Aircraft CG Envelopes

LONGITUDINAL | LATERAL | VERTICAL

By George Shpati

September 17, 2011

Agenda

- Objective
- Impact of CG on Aircraft Design
- Longitudinal CG Envelope
- Lateral CG Envelope
- Vertical CG Envelope
- Summary

Objective

To analyze and discuss the importance of CG envelopes.

- What they represent
- What they size
- How they are constructed

Generate discussion regarding different methodologies…

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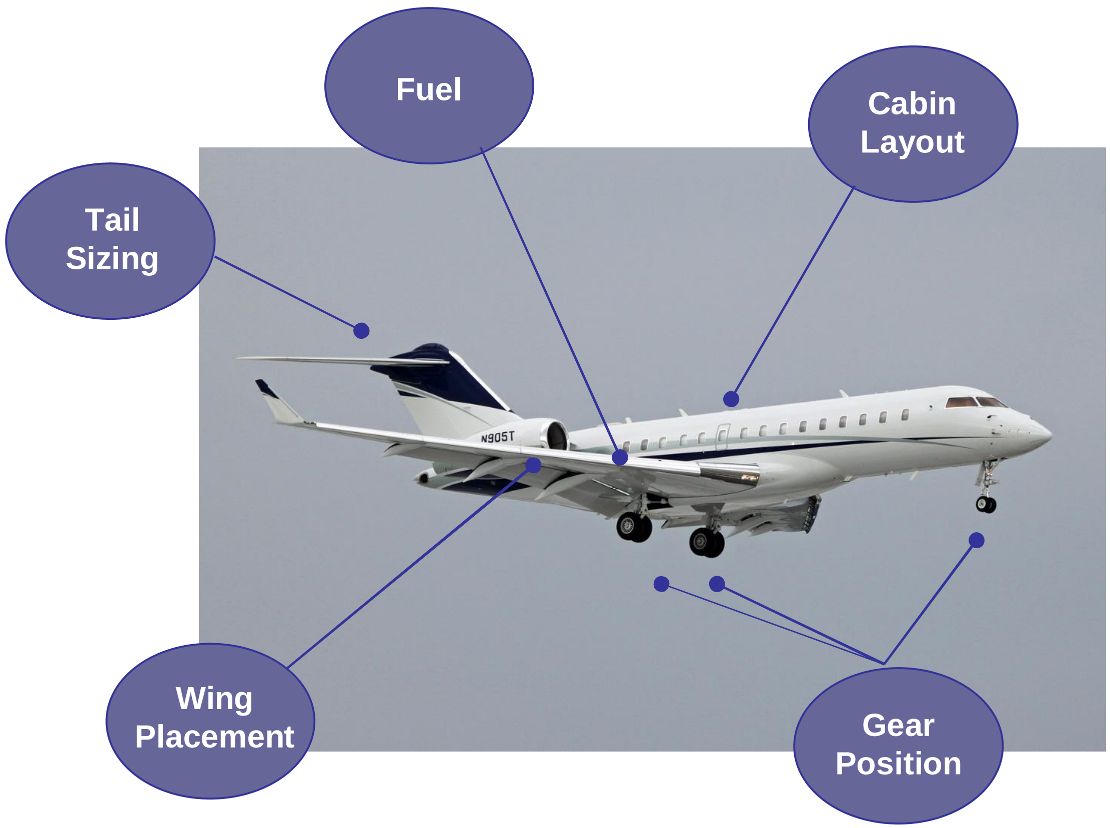
Impact of CG on Aircraft Design

CG affects the physical configuration of the aircraft, aerodynamic performance and load carrying capacity.



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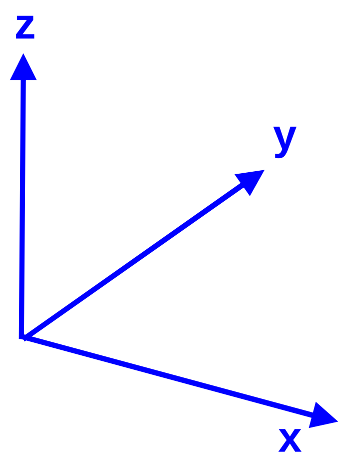
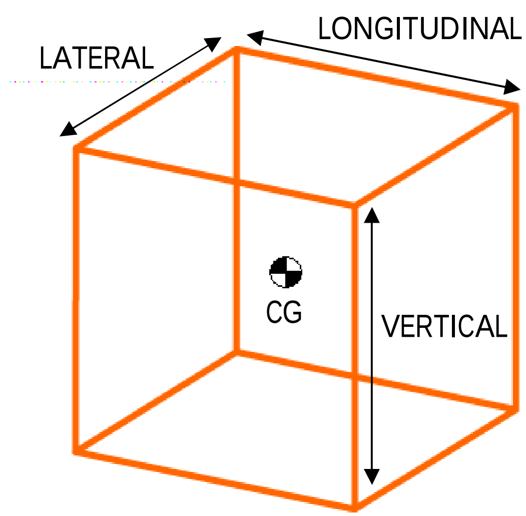
Impact of CG on Aircraft Design

3-dimensional CG envelope





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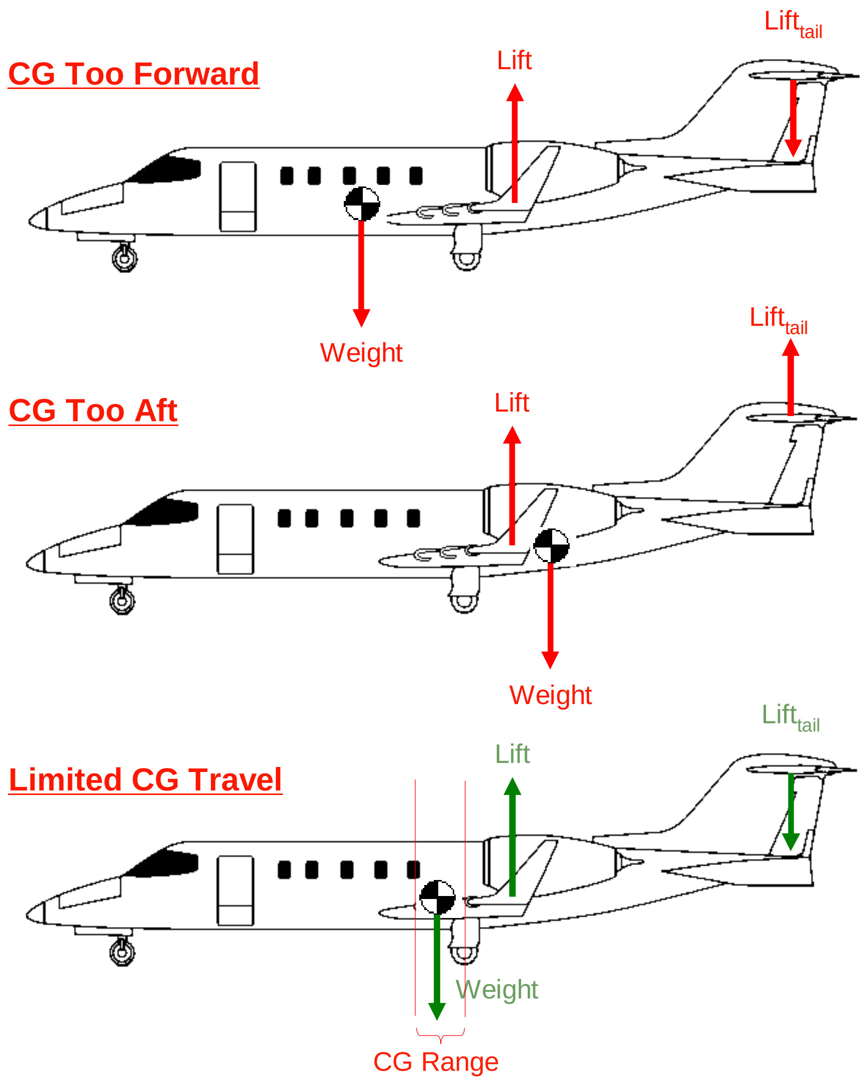
Longitudinal CG Envelope



Longitudinal CG Envelope

Implications of a forward CG location:

- Insufficient elevator authority
  Landing - Unable to flare (pitch up) at low speeds, the aircraft is too nose-heavy.
  Take off - Unable to produce enough moment to rotate the nose.
  } Need longer runway to attain sufficient speed to rotate a/c

- Increased longitudinal stability
  The forward CG has a greater distance to the Aircraft Neutral Point ⇔ Greater Static Margin ⇔ Better aircraft attitude after a disturbance due to a gust.

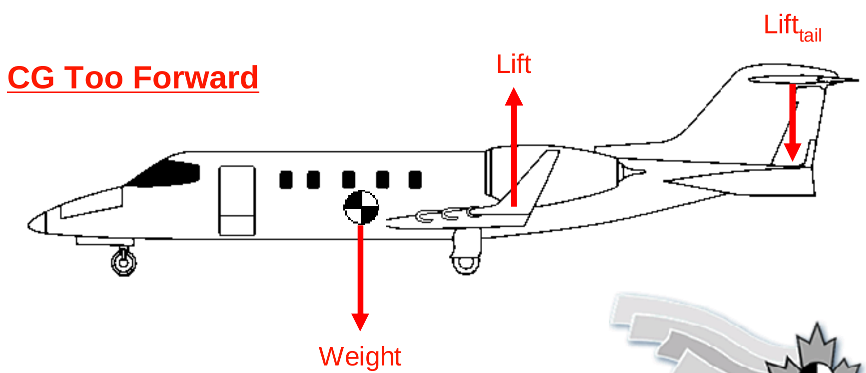
- Poor performance @ any given airspeed
  Increased downward force on the tail to resist the nose tendency to drop ⇔ increased angle of attack to trim the aircraft ⇔ increased drag

- Reduced cruise speed for a given thrust and airplane weight *(same reason as above)*

- Increased stall speed
  The stalling angle of attack is reached at a higher speed due to increased wing loading (an increase of the airspeed to reach a certain AoA)

- Excessive loads on the Nose Landing Gear
  Possible damage to the airplane when landing.

- Increased downward tail load to maintain level flight



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Longitudinal CG Envelope

Implications of an <u>aft</u> CG location:

- Tendency to nose up
  Landing - Nose-down elevator might be required to counter the nose-up tendency during flare
  Take off - A/c likely to nose up prematurely ⇔ drag increases ⇔ reduced climb performance
  } Aircraft becomes more likely to stall

- Decreased longitudinal stability
  The Aircraft Neutral Point has a smaller moment arm (distance) with respect to the CG ⇔ Small Static Margin ⇔ Unstable aircraft attitude after a disturbance (i.e. gust). The aircraft response due to its design is inadequate to return itself to equilibrium, pilot input needed.

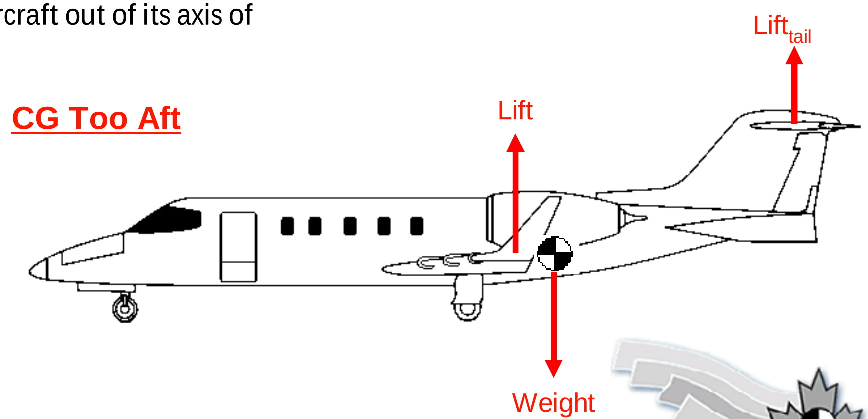
- Increased potential for a violent stall

- Higher cruise speed
  Small angle of attack and less downward deflection from the stabilizer is required to overcome the nose-down pitch tendency.

- Spin recovery becomes more difficult as the CG moves rearward.
  Centrifugal forces acting about the CG, during a "flat" spin, pull the aircraft out of its axis of spinning, making it difficult to nose down and recover.

- Aircraft structure becomes overstressed
  Light forces acting on the elevator

- Possibility of a tip over if the CG is far aft the Neutral Point.



