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Wind Averaged Drag Coefficient: Its Evolution and Current Use

SAE Commercial Vehicle Engineering Congress 2018

18AERO-0007

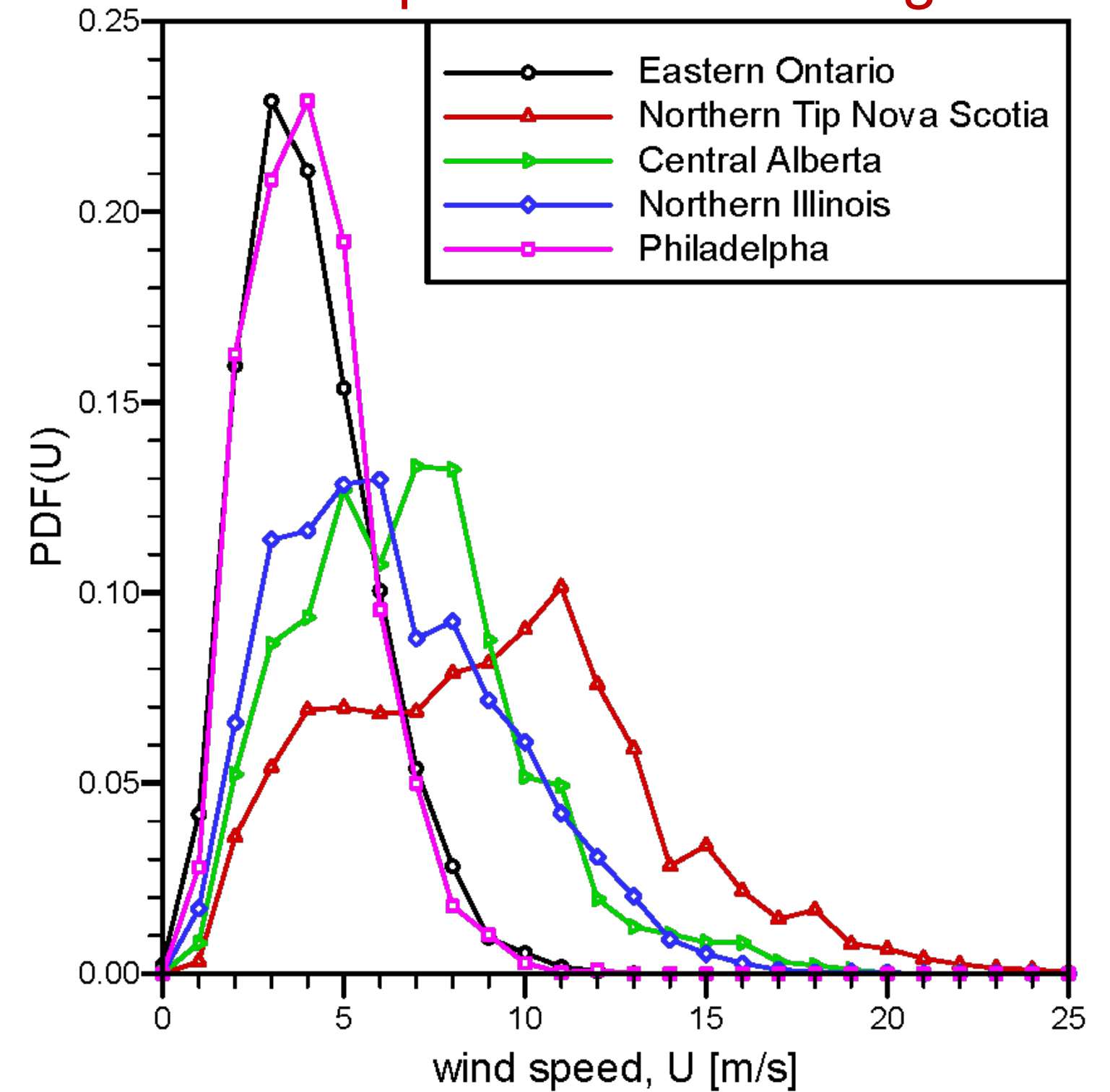
Brian McAuliffe



Terrestrial Winds

- Local wind conditions vary significantly

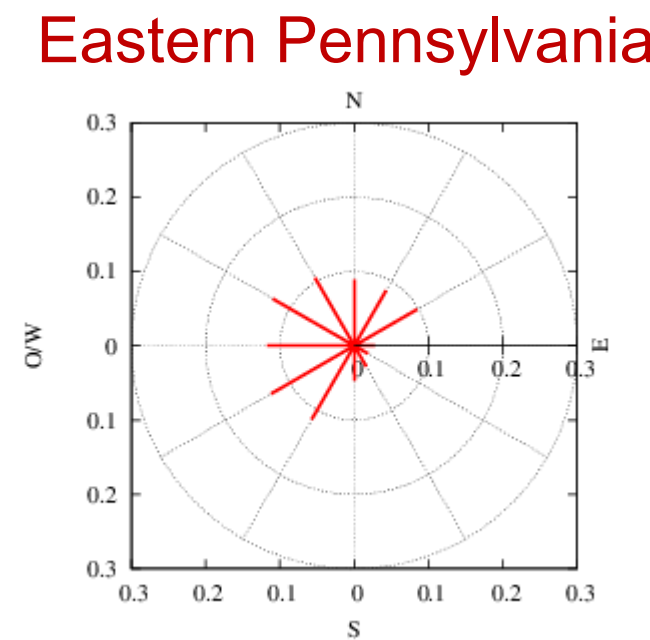
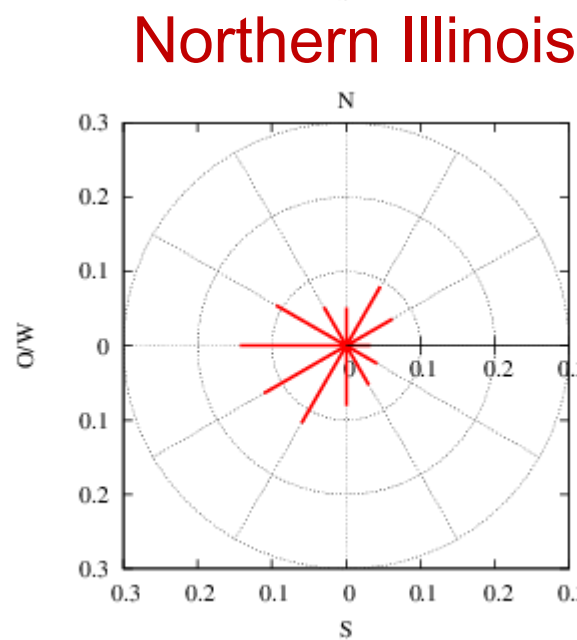
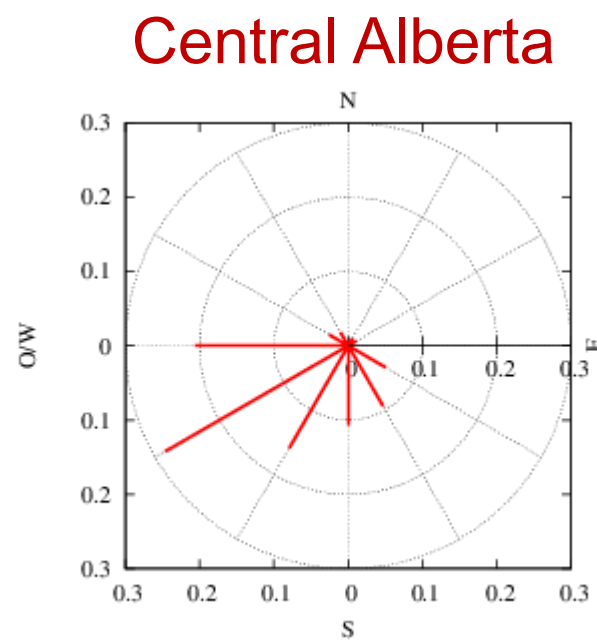
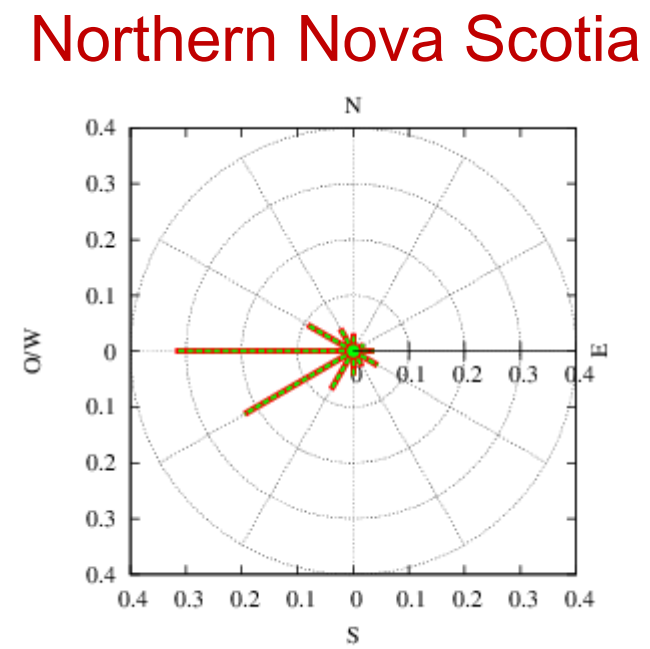
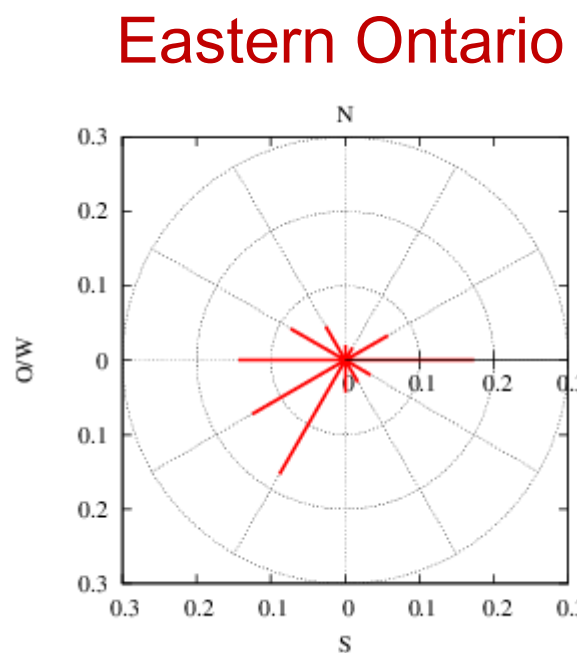
Wind speeds at 30 m height



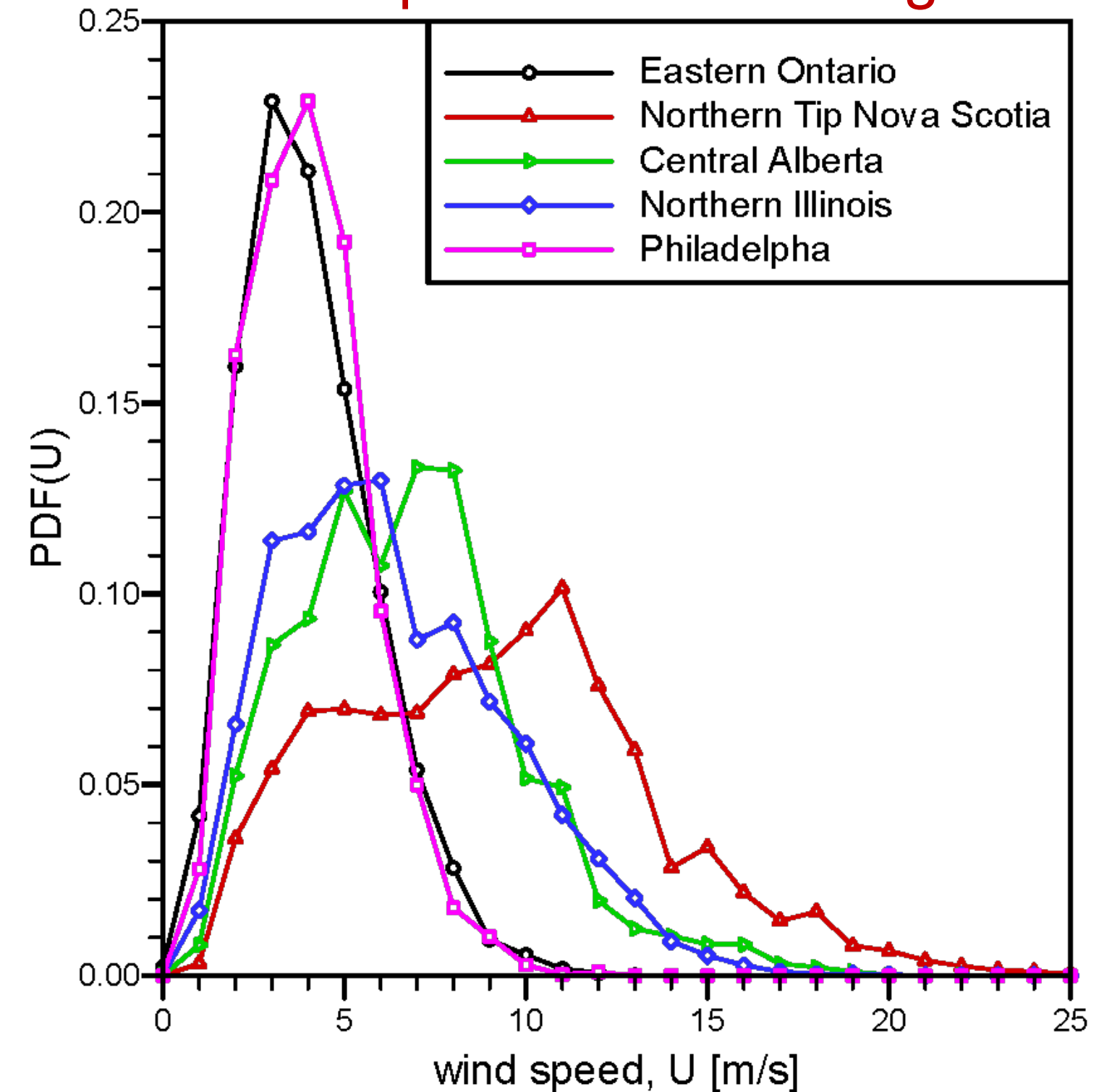
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Wind directions
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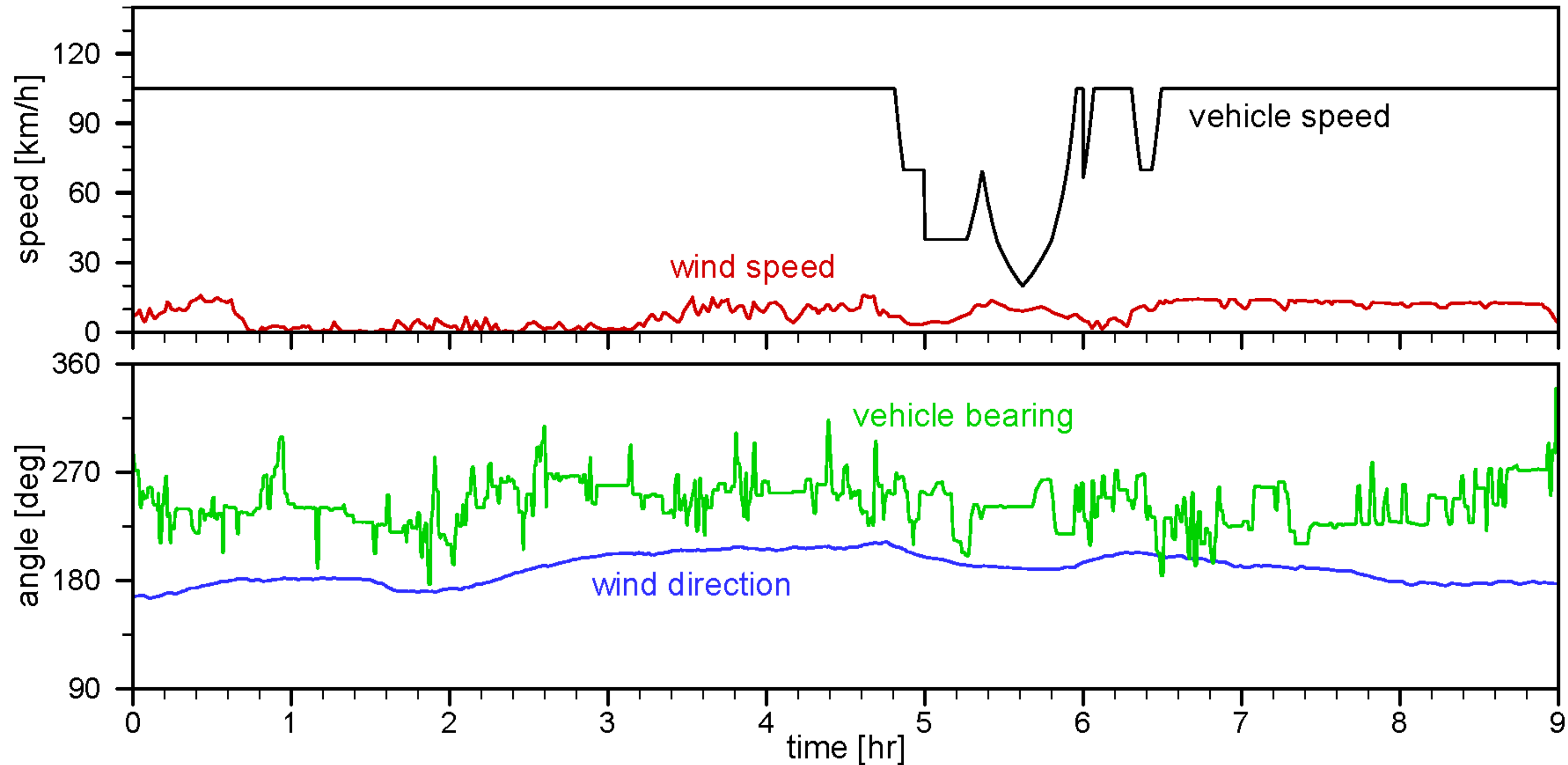


Wind speeds at 30 m height



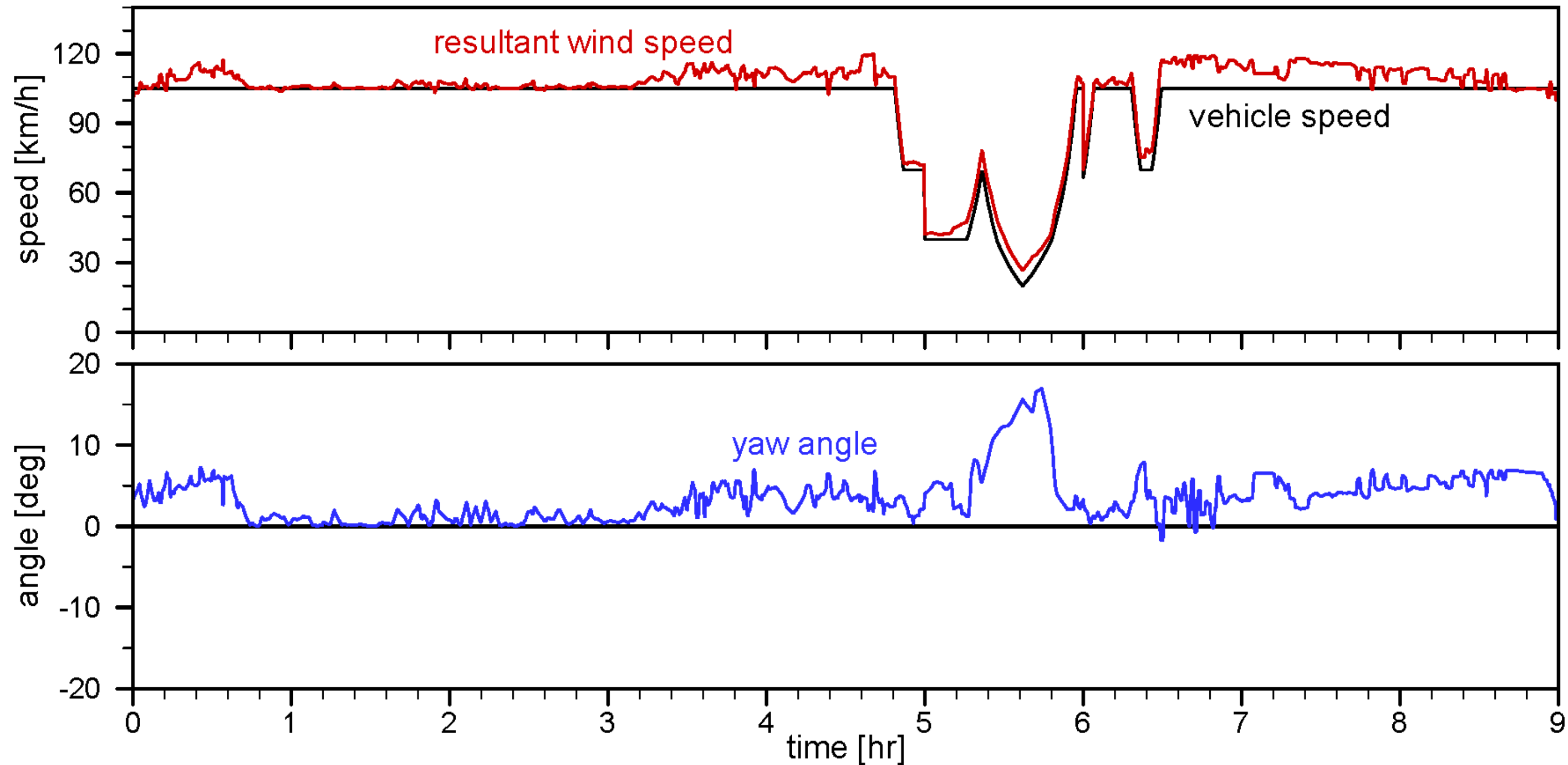
Winds Experienced While in Motion

Vehicle traveling on Highway 20/401 from Montreal to Windsor



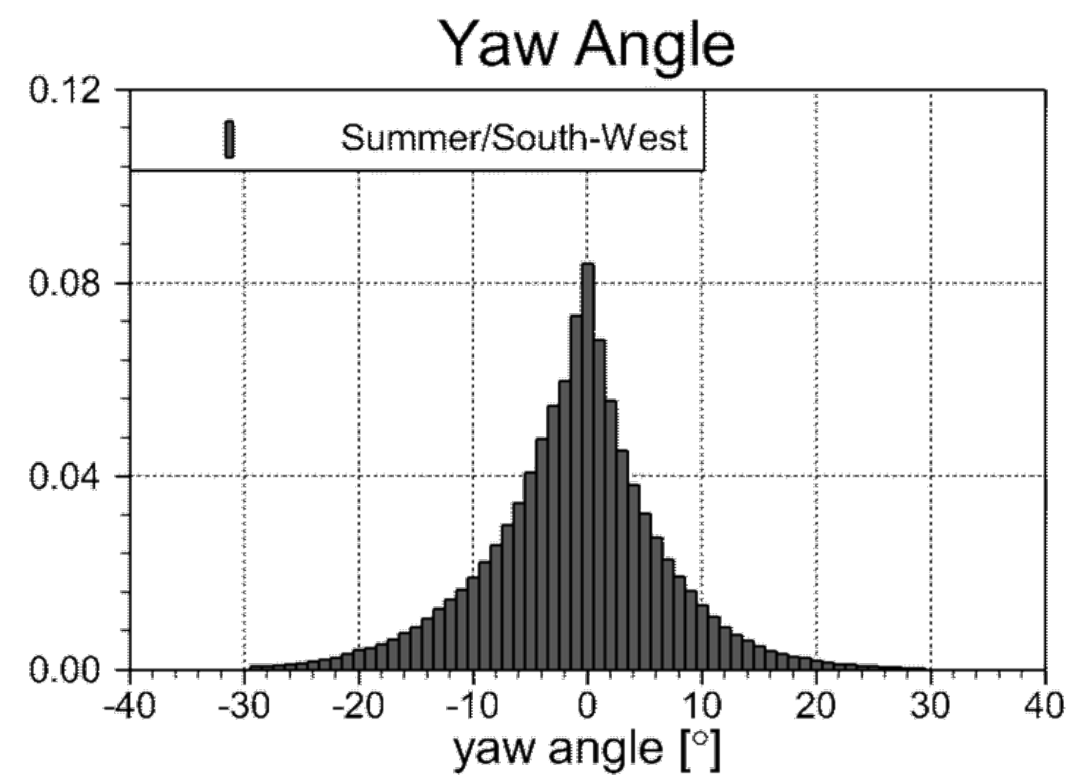
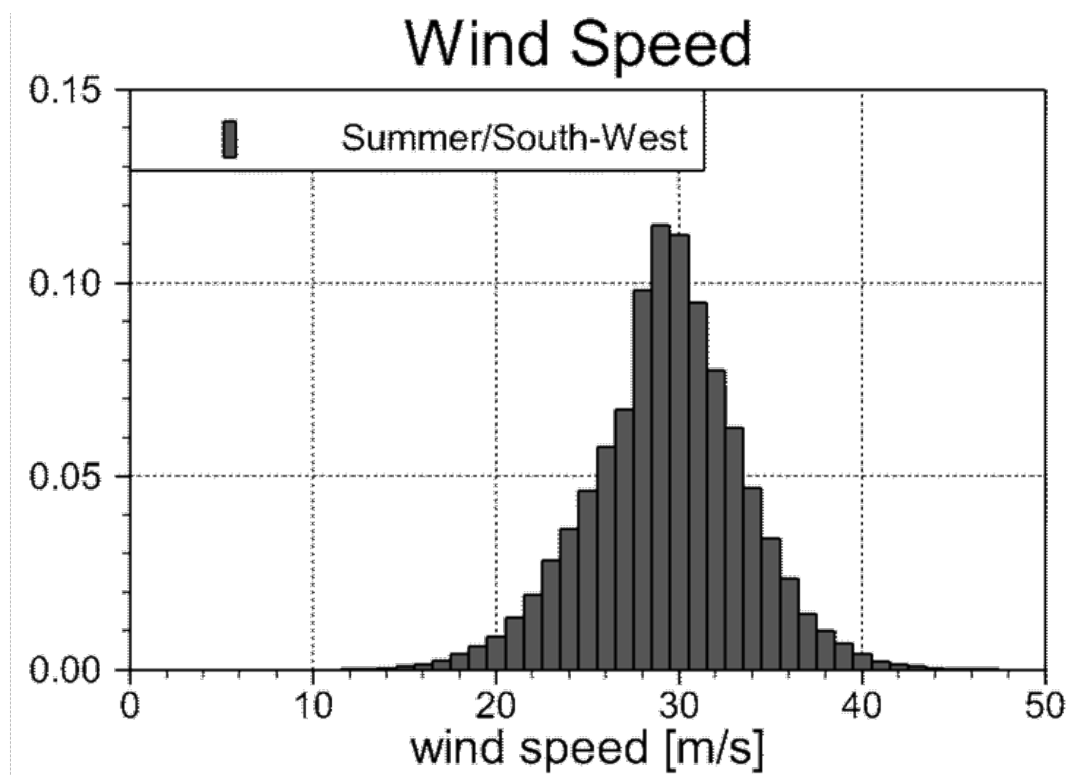
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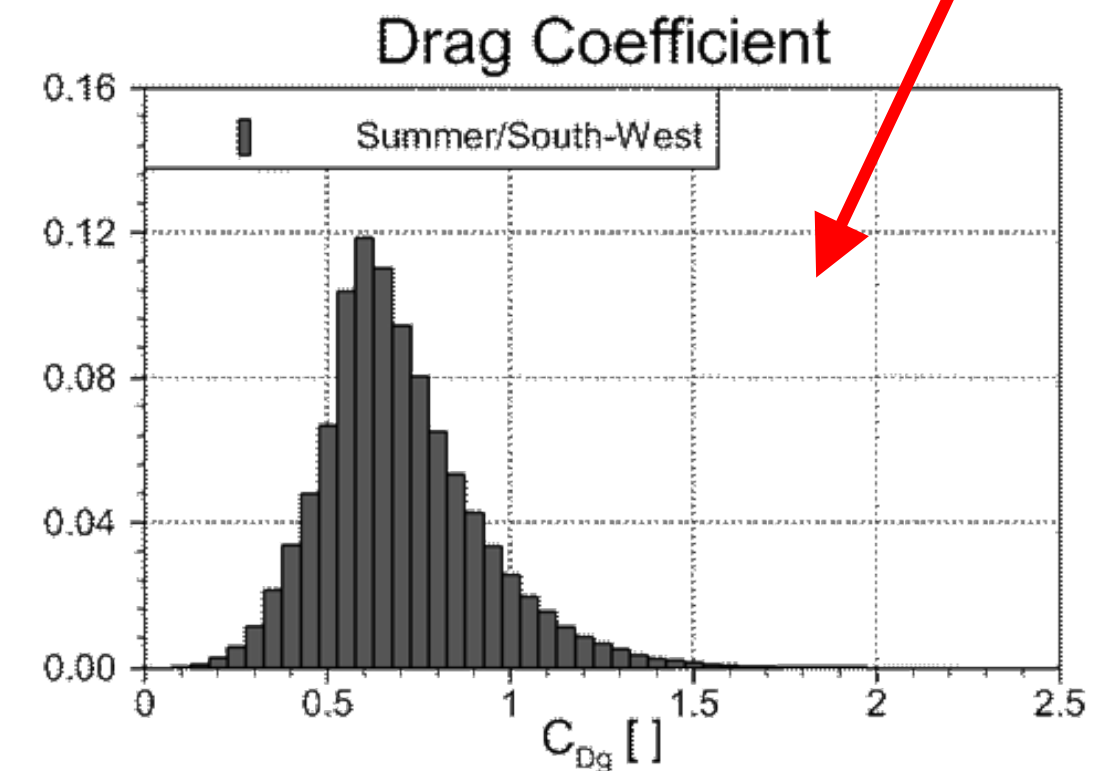
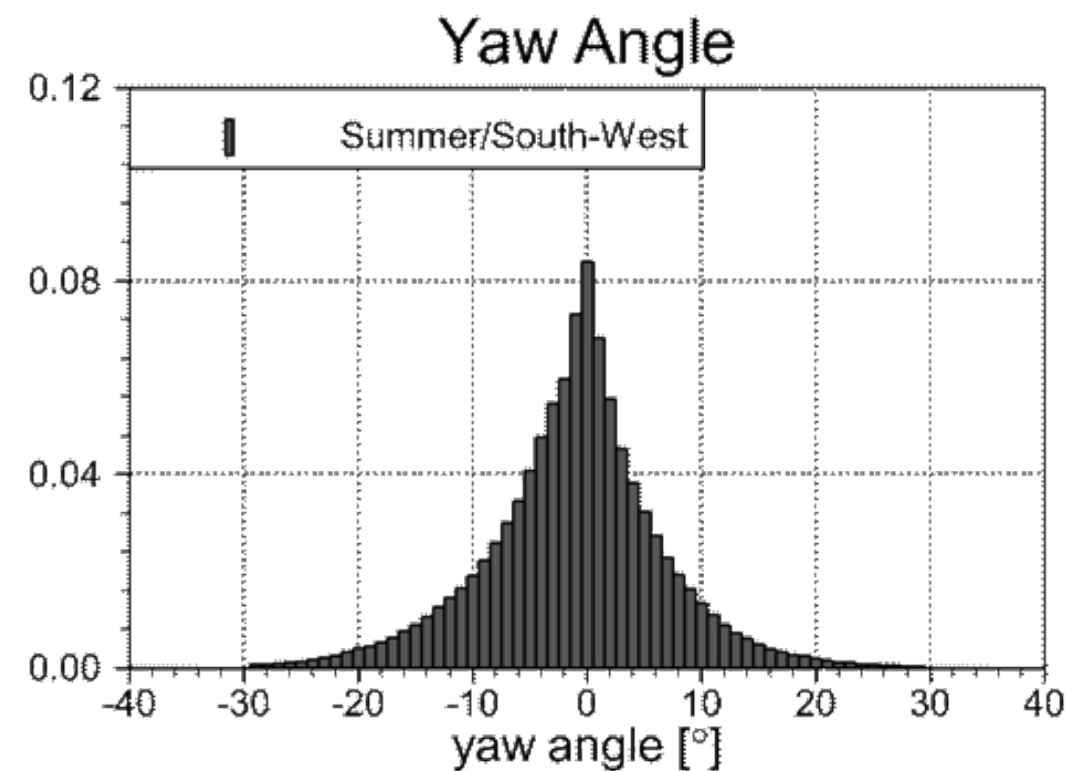
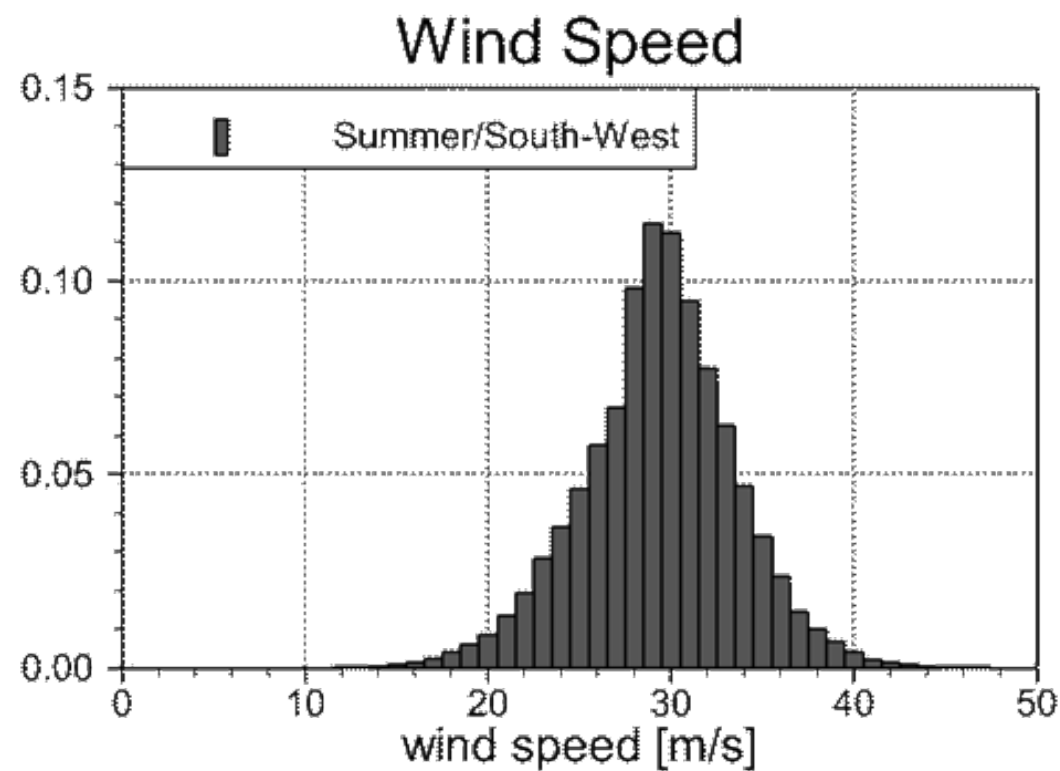
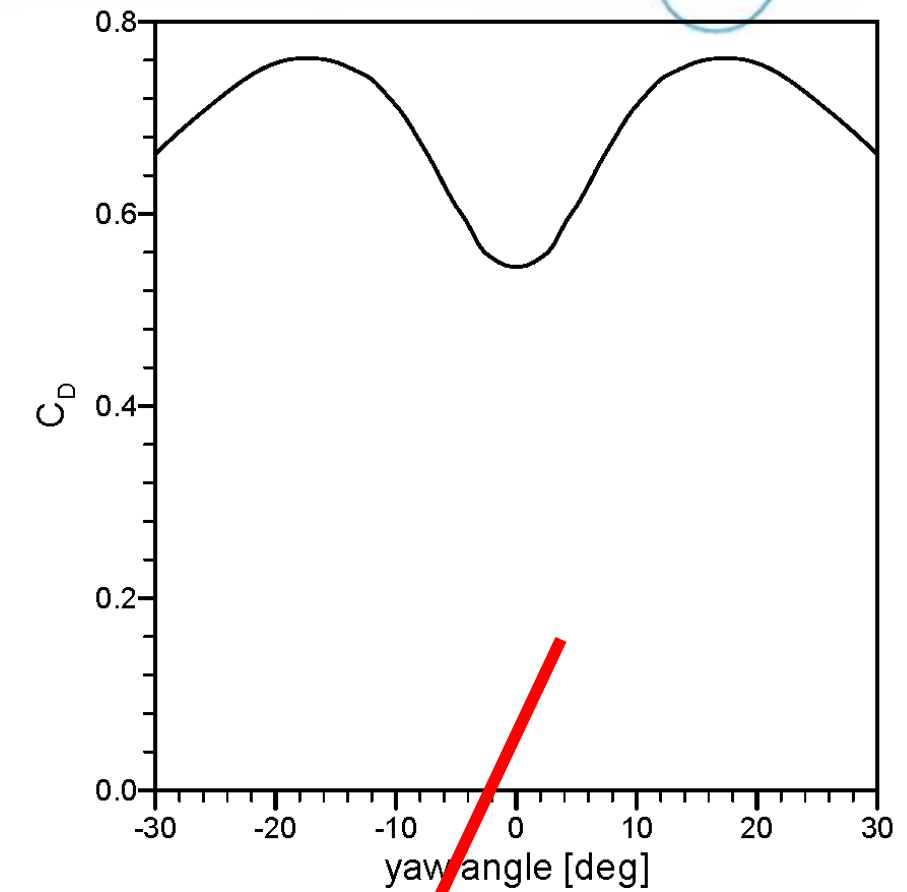
Importance of Yaw Evaluations

