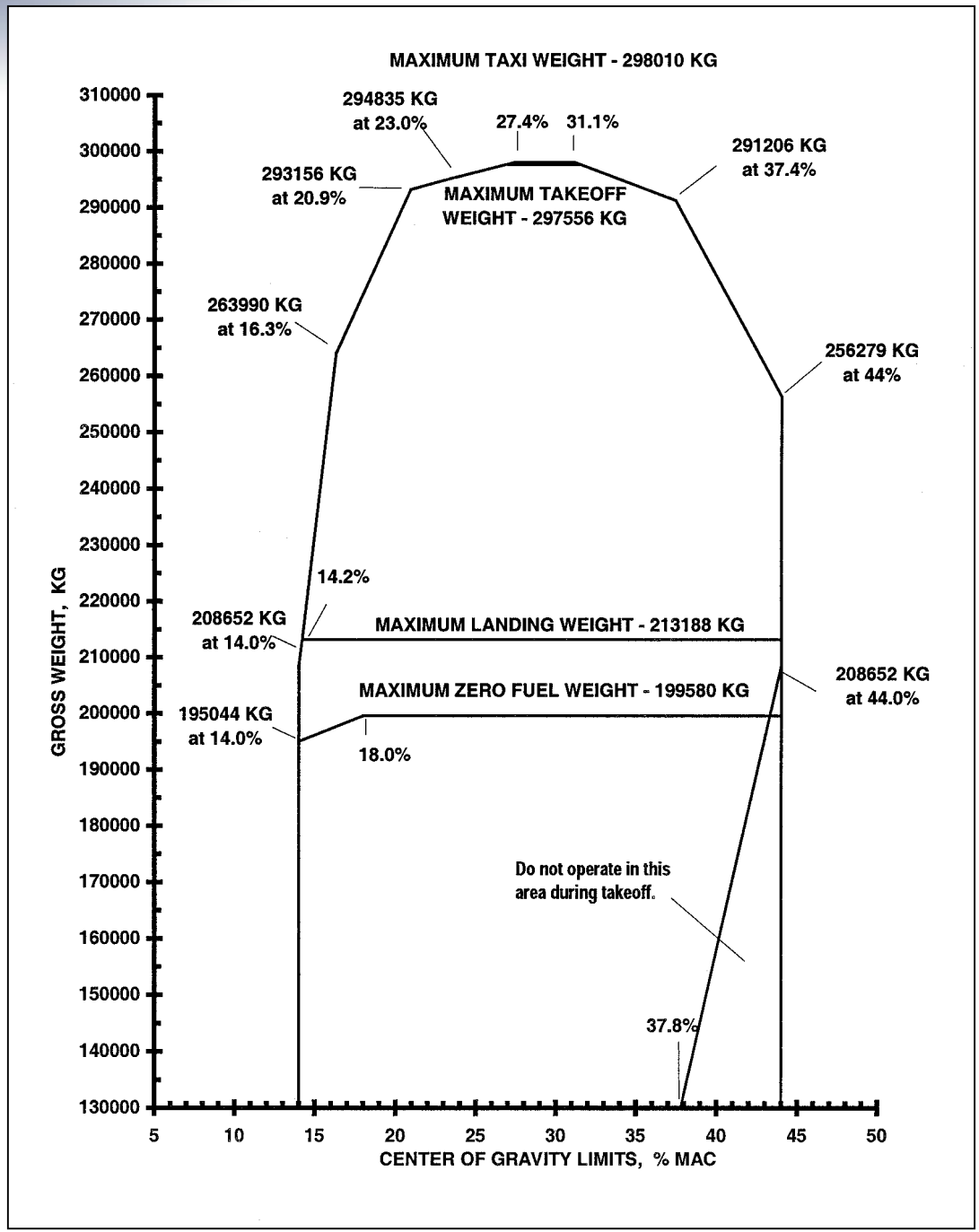
Center of Gravity Limitations

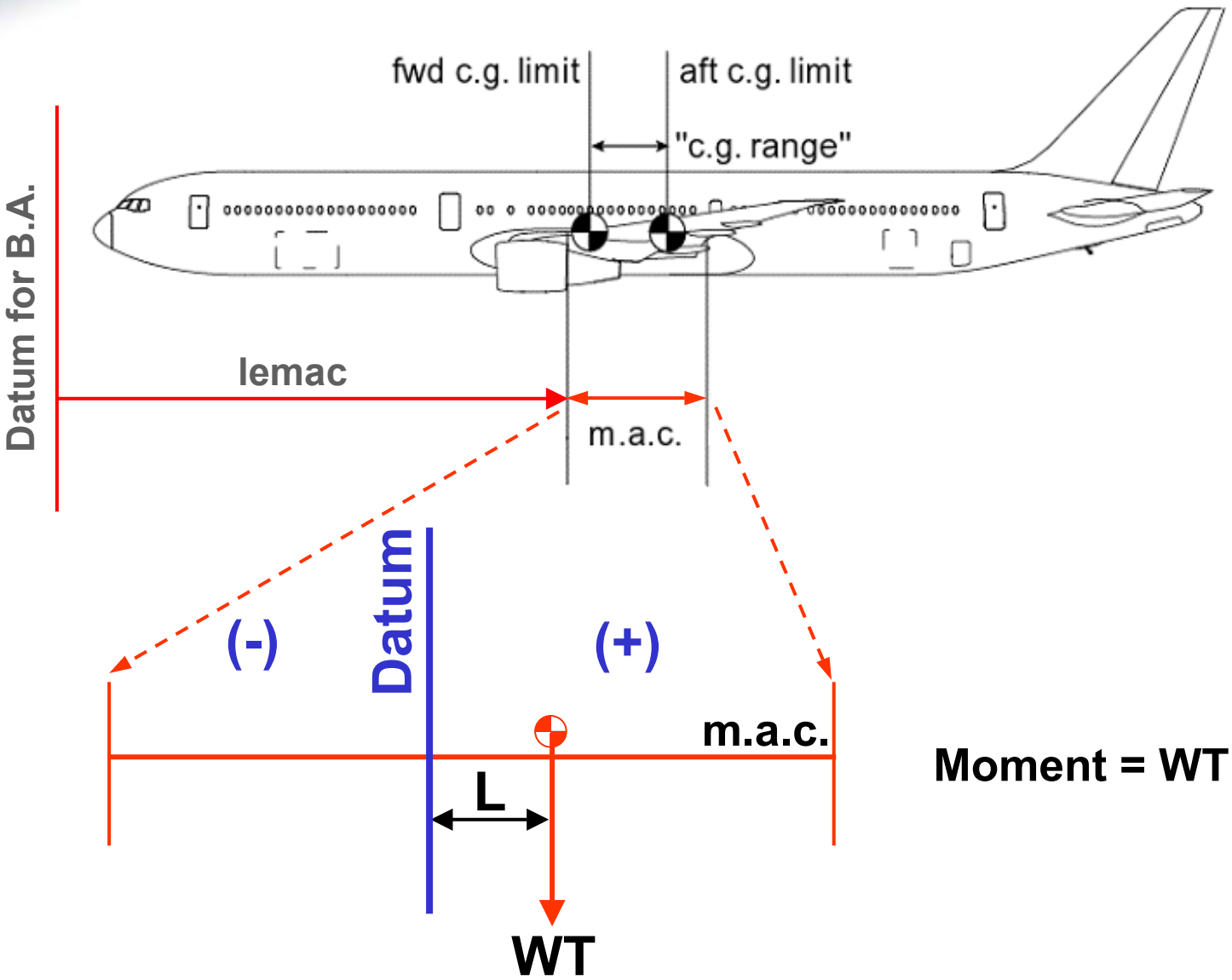
Example 777-200 Center of Gravity Limits (Ref. AFM or WBM)

How does Boeing determine C.G. limits such as these for any given airplane model?



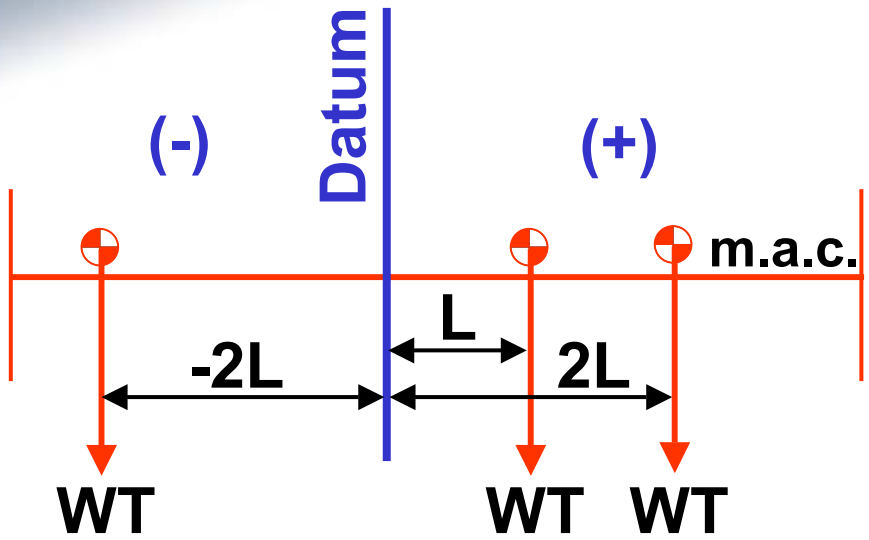
Development of the Weight versus Moment C.G. Grid

Development of the Weight versus Moment C.G. Grid



Moment = WT * L

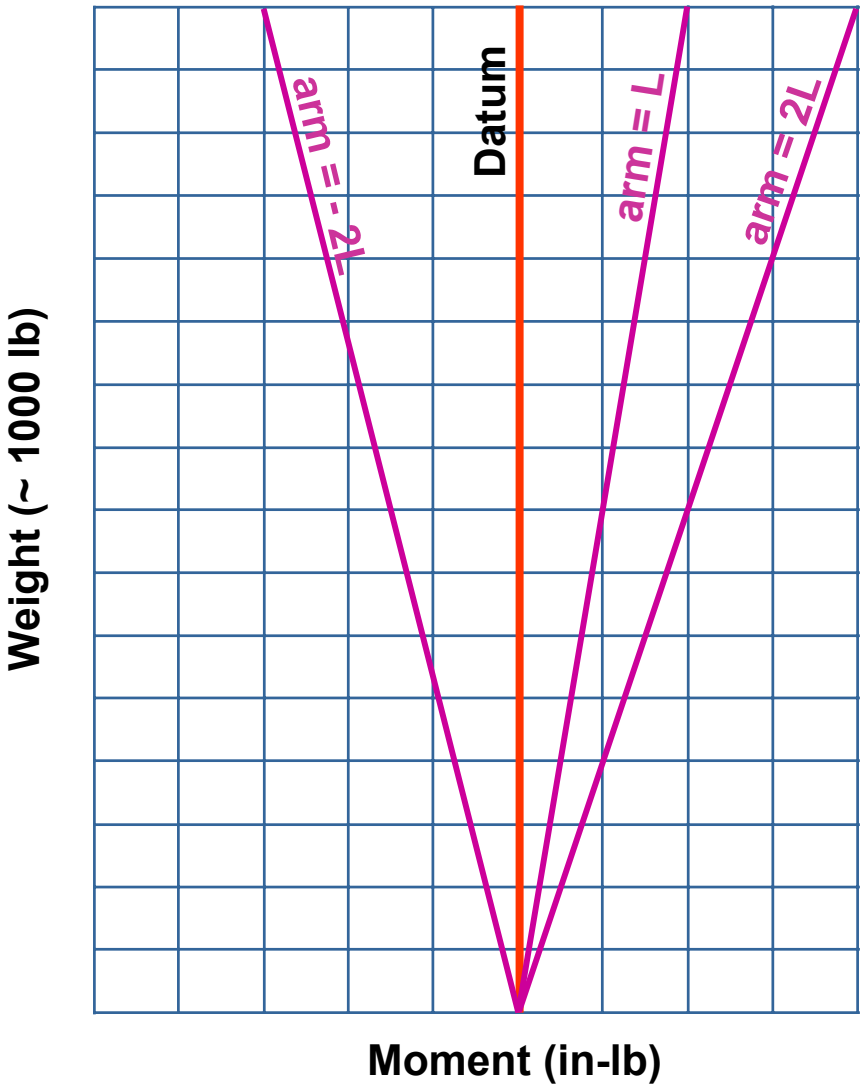
Development of the Weight versus Moment C.G. Grid



