Designing Aircraft Systems
within
Systems of Systems

Hydro-Mechanical and Electrical Systems
Examples

October 26, 2004

Sources of materials

- The system schematics are Boeing proprietary graciously given by Boeing personnel for the educational purposes of this course
  - Page 6 MD-11 braking system architecture
  - Page 15 B717 autobrake system control
  - Page 17 MD-11 electrical power system architecture
  - Page 18 MD-11 hydraulic power system architecture
- The rest of the material is taken from the personal experience of the author as first a system design engineer and as an engineering executive

Designing within Systems of Systems

- Braking System design examples

Within….

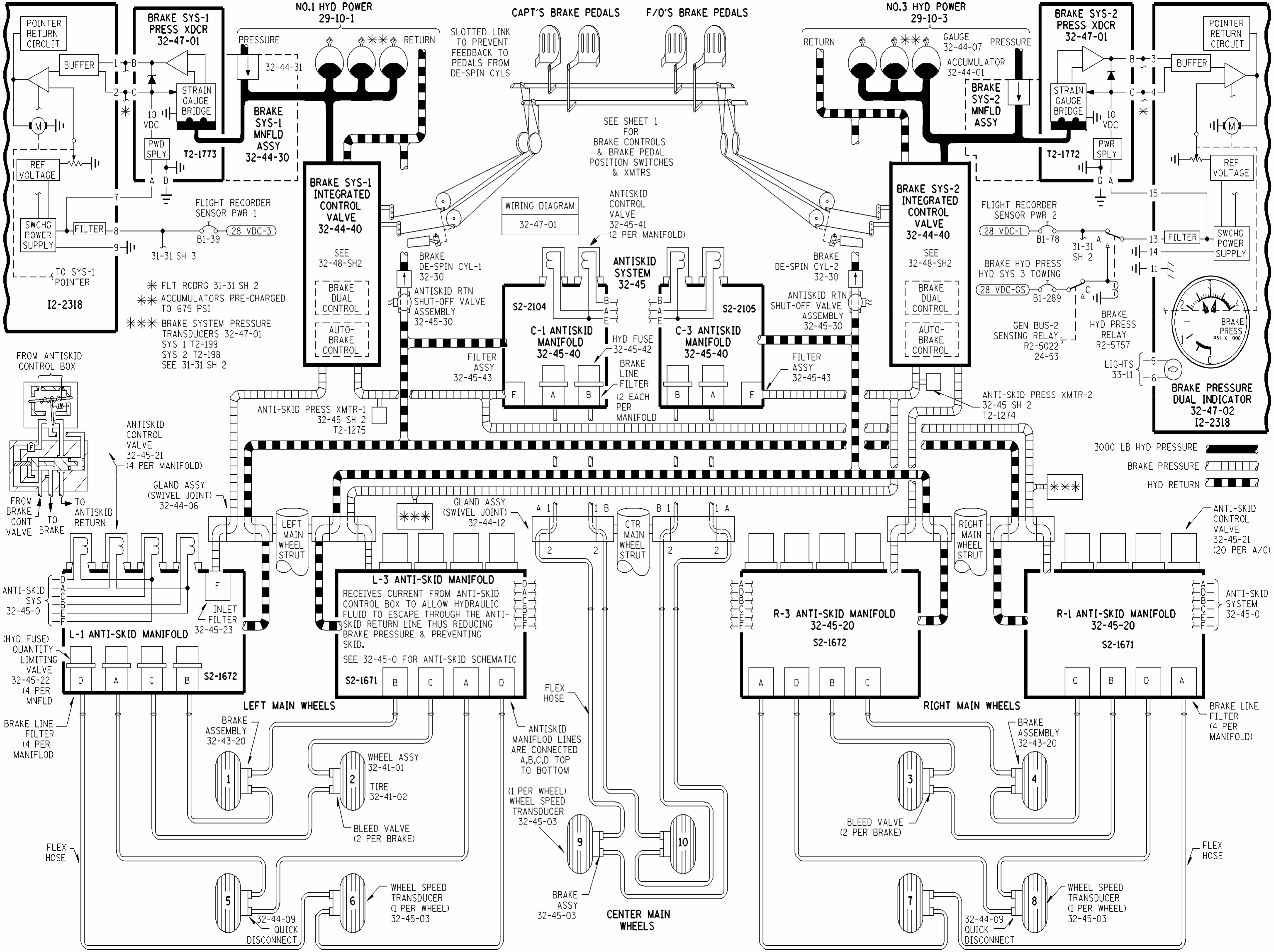
- An aircraft system of systems
- A design process & corporate system
- Airline and ATC systems
- Economic and educational systems

Systems Engineer/Manager Certification Course

- “The course I wanted when I was a starting system designer”
- 15 Subjects from aero to electrical installations, to design for safety, maintainability, certification, to…
- 58 class periods, a year’s commitment
- Applauded by the FAA certification branch

Braking System Design Objectives

- Safety
- Performance: Landing, RTO distances, energy
- Longevity, reliability, dispatchability
- Design, production, maintenance costs (DTC)
- Weight, strength
- Schedule, cycle-time
- Technology
- Certification / Regulatory compliance / Testing
- Human Factors / Pilot interface


