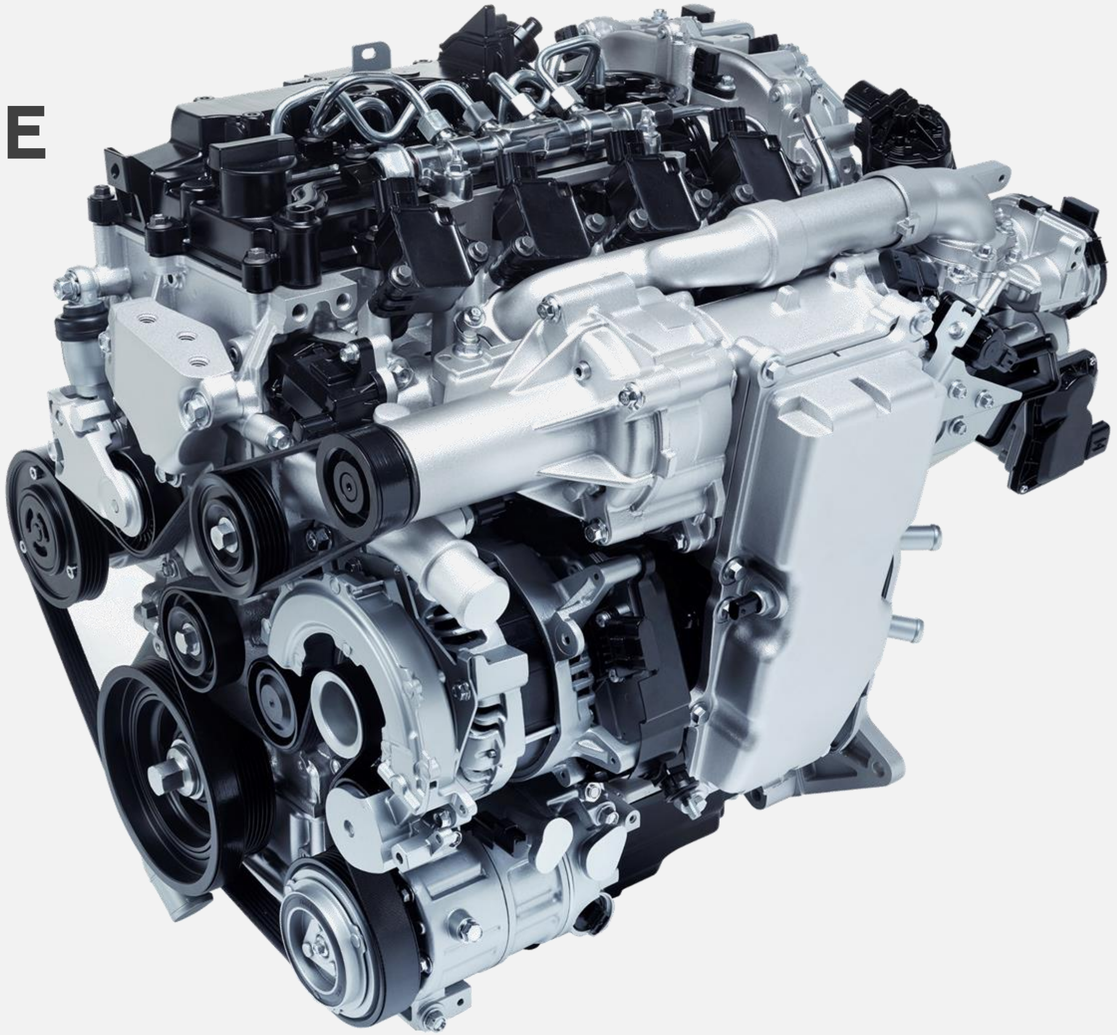
SKYACTIV-X
AN INNOVATIVE GASOLINE ENGINE WITH COMPRESSION IGNITION



Christian Schultze

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EUROPEAN R&D CENTRE
MAZDA MOTOR EUROPE

0. INTRODUCTION

1. SKYACTIV ROADMAP

2. CHALLENGES AND SOLUTIONS

3. SKYACTIV-X

4. CUSTOMER BENEFITS

SUSTAINABLE ZOOM-ZOOM 2030

AT MAZDA, WE SEE IT AS OUR MISSION TO BRING ABOUT A BEAUTIFUL EARTH AND TO ENRICH PEOPLE'S LIVES AS WELL AS SOCIETY. WE WILL CONTINUE TO SEEK WAYS TO INSPIRE PEOPLE THROUGH THE VALUE FOUND IN CARS

PEOPLE

ENHANCE CUSTOMERS' MENTAL WELL-BEING WITH THE SATISFACTION THAT COMES FROM PROTECTING THE EARTH AND CONTRIBUTING TO SOCIETY WITH A CAR THAT OFFERS TRUE DRIVING PLEASURE

EARTH

THROUGH CONSERVATION INITIATIVES, CREATE A SUSTAINABLE FUTURE IN WHICH PEOPLE AND CARS COEXIST WITH A BOUNTIFUL, BEAUTIFUL EARTH

SOCIETY

REALIZE CARS AND A SOCIETY THAT OFFER SAFETY AND PEACE OF MIND, AND CREATE A SYSTEM THAT ENRICHES LIVES BY OFFERING UNRESTRICTED MOBILITY TO PEOPLE EVERYWHERE

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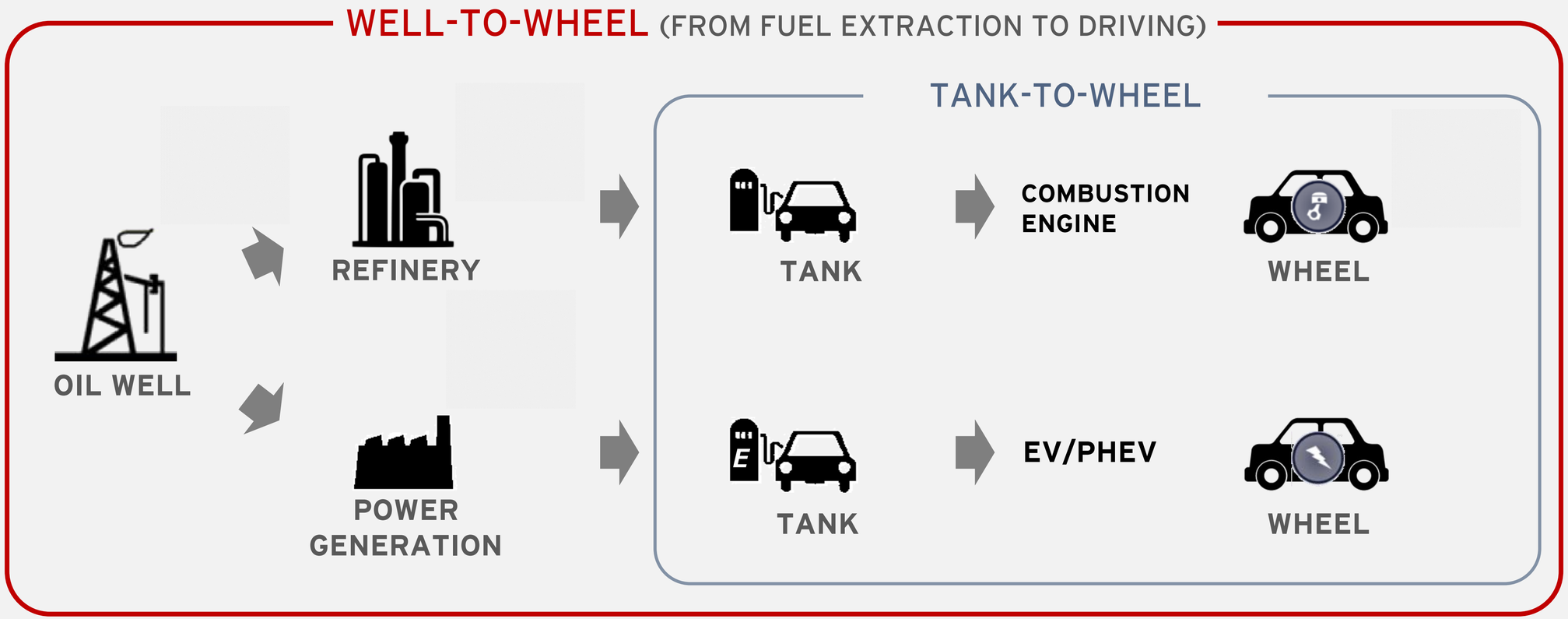
MAZDA'S APPROACH TO ISSUES FACING THE EARTH