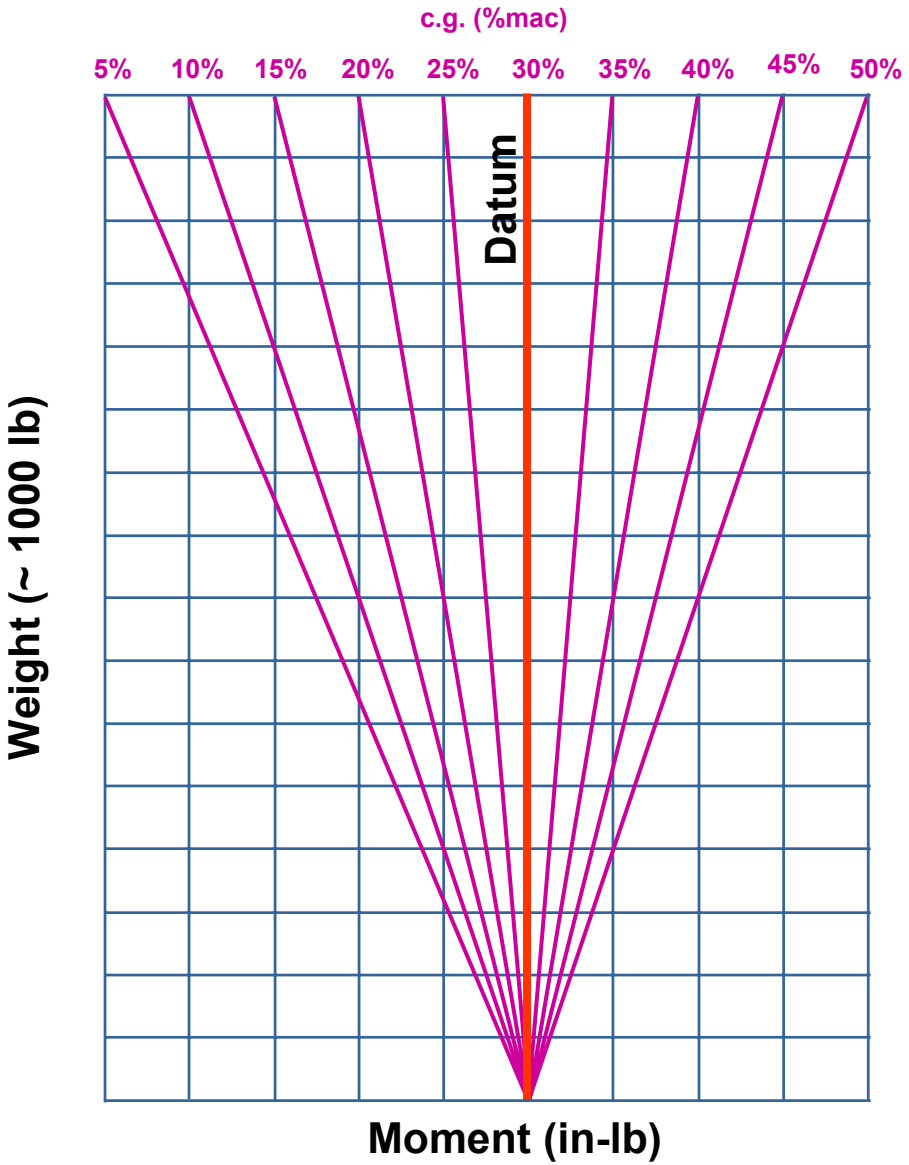
$Moment_1 = WT * L$

$Moment_2 = WT * 2L$

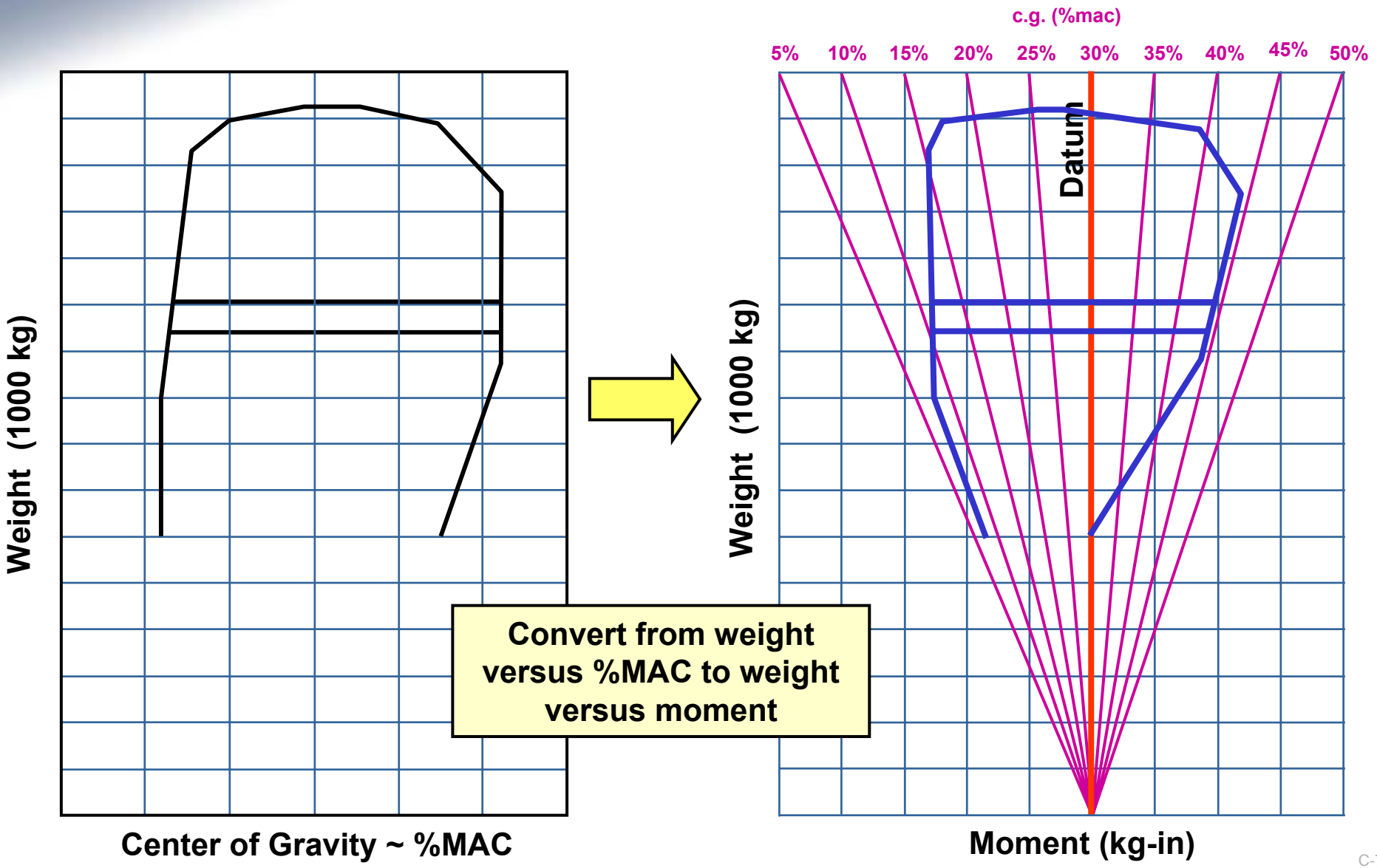
$Moment_3 = WT * (-2L)$



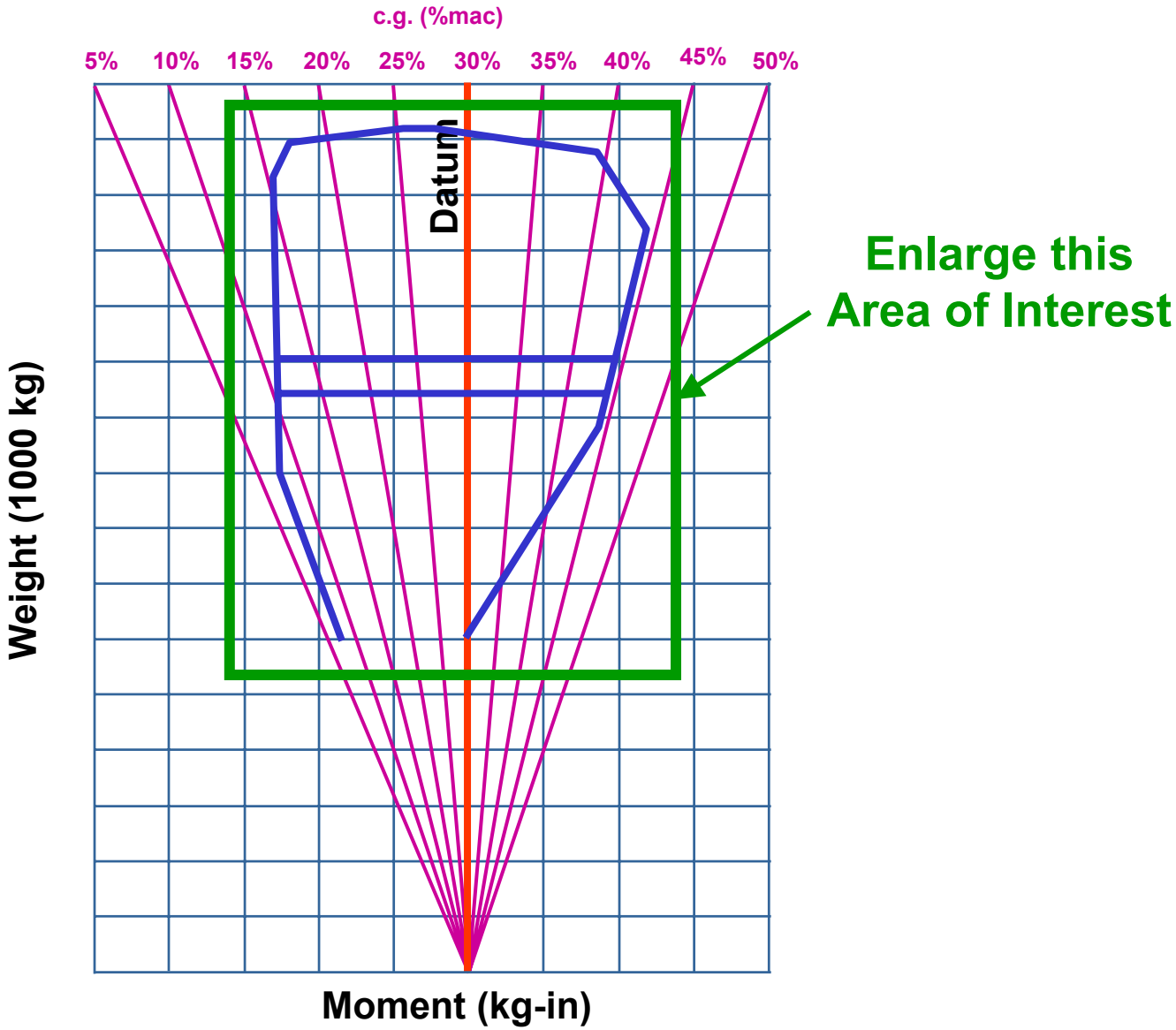
Development of the Weight versus Moment C.G. Grid



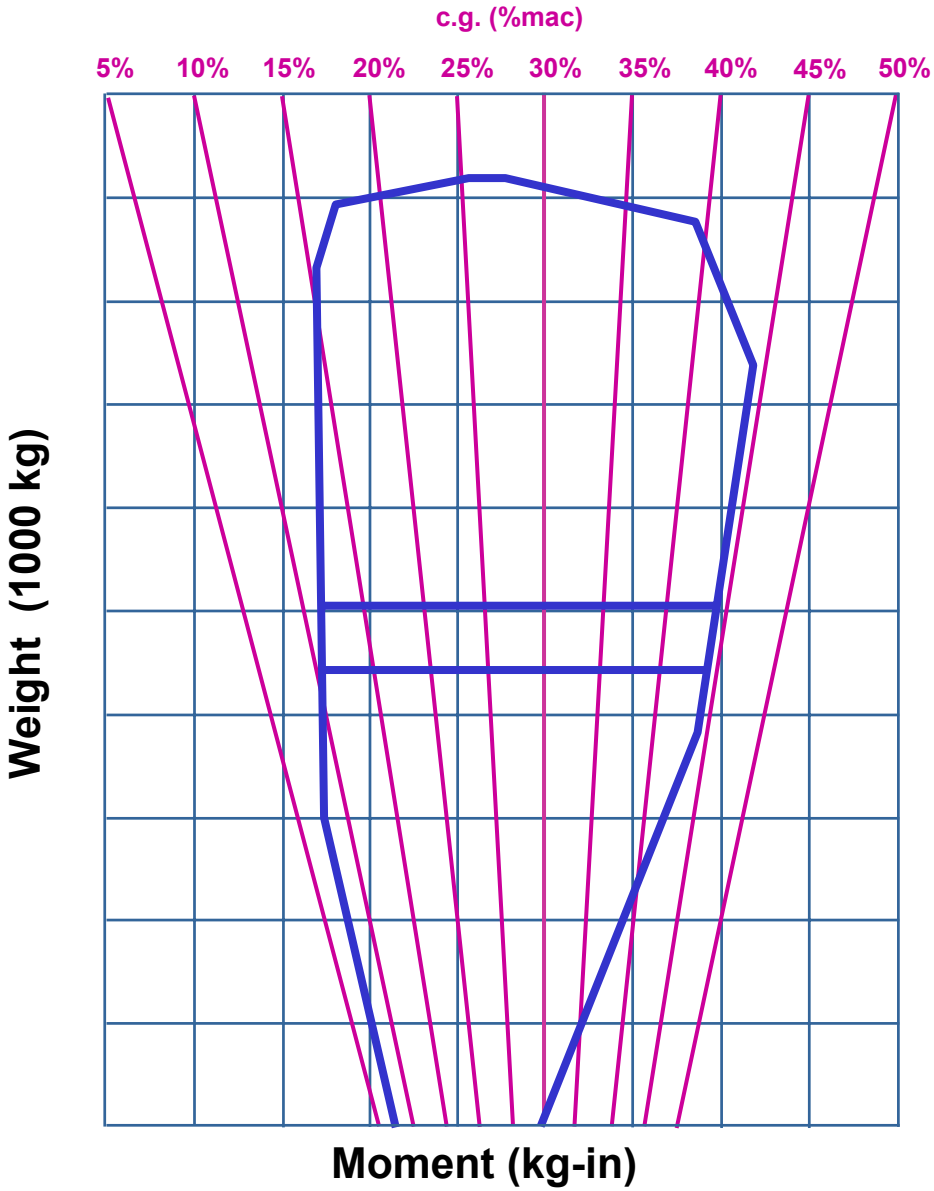
Development of the Weight versus Moment C.G. Grid



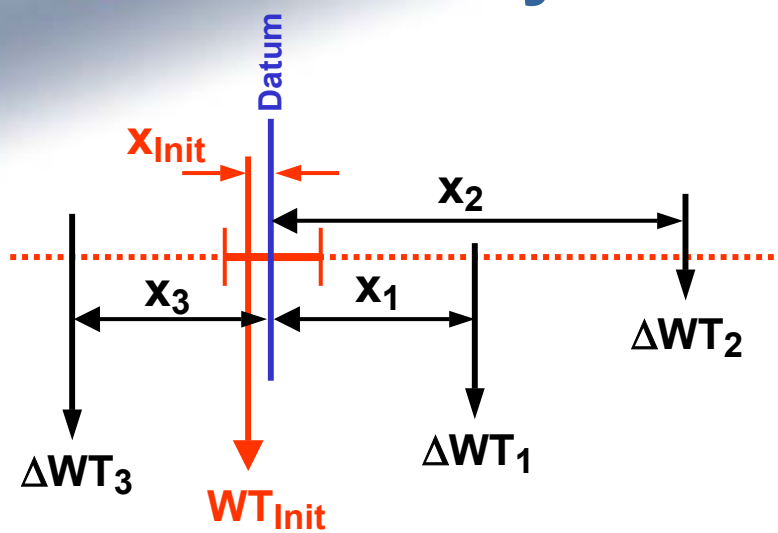
Development of the Weight versus Moment C.G. Grid

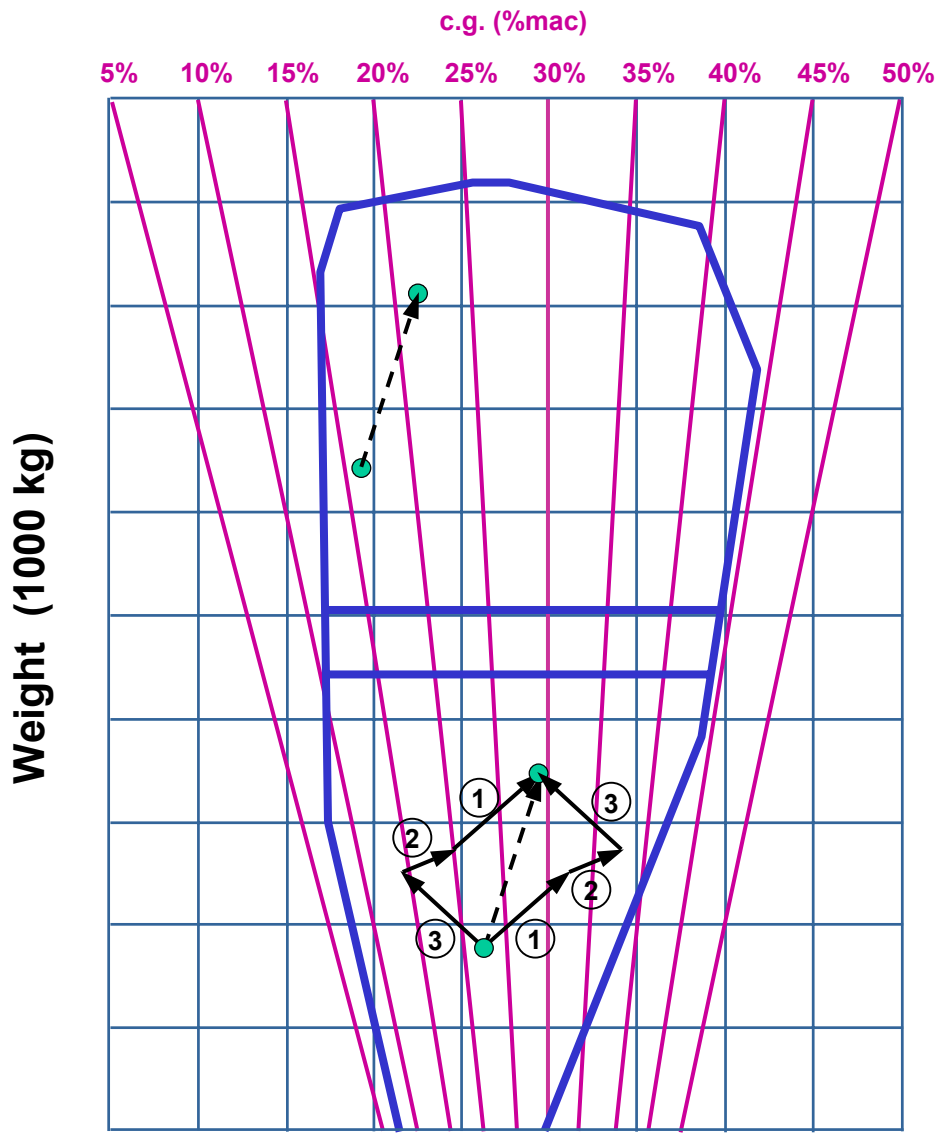


Development of the Weight versus Moment C.G. Grid



Advantage of this Format is the Ability to Add Vectors Graphically





Total Moment = $WT_{Init} * x_{Init} + (\Delta WT_1 * x_1) + (\Delta WT_2 * x_2) - (\Delta WT_3 * x_3)$

Total Weight = $WT_{Init} + \Delta WT_1 + \Delta WT_2 + \Delta WT_3$

- **Order of application does not affect final result**
- **Starting point does not affect final Δ weight and Δ moment**

Determining Desired Forward and Aft C.G. Limits

Design Objectives

- The forward and aft C.G. limits for a given airplane model are selected by Boeing during the design of the airplane, and are meant to allow for airline-to-airline variations in:
  - Operational Empty Weights
  - Interior Seating Arrangements
  - Cargo Loading – Bulk, Pallets, Containers
  - Fuel Loading and Usage
  - Operational Curtailments
- The airplane structure and layout is then designed to allow for loading of the airplane within these selected (and eventually certified) limits.
- Let’s look at an example of how this process might proceed using an airplane model we will call the 7G7-X00.

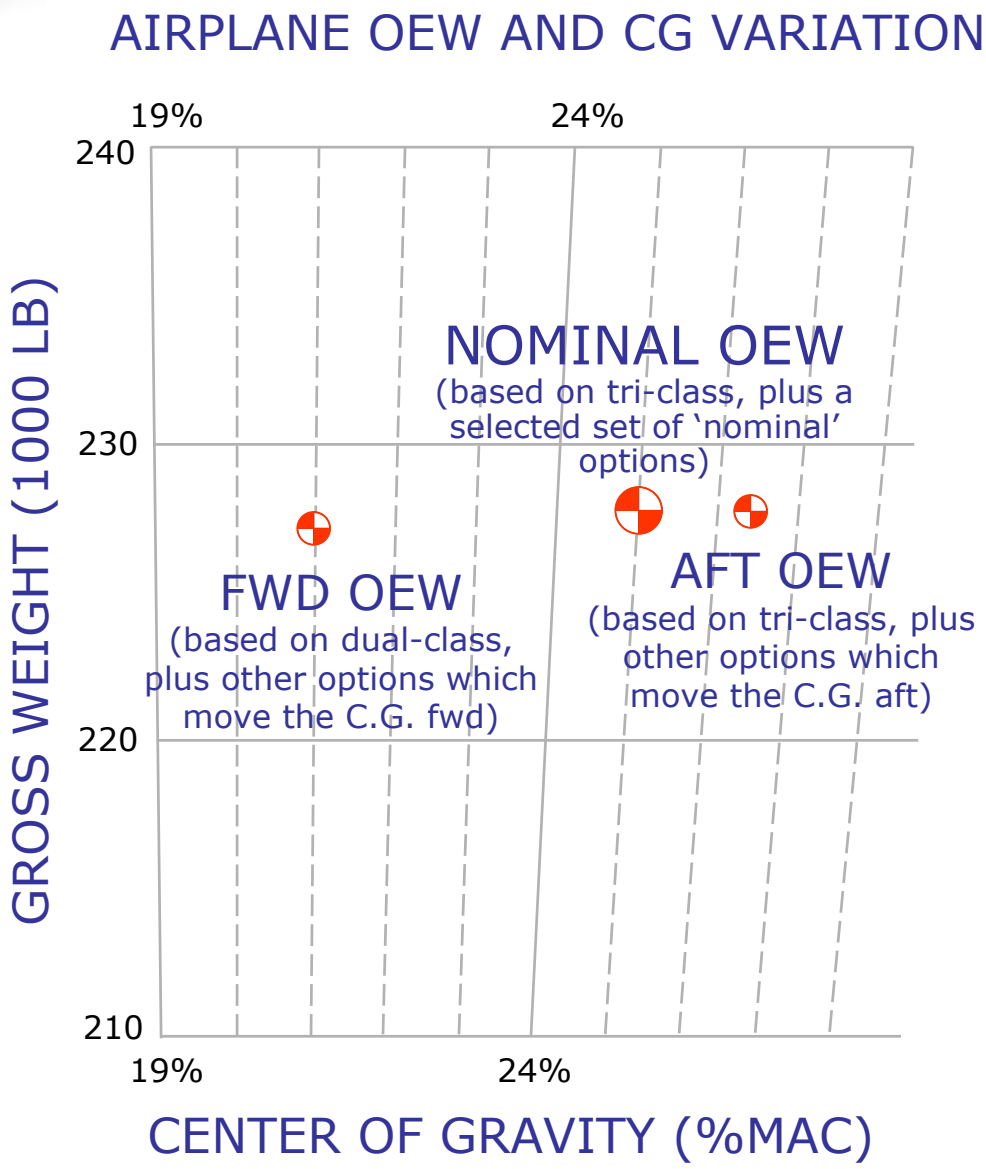
Determining Desired Fwd and Aft C.G. Limits: Accounting for OEW Variations

Accounting for OEW Variations

Boeing's design objective is to provide forward and aft C.G. limits which will allow for airline variations in airplane configuration:

- Interior seat layout, locations of galleys, lavatories, emergency equipment, etc.
- Optional configurations and features (e.g., in-flight entertainment, pallets vs. containers, EE bay options, etc.)

Accounting for OEW Variations



(7G7-X00 Example)

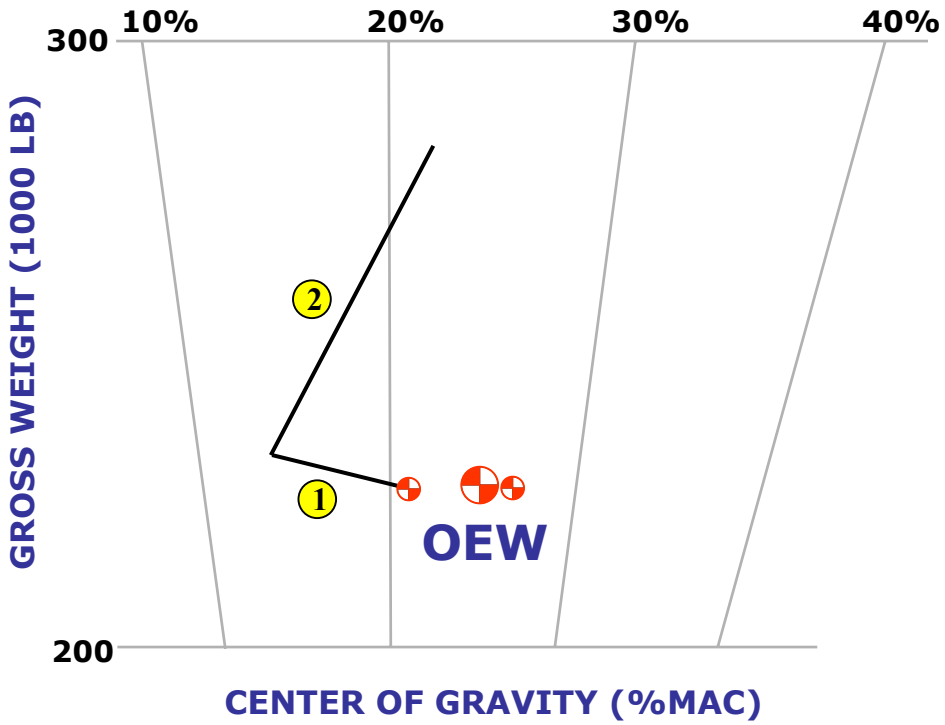
Determining Desired Fwd and Aft C.G. Limits: Accounting for Interior Seating Arrangement Variations

Accounting for Interior Seating Arrangement Variations

Boeing's design objective is to provide forward and aft C.G. limits which will allow for airline variations in interior seating arrangements:

- Ability to load various combinations of passengers, from empty to full.
- Ability to use various combinations of tri-class and dual-class seating arrangements on wide body aircraft.
- Ability to use various combinations of dual-class and single-class seating arrangements on narrow body aircraft.

