Working Principle of IC Engines

A Design Thinking Framework Approach

Mechanical Engineering | Thermal Engineering

EMPATHIZE DEFINE IDEATE PROTOTYPE TEST

Design Thinking Framework Overview

EMPATHIZE

Understand learner needs & misconceptions

Slides 3–5

DEFINE

Problem statement, objectives & fundamentals

Slides 6–8

IDEATE

Cycles, strokes, thermodynamics & comparisons

Slides 9–20

PROTOTYPE

Case studies, trends & engine design challenge

Slides 21–25

TEST

Assessment, key takeaways & reflection

Slides 26–28

Understanding Our Learners

PHASE 1

Who Are Our Learners?

- 2nd/3rd year Mechanical Engineering students
- Have completed basic thermodynamics and mechanics
- Can state laws of thermodynamics but struggle to apply them to engines
- Find P-V and T-S diagrams abstract and disconnected from reality
- Want to understand 'what actually happens inside an engine'

Empathy Map — Pain Points

"I memorized the Otto cycle but can't explain why compression matters."

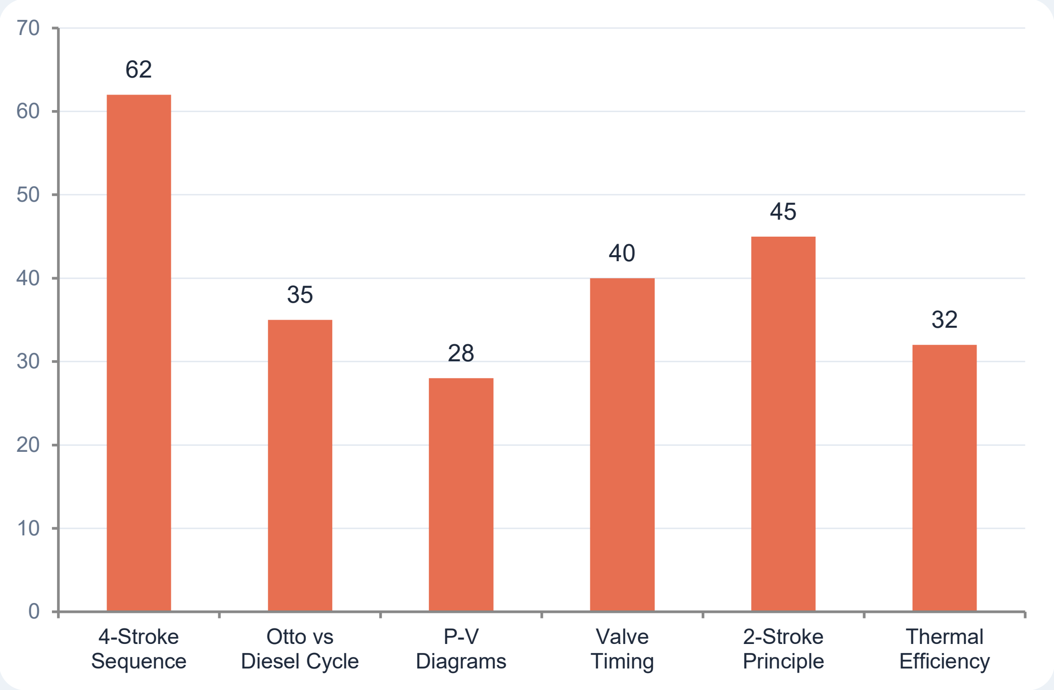
"P-V diagrams look like abstract math, not real engine behaviour."

"I don't understand why diesel engines don't need spark plugs."

"Two-stroke vs four-stroke — I mix up the stroke sequences."