APPROACH CO_2 REDUCTION FROM A WELL-TO-WHEEL PERSPECTIVE TO REDUCE CO_2 EMISSIONS THROUGHOUT THE VEHICLE'S LIFE CYCLE

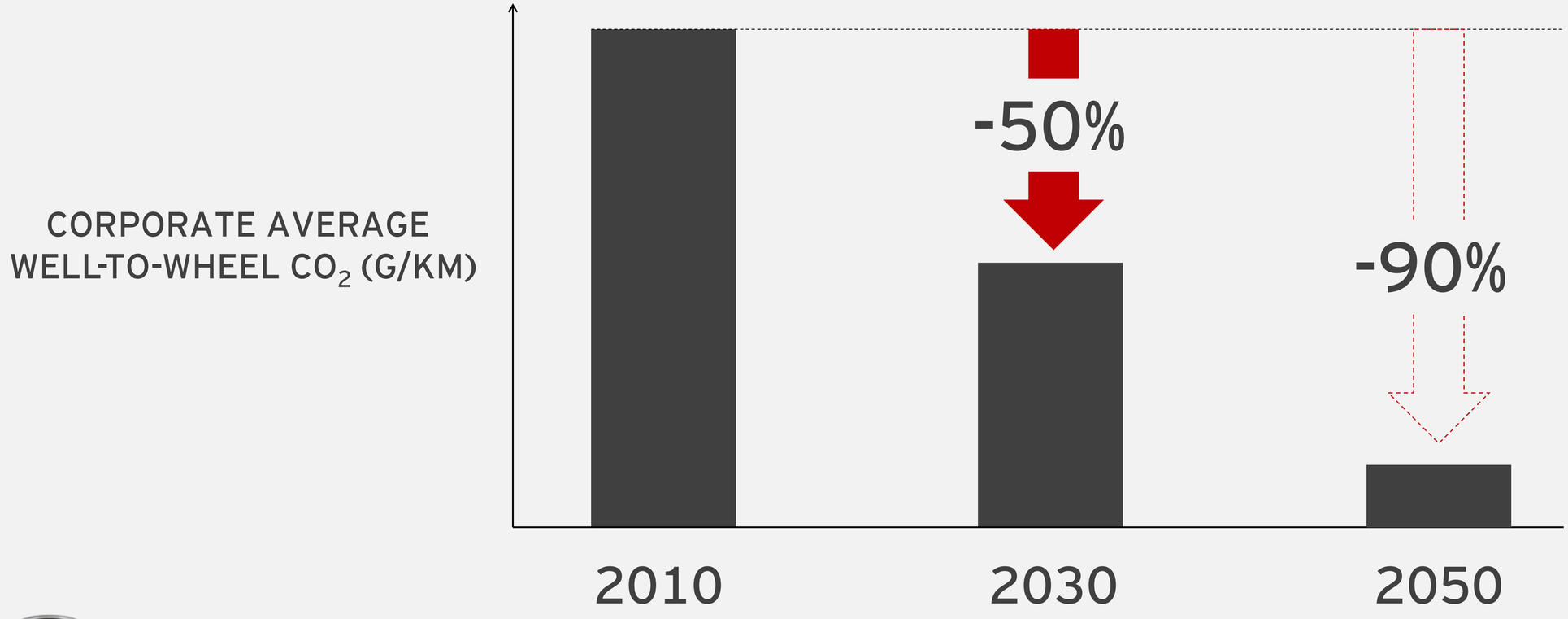


MATERIAL MANUFACTURE, ASSEMBLY, DISPOSAL

LIFE CYCLE ASSESSMENT

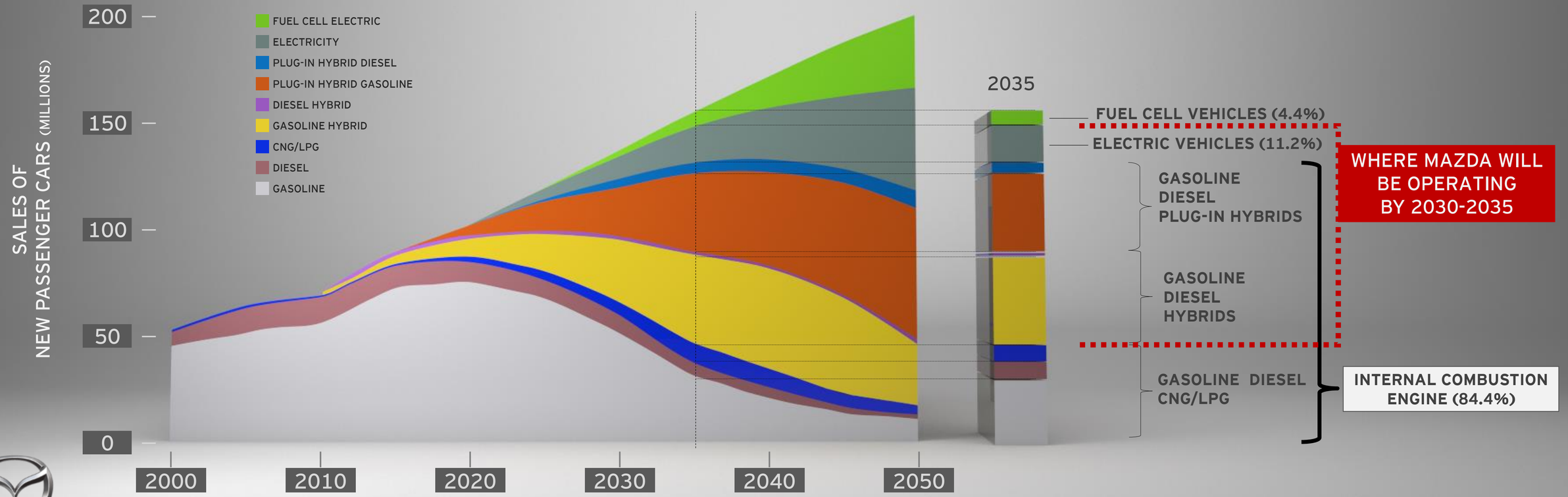
TARGETS FOR CO_2 REDUCTION

AIM TO REDUCE CORPORATE AVERAGE WELL-TO-WHEEL CO_2 EMISSIONS TO 50% OF 2010 LEVELS BY 2030



IMPORTANCE OF REDUCING CO_2 FROM COMBUSTION ENGINES

THE COMBUSTION ENGINE WILL HELP POWER THE MAJORITY OF VEHICLES GLOBALLY FOR MANY YEARS TO COME AND CAN MAKE THE BIGGEST CONTRIBUTION TO CO_2 REDUCTION



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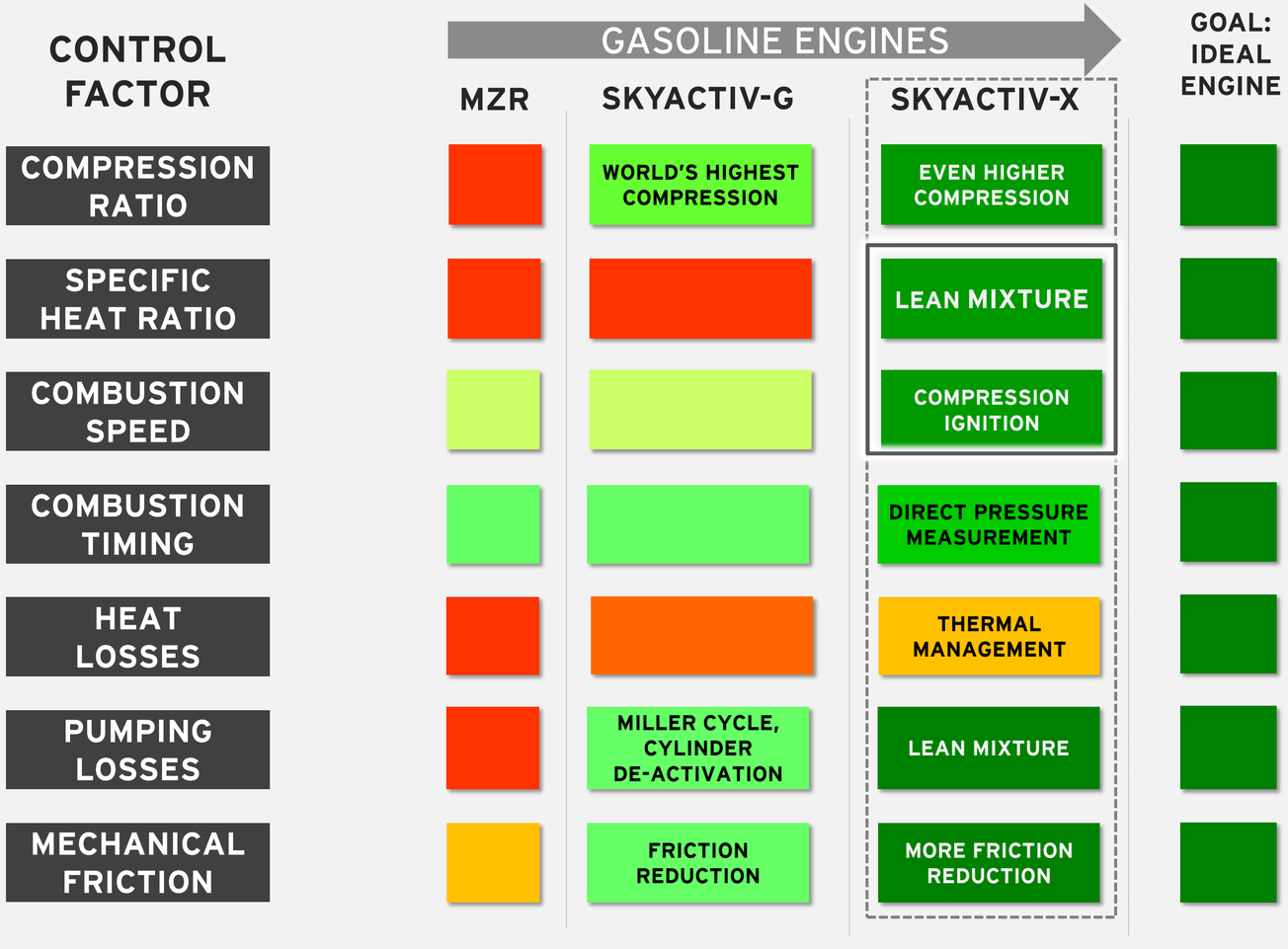
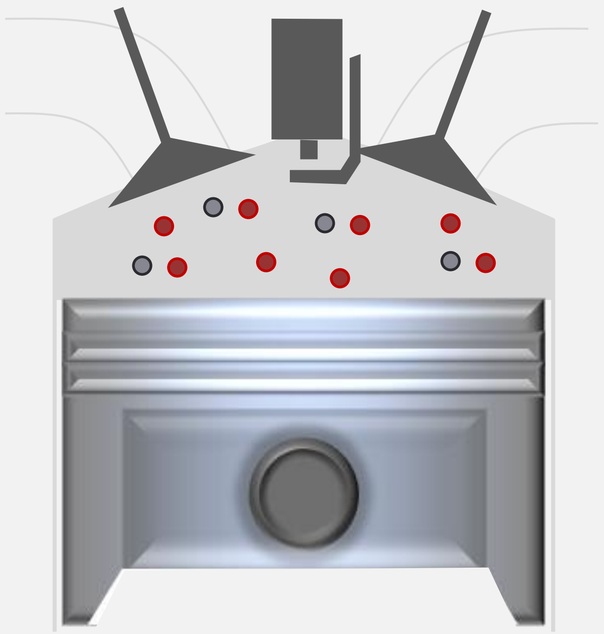
ROAD MAP TO IDEAL COMBUSTION