NO.1 HYD POWER
29-10-1
NO.3 HYD POWER
29-10-3
CAPT'S BRAKE PEDALS
F/O'S BRAKE PEDALS
POINTER RETURN CIRCUIT
BUFFER
BRAKE SYS-1 PRESS XDCR 32-47-01
STRAIN GAUGE BRIDGE
10 VDC
PWD SPLY
T2-1773
REF VOLTAGE
SWCHG POWER SUPPLY
FILTER
TO SYS-1 POINTER
I2-2318
PRESSURE
RETURN
32-44-31
BRAKE SYS-1 MNFLD ASSY 32-44-30
SLOTTED LINK TO PREVENT FEEDBACK TO PEDALS FROM DE-SPIN CYLS
SEE SHEET 1 FOR BRAKE CONTROLS & BRAKE PEDAL POSITION SWITCHES & XMTRS
BRAKE SYS-1 INTEGRATED CONTROL VALVE 32-44-40
SEE 32-48-SH2
BRAKE DUAL CONTROL
AUTO-BRAKE CONTROL
FLIGHT RECORDER SENSOR PWR 1
B1-39
28 VDC-3
31-31 SH 3
WIRING DIAGRAM
32-47-01
ANTISKID CONTROL VALVE 32-45-41 (2 PER MANIFOLD)
ANTISKID SYSTEM 32-45
* FLT RCDRG 31-31 SH 2
** ACCUMULATORS PRE-CHARGED TO 675 PSI
*** BRAKE SYSTEM PRESSURE TRANSDUCERS 32-47-01
SYS 1 T2-199
SYS 2 T2-198
SEE 31-31 SH 2
BRAKE DE-SPIN CYL-1 32-30
ANTISKID RTN SHUT-OFF VALVE ASSEMBLY 32-45-30
S2-2104
C-1 ANTISKID MANIFOLD 32-45-40
HYD FUSE 32-45-42
BRAKE LINE FILTER (2 EACH PER MANIFOLD
S2-2105
C-3 ANTISKID MANIFOLD 32-45-40
FILTER ASSY 32-45-43
ANTI-SKID PRESS XMTR-1 32-45 SH 2 T2-1275
ANTI-SKID PRESS XMTR-2 32-45 SH 2 T2-1274
RETURN
GAUGE 32-44-07
PRESSURE
ACCUMULATOR 32-44-01
BRAKE SYS-2 MNFLD ASSY
BRAKE SYS-2 PRESS XDCR 32-47-01
T2-1772
PWR SPLY
BRAKE SYS-2 INTEGRATED CONTROL VALVE 32-44-40
FLIGHT RECORDER SENSOR PWR 2
28 VDC-1
B1-78
31-31 SH 2
BRAKE HYD PRESS HYD SYS 3 TOWING
28 VDC-GS
B1-289
GEN BUS-2 SENSING RELAY R2-5022 24-53
BRAKE HYD PRESS RELAY R2-5757
DE-SPIN CYL-2 32-30
LIGHTS 33-11
BRAKE PRESS PSI X 1000
BRAKE PRESSURE DUAL INDICATOR 32-47-02 I2-2318
3000 LB HYD PRESSURE
BRAKE PRESSURE
HYD RETURN
FROM ANTISKID CONTROL BOX
FROM BRAKE CONT VALVE
TO BRAKE
TO ANTISKID RETURN
ANTISKID CONTROL VALVE 32-45-21 (4 PER MANIFOLD)
GLAND ASSY (SWIVEL JOINT) 32-44-06
LEFT MAIN WHEEL STRUT
GLAND ASSY (SWIVEL JOINT) 32-44-12
CTR MAIN WHEEL STRUT
RIGHT MAIN WHEEL STRUT
ANTI-SKID CONTROL VALVE 32-45-21 (20 PER A/C)
ANTI-SKID SYS 32-45-0
INLET FILTER 32-45-23
L-1 ANTI-SKID MANIFOLD
S2-1672
(HYD FUSE) QUANTITY LIMITING VALVE 32-45-22 (4 PER MNFLD)
L-3 ANTI-SKID MANIFOLD
RECEIVES CURRENT FROM ANTI-SKID CONTROL BOX TO ALLOW HYDRAULIC FLUID TO ESCAPE THROUGH THE ANTI-SKID RETURN LINE THUS REDUCING BRAKE PRESSURE & PREVENTING SKID.
SEE 32-45-0 FOR ANTI-SKID SCHEMATIC
S2-1671
R-3 ANTI-SKID MANIFOLD 32-45-20
S2-1672
R-1 ANTI-SKID MANIFOLD 32-45-20
S2-1671
ANTI-SKID SYSTEM 32-45-0
LEFT MAIN WHEELS
RIGHT MAIN WHEELS
BRAKE LINE FILTER (4 PER MANIFOLD
BRAKE ASSEMBLY 32-43-20
WHEEL ASSY 32-41-01
TIRE 32-41-02
BLEED VALVE (2 PER BRAKE)
ANTISKID MANIFLOD LINES ARE CONNECTED A,B,C,D TOP TO BOTTOM
FLEX HOSE
(1 PER WHEEL) WHEEL SPEED TRANSDUCER 32-45-03
BRAKE ASSY 32-45-03
CENTER MAIN WHEELS
WHEEL SPEED TRANSDUCER (1 PER WHEEL) 32-45-03
32-44-09 QUICK DISCONNECT
BRAKE LINE FILTER (4 PER MANIFOLD)
1
2
3
4
5
6
7
8
9
10

Braking system architecture

- Architecture determined by ***Safety***
- Basic safety design requirements
- Architecture largely determines economics
  - Modularity, LRU’s, reuse…
  - Partition to control variability (redundancy)
  - Interfaces
- Basic system engineering trades
  - Design/production cost, performance, cycle time

Architecture – safety analysis

- FAR 25.1309 Probabilistic safety analysis
- The analytical tools
  - Functional Hazard Analysis (FHA), redundancy, hazard level, separation
  - Fault Tree Analysis (FTA)
  - *Failure Mode and Effects Analysis (FMEA)*
  - *Zonal Analysis & Events Reviews*

Design challenges
Landing gear dynamics

- Brake energy

$K(e) = \frac{1}{2}\, W/g \times (Vx,z)^2$

$= \frac{1}{2}\,(450{,}000\ \text{lb})/32.5\ \text{ft/sec}^2 \times (220\ \text{ft/sec})^2$

$\sim 340{,}000{,}000$ ft lbs.

- Vertical energy

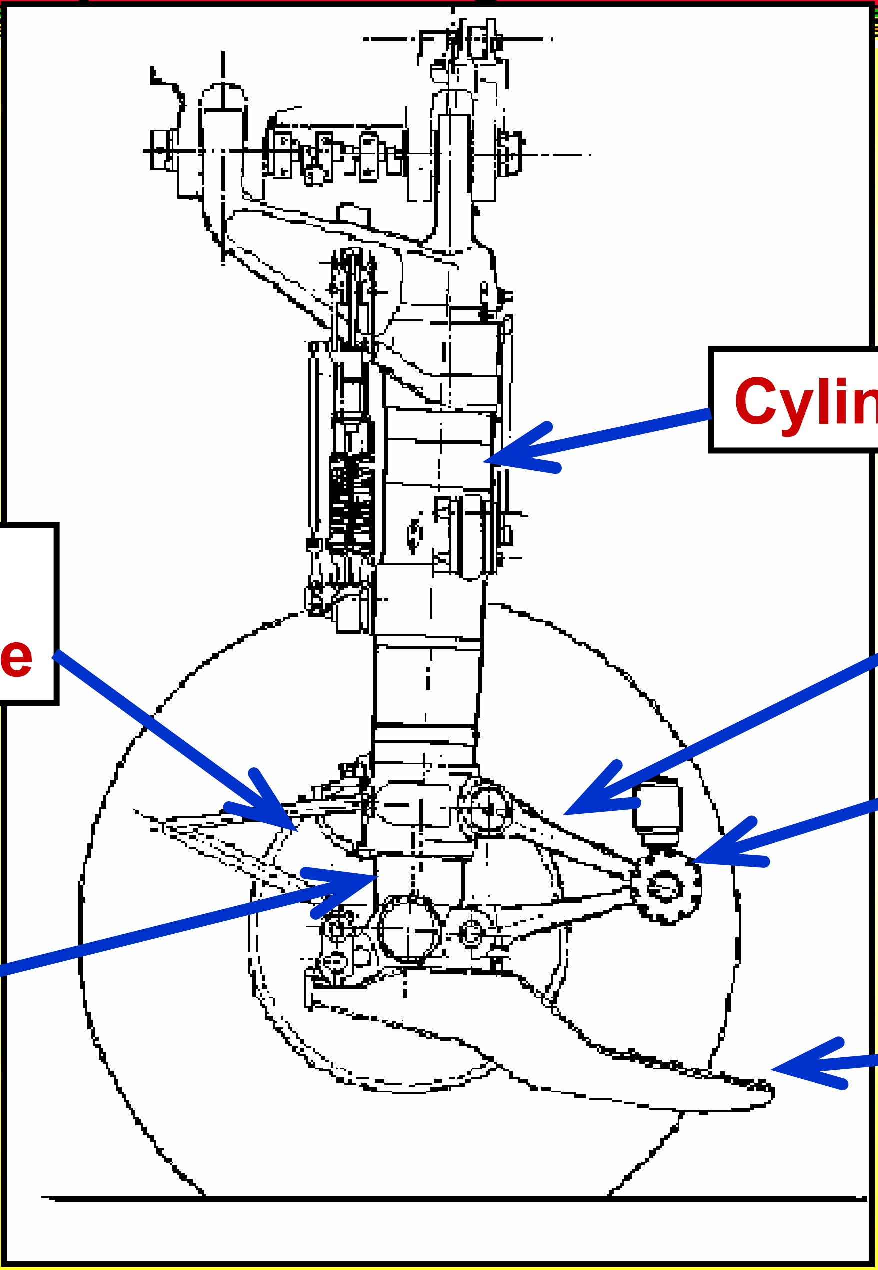
$= \frac{1}{2}\,(450{,}000\ \text{lb})/32.5\text{ft/sec}^2 \times (10\text{ft/sec})^2$

$\sim 700{,}000$ ft lbs.