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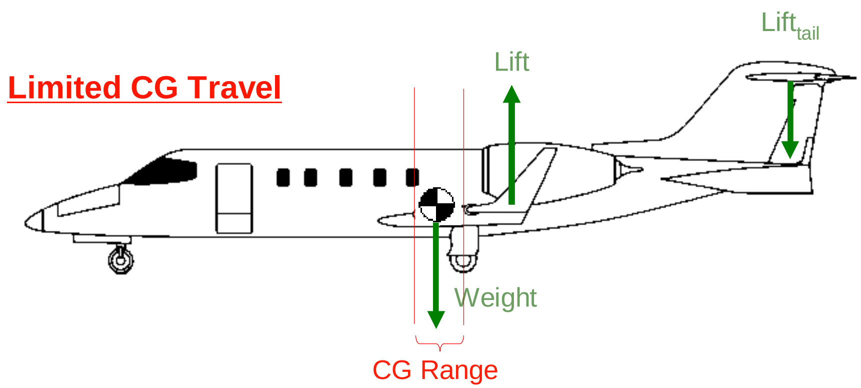
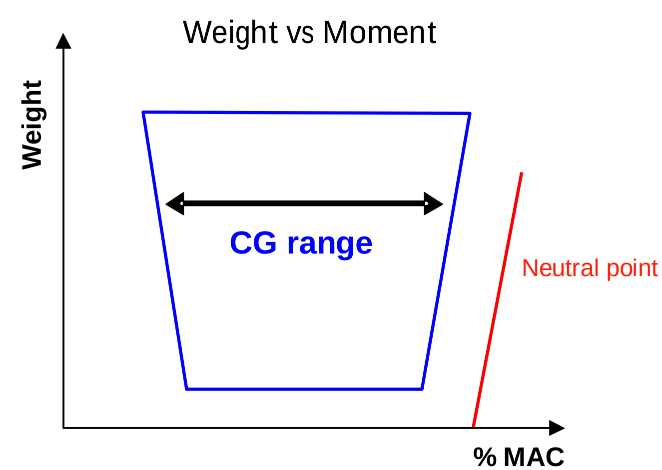
Longitudinal CG Envelope

CG Location within design limits

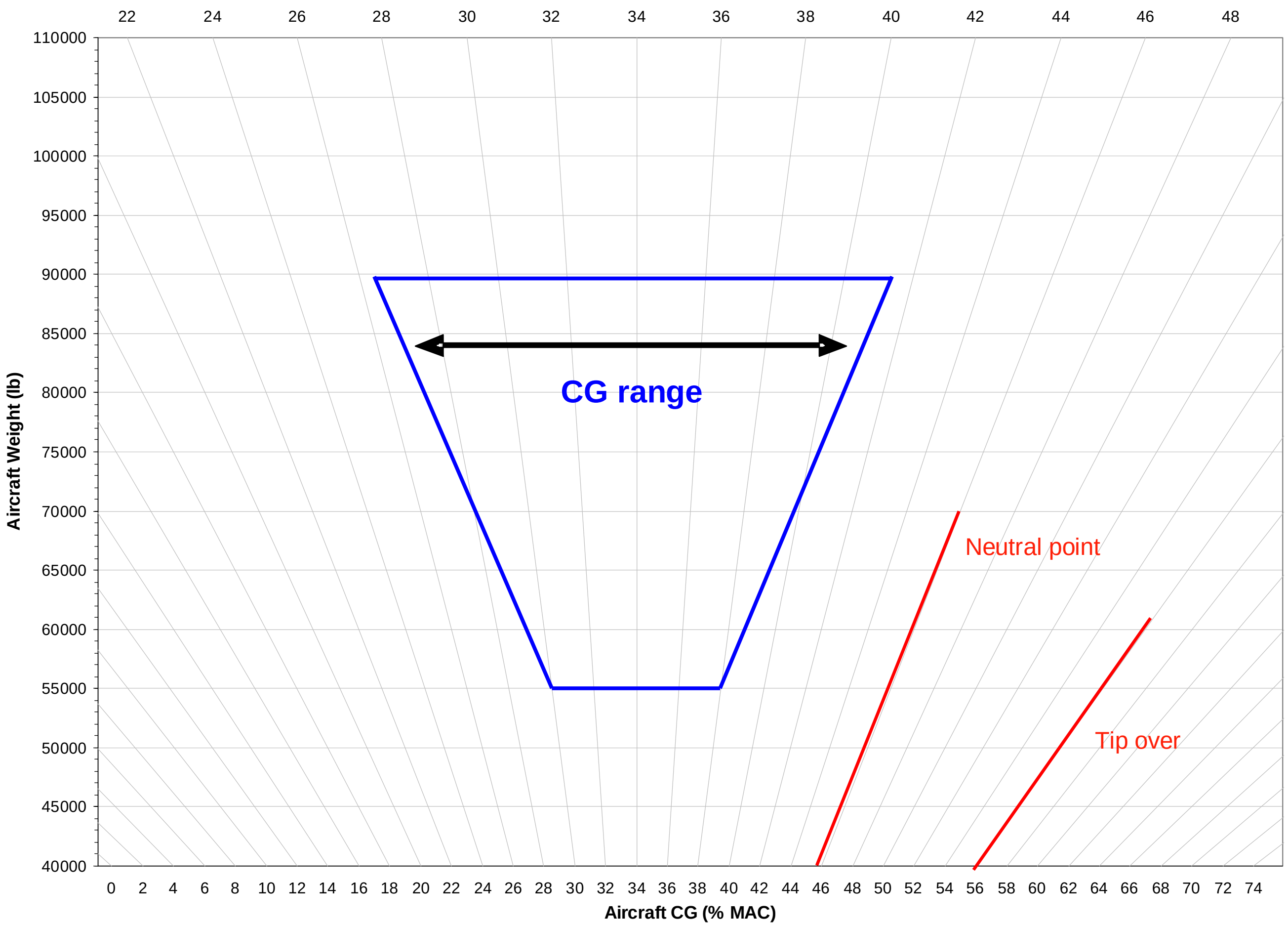


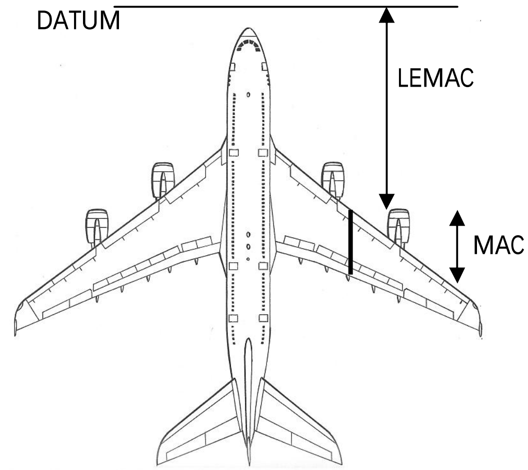
- Landing becomes a driver in establishing the forward CG
- Stability & Control becomes a driver in establishing the aft CG



Longitudinal CG Envelope

An example of a Weight vs Moment (Fan Graph)





Let's suppose that the datum point for a trimmed aircraft is at:
MAC=34% CG=500 in

$$\% \text{ MAC} = \left(\frac{\text{CG - LEMAC}}{\text{MAC}} \right) \times 100$$

Grid lines are needed for a weight range of 40'000 lb < x < 110'000 lb

Vary %MAC from 0° to 80° and calculate the following for each variation:

CG = (%MAC * MAC) + LEMAC

$$\text{Moment} = \frac{\text{CG – Datum CG}}{\text{Weight}}$$

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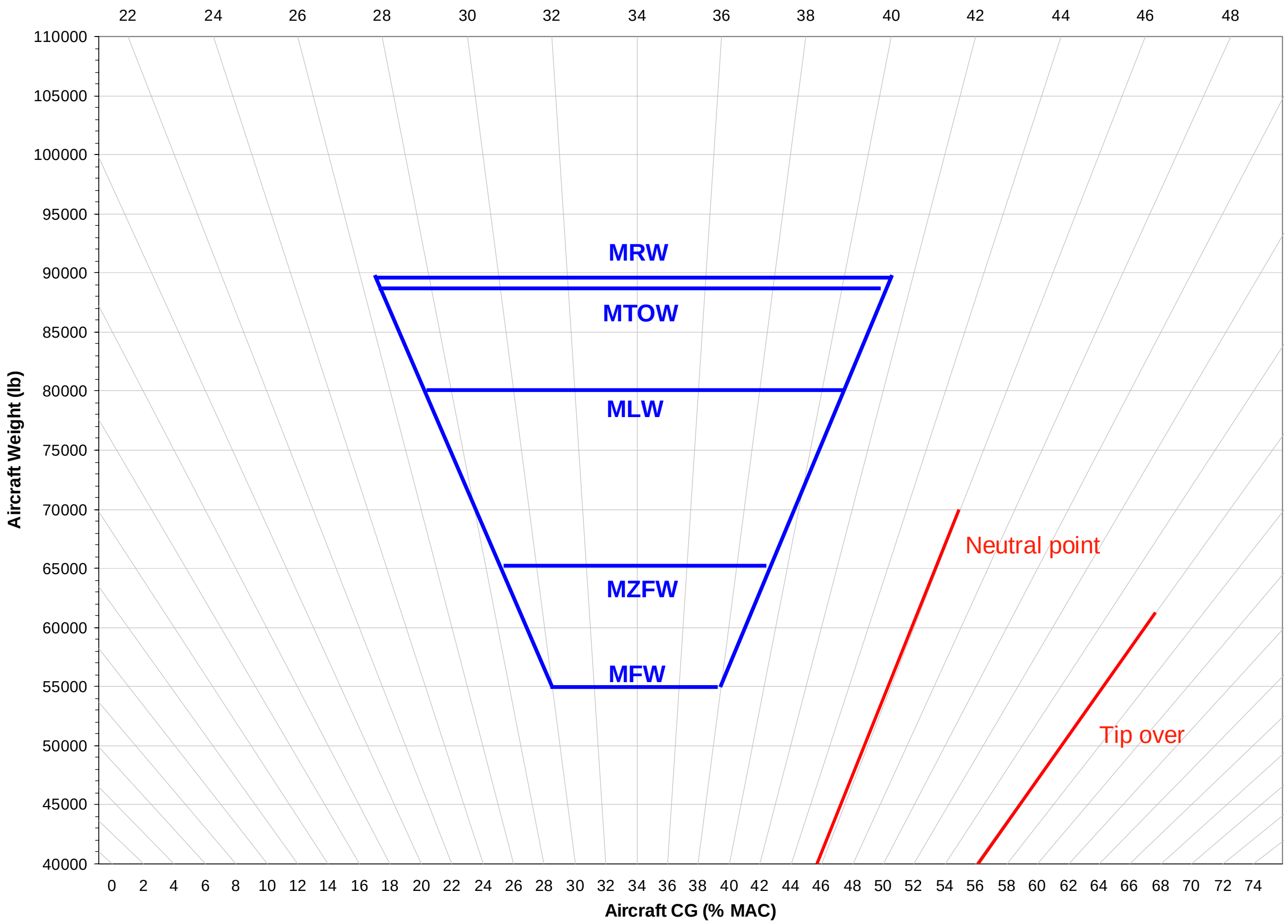

CERTIFIED WEIGHT LIMITATIONS:

MRW - Maximum Ramp Weight
Designs gear and support structure

MTOW - Maximum Take-Off Weight
Designs wing

MLW - Maximum Landing Weight
Designs gear, flaps, portions of wing, the h-tail and aft fuselage