GOAL: EXTREMELY LEAN COMBUSTION

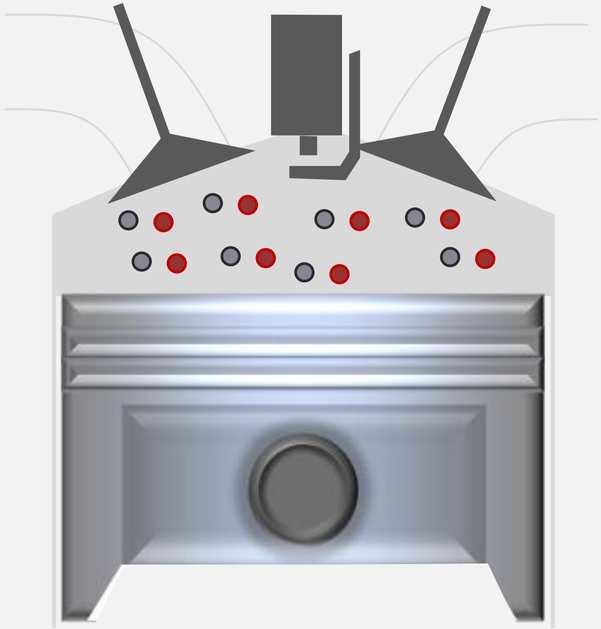
RICH MIXTURE



TOO MUCH FUEL,
NOT ENOUGH AIR

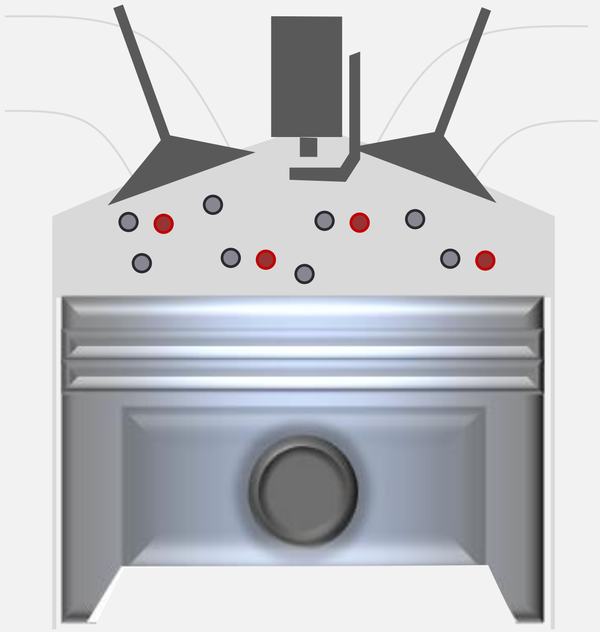
UNBURNT FUEL WASTED

STOICHIOMETRIC MIXTURE



FUEL AND AIR
APPROPRIATELY MIXED

LEAN MIXTURE



MORE AIR THAN FUEL

SIDE VIEW OF CYLINDER

AIR

FUEL

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GOAL: LEAN COMBUSTION

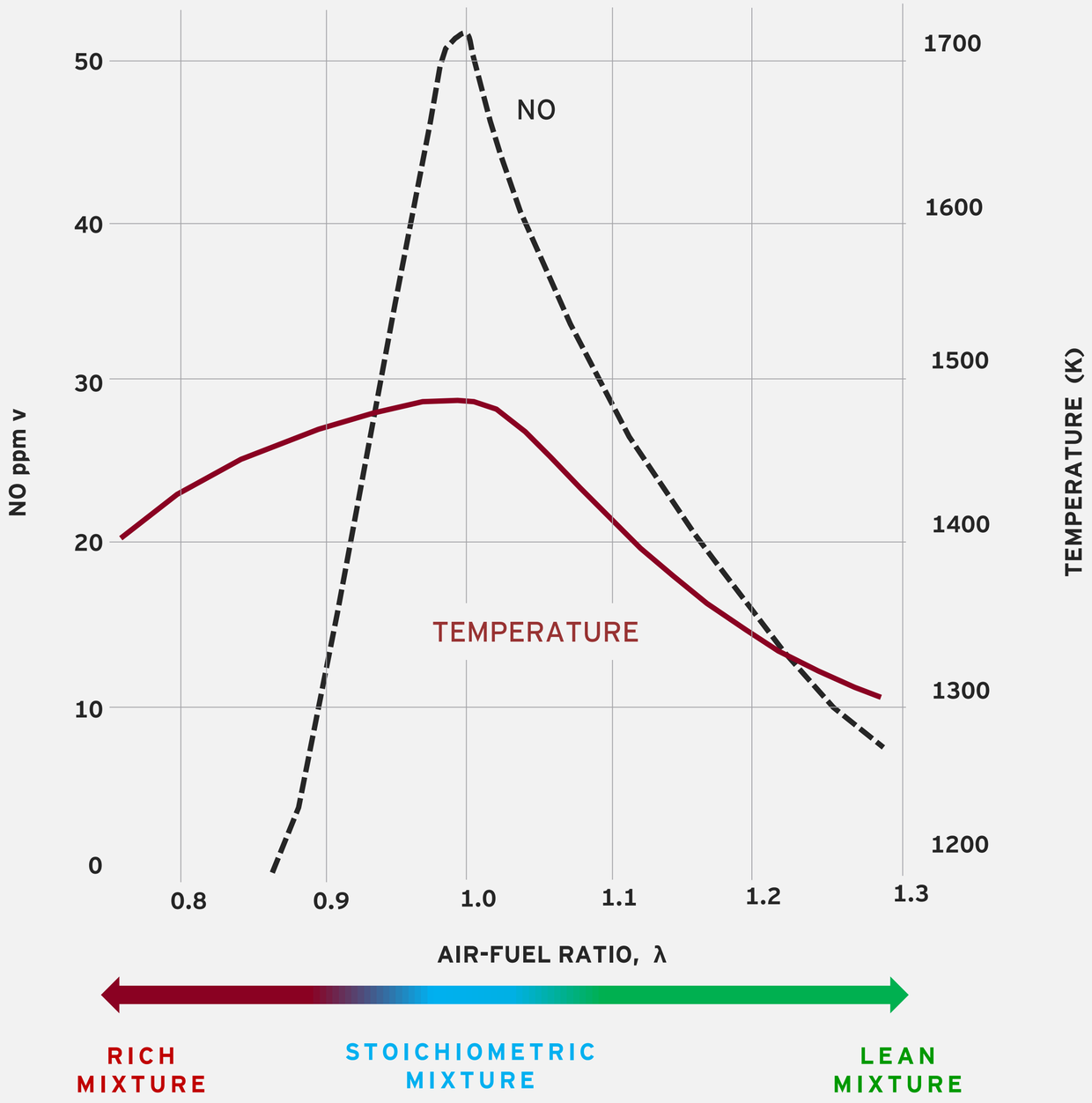
WHY IS EXTREMELY LEAN GOOD?

EXTREMELY LEAN COMBUSTION IS COOLER

- COOLER COMBUSTION MAKES LESS NO_X
- COOLER COMBUSTION WASTES LESS ENERGY HEATING UP THE ENGINE

THE "UNUSED" AIR GETS PUT TO WORK

- SURPLUS AIR ABSORBS COMBUSTION HEAT AND TURNS IT INTO PRESSURE, PUSHING DOWN ON THE PISTON

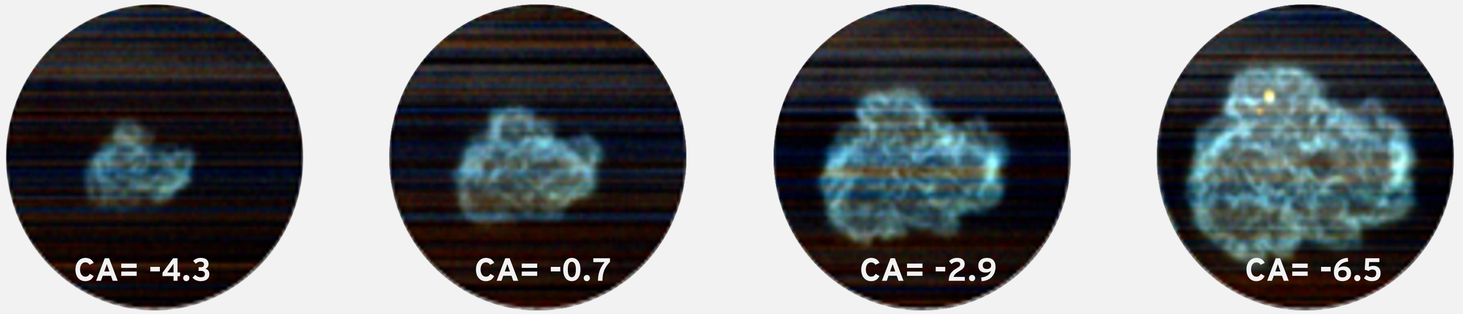


CHALLENGE: LEAN COMBUSTION IS UNRELIABLE

BUT LEAN COMBUSTION IS NOT STABLE

- NORMAL FLAME PROPAGATION

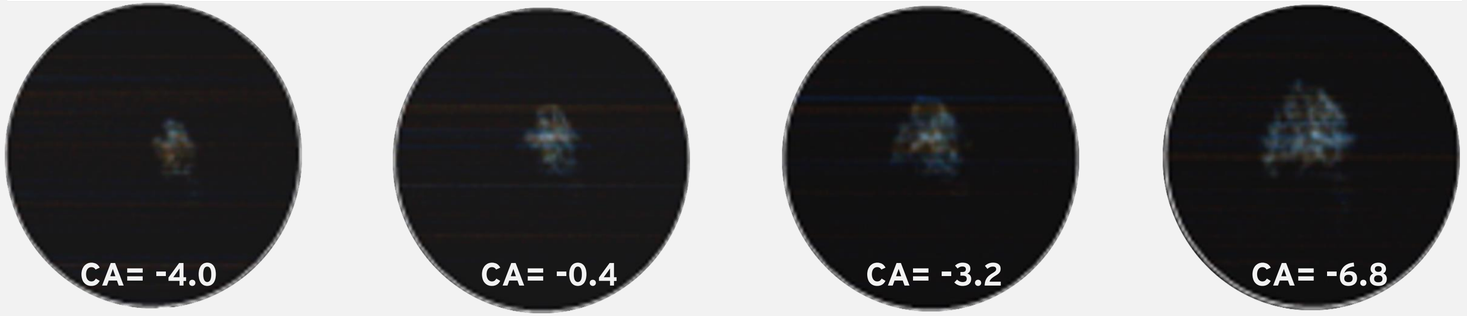
STOICHIOMETRIC MIXTURE (LAMBDA = 1)



(ACTUAL COMBUSTION AT 750 RPM)