- Dynamics – natural frequencies

Aircraft System Design - MIT

Main Gear



Cylinder

Wheel and Brake

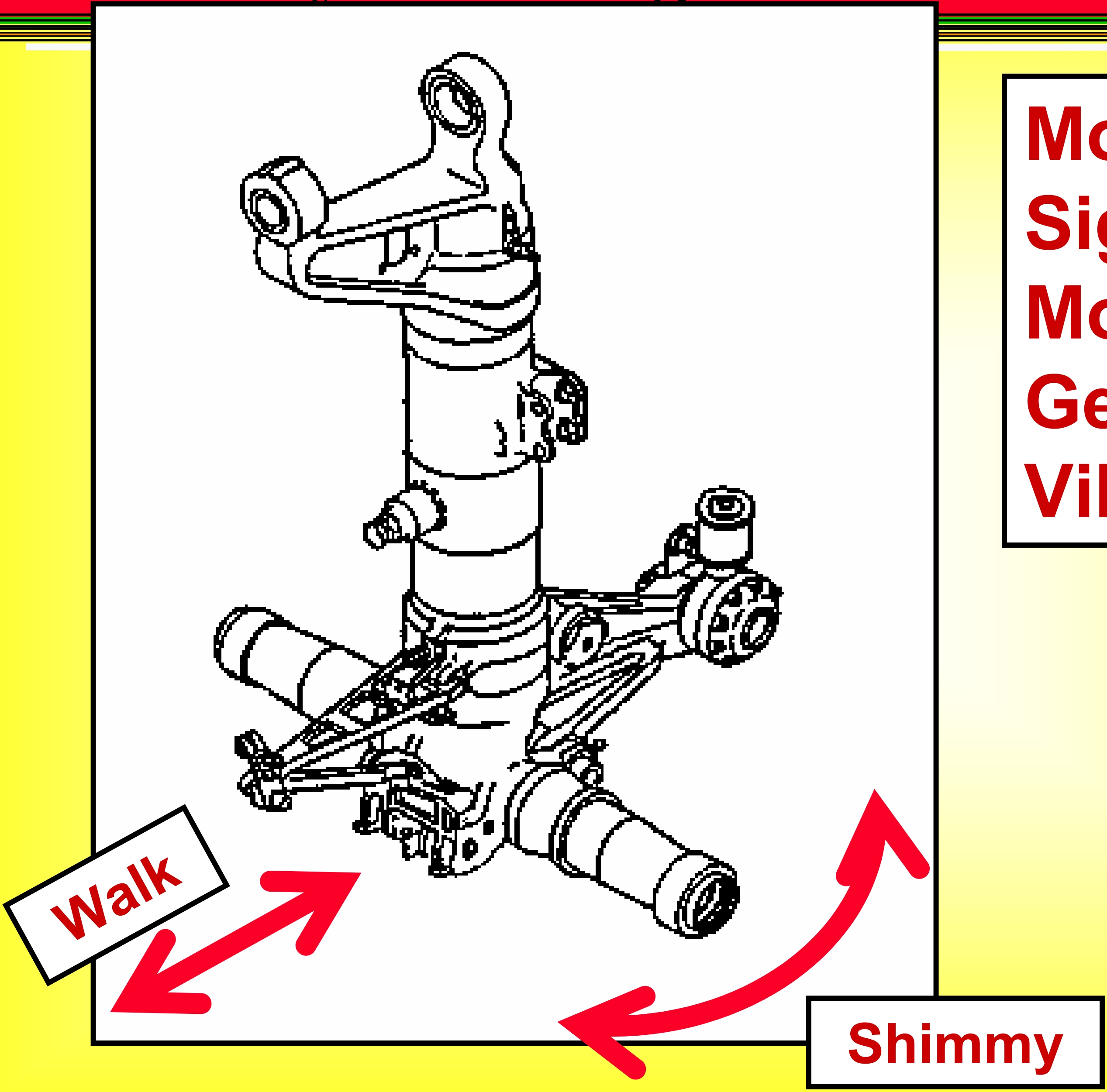
Torque Links

Shimmy Damper and Apex Bolt

Piston

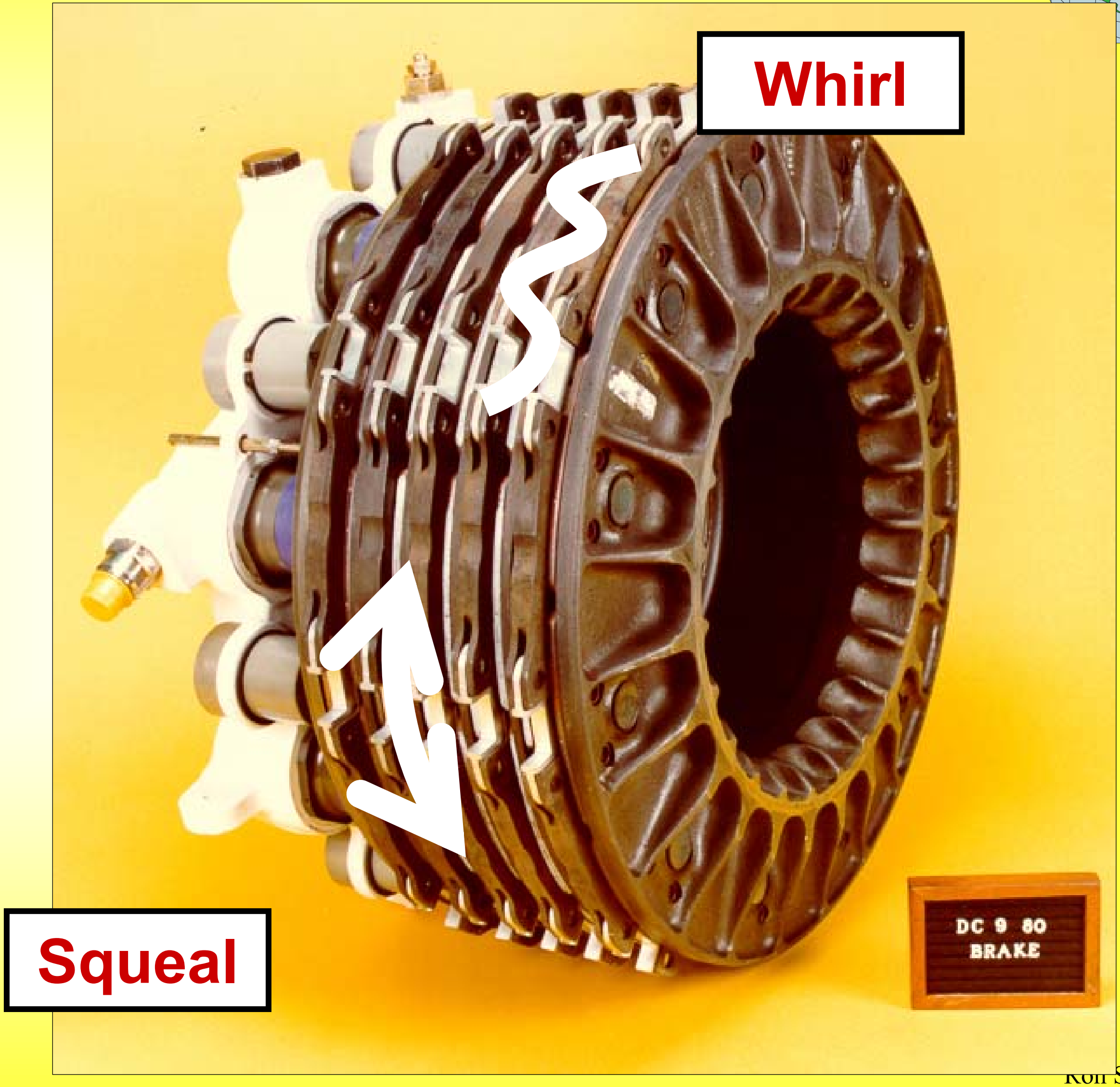