Accounting for Interior Seating Arrangement Variations

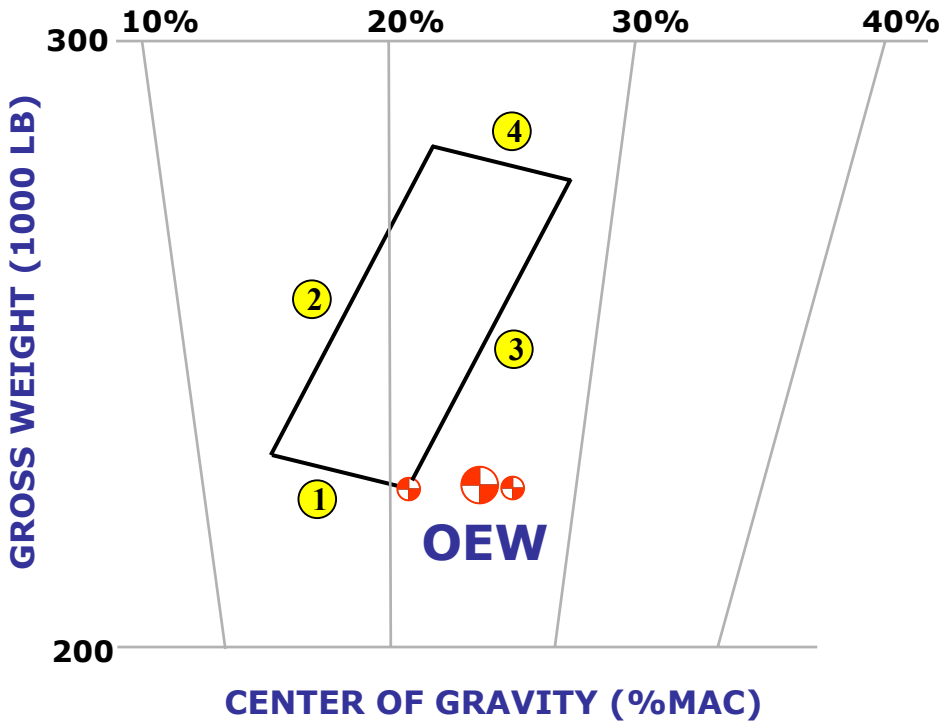


(7G7-X00 Example)

Extreme Fwd Loading: Front-to-Rear

1. **Load first-class seats**
2. **Load economy-class seats**

Accounting for Interior Seating Arrangement Variations



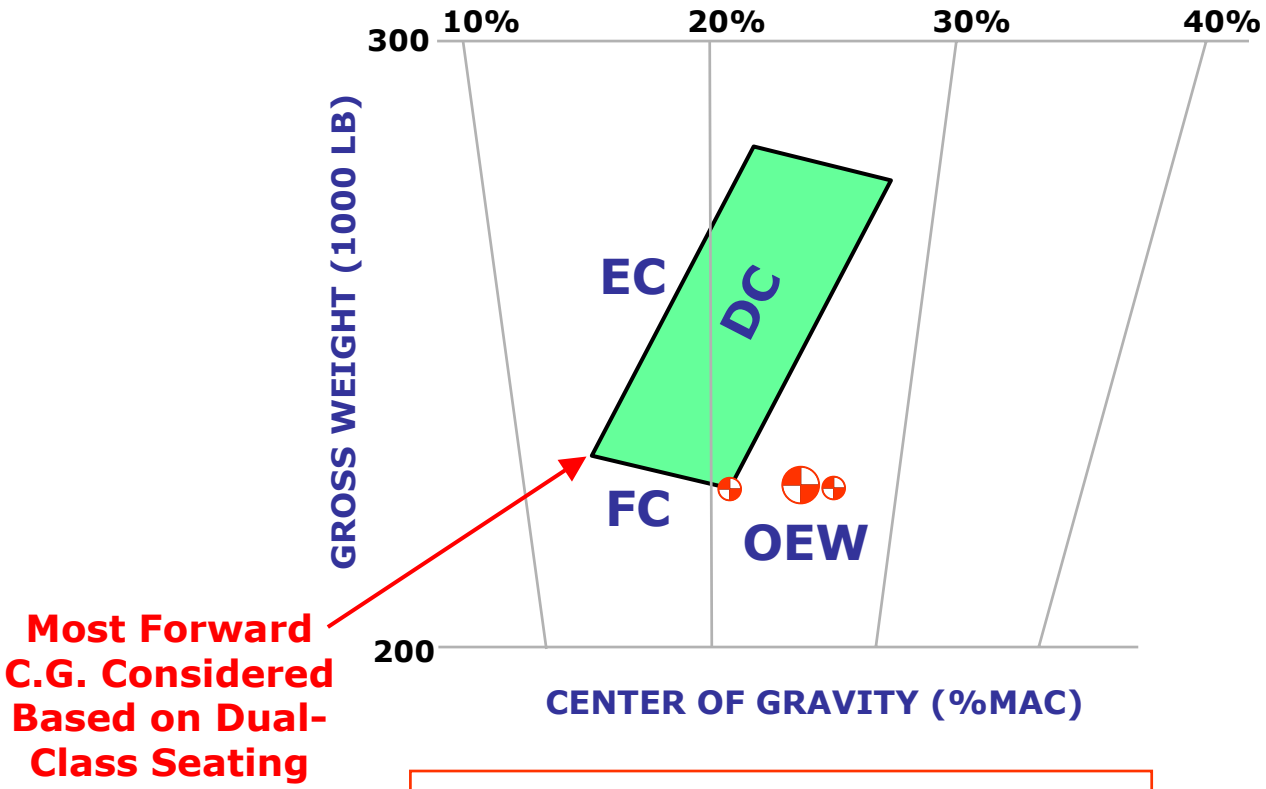
(7G7-X00 Example)

Extreme Fwd Loading: Rear-to-Front

3 **Load economy-class seats**

4 **Load first-class seats**

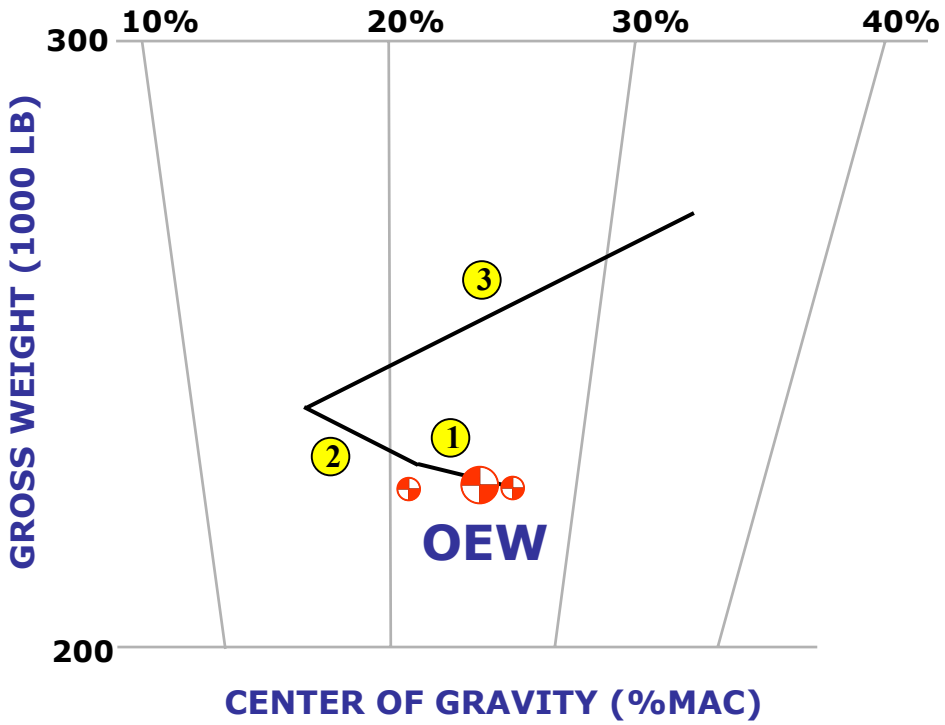
Accounting for Interior Seating Arrangement Variations



(7G7-X00 Example)

Dual-Class Defines the Most Forward Loading Interior Arrangement Considered

Accounting for Interior Seating Arrangement Variations

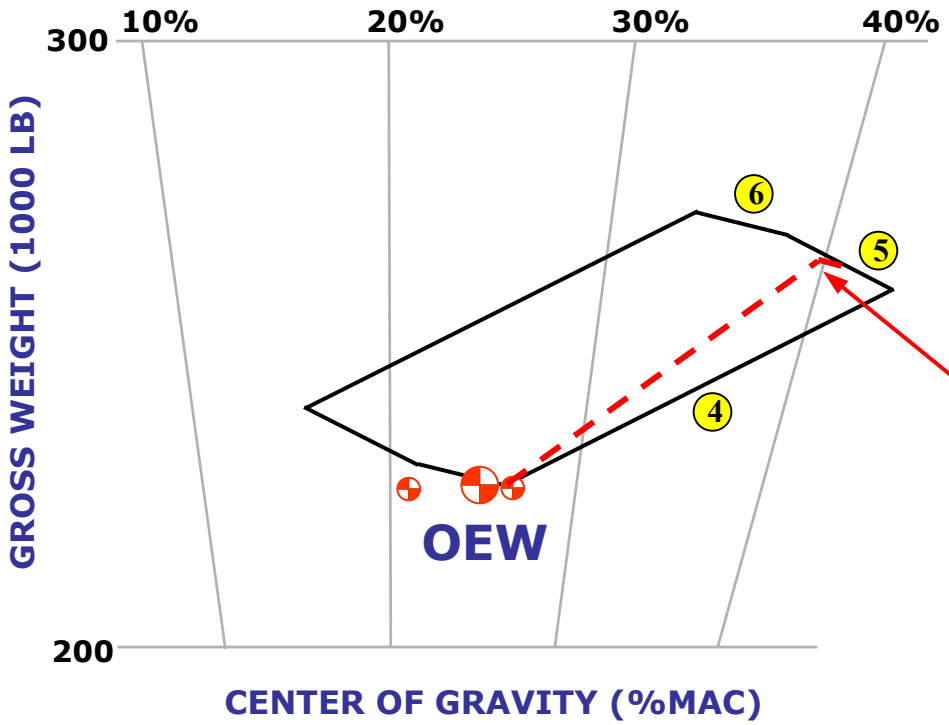


(7G7-X00 Example)

Extreme Aft Loading: Front-to-Rear

1. **Load first-class seats**
2. **Load business-class seats**
3. **Load economy-class seats**

Accounting for Interior Seating Arrangement Variations



(7G7-X00 Example)

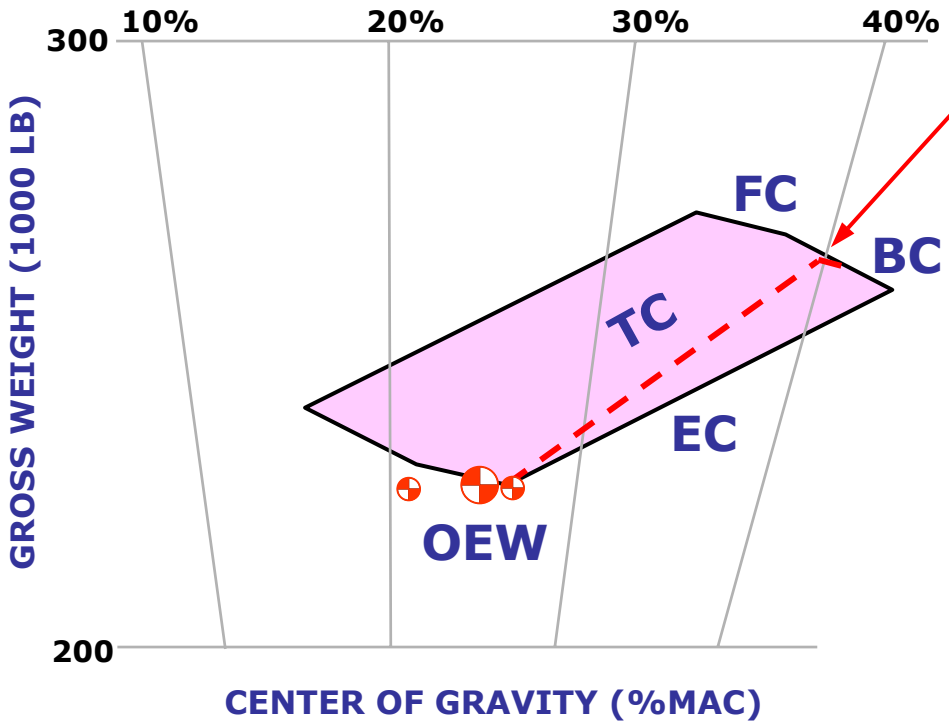
Chosen as more "reasonable" passenger loading for most-aft C.G.

(rare to have business and first empty, with economy full)

Extreme Aft Loading: Rear-to-Front

4. **Load economy-class seats**
5. **Load business-class seats**
6. **Load first-class seats**

Accounting for Interior Seating Arrangement Variations

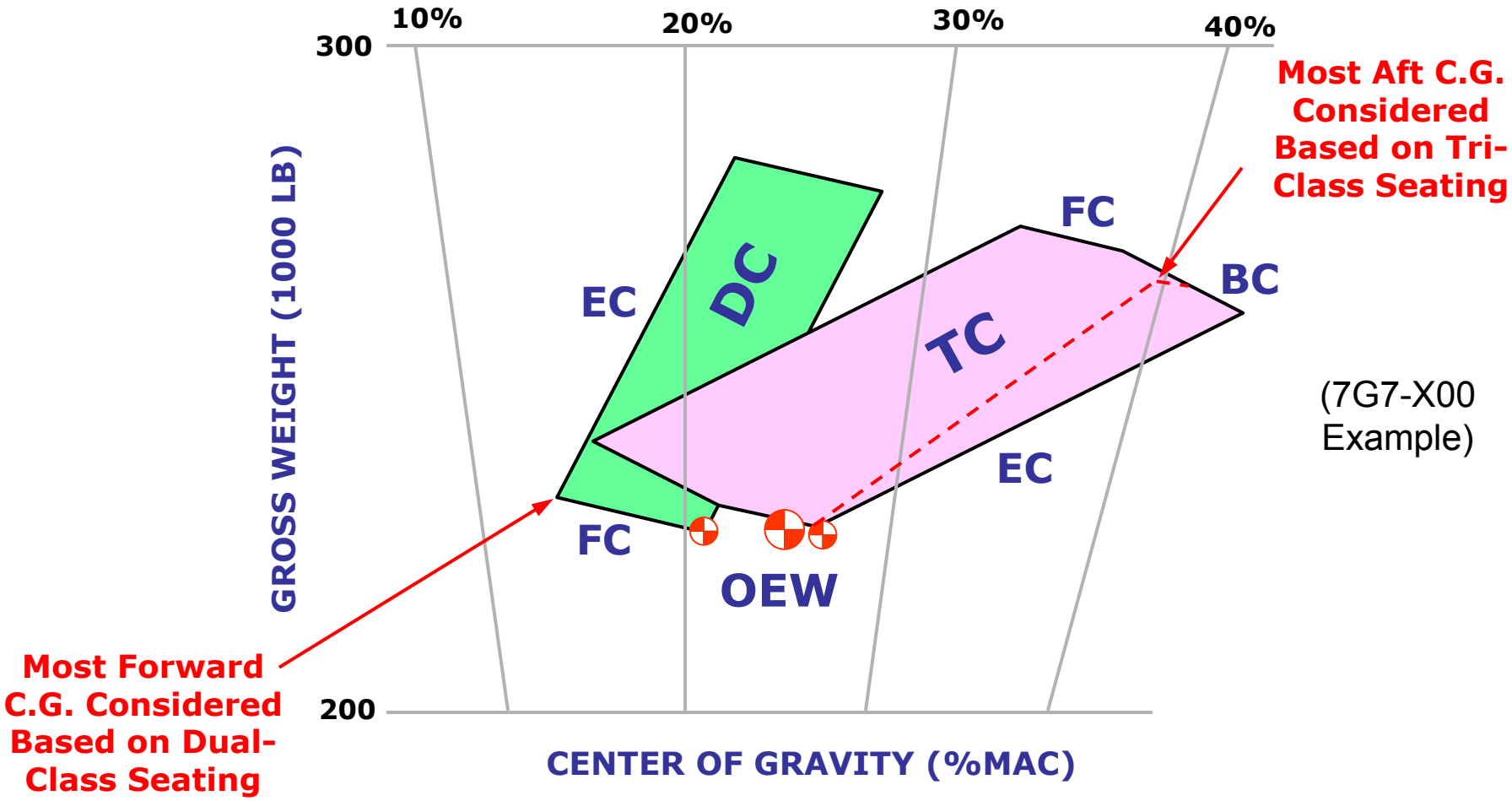


Most Aft C.G. Considered Based on Tri-Class Seating

(7G7-X00 Example)

Tri-Class Defines the Most Aft-Loading Interior Arrangement Considered

Accounting for Interior Seating Arrangement Variations - Summary



(7G7-X00 Example)

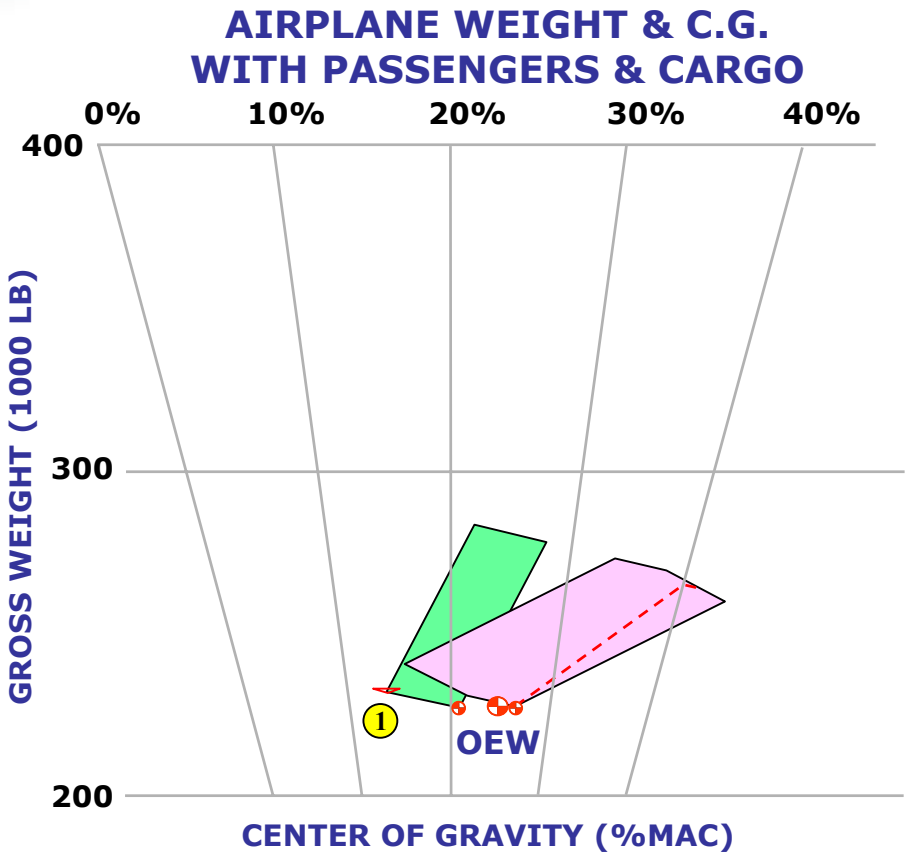
Determining Desired Fwd and Aft C.G. Limits: Accounting for Cargo Loading Variations

Accounting for Cargo Variations

Boeing's design objective is to provide forward and aft C.G. limits which will allow for airline variations in cargo loading:

- Loading any number of passengers and only their baggage in the cargo compartments. (Baggage may be placed forward or aft for balance.)
- Loading any number of passengers with no baggage or cargo in the cargo compartments.
- Loading any number of passengers with full cargo (containerized and/or bulk).
- Loading any number of passengers with full containerized cargo only. (There should be no requirement to balance the airplane with bulk cargo.)