Needs Assessment Survey

PHASE 1



Key Insights

- P-V diagrams & thermal efficiency are least understood areas
- Students can list strokes but not explain the thermodynamic reason behind each
- Connecting cycle theory to real engine performance is the biggest gap
- Animation and step-by-step process breakdowns strongly preferred

How Might We Statements

PHASE 1

1	**How might we make thermodynamic cycles tangible?**	*Link every P-V diagram point to a physical piston position*
2	**How might we show why compression ratio matters?**	*Compare efficiency at different CRs with real data*
3	**How might we clarify SI vs CI differences?**	*Side-by-side cycle walkthroughs highlighting key divergence*
4	**How might we connect 2-stroke and 4-stroke logically?**	*Overlay stroke diagrams to show what's combined in 2-stroke*
5	**How might we make efficiency calculations meaningful?**	*Tie formulas to real-world fuel consumption numbers*

Problem Statement & Learning Objectives

PHASE 2

Mechanical engineering students need a process-level understanding of how IC engines convert fuel energy into mechanical work because superficial memorization of stroke sequences does not enable them to analyse, troubleshoot, or optimise real engine performance.

1 Describe Strokes

Explain the four strokes and the thermodynamic event in each

Understand

2 Interpret P-V Diagrams

Read and annotate Otto and Diesel cycle P-V diagrams

Analyze

3 Compare Cycles

Differentiate Otto, Diesel, and Dual cycles quantitatively

Analyze

4 Calculate Efficiency

Compute air-standard efficiency and mean effective pressure

Apply

5 Contrast 2T vs 4T

Compare two-stroke and four-stroke working principles

Evaluate

6 Apply to Real Engines

Predict how parameter changes affect engine performance

Create

Fundamental Concept — Energy Conversion in IC Engines

PHASE 2

The working principle of an IC engine is the systematic conversion of chemical energy in fuel to mechanical work through a repeating thermodynamic cycle of intake, compression, combustion-expansion, and exhaust — all occurring inside the engine cylinder.

Chemical → Thermal

Fuel combustion releases heat energy, raising gas temperature and pressure inside the cylinder.

Thermal → Mechanical

High-pressure gases push the piston down; the connecting rod and crankshaft convert this to rotation.

Cyclic Operation

The process repeats every 2 or 4 strokes, producing continuous rotary power at the flywheel.

Evolution of Engine Cycles — Historical Context

PHASE 2

1824

Carnot publishes ideal heat engine cycle theory

1860

Lenoir builds first practical IC engine (non-compression)

1876

Otto patents the 4-stroke spark-ignition cycle

1893

Diesel patents the compression-ignition cycle

1906

Dual/mixed cycle proposed (Sabathe/Trinkler)

1990s

Modern VVT, direct injection refine cycle efficiency

Four-Stroke SI Engine — Stroke-by-Stroke

PHASE 3

INTAKE

Stroke 1 (0°–180°)

Inlet valve opens. Piston moves from TDC to BDC, creating vacuum. Air-fuel mixture is drawn into the cylinder.

COMPRESSION

Stroke 2 (180°–360°)

Both valves closed. Piston moves BDC→TDC. Mixture is compressed to 1/8–1/12 of original volume. Temperature rises to ~400°C.

POWER

Stroke 3 (360°–540°)

Spark plug fires near TDC. Rapid combustion raises pressure to ~40–60 bar. Hot gases push piston from TDC to BDC — this is the only working stroke.

EXHAUST

Stroke 4 (540°–720°)

Exhaust valve opens. Piston moves BDC→TDC, sweeping burnt gases out. Residual pressure assists initial gas expulsion.

One complete cycle = 4 strokes = 2 crankshaft revolutions = 720° of crank rotation.

Otto Cycle (Air-Standard) — Ideal SI Engine

PHASE 3

Otto Cycle P-V Diagram — 4 Processes

1→2	**Isentropic Compression** Piston compresses air-fuel adiabatically; pressure and temperature rise.
2→3	**Constant Volume Heat Addition** Spark ignites mixture; combustion is so fast it occurs at ~constant volume.
3→4	**Isentropic Expansion** High-pressure gases expand adiabatically, pushing the piston — power stroke.
4→1	**Constant Volume Heat Rejection** Exhaust valve opens; pressure drops to atmospheric at ~constant volume.