- Winds change every minute / hour / day / week / month / season / year



Importance of Yaw Evaluations

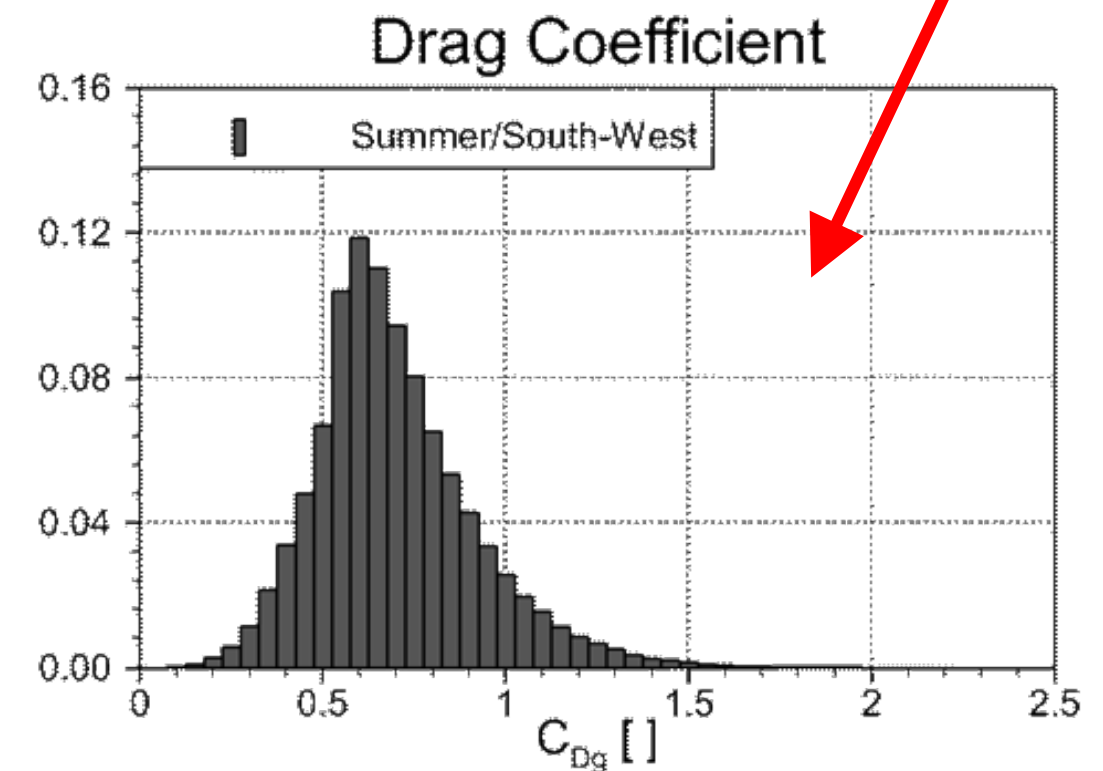
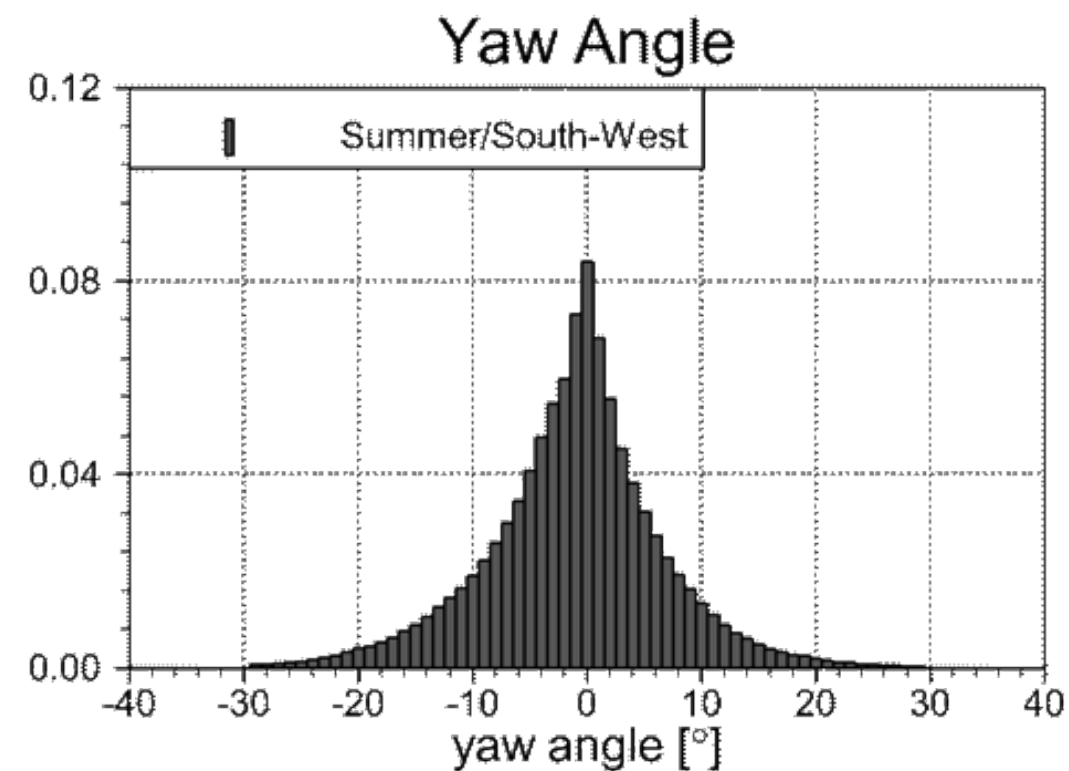
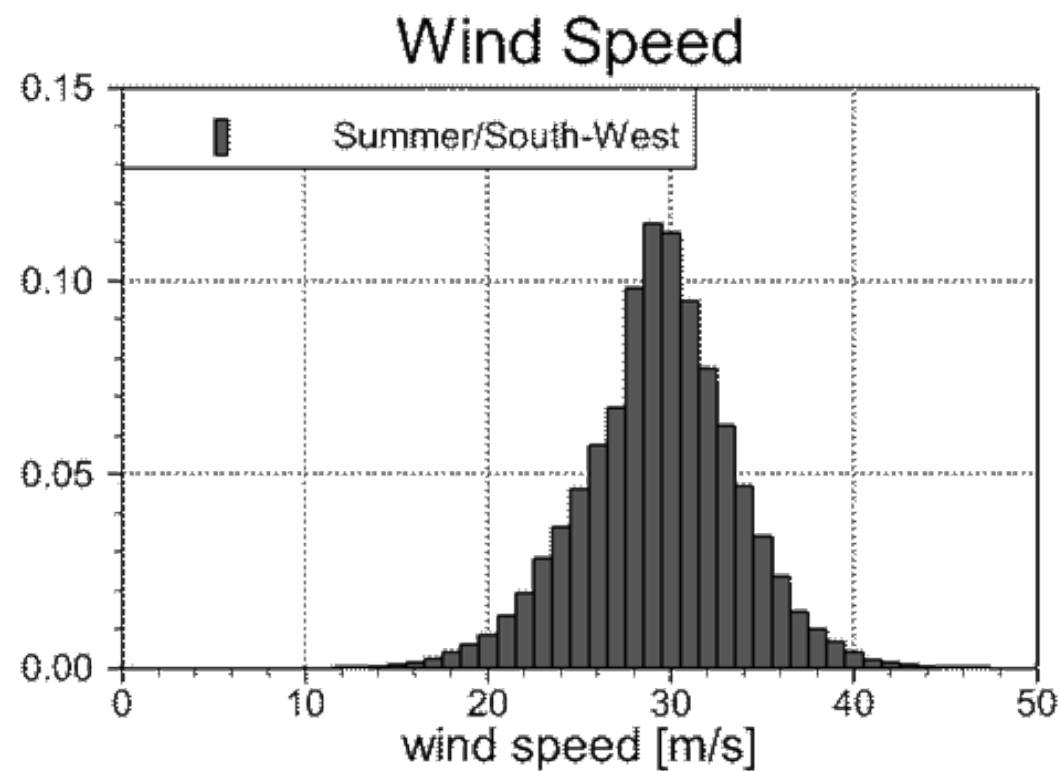
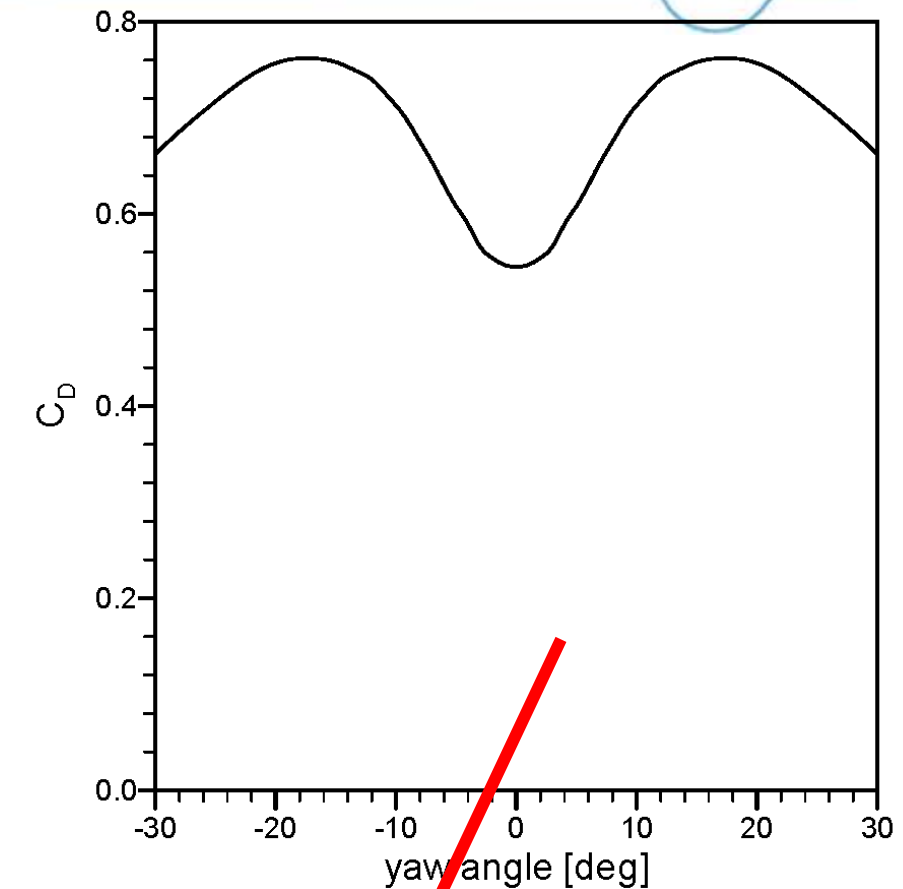
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- Leads to large variation in vehicle drag along a route



Importance of Yaw Evaluations

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Can we define vehicle drag performance with a single metric?




Wind Averaged Drag Coefficient

- Single-metric measure for head-to-head comparison
- Assumes a specific/average wind climate
- Method originally applied in 1970's (example, Buckley et al., 1978)

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- Increasing levels of simplification***
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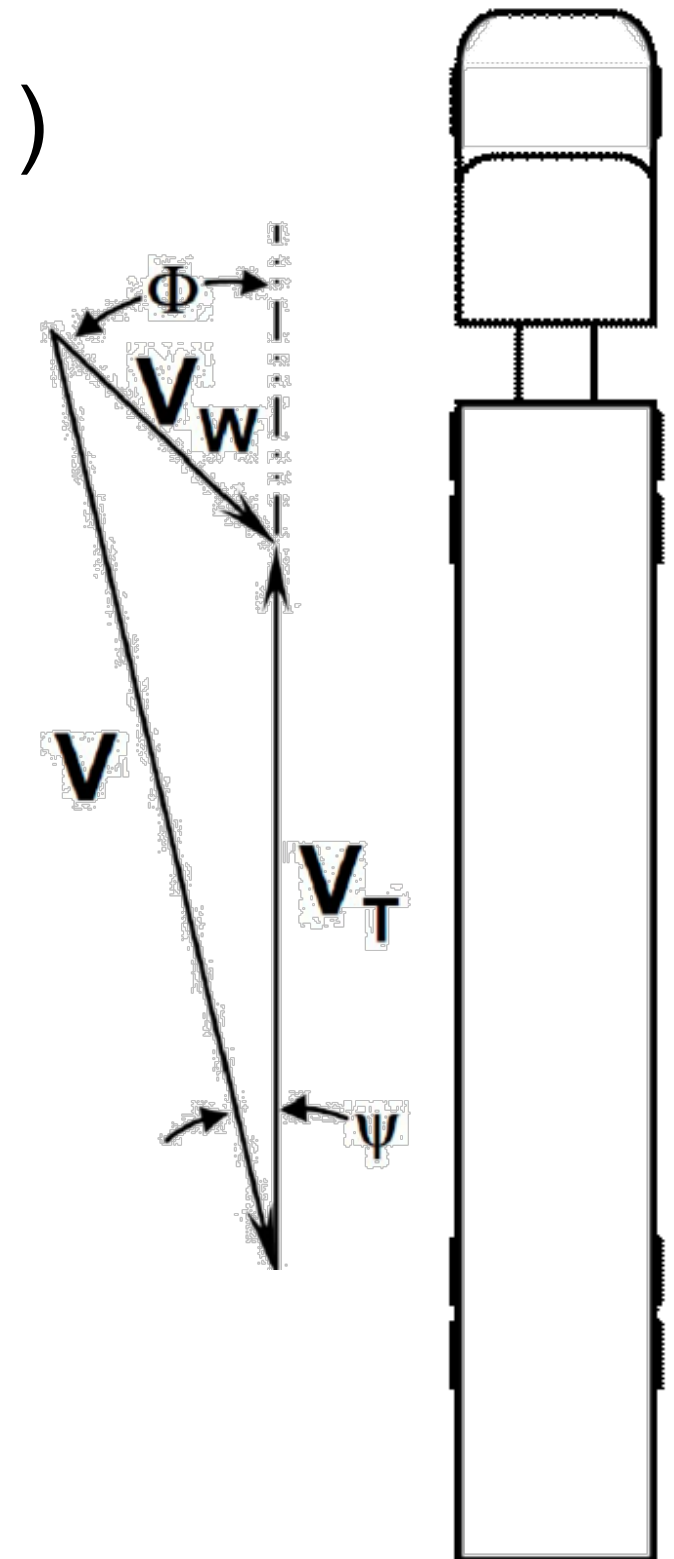
Increasing levels of simplification



Objective of this study:
Investigate the potential errors and implications of using the simplified methods

Formulation

- Requires apparent wind speed (V) and direction (yaw angle, ψ)

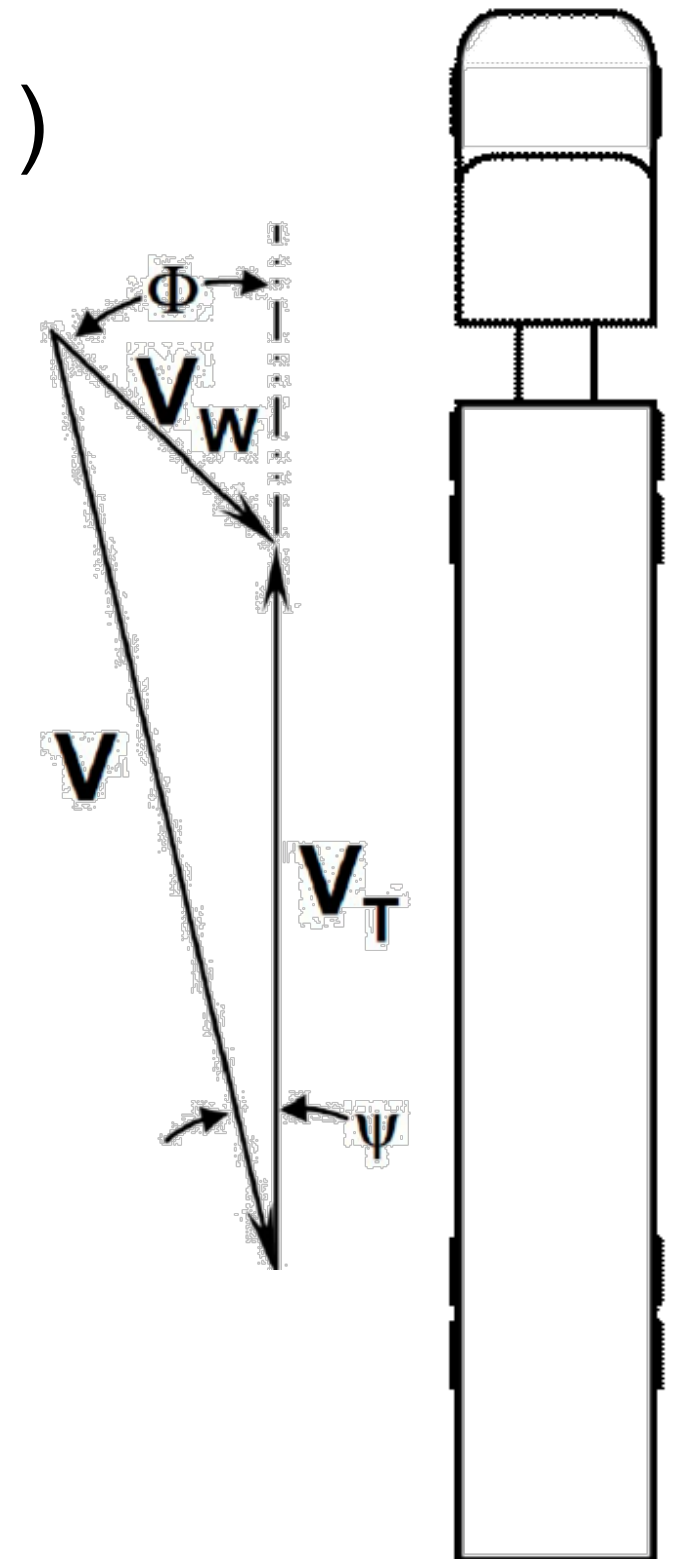


Formulation

- Requires apparent wind speed (V) and direction (yaw angle, ψ)
- Wind-Averaged Drag Coefficient:

$$WAC_D = \int_0^{2\pi} \int_0^{V_{\max}} C_D(\psi) \left[1 + \left(\frac{V_w}{V_T} \right)^2 + 2 \left(\frac{V_w}{V_T} \right) \cos(\phi) \right] p(V_w, \phi) d\phi dV_w$$

where $\int_0^{2\pi} \int_0^{V_{\max}} p(V_w, \phi) d\phi dV_w = 1.0$



Formulation

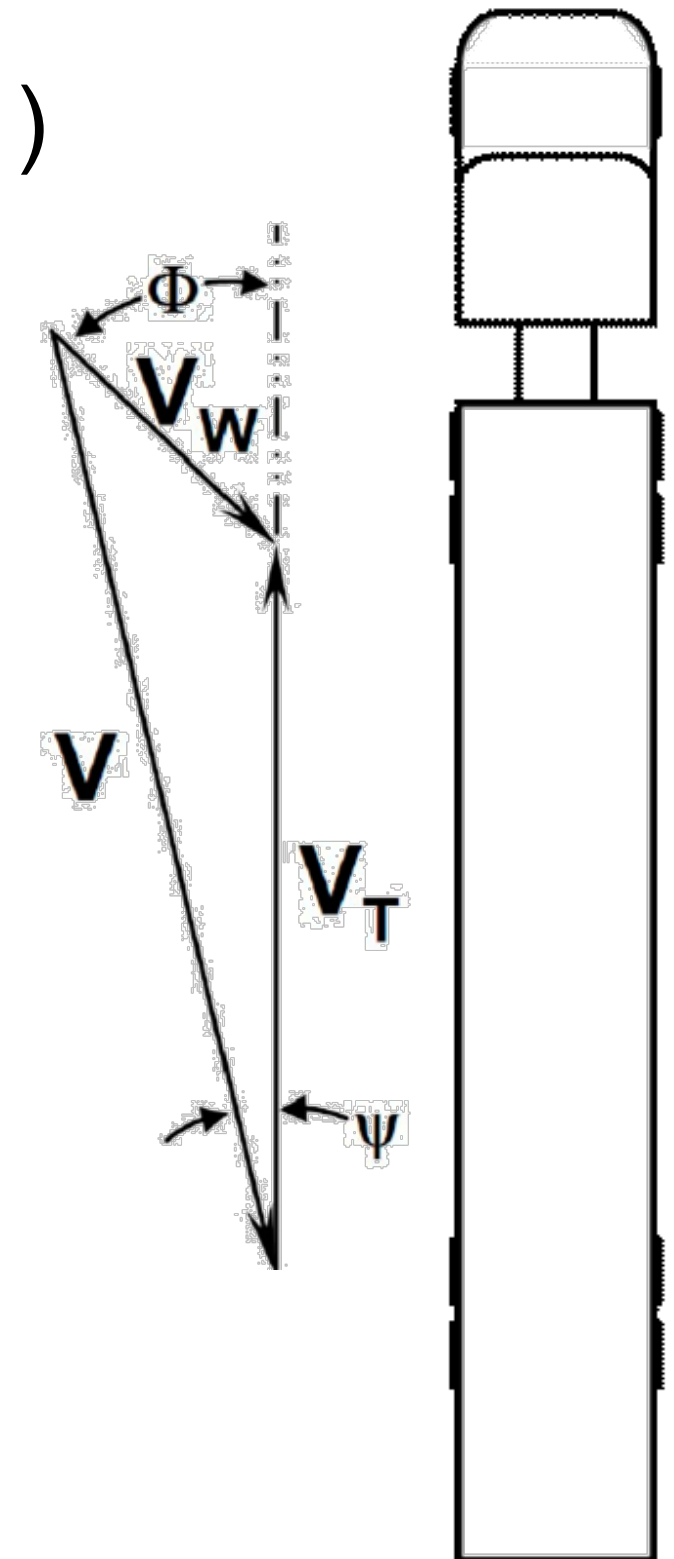
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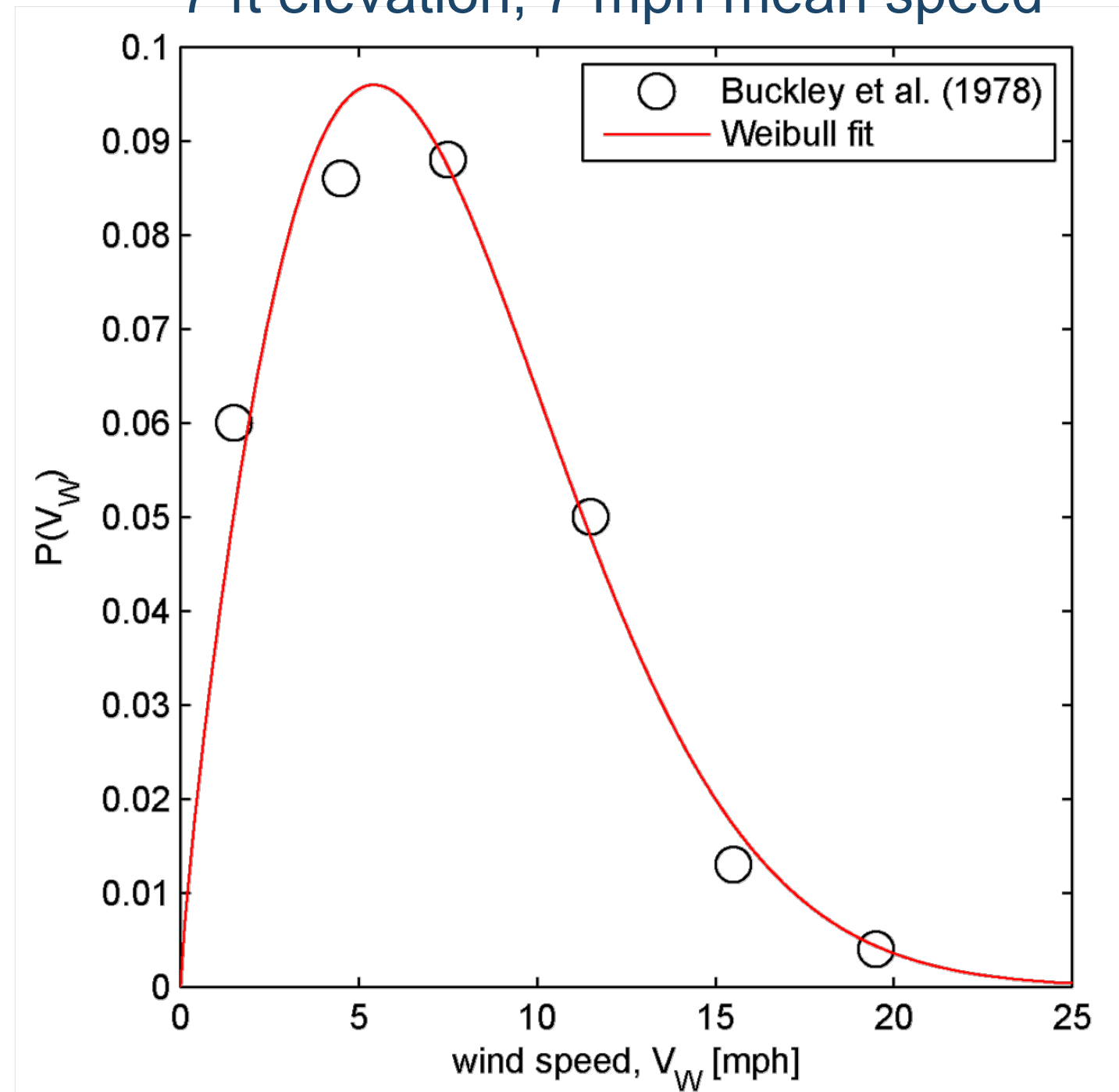
probability of encountering wind speed V_w from direction ϕ



Full Wind Distribution Method

- Need wind distribution:
 - Fit of Weibull distribution to data presented by Buckley et al. (1978)