- THE FUEL MOLECULES ARE SPACED SO FAR APART THAT A CHAIN REACTION ISN'T GUARANTEED

SUPER LEAN MIXTURE (LAMBDA = 2)



FLAME CANNOT PROPAGATE

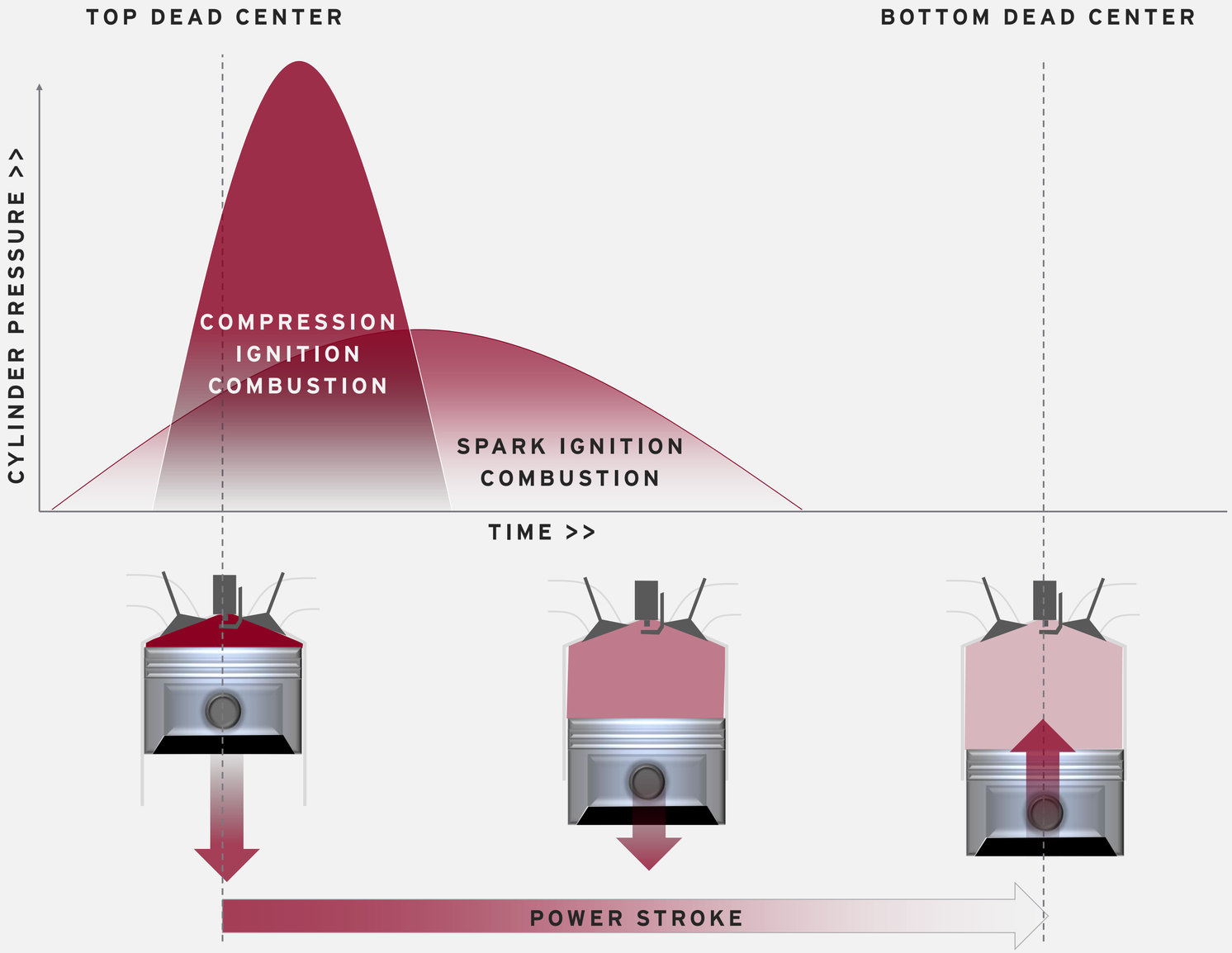
CA = CRANK ANGLE

BENEFIT: FASTER COMBUSTION IS MORE EFFICIENT

COMPRESSION IGNITION COMBUSTION IS FASTER

- IDEAL COMBUSTION ENGINE BURNS ALL THE FUEL INSTANTLY
- REAL COMBUSTION TAKES TIME
- COMBUSTION ENERGY CAN ONLY BE PARTLY USED

FASTER COMBUSTION GETS MORE WORK OUT OF THE SAME ENERGY



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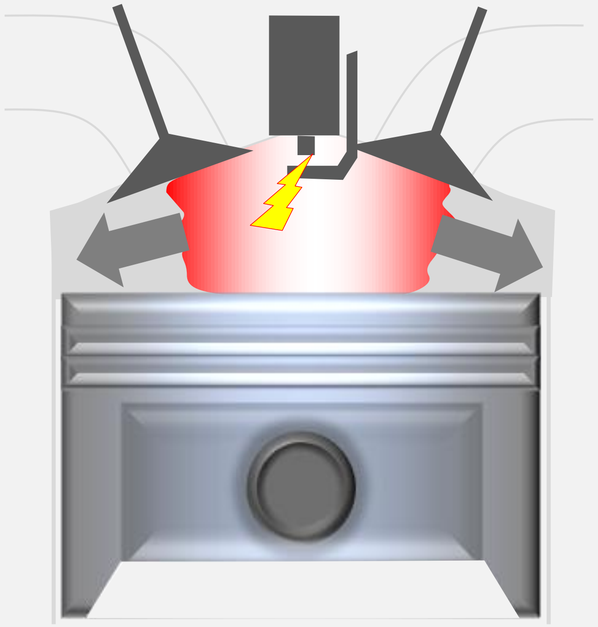
CHALLENGE

CONTROLLING **WHEN** COMPRESSION IGNITION HAPPENS

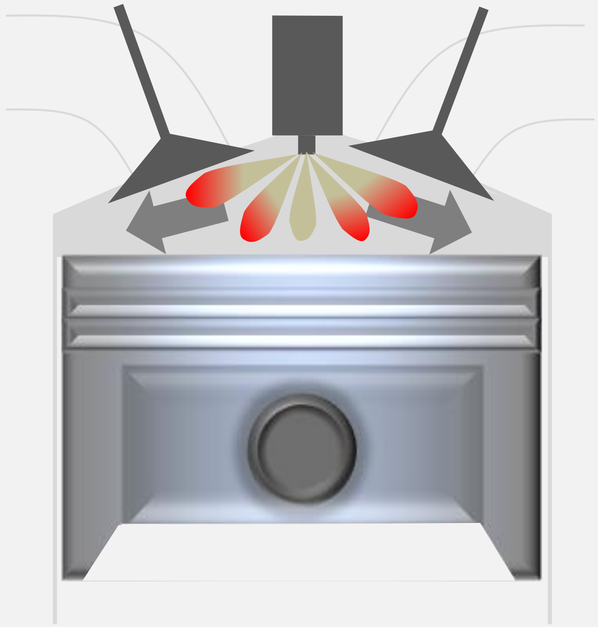
CHALLENGE: HCCI COMBUSTION TIMING IS UNCONTROLLED

SPARK IGNITION (GASOLINE)



COMBUSTION STARTS WITH A SPARK

COMPRESSION IGNITION (DIESEL)



COMBUSTIONS STARTS WHEN FUEL IS INJECTED

HCCI (GASOLINE)

COMBUSTION STARTS WHENEVER HEAT AND PRESSURE ARE HIGH ENOUGH

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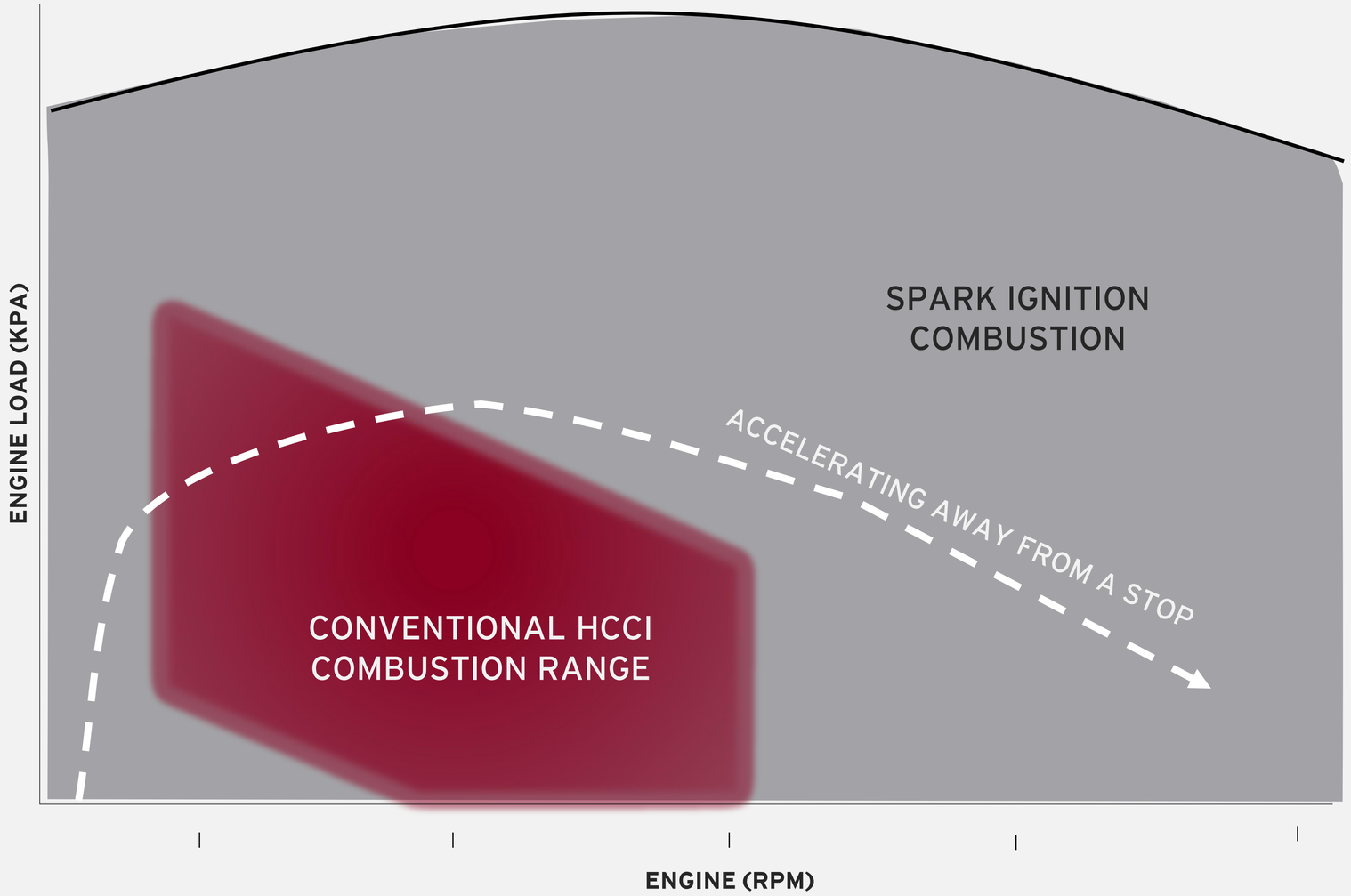
CHALLENGE: HCCI COMBUSTION TIMING IS UNCONTROLLED