Key Equations

Air-Standard Efficiency

$$\eta = 1 - 1 / r^{(\gamma-1)}$$

Compression Ratio

$$r = V_1 / V_2 = (V_s + V_c) / V_c$$

Work Output

$$W_{net} = Q_{in} - Q_{out}$$

Mean Effective Pressure

$$MEP = W_{net} / V_s$$

Where

$$\gamma = C_p/C_v = 1.4 \text{ (for air)}$$

Diesel Cycle (Air-Standard) — Ideal CI Engine

PHASE 3

Diesel Cycle — 4 Processes

1→2 **Isentropic Compression**

Air only (no fuel) compressed to very high pressure and temperature (~600–700°C).

2→3 **Constant Pressure Heat Addition**

Fuel injected into hot air; burns gradually at constant pressure as piston moves down.

3→4 **Isentropic Expansion**

Remaining expansion of gases pushes the piston — power delivery continues.

4→1 **Constant Volume Heat Rejection**

Exhaust valve opens; pressure drops quickly at approximately constant volume.

Key Equations

Air-Standard Efficiency

$$\eta = 1 - [1/r^{(\gamma-1)}] \times [(\rho^\gamma - 1) / \gamma(\rho - 1)]$$

Cut-off Ratio

$\rho = V_3 / V_2$ (volume at end/start of heat addition)

Key Insight

Higher r → higher η, but $\rho > 1$ always reduces η vs Otto

Typical CR

r = 14:1 to 25:1 (much higher than SI)

Dual (Mixed) Cycle — Realistic Approximation

PHASE 3

Why the Dual Cycle?

Real combustion is neither purely constant-volume nor constant-pressure. The Dual (Sabathe) cycle combines both — an initial rapid pressure rise at constant volume followed by continued heat addition at constant pressure. This models actual engine combustion more accurately.

1→2	Isentropic compression
2→3	Constant volume heat addition (partial)
3→4	Constant pressure heat addition (remaining)
4→5	Isentropic expansion (power)
5→1	Constant volume heat rejection

When to Use Which?

Otto Cycle
Best for SI engines (fast combustion ≈ constant V)

Diesel Cycle
Best for slow-speed CI engines (gradual combustion ≈ constant P)

Dual Cycle
Best for modern high-speed CI engines (CRDI) — most realistic model

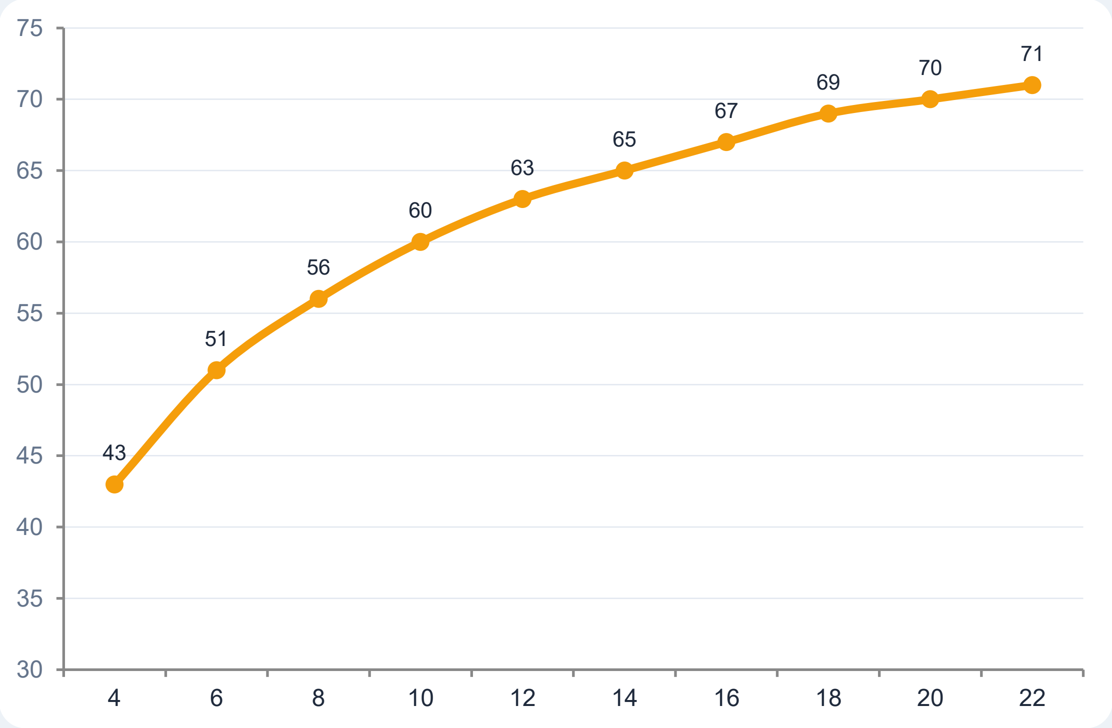
Cycle Comparison — Otto vs Diesel vs Dual