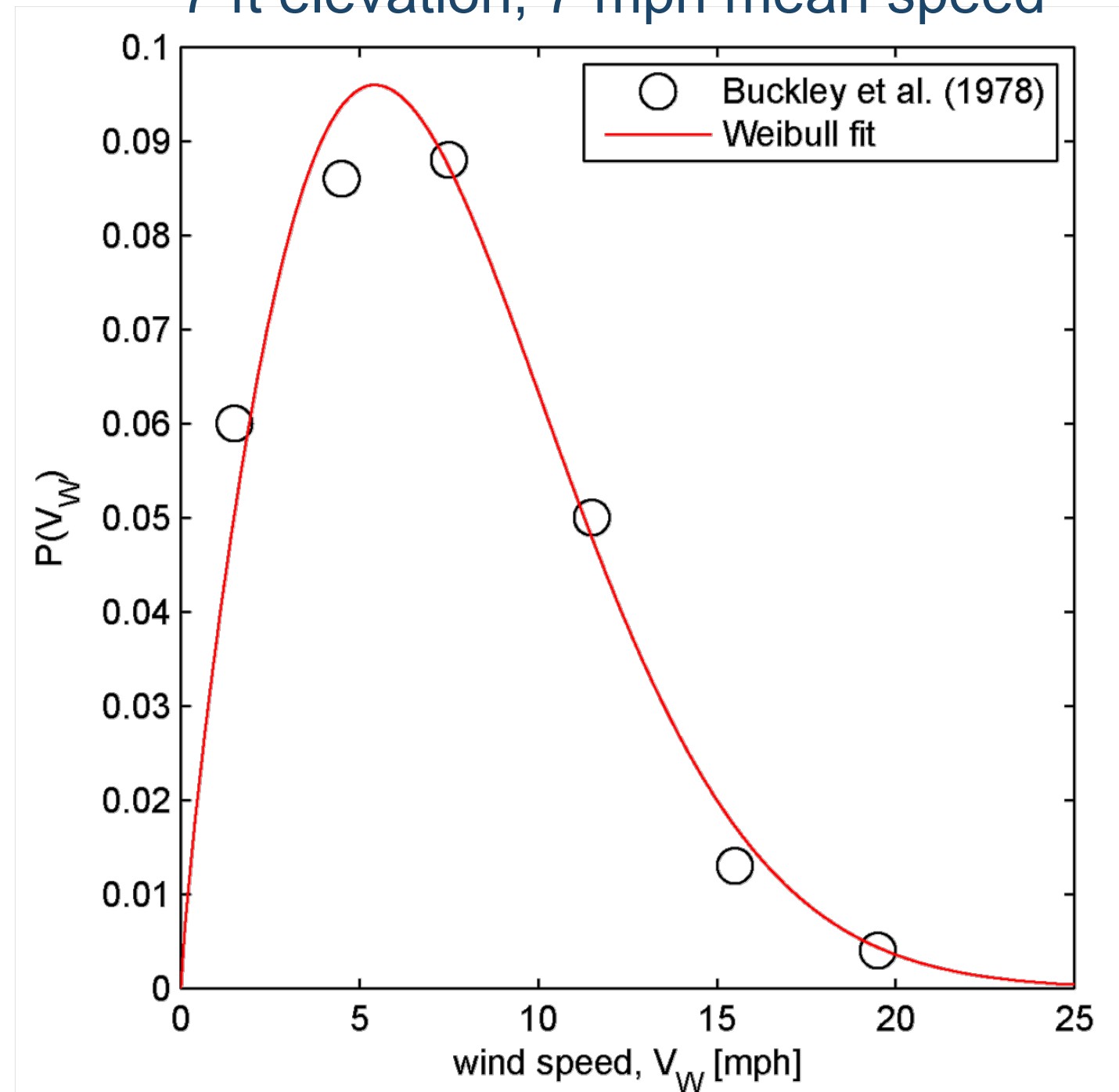
10 year U.S. national daytime average
7 ft elevation, 7 mph mean speed



Full Wind Distribution Method

- Need wind distribution:
 - Fit of Weibull distribution to data presented by Buckley et al. (1978)
- Assume J1252 average US wind speed of 7 mph (11.3 km/h)
- Assume equal probability from any direction

10 year U.S. national daytime average
7 ft elevation, 7 mph mean speed



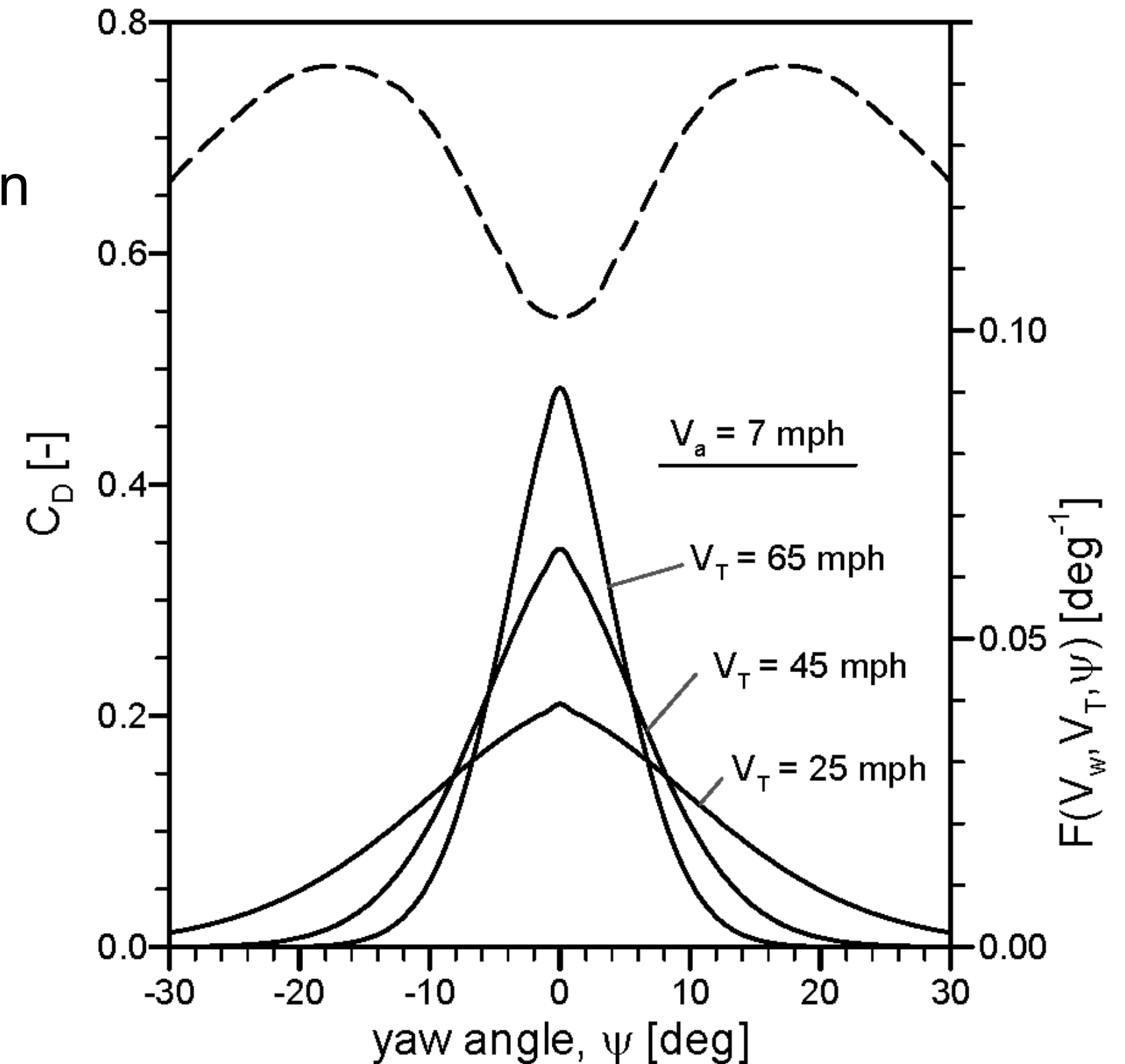
Full Wind Distribution Method

- Calculation Methods:
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Full Wind Distribution Method

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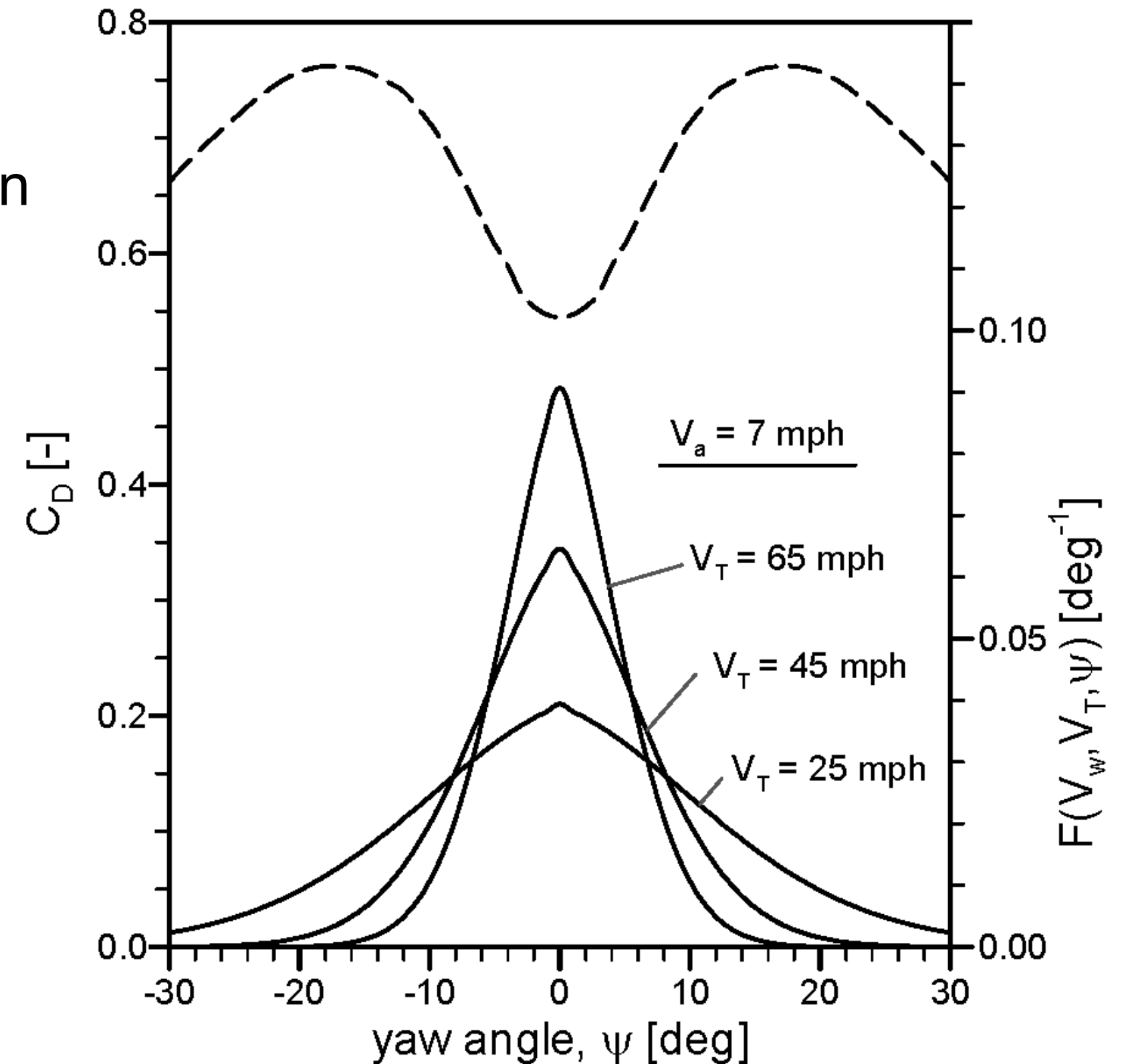


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quicker algorithm once discrete
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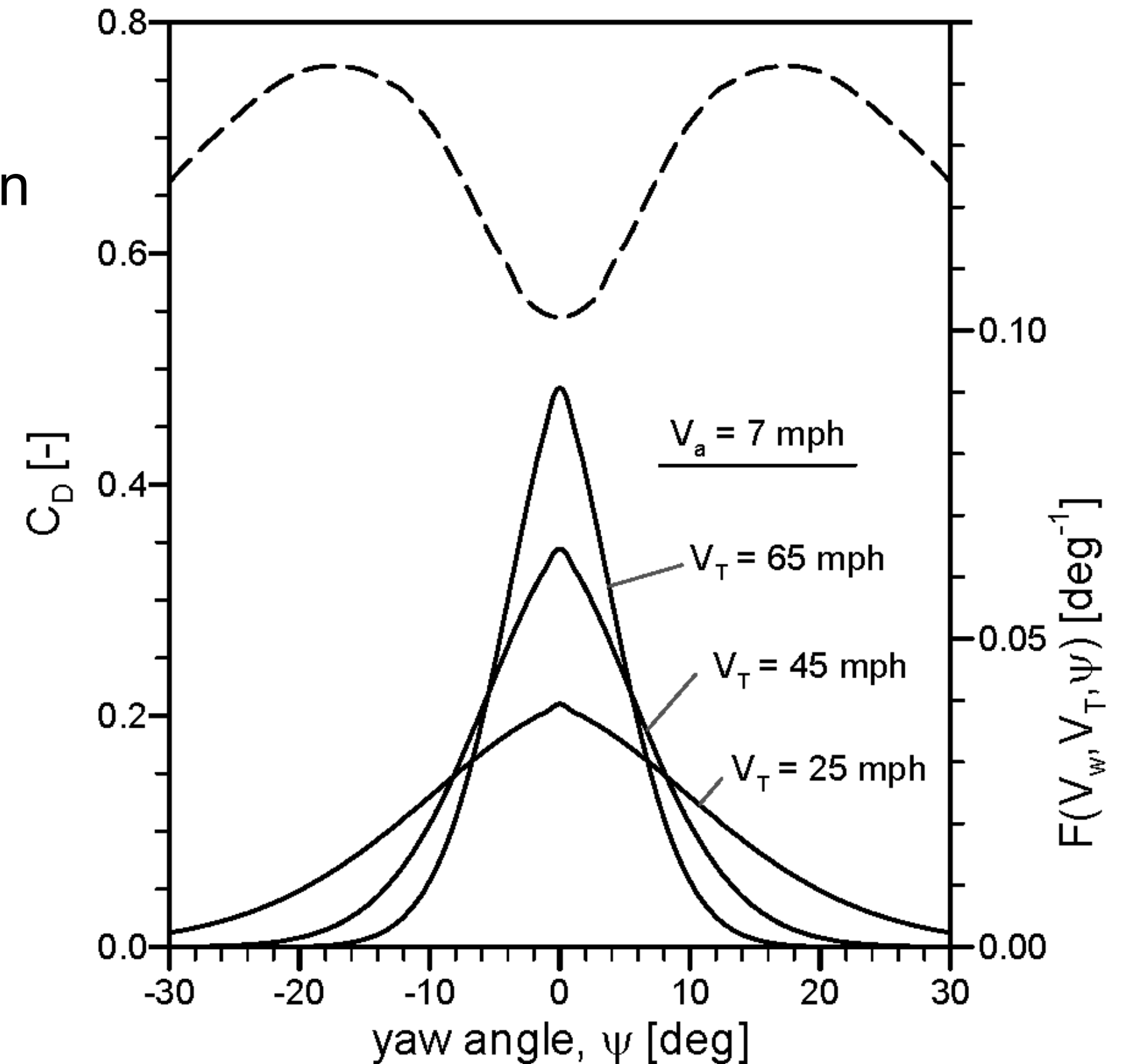
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➤ Requires C_D data to $\pm 15^\circ$ or higher

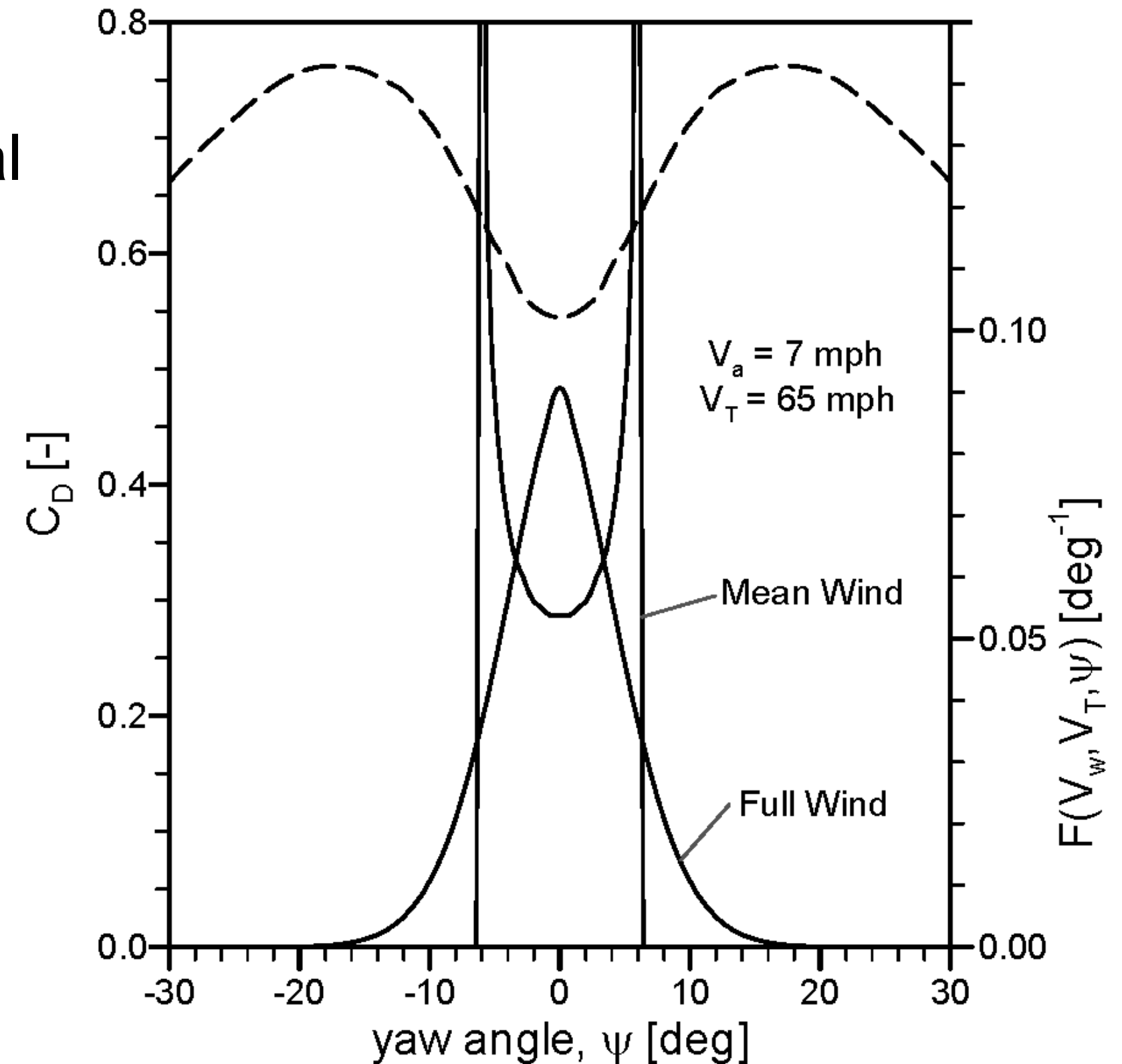


Mean Wind Distribution Method

- Neglect wind-speed distribution and assume average wind speed V_a with equal probability from any direction

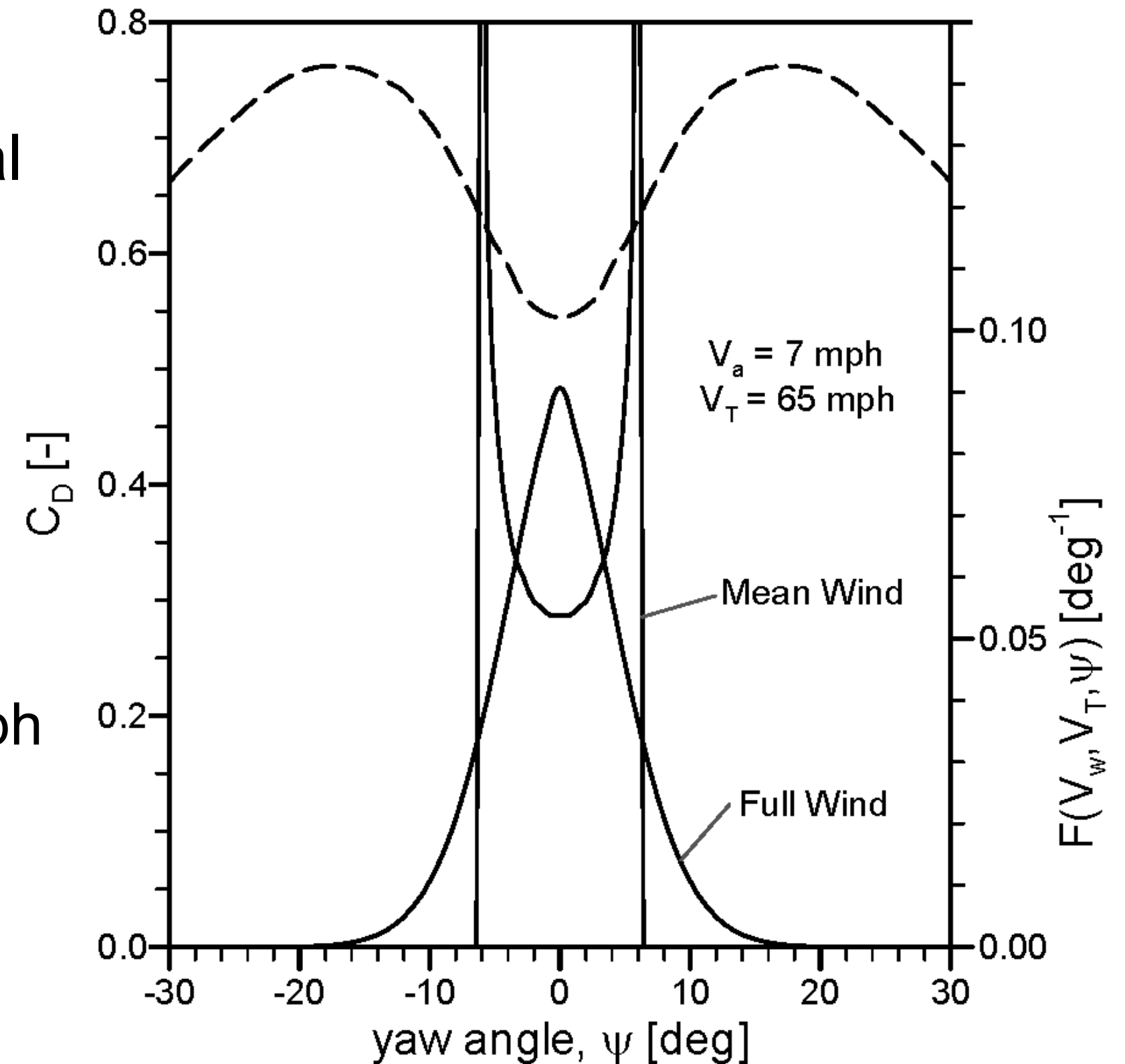
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- Very different yaw-weighting function



Mean Wind Distribution Method

- Neglect wind-speed distribution and assume average wind speed V_a with equal probability from any direction
- Very different yaw-weighting function
- Requires smaller yaw-angle range:
 - only $\pm 6.2^\circ$ for $V_T = 65$ mph and $V_a = 7$ mph



Mean Wind Distribution Method (SAE J1252)

- J1252-specified method uses ϕ increments of 30° for numerical integration
 - 12 wind directions
 - Neglects yaw angles within $\pm 1.4^\circ$ (for $V_T = 65$ mph and $V_a = 7$ mph)

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- Simplest of numerical integration methods
 - average of the integrand over the 12 discrete angles: $\phi_i = \frac{\pi}{6}i - \frac{\pi}{12}$

$$M_i = 1 + \left(\frac{V_a}{V_T}\right)^2 + 2\left(\frac{V_a}{V_T}\right)\cos(\phi_i)$$

$$WAC_D(V_a, V_T) \approx \frac{1}{6} \sum_{i=1}^6 [C_D(\psi_i) M_i]$$

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not even trapezoidal integration?

Weighted Wind Distribution Method

- Generalization of method published by MIRA
- Simplified *Full-Wind* method using the *Mean-Wind* approach
 - Effectively a coarse integration approach

Weighted Wind Distribution Method

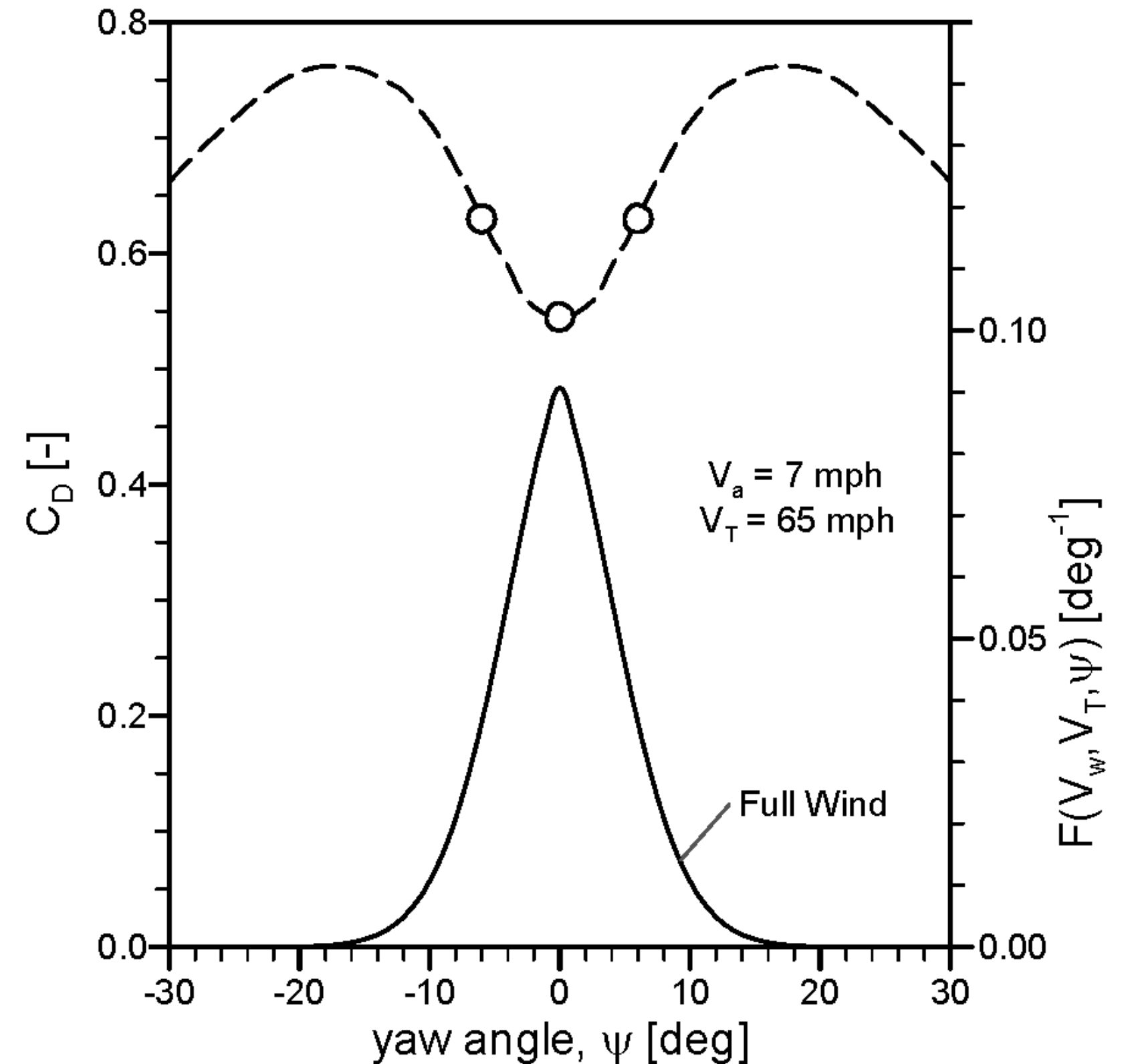
- Generalization of method published by MIRA
- Simplified *Full-Wind* method using the *Mean-Wind* approach
 - Effectively a coarse integration approach
- Calculate WAC_D for 6 or 7 discrete wind speeds at a given ground speed, then add together with appropriate weighting factors for each (*sum of weights = 1*)

3-Point Method

- Observed in many papers by Exa
- Simplified to represent a single condition:
 - Ground speed of 65 mph
 - Average wind speed of 7 mph

3-Point Method

- Observed in many papers by Exa
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- Average of data at 3 yaw angles (-6,0,+6)

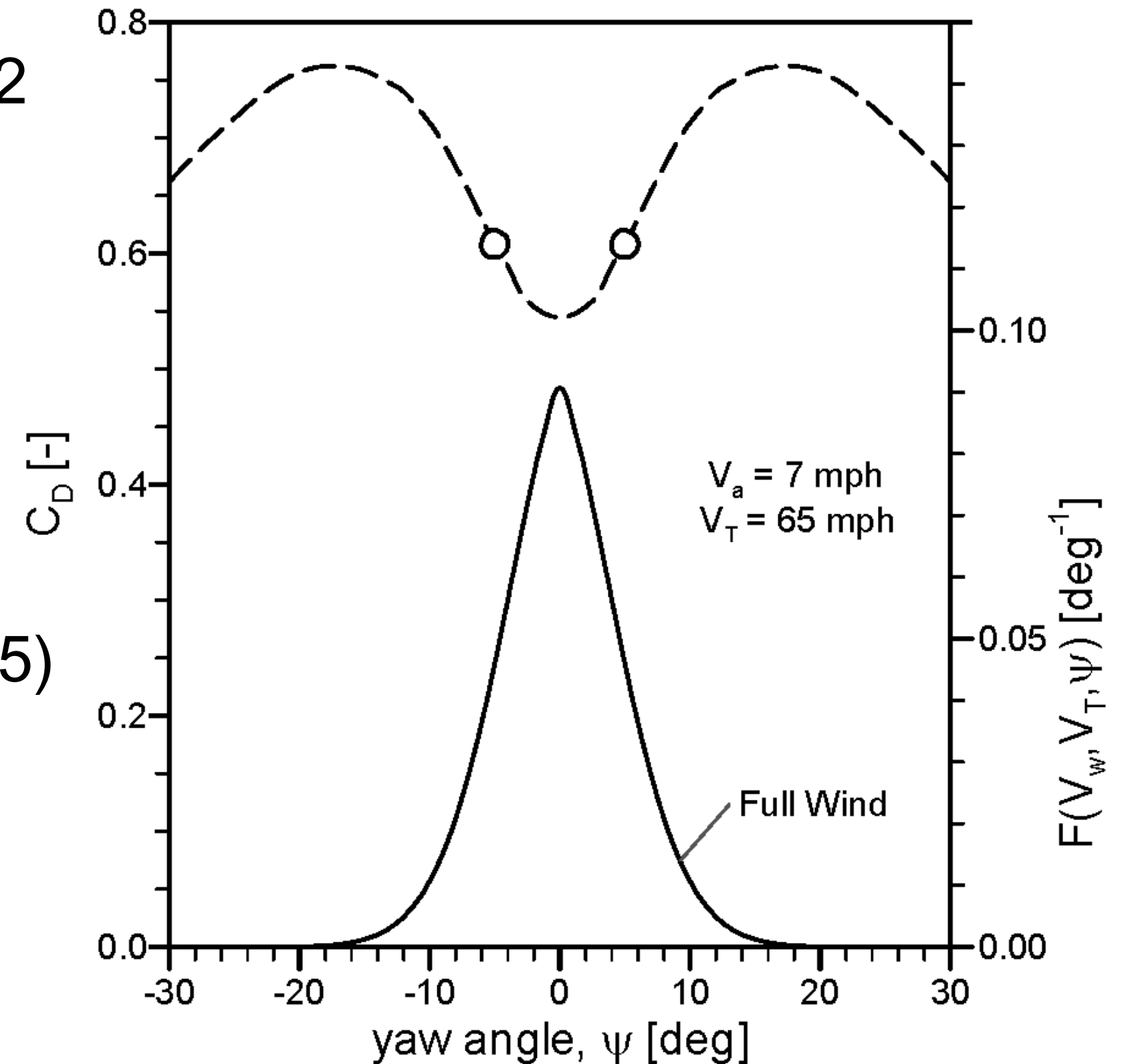


2-Point Method

- Method selected by EPA for GHG Phase 2
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2-Point Method