Spray Deflector

Aircraft System Design - MIT

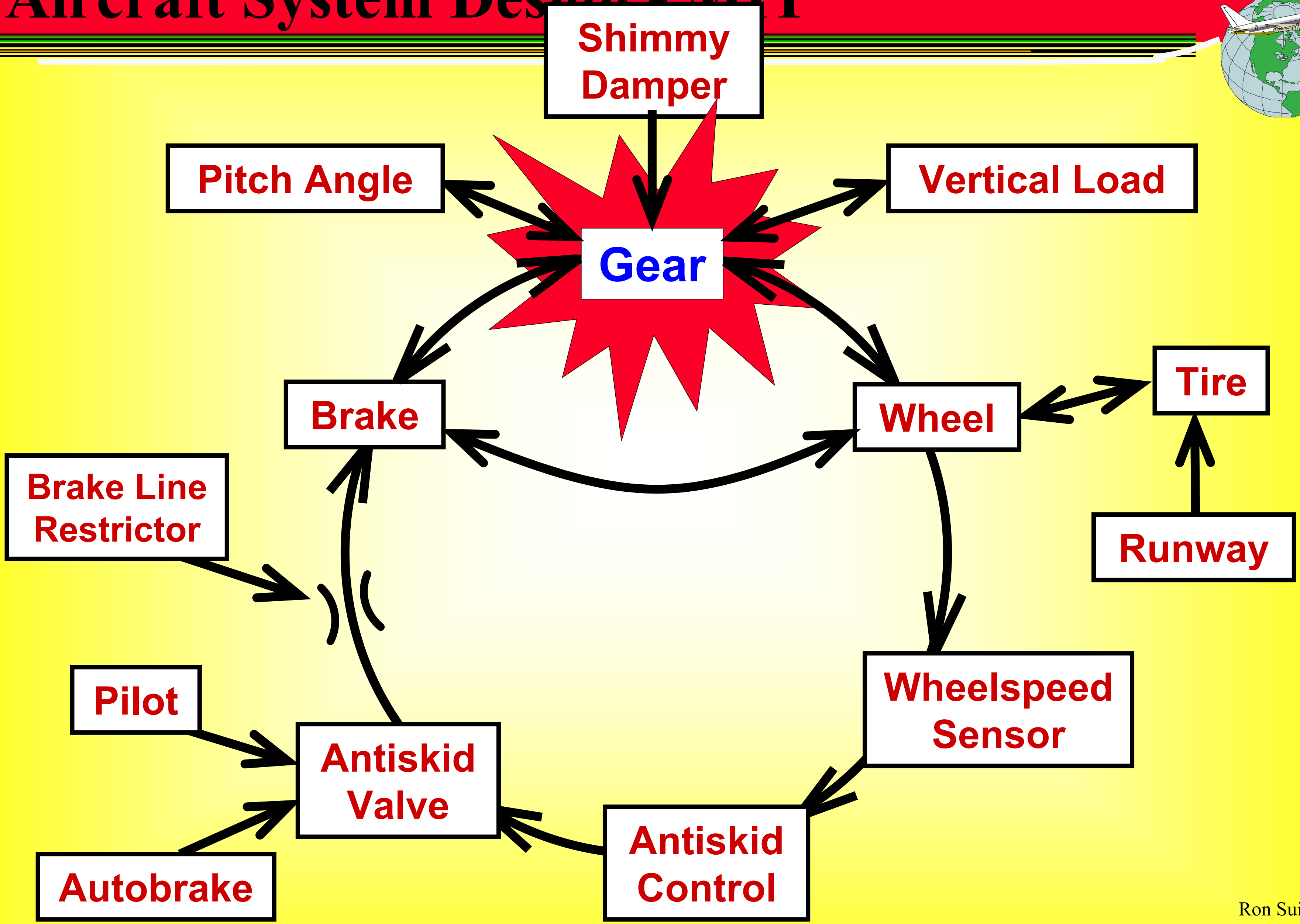


Most Significant Modes of Gear Vibration

Most Significant Modes of Brake Vibration



Aircraft System Design - MIT

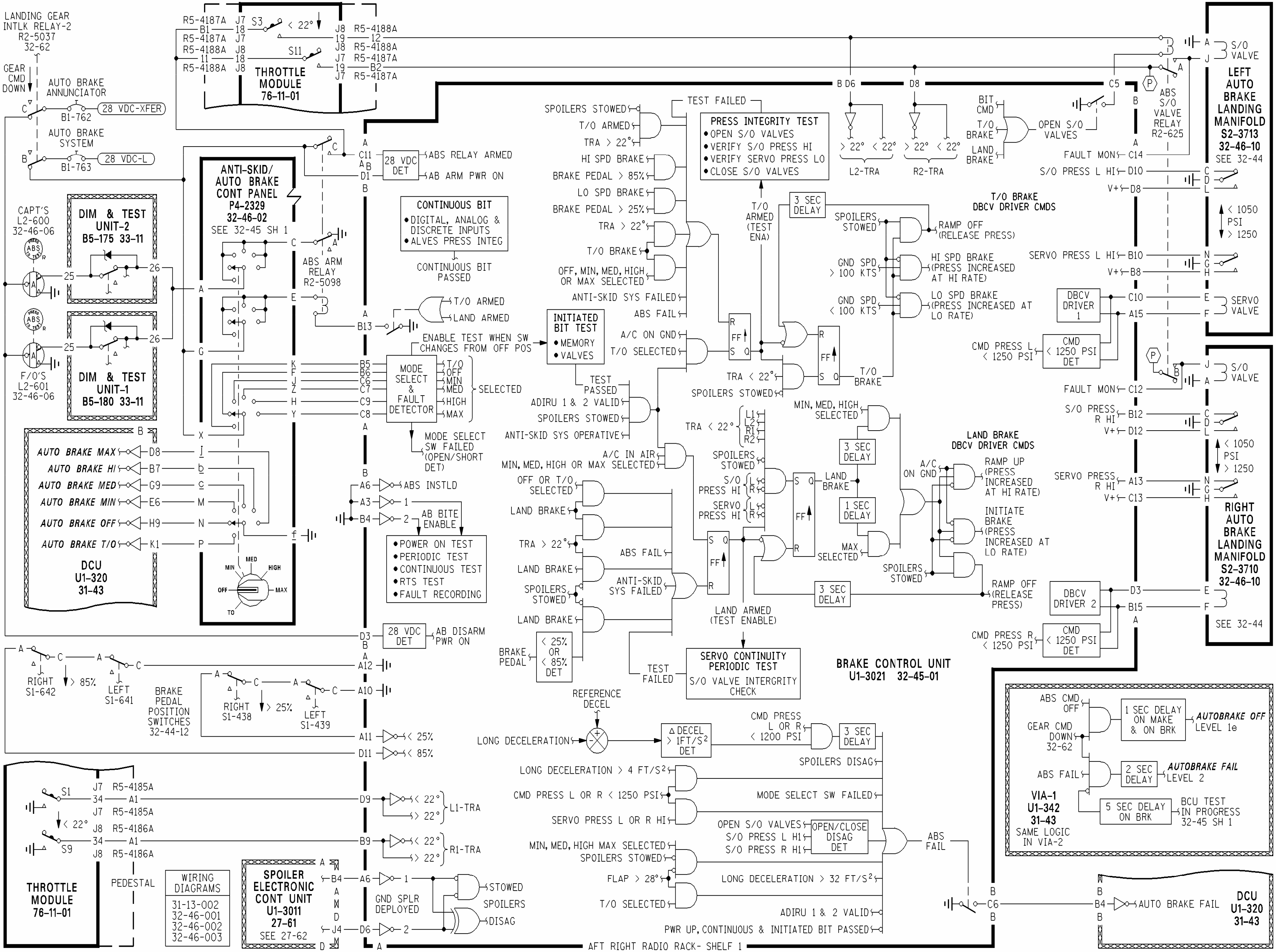