SPARK IGNITION IS STILL NEEDED

- CONVENTIONAL HCCI COMBUSTION IS LIMITED IN IT'S RANGE OF APPLICATION
- A PRACTICAL ENGINE NEEDS TO OPERATE IN DUAL MODES - HCCI AND SI
- A SPARK PLUG IS REQUIRED
- NEEDS TO SWITCH SMOOTHLY BETWEEN OPERATING MODES



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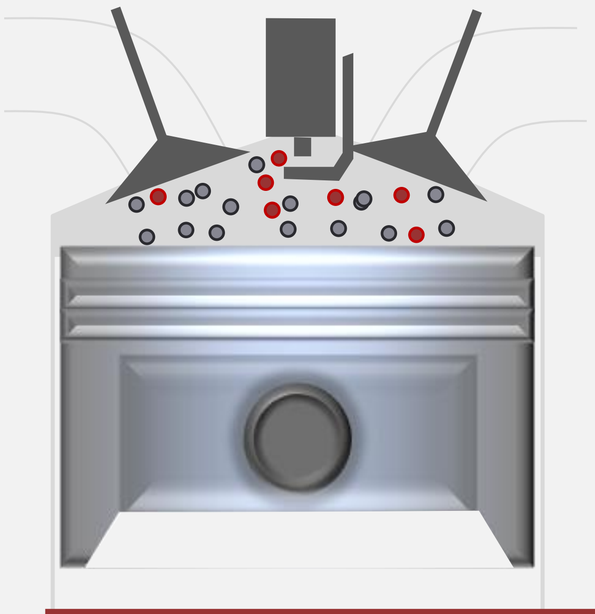
BREAKTHROUGH SOLUTION

SPARK CONTROLLED COMPRESSION IGNITION (SPCCI)

THE BREAKTHROUGH: CONTROL COMPRESSION IGNITION WITH A SPARK!

VERY LEAN MIXTURE
VERY HIGH COMPRESSION



DESIGN THE ENGINE TO RUN JUST BELOW THE THRESHOLD OF COMPRESSION IGNITION

START COMBUSTION
WITH A SPARK

EXPANDING FIREBALL ADDS MORE HEAT AND PRESSURE

SPARK CONTROLLED COMPRESSION
IGNITION (SPCCI)

COMPRESSION IGNITION IS TRIGGERED IN THE REST OF THE CYLINDER

TIME

PUSHING CONDITIONS
OVER THE THRESHOLD

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THE BREAKTHROUGH: SPCCI - COMPRESSION IGNITION WHEN YOU WANT IT

HOW SPCCI WORKS

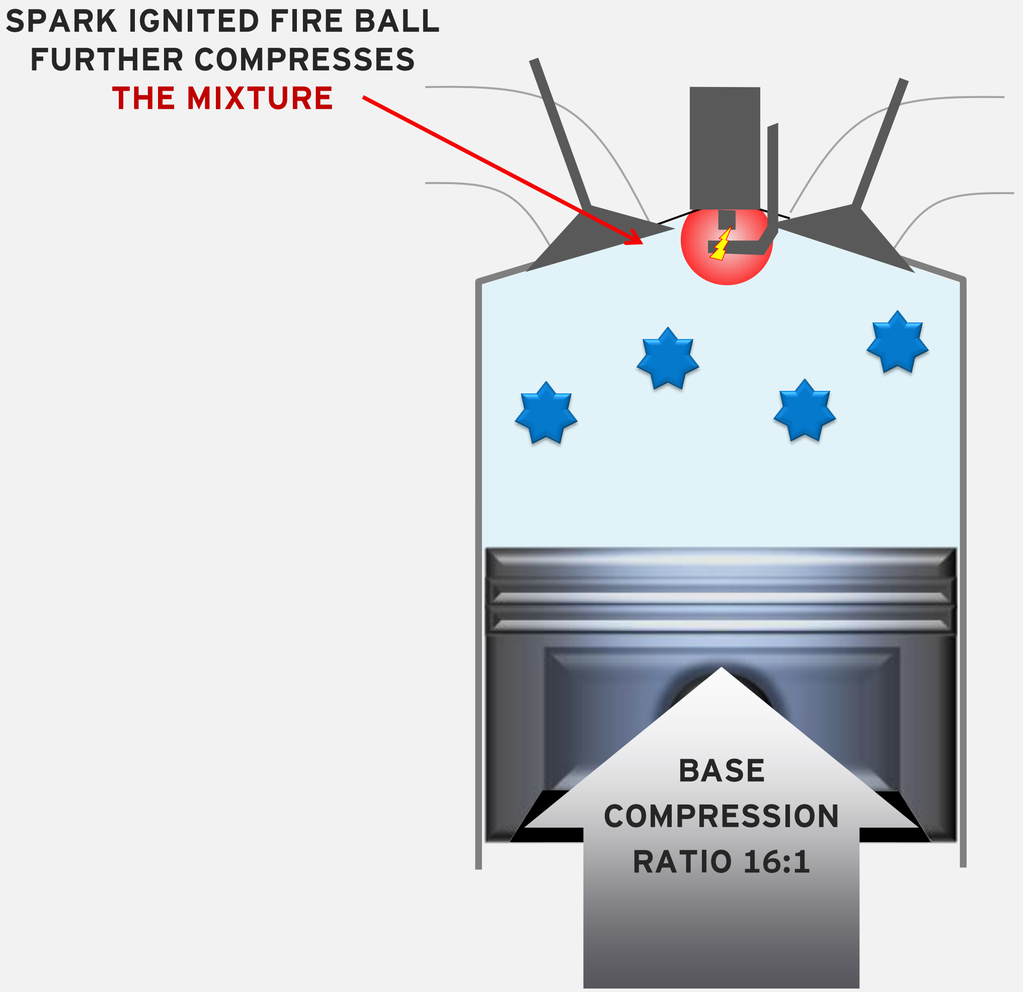
1. AIR AND FUEL ARE COMPRESSED TO NEAR COMPRESSION IGNITION CONDITIONS

2. THE SPARK PLUG INITIATES A SMALL FIREBALL

3. THE FIREBALL EXPANDS TO INCREASE TEMPERATURE AND PRESSURE UNTIL COMPRESSION IGNITION CONDITIONS ARE MET

4. THE MAJORITY OF AIR AND FUEL IN THE CYLINDER IS COMBUSTED THROUGH COMPRESSION IGNITION

5. THE TIMING OF THE SPARK IGNITION CONTROLS WHEN COMPRESSION IGNITION WILL HAPPEN



CHALLENGE

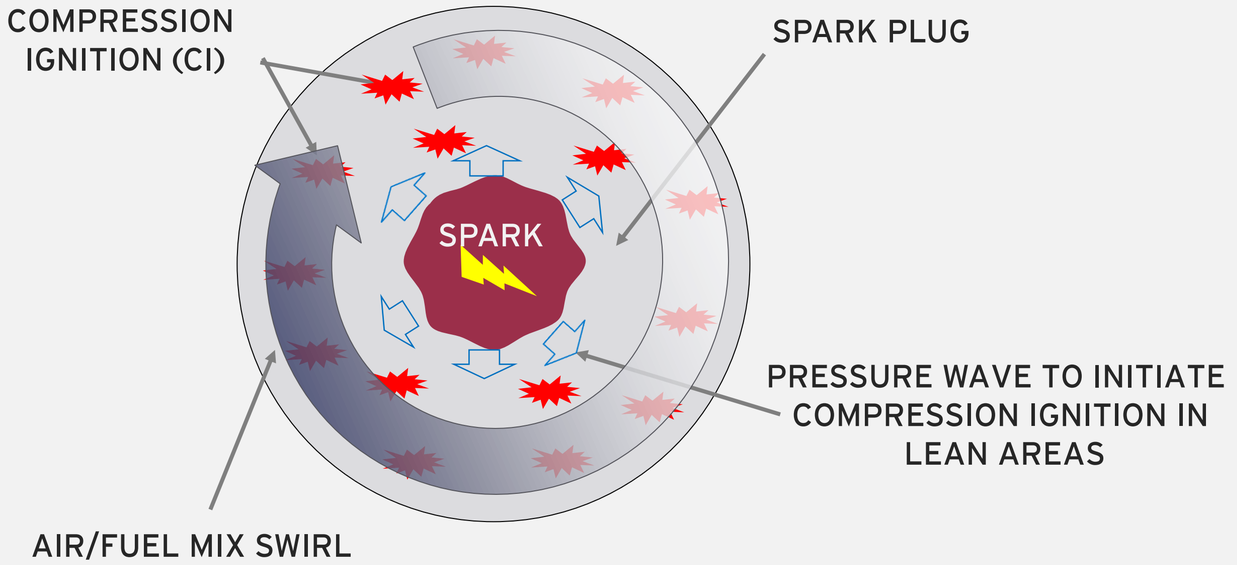
LIGHTING THE FIREBALL NEEDED FOR SPCCI

SOLUTION: VARYING LOCAL FUEL DENSITY

CONTROL FUEL DISTRIBUTION THROUGH CYLINDER SWIRL AND FUEL INJECTION TIMING

- SPCCI NEEDS DISTINCTLY DIFFERENT AIR FUEL RATIOS
- A SLIGHTLY LESS LEAN REGION NEAR THE SPARK PLUG
  ➔ **ALLOWS THE FIREBALL TO IGNITE**
- THE MAJORITY OF THE MIXTURE INSIDE THE CYLINDER REMAINS VERY LEAN
  ➔ **IT COMBUSTS WITH CI**
- SWIRLING THE AIR INSIDE THE CYLINDER AND GENERATING A VORTEX EFFECT
  ➔ **KEEP IT VERY LEAN**