- Method selected by EPA for GHG Phase 2
- Simplified to represent a single condition:
 - Ground speed of 65 mph
 - Average wind speed of 7 mph
- Average of data at 2 yaw angles (-4.5,+4.5)



How to Compare the Methods

1. Specific sets of prototype C_D vs. yaw curves
 2. Statistics from entire wind-tunnel test program
- Compare the following values
- Absolute values, WAC_D
 - Difference from a reference case, ΔWAC_D

How to Compare the Methods

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- Compare the following values
 - Absolute values, WAC_D
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Assume the ***Full-Wind*** Distribution Method provides the true value

- Errors from *Full-Wind* values represented by δWAC_D and $\delta \Delta WAC_D$

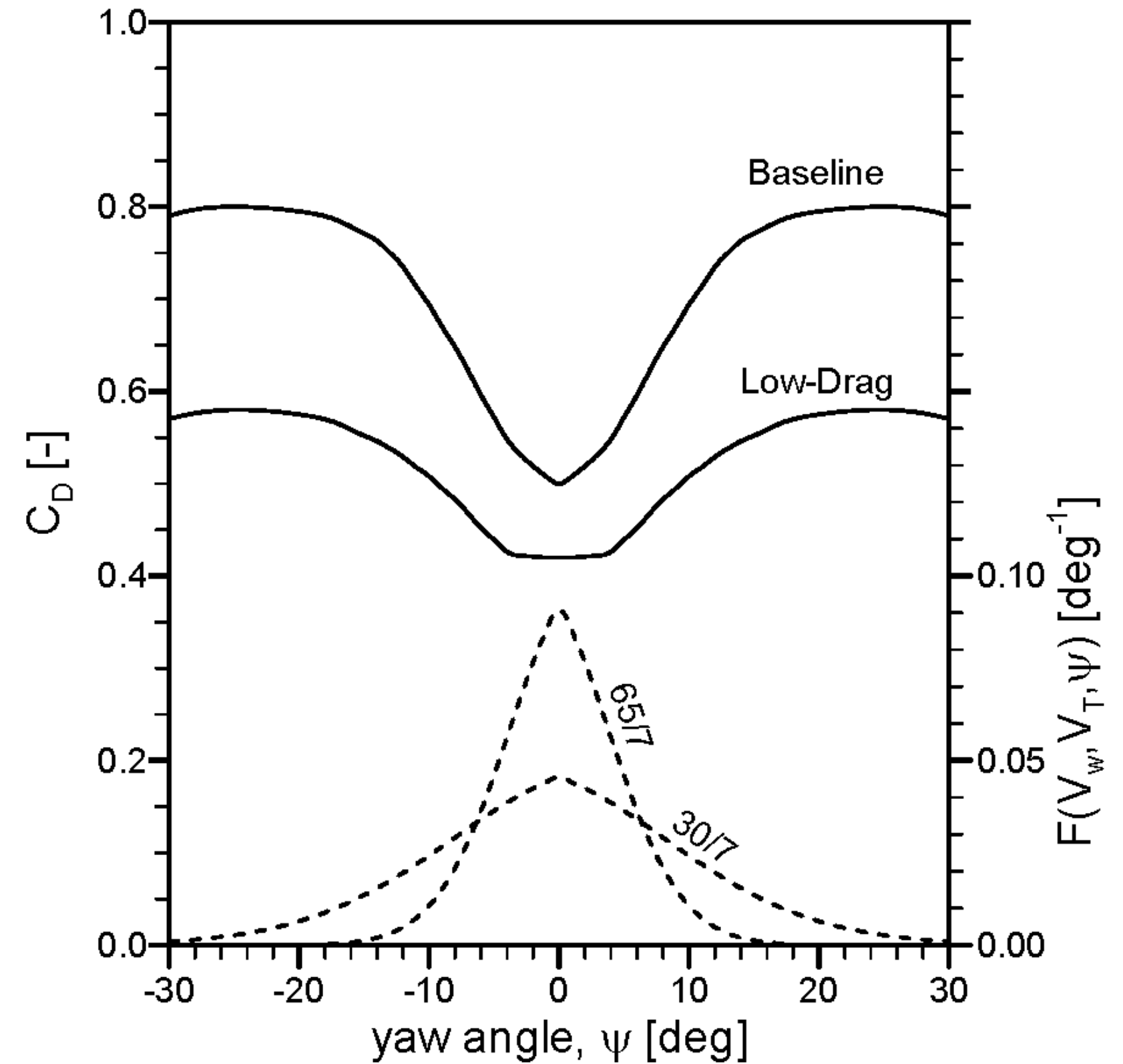
Results Comparison – Prototype Configurations

- Sleeper-cab tractor + 53 ft dry-van trailer
- Changes:
 - Addition of side-skirts + boat-tail



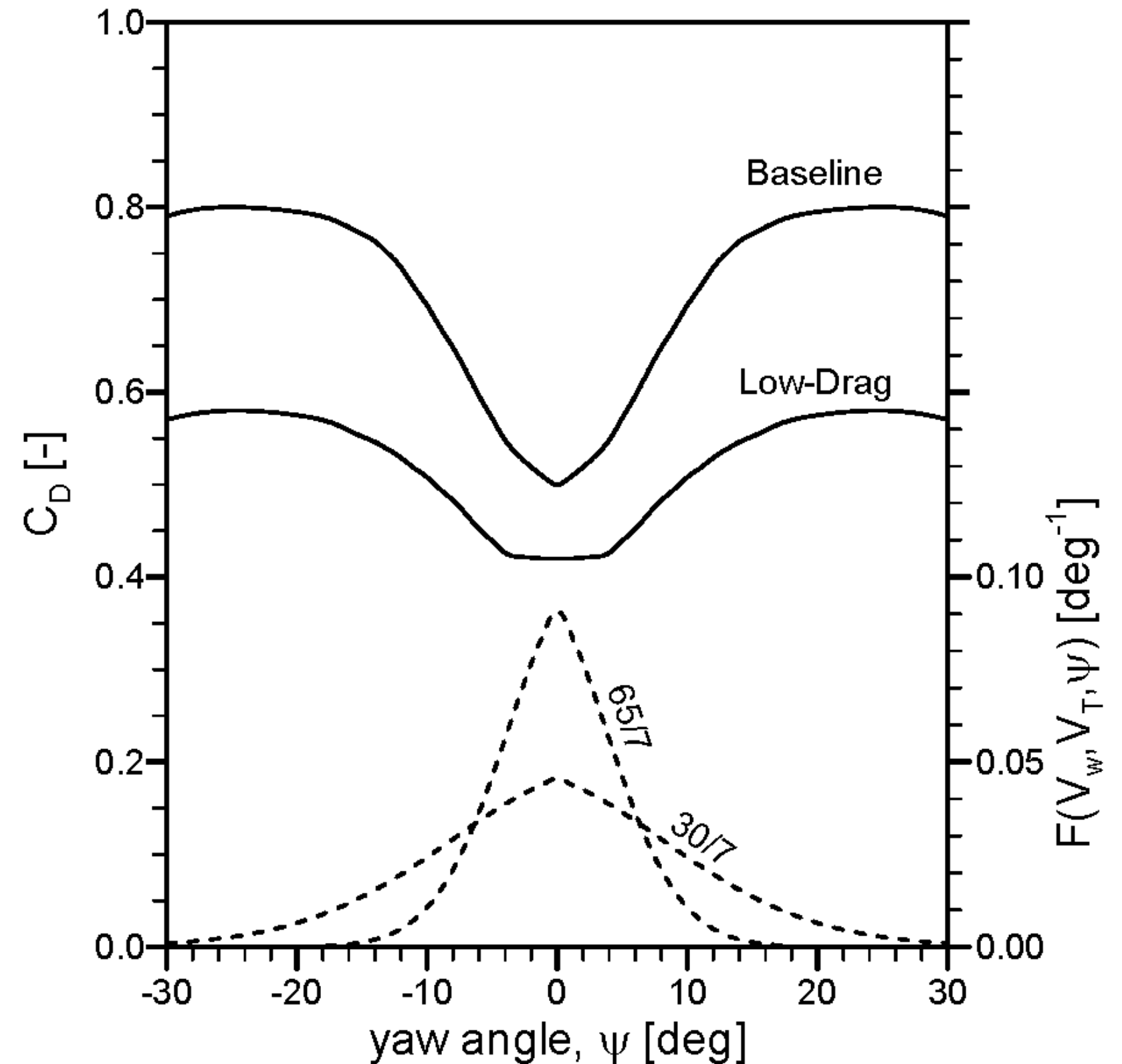
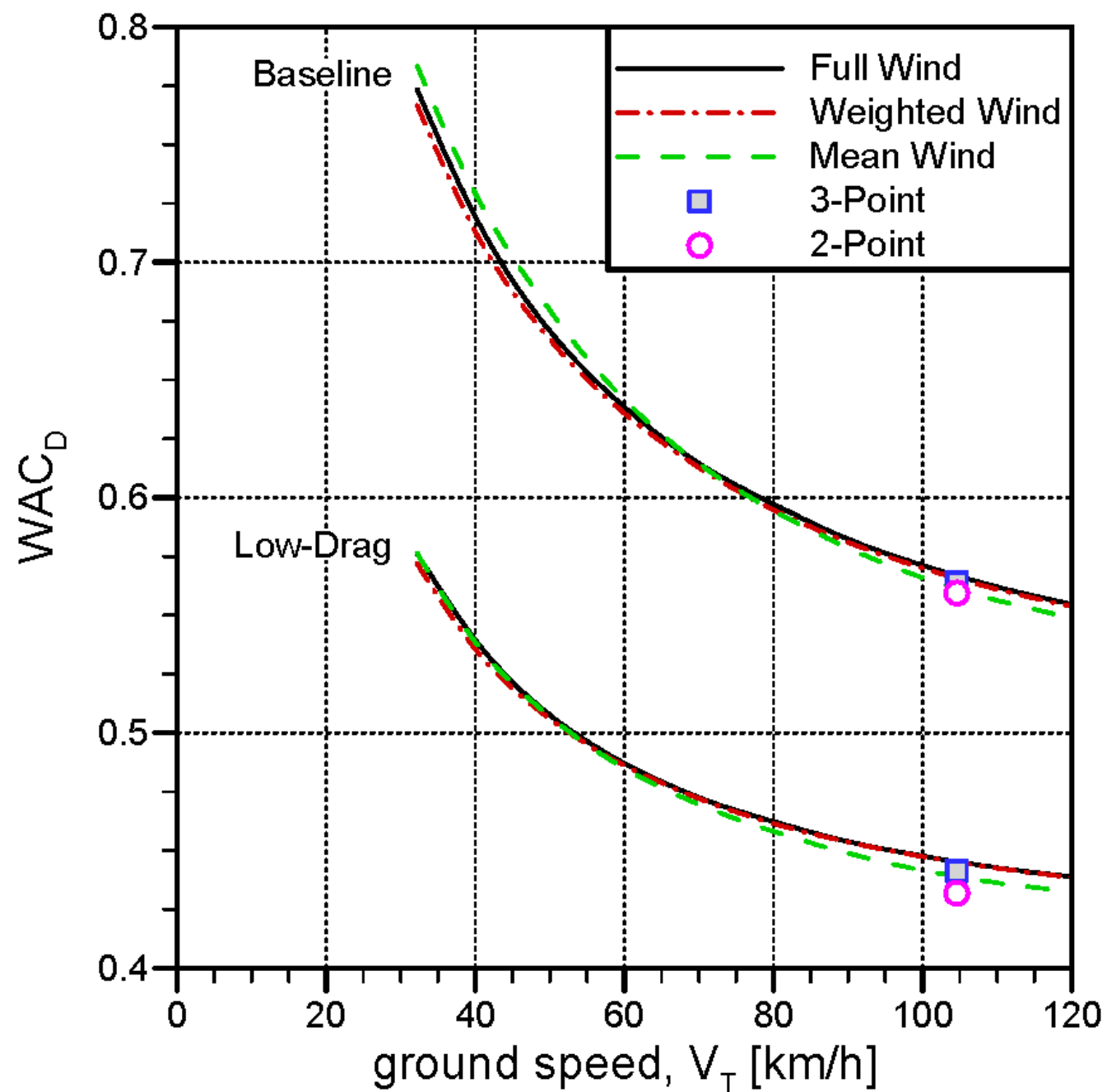
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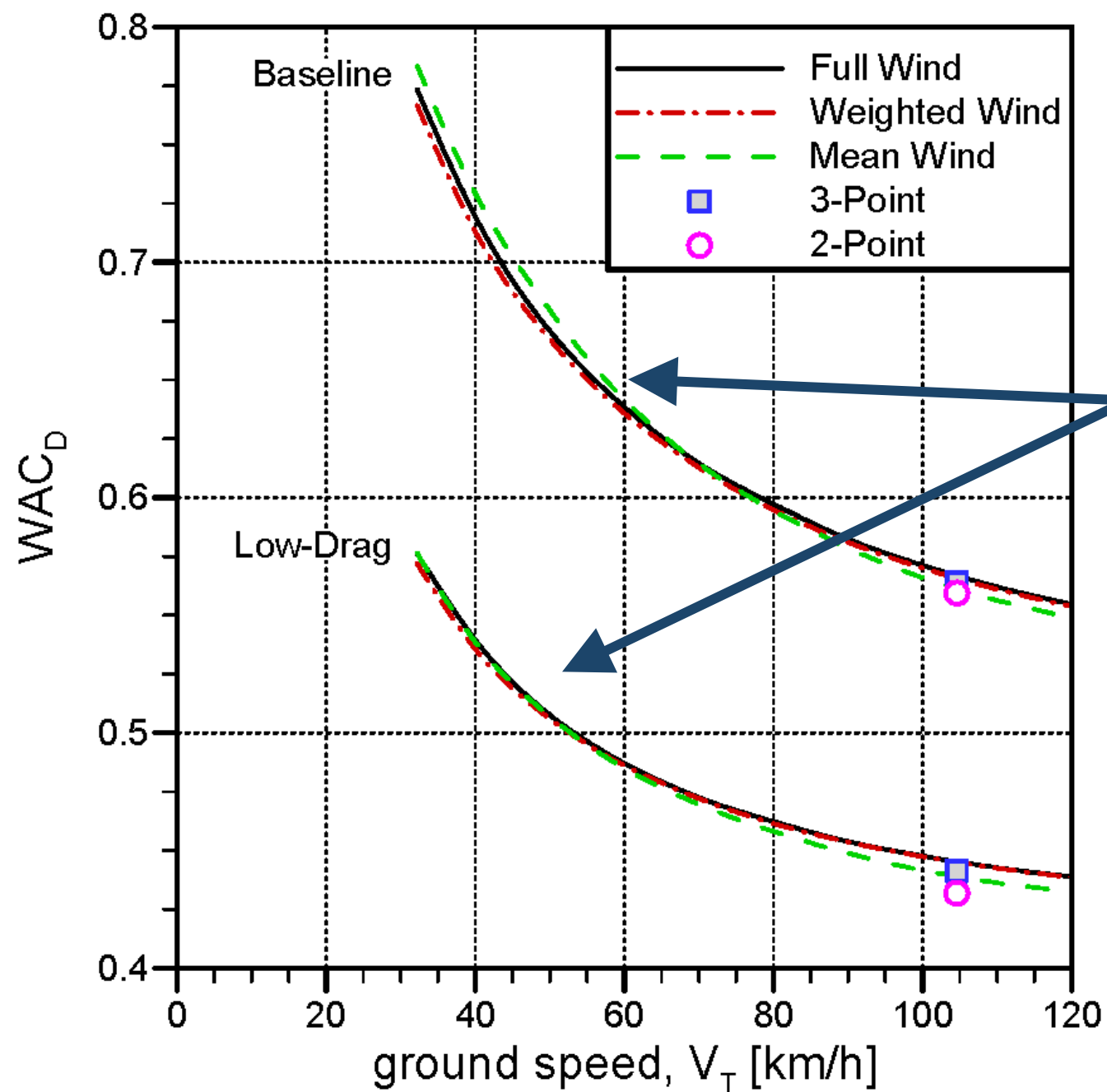
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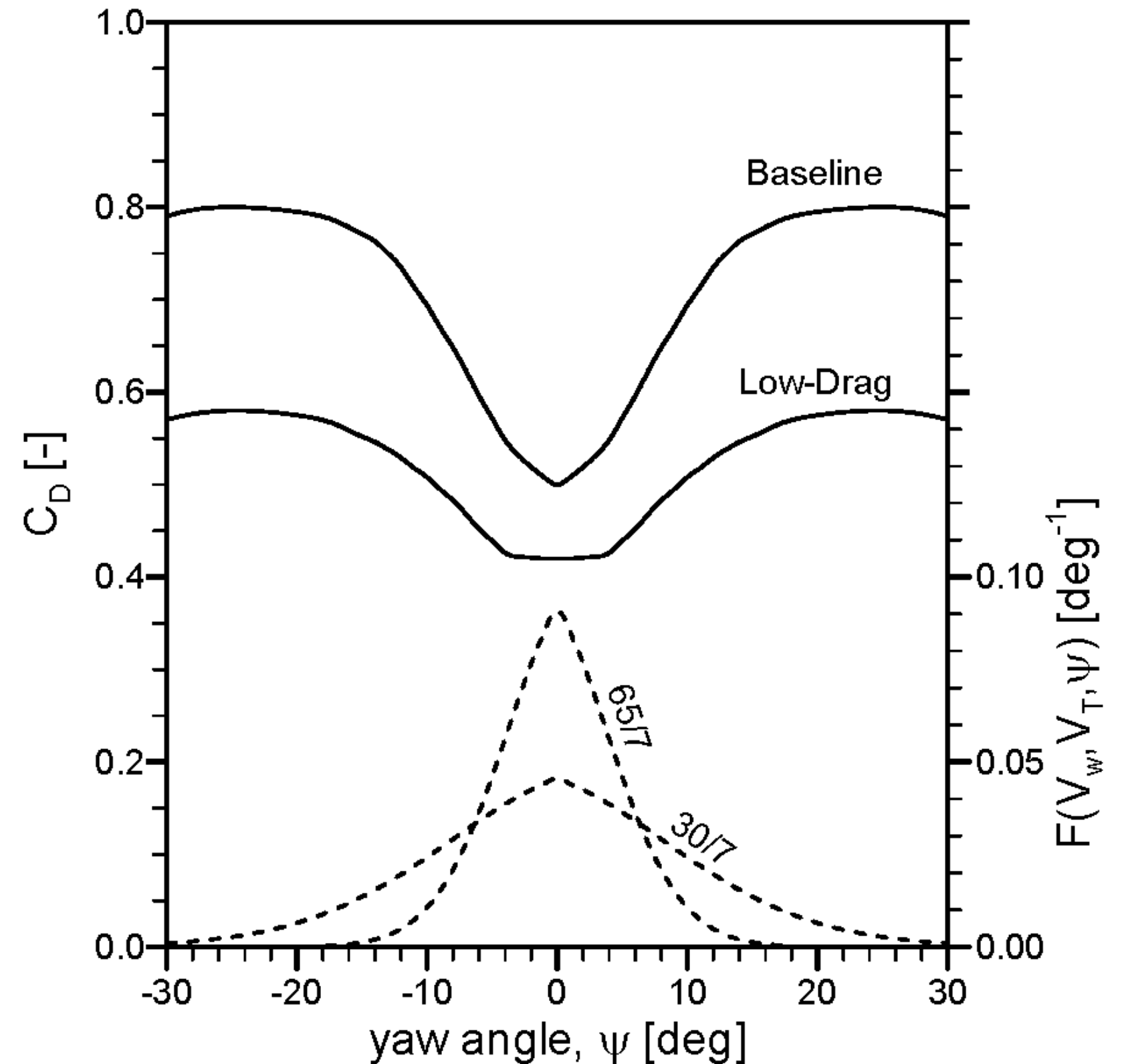


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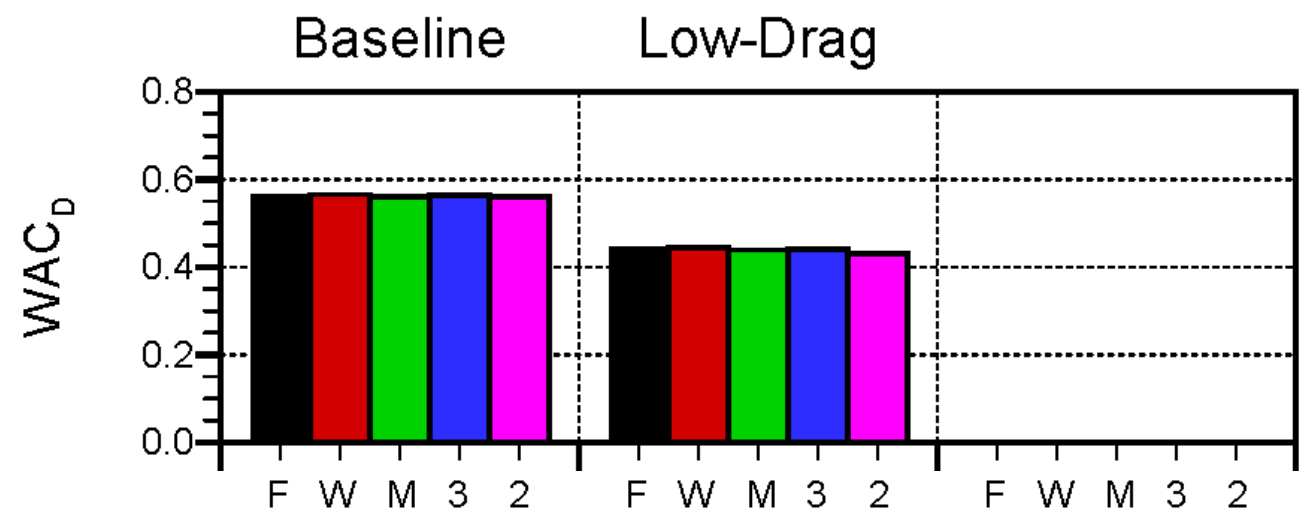
ground-speed variation characterized well by all integration methods



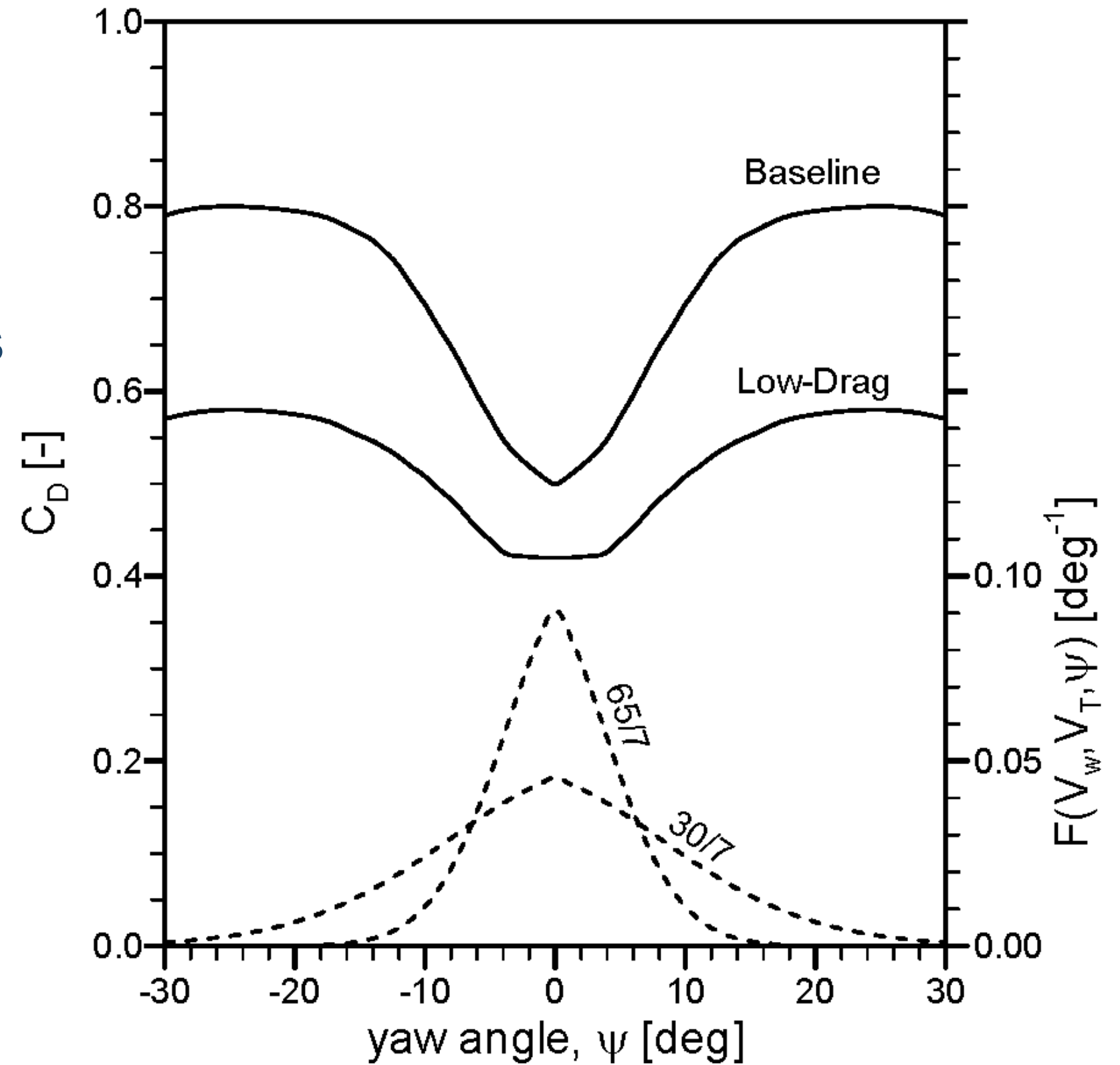
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➤ Sleeper-cab tractor + 53 ft dry-van trailer