MZFW - Maximum Zero Fuel Weight
Designs fuselage and centre wing

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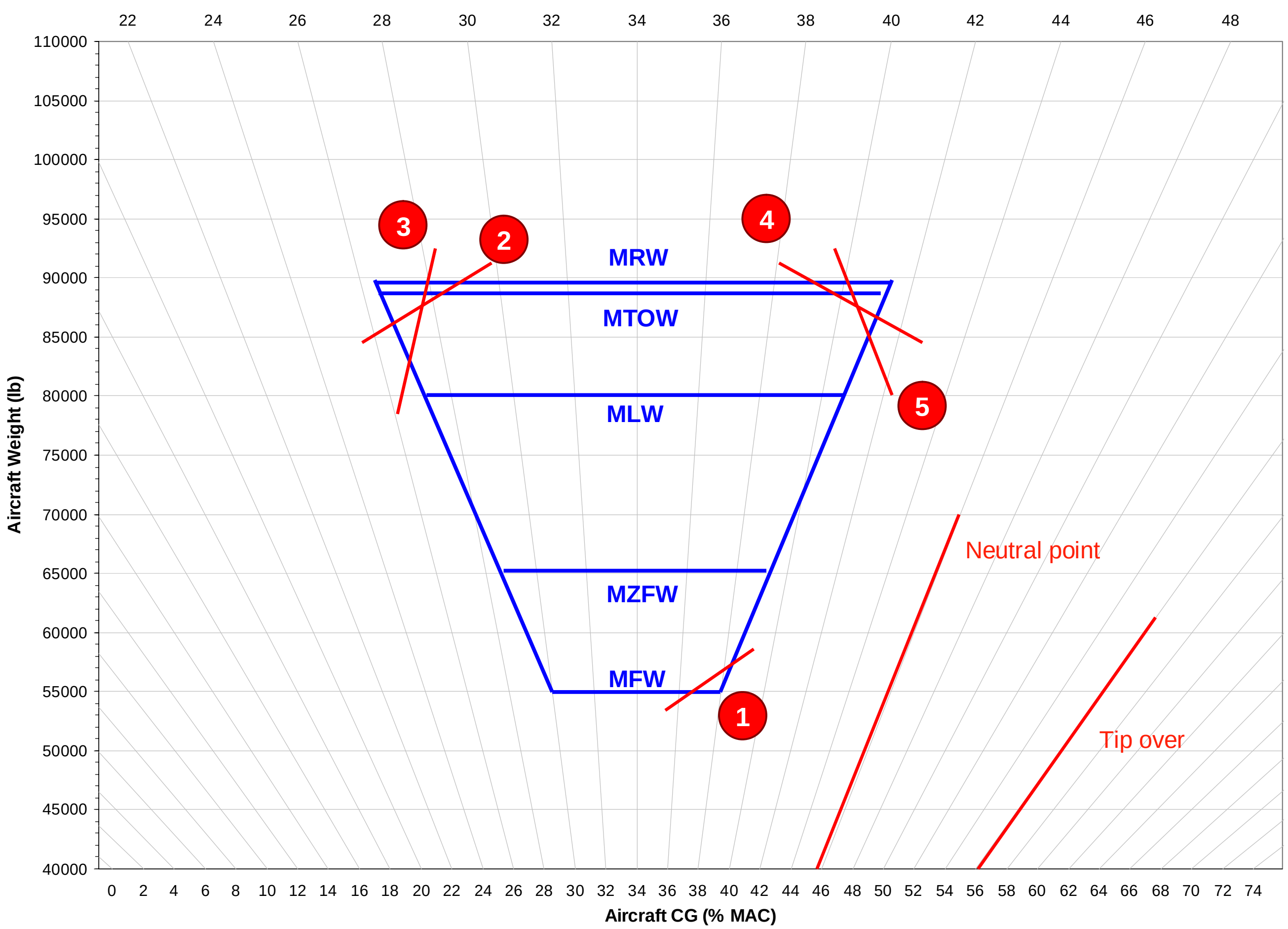

1 Minimum NLG load
Ground operations and steering load requirements

2 Constant NLG Load
Based on static loads, it limits gears and support structures loading

3 Horizontal Stab Trim Line (Take-off)
Maintains constant horizontal tail loading without having to reinforce the structure.

4 Constant MLG Load
Based on static loads, it limits gears and support structure loading.

5 Fuel Vector Line
Dependent on aircraft and fuel tank configuration

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Longitudinal CG Envelope

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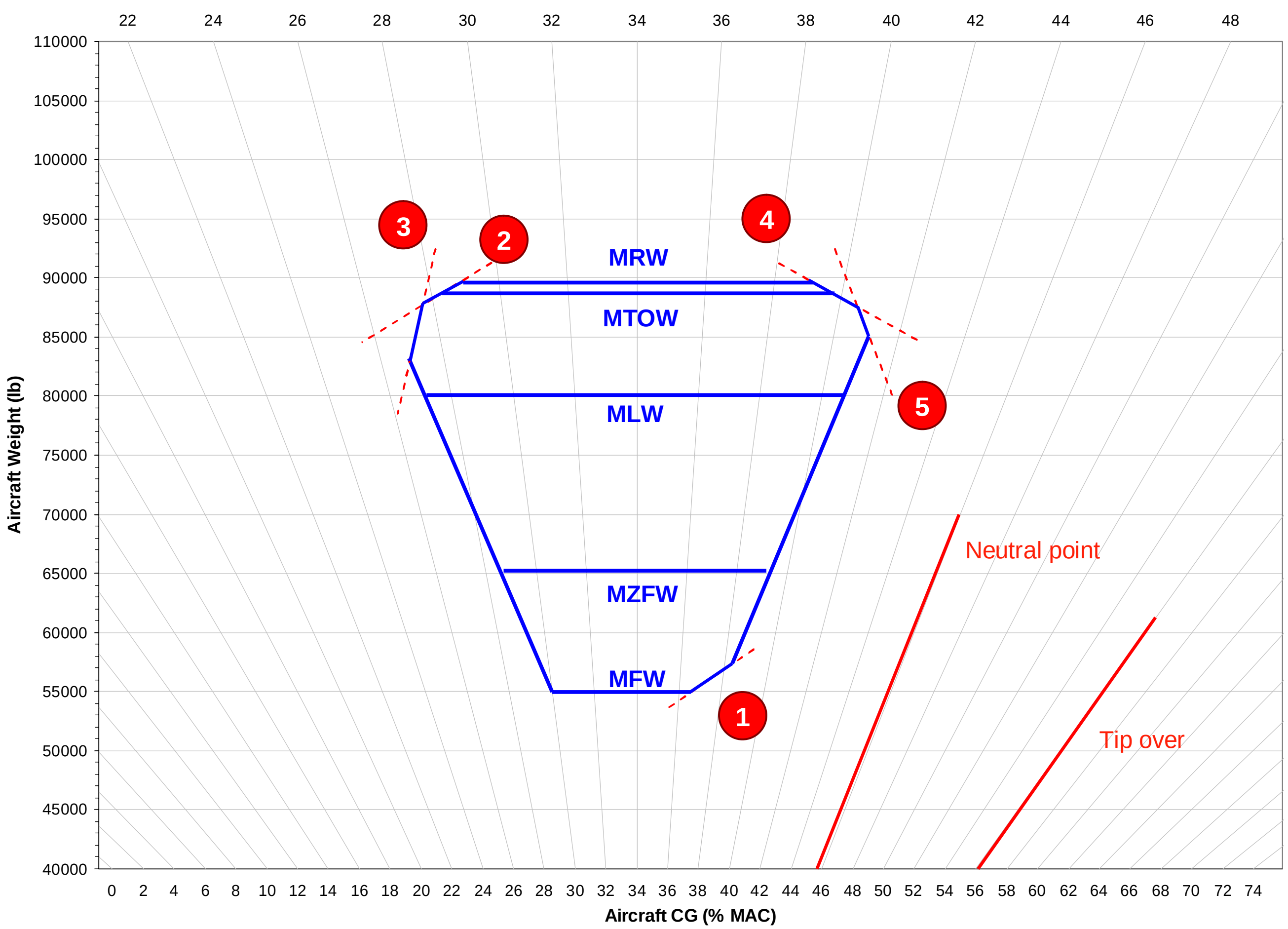

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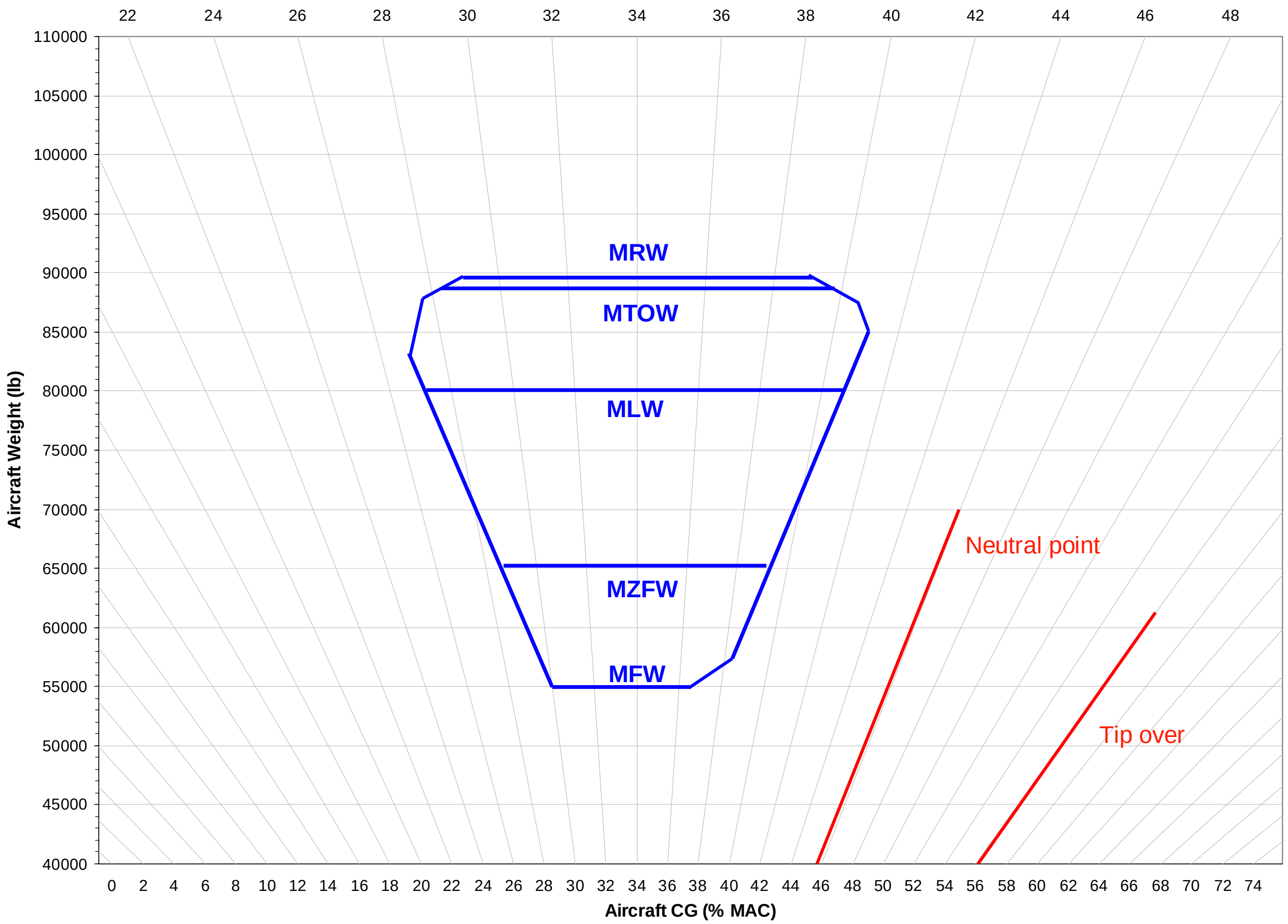

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Lateral CG Envelope

Most aircrafts (empty or loaded) are non-symmetrical about the fuselage centerline.

This asymmetry is attributed to:

1.Empty Aircraft – Lateral CG Offset

a. Structure - Doors are often on one side of the aircraft

a. Systems - Batteries, RAT (Ram Air Turbine), LRUs, avionic racks are not distributed symmetrically.

b. Cabin Layout - Galleys, toilets, Waste system are only on one side.

2.Payload Lateral CG Offset

Payload is not loaded symmetrically about the longitudinal axis of the aircraft.

3.Lateral Fuel Imbalance

Fuel is loaded symmetrically, but special design cases (i.e. surge tank trapped fuel) would pose a severe lateral imbalance.

Generally, the resultant of the asymmetry is small; however, it is the starting point of the Lateral CG Envelope.

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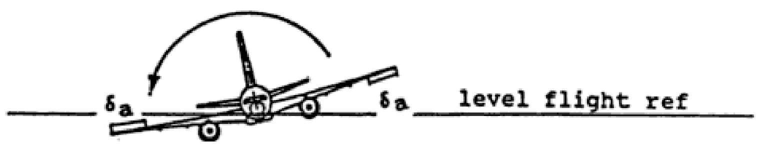
Lateral CG Envelope

The impact of lateral CG imbalance on aircraft handling quality is typically assessed by:

-Fuel imbalance tests

-One engine failure test

The combination of both scenarios provides the maximum rolling moment for the aircraft ➔ crucial in sizing ailerons and spoilers



The applied Rolling Moment due to ailerons and spoilers, assuming a linear analysis is given by the formula:

$$M_\delta \delta = M_{\text{ail}} \delta_{\text{ail}} + M_{\text{sp}} \delta_{\text{sp}}$$

where M_{ail} is the rolling moment due to unit aileron deflection (ft-lb/deg), and M_{sp} is the rolling moment due to unit spoiler deflection (ft-lb/deg).

Lateral asymmetry drives Landing Gear design, in case of a load imbalance on the MLG.