PHASE 3

Parameter	Otto Cycle	Diesel Cycle	Dual Cycle
Heat Addition	Constant Volume	Constant Pressure	Const V + Const P
Heat Rejection	Constant Volume	Constant Volume	Constant Volume
Compression Ratio	6–12	14–25	12–20
Ignition	Spark plug	Self-ignition	Self-ignition
Fuel Injected	Before compression	After compression	After compression
Efficiency (same CR)	Highest	Lowest	Intermediate
Practical Efficiency	25–35%	35–45%	35–45%
Best Models	SI petrol engines	Slow-speed CI	Modern high-speed CI

Effect of Compression Ratio on Efficiency

PHASE 3



Key Observations

- Efficiency rises steeply at low CR, then flattens
- Diminishing returns above r ≈ 12 for SI (knock limit)
- CI engines exploit the 14–22 range where SI cannot operate
- Higher γ (leaner mixtures) also improves efficiency
- Real efficiency is always 60–70% of the air-standard value

Four-Stroke CI (Diesel) Engine — Working

PHASE 3

INTAKE

Air Only

Only air enters the cylinder (no fuel). Inlet valve open, piston moves TDC→BDC.

COMPRESSION

High CR (14–25:1)

Air compressed to 35–45 bar, temp reaches 600–700°C — well above diesel auto-ignition temperature.

POWER

Fuel Injection

Diesel fuel injected as fine spray into superheated air. Ignites spontaneously — no spark needed. Combustion at ~constant pressure initially.

EXHAUST

Gas Expulsion

Exhaust valve opens. Piston pushes burnt gases out. Exhaust gas temperature: ~500–600°C.

Key difference from SI: Only air is compressed (no knock). Fuel injection timing controls power output.

Two-Stroke Engine — Working Principle

PHASE 3

Upward Stroke (BDC → TDC)

Compression:
Piston moves up, compressing the charge above it.

Simultaneously below the piston:
Crankcase vacuum draws fresh charge through the intake port into the crankcase.

At TDC: Spark fires (SI) or fuel injects (CI) — combustion begins.

Downward Stroke (TDC → BDC)

Expansion (Power):
Hot gases push piston down — work is done.

Near BDC:
Exhaust port uncovered first → burnt gases escape.
Then transfer port opens → fresh charge from crankcase enters cylinder and helps push remaining exhaust out (scavenging).

One power stroke per revolution = 360° cycle.

Two-Stroke vs Four-Stroke Comparison

PHASE 3

Parameter	Two-Stroke	Four-Stroke
Cycle Completion	1 revolution (360°)	2 revolutions (720°)
Power Strokes / Rev	1	0.5
Valves	Ports (no valves needed)	Poppet valves + camshaft
Power-to-Weight	Higher (more frequent firing)	Lower
Fuel Efficiency	Lower (charge loss during scavenging)	Higher
Emissions	Higher (unburnt fuel in exhaust)	Lower (better gas control)
Lubrication	Oil mixed with fuel or petroil	Separate oil sump (wet/dry)
Torque Uniformity	More uniform	Less uniform (needs flywheel)
Typical Applications	Small engines, chainsaws, marine	Cars, trucks, generators

Valve Timing & Its Impact on Working

PHASE 3

Why Valves Don't Open/Close at Dead Centres

Inlet Valve Opens (IVO)

10–20° BTDC — Ensures valve is fully open when intake stroke begins

Inlet Valve Closes (IVC)

20–40° ABDC — Exploits charge inertia — more mixture enters even after BDC

Exhaust Valve Opens (EVO)

30–50° BBDC — Blow-down begins early; residual pressure assists exhaust

Exhaust Valve Closes (EVC)

10–15° ATDC — Overlap with IVO helps scavenge residual exhaust

Valve Overlap & Its Significance

What is it?
Period when both inlet and exhaust valves are open simultaneously (typically 15–40° of crank angle).

