comments (noted above). The draft version defined a runway as "slippery when wet"

When a friction survey, conducted for pavement evaluation/friction deterioration in accordance with AC 150/5320-12C (or current version), indicates that at least 1,000 consecutive feet (304 meters) of runway length (per test run) does not meet the minimum friction level classification specified in table 3-2 of that AC.

The reason for removing this definition from the final AC 25-32 was because it more properly belonged in Advisory Circulars addressing airport field condition assessments (AC 150/5200-30, specifically).[28] The term "slippery when wet" is currently defined in draft Advisory Circular 150/5200-30D (Ref. 35):

Slippery When Wet Runway

A wet runway where the surface friction characteristics would indicate diminished braking action as compared to a normal wet runway.

Note: Slippery When Wet is only reported when a pavement maintenance evaluation indicates the averaged Mu value on the wet pavement surface is below the Minimum Friction Level classification specified in Table 3-2 of AC 150/5320-12, *Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces*. Some contributing factors that can create this condition include: Rubber buildup, groove failures/wear, pavement macro/micro textures.

Note that this definition is less conservative than that contained in the draft AC 25-32, since it requires that the "averaged Mu value on the wet pavement surface" be below the AC 150/5320-12C MIN LEVEL, while the draft AC 25032 definition only requires the averaged Mu to be below the MIN LEVEL for any consecutive 1000 ft. or more (as opposed to the average over the entire "wet pavement surface"). By either definition, however, AC 150/5320-12C would require that for such a runway "corrective action should be taken immediately after determining the cause(s) of the friction deterioration."

The only runway discussed in this paper that would have met the definition of "slippery when wet" (by either the draft AC 25-32 or draft AC 150/5200-30D definitions), and therefore could have been classified as RCAM code 3, was KMDW runway 13C. Figure 17 shows that for the SFT Lane 2 Run 1 test, the average μ over the run was 0.49, which is below the 0.50 value corresponding to the 40 mph MIN LEVEL for the SFT shown in Fig. 27.[29] The other runways discussed above would be classified as RCAM code 5, implying that the μ_B that could have been achieved on these runways is that defined by the §25.109(c) model. However, as shown in Fig. 25 and discussed above, the actual μ_B achieved in each case was well below the §25.109(c) level.

[28] Per telephone conversations between NTSB and FAA staff.

[29] For the μ_B calculation based on the KMDW SFT measurements shown in Figs. 16 and 25, the SFT μ in the first 3000 ft. was used (assumed to average about 0.54).

C. FAA actions, part 2: TAPHC ARAC Task 2b, and SAFO 15009

As discussed above, in December 2015 the FAA issued AC 25-32, which addresses contaminated runway landing performance, and proposes μ_B models for computing landing distances on wet and flooded runways (the §25.109(c) and AMC 25.1591 models, respectively). In parallel, the FAA has recognized that the actual μ_B achieved on some wet runways may be less than that specified in §25.109(c), and that the runway length required to stop on these runways may exceed the lengths specified in some airplane AFMs. Accordingly, the FAA issued SAFO 15009 on August 11, 2015 (Ref. 37), warning operators and pilots that "the advisory data for wet runway landings may not provide a safe stopping margin under all conditions." Furthermore, in March 8, 2013, the FAA assigned an additional task addressing wet runway stopping performance to the Transport Airplane Performance and Handling Characteristics (TAPHC) Aviation Rulemaking Advisory Committee (ARAC). These items are discussed below.

The notice in the *Federal Register* announcing the new tasking assigned to the TAPHC ARAC (Ref. 38) states:

> The FAA tasked ARAC to consider several areas within the airplane performance and handling qualities requirements of the 14 CFR part 25 airworthiness standards and guidance for possible revision. The task includes prioritizing the list of topic areas provided in this notice based on prioritization criteria established by the [Flight Test Harmonization Working Group (FTHWG)]. The prioritization criteria should consider harmonization of regulatory requirements and associated guidance material for airworthiness certification of airplane designs. Recommendations may result in subsequent ARAC taskings for standards recommendations in follow-on phases. ARAC may also recommend additional topics in the general area of airplane performance and handling qualities that are not on the list provided in this notice.
>
> The working group will provide a draft report to ARAC recommending focus areas and work plans to address those areas the FTHWG identified as high priorities for airworthiness standards development relative to new airplane designs. This report will provide the rationale for the priority recommended as well as identify those items for which coordination with other working groups or experts outside the FTHWG may be needed. The report will also include a proposed schedule for accomplishment of the plan, including whether multiple topics can be worked simultaneously. If there is disagreement within the working group, those items should be documented, including the rationale from each party and the reasons for the disagreement. The following subject areas should be considered:
>
> 1. *Fly-by-wire (FBW) Flight Controls*. …
>
> 2. *Takeoff and Landing Performance*. Regulatory requirements and associated guidance material for airworthiness certification in the following areas listed below. (Note: This topic area excludes items addressed by the Takeoff and Landing Performance Assessment Aviation Rulemaking Committee.)
>
> a. Flight test methods used to determine maximum tailwind and crosswind capability. ...
>
> b. Wet runway stopping performance. Recent landing overruns on wet runways have raised questions regarding current wet runway stopping performance requirements and methods. Analyses indicate that the braking coefficient of friction in each case was significantly lower than expected for a wet runway (i.e., lower than the level specified in FAA regulations). Consideration should also be given to the scheduling of landing performance on wet porous friction course and grooved runway surfaces. Recommendations may include the need for additional data gathering, analysis, and possible rulemaking.

The TALPA ARC recommendations include amending Part 25 certification standards to require that the landing distances on wet runways be based on a μ_B computed using the methods defined in §25.109 (see below). Since the ARAC Task 2b is focused on wet-runway μ_B models specifically, it would not seem that the statement in Ref. 38 that "this topic area excludes items addressed by the [TALPA ARC]" is intended to exclude examination of the μ_B models, even though those were addressed by the TALPA ARC. In fact, the ARAC started its review of wet runway stopping performance and associated μ_B models in September, 2015.[30]

In addition to adding the wet runway stopping performance task to the TAPHC ARAC in March 2013, on August 11, 2015 the FAA issued SAFO 15009 concerning "Turbojet Braking Performance on Wet Runways" (see Ref. 37). The SAFO "warns airplane operators and pilots that the advisory data for wet runway landings may not provide a safe stopping margin under all conditions," and states that

> Landing overruns which occur on wet runways typically involve multiple contributing factors such as long touchdown, improper use of deceleration devices, tailwind and less available friction than expected. Several recent runway landing incidents/accidents have raised concerns with wet runway stopping performance assumptions. Analysis of the stopping data from these incidents/accidents indicates the braking coefficient of friction in each case was significantly lower than expected for a wet runway as defined by the Federal Aviation Administration (FAA) in Federal Air Regulation (FAR) 25.109 and Advisory Circular (AC) 25-7C methods. These incidents/accidents occurred on both grooved and un-grooved or non-Porous Friction Course overlay (PFC) runways. The data indicates that applying a 15%

[30] Per telephone conversations between NTSB and FAA staff, November 2015.

safety margin to wet runway time-of-arrival advisory data, as recommended by SAFO 06012, may be inadequate in certain wet runway conditions.

This statement summarizes the findings concerning the six wet-runway overrun events considered in this paper. The SAFO states that there are typically "multiple contributing" factors to wet-runway overruns, only one of which is "less available friction than expected." The other contributors include a long touchdown, tailwind, and "improper use of deceleration devices." Several of these contributors are also present in the overrun events considered here; however, the fact that operational errors occur makes it even more important that the baseline data and safety factors upon which wet-runway landing distances are based be accurate, and that overly optimistic μ_B models be corrected.

SAFO 15009 goes on to say that

> The root cause of the wet runway stopping performance shortfall is not fully understood at this time; however issues that appear to be contributors are runway conditions such as texture (polished or rubber contaminated surfaces), drainage, puddling in wheel tracks and active precipitation. Analysis of this data indicates that 30 to 40 percent of additional stopping distance may be required in certain cases where the runway is very wet, but not flooded.

Based on examinations of the runways involved, rubber contamination, drainage, and puddling in wheel tracks were *not* contributors to the KOWA, MKJP, KMDW, KCXO, or KSGR events, though precipitation was present or recent in each case.[31] As discussed in the preceding sections, the shortfall in μ_B may not be solely the result of a shortfall in μ_{max} (which will decrease as a result of the items listed in the SAFO), but may also result from a lower than assumed η_{AS}. As argued above, the constant η_{AS} = 0.80 specified in §25.109 is likely overly optimistic in light of research and flight test data, and the overrun events themselves.

SAFO 15009 indicates that the FAA agrees with the NTSB's concern expressed in safety recommendation A-11-029 that "data contained in the Aircraft Flight Manuals (and/or performance supplemental materials) may underestimate the landing distance required to land on wet, ungrooved runways," and appears to contradict the FAA's own statement in its last response to this recommendation (in August 2012) that "more testing would be required to make a case that [the] landing distances [in the BAe 125-800A AFM] are underestimated."

SAFO 15009 recommends that

> Directors of safety and directors of operations (Part 121); directors of operations (part 135, and 125), program managers, (Part 91K), and Pilots (Part 91) should take appropriate action within their operation to address the safety concerns with landing performance on wet runways discussed in this SAFO.

The SAFO also suggests some ways of taking "appropriate action" to address the safety concerns, such as "assuming a braking action of medium or fair when computing time-of-arrival landing performance or increasing the factor applied to the wet runway time-of-arrival landing performance data." The wet-runway stopping performance issues discussed in this paper confirm that this is good advice.

VIII. Conclusions

The material in this paper supports a number of observations and conclusions regarding airplane stopping performance on wet runways, and the modeling of μ_B on these runways in particular. These observations and conclusions are outlined below.

A. Need for more conservative μ_B models for computing AFM wet-runway landing distances

The μ_B deficit observed in the events considered in this paper makes the stopping performance of the airplanes involved more consistent with AFM landing distances for runways contaminated with standing water, than for runways that are merely "wet." For this reason, observers may be (understandably) quick to conclude that the runways involved must be more contaminated (contain a greater depth of water) than assumed in the wet runway models underlying the AFM distances. However, examination of the runways involved, including an examination of their macrotexture and cross-slope, do not support a conclusion that the runways could have been flooded given the rainfall rates during the events in question. Furthermore, the μ_B actually achieved in a number of these events *is* consistent with the NASA CFME model for a wet – not flooded – runway. In other words, the NASA CFME model

[31] Based on information in Ref. 15, it is not possible to exclude drainage and puddling problems or rubber deposits on the runway as contributors to the CYOW event, though Ref. 15 excludes the possibility of dynamic hydroplaning in that event.

for a wet runway is more conservative than those underlying the airplane AFMs, and moreover, matches the actual airplane performance achieved during the events better than those underlying the AFMs.

The NASA CFME model is also more conservative than the §25.109(c) model. The analysis presented in Section VI illustrates why: the §25.109(c) model assumes a runway that achieves a friction classification level between the MAINT LEVEL and NEW LEVEL specified in AC 150/5320-12C, while the NASA CFME method relies on actual CFME measurements on the runway – which can be lower than the MAINT LEVEL.

The FAA has recognized the reality of this μ_B deficit, and the need to address it, in several documents and actions. SAFO 15009 warns operators that "the advisory data for wet runway landings may not provide a safe stopping margin under all conditions," and advises them to assume "a braking action of medium or fair when computing time-of-arrival landing performance or [increase] the factor applied to the wet runway time-of-arrival landing performance data." Moreover, the Transport Airplane Performance and Handling Characteristics ARAC was given a new task to address "wet runway stopping performance."

In addition, AC 25-32, *Landing Performance Data for Time-of-Arrival Landing Performance Assessments*, incorporates many of the recommendations of the TALPA ARC, including the RCAM. However, wet (not flooded) runways can either be classified as RCAM code 5 (associated with μ_B levels defined by the §25.109(c) model), or as RCAM code 3 "slippery when wet" (for which μ_B = 0.16 constant). The "slippery when wet" designation applies when the average CFME μ of the runway falls below the AC 150/5320-12C MIN LEVEL – a condition that only one of the runways examined in this paper met. The actual μ_B levels achieved on the other runways was *between* those specified by RCAM codes 5 and 3. Consequently, the RCAM as currently specified in Ref. 32 will likely overestimate the μ_B that can actually be achieved on operational, wet runways.

B. Need for "closed-loop" demonstration of μ_B

This paper notes that for a μ_B model to be correct, the product of μ_{max} and η_{AS} must be correct. The NASA CFME model produces an accurate estimate of μ_B with μ_{max} values that are somewhat higher than those assumed in §25.109(c), and with η_{AS} values that are substantially lower than the 0.80 allowed in §25.109(c) for fully-modulating braking systems (and not considering that manufacturers may choose to "demonstrate" higher values using the torque and wheel-slip methods defined in Ref. 9). The resulting NASA CFME μ_B values are significantly lower than those predicted by §25.109(c), but match the μ_B values actually achieved during the overrun events and the Falcon 20 and DHC-8-400 flight tests relatively well.