Accounting for Cargo Variations



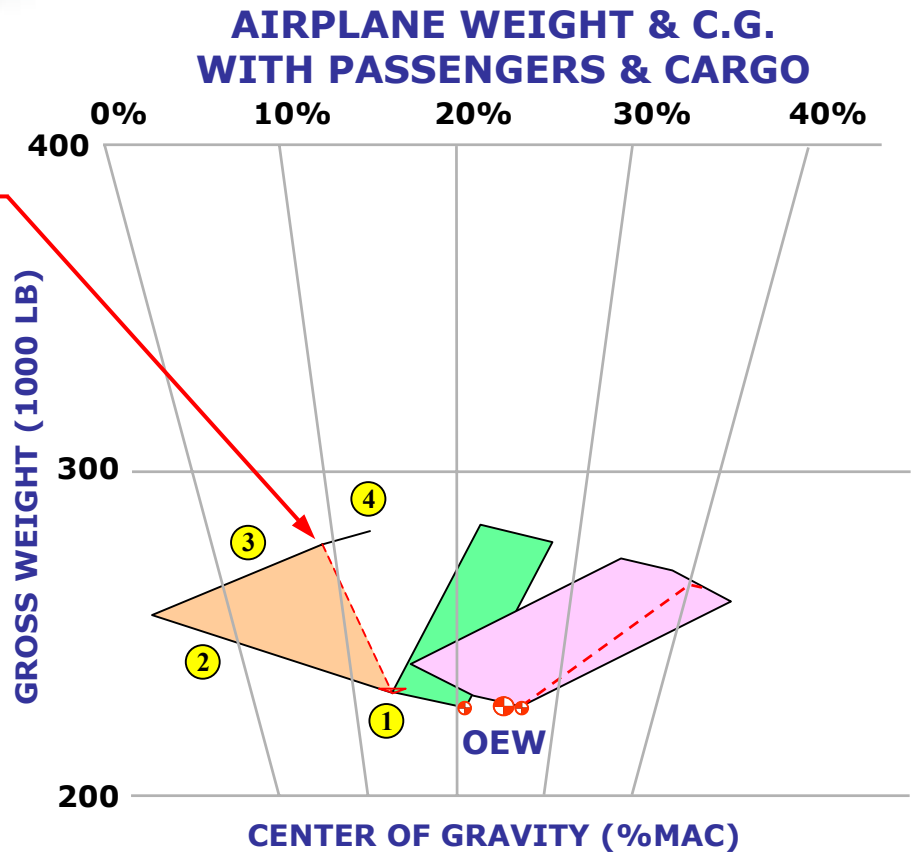
(7G7-X00 Example)

Loading Cargo: Most fwd C.G.

1 **Passenger Bags**

Accounting for Cargo Variations

Most Forward C.G. Considered Based on Loading Passengers and Full Cargo (no bulk)

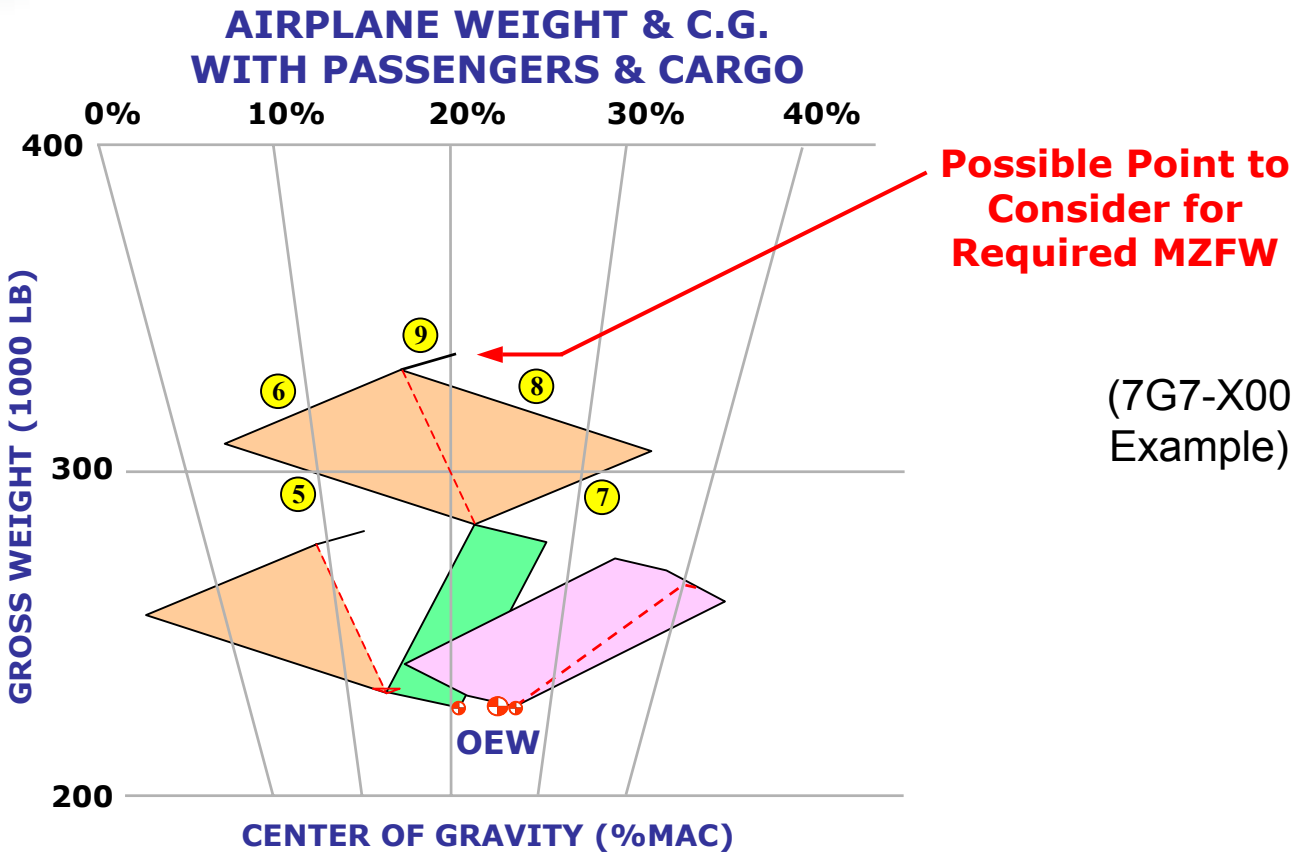


(7G7-X00 Example)

Loading Cargo: Most fwd C.G.

1. Passenger Bags
2. Forward Cargo compartment
3. Aft Cargo compartment
4. Bulk Cargo compartment

Accounting for Cargo Variations

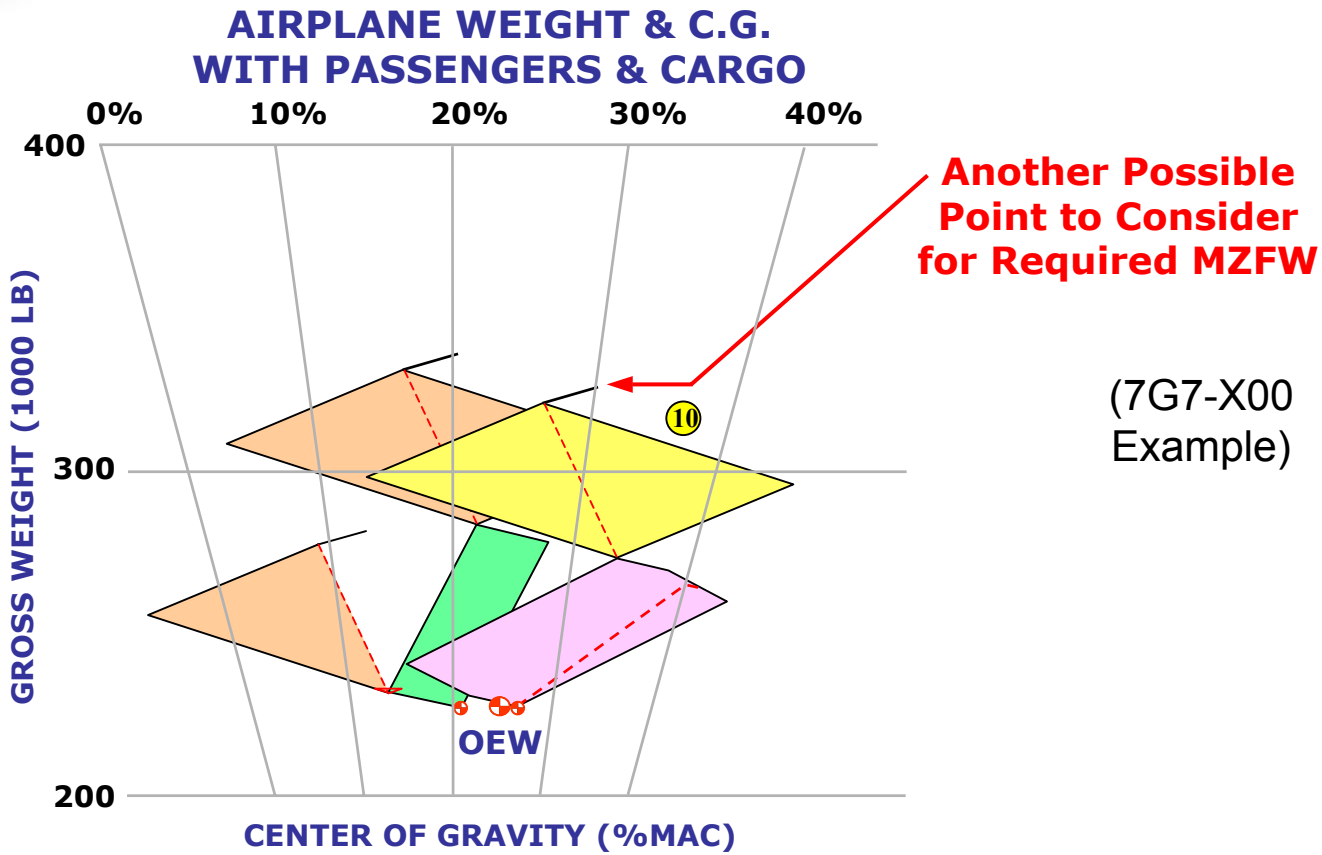


(7G7-X00 Example)

Loading Cargo: Required MZFW

- 5 Forward Cargo compartment
- 6 Aft Cargo compartment
- 7 Forward Cargo compartment
- 8 Aft Cargo compartment
- 9 Bulk Cargo compartment

Accounting for Cargo Variations



(7G7-X00 Example)

Loading Cargo: Required MZFW

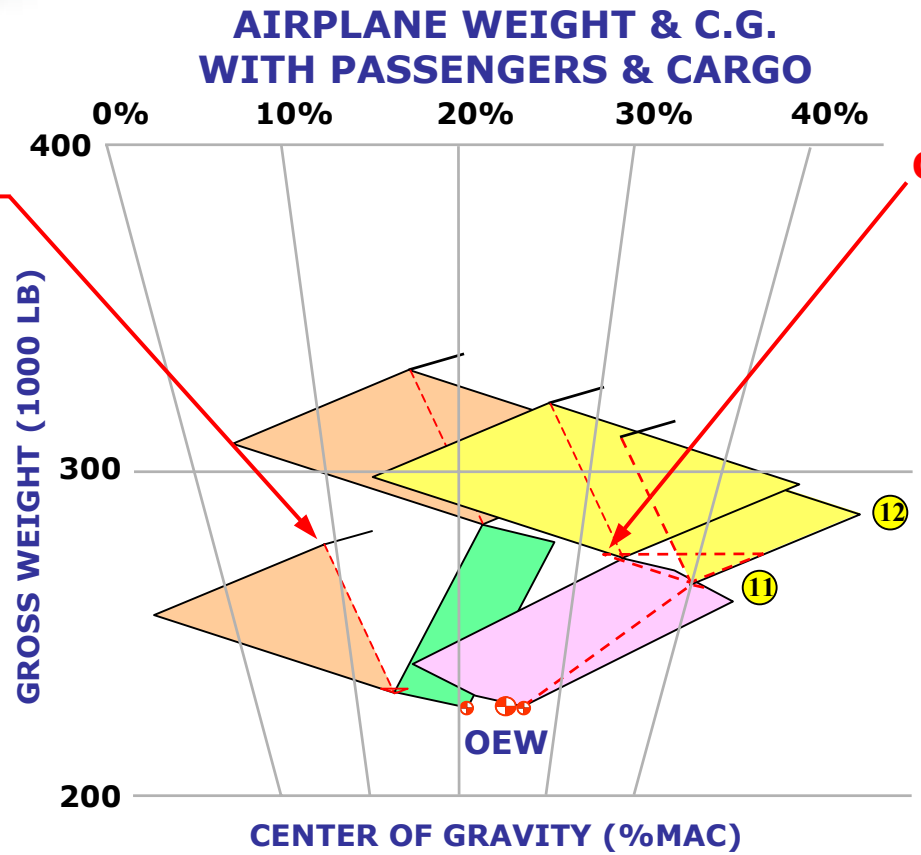
10 **Repeat steps 5 through 9, beginning at the highest weight for tri-class passengers**

Accounting for Cargo Variations

Most Forward C.G. Considered Based on Loading Passengers and Full Cargo (no bulk)

Most Aft C.G. Considered Based on Loading Passengers and Baggage

(7G7-X00 Example)



Loading Cargo: Most aft C.G.

- 11 **Passenger Bags**
- 12 **Aft and Forward Cargo**

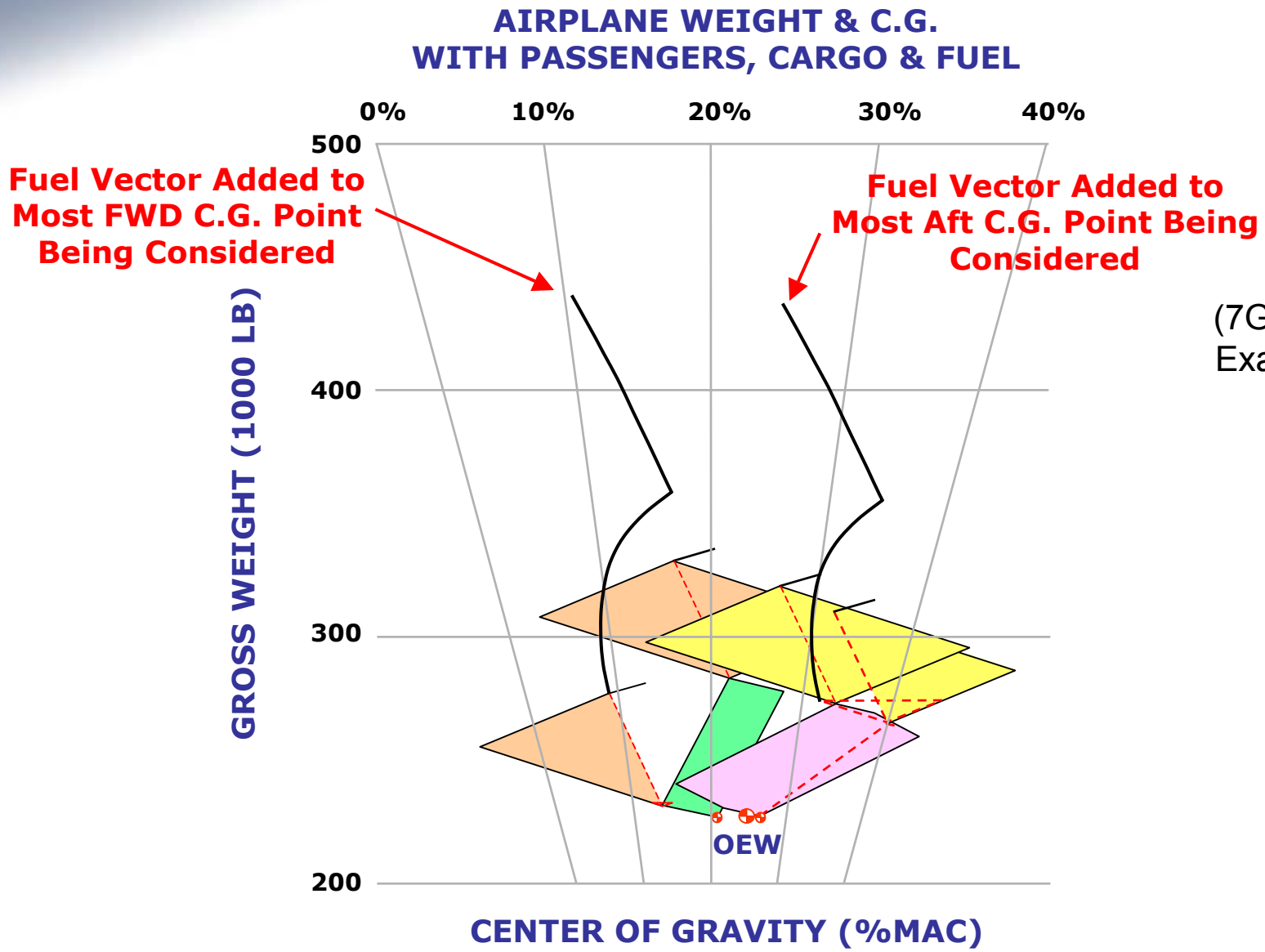
Determining Desired Fwd and Aft C.G. Limits: Accounting for Fuel Loading and Usage Variations

Accounting for Fuel Loading and Usage Variations

Boeing's design objective is to provide forward and aft C.G. limits which will allow for airline variations in fuel loading and usage:

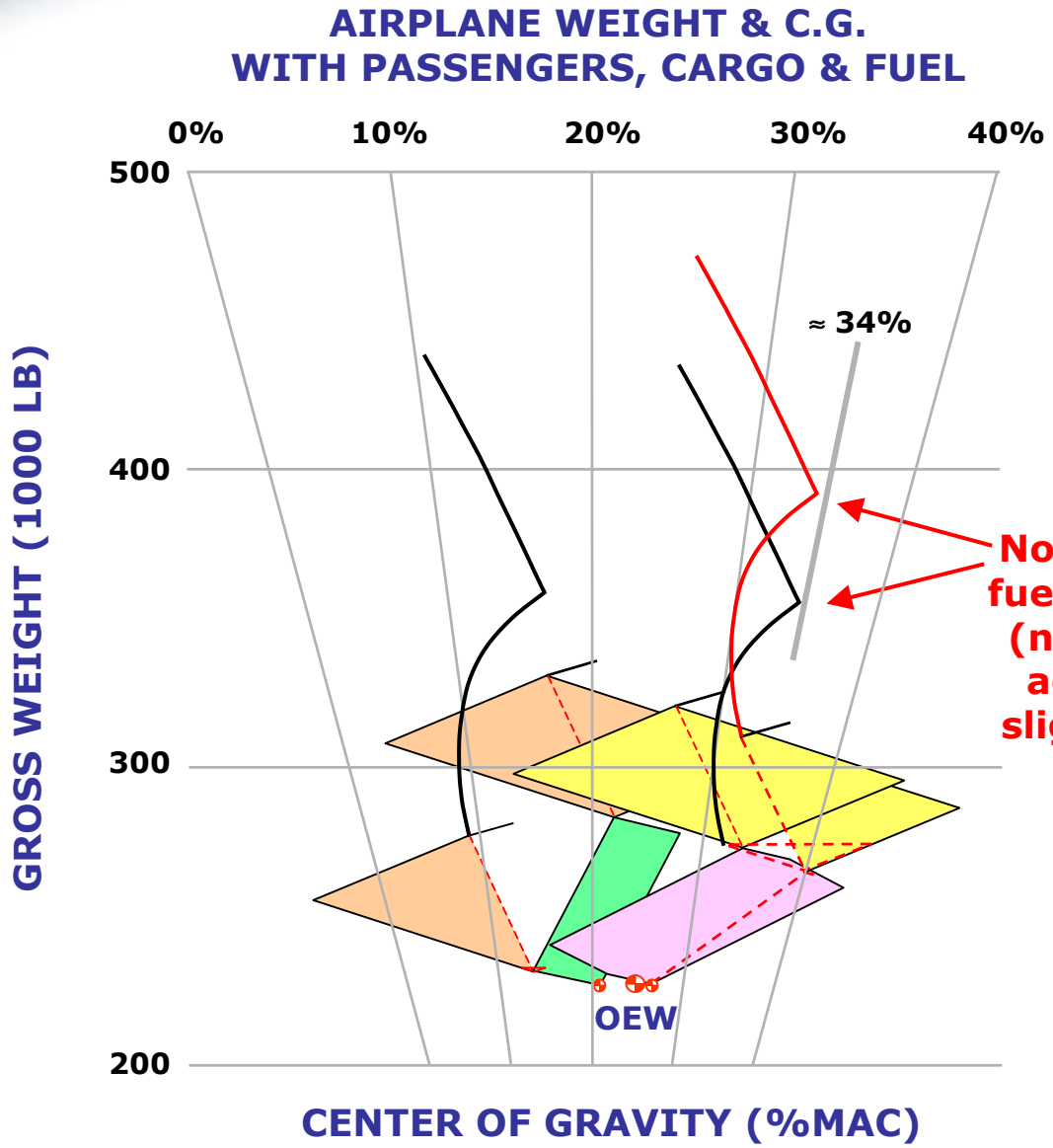
- Use of the total fuel capacity – from empty to full.
- Ability to load to the maximum gross weight.