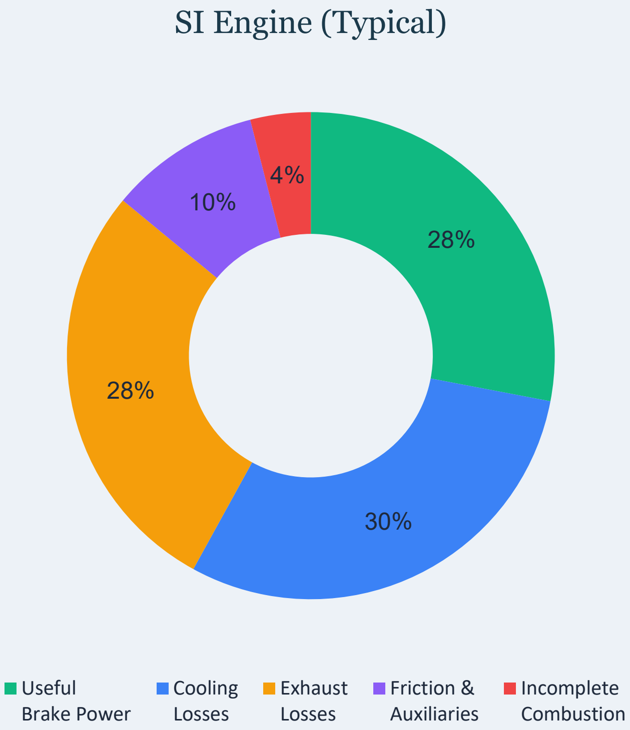
Benefits:

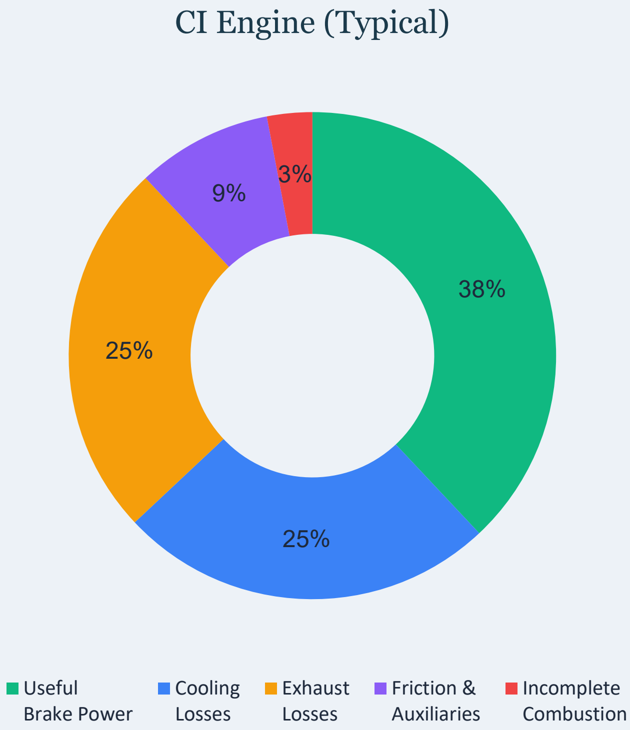
- Better scavenging of residual exhaust gases
- Improved volumetric efficiency at high RPM
- Cooler combustion chamber (reduced thermal stress)

Modern VVT systems:
Vary overlap dynamically for optimal performance across the RPM range (e.g., Honda VTEC, Toyota VVT-i).