Given these results, either the assumption of η_{AS} = 0.80 in §25.109(c) (and the adequacy of the torque and wheel-slip methods for computing higher values of η_{AS}), the μ_{max} specified in §25.109(c) (rooted in the ESDU 71026 models), or both, must be considered suspect. The reduced μ_B documented in the events considered in this paper can be explained by:

- A wet-runway η_{AS} that is significantly less than 80% (even for fully-modulating anti-skid systems);
- A wet-runway μ_{max} that is significantly less than what ESDU 71026 would predict based on the pavement macrotexture and airplane tire p;
- A combination of these factors.

NTSB discussions with staff at airplane and brake system manufacturers indicate that these organizations are very confident that the wet-runway η_{AS} of fully-modulating anti-skid systems is at least 80%, and that the torque and wheel-slip methods outlined in AC 25-7C for demonstrating η_{AS} are valid. These organizations might be skeptical of the suggestion that η_{AS} could be significantly lower than 80%, as it is modeled in the NASA CFME model (see Eqs. (15a) and (15b)). On the other hand, the NASA CFME and ESDU models, reflecting research results, indicate that η_{AS} decreases as μ_{max} decreases, even for fully-modulating systems; this behavior is not reflected in the §25.109(c) model. Furthermore, while §25.109(c) requires a demonstration that the anti-skid braking system operates as expected, there is no requirement to demonstrate that the μ_{max} specified by §25.109(c), when combined with the η_{AS} assumed (or "demonstrated") by the manufacturer, is consistent with the stopping distance actually obtained during flight tests on wet runways.

The μ_{max} available from a wet but non-flooded runway at a given V_G depends on its surface macrotexture and microtexture, as well as the presence of rubber and loose surface deposits, such as sand or grit. ESDU 71026 classifies runway surfaces with regard to macrotexture, but the effect of microtexture is reflected simply in the very large range of possible μ_{max} for a particular runway class (see Ref. 2). Microtexture has a strong influence on μ_{max}, but the research reviewed in this paper does not identify a means for measuring this quantity directly. If the reduced μ_B documented in this paper is the result of fine microtextures on the runway surfaces involved, then this too indicates the inadequacy of the §25.109(c) model, since that model does not account for the range of microtextures that are possible on existing runways.

The combined μ_B model, and the NASA CFME model it employs, avoid the need to quantify the runway macrotexture and microtexture directly because they are rooted in a measurement of μ on the runway in question (via a CFME device), or an assumption of the minimum CFME μ the runway can provide (based on the AC 150/5320-12C friction classification levels and maintenance standards). Factors that act to reduce or increase the CFME μ will affect μ_{max} in a similar way; for example, reductions in macrotexture and microtexture, and greater rubber contamination, all act to reduce both the CFME μ and the runway μ_{max}. Furthermore, AC 150/5320-12C indicates that CFME runs at different speeds can help identify the effects of both macrotexture (from 40 mph runs) and microtexture (from 60 mph runs).

As shown in this paper, the combined μ_B model provides a reliable means for estimating the final airplane μ_B, even when the details of the runway macrotexture, microtexture, and rubber contamination are unknown. Nonetheless, measurements of runway macrotexture, cross-slope, and rubber contamination are always useful, in order to estimate water depths using the TTI model (so as to evaluate the possibility of dynamic hydroplaning), and to help understand the surface condition that produced the CFME measurements. Indeed, if a method for measuring microtexture directly is ever developed, the potential for understanding poor μ_B performance on wet runways will be significantly improved.

As the Transport Airplane Performance and Handling Characteristics ARAC continues its work, the requirement for a "closed-loop" validation of the μ_B models underlying AFM wet-runway landing distances should be seriously considered. This validation would consist of demonstrating that the landing distances computed from the assumed μ_{max} and η_{AS} match the landing distances actually achieved on a wet runway. In particular, the behavior of η_{AS} as μ_{max} decreases should be tested and modeled, so as to correctly predict the performance of the system over a range of CFME runway friction classifications.

C. Range of μ_B levels on wet runways

The runway friction classification levels in AC 150/5320-12C, and the transformation of these levels into airplane μ_B as presented in Section VI, indicate that μ_{max} can vary widely across different runways, and deteriorate over time on any given runway. Consequently, the validation of any μ_B model by flight testing (as advocated above) should also include an evaluation of μ_{max} on the runway used for testing. CFME and macrotexture measurements should be a part of such an evaluation.

CFME measurements converted to μ_{max} using the NASA CFME model, and the actual μ_B attained on the runway (determined using the method outlined in Section II), can be used to determine the actual η_{AS} achieved on that runway. This in turn can be a means of investigating the dependence of η_{AS} on μ_{max}.

In general, the wet runway landing distances published in airplane AFMs are not functions of different CFME friction levels, even though the actual distances required will vary as the slipperiness of the wet runway varies. If a single "slipperiness level" is chosen to be representative of the range of possible wet runways, the REP LEVEL described in Section VI, which lies halfway between the AC 150/5320-12C MAINT LEVEL and MIN LEVEL, would be more appropriate than the level defined by §25.109(c). An "average" friction level is not adequate, since by definition half of the runways would perform below that average. A conservative estimate of μ_B is particularly important for airplanes that do not have thrust reversers, and that therefore depend on effective wheel braking for decelerating from high touchdown speeds.

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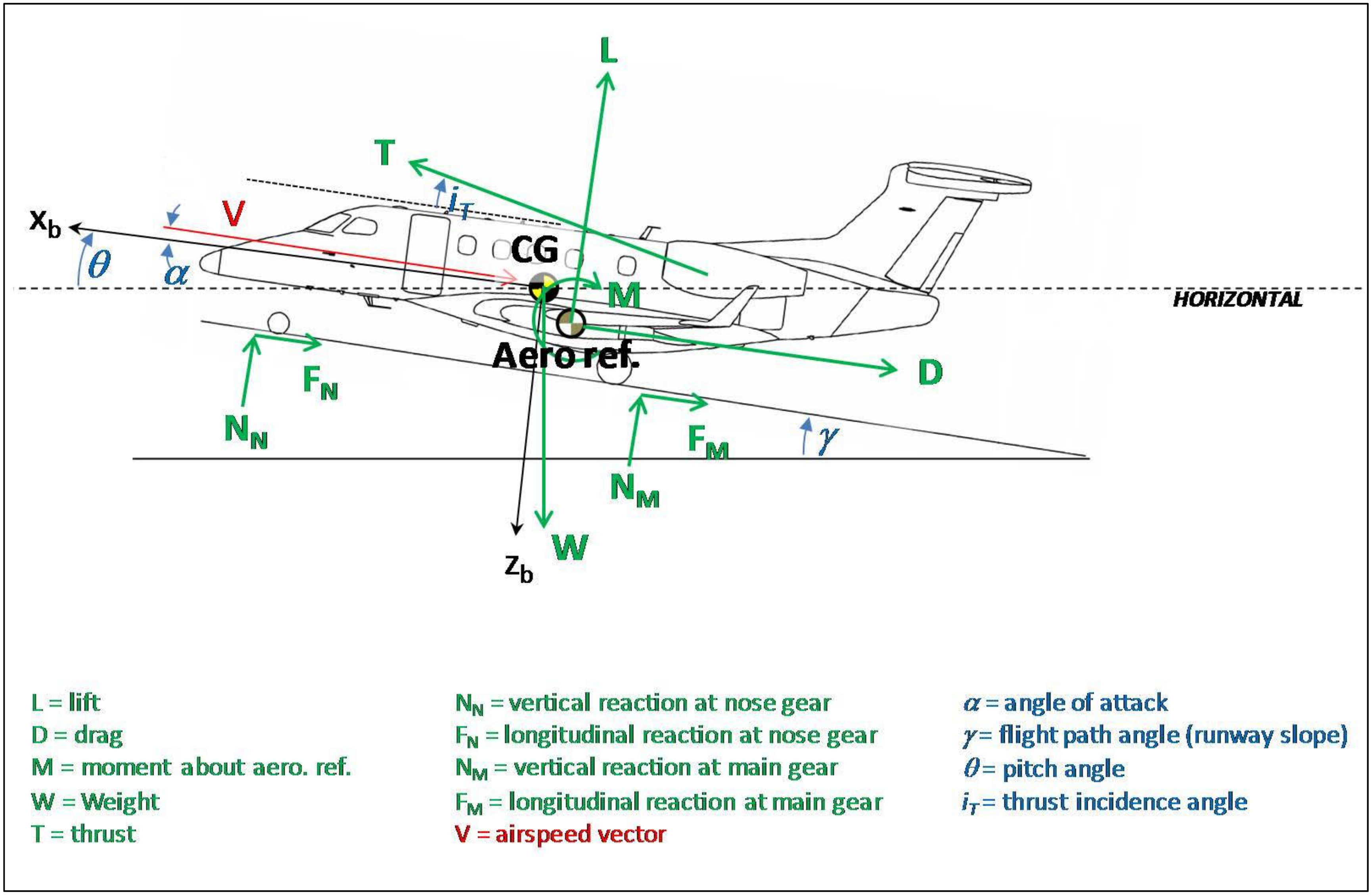

Figure 1. Free body diagram of forces on airplane during ground roll.

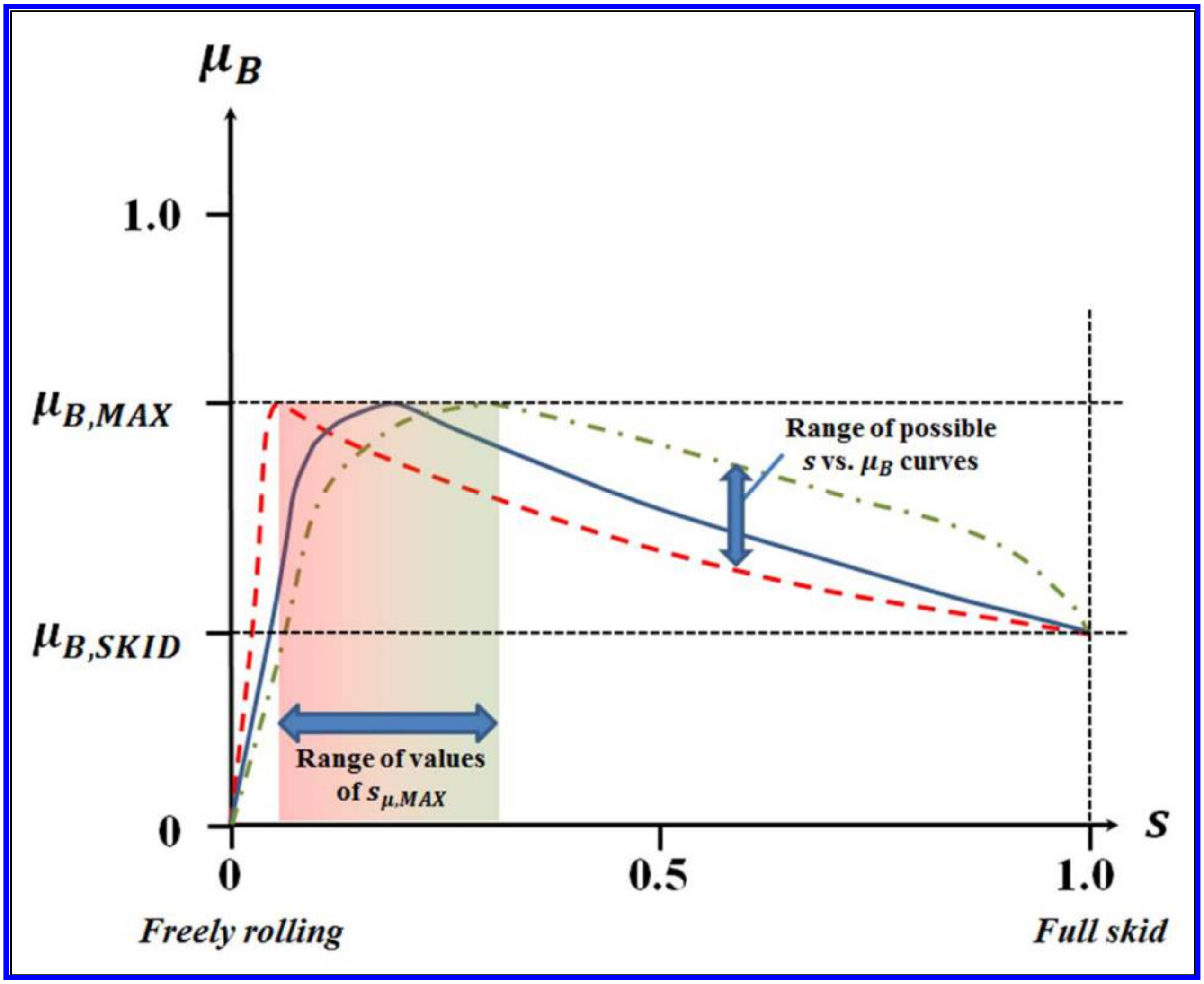

Figure 2. Plot of μ_B vs. s (adapted from Ref. 2).