Accounting for Fuel Loading and Usage Variations



(7G7-X00 Example)

Accounting for Fuel Loading and Usage Variations



(7G7-X00 Example)

Notice that adding the fuel vector to full cargo (no bulk) would have actually produced a slightly more fwd C.G.

Determining Desired Fwd and Aft C.G. Limits: Accounting for Operational Curtailment Variations

Accounting for Operational Curtailment Variations

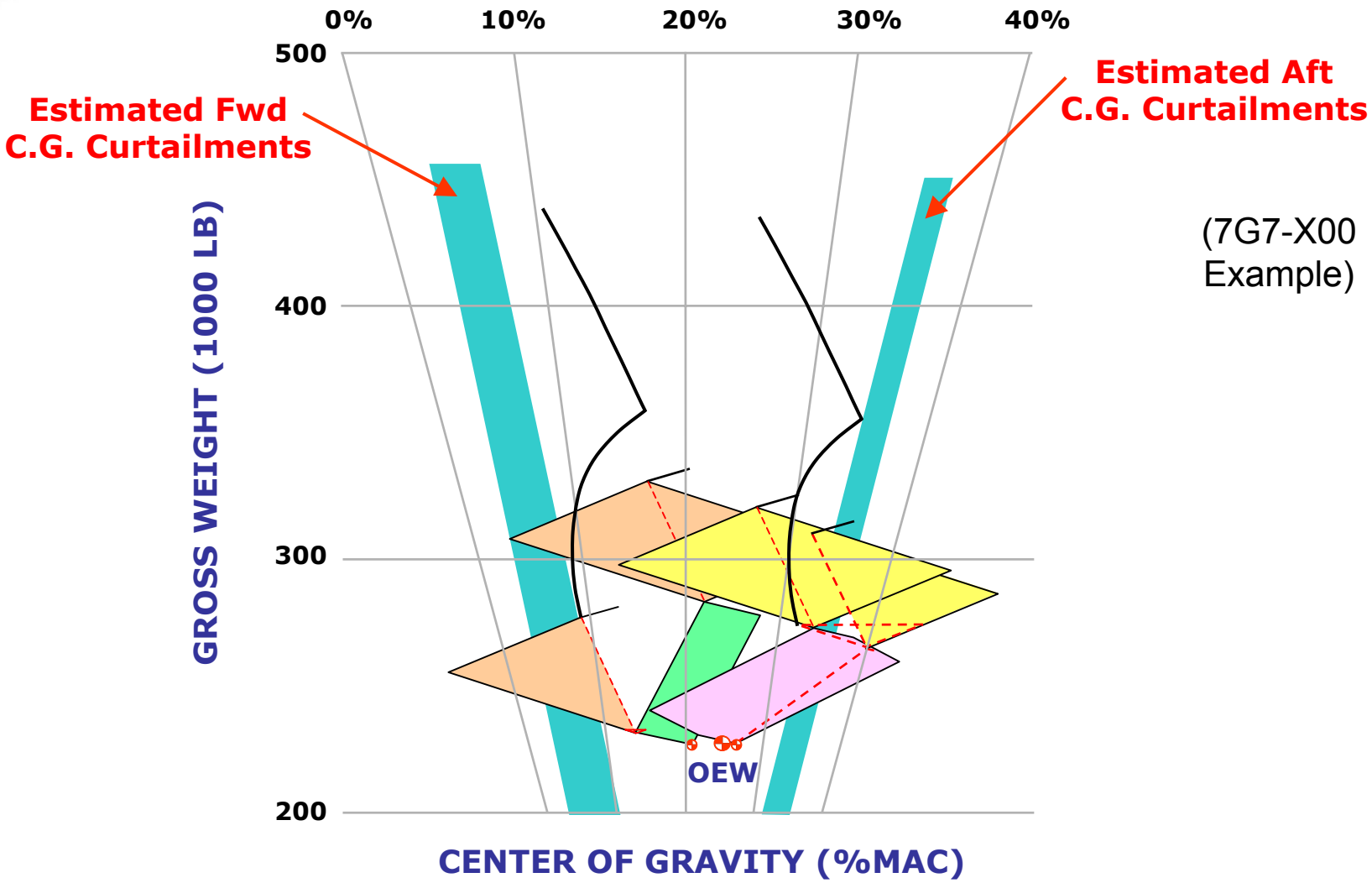
Boeing's design objective is to provide forward and aft C.G. limits which will allow for airline variations in "operational curtailments" to these C.G. limits. Operational curtailments are generally used to account for:

- Landing gear and flap movement.
- In-flight movement of passengers, crew, and service carts.
- Difference between actual and assumed C.G. locations for cargo, passenger seating, fuel loading and usage, water movement and usage.

*** (Note: Later in this course we will be discussing the concept and use of operational curtailments in detail.) ***

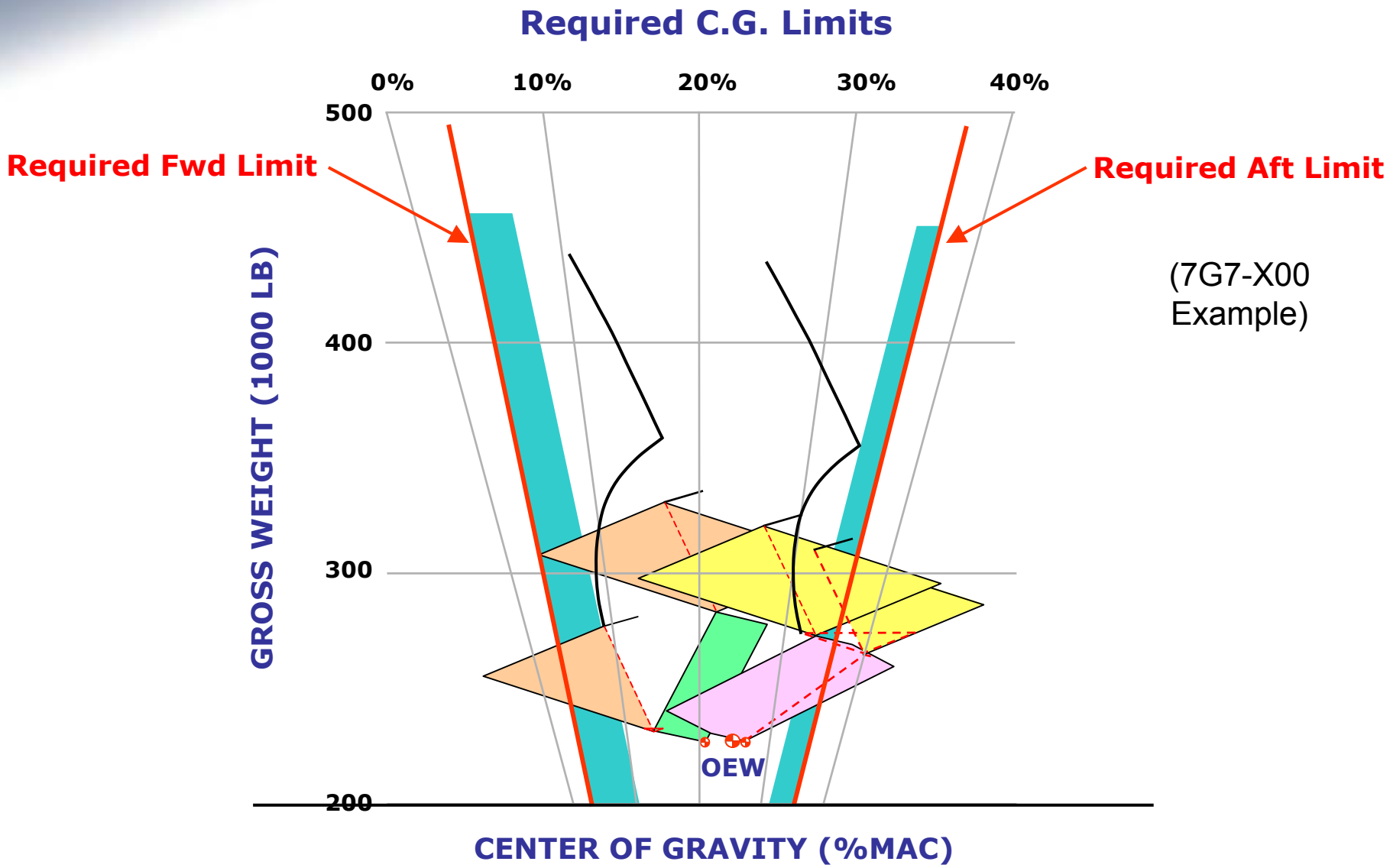
Accounting for Operational Curtailment Variations

Including Forward and Aft Curtailments



(7G7-X00 Example)

Accounting for Operational Curtailment Variations



(7G7-X00 Example)

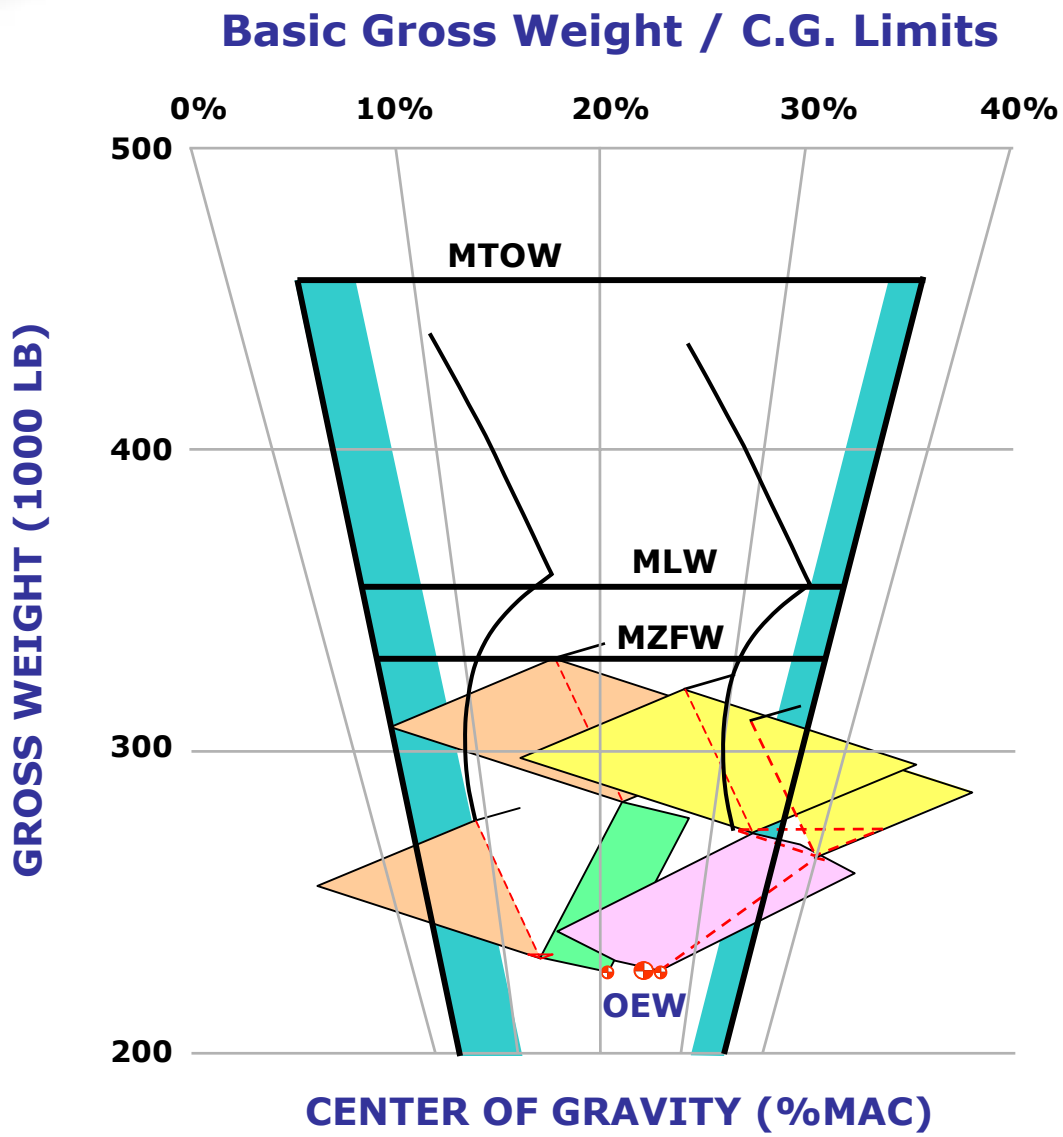
Weight and Structural Limitations on the C.G. Envelope

Weight and Structural Limitations on the C.G. Envelope

The allowable forward and aft C.G. limits may be further constrained by:

- Certified weight limitations – MTW, MTOW, MLW, MZFW.
- Structural limitations imposed by various parts of the airplane's structure.
- Additional limitations imposed in order to maintain control of the airplane during its operation.

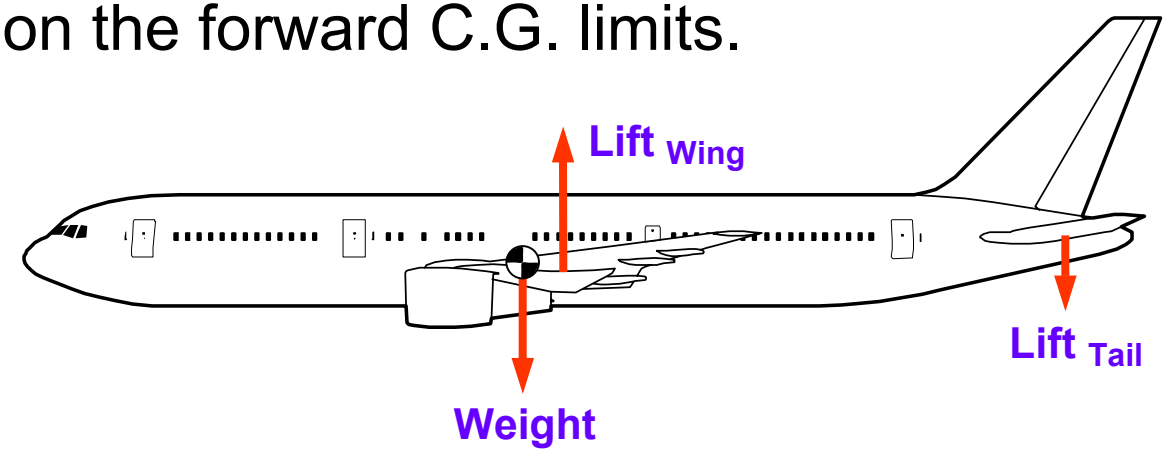
Certified Weight Limitations



(7G7-X00 Example)

Constant Wing Load

- The strength of the wing's structure can impose a limitation on the forward C.G. limits.



WING LOAD

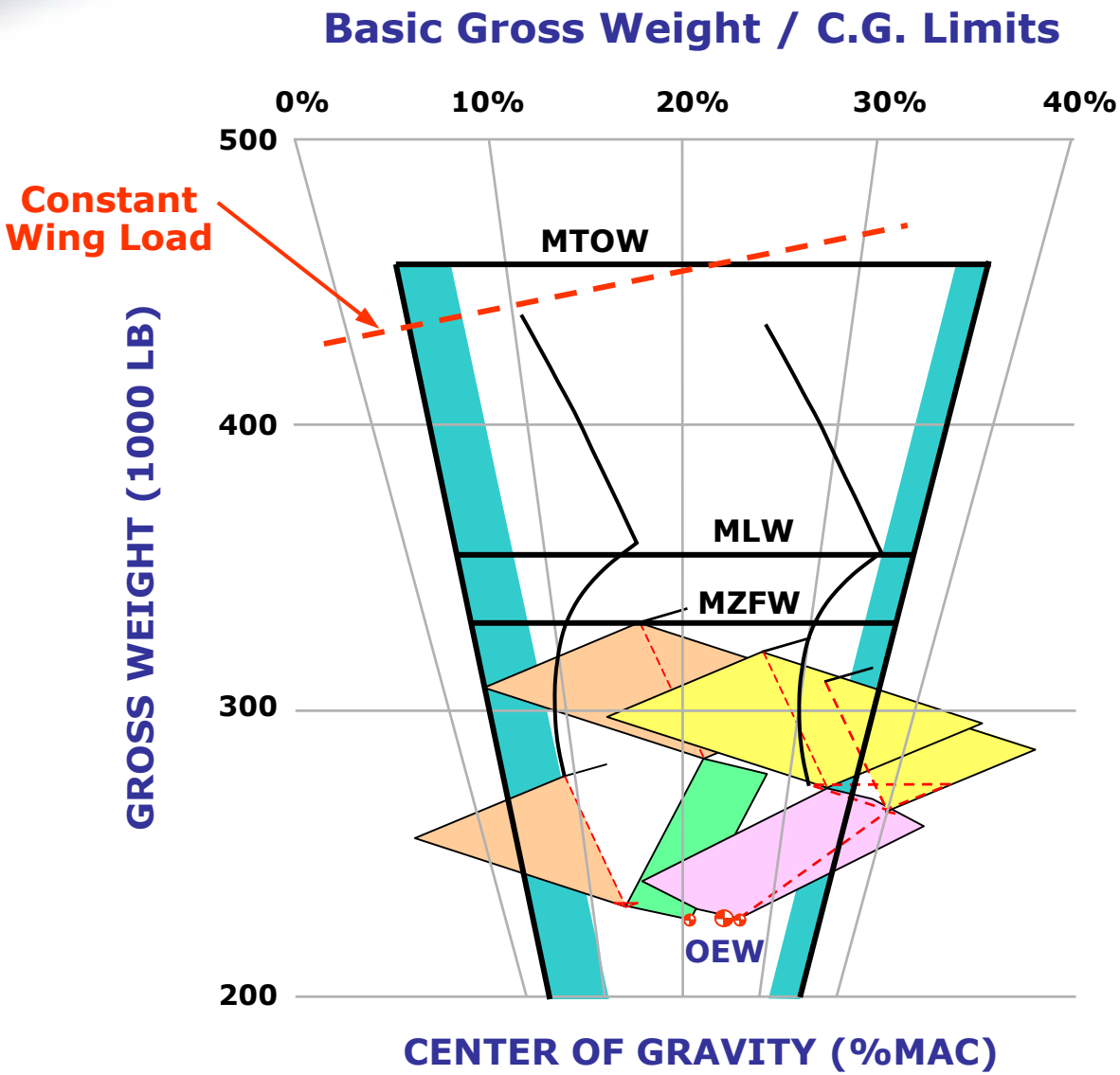
For the airplane to be in equilibrium, the sum of the moments about the tail must = 0:

$$\Sigma M_{Tail} = W\,(B.A._{Tail} - B.A._{C.G.}) - L_{Wing}(B.A._{Tail} - B.A._{Wing}) = 0$$

$$L_{Wing} = \frac{W\,(B.A._{Tail} - B.A._{C.G.})}{(B.A._{Tail} - B.A._{Wing})}$$

- The load on the wing is increased both by increasing airplane weight, and by forward movement of the center of gravity. Eventually, the wing's limits are reached.