$V_T = 65 \text{ mph}$, $V_a = 7 \text{ mph}$



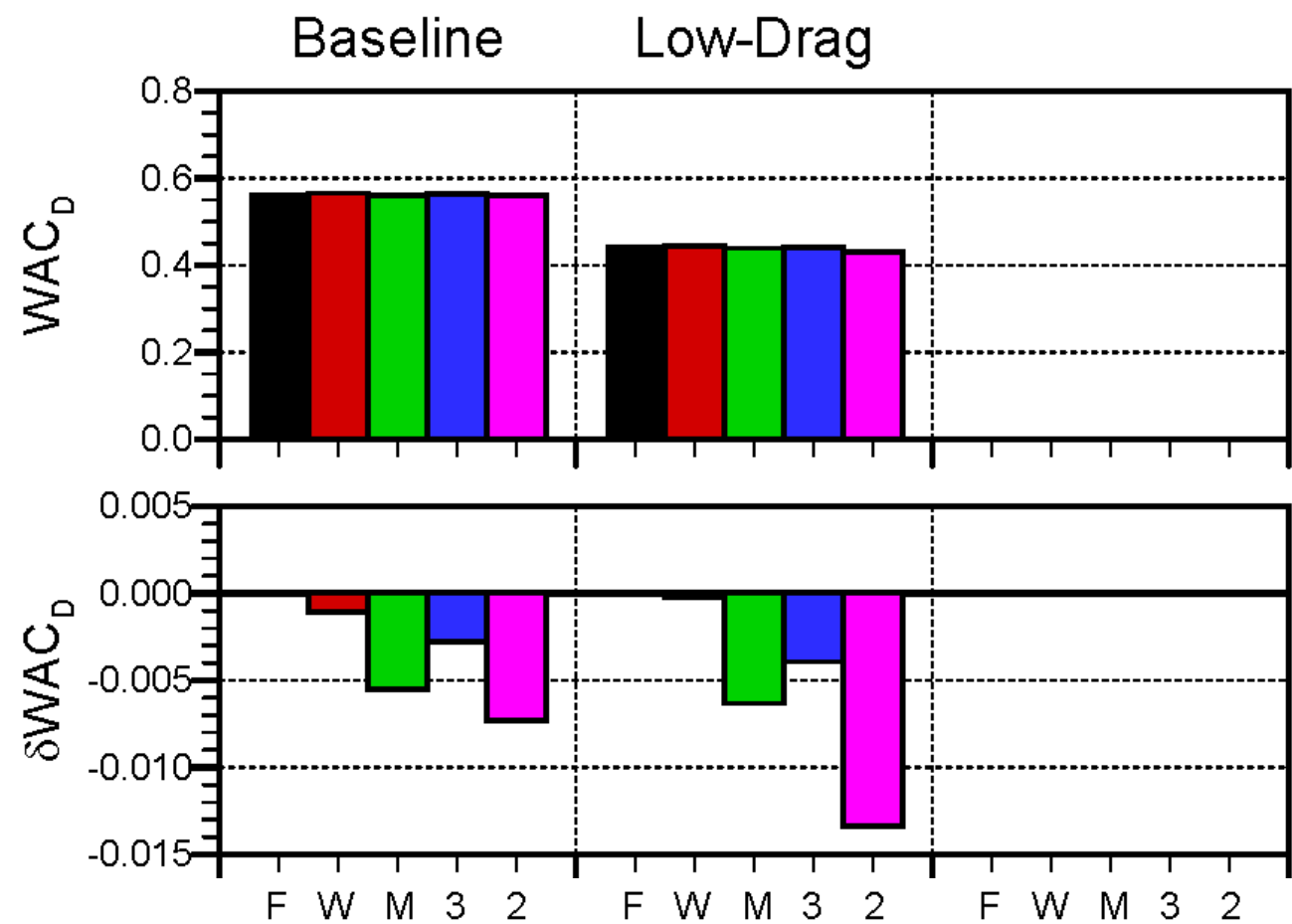
absolute values



Results Comparison – Prototype Configurations

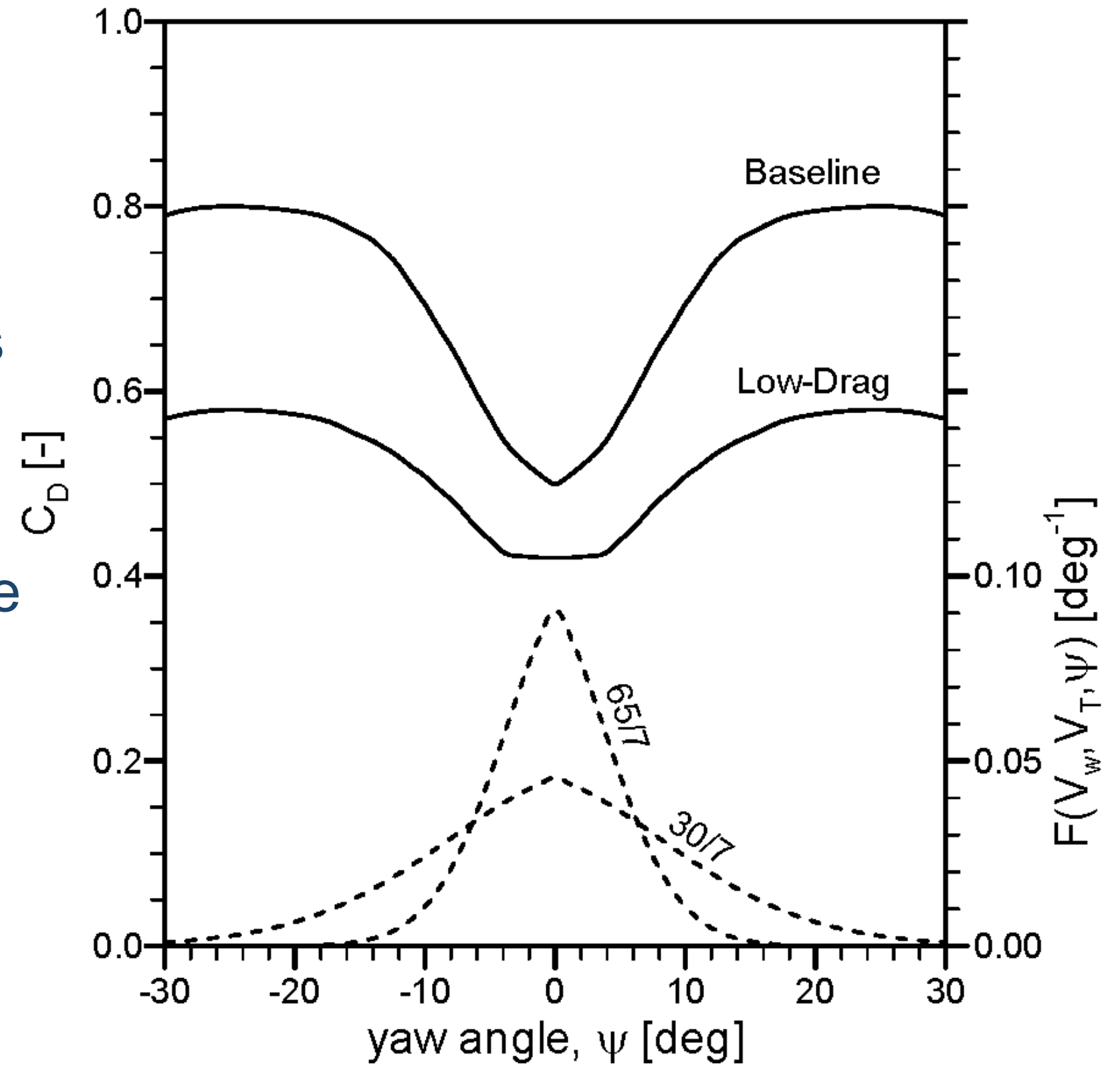
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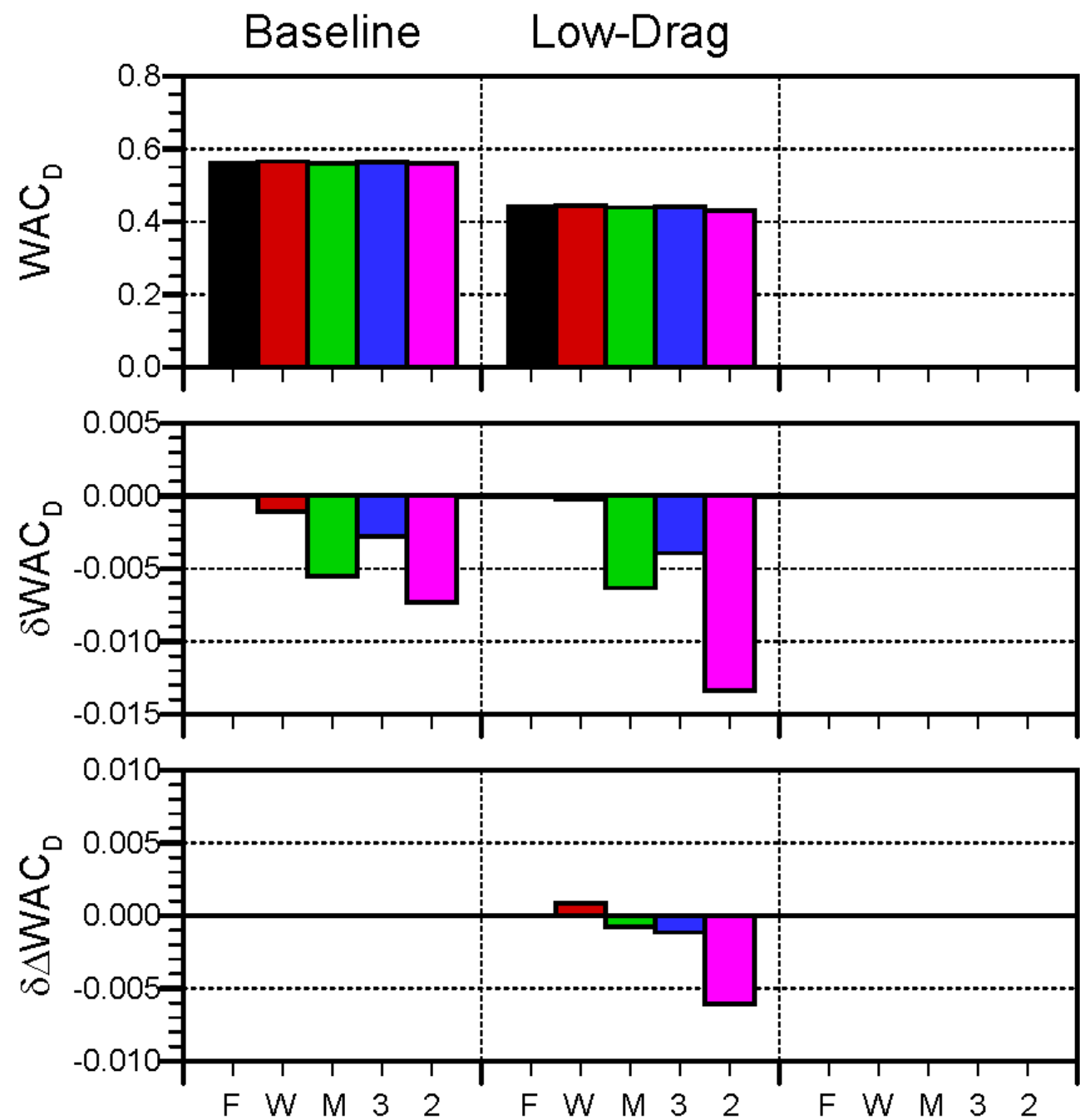
error in absolute values



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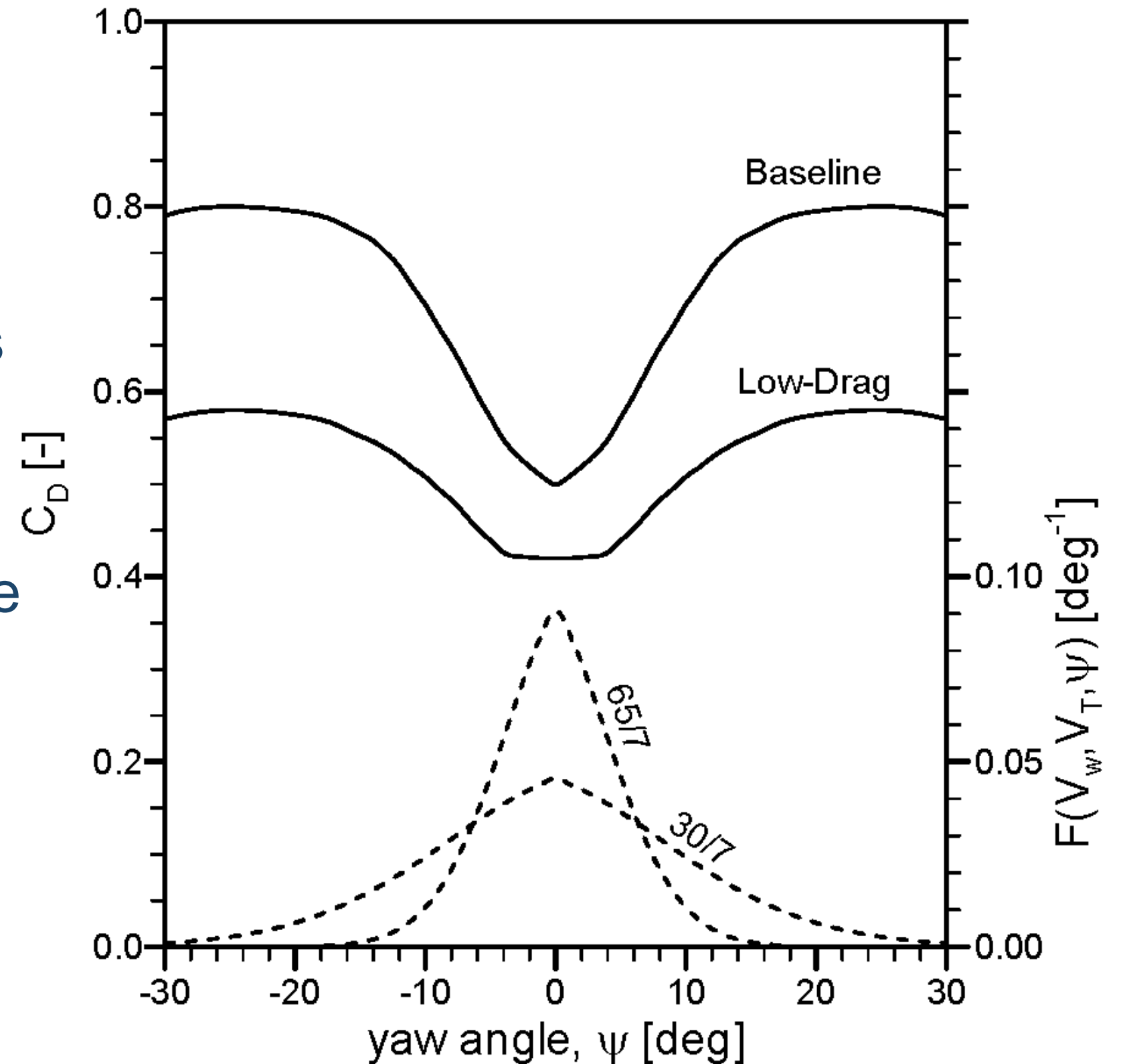
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absolute values

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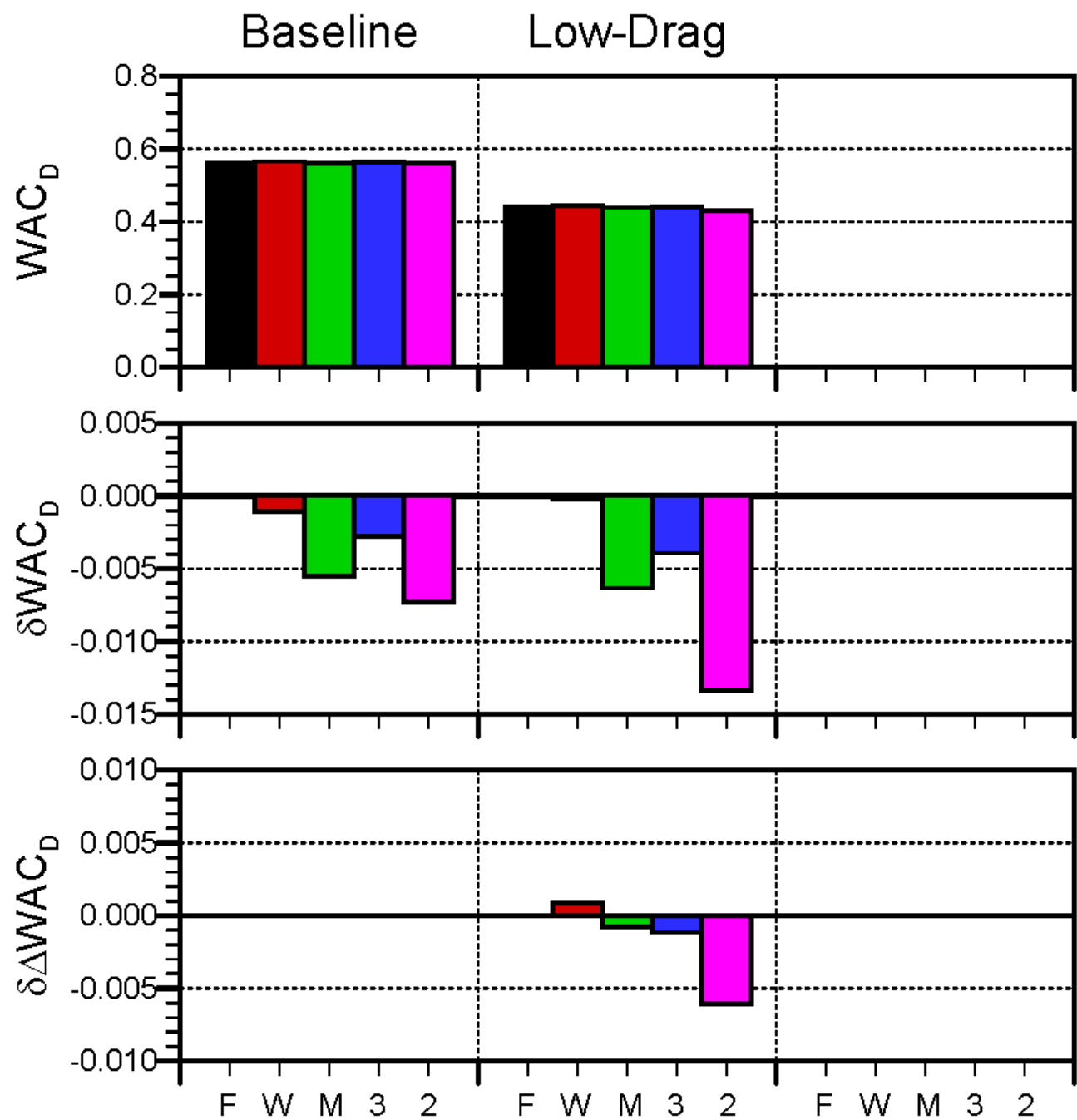
errors in differences



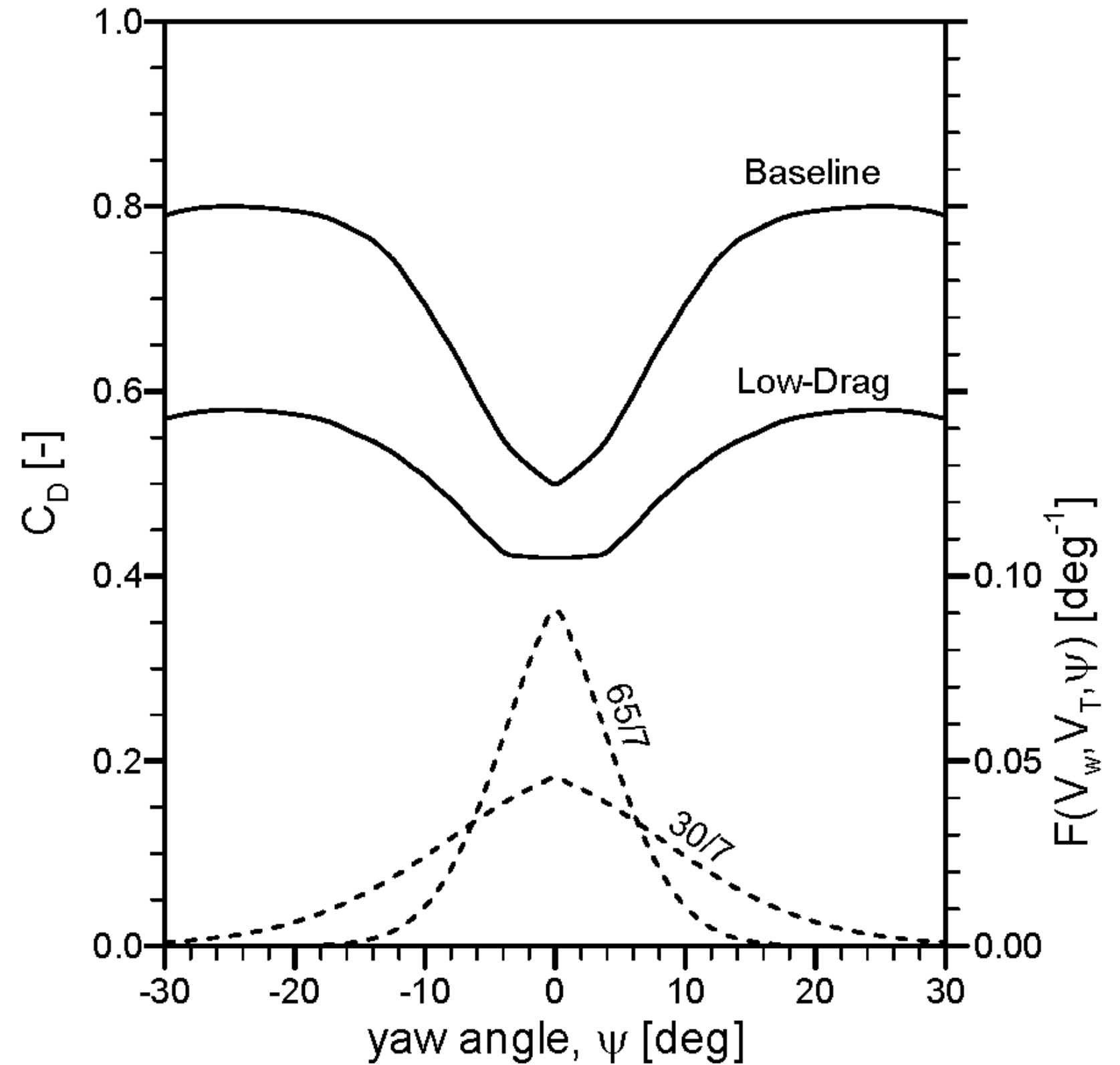
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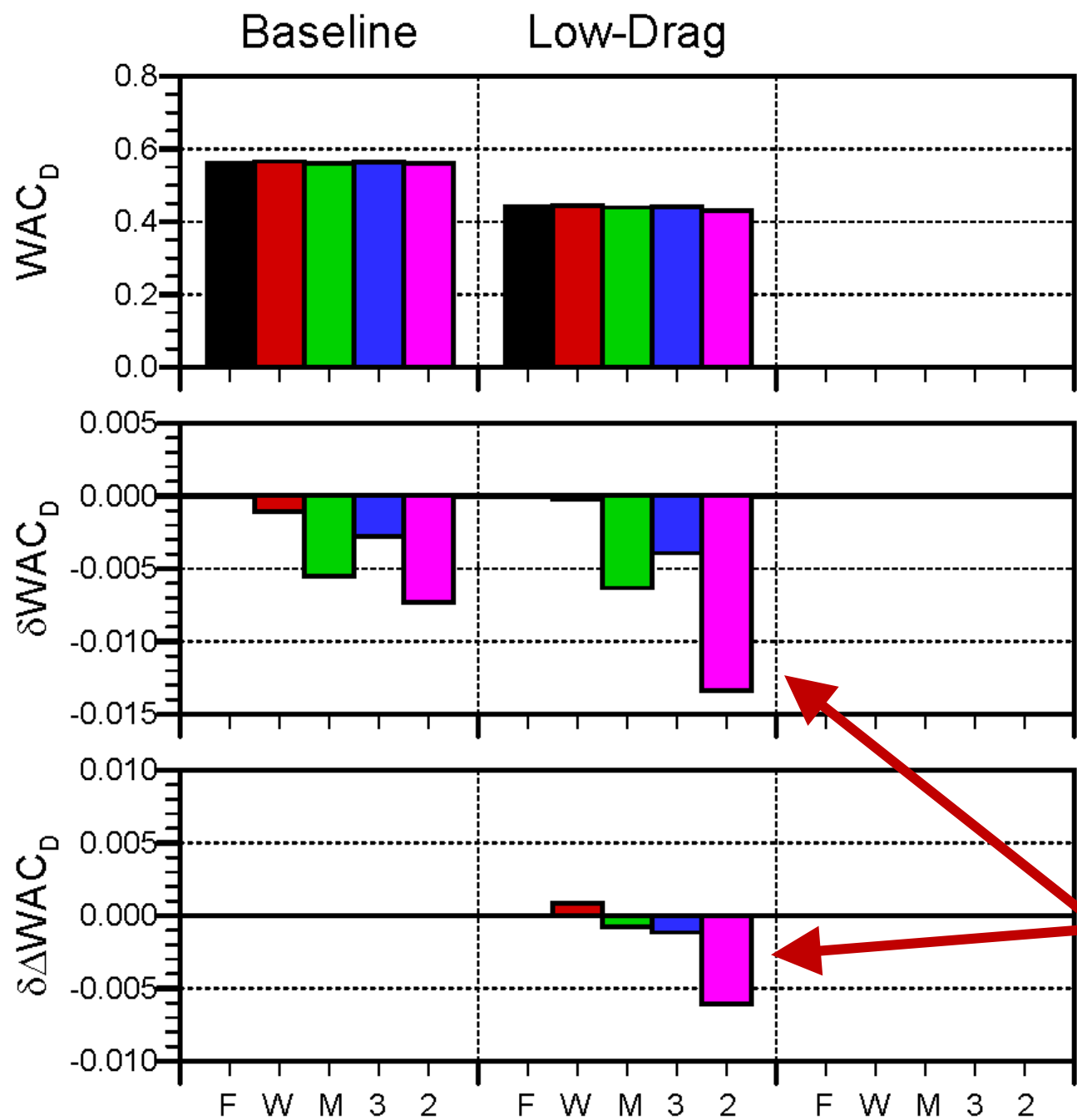
*larger errors
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Results Comparison – Prototype Configurations

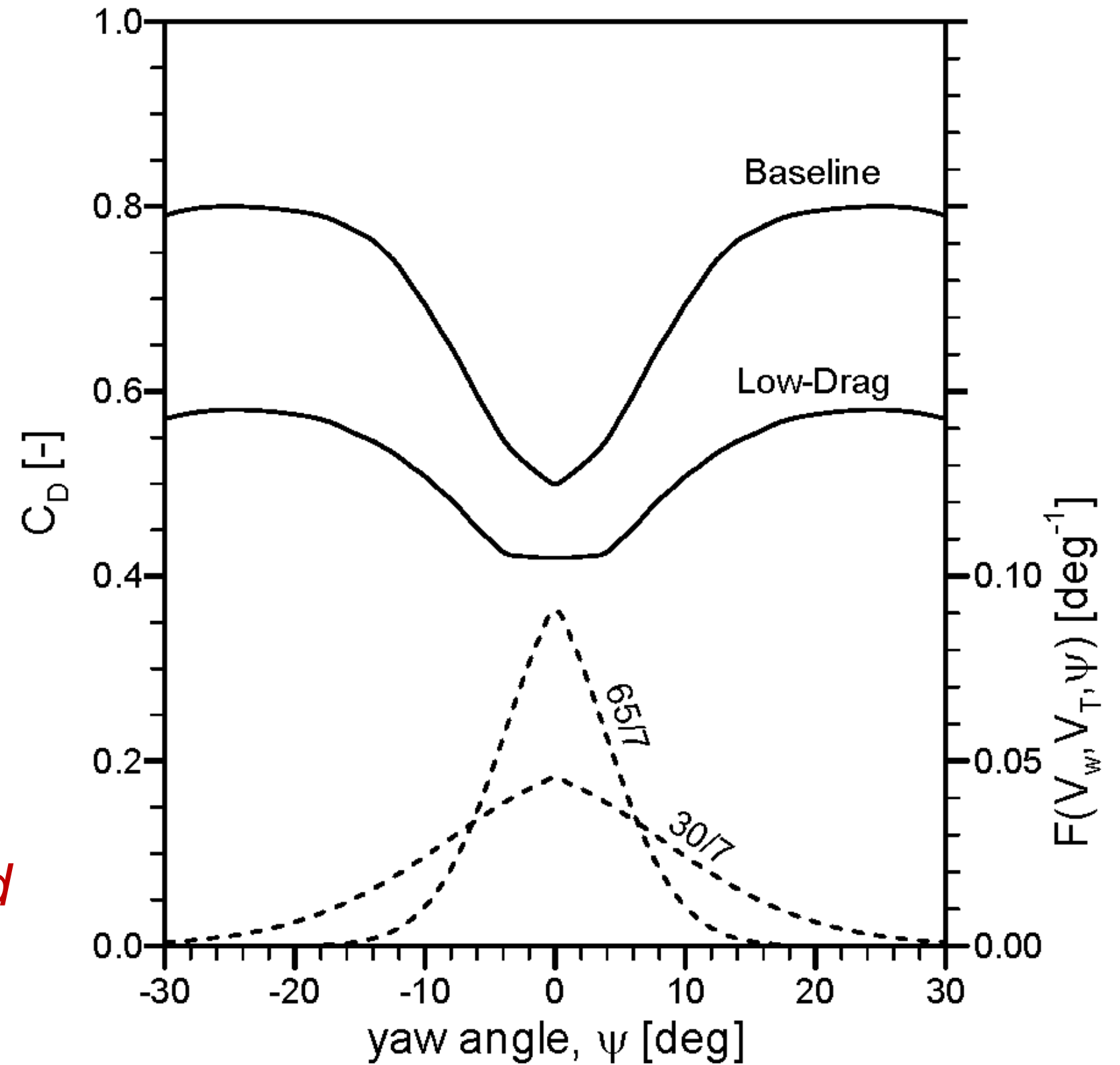
➤ Sleeper-cab tractor + 53 ft dry-van trailer

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larger errors in absolutes than in differences

2-Point method shows largest errors

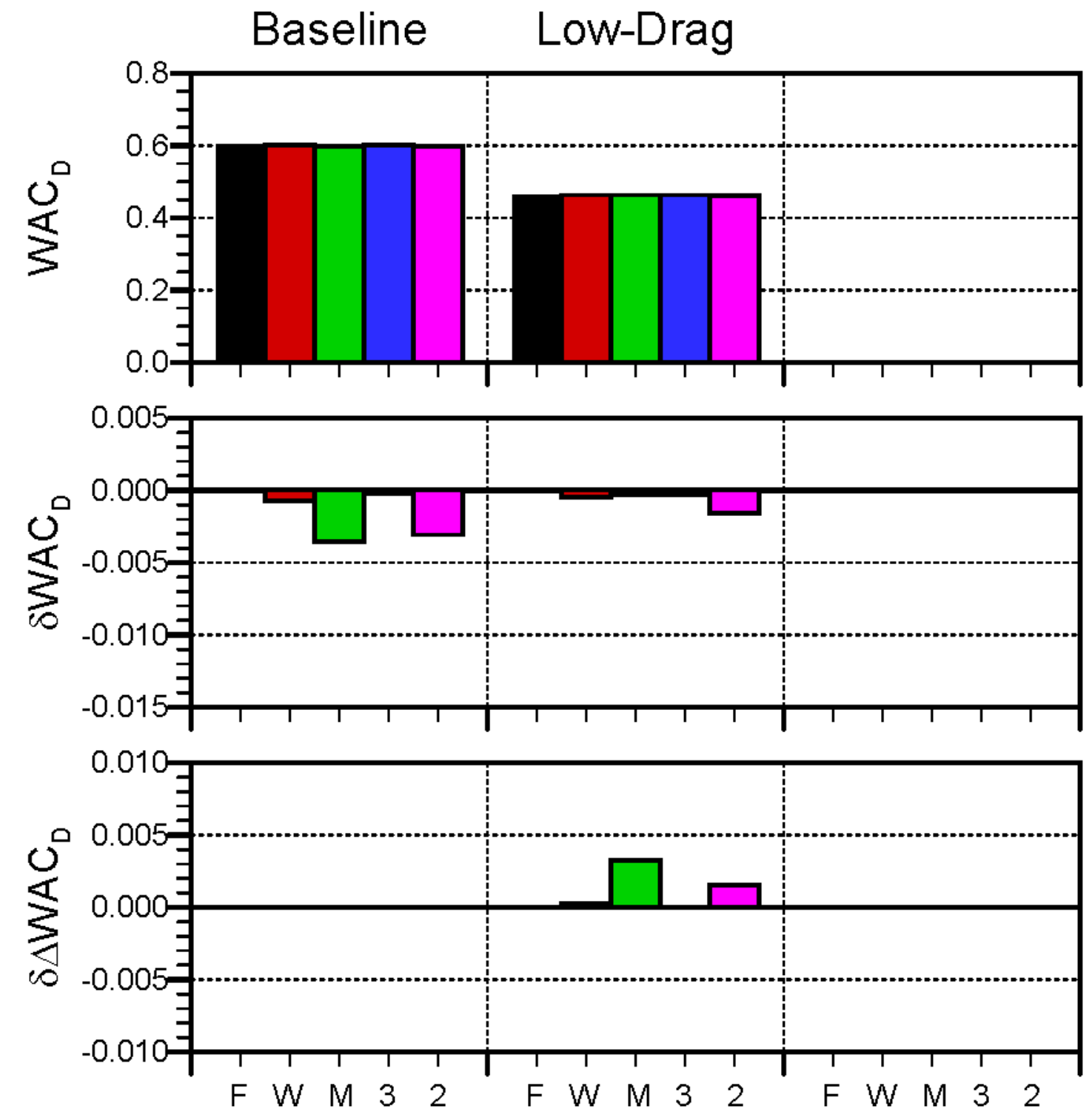


Results Comparison – Prototype Configurations

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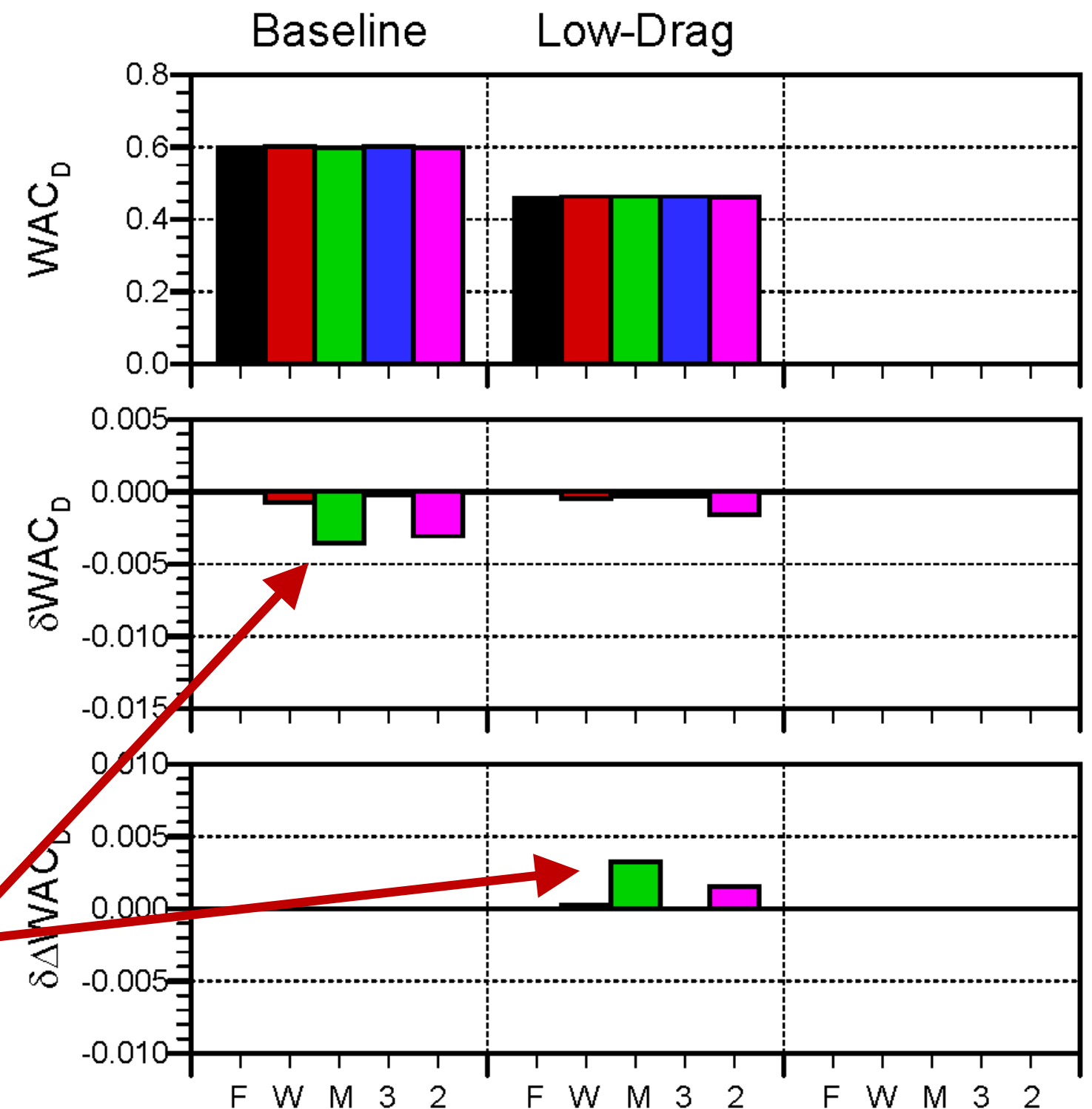
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Mean Wind method shows largest errors