Ron Suiter
Suiter & Associates

Auto Brake design for safety

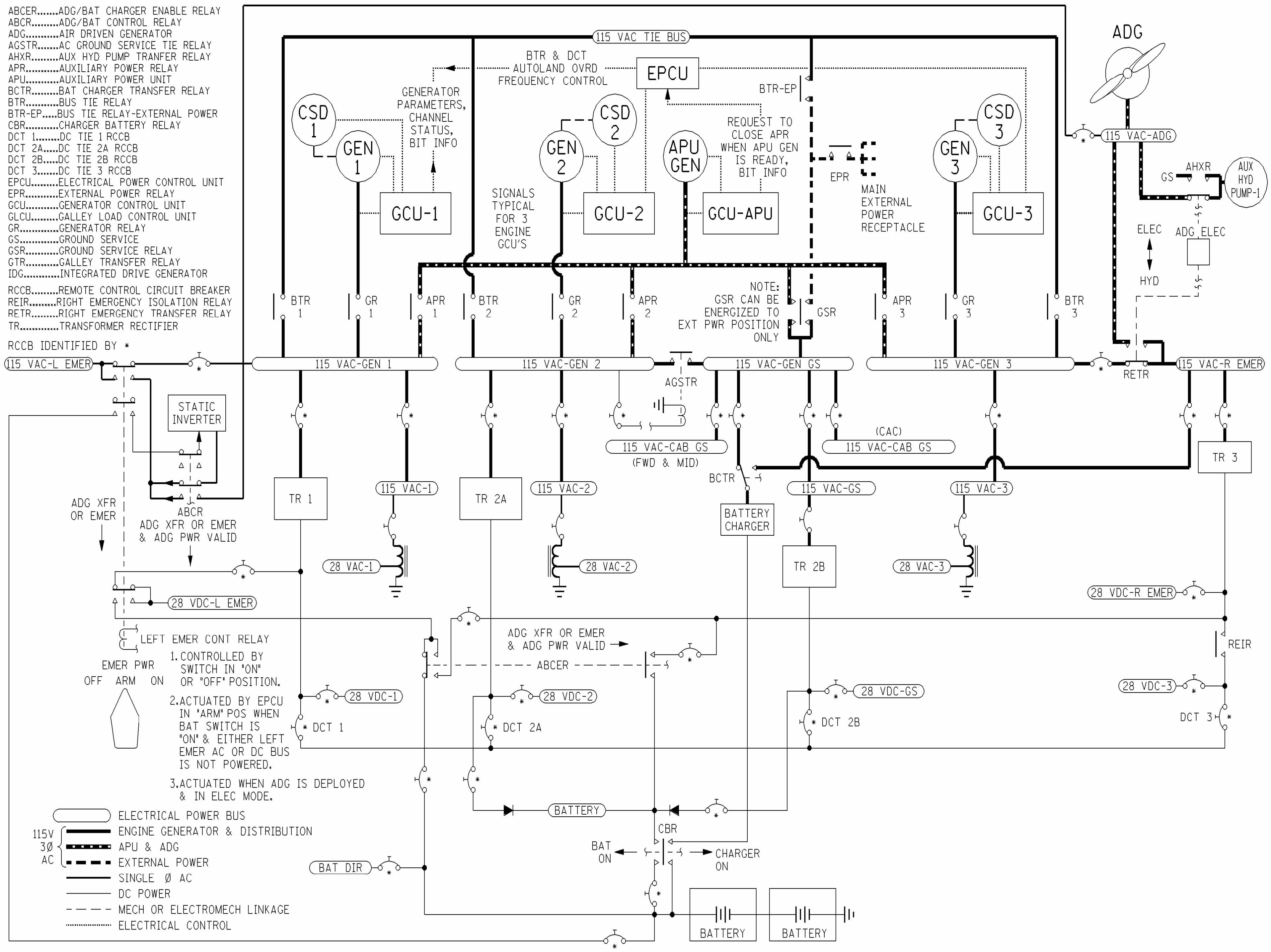
- Fault tree analysis to ensure the probability of the brakes coming on when not commanded is less than 10^{-9}