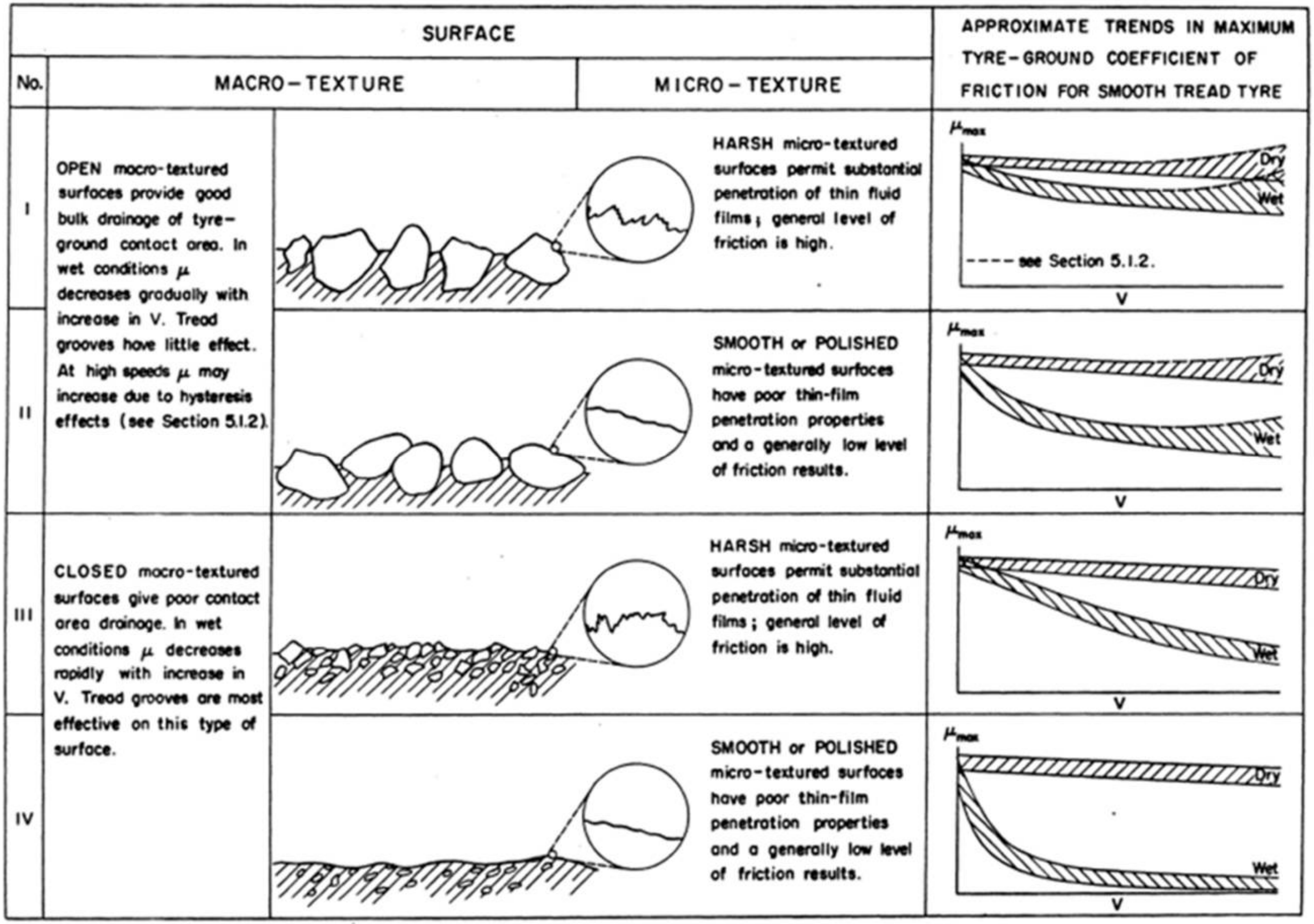

Figure 3. Effect of surface texture on μ_B, from ESDU 71026 (Ref. 2).

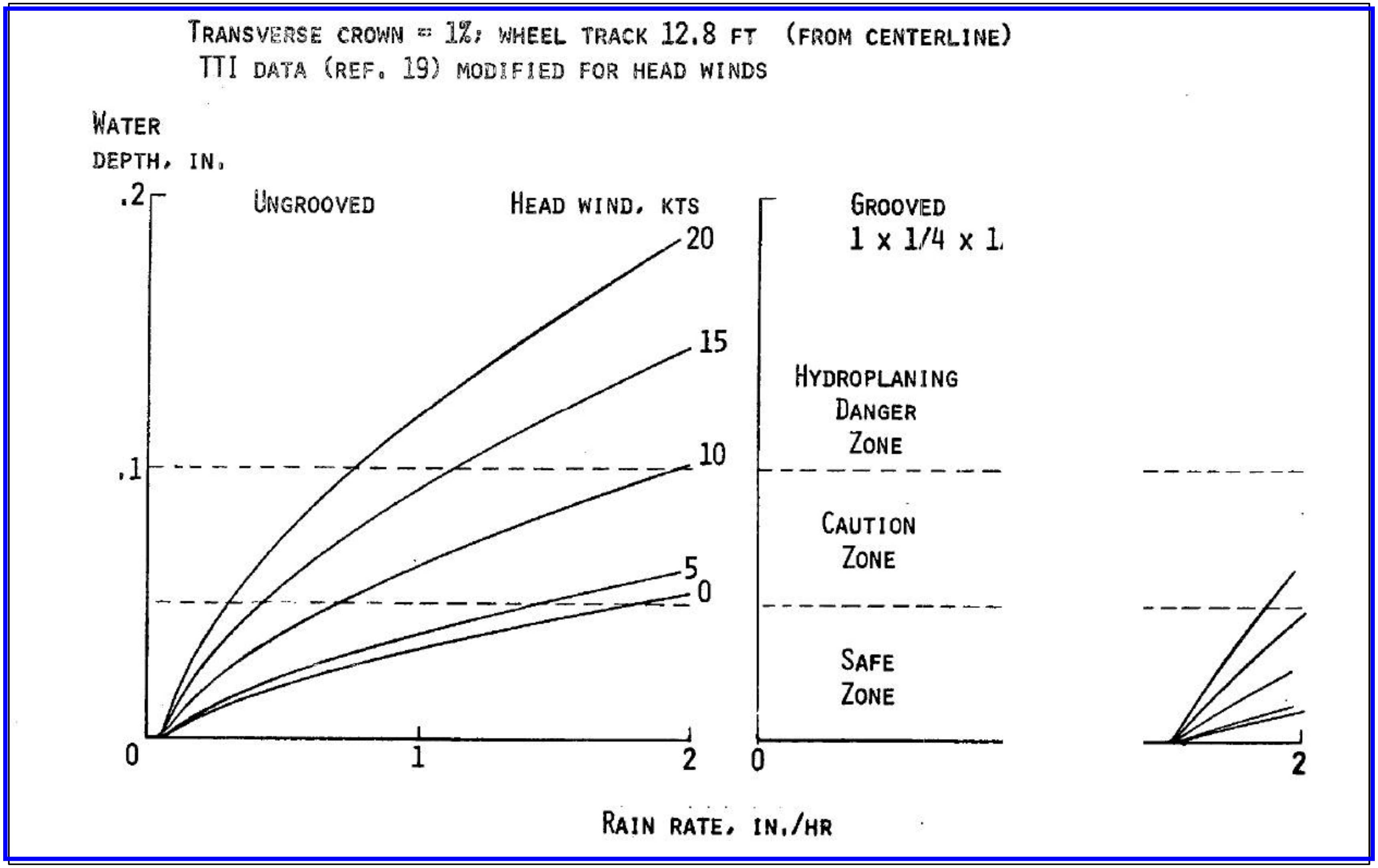

Figure 4. Runway hydroplaning potential during rainstorms, from Ref. 5.

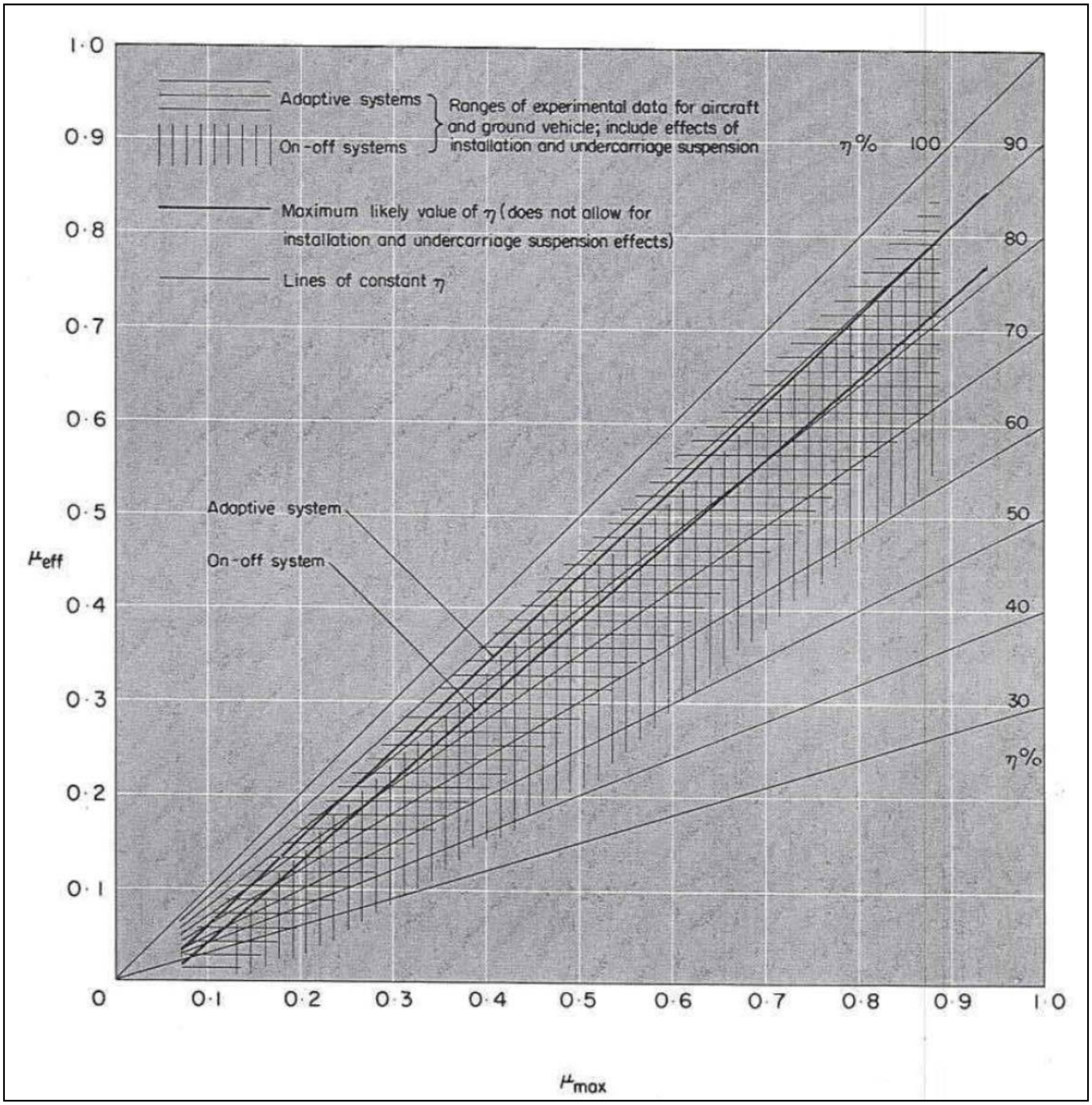

Figure 5. Brake system anti-skid efficiency (η_{AS}), from ESDU 71026 (Ref. 2).

Figure 6. Main wreckage of BAe 125-800A N818MV, Owatonna, MN, 7/31/2008 (see Refs. 10 and 18).

Figure 7. Wreckage of American Airlines flight 331, Kingston, Jamaica, 12/22/2009 (from Ref. 16).

Figure 8. Wreckage of Trans States Airlines flight 8050, Ottawa, Ontario, 06/16/2010 (from Ref. 15).