Energy Balance of an IC Engine

PHASE 3





Key Performance Parameters

PHASE 3

Indicated Power (IP)

$$IP = Pm \times L \times A \times N \times K$$

Total power developed inside the cylinder by gas pressure

Brake Power (BP)

$$BP = 2\pi NT / 60{,}000$$

Useful power available at the crankshaft output (IP minus friction)

Friction Power (FP)

$$FP = IP - BP$$

Power lost to friction in bearings, piston rings, and accessories

Mechanical Efficiency

$$\eta_{mech} = BP / IP$$

How much indicated power reaches the output (typically 80–90%)

Brake Thermal Efficiency

$$\eta_{th} = BP / (\dot{m}f \times CV)$$

Fraction of fuel energy converted to useful brake power

Specific Fuel Consumption

$$SFC = \dot{m}f / BP \quad (g/kWh)$$

Fuel consumed per unit power — lower is better (230–350 g/kWh typical)

Case Study 1 — Mazda Skyactiv-X (SPCCI Engine)

PHASE 4

Technical Innovation

- Type: 2.0L 4-cylinder, SPCCI (Spark Controlled Compression Ignition)
- Compression Ratio: 16.3:1 (highest ever for a production SI engine)
- Principle: Runs on ultra-lean mixture ($\lambda \approx 2$). Spark creates a small flame ball → pressure rise triggers compression ignition of remaining charge
- Result: Combines Otto-cycle control with Diesel-cycle efficiency
- Fuel economy: ~20–30% better than conventional SI

DT Analysis

Empathize	Drivers want petrol convenience with diesel economy
Define	Achieve CI-level efficiency without a diesel engine's cost/weight
Ideate	HCCI concept + spark assist for combustion control
Prototype	Supercharged engine with in-cylinder pressure sensor
Test	20-30% fuel savings; CO_2 < 100g/km in EU testing

Case Study 2 — Formula 1 Power Unit (2026 Reg)

PHASE 4

1.6L

V6 Turbo Hybrid

>50%

Thermal Efficiency

~1000

bhp Combined

15,000

RPM Limit

How Working Principles Are Pushed to Extremes

- Pre-chamber ignition (jet ignition): small auxiliary chamber creates turbulent flame jets → ultra-lean main combustion
- MGU-H recovers exhaust energy (turbo compound cycle), MGU-K recovers braking energy — extends the thermodynamic cycle
- Extreme CR (~18:1 with knock mitigation), optimised valve timing, and controlled detonation strategies
- Achieved 50%+ brake thermal efficiency — unmatched in any production or racing SI engine in history

Future Trends in Engine Working Principles

PHASE 4

HCCI / RCCI

Homogeneous or Reactivity Controlled CI: entire charge auto-ignites simultaneously for ultra-low NOx and soot.

Opposed-Piston Cycle

Two pistons share one cylinder; no head, no valves. Achates Power: 50%+ BTE target with 2-stroke uniflow scavenging.

Variable Compression

Infiniti VC-Turbo changes CR from 8:1–14:1 in real time using a multi-link mechanism. Optimises cycle per load.

Water Injection

Injecting water into the cylinder lowers charge temperature, suppresses knock, and allows higher effective CR.

E-Fuels & Hydrogen

Carbon-neutral synthetic fuels and H_2 direct injection maintain the IC cycle but eliminate fossil CO_2 emissions.

Digital Twins

Real-time CFD simulation of in-cylinder processes enables cycle-by-cycle combustion optimisation via AI.

Student Design Challenge

PHASE 4

Challenge: A small generator manufacturer needs a 5 kW portable engine. Analyse the working cycle, calculate required displacement, choose 2-stroke vs 4-stroke, and predict performance parameters. Justify every decision using thermodynamic principles.

1

Choose Cycle Type

2T or 4T? SI or CI? Justify based on application needs & efficiency.

2

Calculate Displacement

Use BP, MEP, N, and K to determine required swept volume.

3

Draw the P-V Cycle

Sketch the ideal + actual P-V diagram for your chosen engine.

4

Predict Performance

Calculate η_th, SFC, IP, FP and compare with industry benchmarks.

Reference Data for Design Challenge

PHASE 4

Parameter	Typical Range	Notes
MEP (SI, naturally aspirated)	8–12 bar	Higher with turbo (12–20 bar)
MEP (CI, turbocharged)	10–20 bar	Up to 25 bar in modern CRDI
Speed (portable generator)	3000 or 3600 rpm	Fixed for 50Hz or 60Hz output
Mechanical Efficiency	80–90%	Lower for smaller engines
Brake Thermal Efficiency (SI)	25–35%	Depends on CR and load
Brake Thermal Efficiency (CI)	35–45%	Higher CR advantage
SFC (SI)	280–350 g/kWh	Target < 300 for modern design
SFC (CI)	230–280 g/kWh	Better fuel economy
Volumetric Efficiency	75–90%	Higher with good port design

Sources: Heywood (2018), Pulkrabek (2014), SAE International technical papers.