TOP DOWN VIEW OF CYLINDER



CHALLENGE

PREVENTING UNCONTROLLED AUTO-IGNITION

CHALLENGE: COMPRESSION IGNITION ONLY WHEN WE WANT IT

A HIGHER COMPRESSION RATIO INCREASES THE POTENTIAL FOR KNOCK

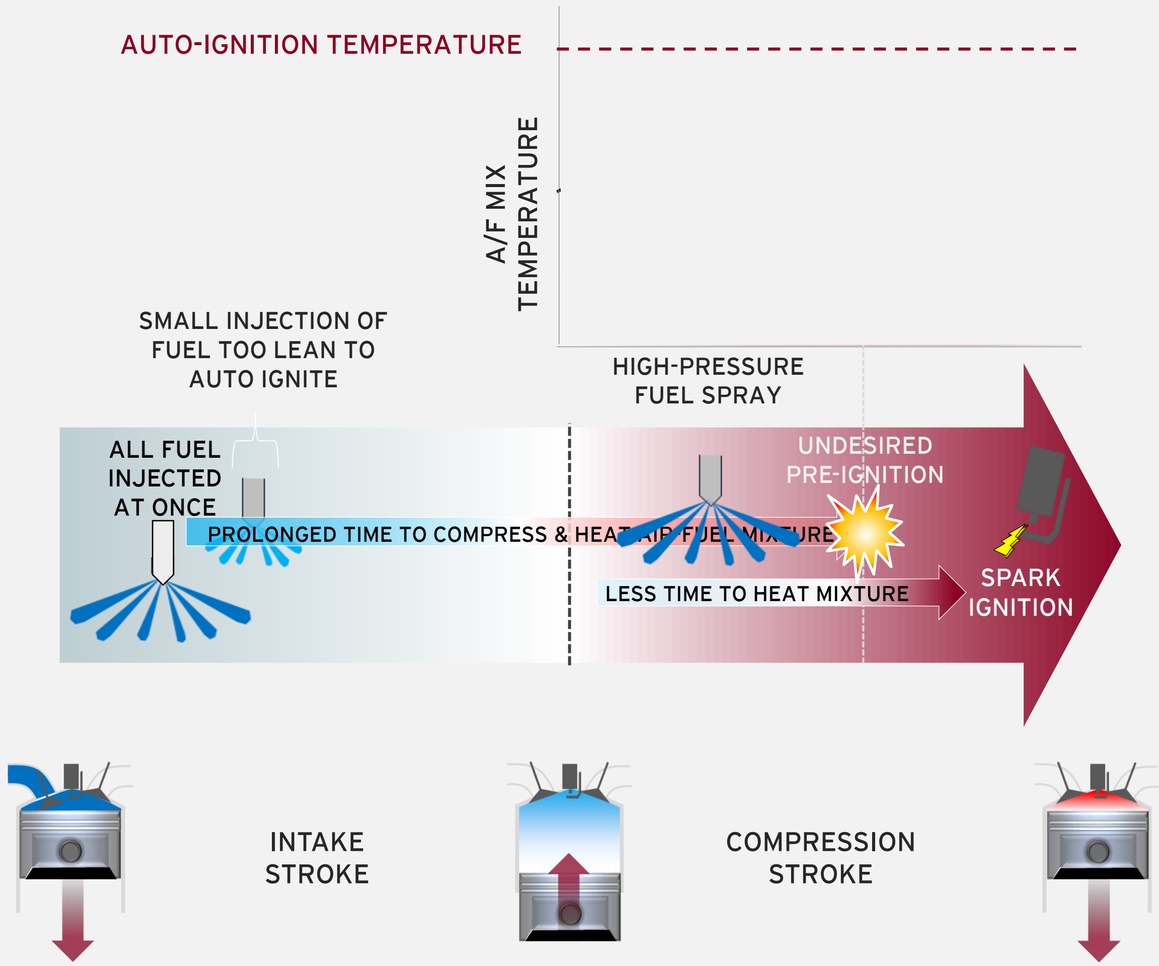
- KNOCK IS THE SPONTANEOUS COMBUSTION OF AIR AND FUEL UNDER HIGH TEMPERATURES AND PRESSURES
- COMPRESSION IGNITION IS KNOCK!
- VERY HIGH COMPRESSION CAN ALSO INCREASES UNWANTED AUTO IGNITION WHICH CAN SEVERELY DAMAGE AN ENGINE
- DURING THE COMPRESSION STROKE WE NEED TO PREVENT COMPRESSION IGNITION BUT RETAIN A HIGH COMPRESSION RATIO

SOLUTION: SPLIT FUEL INJECTION STRATEGY

REDUCE TIME TO HEAT UP THE FUEL MIX

- CI CAN OCCUR PREMATURELY WHEN THE MIXTURE IS HEATED ABOVE ITS AUTO-IGNITION TEMPERATURE
- IF ALL FUEL IS INJECTED EARLY DURING THE INTAKE STROKE IT WILL HEAT UP DURING THE COMPRESSION STROKE
- IF ONLY A PORTION OF FUEL IS INITIALLY INJECTED
  ➔ **THE MIXTURE IS KEPT TOO LEAN TO AUTO-IGNITE**
- IF REMAINING FUEL IS INJECTED LATER IN THE COMPRESSION STROKE
  ➔ **LESS HEAT UP TIME**

INCREASE ATOMIZATION AND MIXING BY UPGRADED FUEL SYSTEM



CHALLENGE

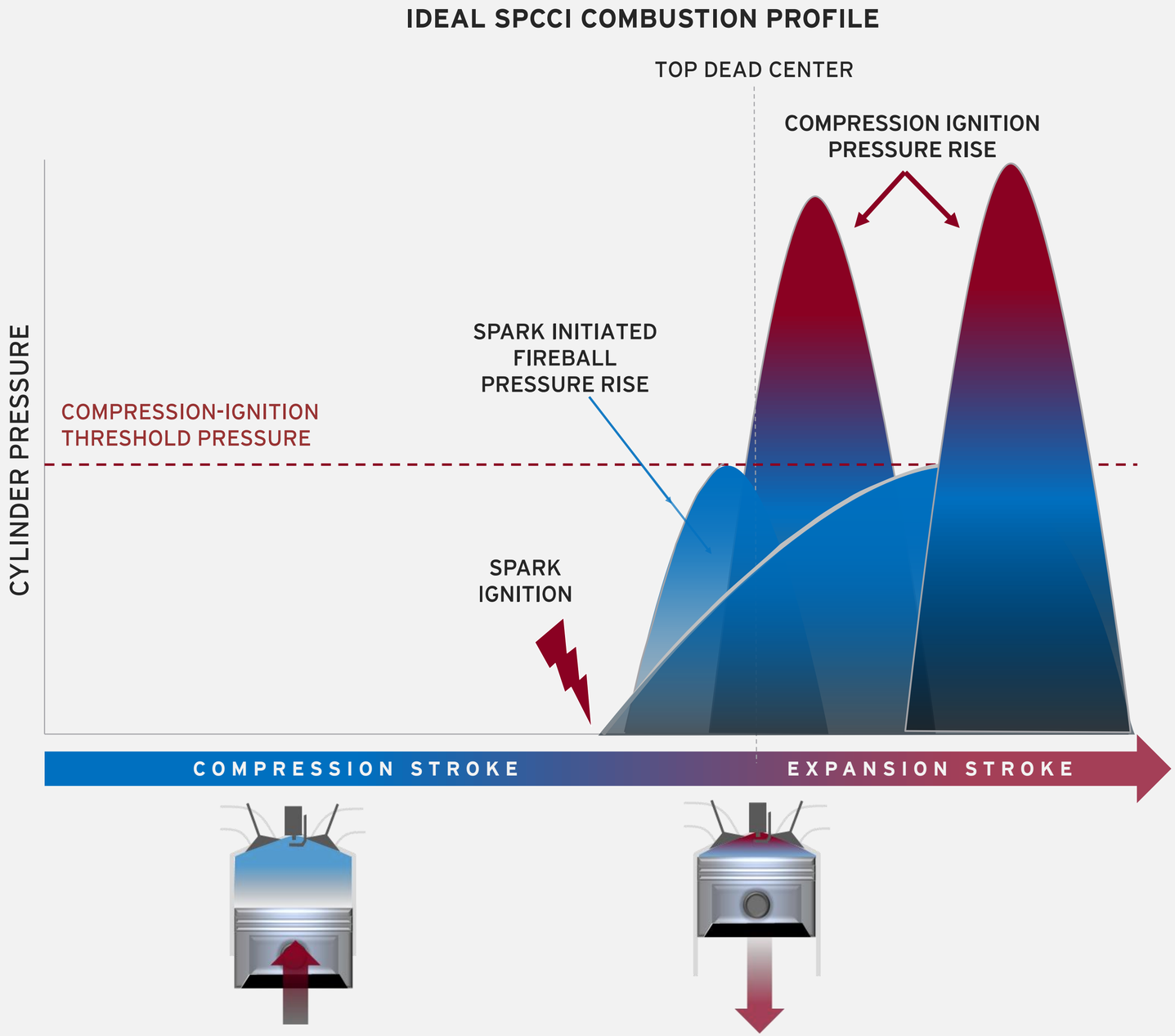
KEEPING TRACK TO MAINTAIN RELIABILITY

CHALLENGE: CONSTANT CONTROL OF SPCCI

MAINTAINING THE IDEAL TIMING AND PRESSURE RISE

- LEAN COMPRESSION IGNITION SHOULD HAPPEN SHORTLY AFTER TOP DEAD CENTER
- COMPRESSION IGNITION MUST BE INITIATED BY A PRESSURE RISE FROM THE SPARK-INITIATED FIREBALL
- FIREBALL GENERATED PRESSURE ALSO CHANGES WITH VARIOUS AMBIENT CONDITIONS