Figure 9. Security camera still images of Southwest Airlines flight 1919 just prior to exiting the left side near the end of runway 13C at KMDW on 4/26/2011. The view down runway 13C is shown on the left; the view down runway 31C is shown on the right.

Figure 10a. Wreckage of N322QS, Conroe, TX, 9/14/2014 (see Ref. 21).

Left tire Right tire

Figure 10b. Post-accident photos of N322QS main gear tires, showing evidence of reverted-rubber hydroplaning.

Figure 11a. Wreckage of N584JS, Sugar Land, TX, 11/21/2014.

Figure 11b. Post-accident photo of N584JS left main gear tire, showing evidence of reverted-rubber hydroplaning (photo of right tire not available).

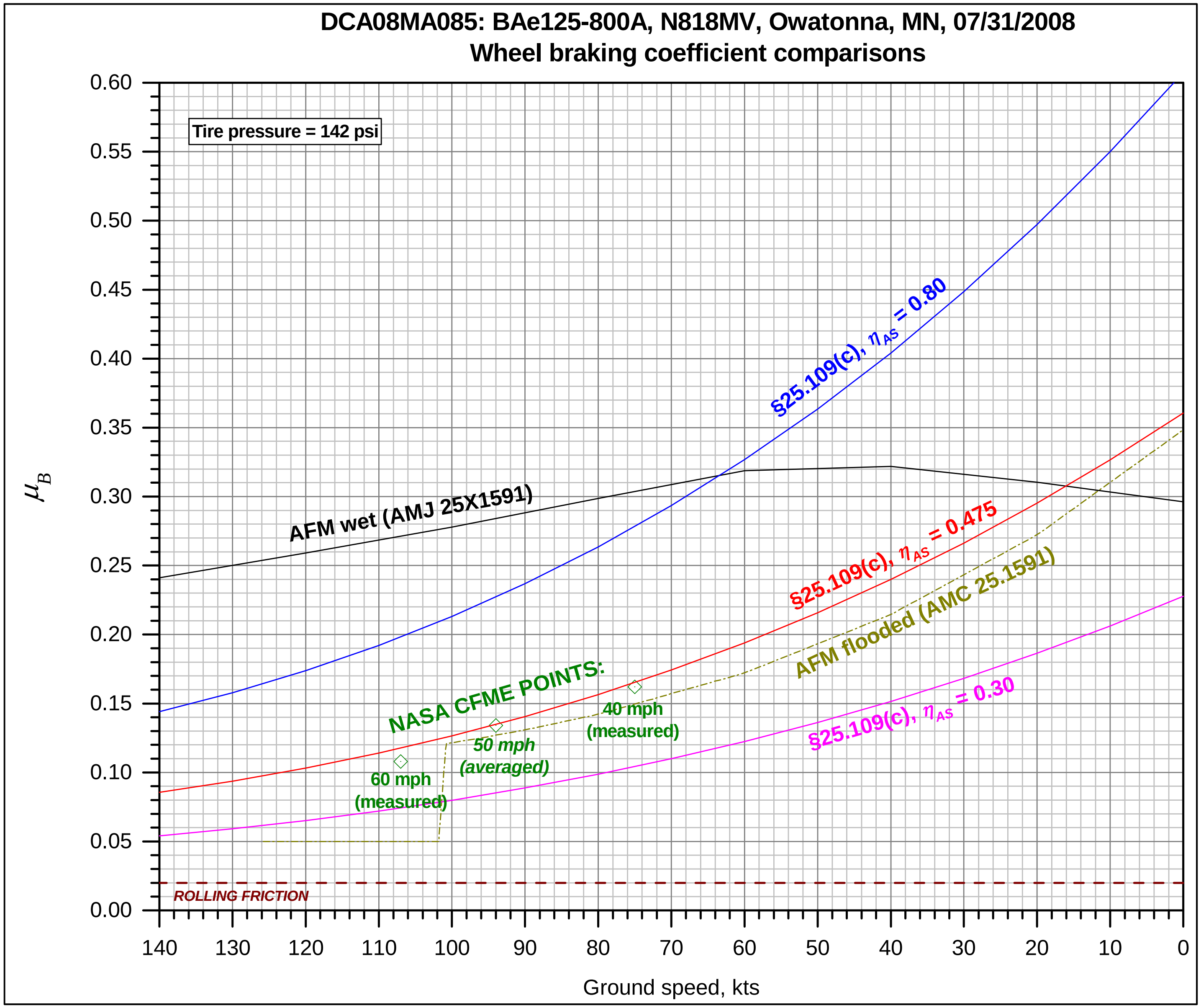

Figure 12. μ_B comparisons for the BAe 125-800A (N818MV) accident in Owatonna, MN, 7/31/2008.

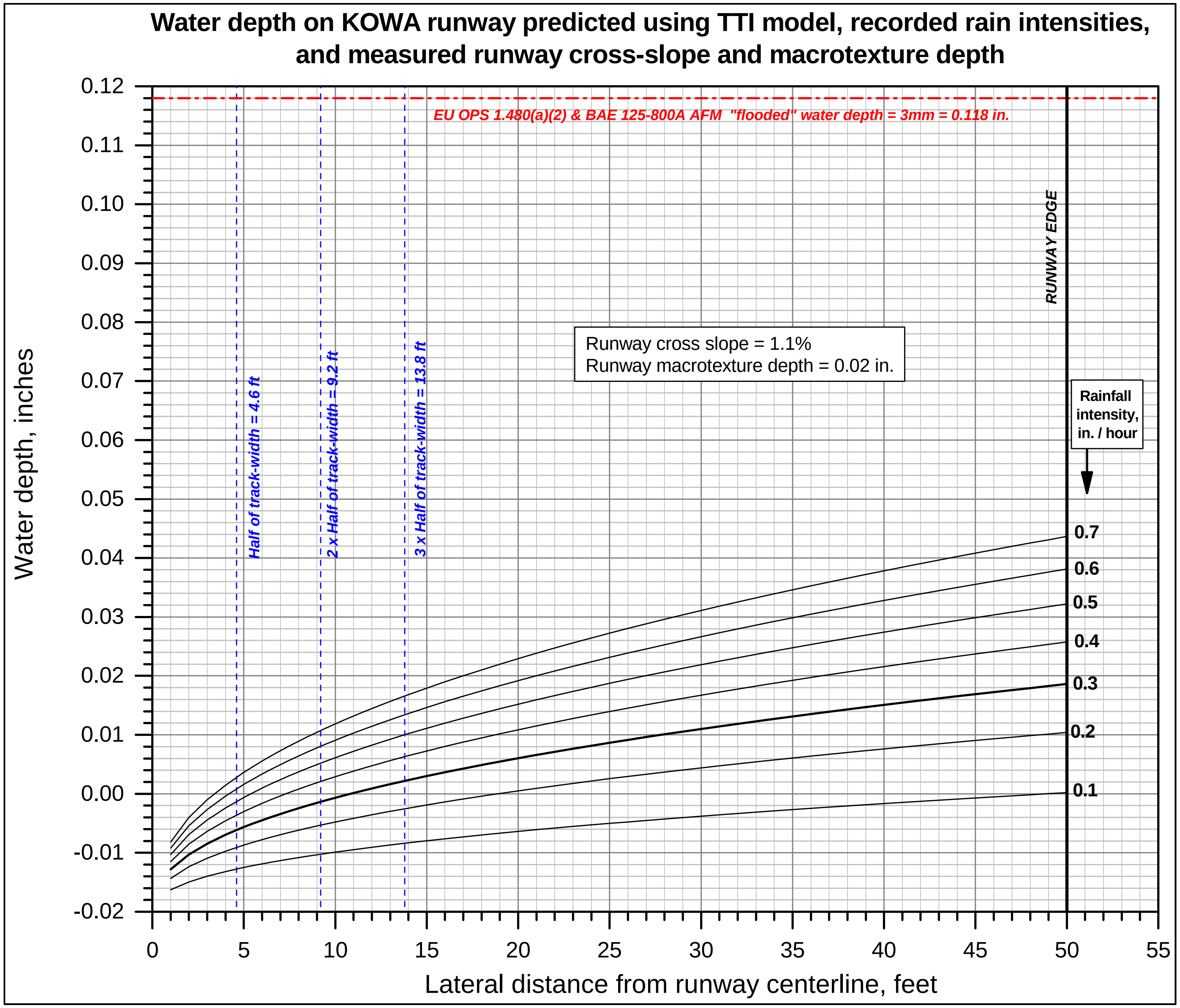

Figure 13. Water depth calculations for the BAe 125-800A (N818MV) accident in Owatonna, MN, 7/31/2008.

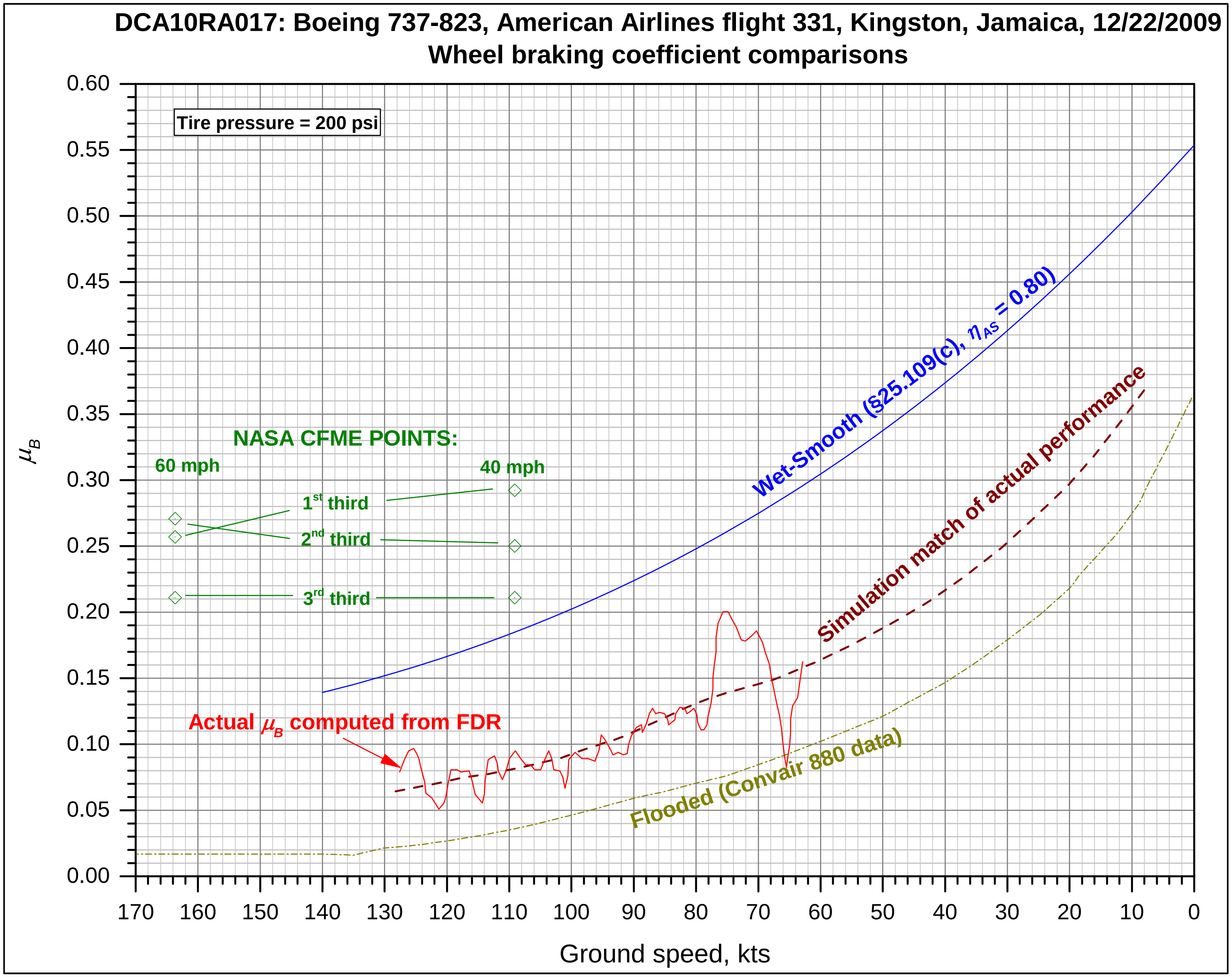

Figure 14. μ_B comparisons for the American Airlines flight 331 accident in Kingston, Jamaica, 12/22/2009.