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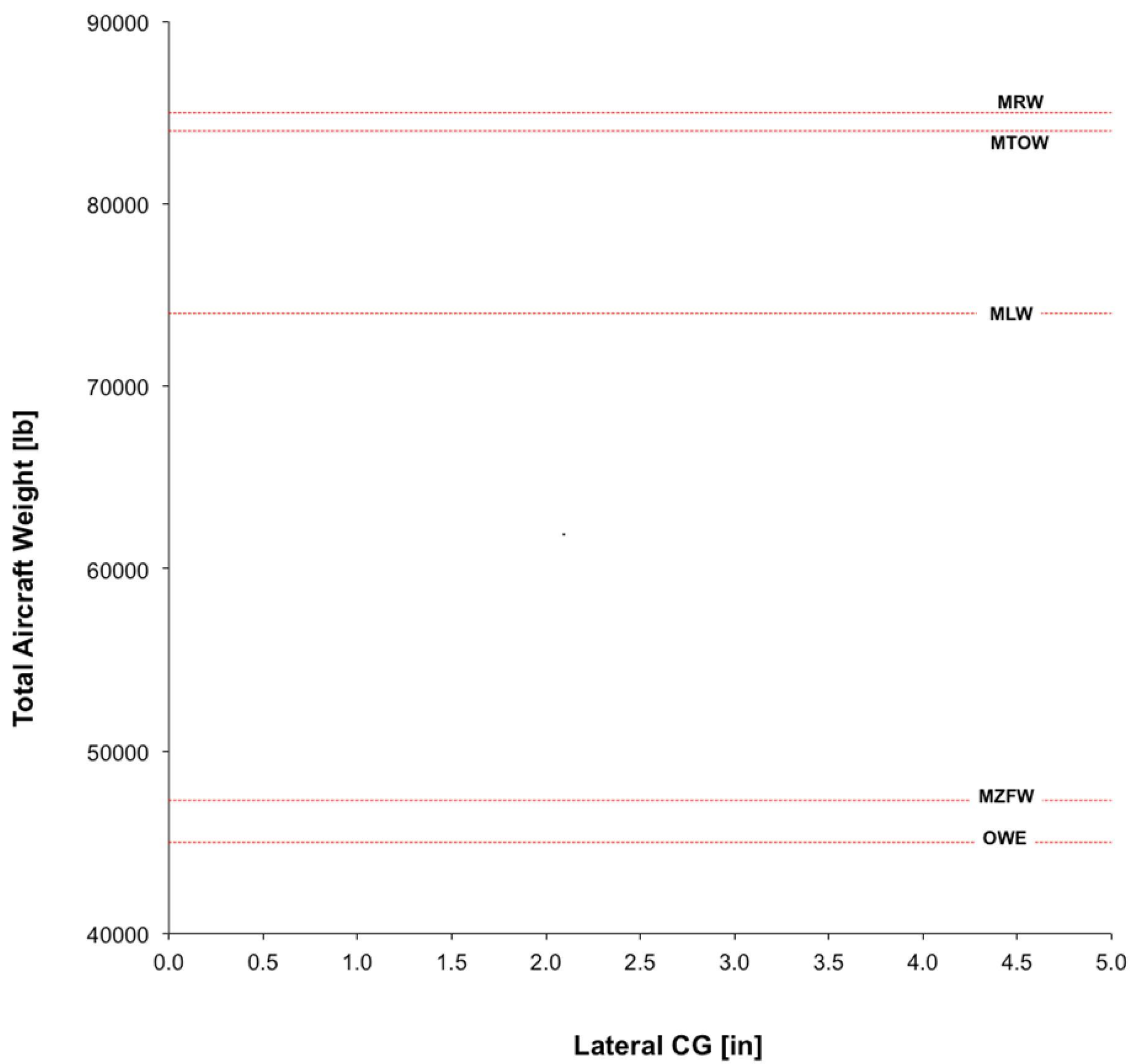
Lateral CG Envelope



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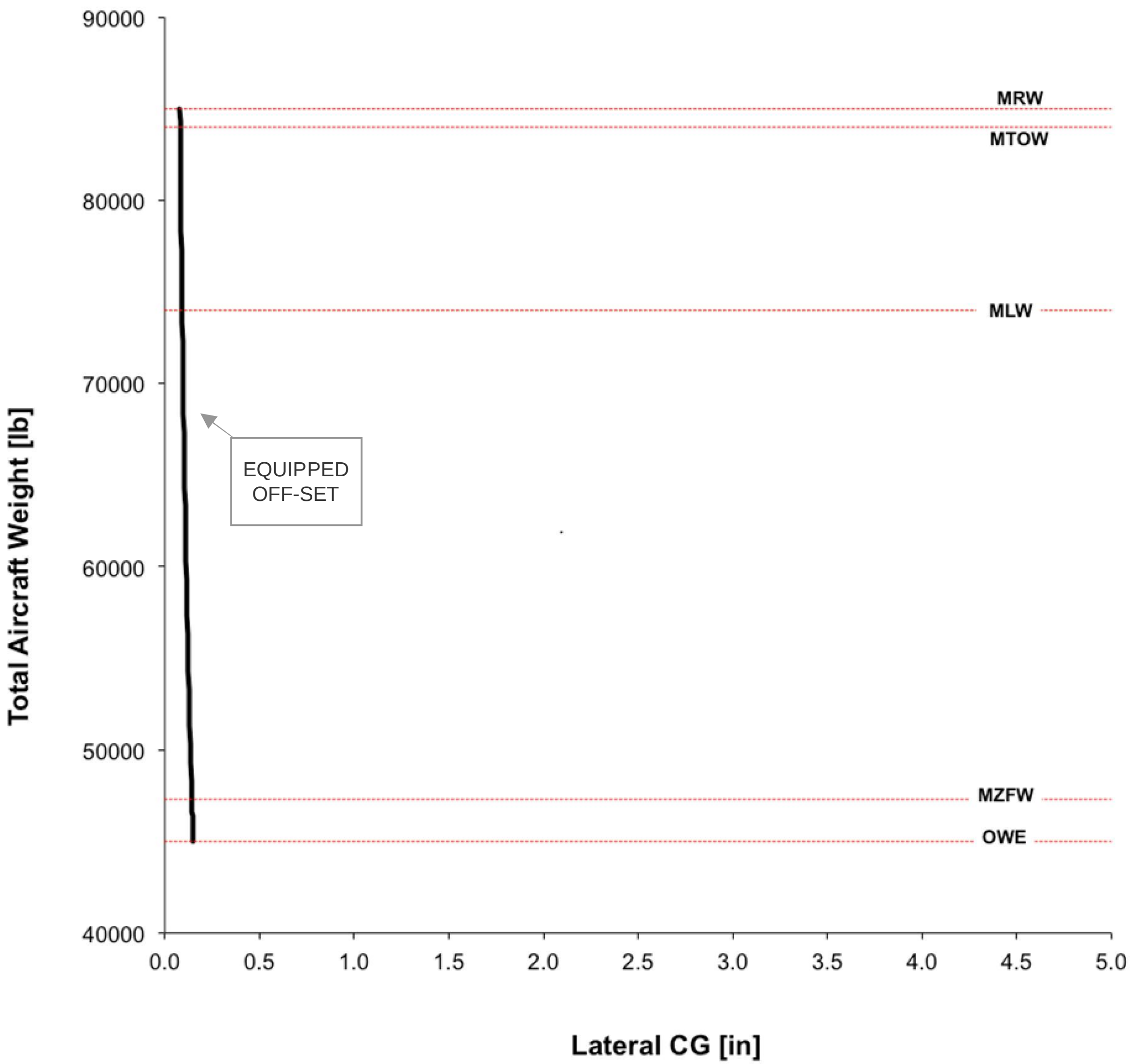

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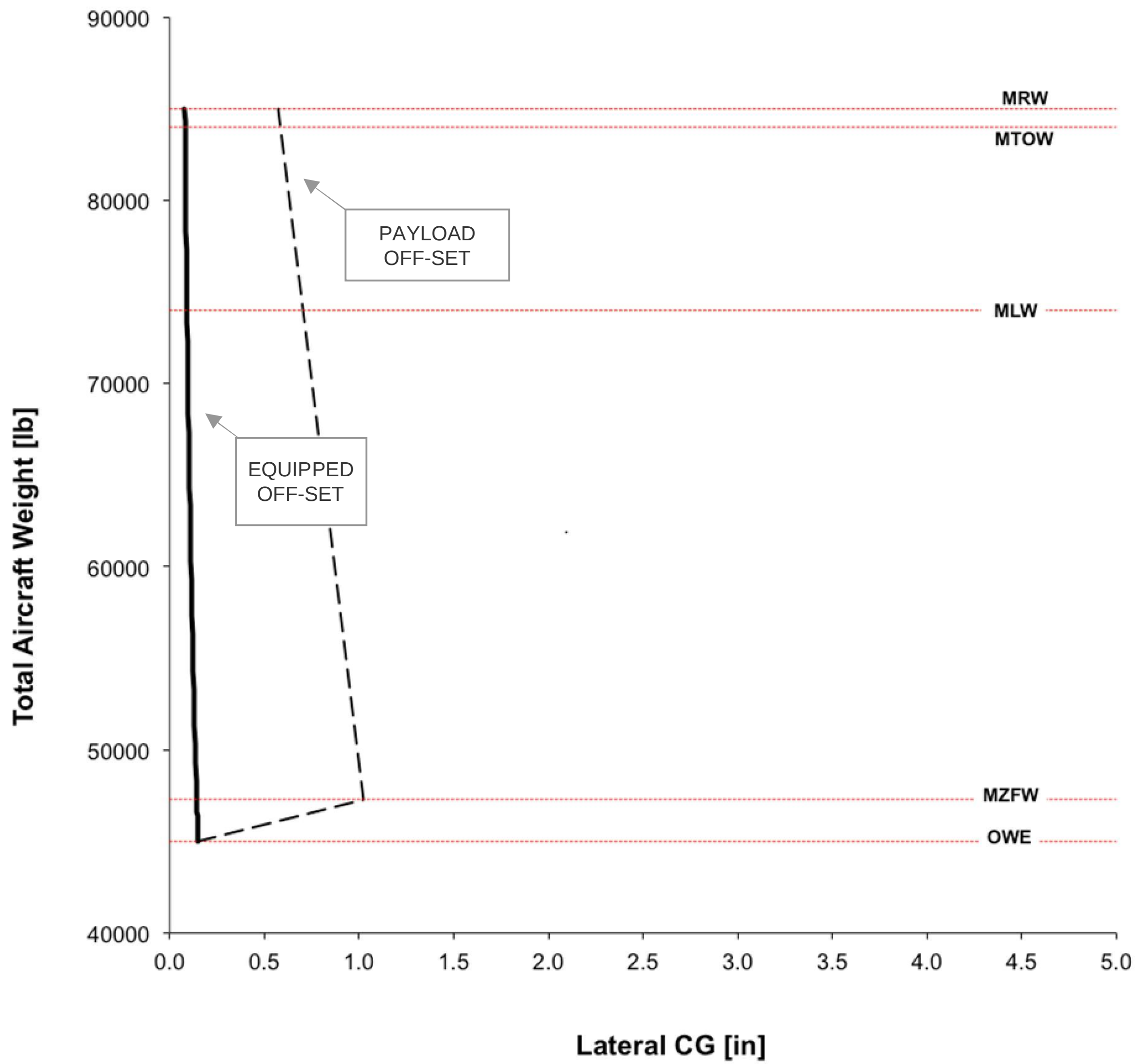