Assessment Activities

PHASE 5

Stroke Sequence Diagram

Draw and label the 4-stroke sequence with crank angle positions and valve states.

LO1

P-V Diagram Annotation

Given an unlabelled P-V diagram, identify all processes, state heat addition/rejection type.

LO2

Cycle Efficiency Calculation

Compute Otto, Diesel, and Dual cycle efficiencies for given CR and cut-off ratio values.

LO3, LO4

Generator Design Challenge

Complete the 5 kW generator engine design with cycle diagram and performance predictions.

LO5, LO6

Reflection Prompts

- How does understanding the P-V cycle change your view of fuel efficiency claims?
- If you could change one working parameter of a car engine, what would it be and why?

Key Takeaways

PHASE 5

1. IC engines work by converting chemical fuel energy → thermal energy → mechanical work through a repeating thermodynamic cycle.
2. The four-stroke cycle (intake, compression, power, exhaust) requires 720° of crank rotation; only the power stroke produces work.
3. The Otto cycle (constant-V heat addition) models SI engines; the Diesel cycle (constant-P) models CI engines; the Dual cycle is most realistic.
4. Compression ratio is the single most important parameter affecting cycle efficiency — higher CR means higher η.
5. Two-stroke engines fire every revolution but sacrifice efficiency; four-stroke engines are more efficient but heavier per unit power.
6. Valve timing, energy balance, and performance parameters (IP, BP, SFC, η) connect cycle theory to real-world engine behaviour.

References & Resources

PHASE 5

1. Heywood, J.B. (2018). Internal Combustion Engine Fundamentals, 2nd Ed. McGraw-Hill.
2. Pulkrabek, W. (2014). Engineering Fundamentals of the Internal Combustion Engine, 2nd Ed. Pearson.
3. Stone, R. (2012). Introduction to Internal Combustion Engines, 4th Ed. Palgrave Macmillan.
4. Cengel, Y.A. & Boles, M.A. (2019). Thermodynamics: An Engineering Approach, 9th Ed. McGraw-Hill.
5. SAE International — www.sae.org — Technical papers on engine cycles and combustion.
6. NPTEL IC Engines Course — nptel.ac.in — Free video lectures (IIT faculty).