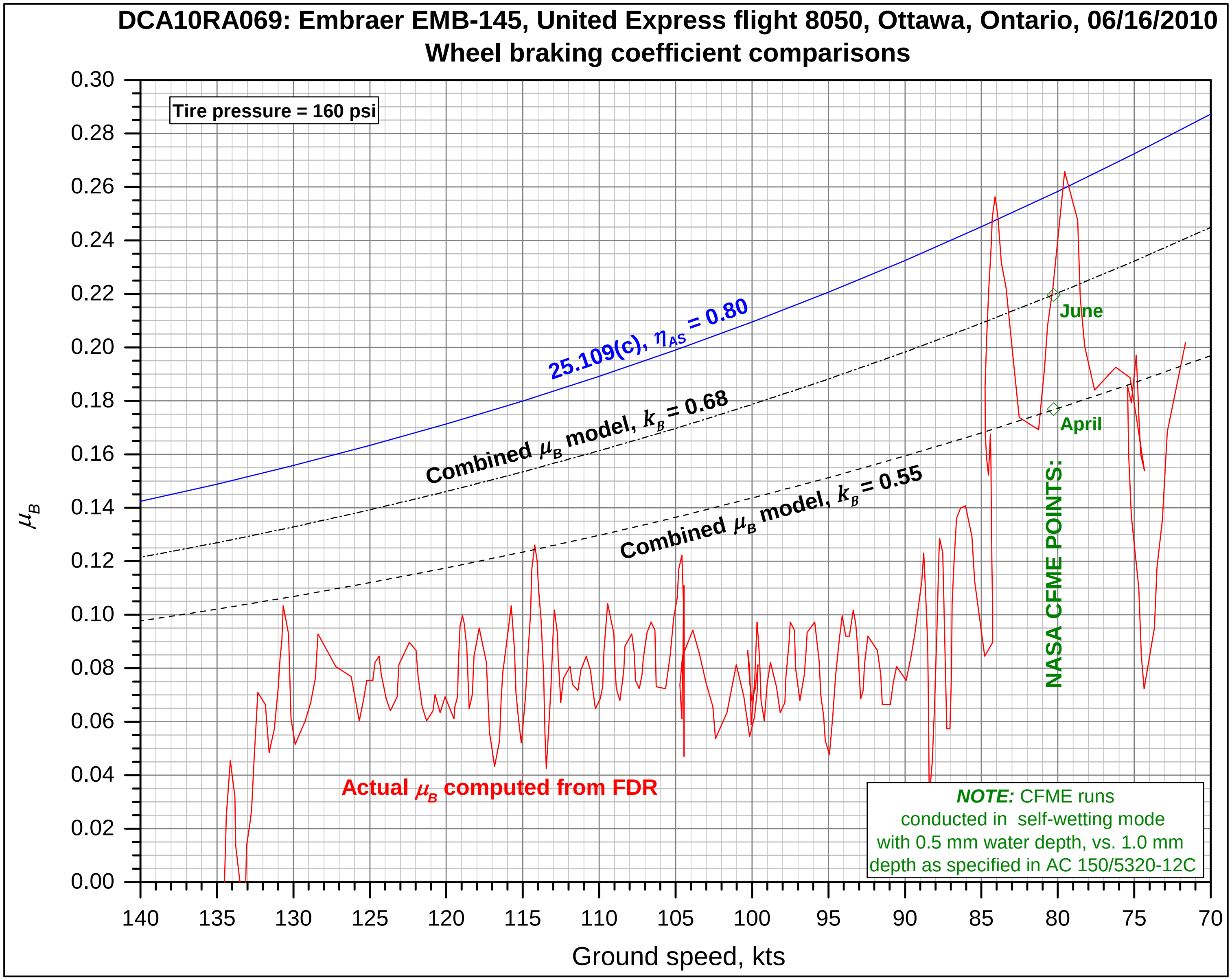

Figure 15. μ_B comparisons for the United Express flight 8050 accident in Ottawa, Ontario, 06/16/2010.

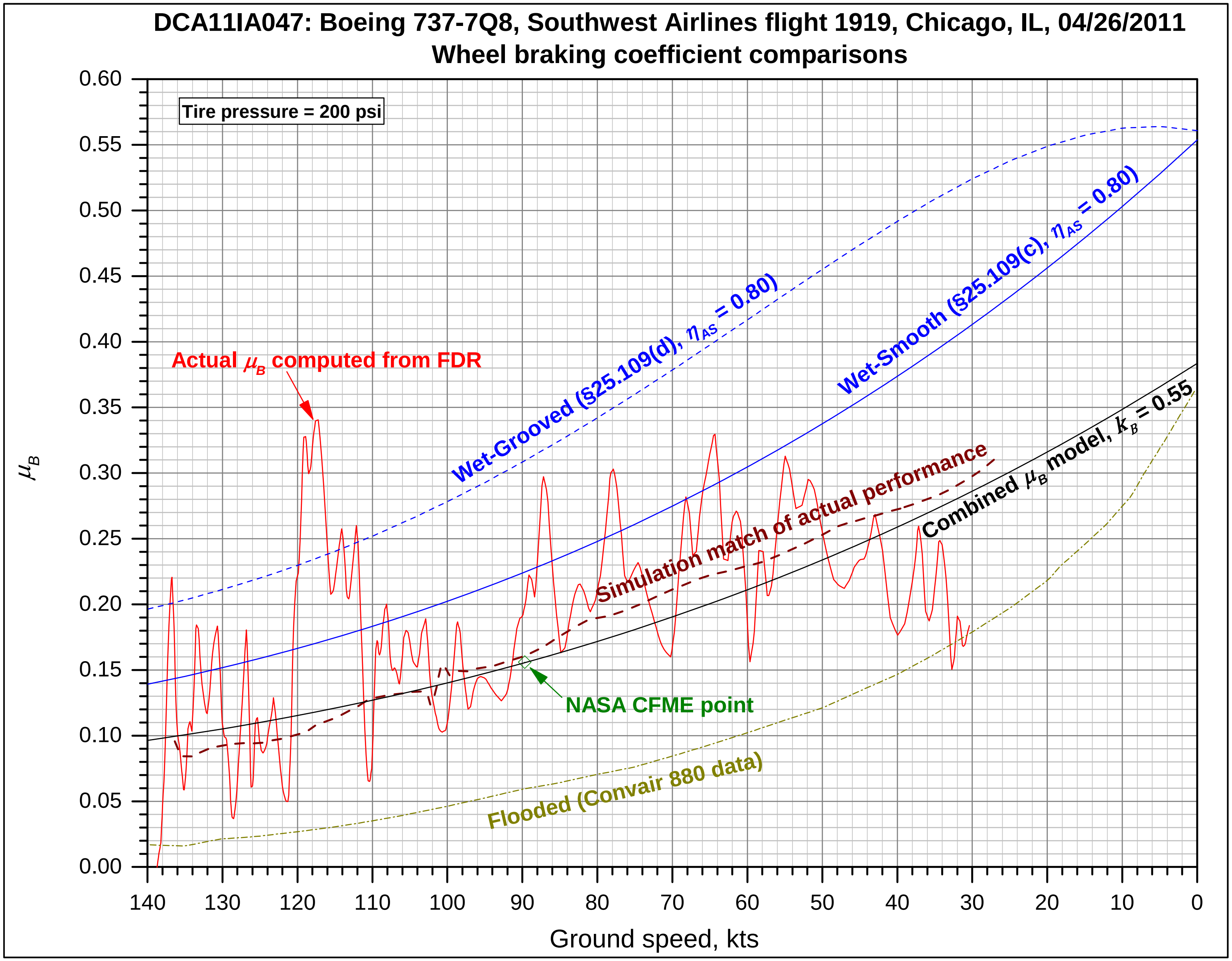

Figure 16. μ_B comparisons for the Southwest Airlines flight 1919 incident in Chicago, IL, 04/26/2011.

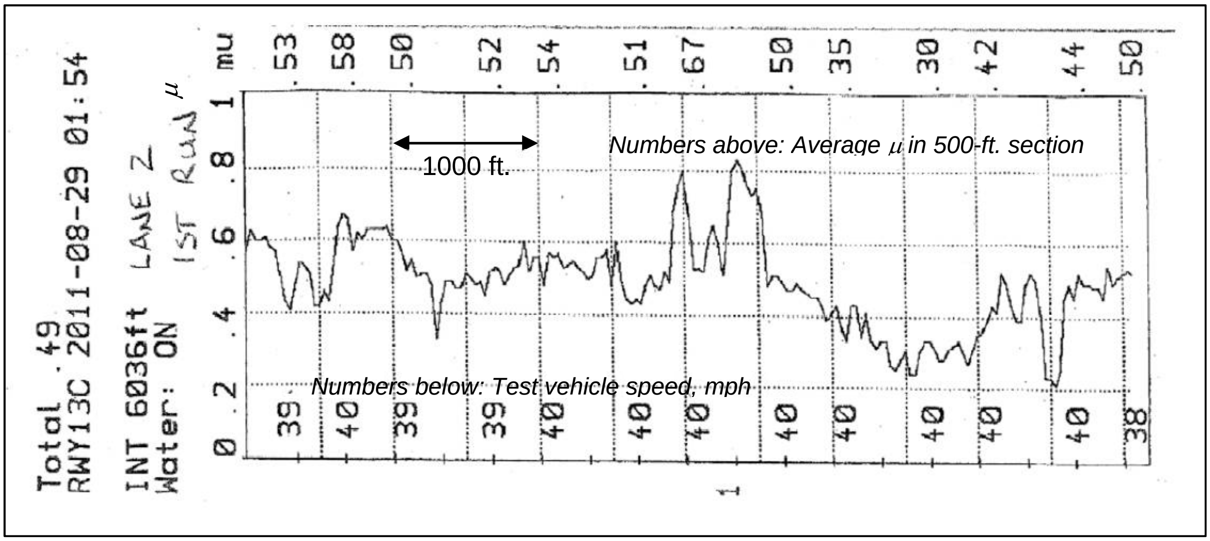

Figure 17a. 40 mph SFT run on KMDW runway 13C, 10 ft. left of centerline (from Ref. 21).

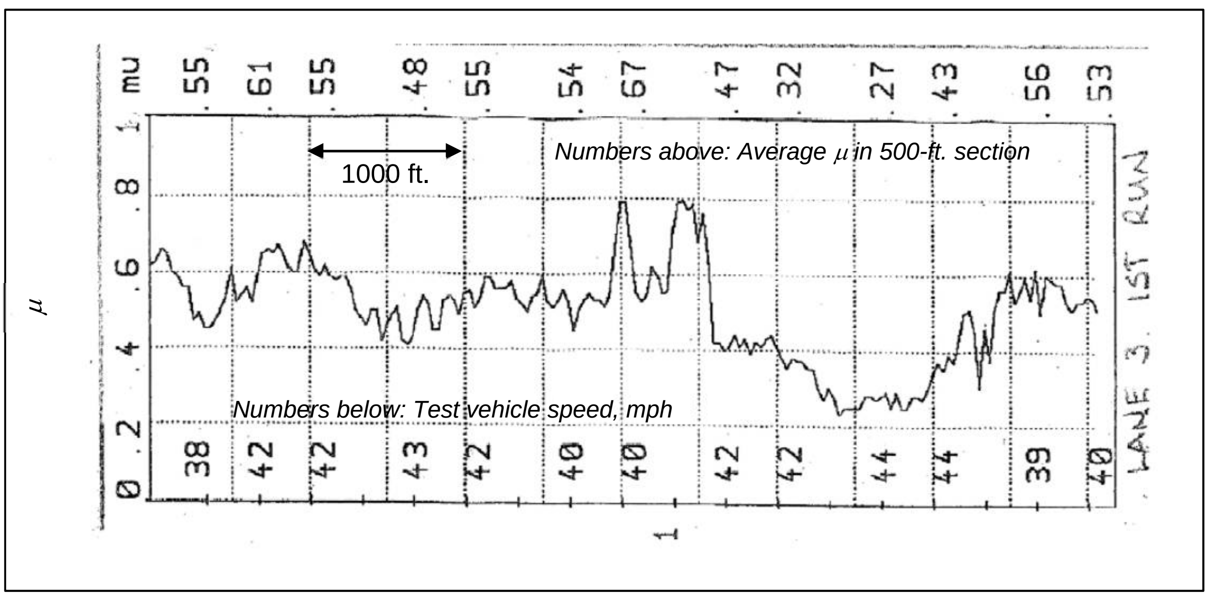

Figure 17b. 40 mph SFT run on KMDW runway 13C, 10 ft. right of centerline (from Ref. 21).