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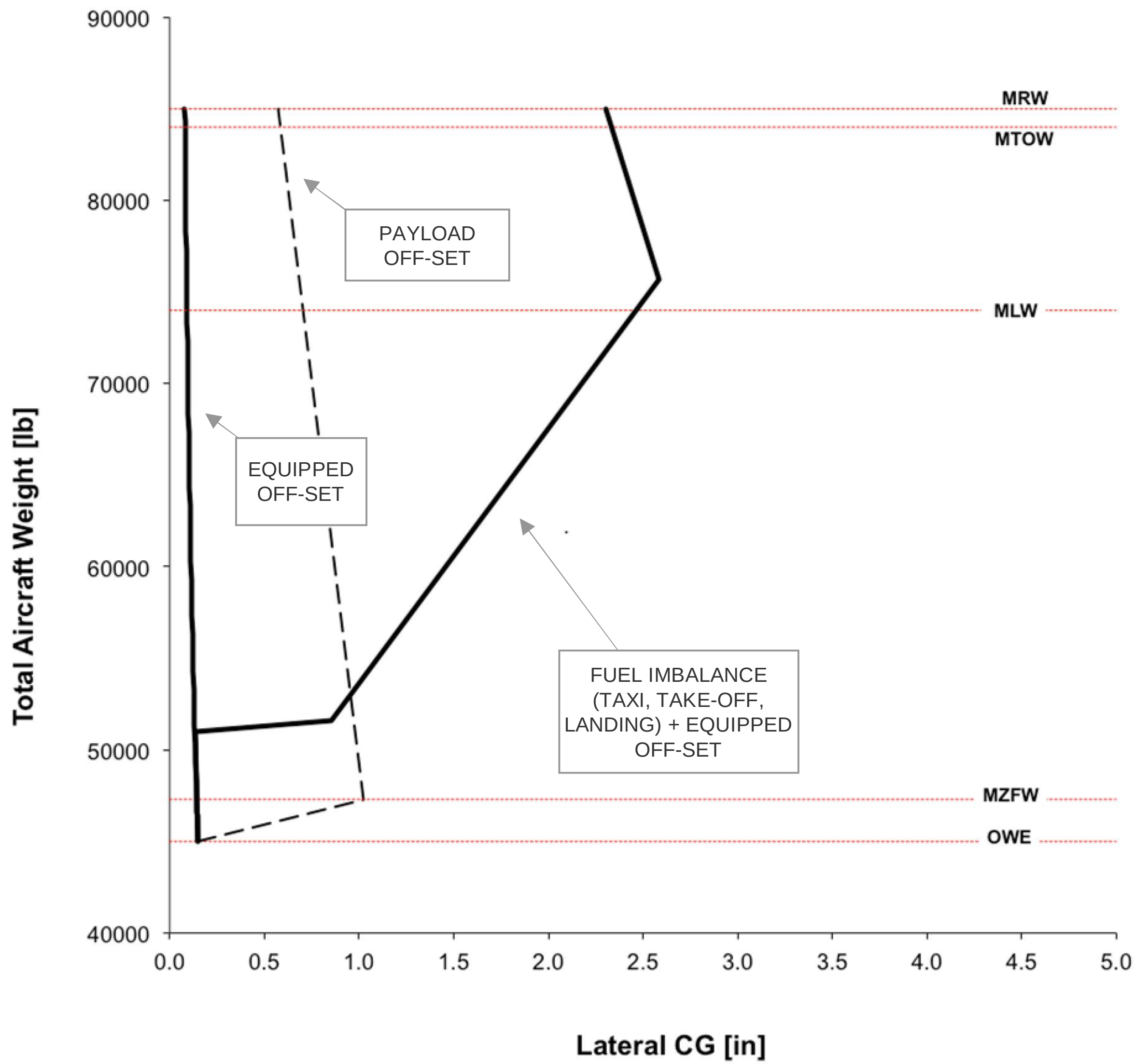

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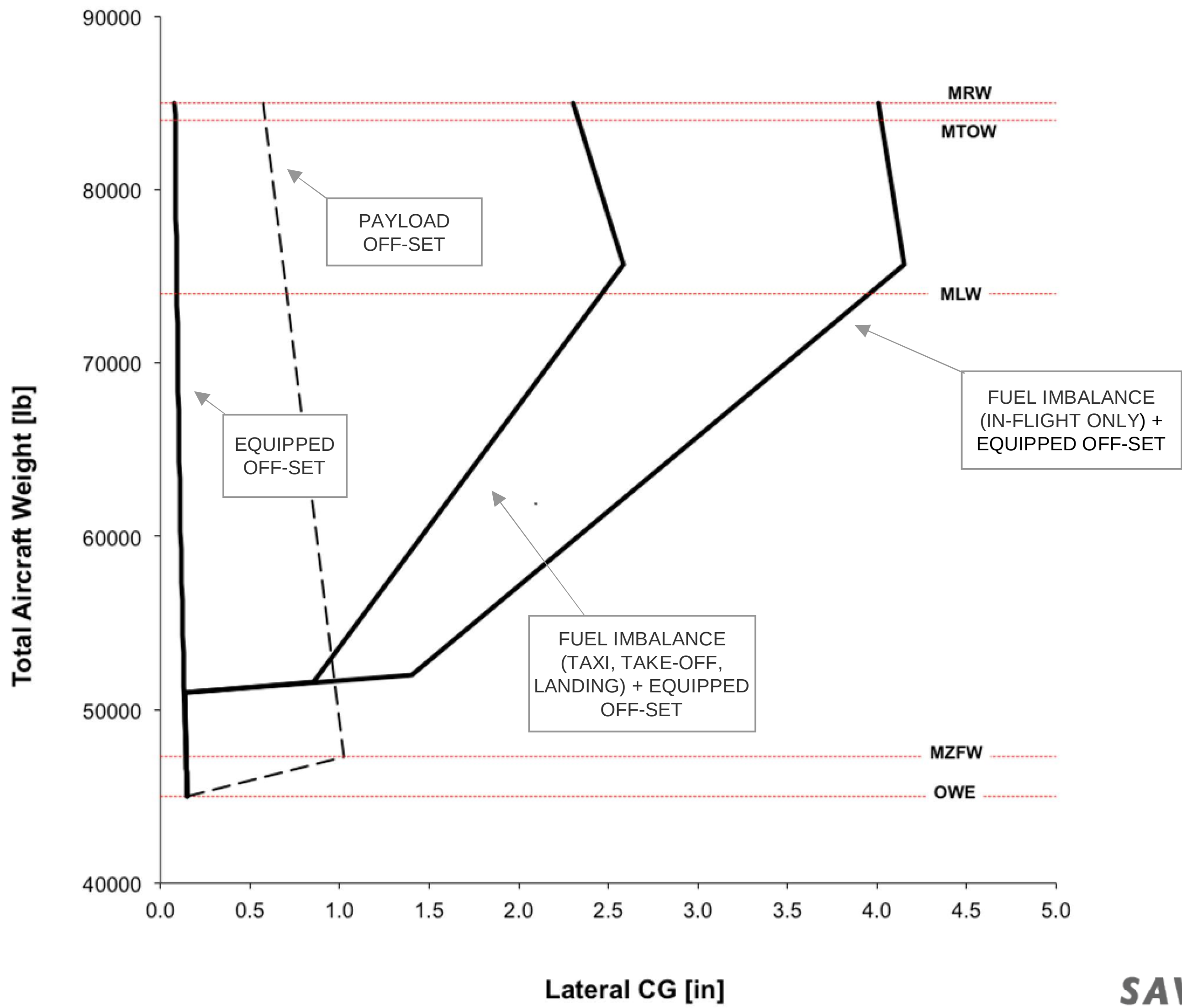

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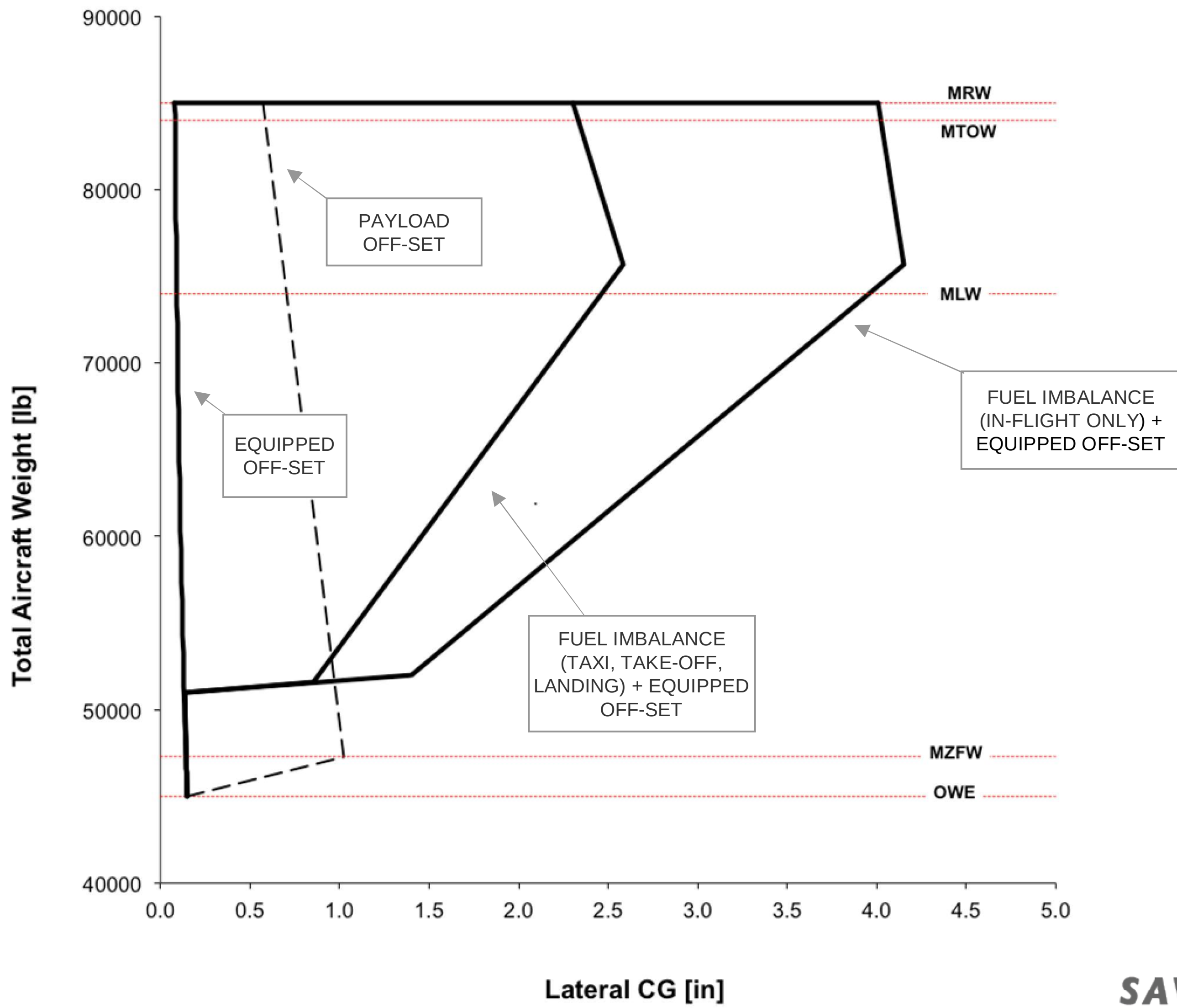

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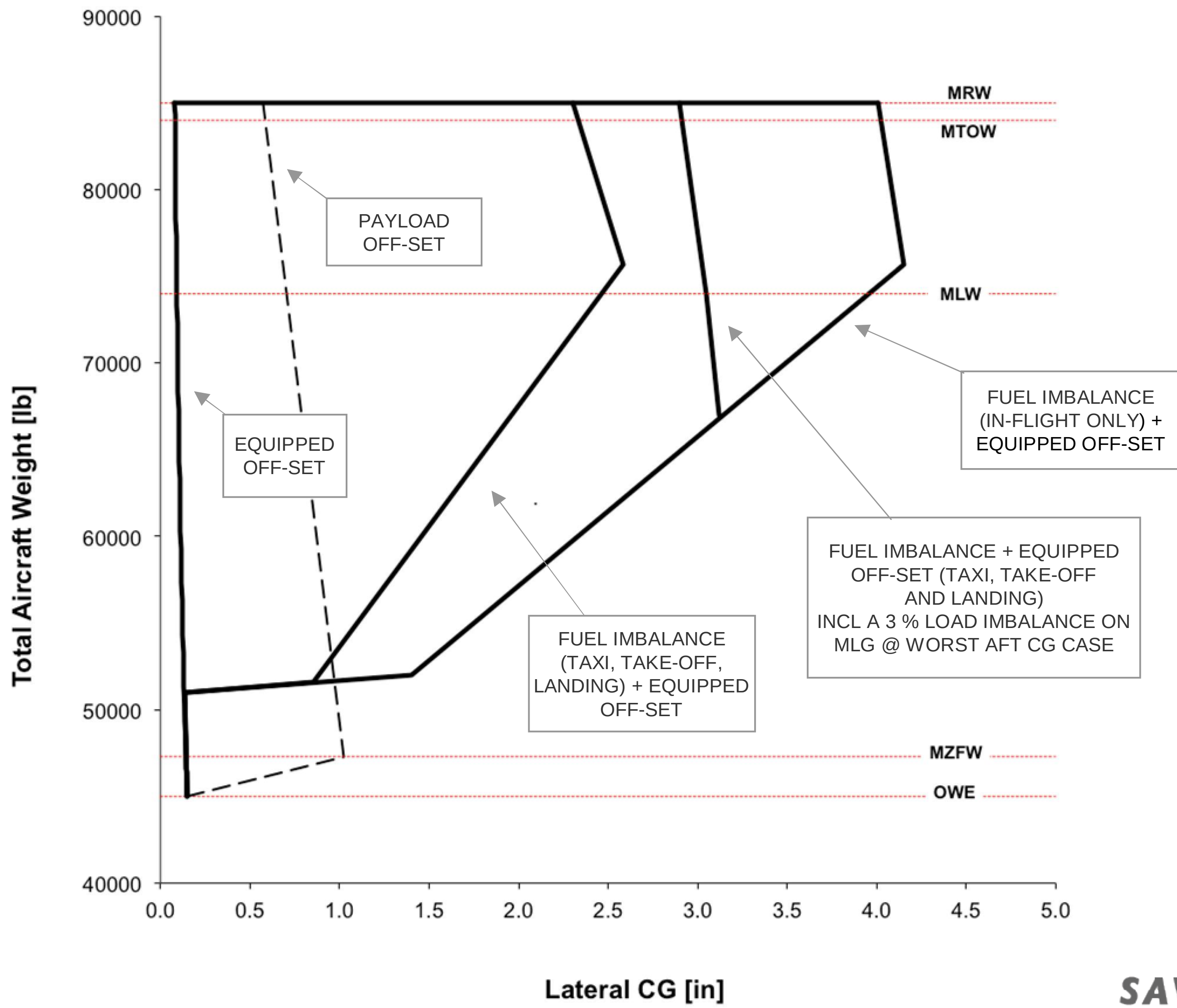

