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

Datum for B.A.

m.a.c.

fwd c.g. limit
aft c.g. limit
"c.g. range"

Datum

(-) (+)

m.a.c.

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

Weight (~ 1000 lb)

Moment (in-lb)

Datum

c.g. (%mac)

5% 10% 15% 20% 25% 30% 35% 40% 45% 50%
Development of the Weight versus Moment C.G. Grid

Convert from weight versus %MAC to weight versus moment

Center of Gravity ~ %MAC

Moment (kg-in)

Datum

c.g. (%mac)

5% 10% 15% 20% 25% 30% 35% 40% 45% 50%
Development of the Weight versus Moment C.G. Grid

Weight (1000 kg)

 Momentum (kg-in)

Datum

Enlarge this Area of Interest
Development of the Weight versus Moment C.G. Grid

Weight (1000 kg)

Moment (kg-in)

c.g. (%mac)

5% 10% 15% 20% 25% 30% 35% 40% 45% 50%
Advantage of this Format is the Ability to Add Vectors Graphically

Total Moment = \( WT_{\text{Init}} \times x_{\text{Init}} + (\Delta WT_{1} \times x_{1}) + (\Delta WT_{2} \times x_{2}) - (\Delta WT_{3} \times x_{3}) \)

Total Weight = \( WT_{\text{Init}} + \Delta WT_{1} + \Delta WT_{2} + \Delta WT_{3} \)

- Order of application does not affect final result
- Starting point does not affect final \( \Delta \) weight and \( \Delta \) 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
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

AIRPLANE OEW AND CG VARIATION

<table>
<thead>
<tr>
<th>Gross Weight (1000 LB)</th>
<th>Center of Gravity (%MAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>19%</td>
</tr>
<tr>
<td>220</td>
<td>19%</td>
</tr>
<tr>
<td>230</td>
<td>24%</td>
</tr>
<tr>
<td>240</td>
<td>24%</td>
</tr>
</tbody>
</table>

NOMINAL OEW
(based on tri-class, plus a selected set of 'nominal' options)

FWD OEW
(based on dual-class, plus other options which move the C.G. fwd)

AFT OEW
(based on tri-class, plus other options which move the C.G. aft)

(7G7-X00 Example)
Determining Desired Fwd and Aft C.G. Limits: 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

Extreme Fwd Loading: Front-to-Rear
1. Load first-class seats
2. Load economy-class seats

(7G7-X00 Example)
Accounting for Interior Seating Arrangement Variations

(7G7-X00 Example)

Extreme Fwd Loading: Rear-to-Front
1. Load economy-class seats
2. Load first-class seats

GROSS WEIGHT (1000 LB)
CENTER OF GRAVITY (%MAC)

OEW
Accounting for Interior Seating Arrangement Variations

Dual-Class Defines the Most Forward Loading Interior Arrangement Considered

Most Forward C.G. Considered Based on Dual-Class Seating

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

200

300

10%

20%

30%

40%

EC

DC

FC

OEW

(7G7-X00 Example)
Accounting for Interior Seating Arrangement Variations

Extreme Aft Loading: Front-to-Rear
1. Load first-class seats
2. Load business-class seats
3. Load economy-class seats

(7G7-X00 Example)
Accounting for Interior Seating Arrangement Variations

Extreme Aft Loading: Rear-to-Front
- Load economy-class seats
- Load business-class seats
- Load first-class seats

(7G7-X00 Example)

Chosen as more “reasonable” passenger loading for most-aft C.G.
(rare to have business and first empty, with economy full)
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

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

(7G7-X00 Example)

Most Forward C.G. Considered Based on Dual-Class Seating
Determining Desired Fwd and Aft C.G. Limits: Accounting for Cargo Loading 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

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

AIRPLANE WEIGHT & C.G. WITH PASSENGERS & CARGO

OEW

Loading Cargo: Most fwd C.G.

Passenger Bags

(7G7-X00 Example)
Accounting for Cargo Variations

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

Loading Cargo: Most fwd C.G.
- 1. Passenger Bags
- 2. Forward Cargo compartment
- 3. Aft Cargo compartment
- 4. Bulk Cargo compartment

(7G7-X00 Example)
Accounting for Cargo Variations

Possible Point to Consider for Required MZFW

(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

Loading Cargo: Required MZFW

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

Another Possible Point to Consider for Required MZFW (7G7-X00 Example)
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

Loading Cargo: Most aft C.G.
- ① Passenger Bags
- ② Aft and Forward Cargo

(7G7-X00 Example)
Determining Desired Fwd and Aft C.G. Limits: 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

Fuel Vector Added to Most FWD C.G. Point Being Considered

Fuel Vector Added to Most Aft C.G. Point Being Considered

(7G7-X00 Example)
Accounting for Fuel Loading and Usage Variations

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

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

Estimated Fwd C.G. Curtailments

Estimated Aft C.G. Curtailments

(7G7-X00 Example)
Accounting for Operational Curtailment Variations

Required C.G. Limits

GROSS WEIGHT (1000 LB)

CENTERS OF GRAVITY (%MAC)

Required Fwd Limit

Required Aft Limit

(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.
Basic Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

MTOW
MLW
MZFW
OEW

GROSS WEIGHT LIMITATIONS

Certified Weight Limitations

0% 10% 20% 30% 40%

(7G7-X00 Example)
The strength of the wing’s structure can impose a limitation on the forward C.G. limits.