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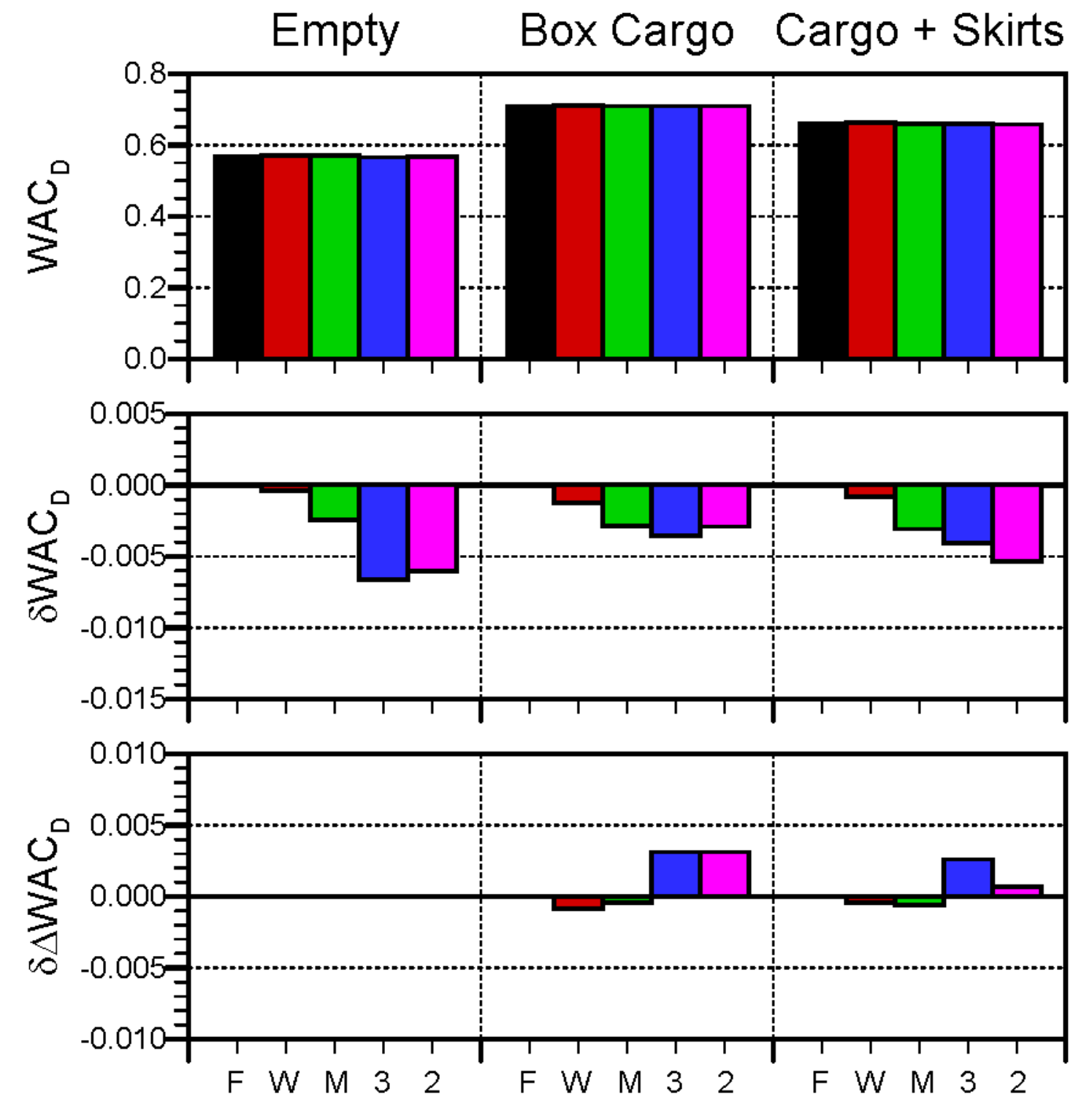


Results Comparison – Prototype Configurations

- Sleeper-cab tractor + 53 ft flat-bed trailer
- Changes:
 - Addition of cargo +/- side-skirts



$V_T = 65$ mph, $V_a = 7$ mph



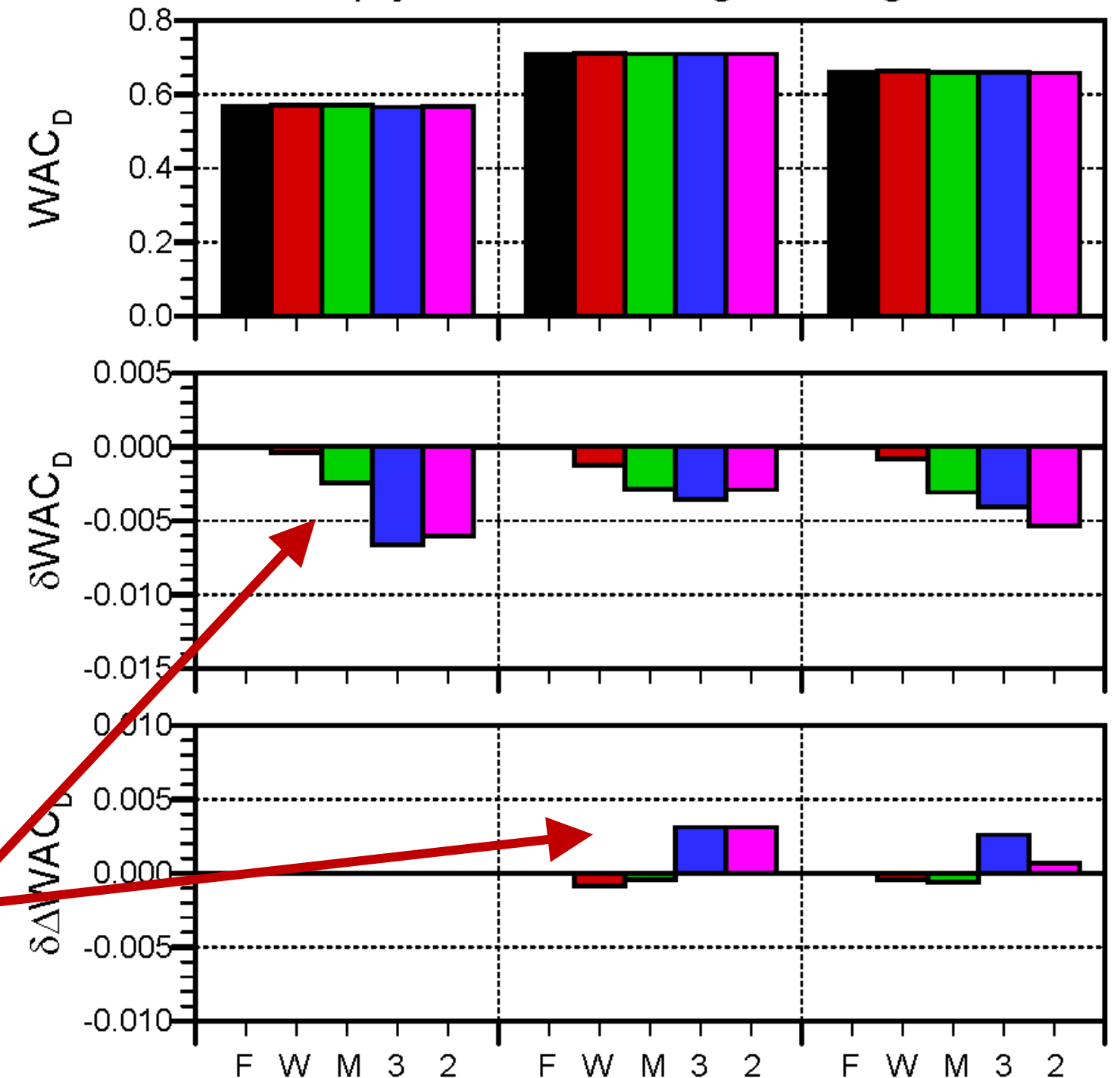
Results Comparison – Prototype Configurations

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$V_T = 65$ mph, $V_a = 7$ mph

Empty Box Cargo Cargo + Skirts



2- & 3-Point method shows largest errors

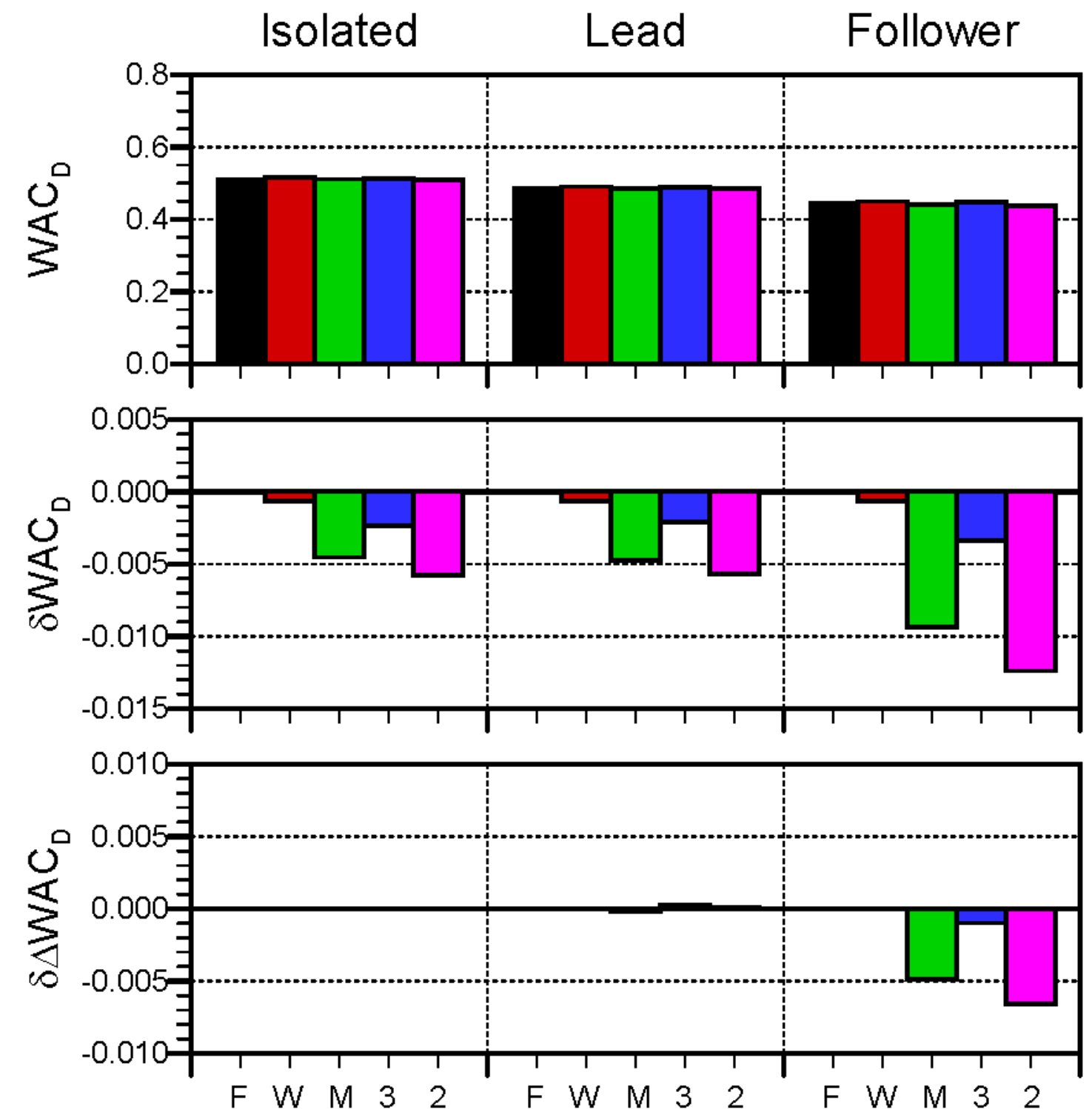
Results Comparison – Prototype Configurations

➤ 2-Truck Platoon

- 10.5 m (34 ft) spacing



$$V_T = 65 \text{ mph}, V_a = 7 \text{ mph}$$



Results Comparison – Prototype Configurations

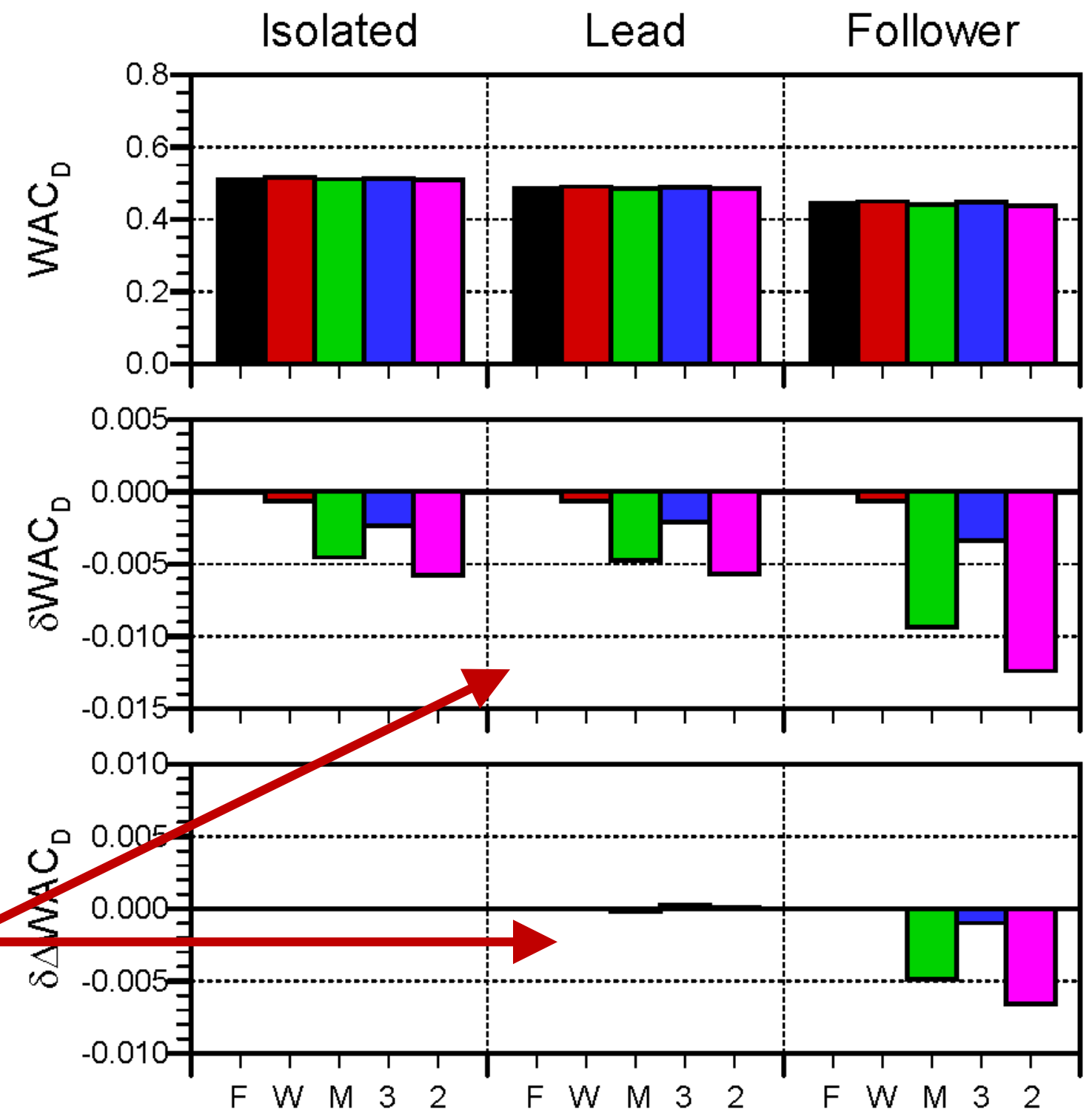
➤ 2-Truck Platoon

- 10.5 m (34 ft) spacing



Mean Wind & 2-Point methods shows largest errors

$V_T = 65$ mph, $V_a = 7$ mph



Results Comparison – Full Test Program

- 89 test cases

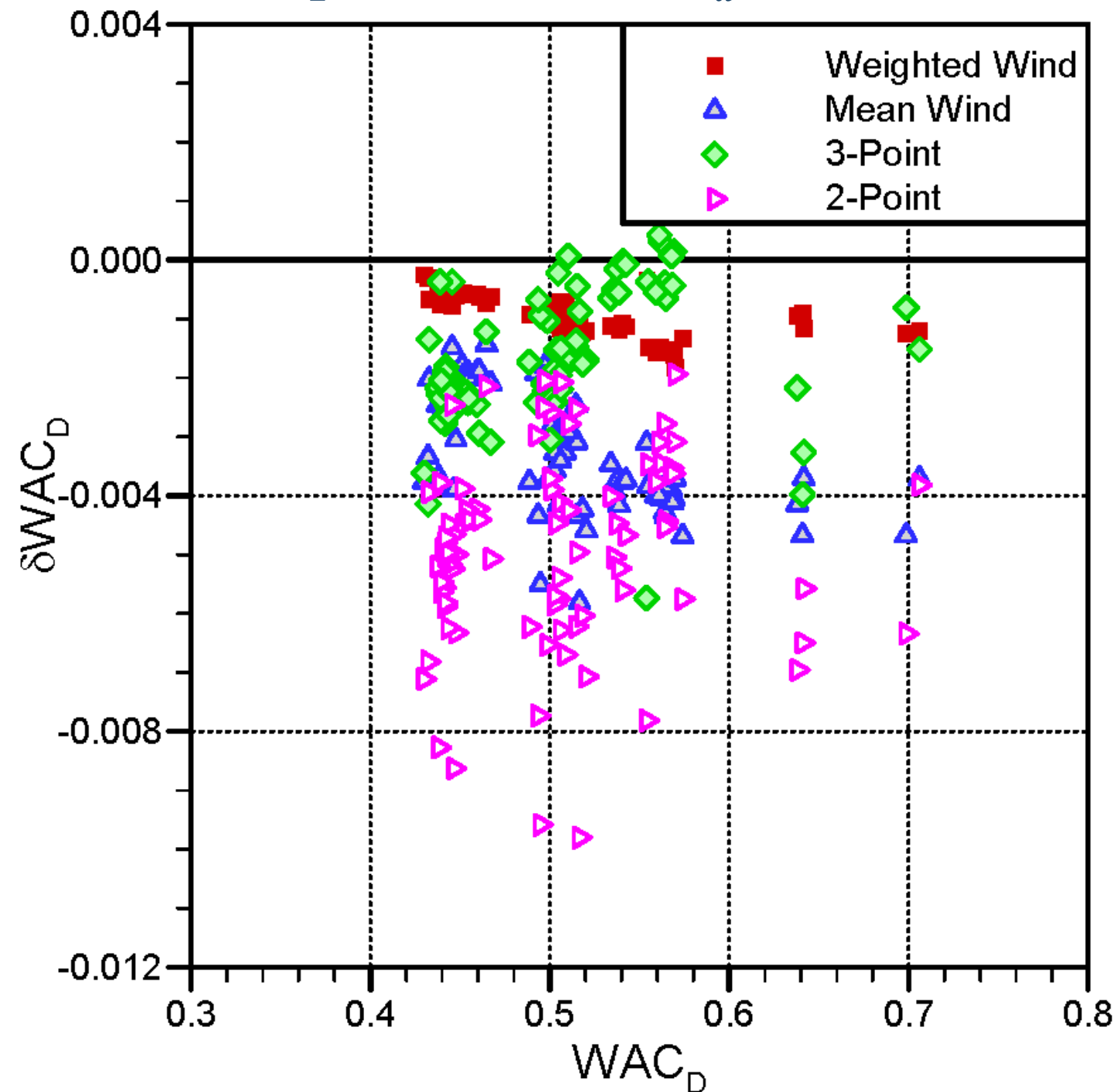
- Tractor Variants:
 - Sleeper-cab and day-cab

- Trailer Variants:
 - Dry-van, reefer, and flatbed

- Configuration Variants:
 - Side-skirts, boat-tails, bogie-fairings, trailer front fairing, bogie movements

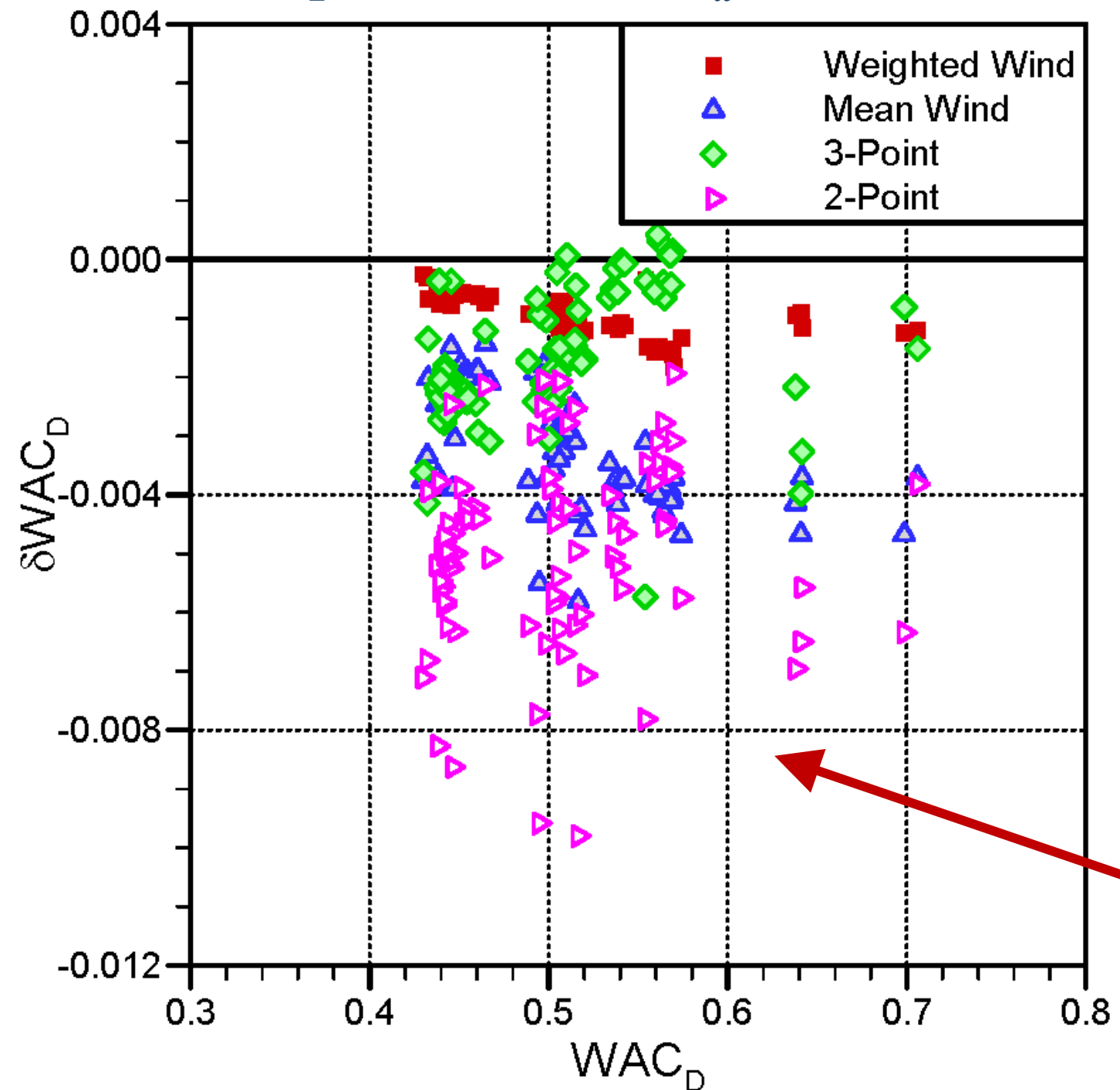
Results Comparison – Full Test Program

Error in **Absolute Values**
 $V_T = 65$ mph, $V_a = 7$ mph



Results Comparison – Full Test Program

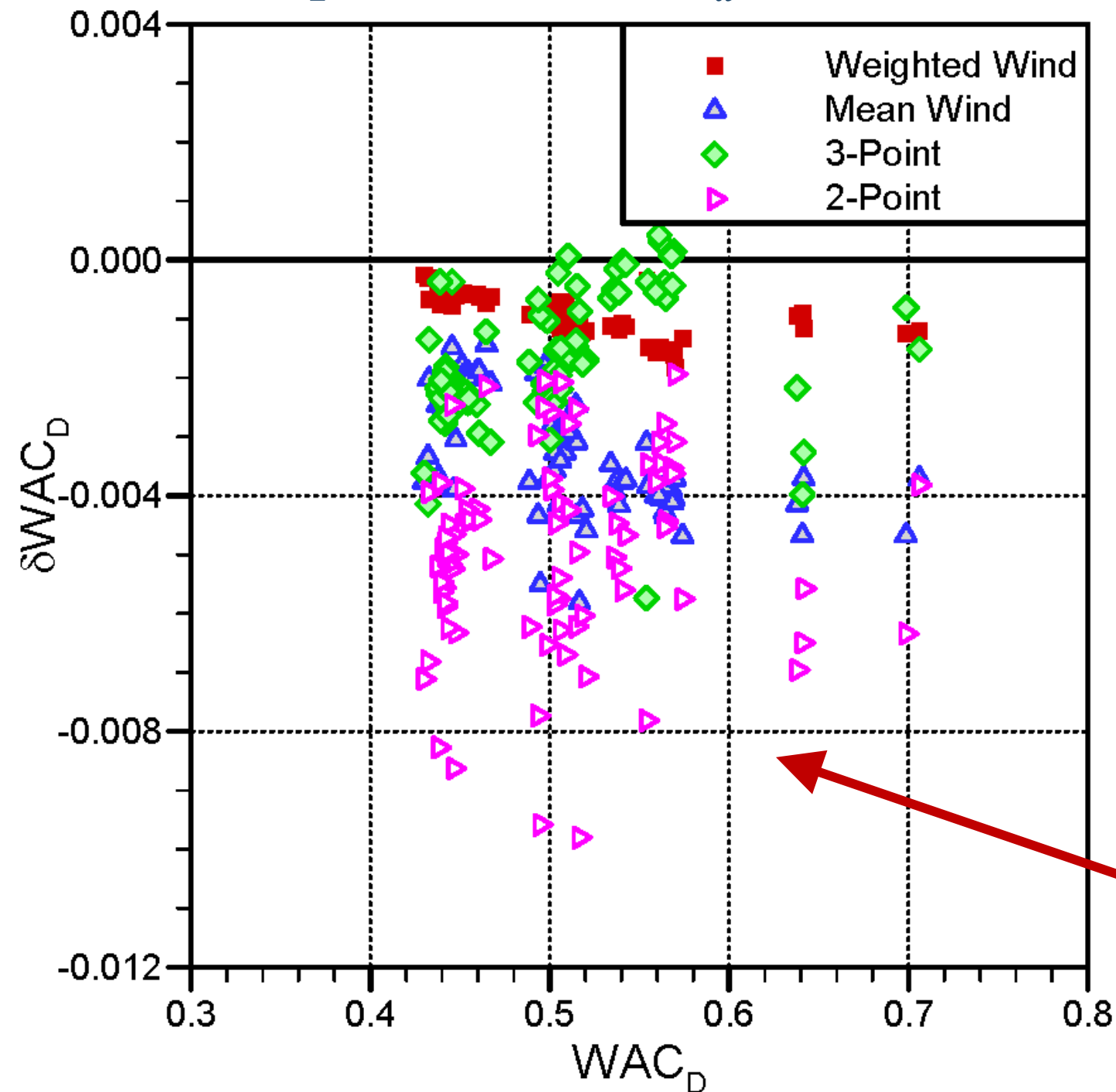
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Simplifications lead to low estimates of WAC_D

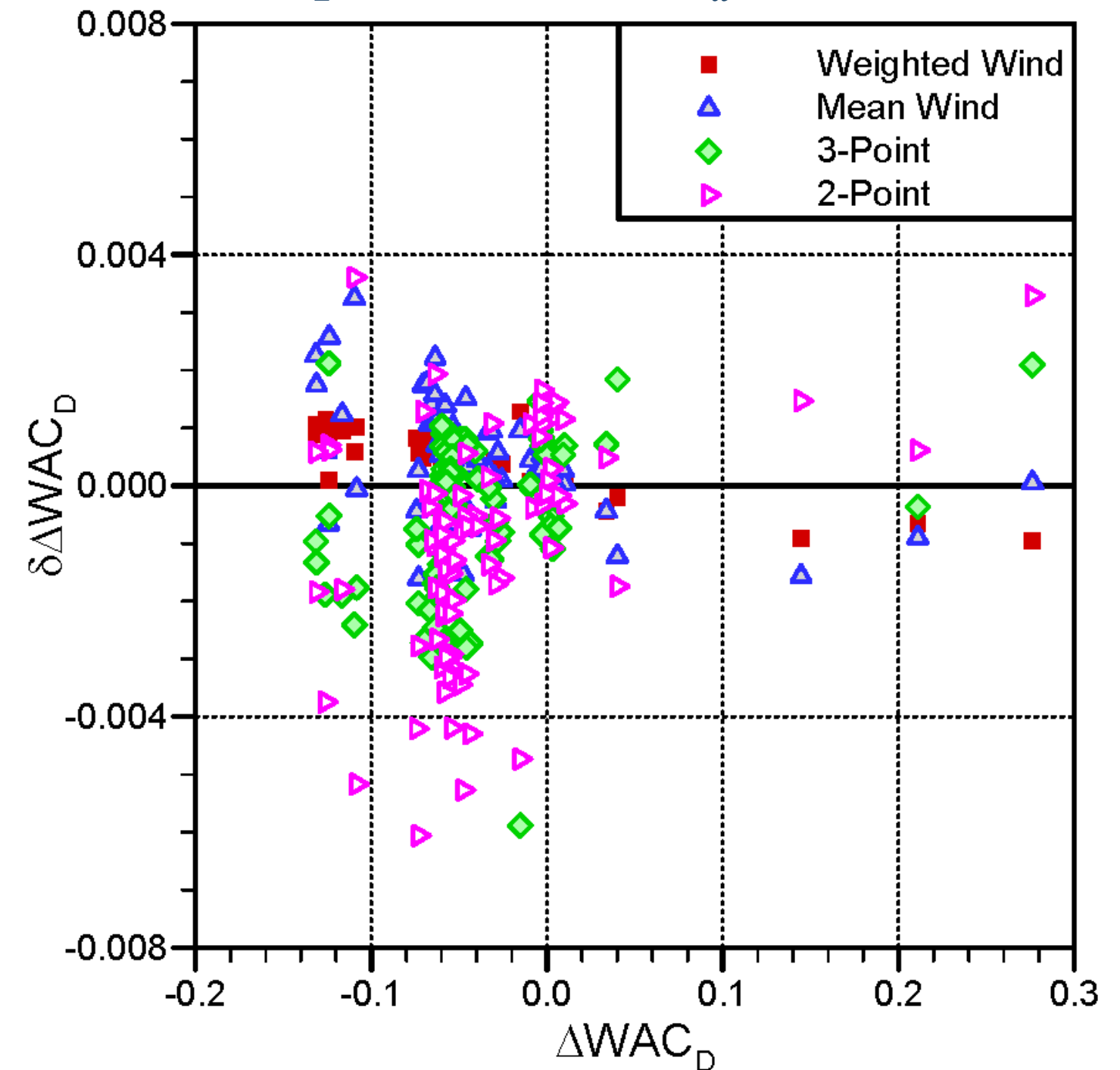
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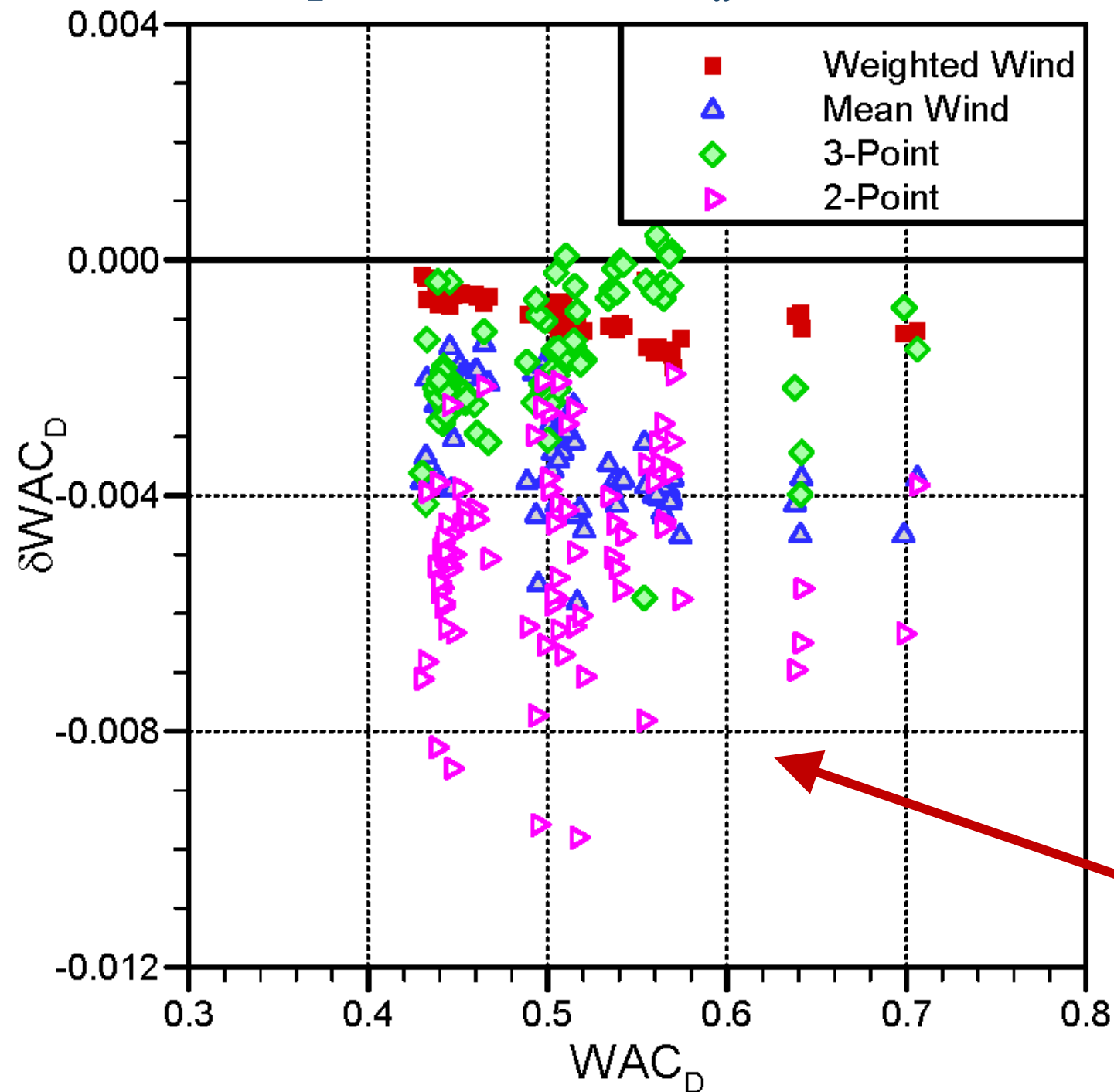
*Simplifications
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estimates of
 WAC_D*