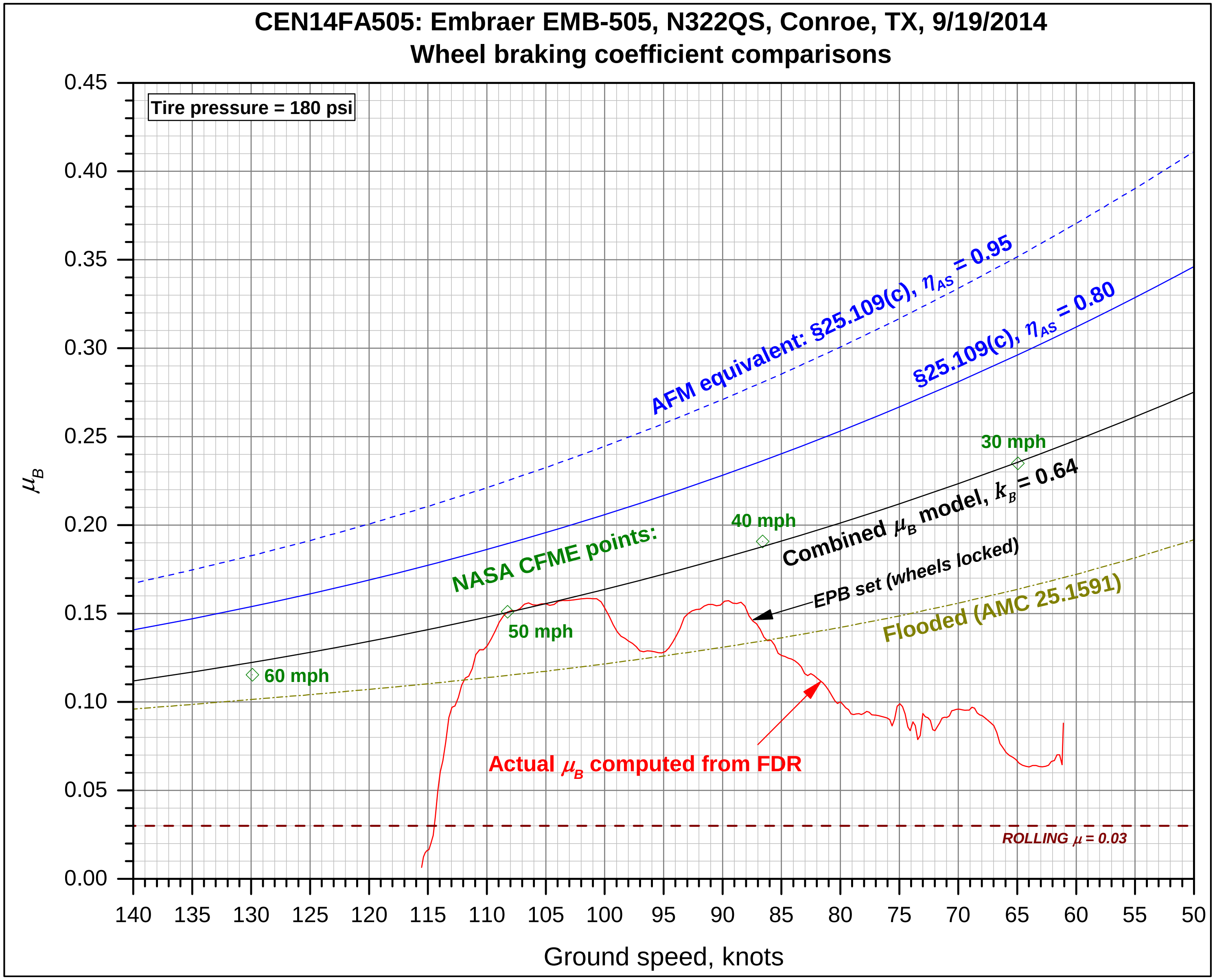

Figure 18. μ_B comparisons for the EMB-505 (N322QS) accident in Conroe, TX, 09/19/2014.

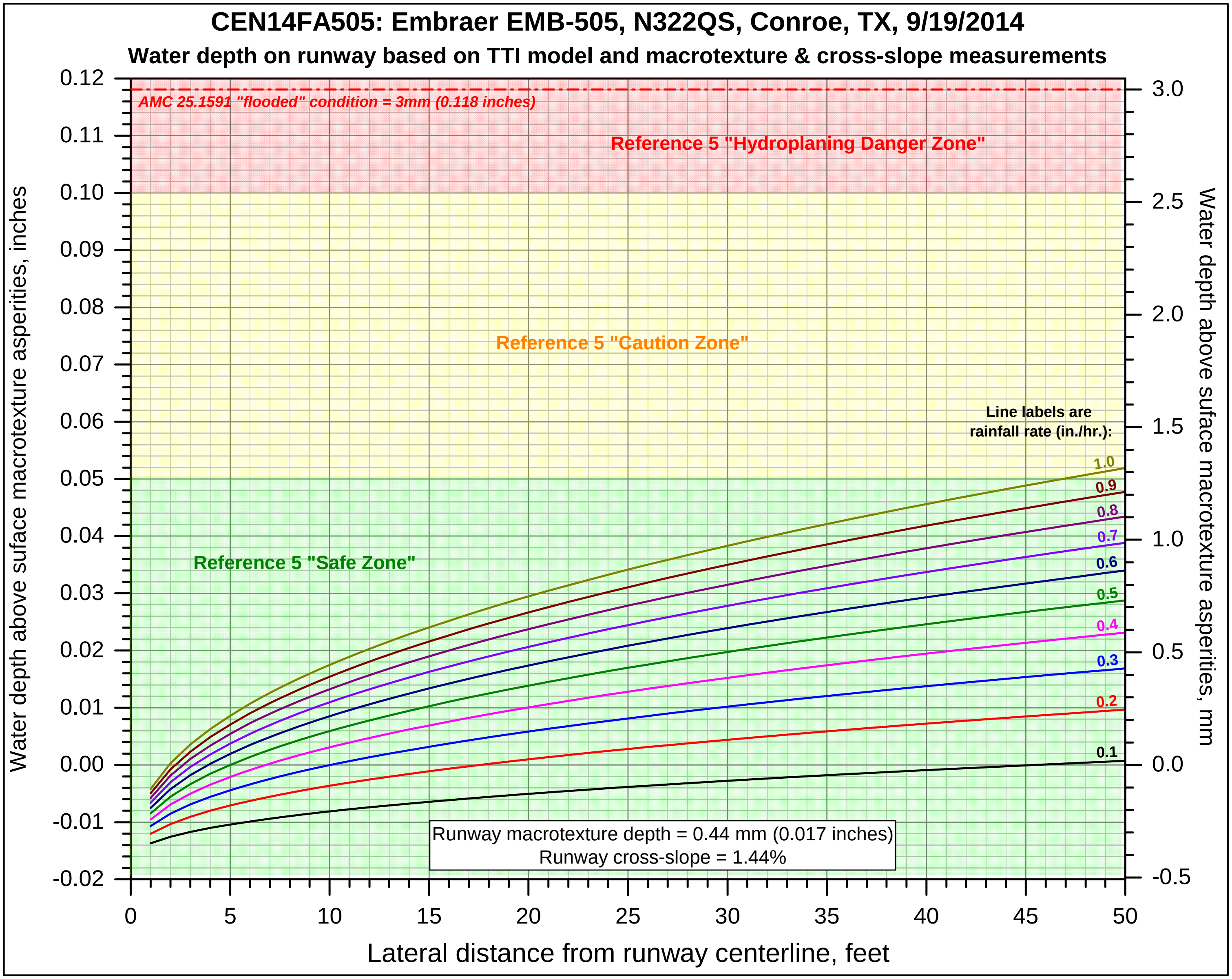

Figure 19. Water depth calculations for the EMB-505 (N332QS) accident in Conroe, TX, 09/19/2014.

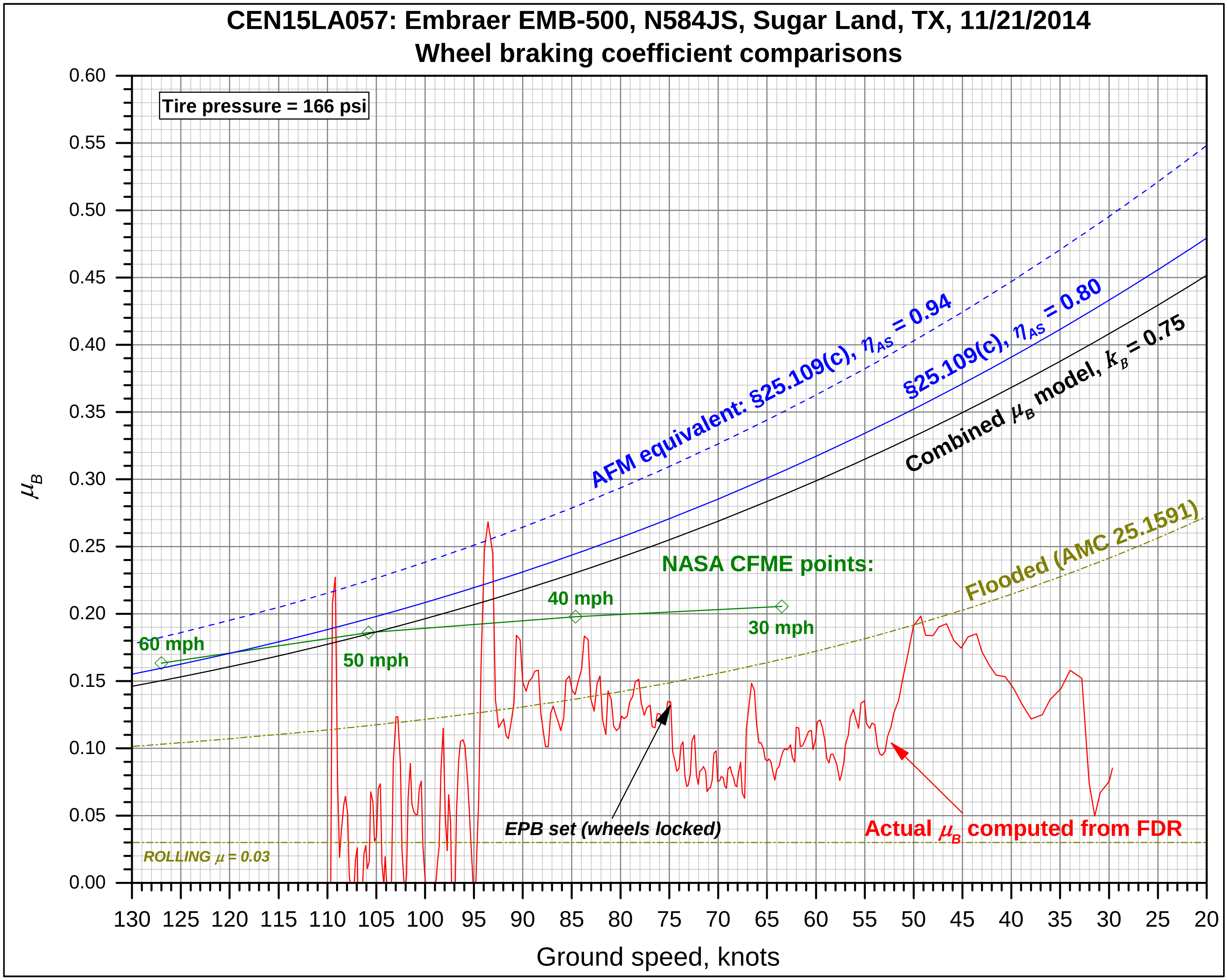

Figure 20. μ_B comparisons for the EMB-500 (N584JS) accident in Sugar Land, TX, 11/21/2014.