- 100 Seat aircraft Autobrake design objective met using Fault Tree Analysis


LANDING GEAR INTLK RELAY-2 R2-5037 32-62
GEAR CMD DOWN
AUTO BRAKE ANNUNCIATOR
B1-762
28 VDC-XFER
AUTO BRAKE SYSTEM
B1-763
28 VDC-L
THROTTLE MODULE 76-11-01
S3 < 22°
S11
R5-4187A J7 B1 18
R5-4187A J7
R5-4188A J8 11 18
R5-4188A J8
J8 R5-4188A 19 12
J8 R5-4188A
J7 R5-4187A 19 B2
J7 R5-4187A
ANTI-SKID/ AUTO BRAKE CONT PANEL P4-2329 32-46-02 SEE 32-45 SH 1
ABS ARM RELAY R2-5098
CAPT'S L2-600 32-46-06
F/O'S L2-601 32-46-06
PRESS ABS TO TEST
DIM & TEST UNIT-2 B5-175 33-11
DIM & TEST UNIT-1 B5-180 33-11
DCU U1-320 31-43
AUTO BRAKE MAX
AUTO BRAKE HI
AUTO BRAKE MED
AUTO BRAKE MIN
AUTO BRAKE OFF
AUTO BRAKE T/O
OFF MIN MED HIGH MAX TO
28 VDC DET
ABS RELAY ARMED
AB ARM PWR ON
CONTINUOUS BIT
• DIGITAL, ANALOG & DISCRETE INPUTS
• ALVES PRESS INTEG
CONTINUOUS BIT PASSED
T/O ARMED
LAND ARMED
ENABLE TEST WHEN SW CHANGES FROM OFF POS
INITIATED BIT TEST
• MEMORY
• VALVES
MODE SELECT & FAULT DETECTOR
T/O OFF MIN MED HIGH MAX
SELECTED
MODE SELECT SW FAILED (OPEN/SHORT DET)
ABS INSTLD
AB BITE ENABLE
• POWER ON TEST
• PERIODIC TEST
• CONTINUOUS TEST
• RTS TEST
• FAULT RECORDING
28 VDC DET
AB DISARM PWR ON
RIGHT S1-642
> 85%
LEFT S1-641
BRAKE PEDAL POSITION SWITCHES 32-44-12
RIGHT S1-438
> 25%
LEFT S1-439
< 25%
< 85%
S1
S9
< 22°
J7 R5-4185A 34 A1
J8 R5-4186A 34 A1
< 22°
> 22°
L1-TRA
R1-TRA
THROTTLE MODULE 76-11-01
PEDESTAL
WIRING DIAGRAMS
31-13-002
32-46-001
32-46-002
32-46-003
SPOILER ELECTRONIC CONT UNIT U1-3011 27-61 SEE 27-62
GND SPLR DEPLOYED
STOWED
SPOILERS
DISAG
SPOILERS STOWED
T/O ARMED
TRA > 22°
HI SPD BRAKE
BRAKE PEDAL > 85%
LO SPD BRAKE
BRAKE PEDAL > 25%
TRA > 22°
T/O BRAKE
OFF, MIN, MED, HIGH, OR MAX SELECTED
ANTI-SKID SYS FAILED
ABS FAIL
A/C ON GND
T/O SELECTED
TEST FAILED
PRESS INTEGRITY TEST
• OPEN S/O VALVES
• VERIFY S/O PRESS HI
• VERIFY SERVO PRESS LO
• CLOSE S/O VALVES
T/O ARMED (TEST ENA)
3 SEC DELAY
FF
TRA < 22°
SPOILERS STOWED
TEST PASSED
ADIRU 1 & 2 VALID
SPOILERS STOWED
ANTI-SKID SYS OPERATIVE
A/C IN AIR
MIN, MED, HIGH OR MAX SELECTED
OFF OR T/O SELECTED
LAND BRAKE
TRA > 22°
ABS FAIL
LAND BRAKE
ANTI-SKID SYS FAILED
SPOILERS STOWED
LAND BRAKE
BRAKE PEDAL
< 25% OR < 85% DET
TEST FAILED
SERVO CONTINUITY PERIODIC TEST
S/O VALVE INTERGRITY CHECK
LAND ARMED (TEST ENABLE)
TRA < 22°
L1 L2 R1 R2
SPOILERS STOWED
S/O PRESS HI
SERVO PRESS HI
L R
3 SEC DELAY
LAND BRAKE
1 SEC DELAY
MAX SELECTED
MIN, MED, HIGH SELECTED
3 SEC DELAY
> 22° < 22° L2-TRA
> 22° < 22° R2-TRA
B D6
D8
BIT CMD
T/O BRAKE
LAND BRAKE
OPEN S/O VALVES
T/O BRAKE DBCV DRIVER CMDS
SPOILERS STOWED
RAMP OFF (RELEASE PRESS)
GND SPD > 100 KTS
HI SPD BRAKE (PRESS INCREASED AT HI RATE)
GND SPD < 100 KTS
LO SPD BRAKE (PRESS INCREASED AT LO RATE)
T/O BRAKE
LAND BRAKE DBCV DRIVER CMDS
A/C ON GND
RAMP UP (PRESS INCREASED AT HI RATE)
INITIATE BRAKE (PRESS INCREASED AT LO RATE)
SPOILERS STOWED
RAMP OFF (RELEASE PRESS)
C5
ABS S/O VALVE RELAY R2-625
FAULT MON C14
S/O PRESS L HI D10
V+ D8
SERVO PRESS L HI B10
V+ B8
DBCV DRIVER 1
C10
A15
CMD PRESS L < 1250 PSI
CMD < 1250 PSI DET
S/O VALVE
SERVO VALVE
< 1050 PSI > 1250
LEFT AUTO BRAKE LANDING MANIFOLD S2-3713 32-46-10 SEE 32-44
FAULT MON C12
S/O PRESS R HI B12
V+ D12
SERVO PRESS R HI A13
V+ C13
DBCV DRIVER 2
D3
B15
CMD PRESS R < 1250 PSI
RIGHT AUTO BRAKE LANDING MANIFOLD S2-3710 32-46-10 SEE 32-44
BRAKE CONTROL UNIT U1-3021 32-45-01
REFERENCE DECEL
LONG DECELERATION
Δ DECEL > 1FT/S² DET
CMD PRESS L OR R < 1200 PSI
3 SEC DELAY
SPOILERS DISAG
LONG DECELERATION > 4 FT/S²
CMD PRESS L OR R < 1250 PSI
MODE SELECT SW FAILED
SERVO PRESS L OR R HI
OPEN S/O VALVES
S/O PRESS L HI
S/O PRESS R HI
OPEN/CLOSE DISAG DET
ABS FAIL
MIN, MED, HIGH MAX SELECTED
SPOILERS STOWED
FLAP > 28°
LONG DECELERATION > 32 FT/S²
T/O SELECTED
ADIRU 1 & 2 VALID
PWR UP, CONTINUOUS & INITIATED BIT PASSED
AFT RIGHT RADIO RACK- SHELF 1
ABS CMD OFF
GEAR CMD DOWN 32-62
1 SEC DELAY ON MAKE & ON BRK
AUTOBRAKE OFF LEVEL 1e
ABS FAIL
2 SEC DELAY
AUTOBRAKE FAIL LEVEL 2
5 SEC DELAY ON BRK
BCU TEST IN PROGRESS 32-45 SH 1
VIA-1 U1-342 31-43 SAME LOGIC IN VIA-2
C6
B4
AUTO BRAKE FAIL
DCU U1-320 31-43

Interfaces w/ the aircraft system

- Electrical power
  - Failure modes
  - Power quality, transients + & -, power xfer
  - Voltage levels & frequency, 115vac 400 Hz, 28vdc
  - Wire separation, EMI & redundancy
- Hydraulic power
  - Availability, redundancy, system separation, failures
  - Flow rates
  - Fluid properties
- Environment
  - Temperature, cooling
  - Vibration & shock, EMI



ABCER	ADG/BAT CHARGER ENABLE RELAY
ABCR	ADG/BAT CONTROL RELAY
ADG	AIR DRIVEN GENERATOR
AGSTR	AC GROUND SERVICE TIE RELAY
AHXR	AUX HYD PUMP TRANFER RELAY
APR	AUXILIARY POWER RELAY
APU	AUXILIARY POWER UNIT
BCTR	BAT CHARGER TRANSFER RELAY
BTR	BUS TIE RELAY
BTR-EP	BUS TIE RELAY-EXTERNAL POWER
CBR	CHARGER BATTERY RELAY
DCT 1	DC TIE 1 RCCB
DCT 2A	DC TIE 2A RCCB
DCT 2B	DC TIE 2B RCCB
DCT 3	DC TIE 3 RCCB
EPCU	ELECTRICAL POWER CONTROL UNIT
EPR	EXTERNAL POWER RELAY
GCU	GENERATOR CONTROL UNIT
GLCU	GALLEY LOAD CONTROL UNIT
GR	GENERATOR RELAY
GS	GROUND SERVICE
GSR	GROUND SERVICE RELAY
GTR	GALLEY TRANSFER RELAY
IDG	INTEGRATED DRIVE GENERATOR
RCCB	REMOTE CONTROL CIRCUIT BREAKER
REIR	RIGHT EMERGENCY ISOLATION RELAY
RETR	RIGHT EMERGENCY TRANSFER RELAY
TR	TRANSFORMER RECTIFIER