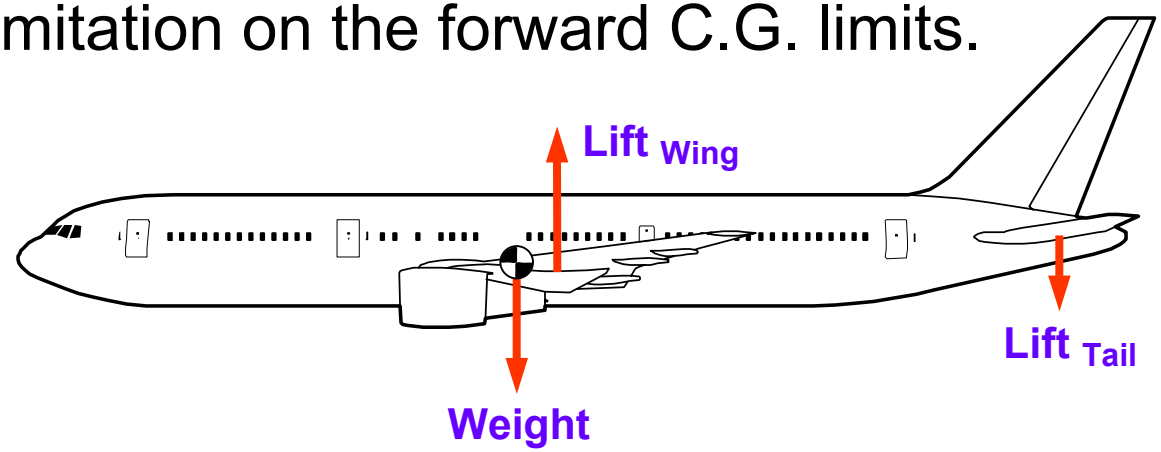
Constant Wing Load



(7G7-X00 Example)

Constant Tail Load

- The strength of the tail and aft body structure can impose a limitation on the forward C.G. limits.



TAIL LOAD

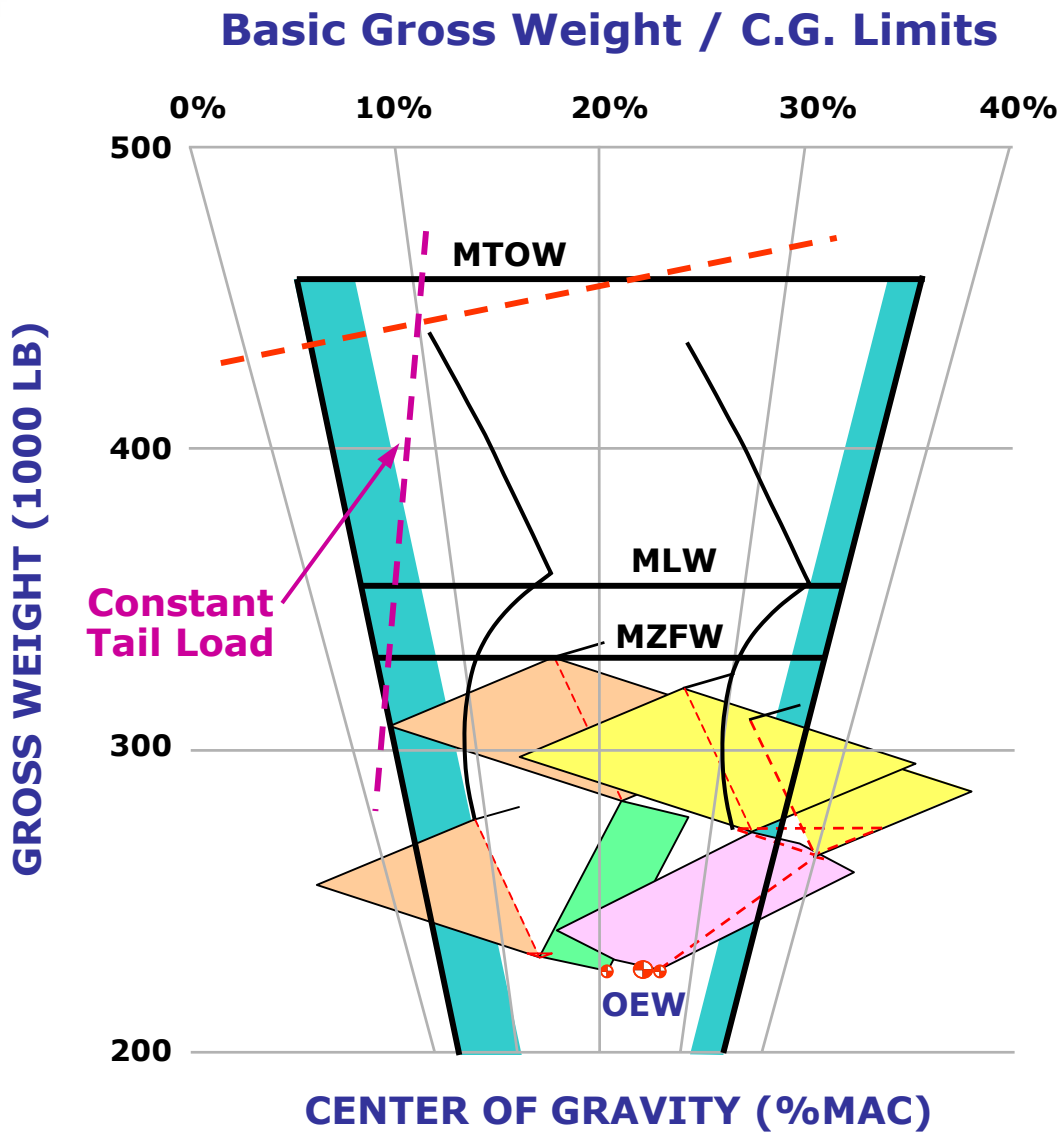
For the airplane to be in equilibrium, the sum of the moments about the wing must = 0 :

$$\Sigma M_{Wing} = W\,(B.A._{Wing} - B.A._{C.G.}) - L_{Tail}\,(B.A._{Tail} - B.A._{Wing}) = 0$$

$$L_{Tail} = \frac{W\,(B.A._{Wing} - B.A._{C.G.})}{(B.A._{Tail} - B.A._{Wing})}$$

- The load on the tail and aft body is increased both by increasing airplane weight, and by forward movement of the center of gravity. Eventually, the tail or aft body's limits are reached.

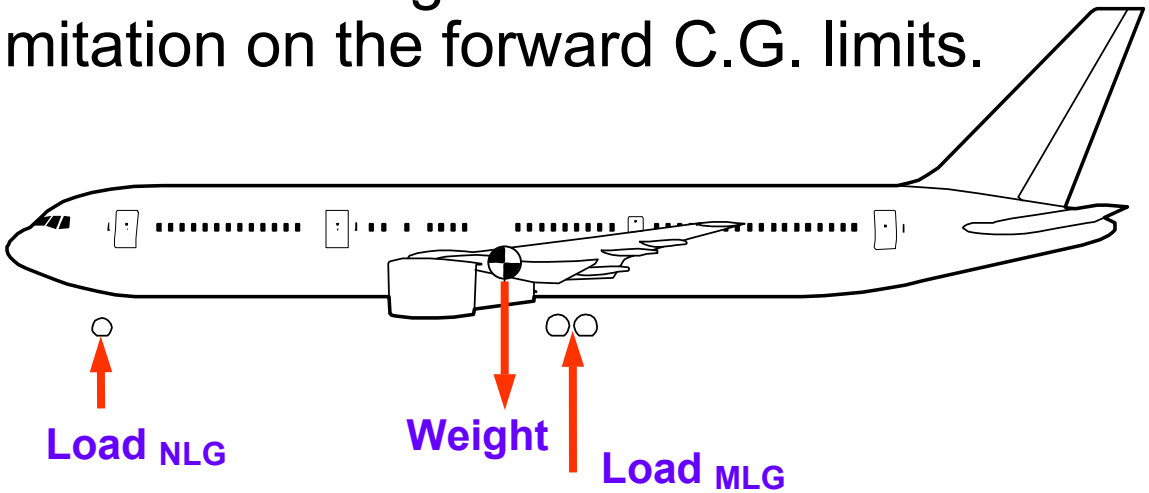
Constant Tail Load



(7G7-X00
Example)

Constant Nose Landing Gear Load

- The strength of the nose gear structure can impose a limitation on the forward C.G. limits.



NOSE LANDING GEAR LOAD

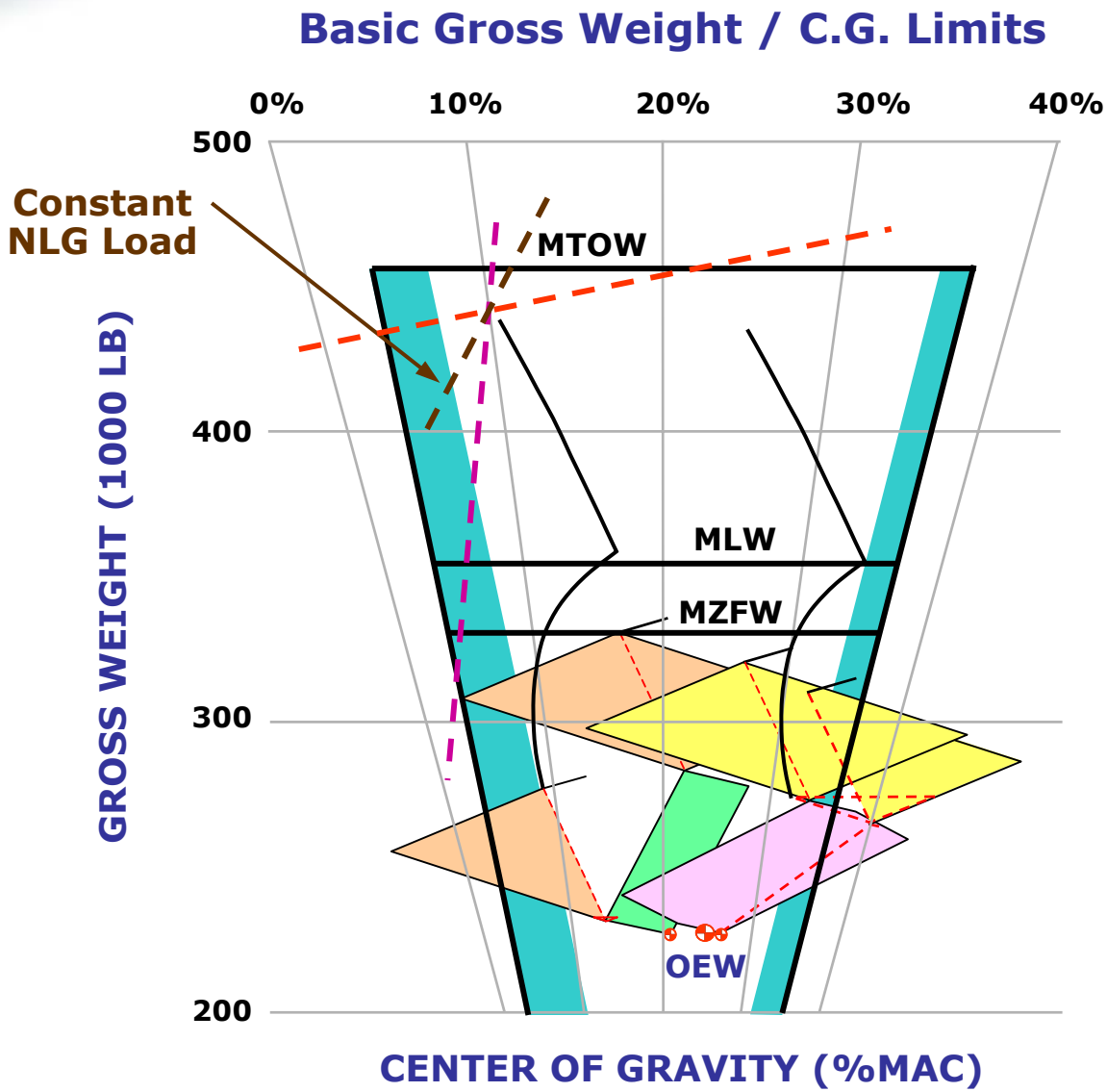
For the airplane to be in equilibrium, the sum of the moments about the main landing gear must = 0 :

$$\Sigma M_{MLG} = W\,(B.A._{MLG} - B.A._{C.G.}) - L_{NLG}\,(B.A._{MLG} - B.A._{NLG}) = 0$$

$$L_{NLG} = \frac{W\,(B.A._{MLG} - B.A._{C.G.})}{(B.A._{MLG} - B.A._{NLG})}$$

- The load on the NLG is increased both by increasing airplane weight, and by forward movement of the center of gravity. Eventually, the NLG limits are reached.

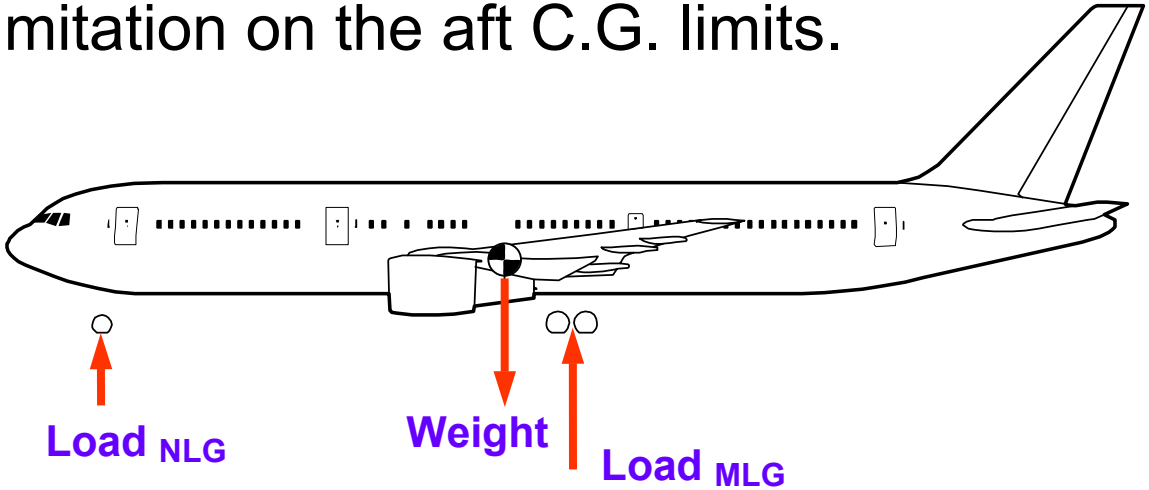
Constant Nose Landing Gear Load



(7G7-X00 Example)

Constant Main Landing Gear Load

- The strength of the main landing gear structure can impose a limitation on the aft C.G. limits.



MAIN LANDING GEAR LOAD

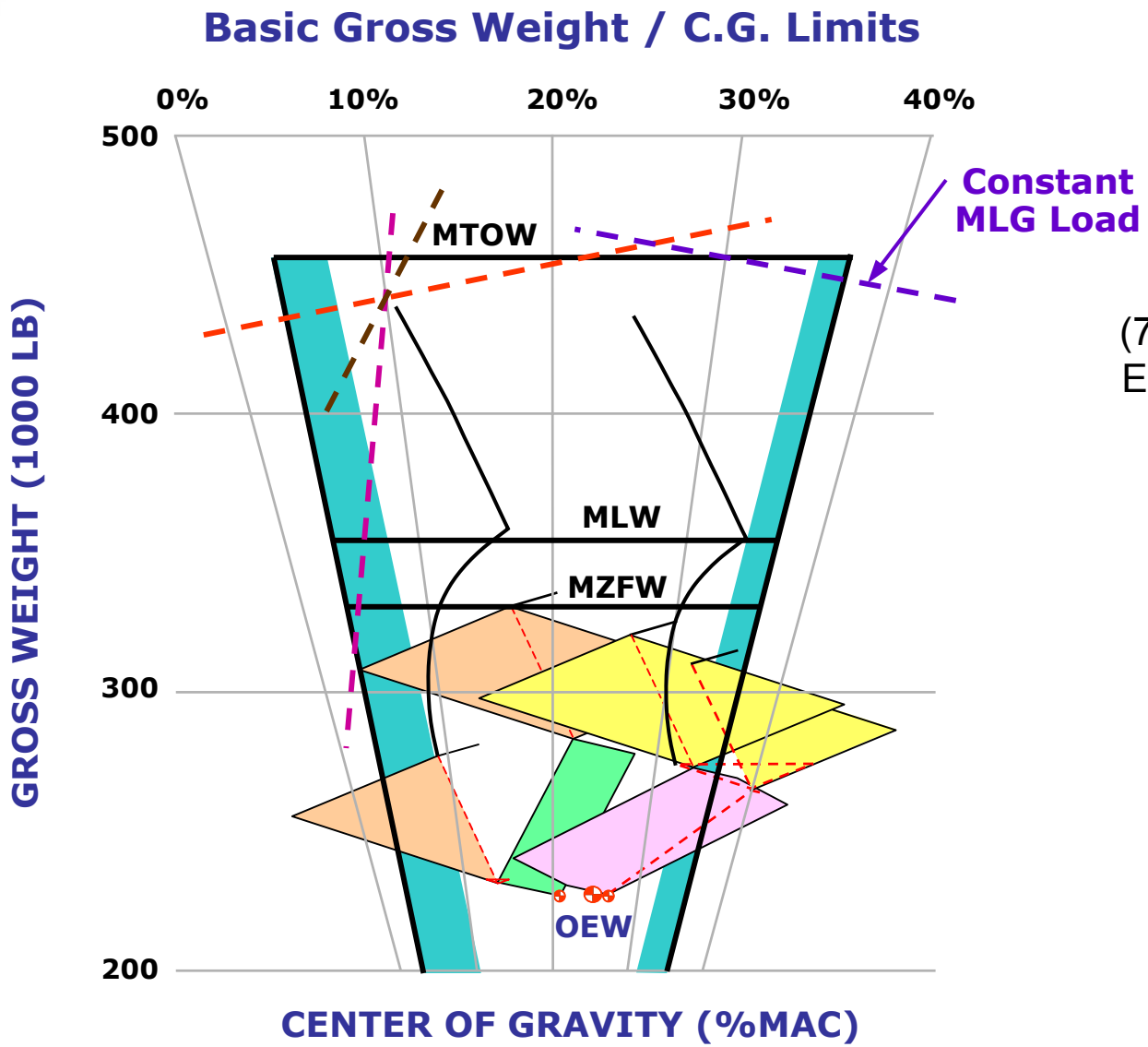
For the airplane to be in equilibrium, the sum of the moments about the nose landing gear must = 0 :