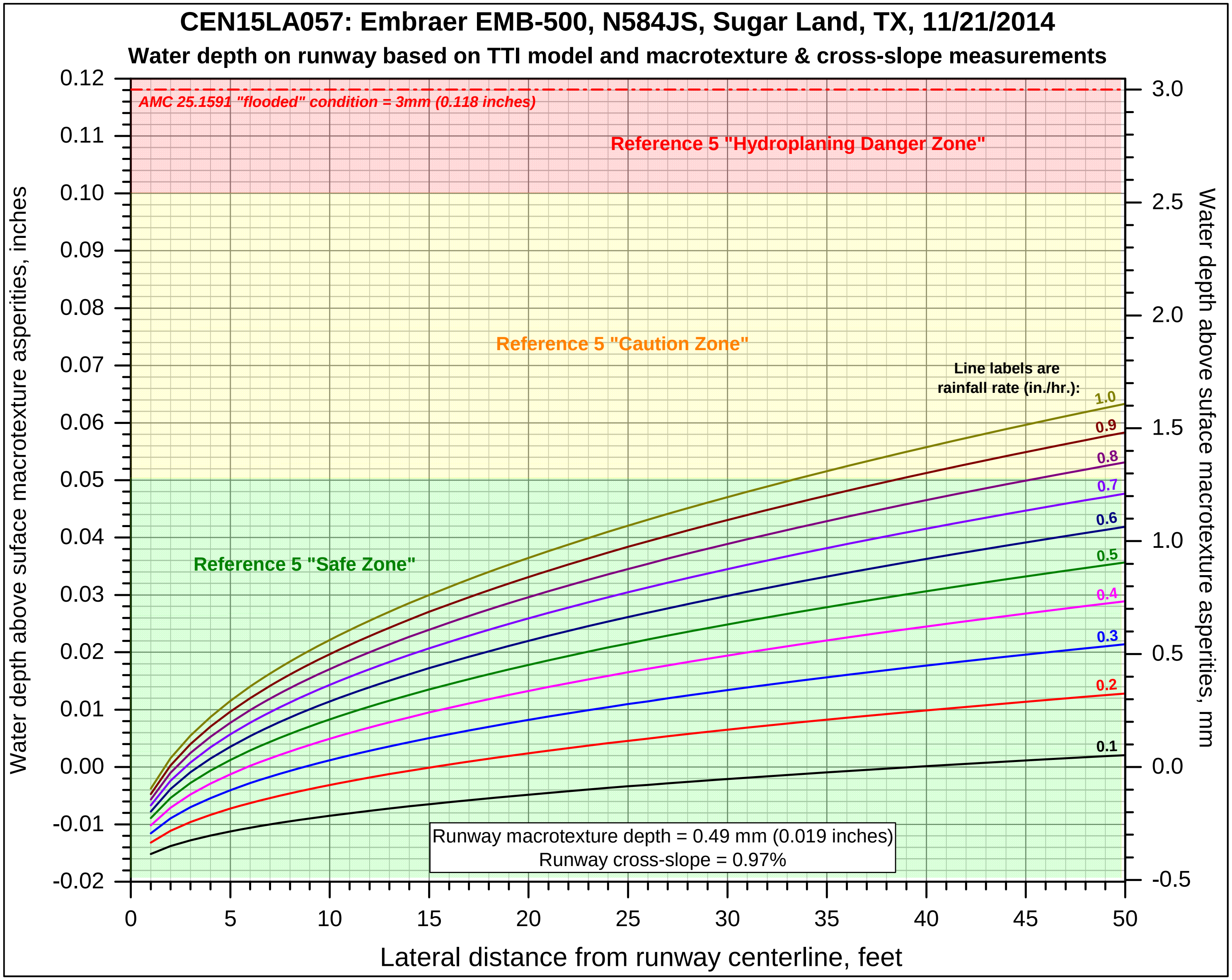

Figure 21. Water depth calculations for the EMB-500 (N584JS) accident in Sugar Land, TX, 11/21/2014.

	40 mph			60 mph		
	Minimum	Maintenance Planning	New Design/ Construction	Minimum	Maintenance Planning	New Design/ Construction
Mu Meter	.42	.52	.72	.26	.38	.66
Dynatest Consulting, Inc. Runway Friction Tester	.50	.60	.82	.41	.54	.72
Airport Equipment Co. Skiddometer	.50	.60	.82	.34	.47	.74
Airport Surface Friction Tester	.50	.60	.82	.34	.47	.74
Airport Technology USA Safegate Friction Tester	.50	.60	.82	.34	.47	.74
Findlay, Irvine, Ltd. Griptester Friction Meter	.43	.53	.74	.24	.36	.64
Tatra Friction Tester	.48	.57	.76	.42	.52	.67
Norsemeter RUNAR (operated at fixed 16% slip)	.45	.52	.69	.32	.42	.63

Figure 22. Friction level classification for runway pavement surfaces (Table 3-2 in Ref. 12).

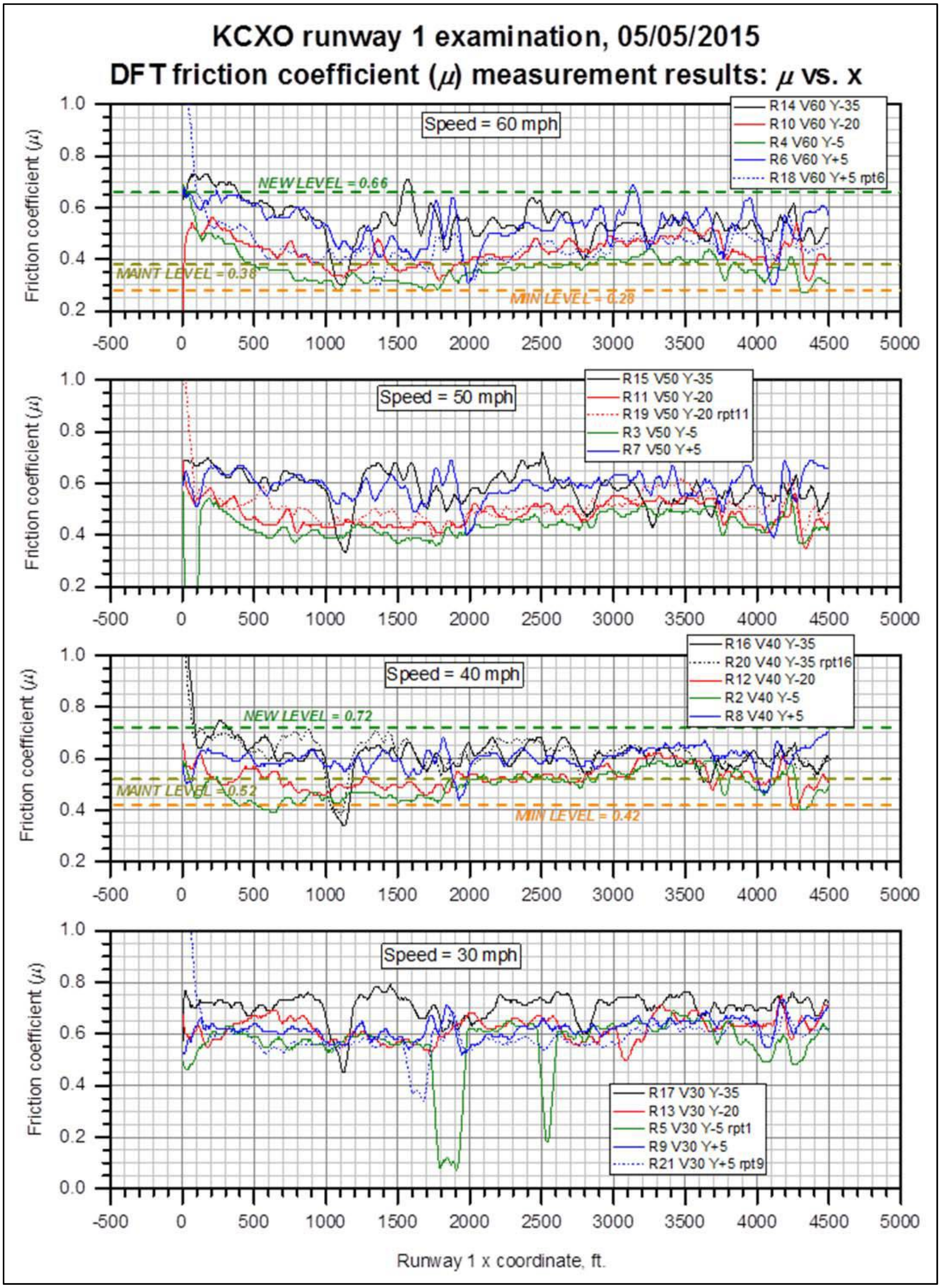

Figure 23. DFT measurements on KCXO runway 1. The runway coordinate system origin as at the threshold; x is down the runway centerline, y is to the right of the runway centerline. Legend entries indicate run number (R), DFT speed in mph (V), and runway y coordinate in ft. (Y).

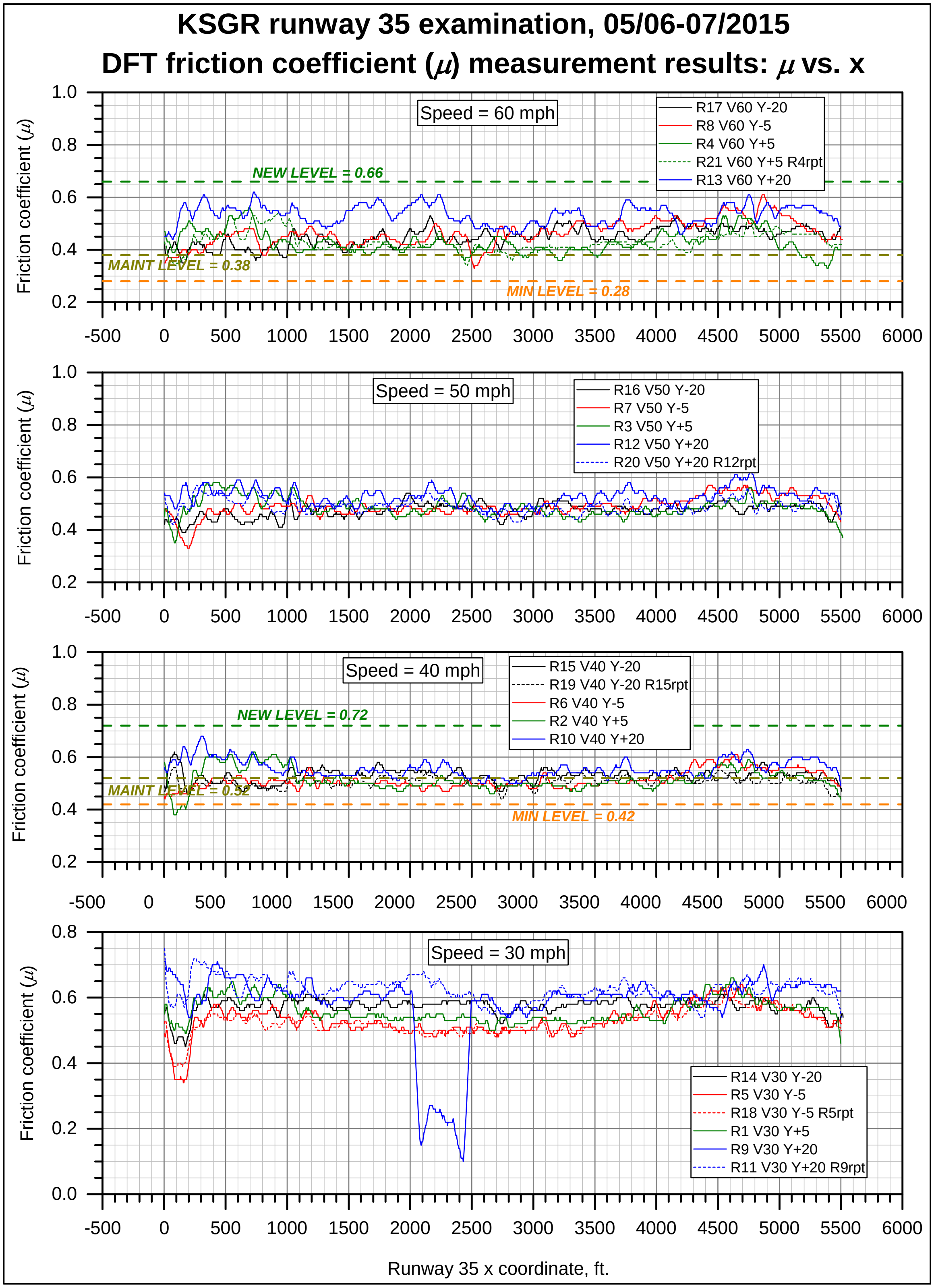

Figure 24. DFT measurements on KSGR runway 35. The runway coordinate system origin as at the threshold; x is down the runway centerline, y is to the right of the runway centerline. Legend entries indicate run number (R), DFT speed in mph (V), and runway y coordinate in ft. (Y).