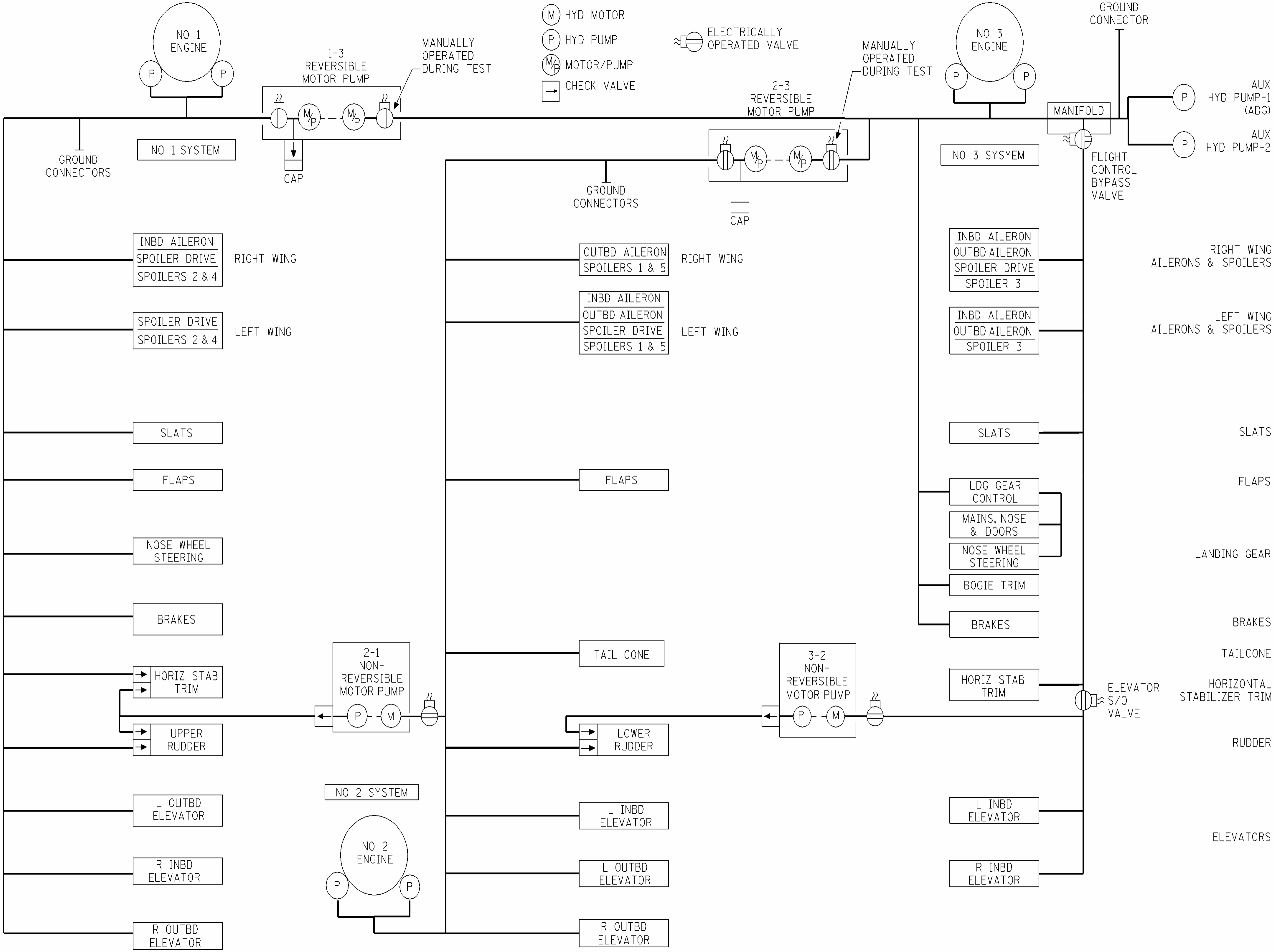
RCCB IDENTIFIED BY *

LEFT EMER CONT RELAY

1. CONTROLLED BY SWITCH IN "ON" OR "OFF" POSITION.
2. ACTUATED BY EPCU IN "ARM" POS WHEN BAT SWITCH IS "ON" & EITHER LEFT EMER AC OR DC BUS IS NOT POWERED.
3. ACTUATED WHEN ADG IS DEPLOYED & IN ELEC MODE.

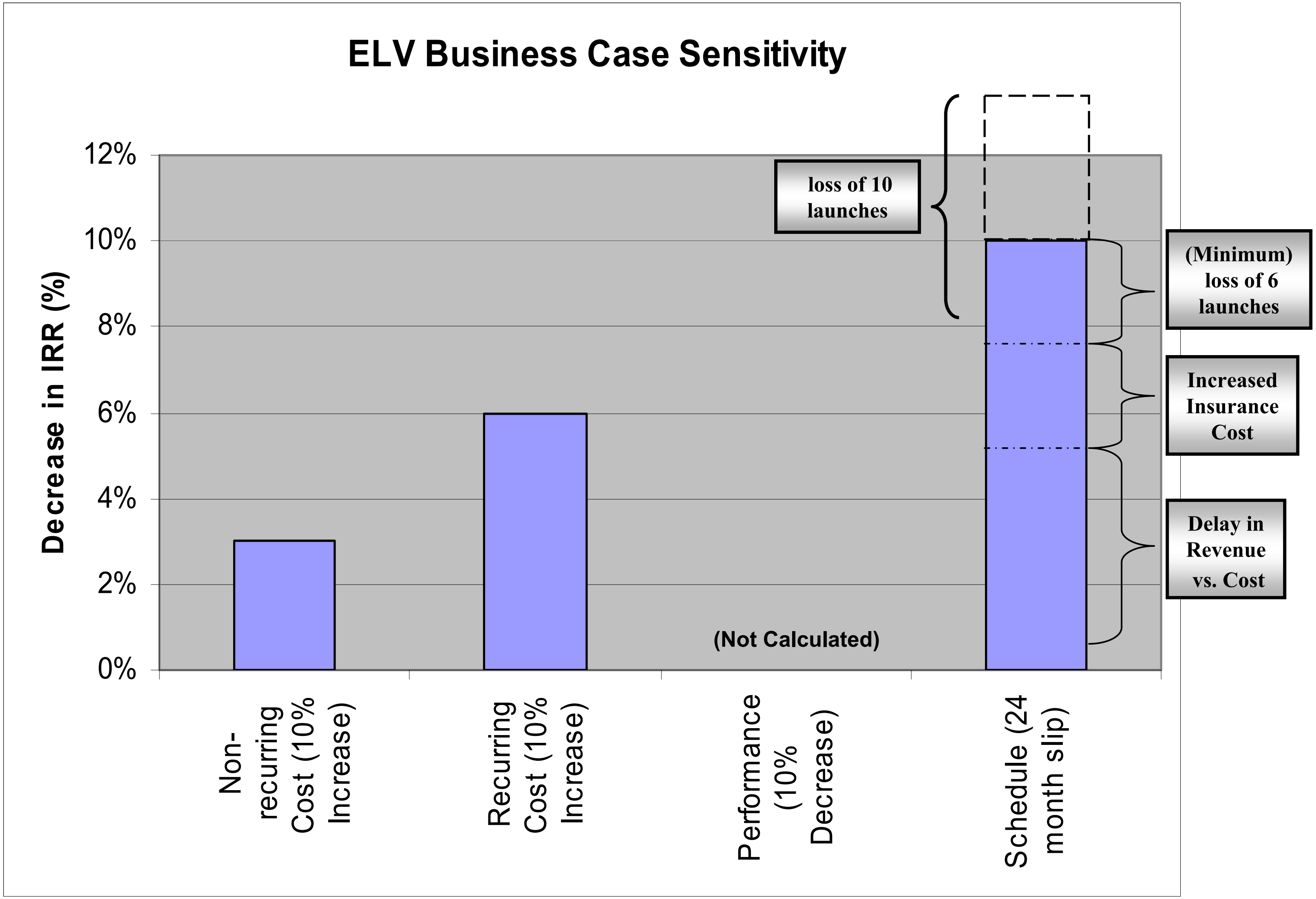
NOTE: GSR CAN BE ENERGIZED TO EXT PWR POSITION ONLY

	ELECTRICAL POWER BUS
115V 3Ø AC	ENGINE GENERATOR & DISTRIBUTION
	APU & ADG
	EXTERNAL POWER
	SINGLE Ø AC
	DC POWER
	MECH OR ELECTROMECH LINKAGE
	ELECTRICAL CONTROL


NO 1 ENGINE
P
P
1-3 REVERSIBLE MOTOR PUMP
MANUALLY OPERATED DURING TEST
M/P
M/P
CAP
GROUND CONNECTORS
NO 1 SYSTEM
M HYD MOTOR
P HYD PUMP
M/P MOTOR/PUMP
CHECK VALVE
ELECTRICALLY OPERATED VALVE
MANUALLY OPERATED DURING TEST
2-3 REVERSIBLE MOTOR PUMP
CAP
GROUND CONNECTORS
NO 3 ENGINE
P
P
GROUND CONNECTOR
MANIFOLD
NO 3 SYSYEM
AUX HYD PUMP-1 (ADG)
AUX HYD PUMP-2
FLIGHT CONTROL BYPASS VALVE
INBD AILERON
SPOILER DRIVE
SPOILERS 2 & 4
RIGHT WING
SPOILER DRIVE
SPOILERS 2 & 4
LEFT WING
OUTBD AILERON
SPOILERS 1 & 5
RIGHT WING
INBD AILERON
OUTBD AILERON
SPOILER DRIVE
SPOILERS 1 & 5
LEFT WING
INBD AILERON
OUTBD AILERON
SPOILER DRIVE
SPOILER 3
RIGHT WING AILERONS & SPOILERS
INBD AILERON
OUTBD AILERON
SPOILER 3
LEFT WING AILERONS & SPOILERS
SLATS
SLATS
SLATS
FLAPS
FLAPS
FLAPS
LDG GEAR CONTROL
MAINS, NOSE & DOORS
NOSE WHEEL STEERING
NOSE WHEEL STEERING
LANDING GEAR
BOGIE TRIM
BRAKES
BRAKES
BRAKES
TAIL CONE
TAILCONE
2-1 NON-REVERSIBLE MOTOR PUMP
P
M
3-2 NON-REVERSIBLE MOTOR PUMP
P
M
HORIZ STAB TRIM
HORIZ STAB TRIM
ELEVATOR S/O VALVE
HORIZONTAL STABILIZER TRIM
UPPER RUDDER
LOWER RUDDER
RUDDER
NO 2 SYSTEM
NO 2 ENGINE
P
P
L OUTBD ELEVATOR
R INBD ELEVATOR
R OUTBD ELEVATOR
L INBD ELEVATOR
L OUTBD ELEVATOR
R OUTBD ELEVATOR
L INBD ELEVATOR
R INBD ELEVATOR
ELEVATORS