Error in **Difference Values**
 $V_T = 65$ mph, $V_a = 7$ mph



Results Comparison – Full Test Program

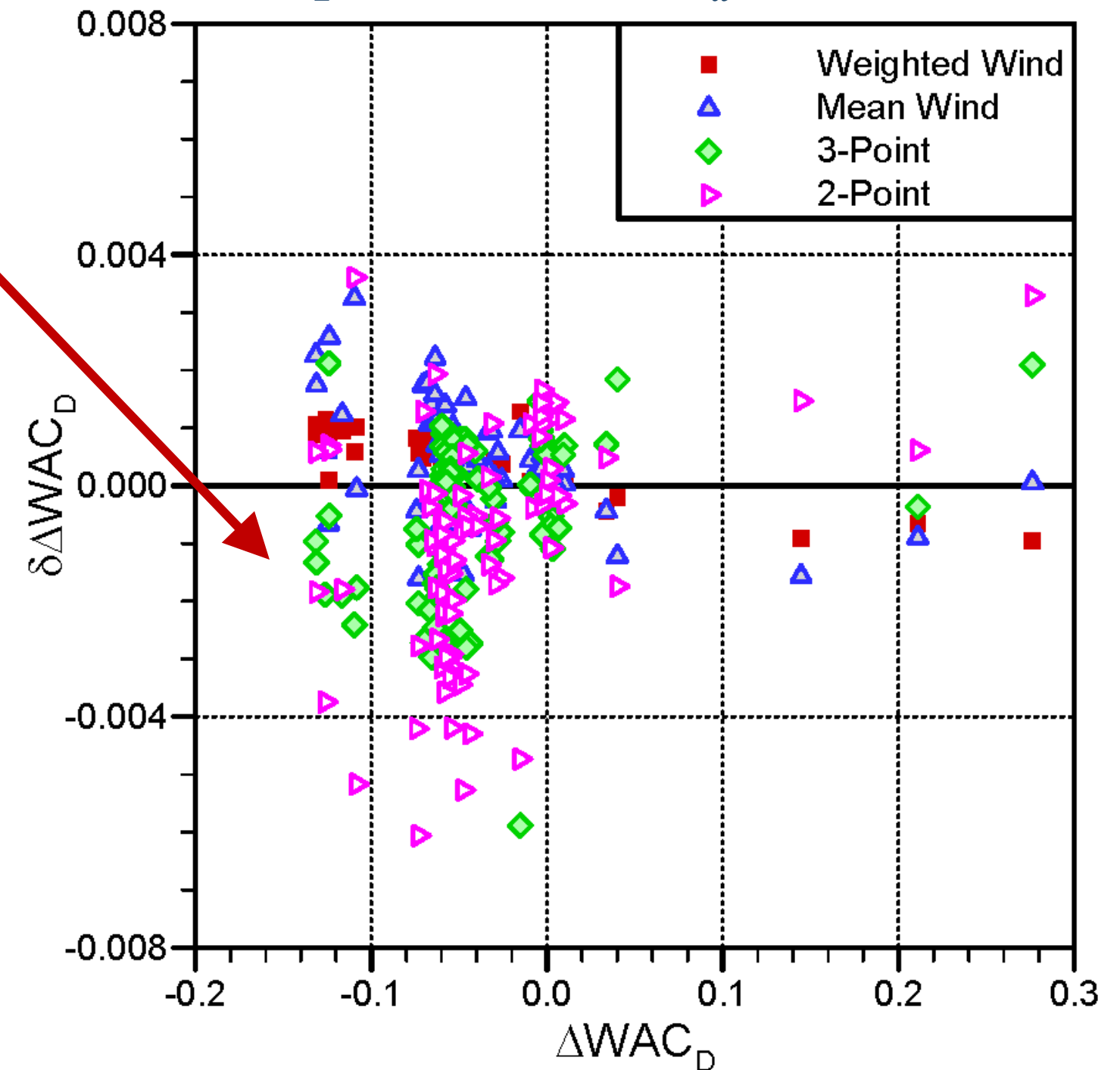
Error in **Absolute Values**
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Multi-point methods show greatest errors

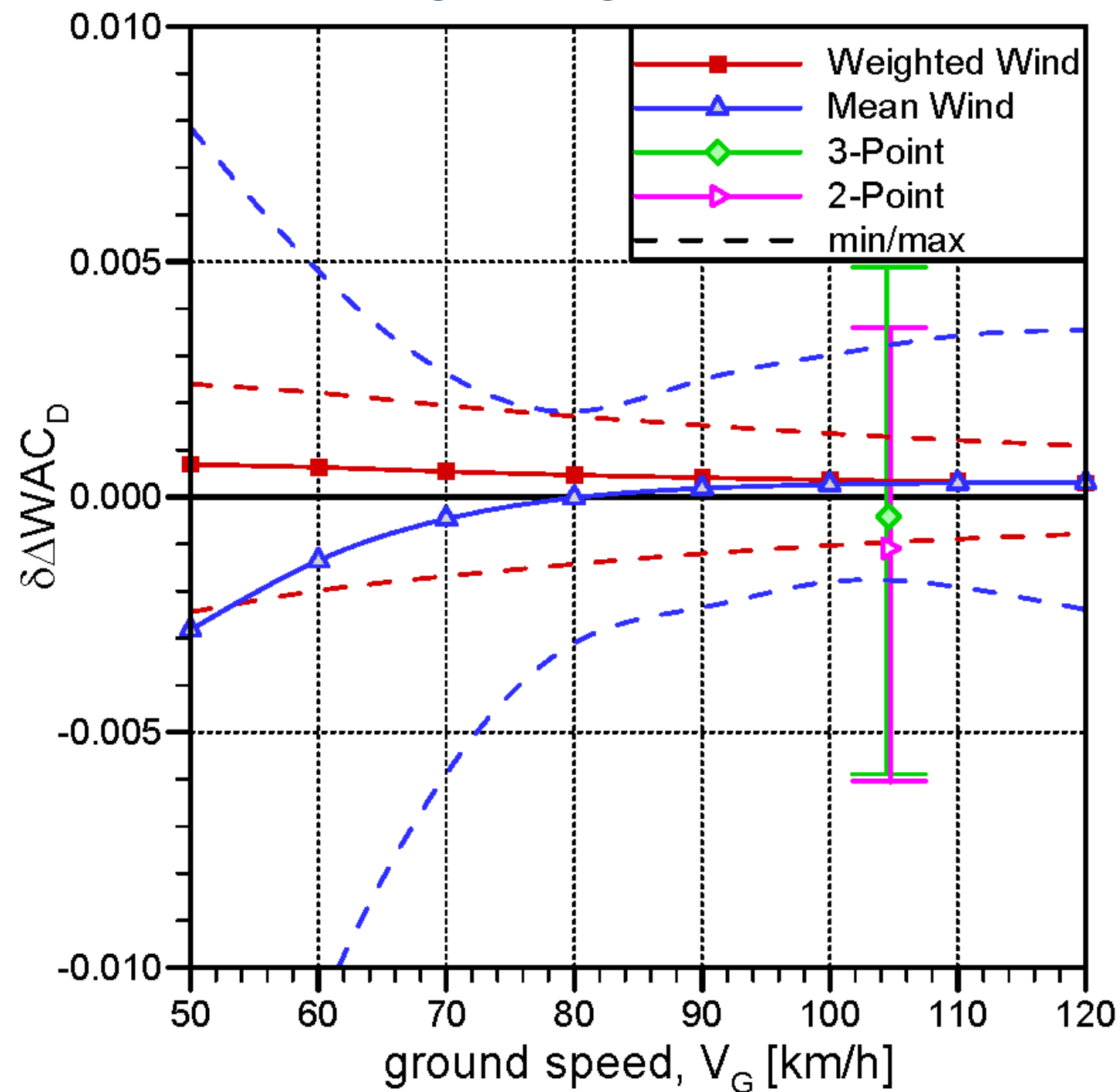
Simplifications lead to low estimates of WAC_D

Error in **Difference Values**
 $V_T = 65$ mph, $V_a = 7$ mph

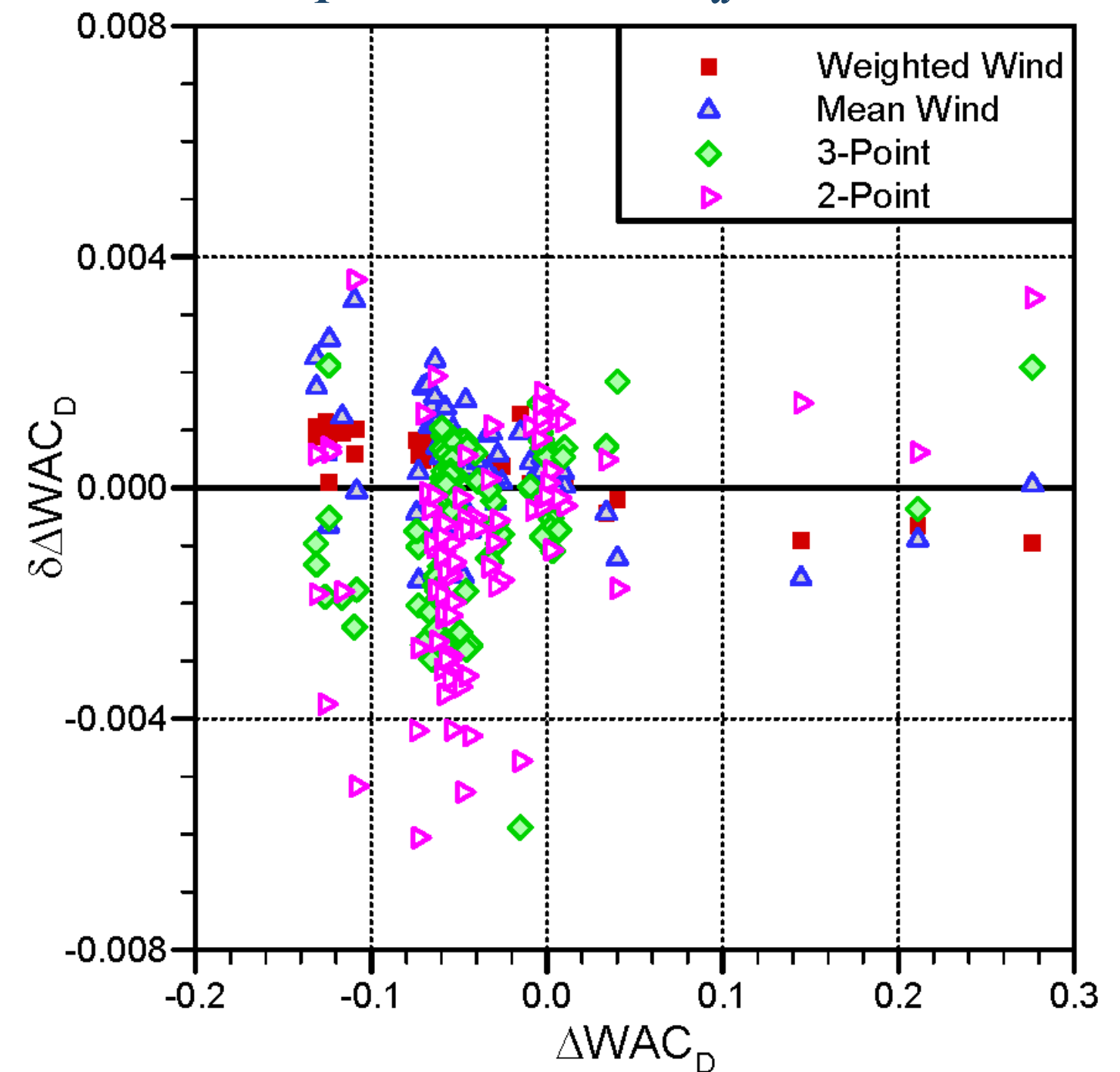


Results Comparison – Full Test Program

Error in Difference Values for range of ground speeds

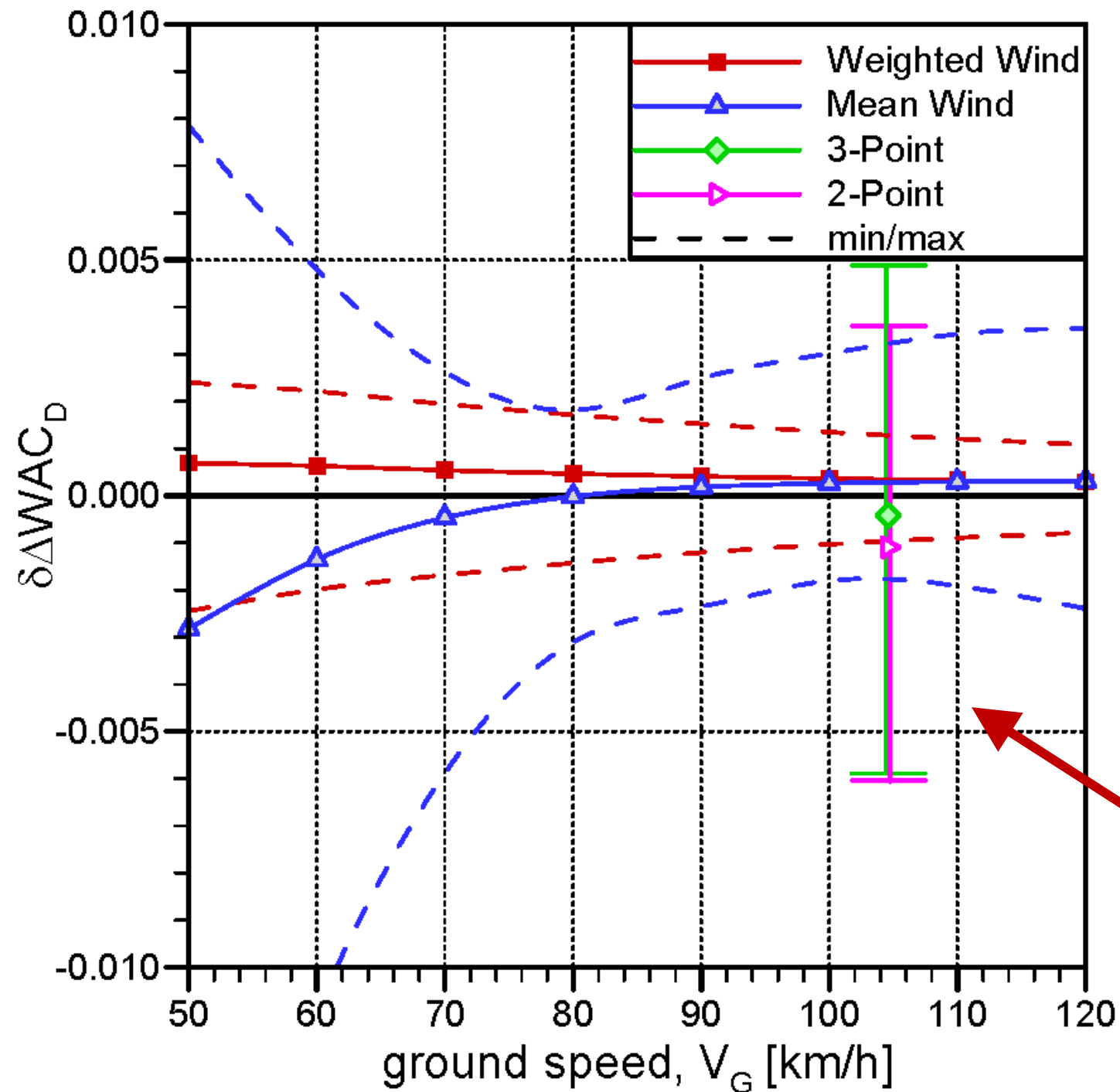


Error in Difference Values $V_T = 65$ mph, $V_a = 7$ mph



Results Comparison – Full Test Program

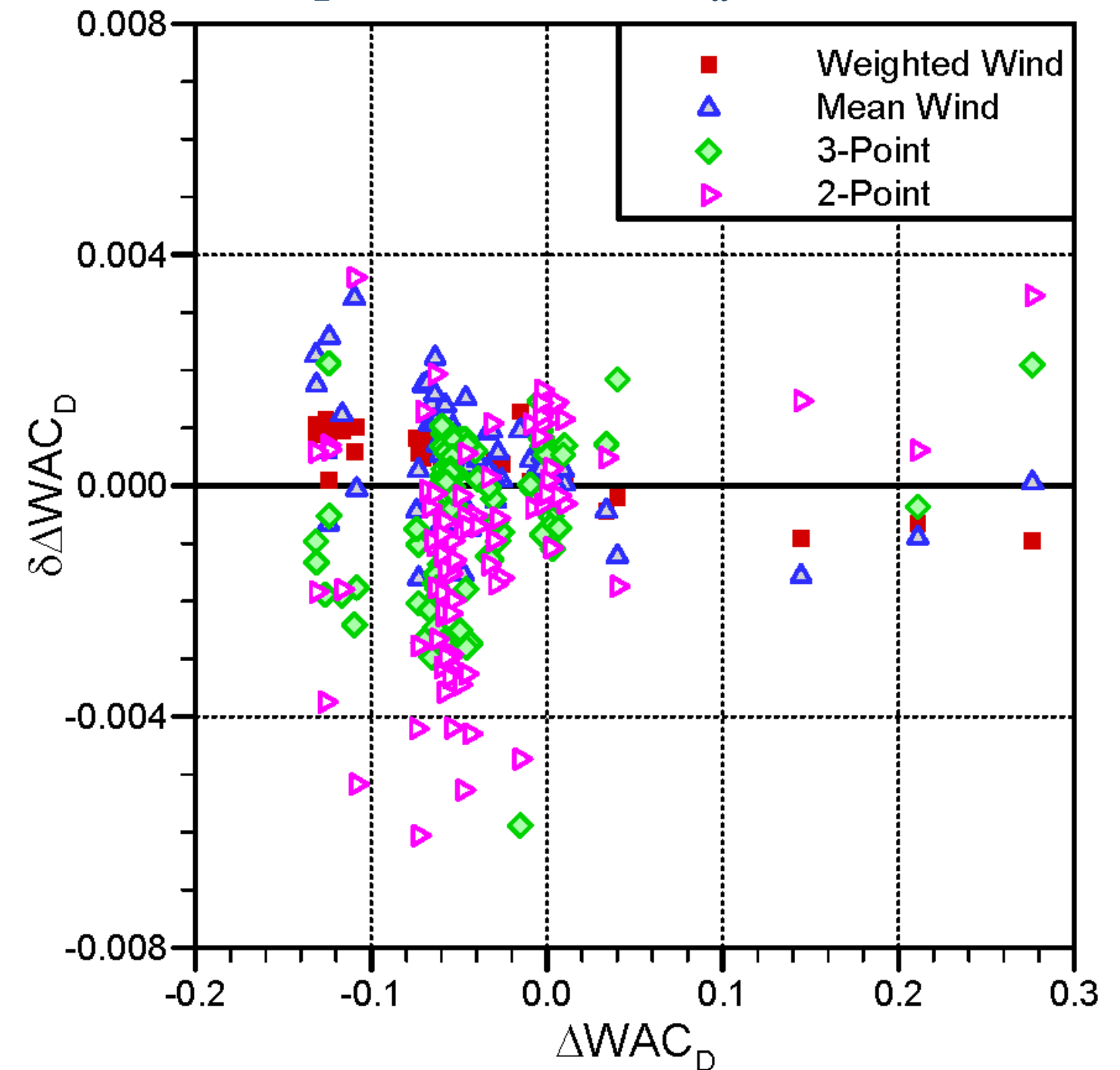
Error in **Difference Values**
for range of ground speeds



*Weighted Wind
most accurate*

*Multi-point
least accurate*

Error in **Difference Values**
 $V_T = 65$ mph, $V_a = 7$ mph



Why This Is Important

- Are drag-change random errors up to $\pm 1\%$ of vehicle drag problematic?

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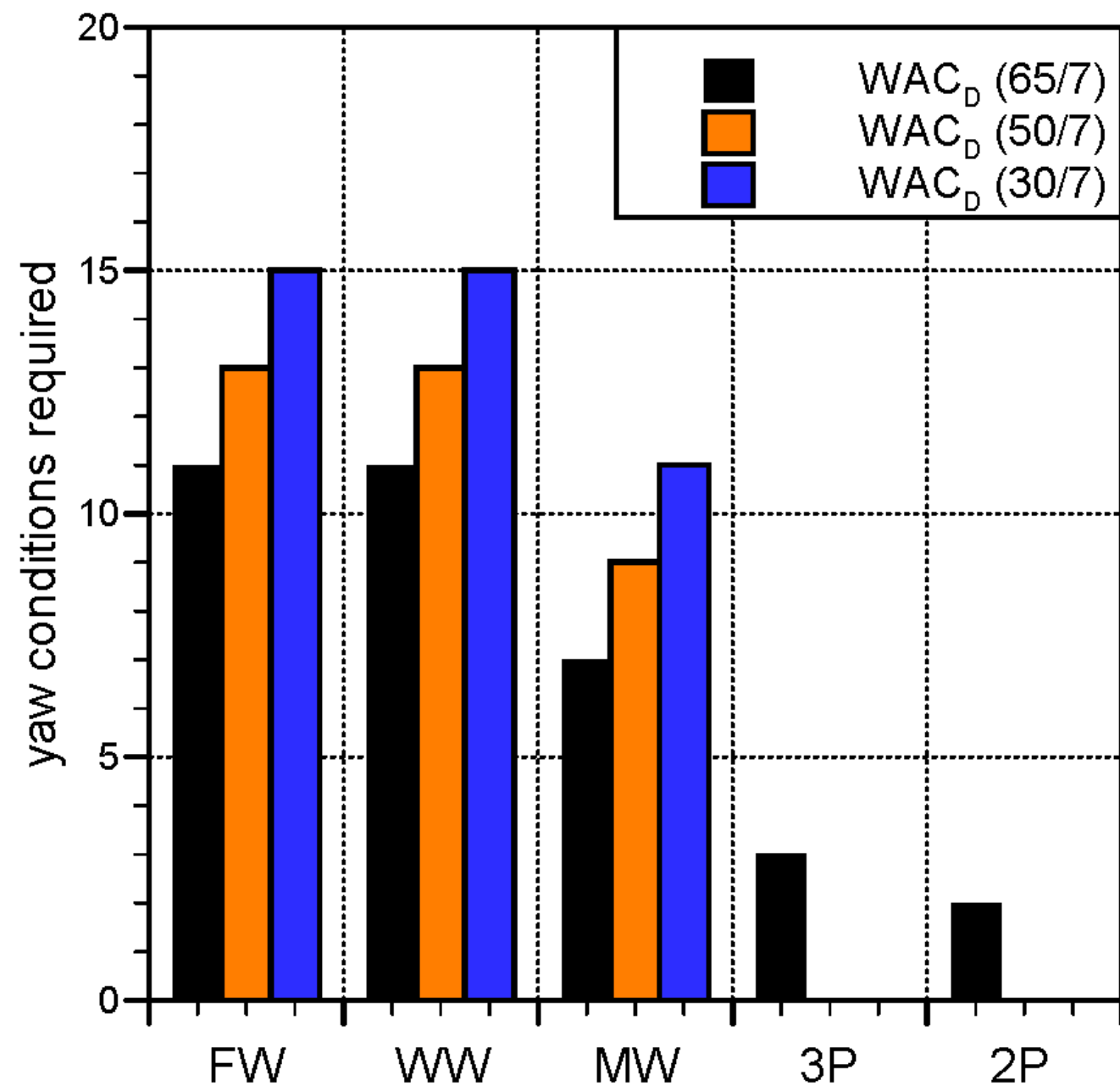
- Are drag-change random errors up to $\pm 1\%$ of vehicle drag problematic?
- Regulations (GHG2) and Fuel-Efficiency Programs (SmartWay) based on bins
 - Bin sizes on the order of 2% to 7% of vehicle drag
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- Are drag-change random errors up to $\pm 1\%$ of vehicle drag problematic?
- Regulations (GHG2) and Fuel-Efficiency Programs (SmartWay) based on bins
 - Bin sizes on the order of 2% to 7% of vehicle drag
 - 1% difference can influence bin placement
- Impact to technology manufacturers:
 - Design to the test method
- Impact to regulators
 - Results may not reflect real-world effectiveness

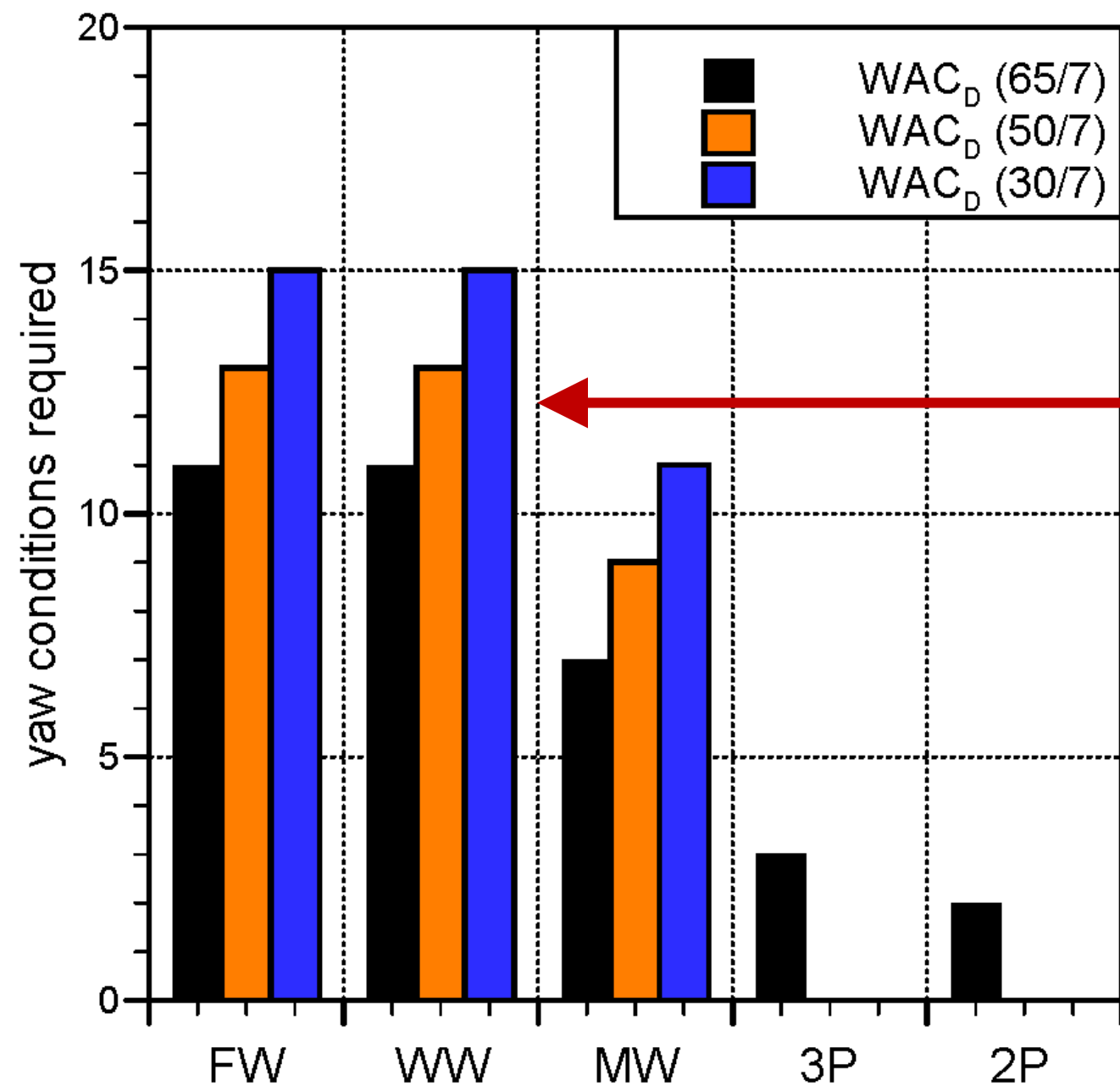
What is the Cost for Improved Accuracy?