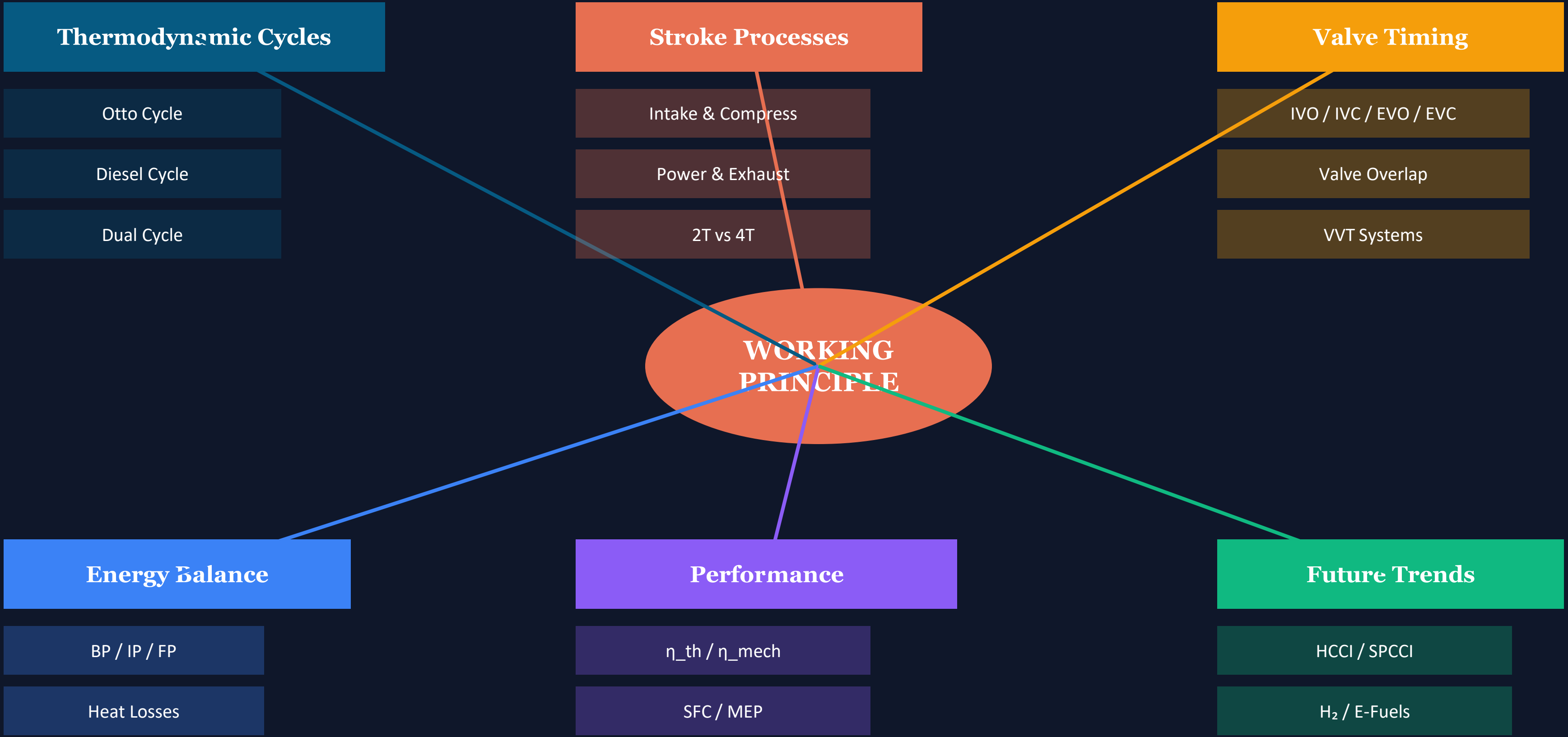
Online Resources

- Animagraffs — Animated engine cycle visualizations: animagraffs.com
- Engineering Explained (YouTube) — Engine working principle deep dives
- MIT OpenCourseWare — Thermodynamics of Power Cycles (2.006)

Appendix — Diagram Descriptions & Data Sources

Slide	Visual Element	Description / Source
4	Bar Chart	Pre-assessment survey (representative, N=150)
10–12	Cycle Process Tables	Based on Heywood Ch.5 and Cengel Ch.9
13	Cycle Comparison Table	Compiled from Pulkrabek Ch.3, Stone Ch.4
14	Efficiency Chart	Calculated from $\eta = 1 - 1/r^{(\gamma-1)}$, $\gamma=1.4$
19	Energy Balance Doughnuts	Typical values from Heywood Table 12.1
21	Skyactiv-X Data	Mazda technical press release (2019)
22	F1 Power Unit	FIA 2026 technical regulations; published estimates

Comprehensive Mind Map — Working Principle of IC Engines



Thermodynamic Cycles
- Otto Cycle
- Diesel Cycle
- Dual Cycle

Stroke Processes
- Intake & Compress
- Power & Exhaust
- 2T vs 4T

Valve Timing
- IVO / IVC / EVO / EVC
- Valve Overlap
- VVT Systems

WORKING PRINCIPLE

Energy Balance
- BP / IP / FP
- Heat Losses

Performance
- η_{th} / η_{mech}
- SFC / MEP

Future Trends
- HCCI / SPCCI
- H_2 / E-Fuels

EMPATHIZE | DEFINE | IDEATE | PROTOTYPE | TEST

Thank You

"Design Thinking is a human-centered approach to innovation that integrates the needs of people, the possibilities of technology, and the requirements for success." — Tim Brown, IDEO

Working Principle of IC Engines | Mechanical Engineering

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