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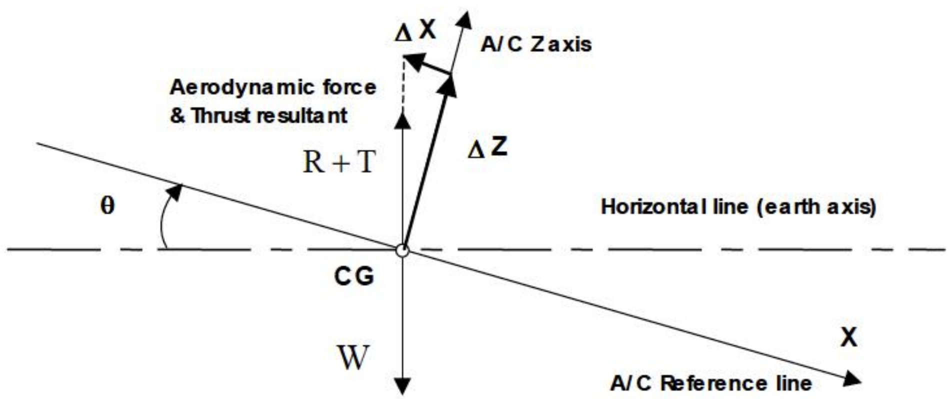
Vertical CG Envelope

The position of the Vertical CG of the aircraft has an impact on both: longitudinal and lateral stability.

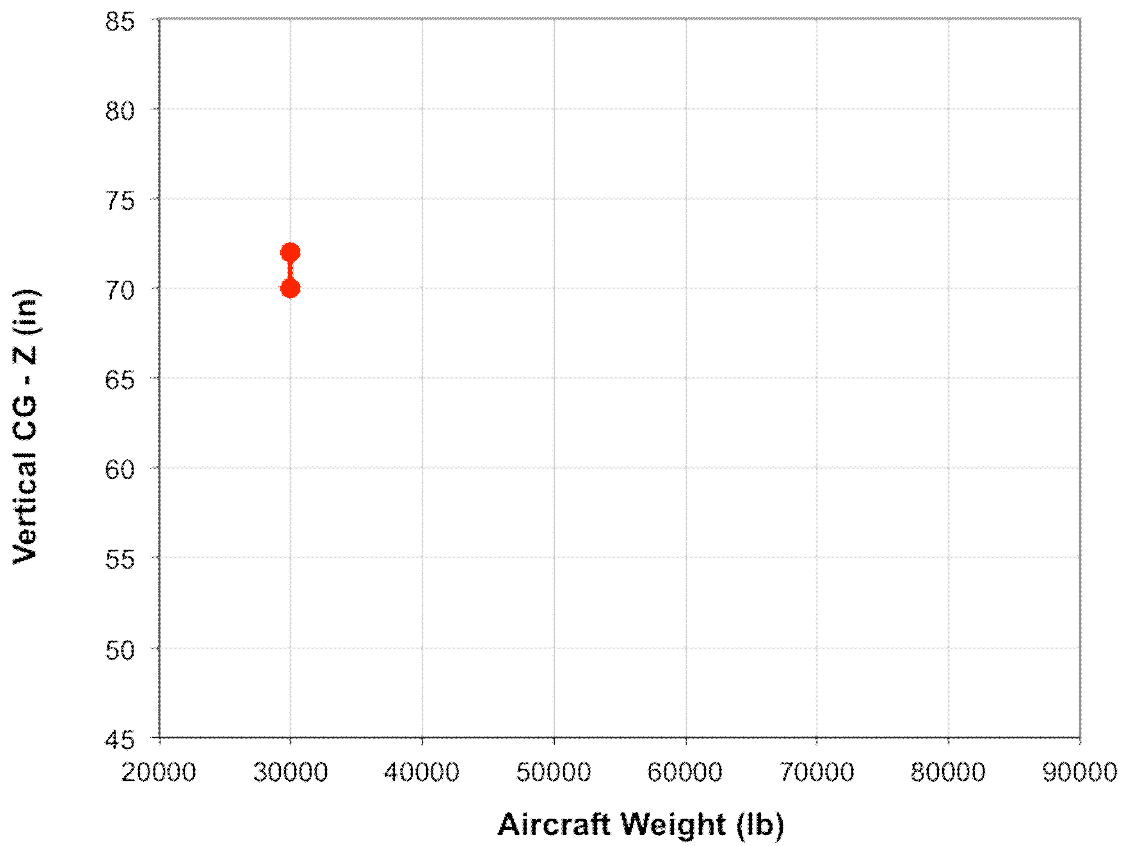
- Lateral — A CG elevation leads to a deterioration of spiral stability, Dutch roll and roll maneuverability.

- Longitudinal — Mainly, static stability is affected.
  A center of gravity elevation at constant longitudinal position is expected to decrease the static stability in climb.
  The higher the angle of attack (θ), the greater the destabilizing effect caused by the ΔX component.
  At level flight (on the horizontal line), the angle is 0° ⇔ the resulting component is also 0.
  Static stability is maintained only when CG Z travels at a pure vertical path in relation with the light path.



$$\Delta X = -\Delta Z \, tg\, \theta$$

Vertical CG Envelope



Description	Gear	Weight [lb]	Z CG [in]
Min. OWE	Down	30000	70
Min. OWE	Up	30000	72
OWE	Up	35000	73
OWE + max payload	Up	40000	72
OWE + max payload + fuel to ramp	Up	85000	57
OWE + max payload + fuel to ramp	Down	85000	56
OWE + full fuel + payload to ramp	Down	85000	55
OWE + full fuel	Down	82000	55
OWE + 1/2 fuel	Down	60000	61
Back to Min. OWE	Down	30000	70

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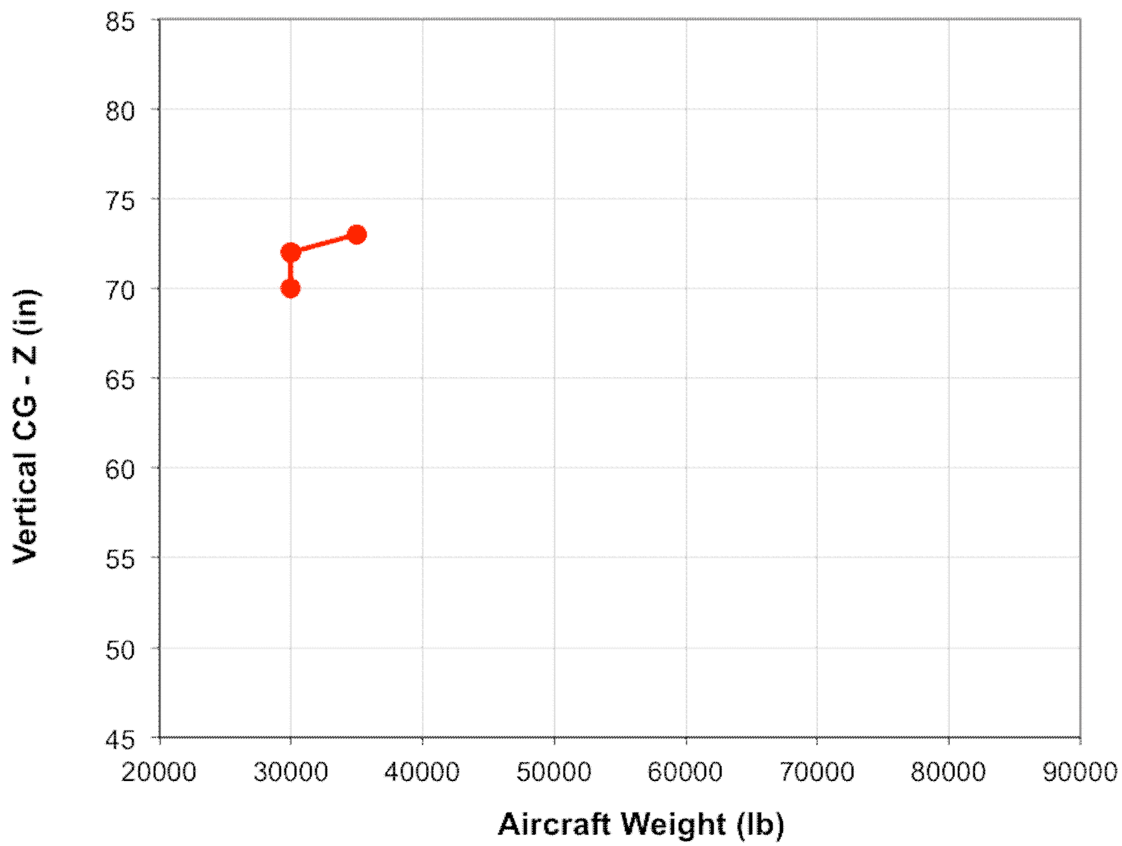
Vertical CG Envelope



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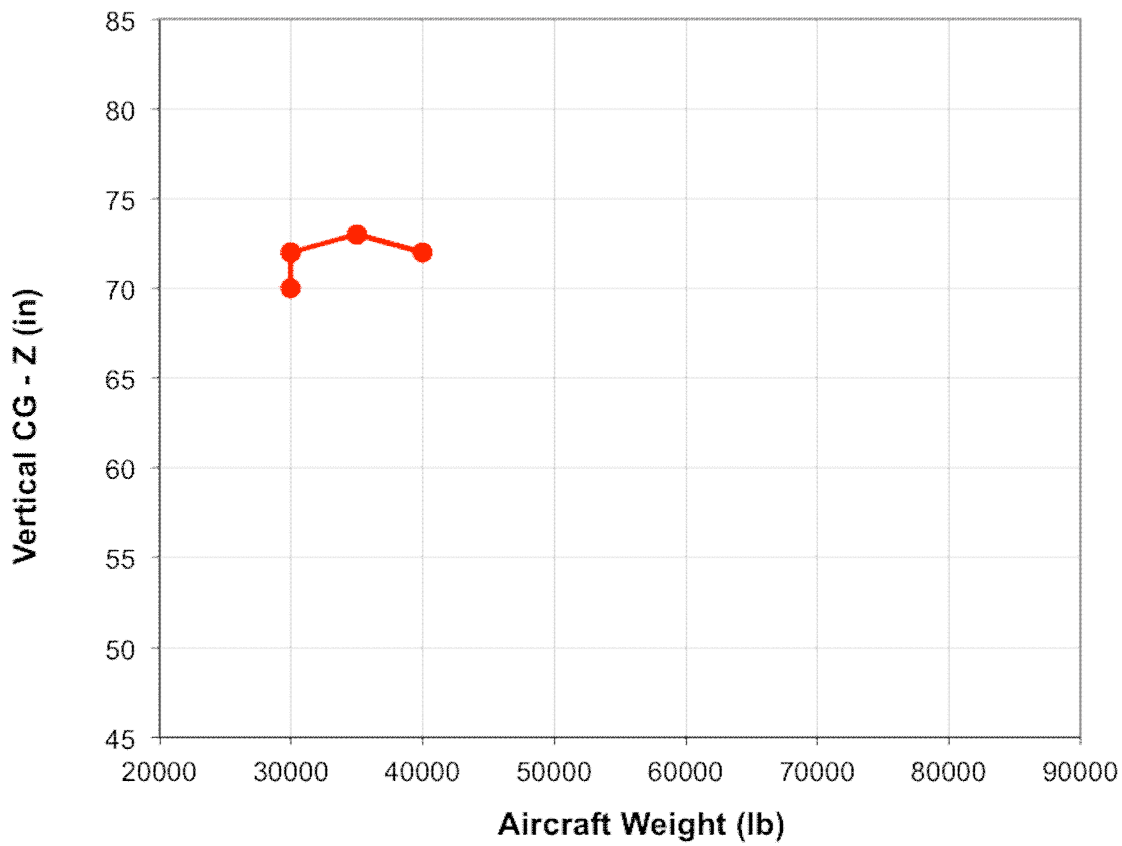
Vertical CG Envelope