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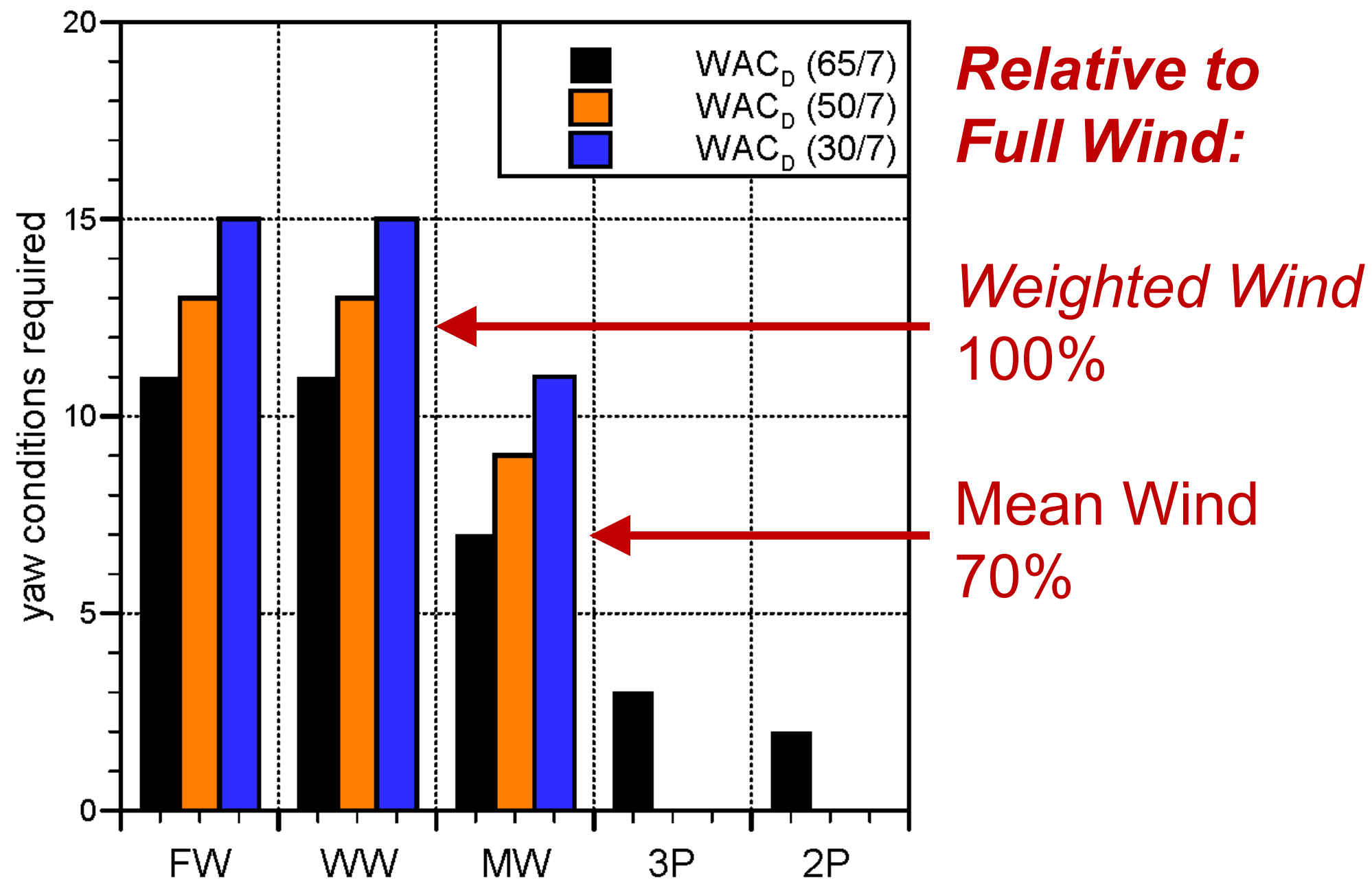


*Relative to
Full Wind:*

*Weighted Wind
100%*

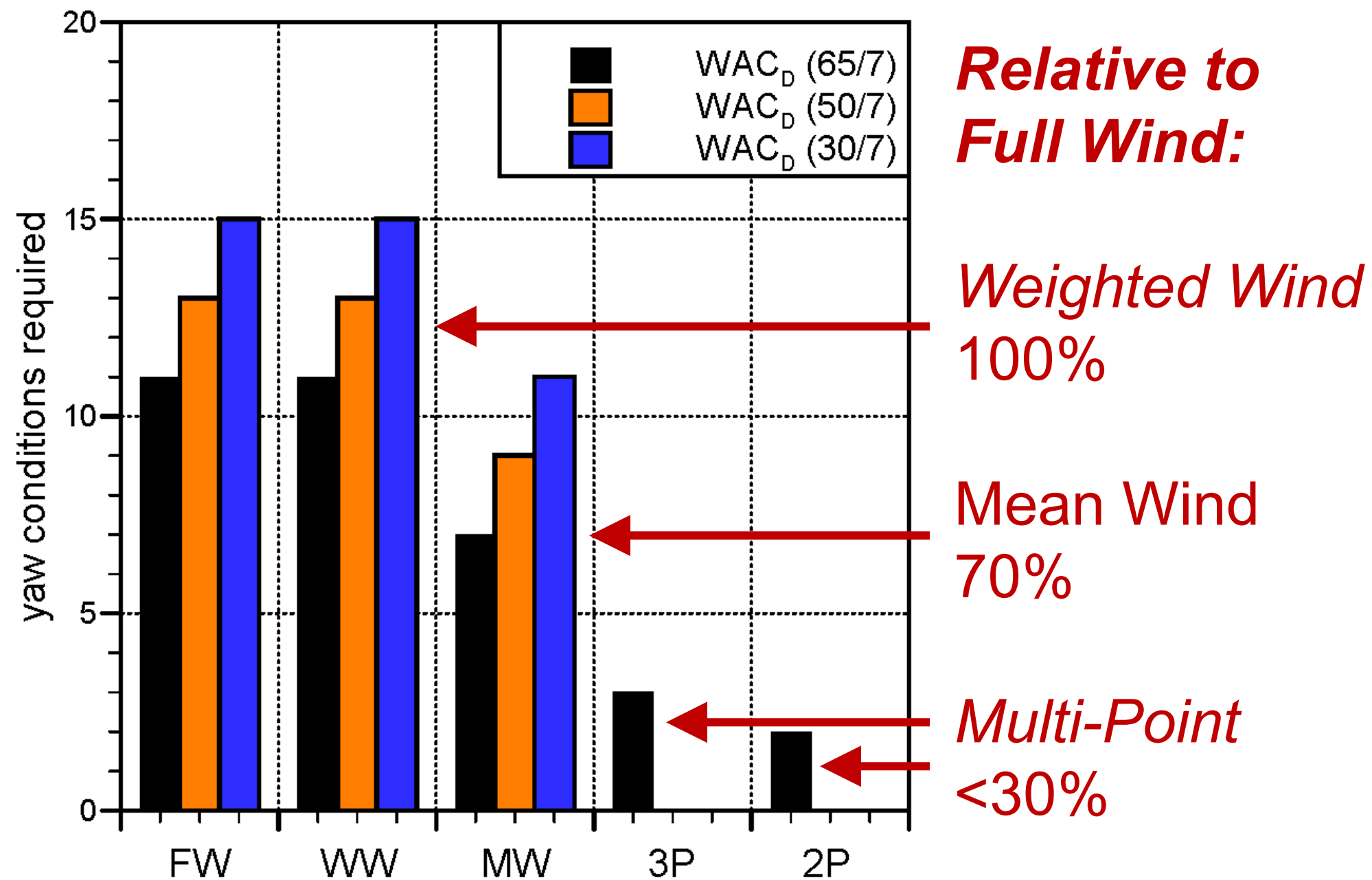
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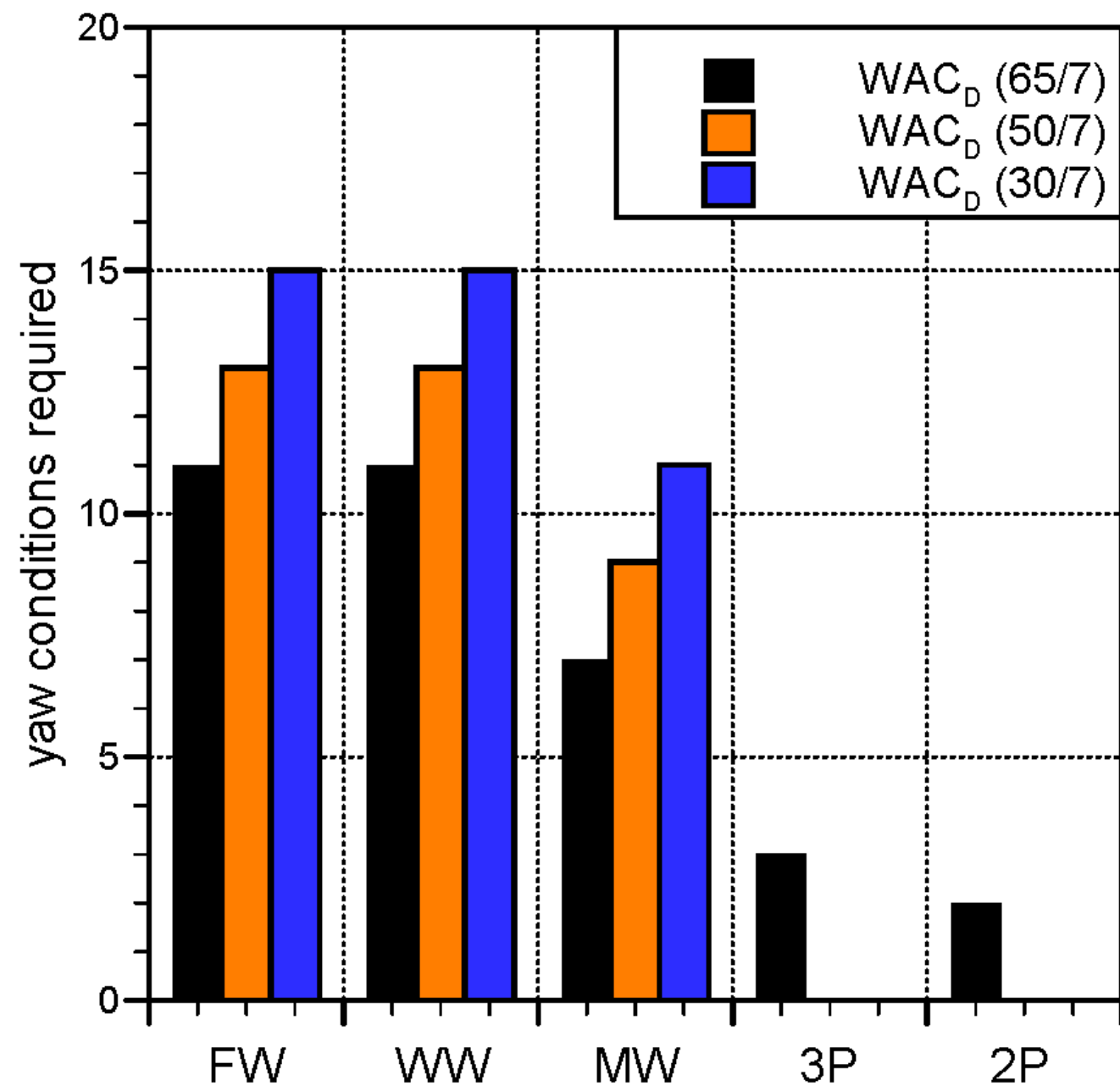
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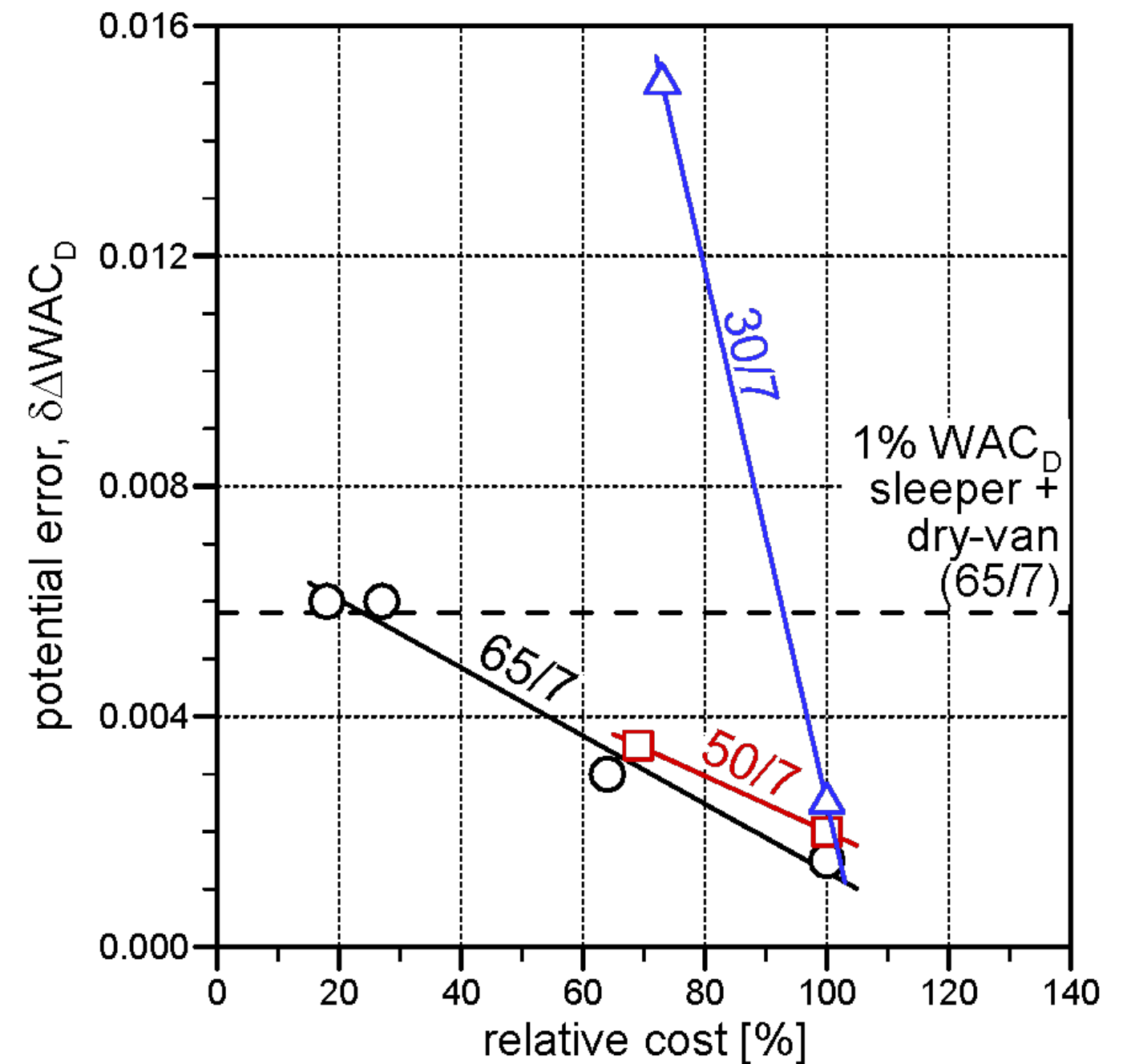


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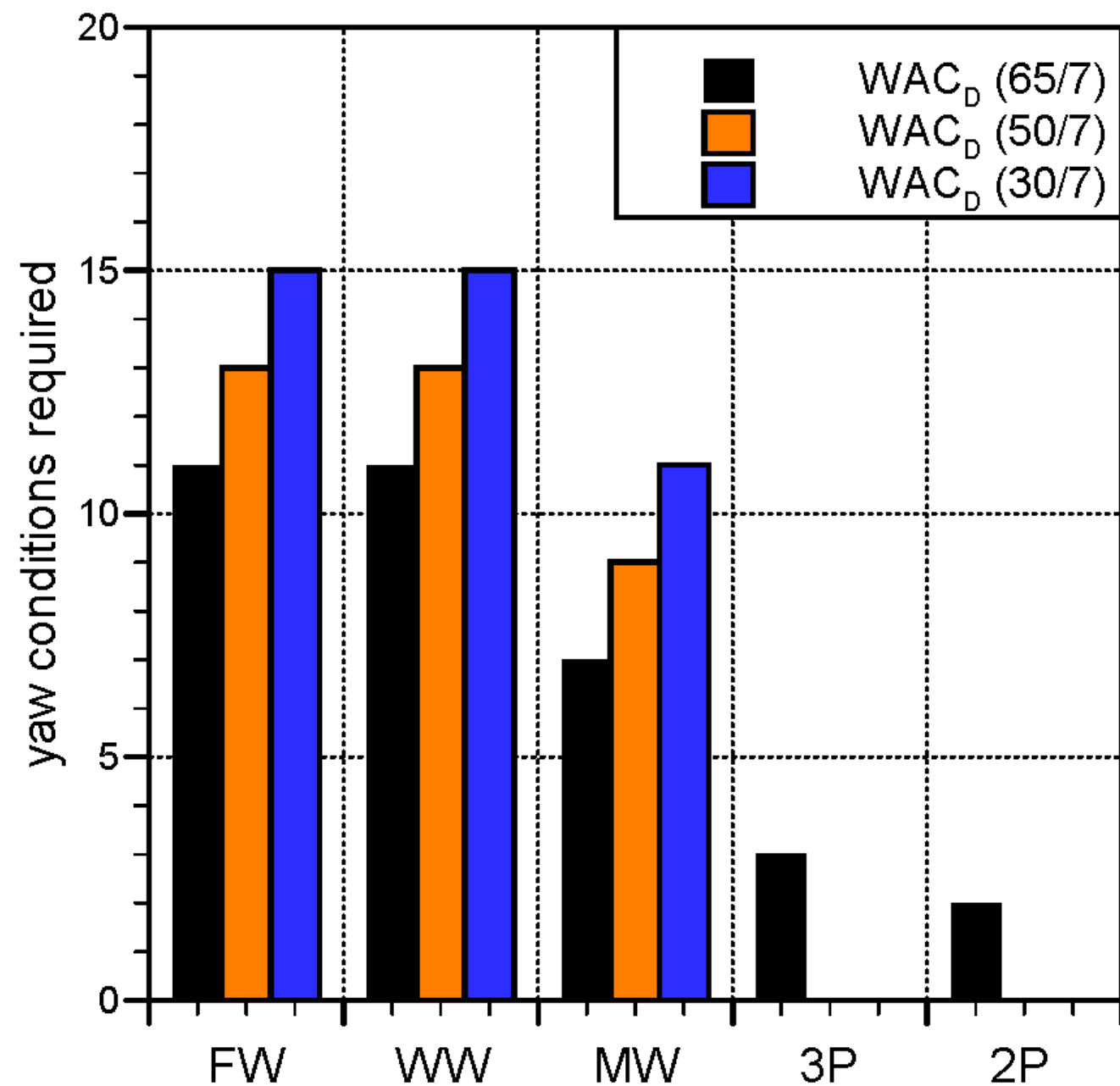


error is related to cost and to the required ground-speed condition

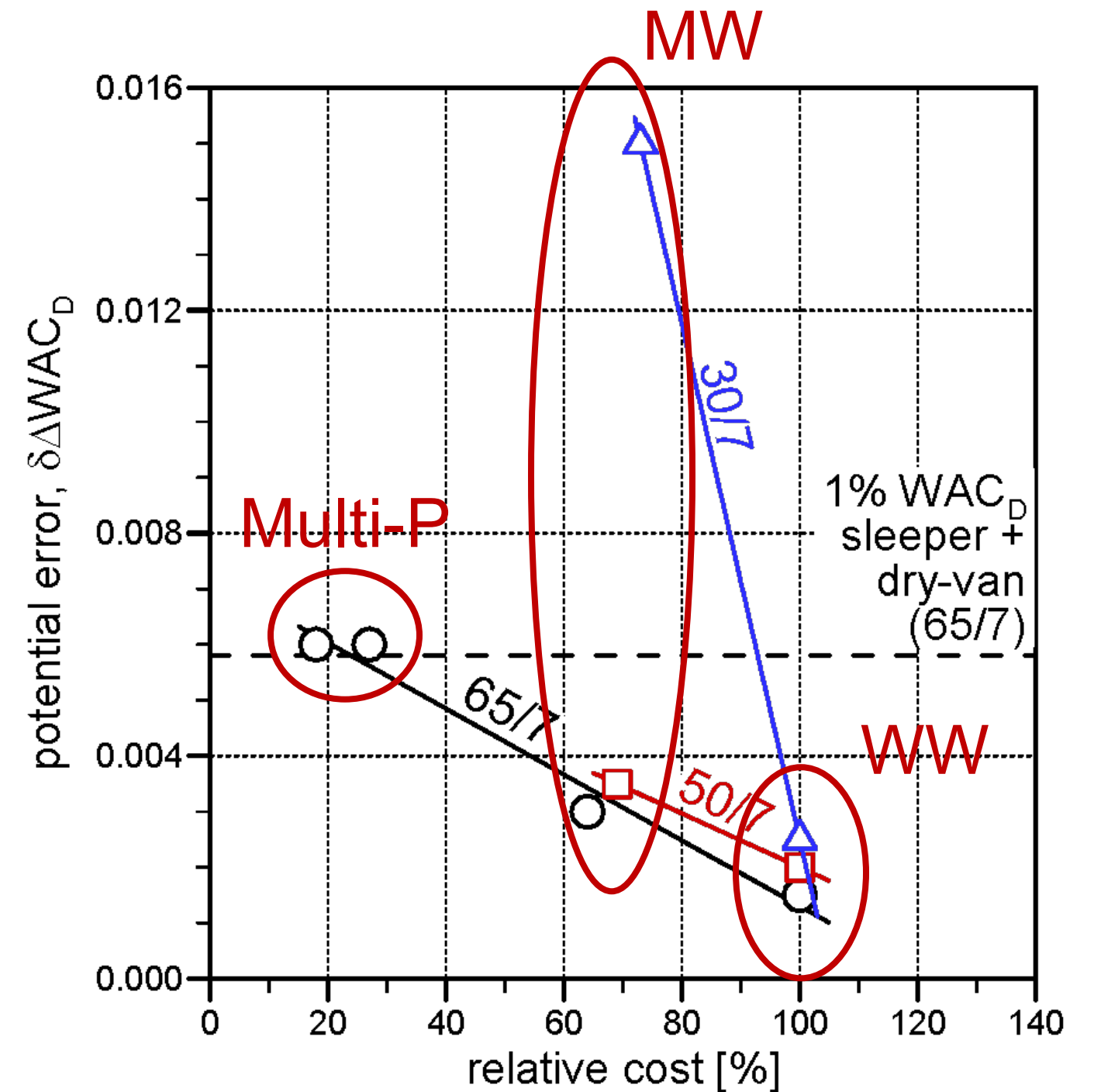


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Recommendation



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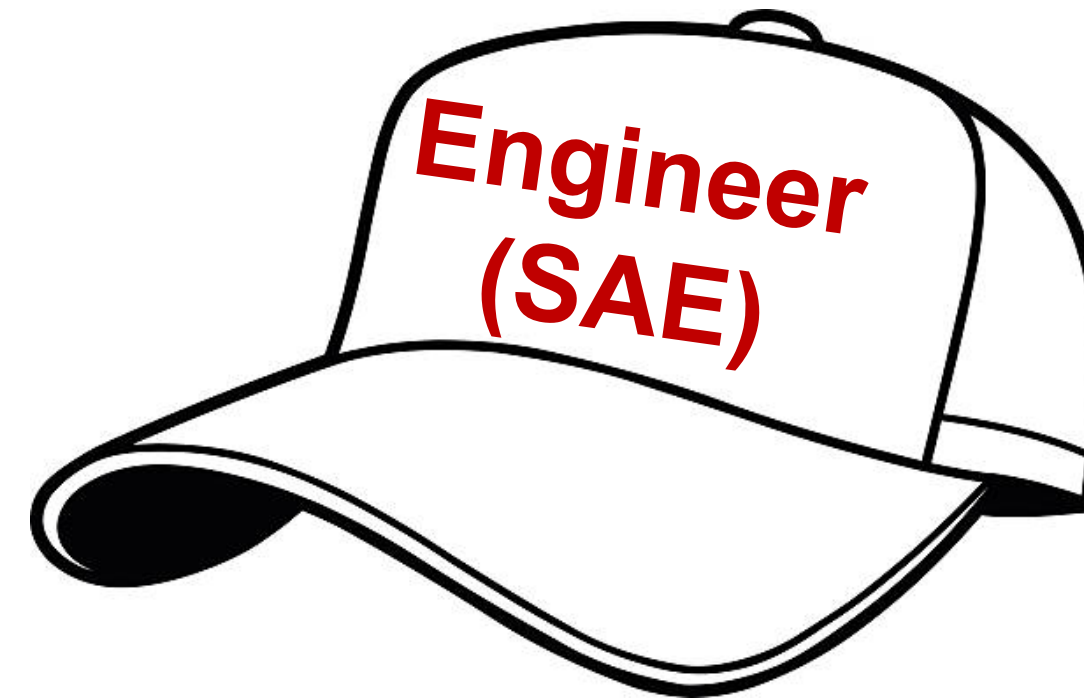


- Accuracy is important
- 1% random error is high!
- Need *Full-Wind* or *Weighted Wind*

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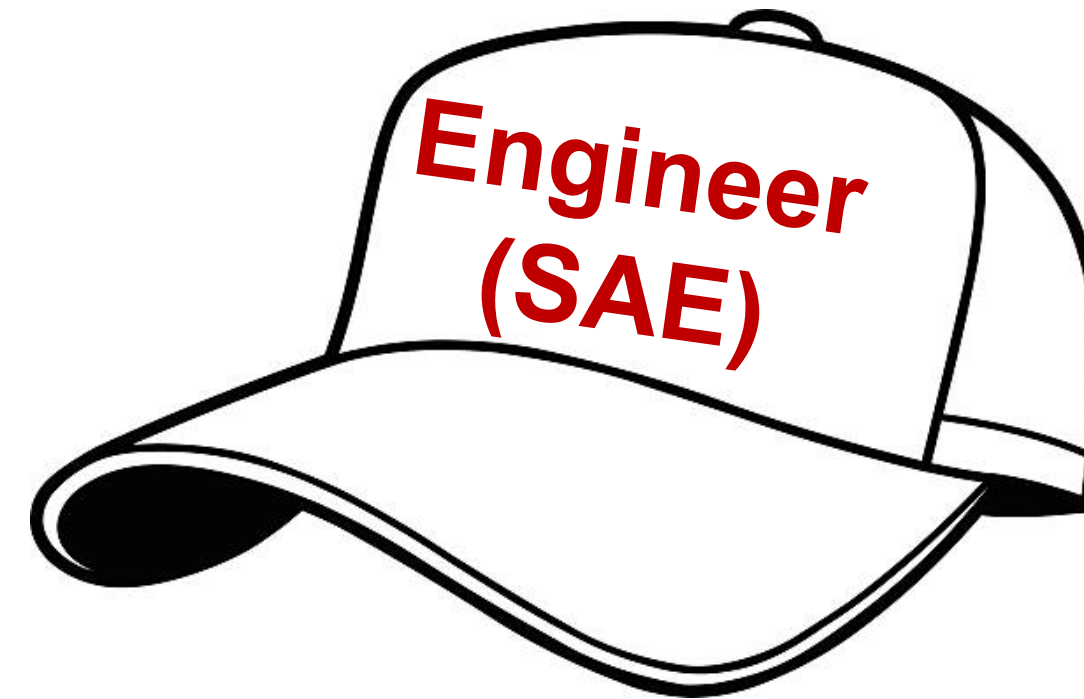


- Consistency & efficiency important
- 0.5% random error is manageable
- *Mean-Wind* is recommended for ground speed ≥ 50 mph (80 km/h)

Recommendation



- Need *Full-Wind* or *Weighted Wind*



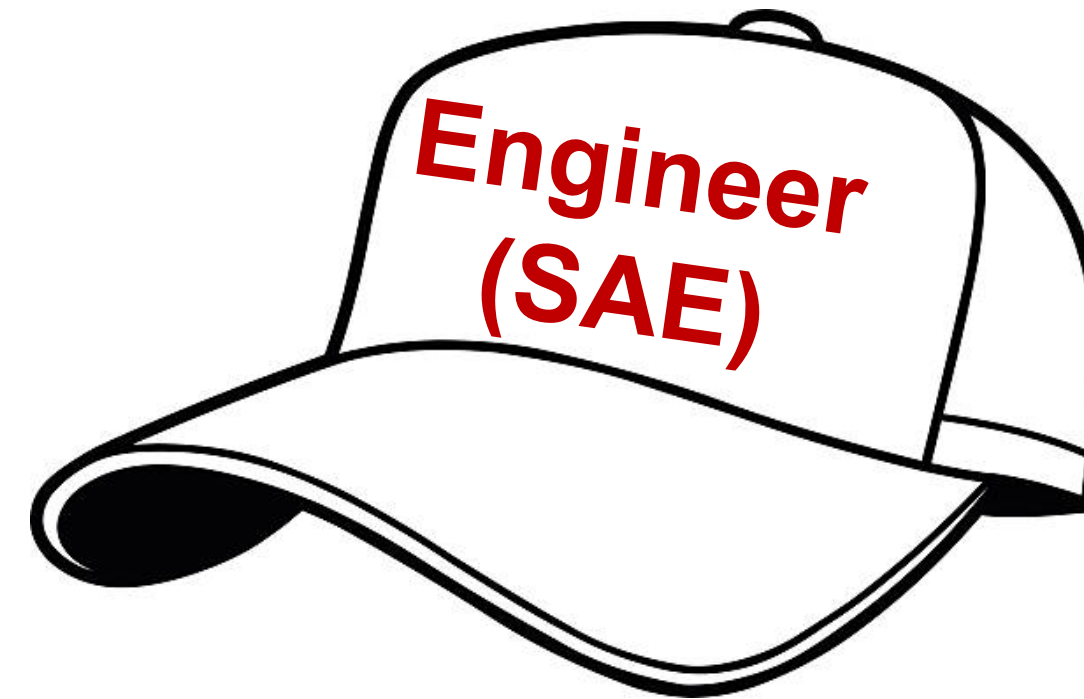
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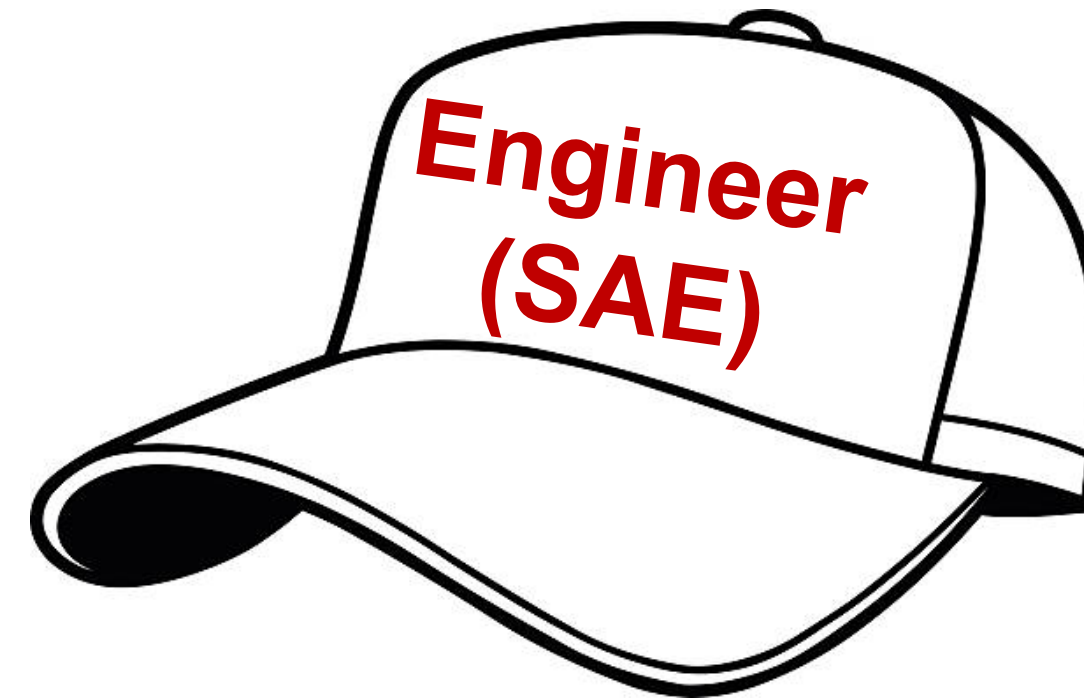
➤ Need *Full-Wind* or *Weighted Wind*

➤ Should introduce uncertainty estimation for WAC_D calculations



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Recommendation



- Need *Full-Wind* or *Weighted Wind*
- *Mean-Wind* is recommended for ground speed ≥ 50 mph (80 km/h)
- Should introduce uncertainty estimation for WAC_D calculations
- Caution to regulators about over-simplified methods...
they often overestimate drag reduction!

Questions?

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Brian.McAuliffe@nrc-cnrc.gc.ca
613-998-9201