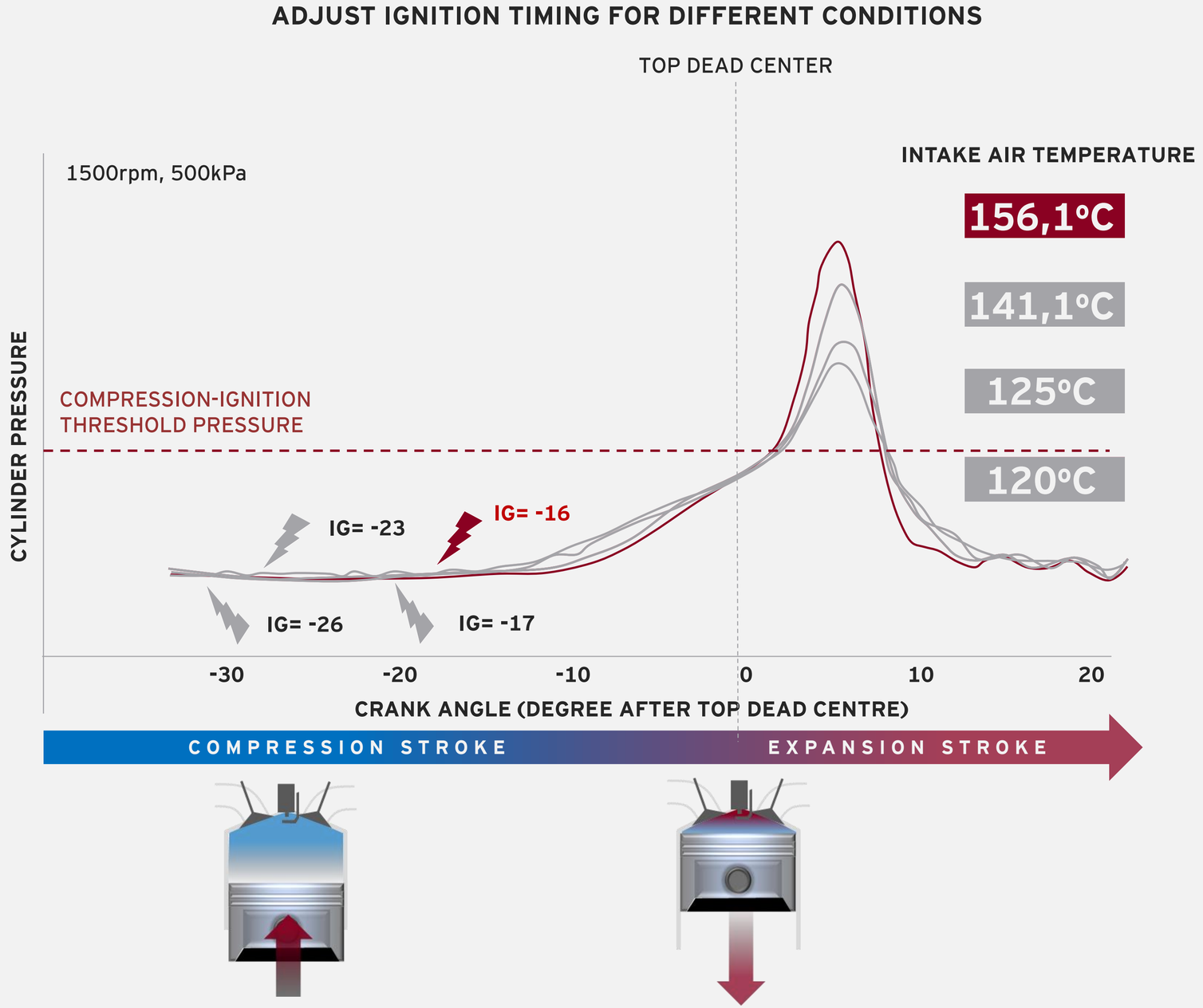
TO KEEP SAME CI TIMING THE SPARK OFF TIMING NEEDS TO BE MODIFIED



SOLUTION: ADAPTIVE SPARK TIMING CONTROL

INDIVIDUAL CYLINDER PRESSURE MONITORING AND FEEDBACK CONTROL OF SPARK TIMING

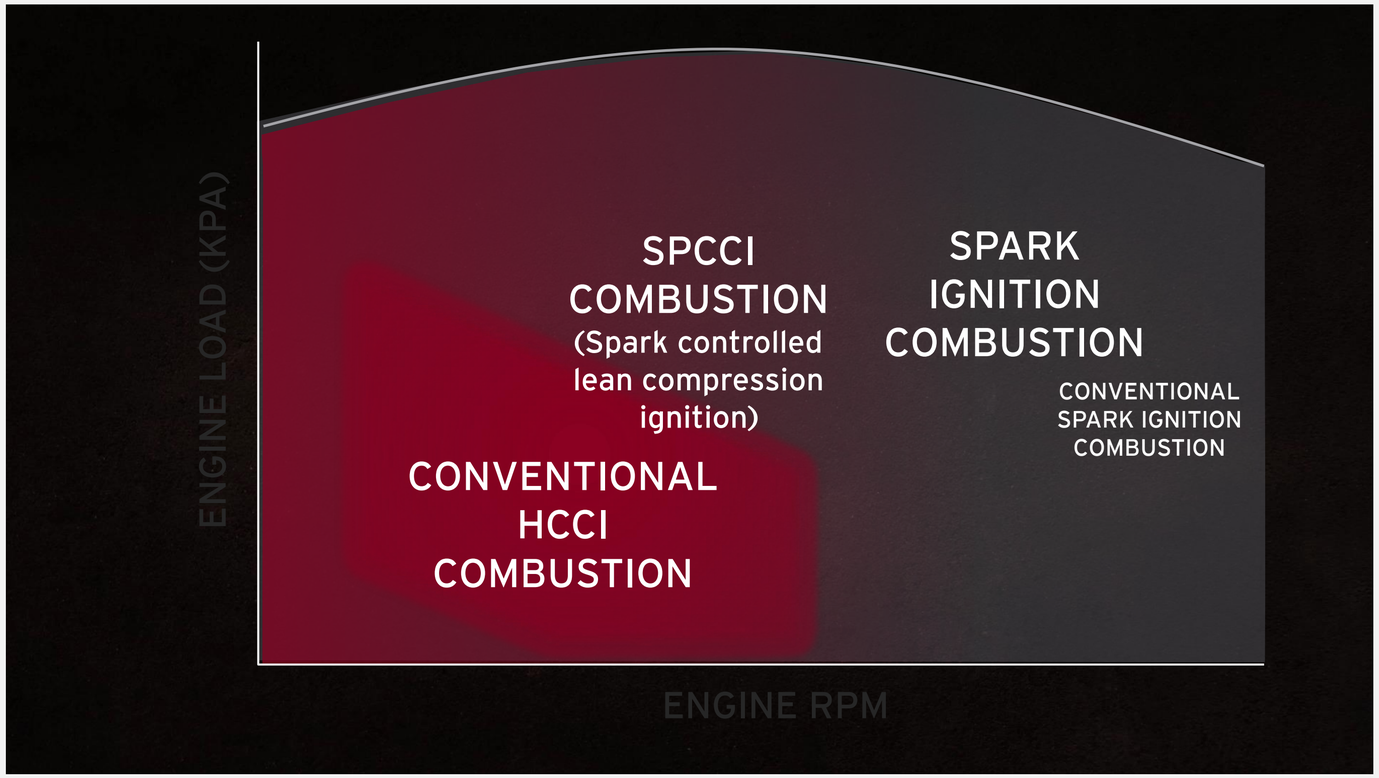
- BY CHANGING THE TIMING OF THE SPARK INITIATED FIREBALL, SPCCI MAINTAINS THE IDEAL CI TIMING
- IN-CYLINDER PRESSURE SENSORS MONITOR EACH COMBUSTION EVENT TO ENSURE CORRECT CI TIMING
- ENABLED BY MODERN FASTER COMPUTER PROCESSING SPEEDS



BREAKTHROUGH: SPARK CONTROLLED COMPRESSION IGNITION

CONTROLLED CI COMBUSTION OVER A WIDE RANGE

- A SPARK PLUG IS USED TO INDUCE AND CONTROL COMPRESSION IGNITION COMBUSTION UNDER A WIDE RANGE OF REAL WORLD DRIVING CONDITIONS
- ALWAYS USES THE SPARK PLUG DURING BOTH CI AND SI COMBUSTION
- SPCCI CAN SEAMLESSLY SWITCH BETWEEN EACH COMBUSTION MODE
- EXPAND THE RANGE OF TRADITIONAL HCCI THROUGHOUT MOST ENGINE LOAD AND SPEED CONDITIONS