$$\Sigma M_{NLG} = L_{MLG}\,(B.A._{MLG} - B.A._{NLG}) - W\,(B.A._{C.G.} - B.A._{NLG}) = 0$$

$$L_{MLG} = \frac{W\,(B.A._{C.G.} - B.A._{NLG})}{(B.A._{MLG} - B.A._{NLG})}$$

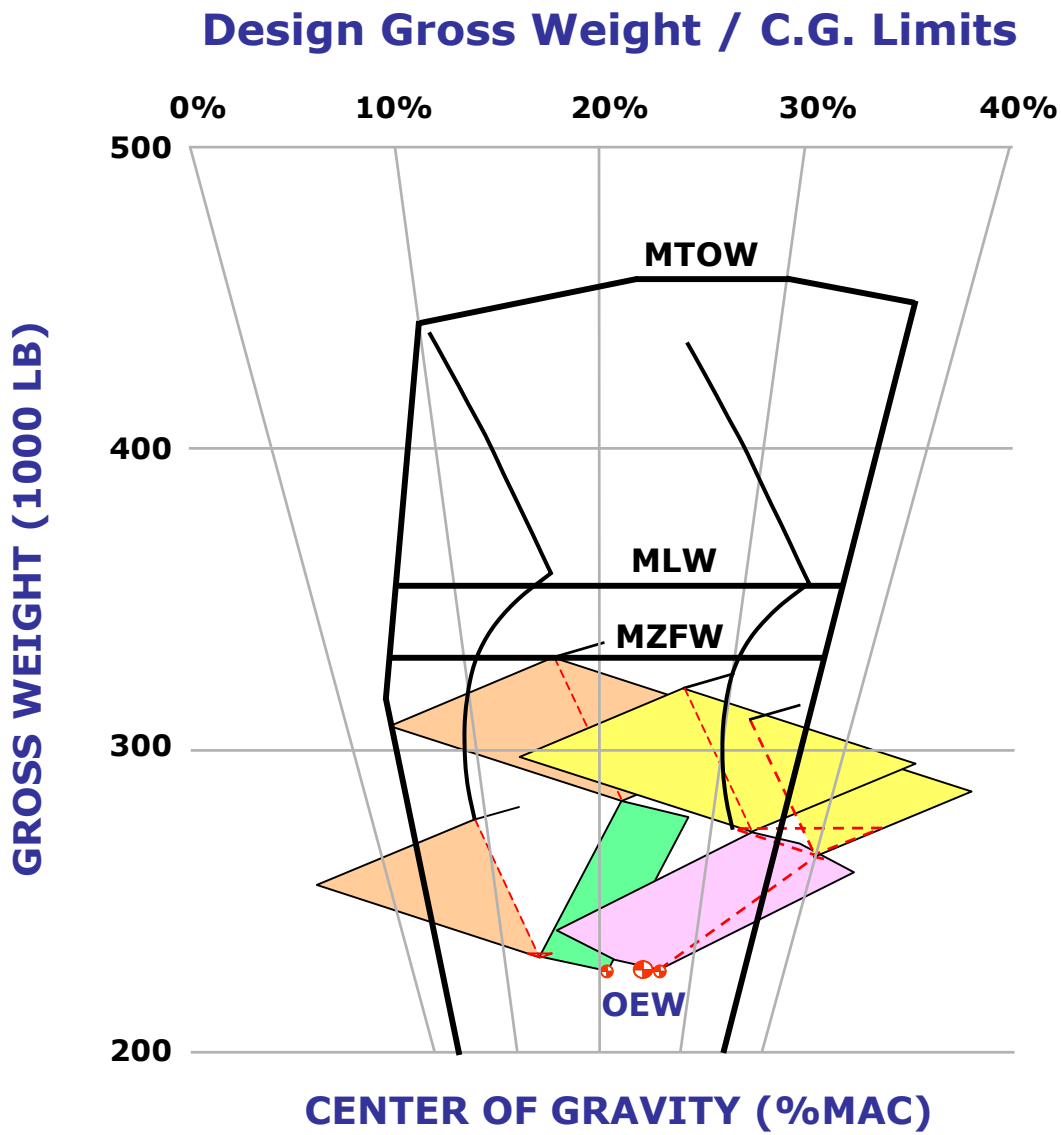
- The load on the MLG is increased both by increasing airplane weight, and by aft movement of the center of gravity. Eventually, the MLG limits are reached.

Constant Main Landing Gear Load



(7G7-X00
Example)

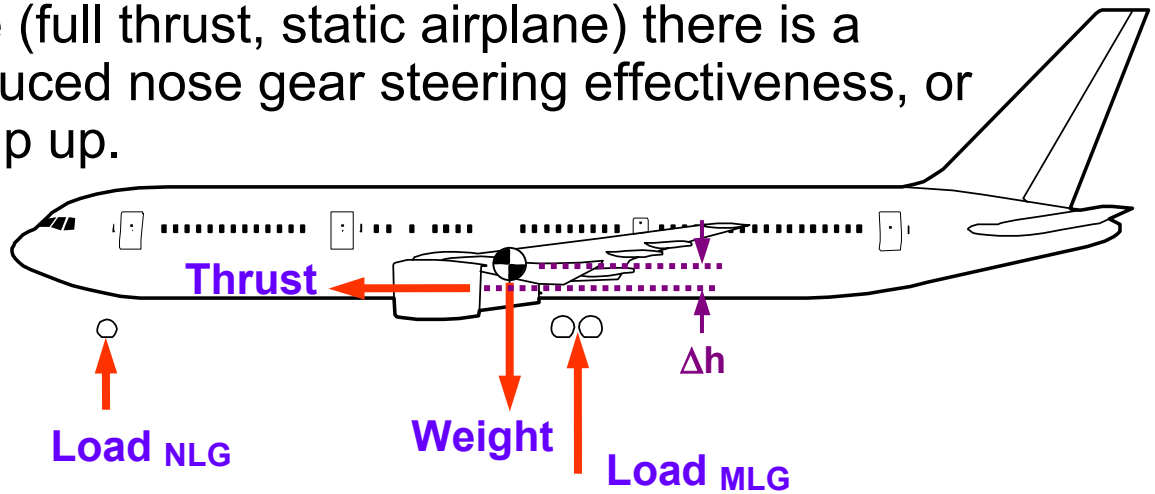
Combining All Structural Limitations



(7G7-X00 Example)

Additional Limitations for Control: Brake Release Tip-Up

- At brake release (full thrust, static airplane) there is a possibility of reduced nose gear steering effectiveness, or actual airplane tip up.



BRAKE RELEASE TIP-UP

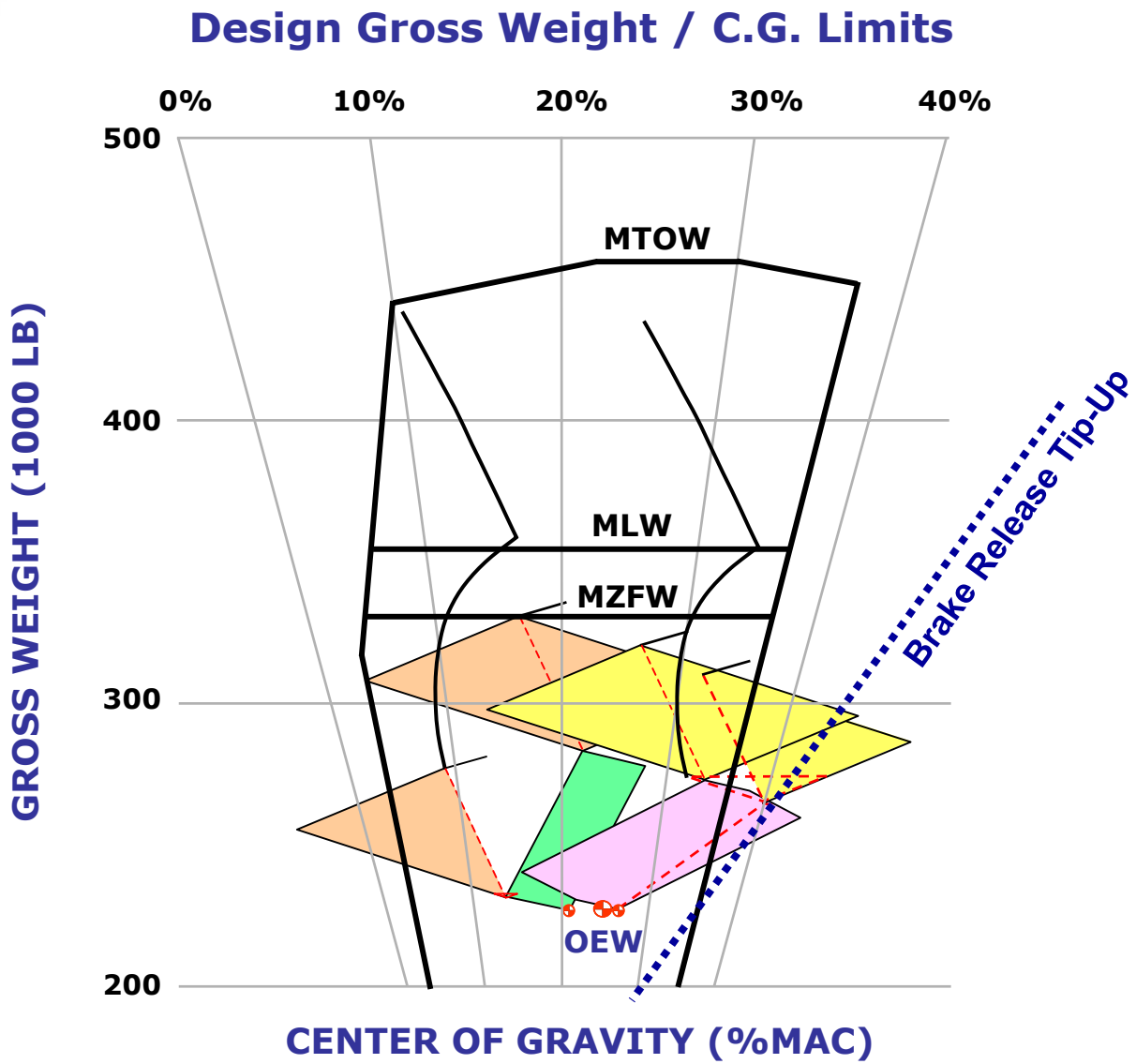
For the airplane to be in equilibrium, the sum of the moments about the airplane CG must = 0 :

$$\Sigma M_{CG} = L_{MLG}(B.A._{MLG} - B.A._{C.G.}) - T\,\Delta h - L_{NLG}(B.A._{C.G.} - B.A._{NLG}) = 0$$

$$L_{NLG} = \frac{L_{MLG}(B.A._{MLG} - B.A._{C.G.}) - T\,\Delta h}{(B.A._{C.G.} - B.A._{NLG})}$$

- The load on the NLG is reduced by: decreasing airplane weight, aft movement of the C.G., and increasing thrust. At light enough NLG loads, steering effectiveness is reduced, and eventually, the NLG load can become negative causing the airplane to tip up.

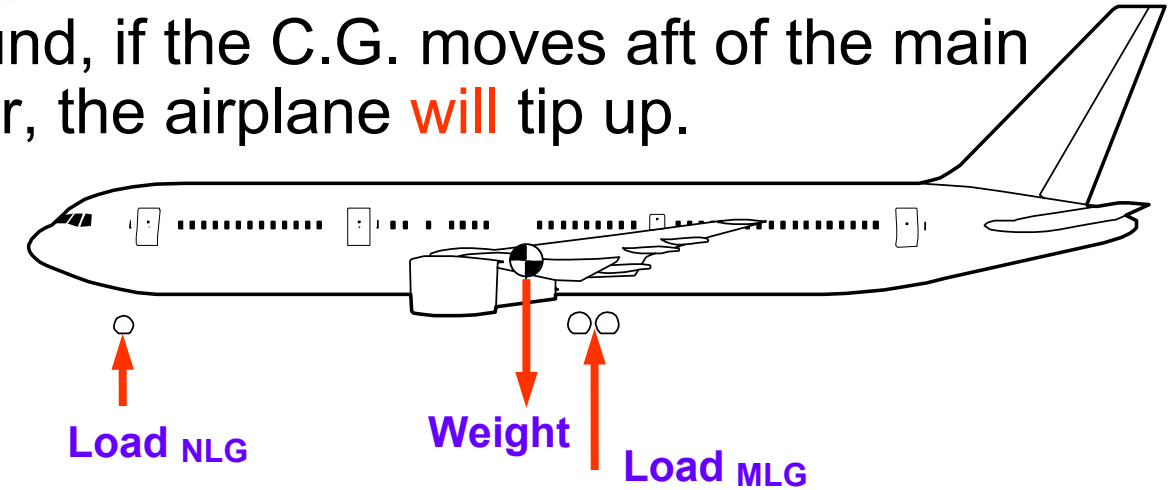
Brake Release Tip-Up



(7G7-X00 Example)

Additional Limitations for Control: Ground Handling - Tipping

- On the ground, if the C.G. moves aft of the main landing gear, the airplane will tip up.



NOSE LANDING GEAR LOAD

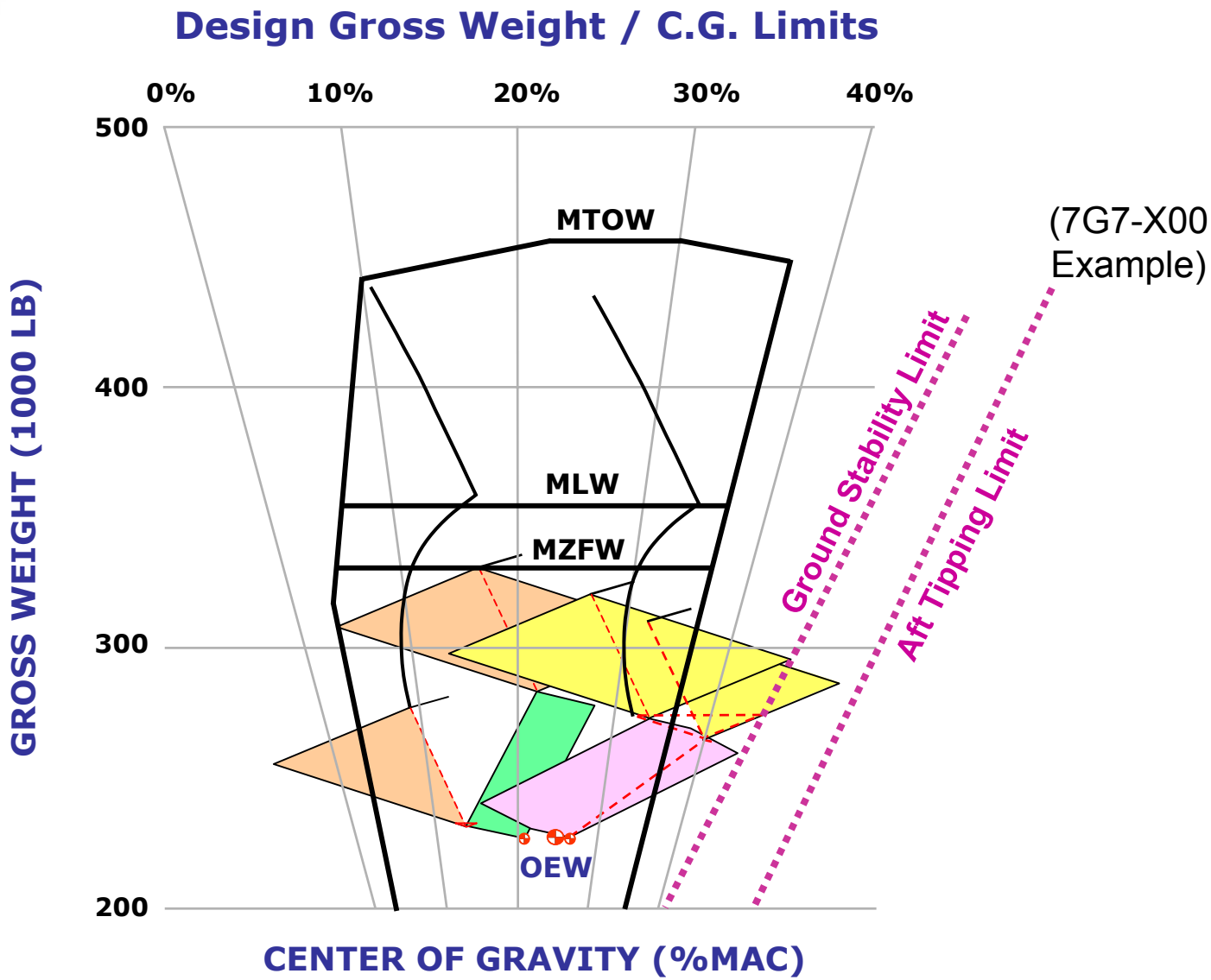
For the airplane to be in equilibrium, the sum of the moments about the main landing gear must = 0 :

$$\Sigma M_{MLG} = W\,(B.A._{MLG} - B.A._{C.G.}) - L_{NLG}\,(B.A._{MLG} - B.A._{NLG}) = 0$$

$$L_{NLG} = \frac{W\,(B.A._{MLG} - B.A._{C.G.})}{(B.A._{MLG} - B.A._{NLG})}$$

- To account for the effects of towing and ground operations, a 'ground stability limit' is imposed at C.G.'s forward of the absolute aft limit. This ground stability limit takes into account 3% ramp slope, Towing forces, 40 knot headwind, etc.