Design Process and Program Management systems

- **SE trades, cost, performance, schedule**
- **Risk management. What is the BIG risk?**


ELV Business Case Sensitivity
Decrease in IRR (%)
0%
2%
4%
6%
8%
10%
12%
Non-recurring Cost (10% Increase)
Recurring Cost (10% Increase)
Performance (10% Decrease)
Schedule (24 month slip)
(Not Calculated)
loss of 10 launches
(Minimum) loss of 6 launches
Increased Insurance Cost
Delay in Revenue vs. Cost

Design Process and Program Management systems

- **Long cycle times – 48 months?**
- **Development cost vs. program ROI**
- **What is the purpose of engineering?**

Impact of the design process on company viability

- Aircraft production example

Results of airplane production analysis:

- Strategic cost driver (1985 - 1990):
  personnel experience dilution
- Policy contradiction (1987-1989):
  increased build target + cap on hiring
- Parts count / design complexity
- Removal of hiring cap (1990):
  - Throughput targets achieved
  - Per-airplane cost declined 45% in one year

Design drives company viability

- 80 + % of product cost determined early
- Company viability / ability to close the business case on new designs determines ability to launch new products
- Flow of new products develops engineering experience base critical to good design

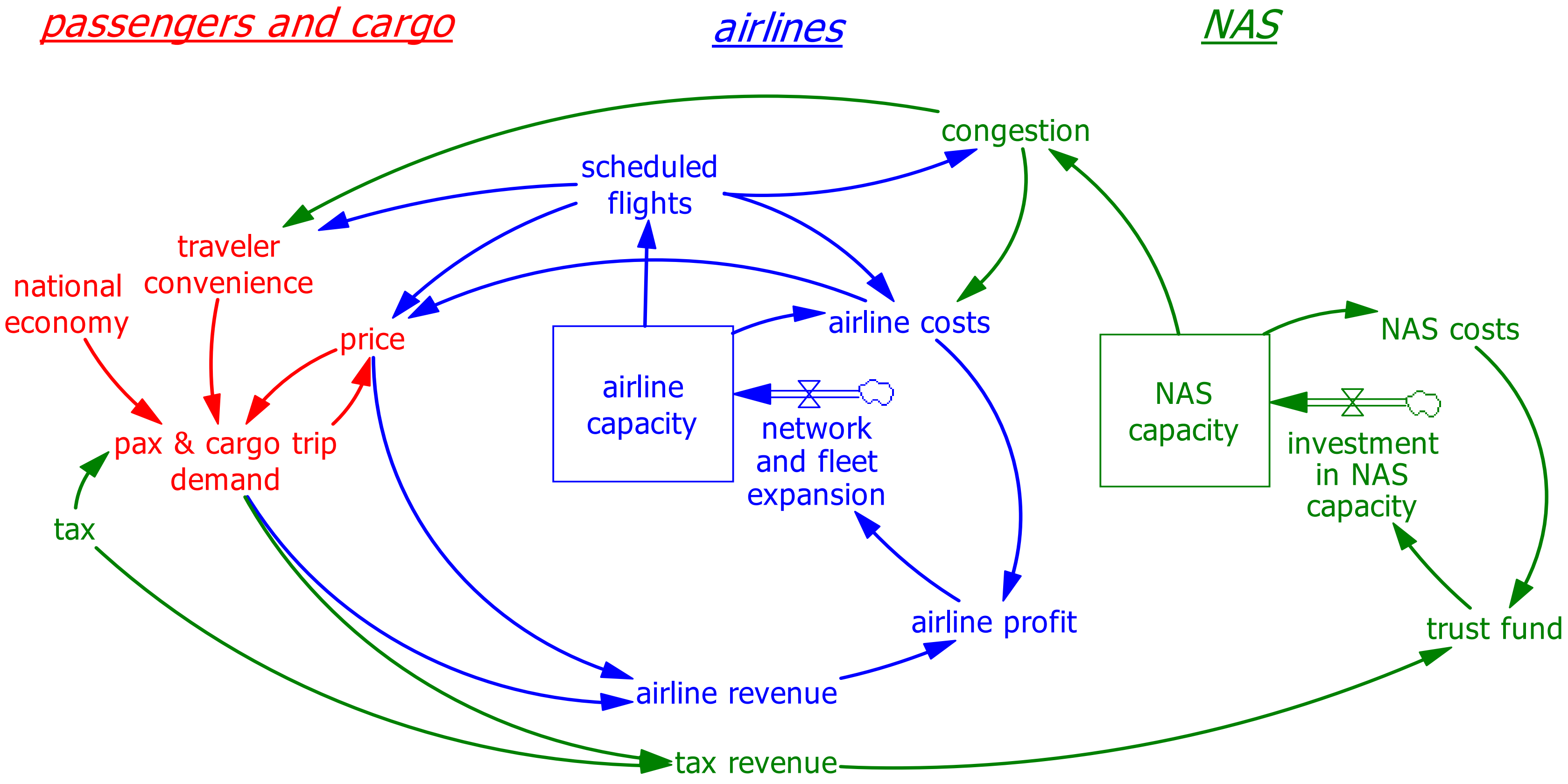
Airline systems

- Airline viability ~ ability to buy / launch airplanes
  - Driven by 7 to 10 year business cycle
  - Sensitive to special events, Gulf, 9/11
  - High capital, labor costs, very thin margins
  - Long aircraft acquisition lead times
  - Business model, network structure

ATM System (of systems)

- Challenge to expand capacity of National Airspace System (NAS) by 2X by 2025?
- Impact of aircraft economics on NAS
- Divide workload between cockpit and ground
- Value to airlines to equip?

NAS Strategy Simulator Overview



passengers and cargo

airlines

NAS

congestion

scheduled flights

traveler convenience

national economy

price

airline costs

airline capacity

network and fleet expansion

NAS costs

NAS capacity

investment in NAS capacity

pax & cargo trip demand

tax

airline profit

trust fund

airline revenue

tax revenue

The critical issues

- SE / program management interface
  - Ability to manage / trade the **BIG** risks
- Design cycle time
- Ability to close business case on new planes
- Personnel experience management
- Enterprise portfolio of technologies and programs to minimize risk
- Program management and corporate culture

Direction of Solution

- Top-down design tools - architecture
- Model-based design - technical **and** organization performance
- Enterprise simulation based technology and program portfolio management decision support
- *Change the paradigm in concurrent engineering & engineering personnel management*
  - *JPL Project Design Center*
  - *Drop pay-to-market HR policies*

The Future

- ***Ability to deal with complexity of systems of systems "top-down"***
    - ***The solution to your system problem can be found in the larger or adjacent systems***
- ***Designing airplanes within the context of…organization, airline/ATC, economic systems***
- ***The challenge – pick YOUR system and improve its viability***