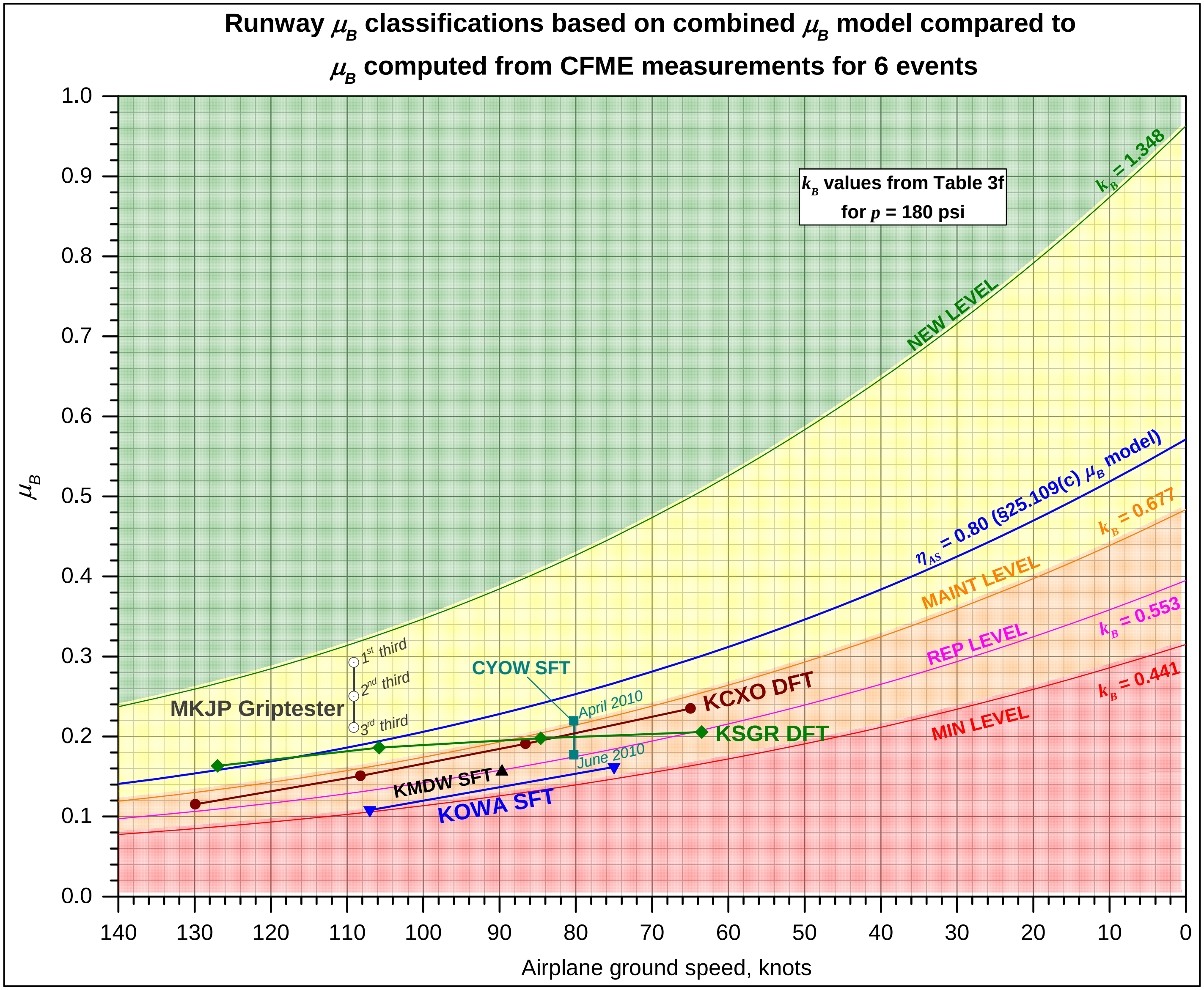

Figure 25. Runway μ_B classifications based on CMB model, compared to μ_B from CFME measurements.

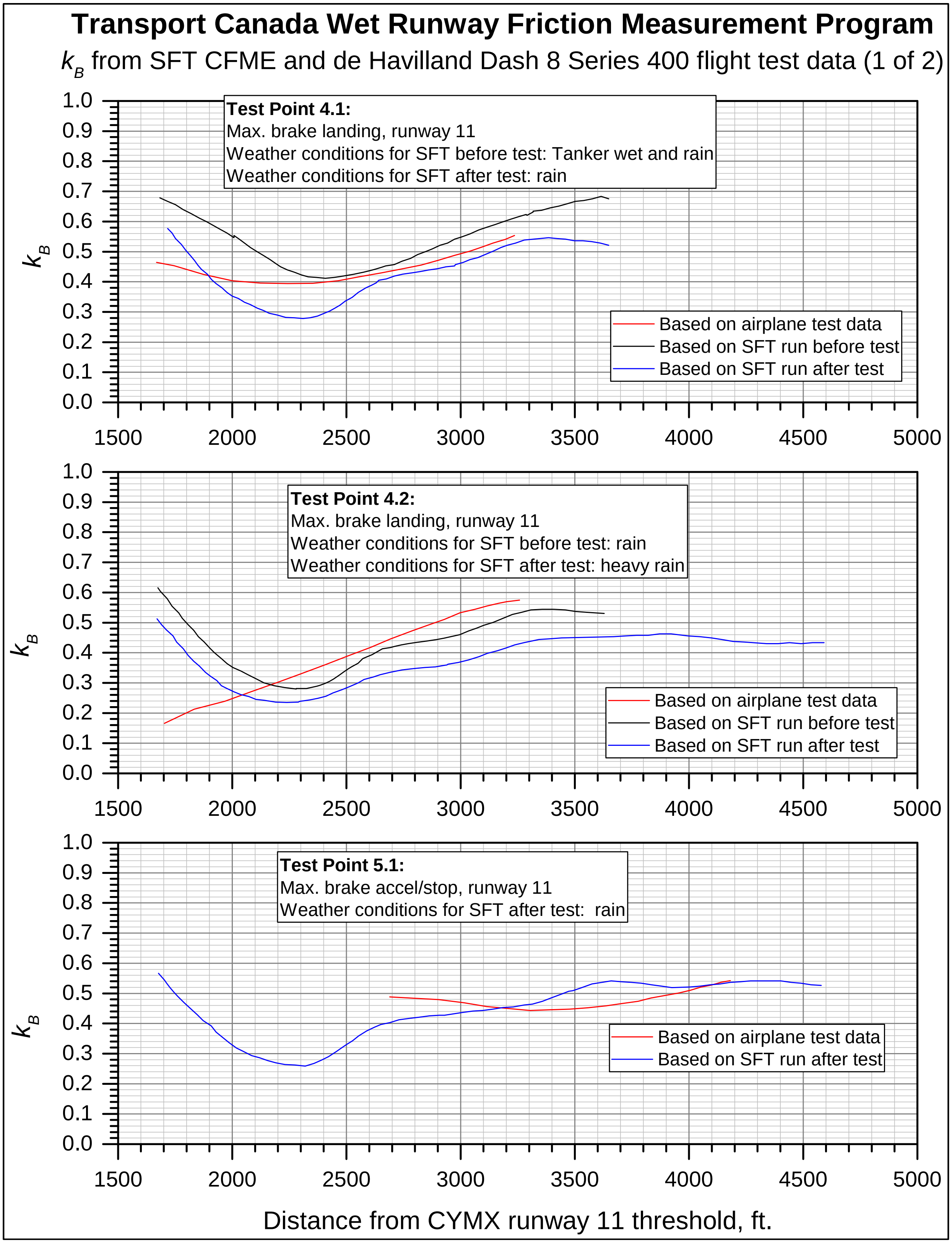

Figure 26a. Comparison of k_B computed from SFT measurements and DHC-8-400 flight test data (page 1 of 2).

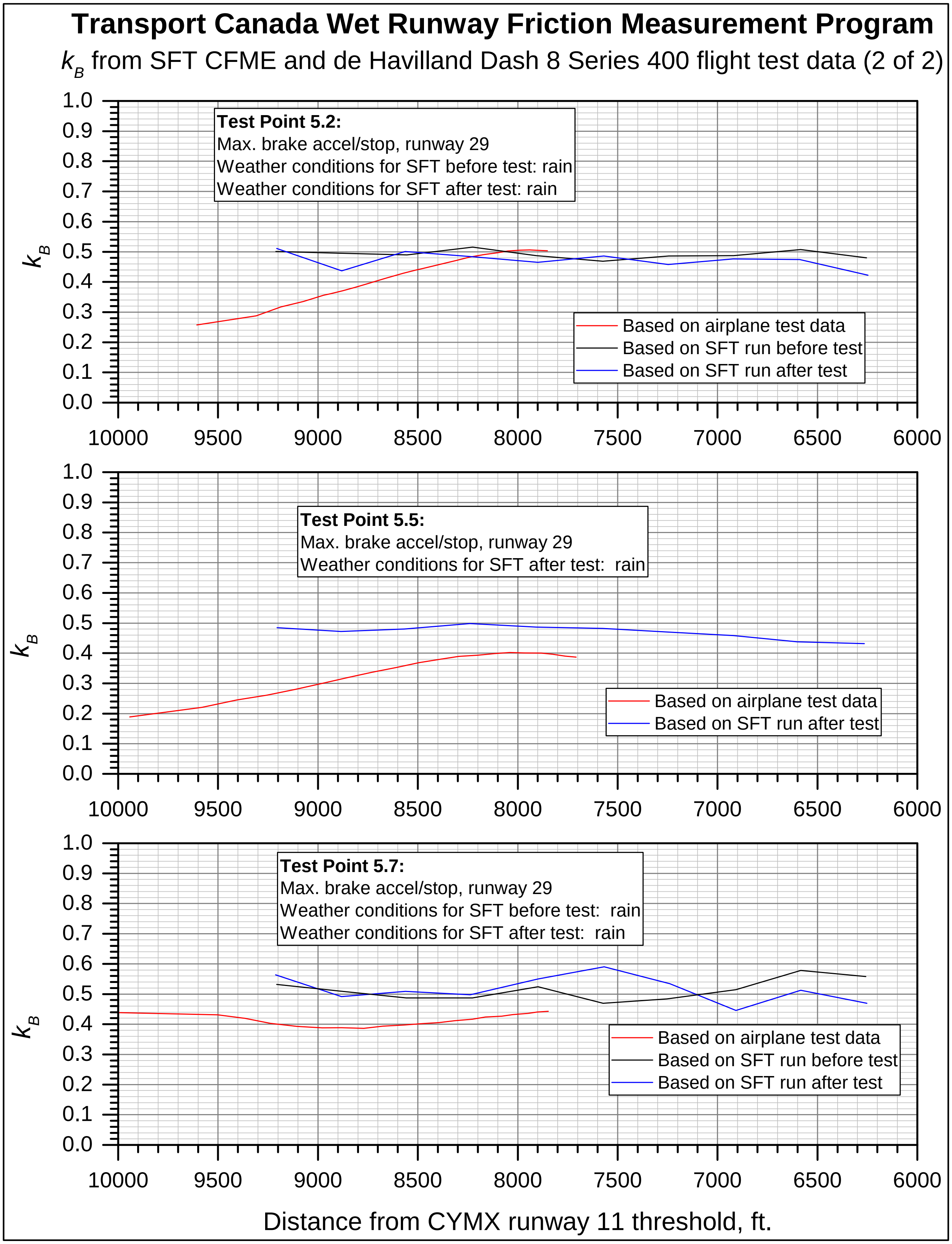

Figure 26b. Comparison of k_B computed from SFT measurements and DHC-8-400 flight test data (page 2 of 2).

Runway Condition Code	Runway Surface Condition Description	Pilot-Reported Braking Action	Wheel Braking Coefficient
6	Dry	—	90% of certified value used to comply with § 25.125[1].
5	Frost Wet (includes damp and ⅛″ (3 mm) depth or less of water) ⅛″ (3 mm) depth or less of: Slush Dry snow Wet snow	Good	Per method defined in § 25.109(c).
4	-15 °C and colder outside air temperature: Compacted snow	Good to Medium[2]	0.20[3]
3	Wet ("Slippery When Wet" runway) Dry snow or wet snow (any depth) over compacted snow Greater than ⅛″ (3 mm) depth of: Dry snow Wet snow Warmer than -15 °C outside air temperature: Compacted snow	Medium[2]	0.16[3]
2	Greater than ⅛″ (3 mm) depth of: Water Slush	Medium[2] to Poor	For speeds below 85% of the hydroplaning speed[4]: 50% of the wheel braking coefficient determined in accordance with § 25109(c), but no greater than 0.16[3]; and For speeds at 85% of the hydroplaning speed[4] and above: 0.05[3].
1	Ice	Poor	0.08[3]
0	Wet ice Water on top of compacted snow Dry snow or wet snow over ice	Nil	Not applicable. (No operations in Nil conditions.)

[1] 100% of the wheel braking coefficient used to comply with § 25.125 may be used if the testing from which that braking coefficient was derived was conducted on portions of runways containing operationally representative amounts of rubber contamination and paint stripes.
[2] The braking action term "FAIR" is in the process of being changed to "MEDIUM" throughout the FAA. Until an official change is published, the term "FAIR" should be used.
[3] These wheel braking coefficients assume a fully modulating anti-skid system. For quasi-modulating systems, multiply the listed braking coefficient by 0.625. For on-off systems, multiply the listed braking coefficient by 0.375. (See AC 25-7C to determine the classification of an anti-skid system.) Airplanes without anti-skid systems will need to be addressed separately on a case-by-case basis.
[4] The hydroplaning speed, V_P, may be estimated by the equation $V_P = 9\sqrt{P}$, where V_P is the ground speed in knots and P is the tire pressure in lb/in^2.

Figure 27: Runway Surface Condition–Pilot Reported Braking Action—Wheel Braking Coefficient Correlation Matrix, from AC 25-32 (Ref. 32).