Ground Handling - Tipping



Examples of C.G. Envelopes for Actual Airplanes

Example 777-200 Center of Gravity Limits

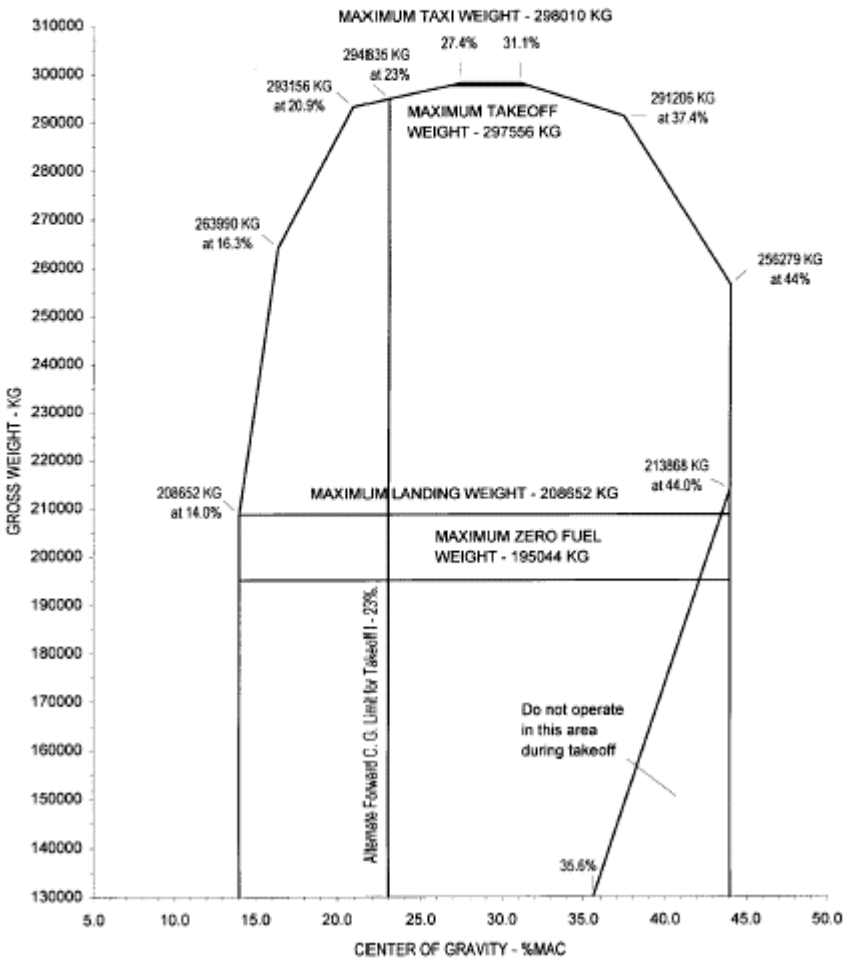
BOEING 777

AIRPLANE FLIGHT MANUAL

CENTER OF GRAVITY LIMITS

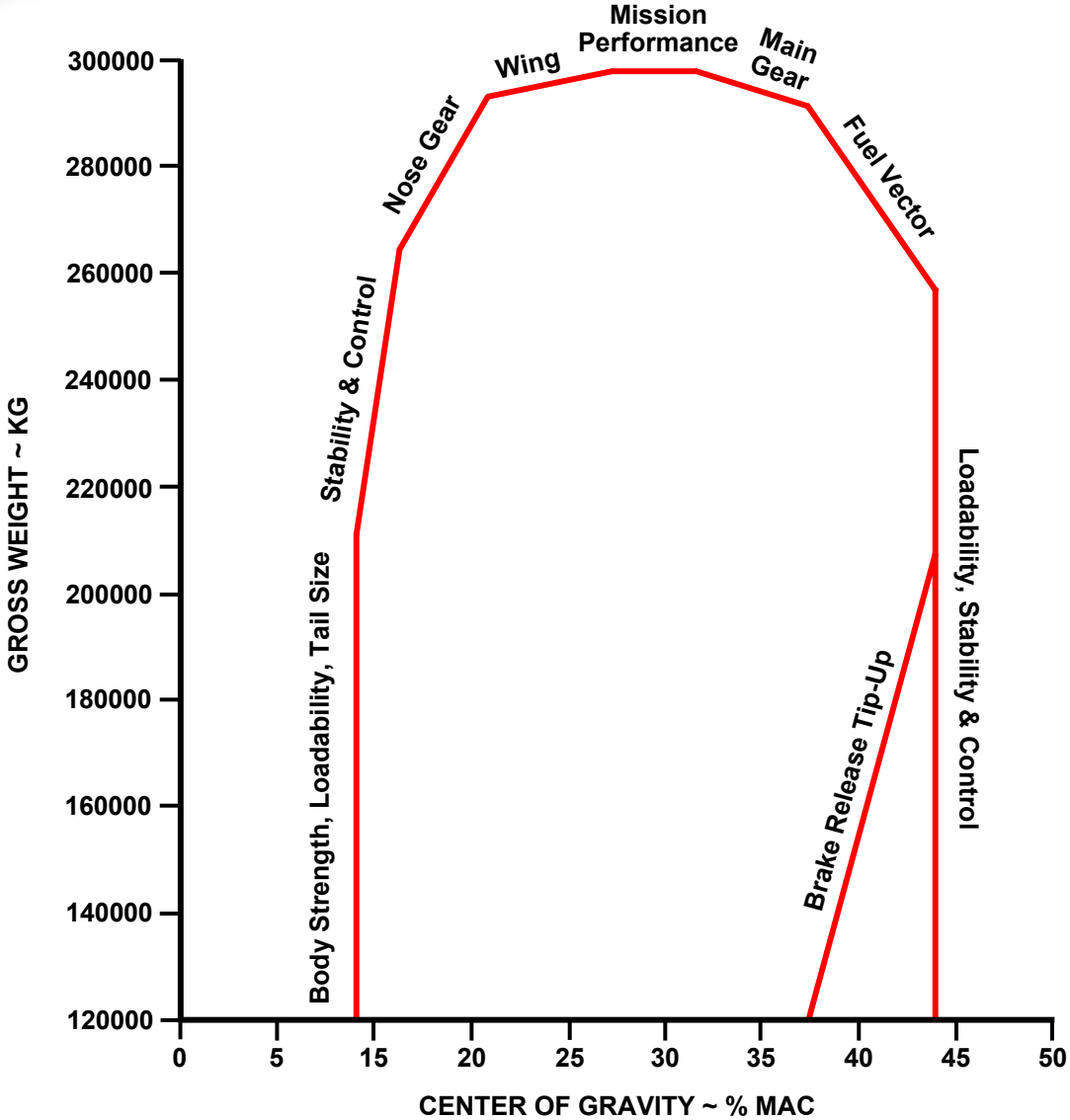
REFER TO APPLICABLE WEIGHT AND BALANCE MANUAL FOR SPECIFIC LOADING AND OPERATING RESTRICTIONS

* Refer to the Airplane Flight Manual Digital Performance Information (AFM-DPI) for operations with Alternate Forward Center of Gravity limits for takeoff.

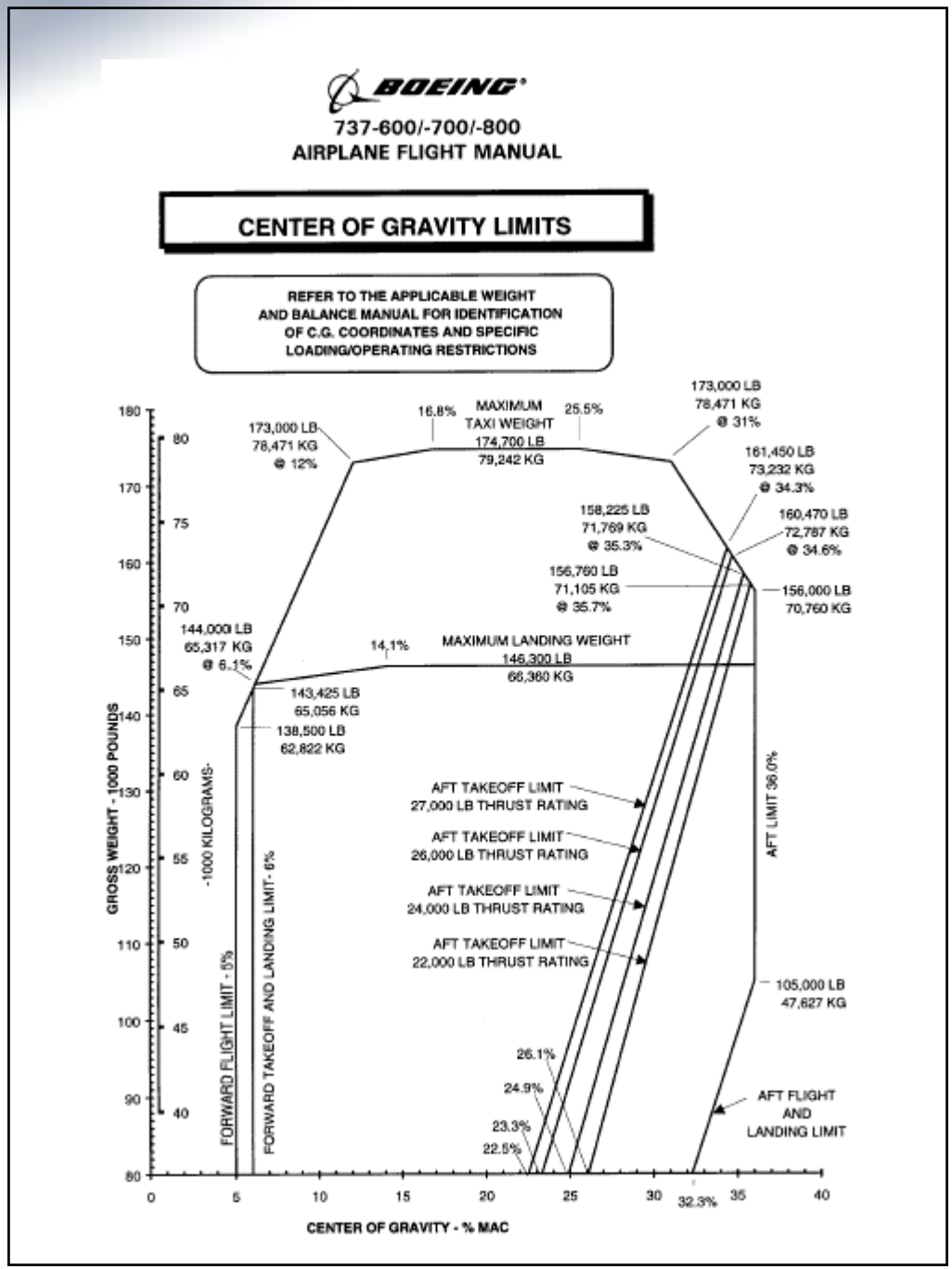


(For training purposes only. Not kept up to date)

Limitations on 777-200 Center of Gravity

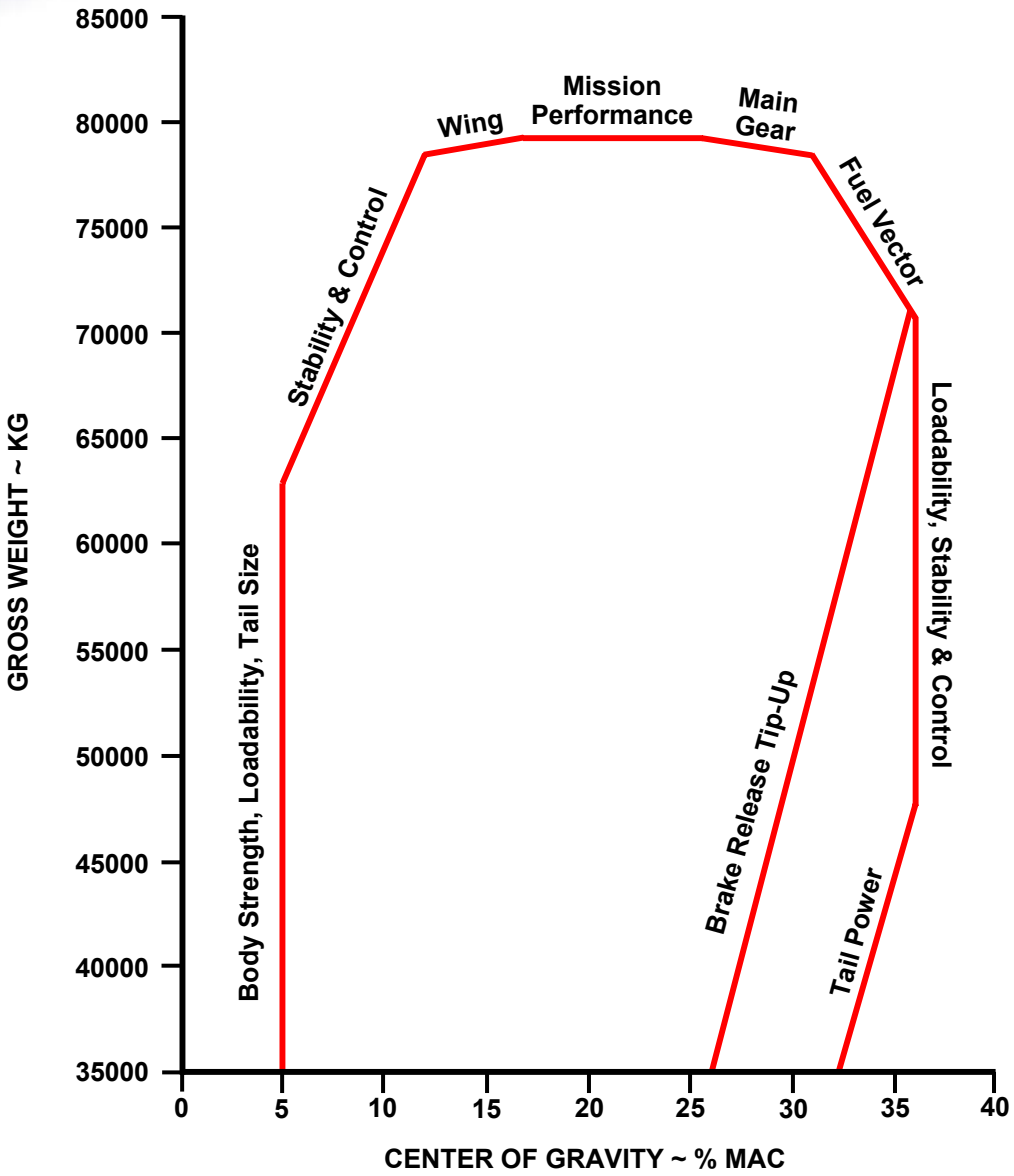


Example 737-800 Center of Gravity Limits

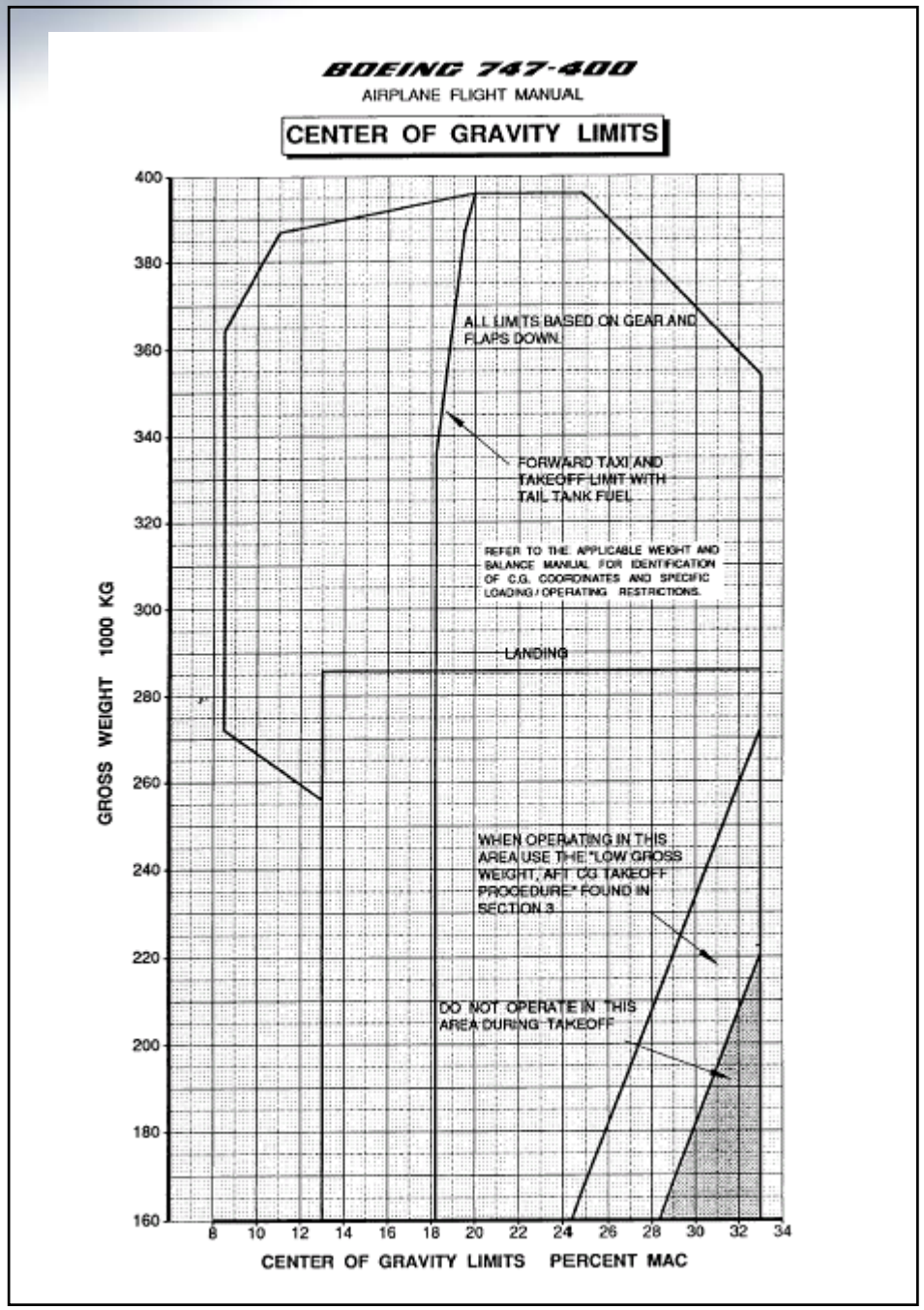


(For training purposes only. Not kept up to date)

Limitations on 737-800 Center of Gravity

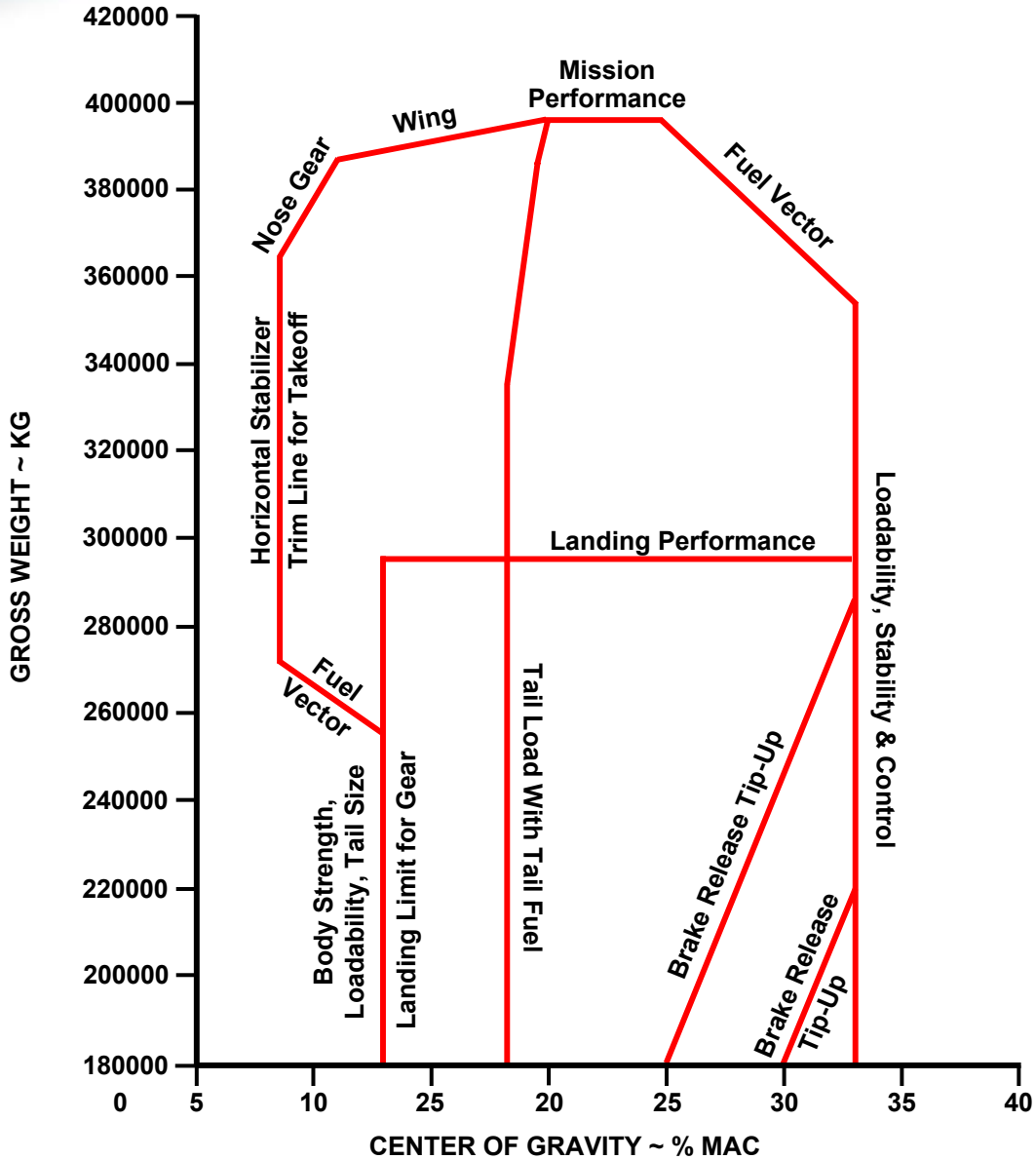


Example 747-400 Center of Gravity Limits



(For training purposes only. Not kept up to date)

Limitations on 747-400 Center of Gravity



End of
Center of Gravity Limitations