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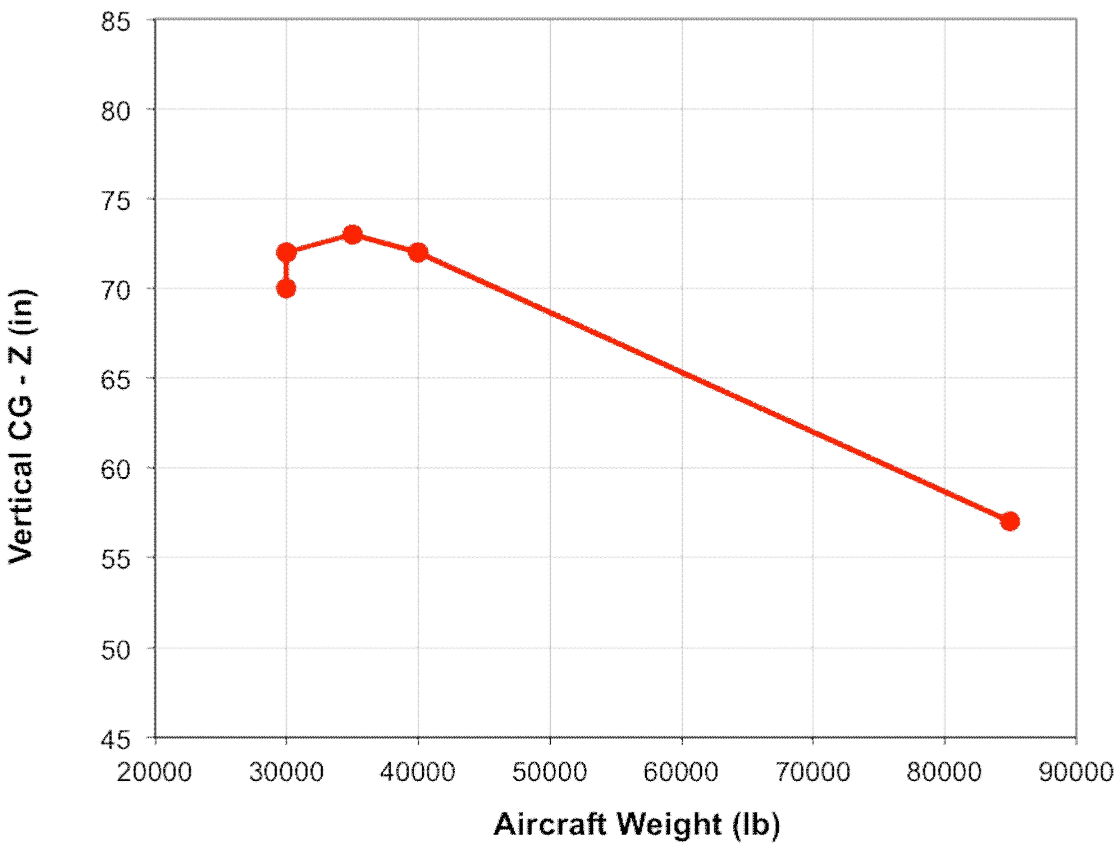

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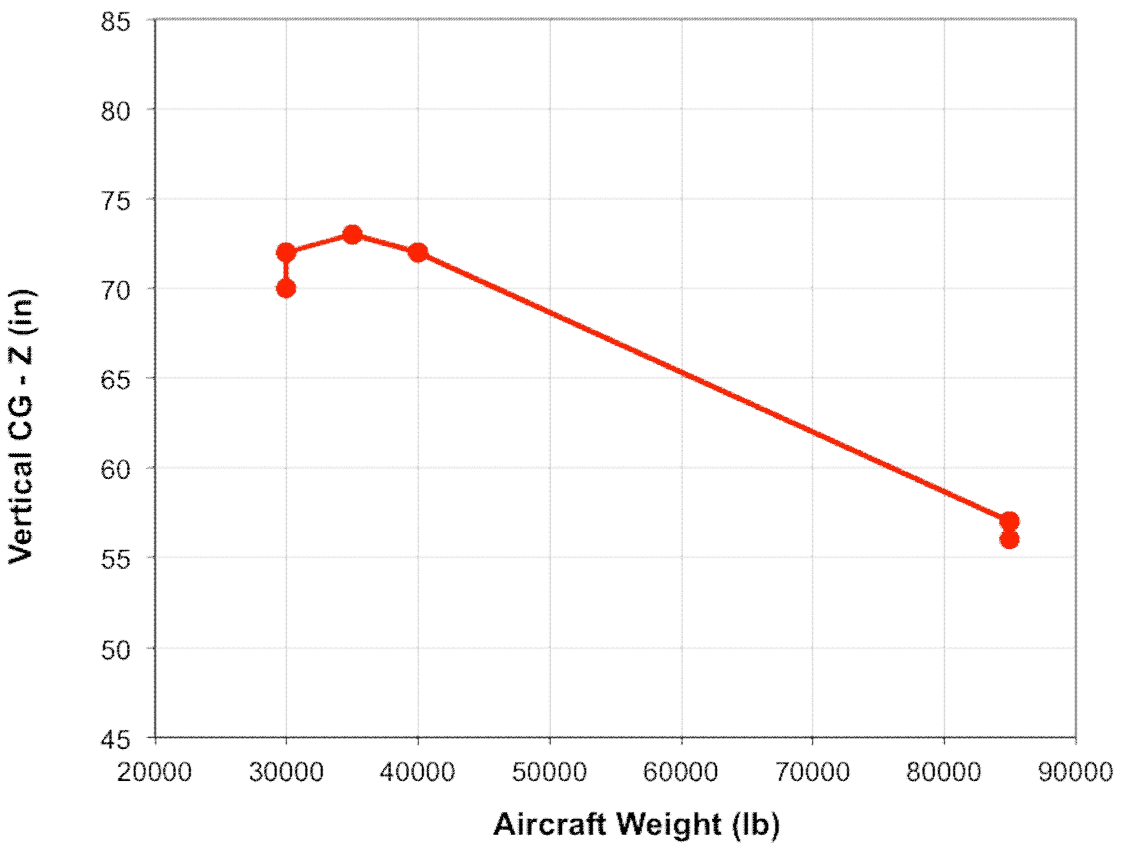

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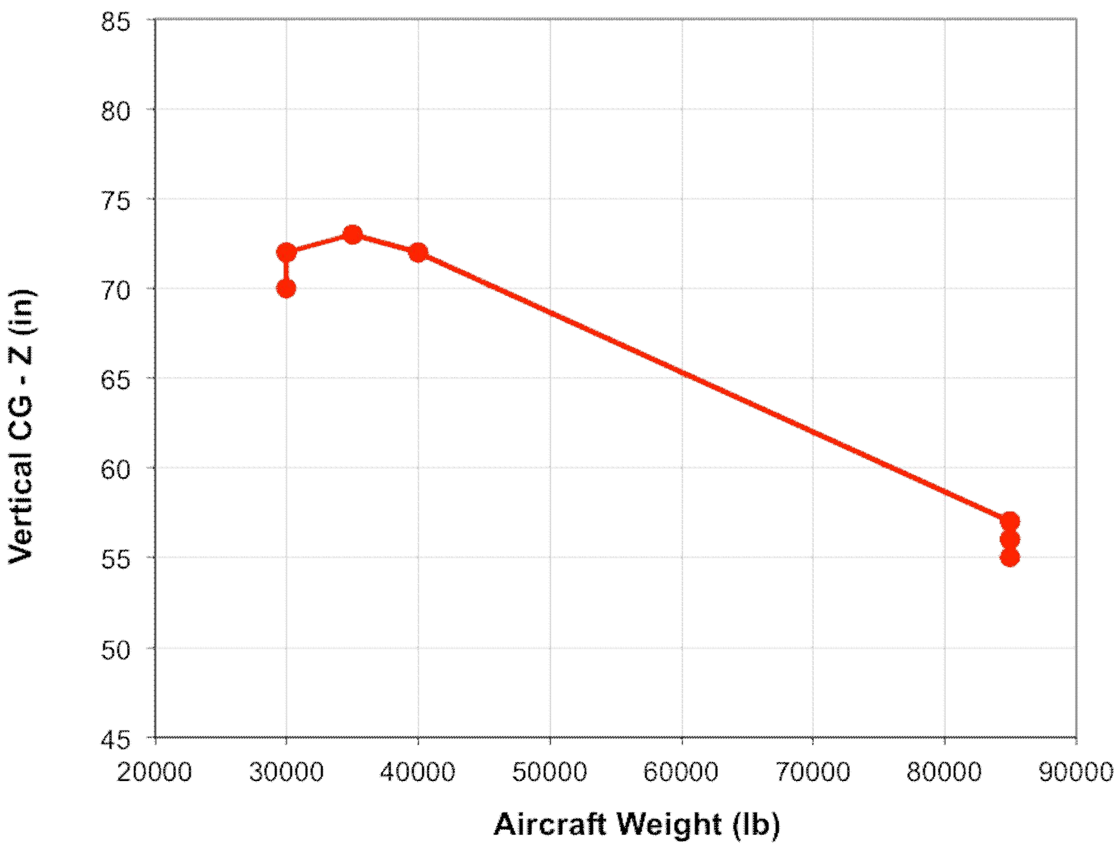

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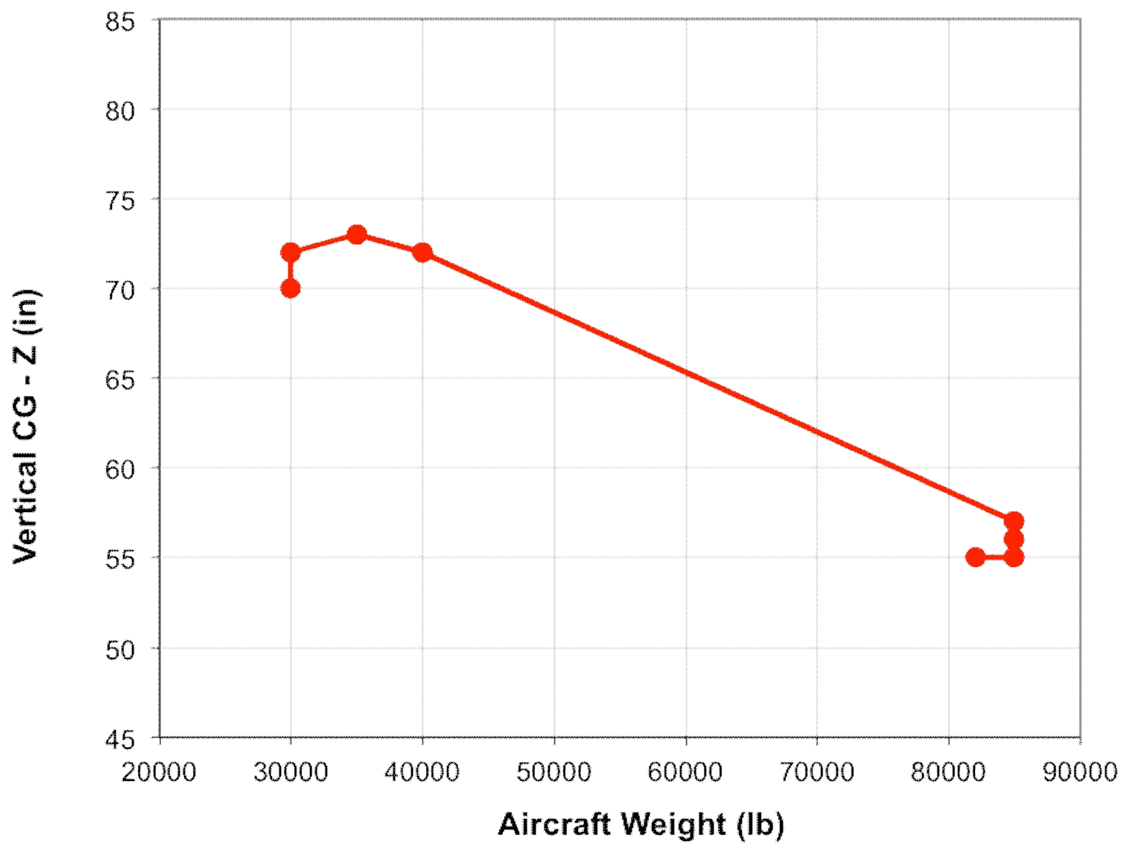