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

\[ \sum M_{\text{Tail}} = W (B.A_{\text{Tail}} - B.A_{\text{C.G.}}) - L_{\text{Wing}}(B.A_{\text{Tail}} - B.A_{\text{Wing}}) = 0 \]

\[ L_{\text{Wing}} = \frac{W (B.A_{\text{Tail}} - B.A_{\text{C.G.}})}{(B.A_{\text{Tail}} - B.A_{\text{Wing}})} \]

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

Basic Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

Constant Wing Load

(7G7-X00 Example)
For the airplane to be in equilibrium, the sum of the moments about the wing must = 0:

\[ \Sigma M_{\text{Wing}} = W (\text{B.A. Wing} - \text{B.A. C.G.}) - L_{\text{Tail}} (\text{B.A. Tail} - \text{B.A. Wing}) = 0 \]

\[ L_{\text{Tail}} = \frac{W (\text{B.A. Wing} - \text{B.A. C.G.})}{(\text{B.A. Tail} - \text{B.A. Wing})} \]

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

Basic Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

MTOW
MLW
MZFW
OEW

Constant Tail Load

(7G7-X00 Example)
For the airplane to be in equilibrium, the sum of the moments about the main landing gear must = 0:

\[ \sum M_{\text{MLG}} = W (B.A._{\text{MLG}} - B.A._{\text{C.G.}}) - L_{\text{NLG}} (B.A._{\text{MLG}} - B.A._{\text{NLG}}) = 0 \]

\[ L_{\text{NLG}} = \frac{W (B.A._{\text{MLG}} - B.A._{\text{C.G.}})}{(B.A._{\text{MLG}} - B.A._{\text{NLG}})} \]

- 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

Basic Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

Constant NLG Load

MTOW

MLW

MZFW

OEW

(7G7-X00 Example)
• The strength of the main landing gear structure can impose a limitation on the aft C.G. limits.

\[
\text{For the airplane to be in equilibrium, the sum of the moments about the nose landing gear must } = 0 : \\
\sum M_{NLG} = L_{MLG} (B.A._{MLG} - B.A._{NLG}) - W (B.A._{C.G.} - B.A._{NLG}) = 0
\]

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

• 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

Basic Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

0% 10% 20% 30% 40%

500

400

300

200

CENTER OF GRAVITY (%MAC)

MTOW

MLW

MZFW

OEW

Constant MLG Load

(7G7-X00 Example)
Combining All Structural Limitations

Design Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

MTOW
MLW
MZFW
OEW

(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.

\[
\sum M_{CG} = L_{MLG} (B.A.\ MLG - B.A.\ CG) - T\ \Delta h - L_{NLG} (B.A.\ CG - B.A.\ NLG) = 0
\]

\[
L_{NLG} = L_{MLG} (B.A.\ MLG - B.A.\ CG) - T\ \Delta h \\
(B.A.\ CG - B.A.\ NLG)
\]

• 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

Design Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

MTOW
MLW
MZFW
OEW

(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

Design Gross Weight / C.G. Limits

GROSS WEIGHT (1000 LB)

CENTER OF GRAVITY (%MAC)

MTOW

MLW

MZFW

OEW

Ground Stability Limit

Aft Tipping Limit

(7G7-X00 Example)
Examples of C.G. Envelopes for Actual Airplanes
Example
777-200 Center of Gravity Limits

(For training purposes only. Not kept up to date)
Limitations on 777-200
Center of Gravity

GROSS WEIGHT ~ KG

CENTER OF GRAVITY ~ % MAC

Body Strength, Loadability, Tail Size
Mission Performance
Main Gear
Loadability, Stability & Control
Brake Release Tip-Up
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

![Diagram showing limitations on 747-400 Center of Gravity](image-url)

- **Mission Performance**
- **Fuel Vector**
- **Wing**
- **Nose Gear**
- **Horizontal Stabilizer**
- **Tail Load With Tail Fuel**
- **Body Strength, Loadability, Tail Size**
- **Landing Limit for Gear**
- **Brake Release Tip-Up**

**GROSS WEIGHT ~ KG**

**CENTER OF GRAVITY ~ % MAC**

- 0 5 10 15 20 25 30 35 40

- 180000 200000 220000 240000 260000 280000 300000 320000 340000 360000 380000 400000 420000