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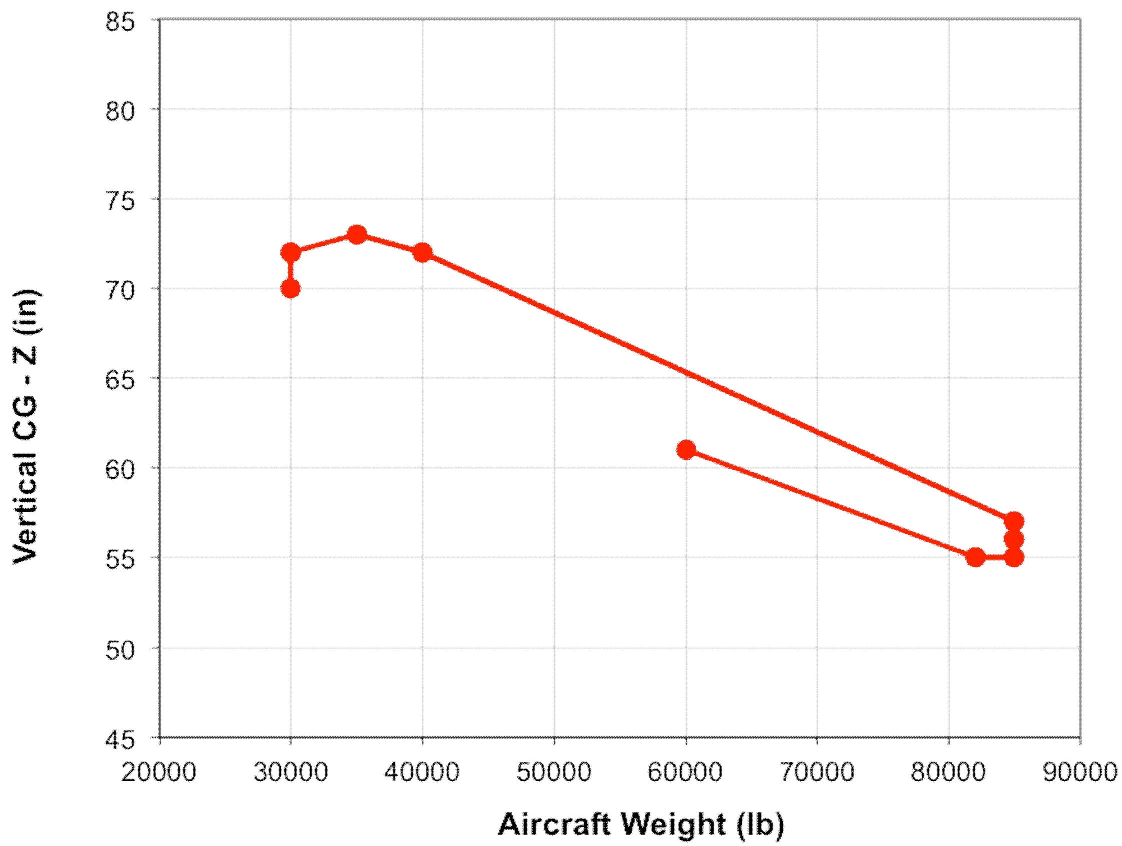

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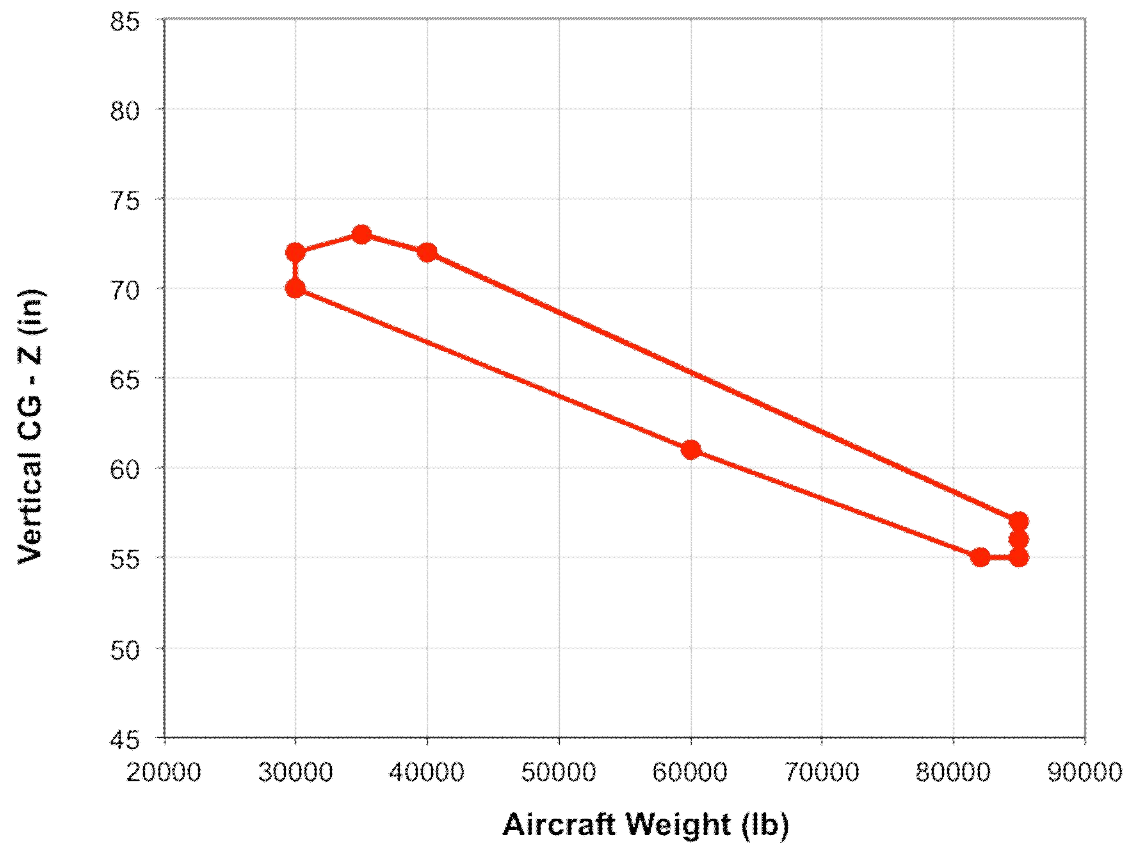

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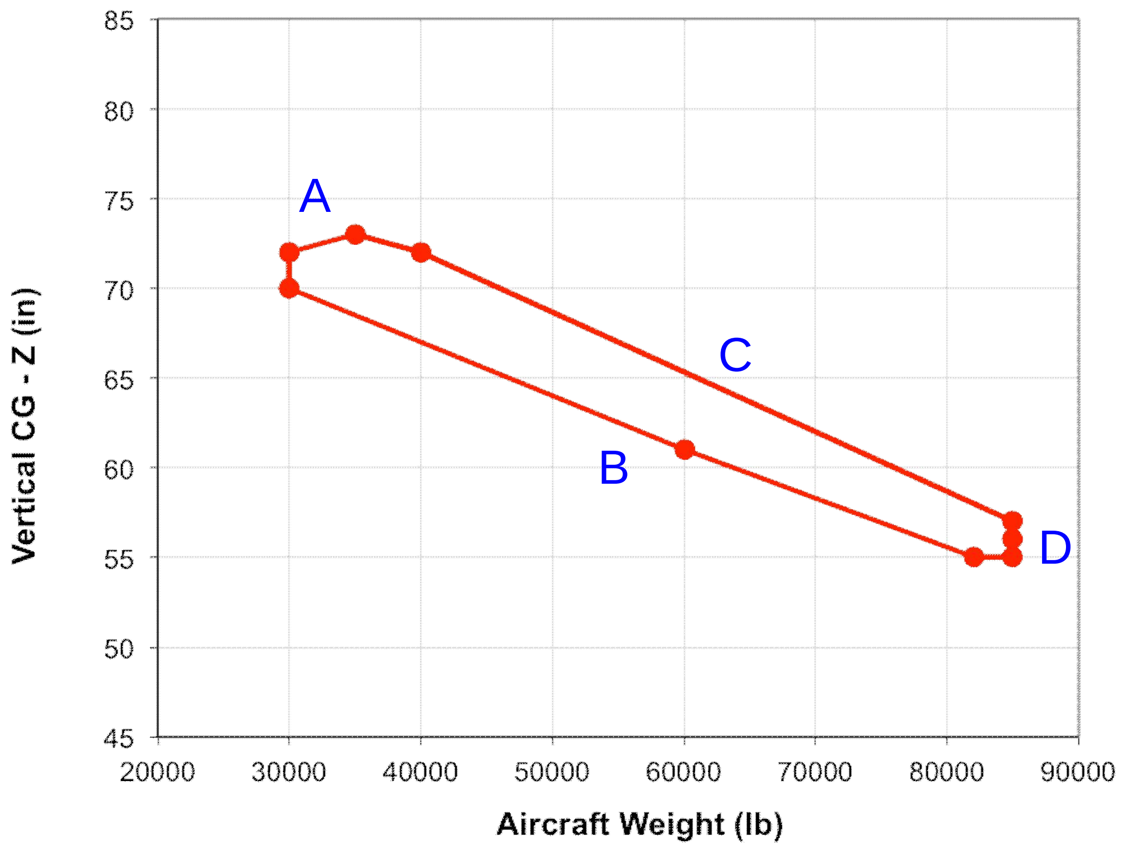

A. Maximum payload
B. Maximum fuel
C. Fuel to Maximum Ramp Weight
D. Payload to Maximum Ramp Weight

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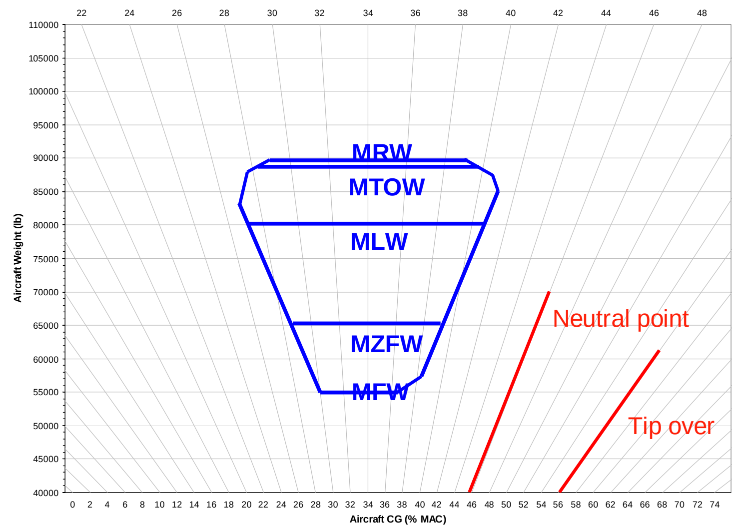
Longitudinal CG Envelope

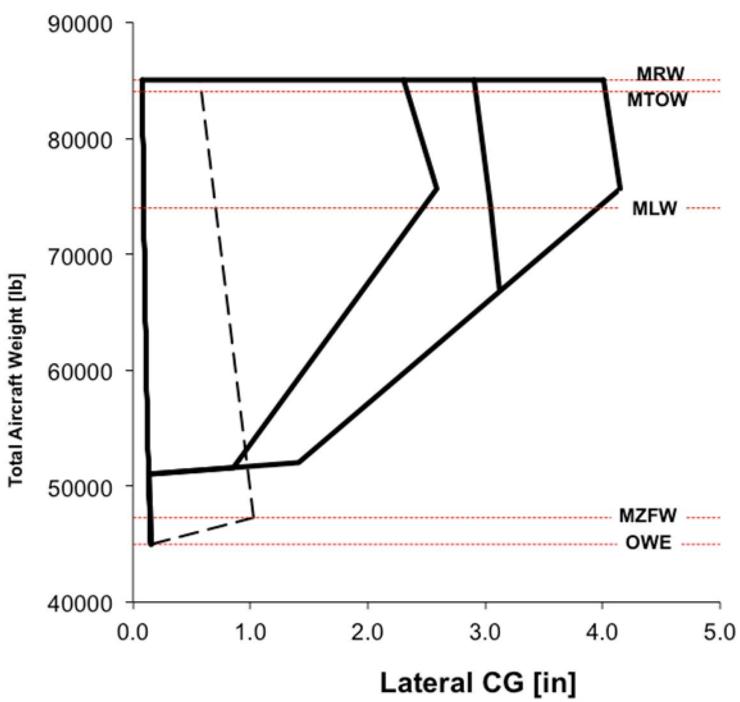
- ➔ Landing becomes a driver in establishing the forward CG
- ➔ Stability & Control becomes a driver in establishing the aft CG



Lateral CG Envelope

Imbalances caused by the asymmetry due to:

1. Empty Aircraft – Lateral CG Offset
2. Payload Lateral CG Offset



Vertical CG Envelope