SPCCI IS MAZDA'S UNIQUE PROCESS FOR CONTROLLING ITS NEXT GENERATION SKYACTIV-X GASOLINE ENGINE

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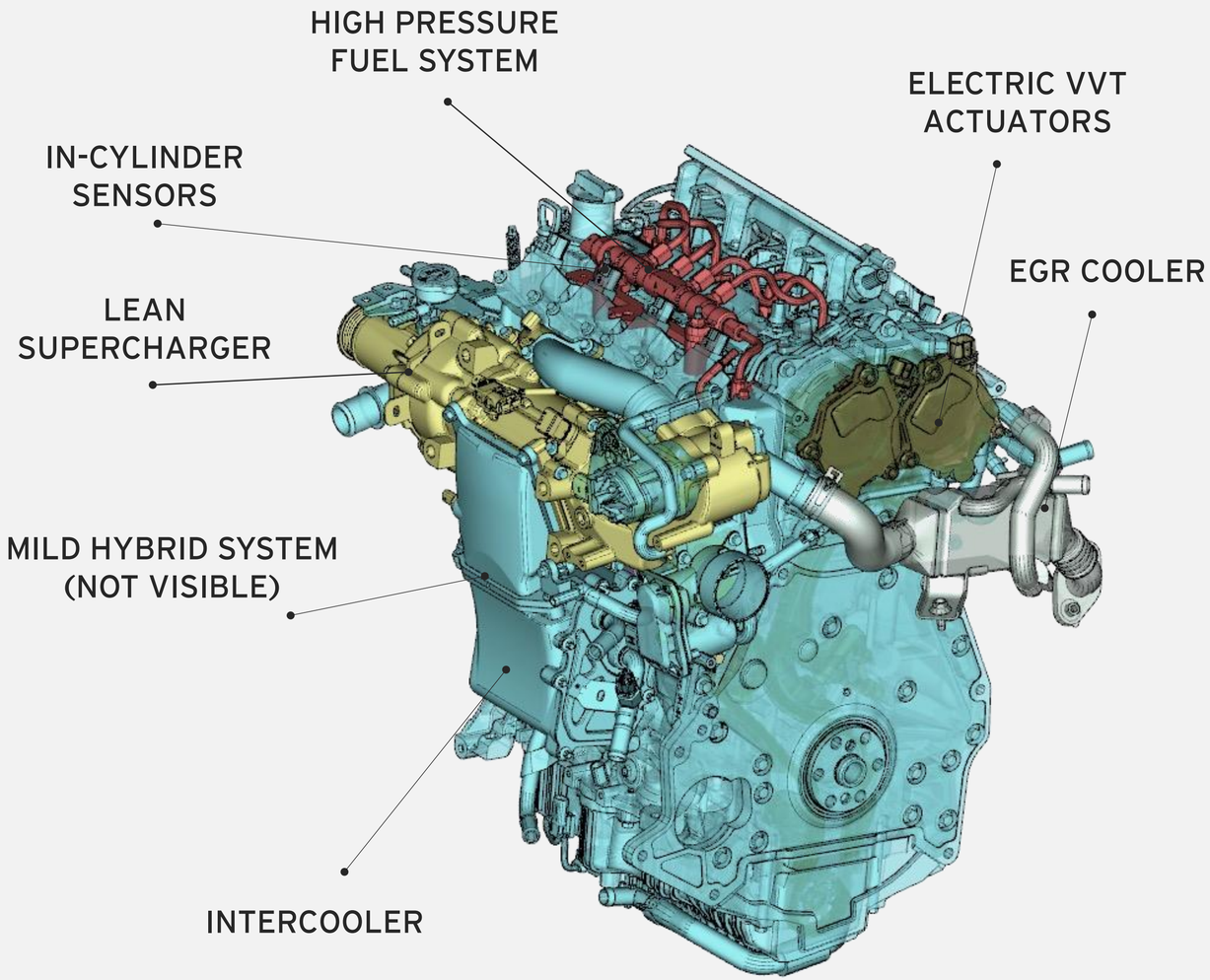
THE SKYACTIV-X ENGINE

RE-INVENTING THE INTERNAL COMBUSTION ENGINE WITHOUT RE-INVENTING THE HARDWARE

- 4-CYLINDER DOHC
- 2.0-LITER (1997CC)
- ALUMINUM CONSTRUCTION
- COMPRESSION RATIO: 16.0:1 (PROTOTYPE STATE)
- 95 OCTANE GASOLINE
- MILD HYBRID ELECTRIFICATION



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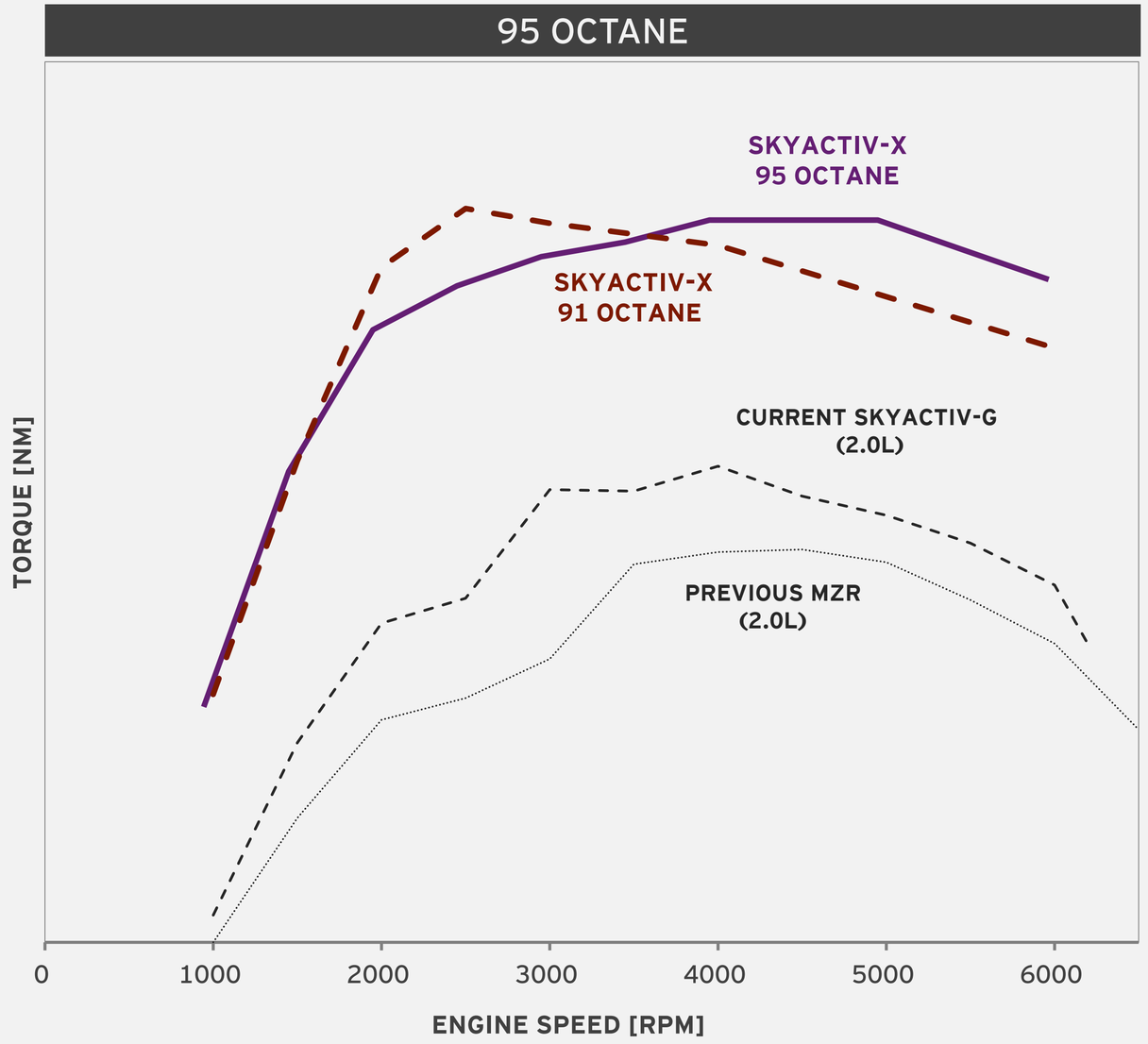
INCREASED OUTPUT

MORE TORQUE WHEN YOU WANT IT

- THE FASTER ENERGY RELEASE OF CI COMBUSTION INCREASES THE TORQUE - ESPECIALLY AT LOWER RPM
- SKYACTIV-X HAS MORE USEABLE TORQUE AT NORMAL DRIVING CONDITIONS
- SPCCI CAN ADAPT TO DIFFERENT OCTANE GASOLINES

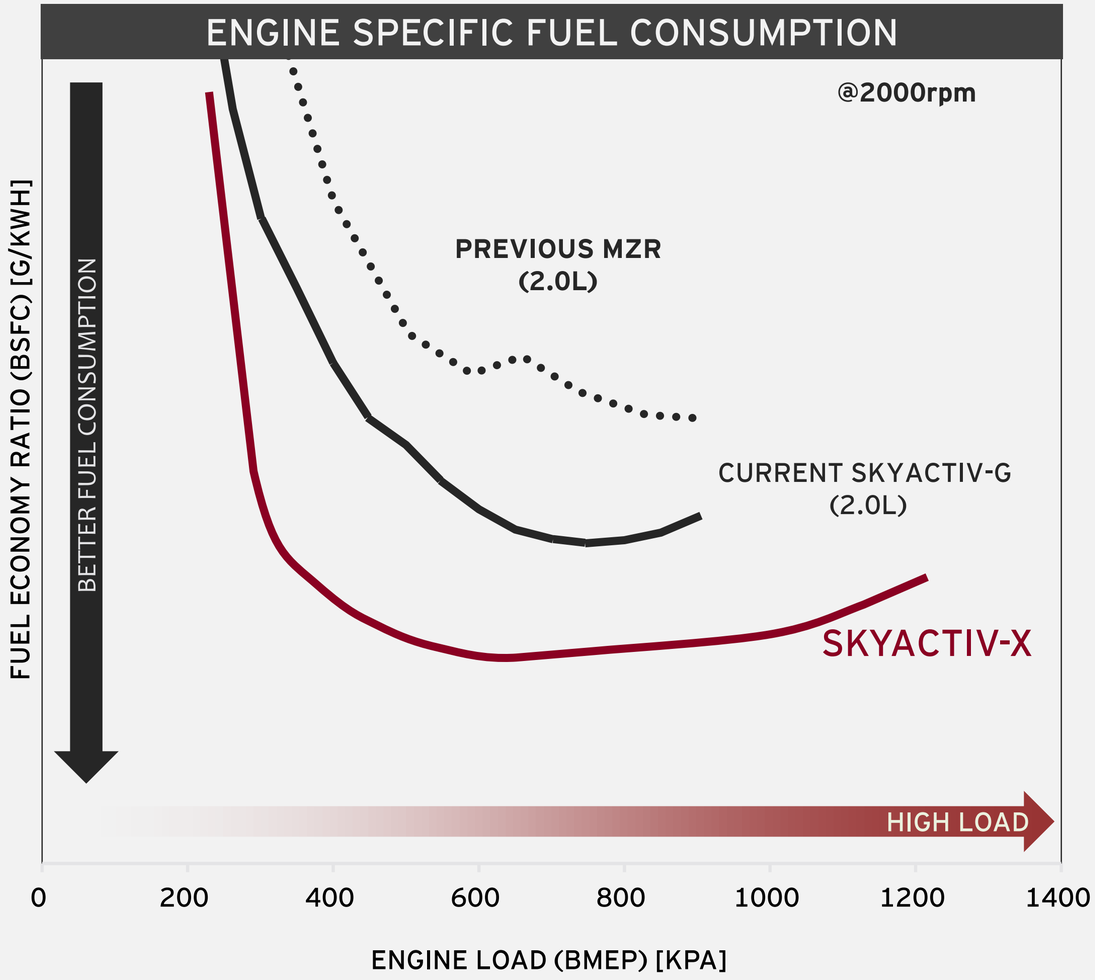


FUEL ECONOMY

TARGETING CLASS-LEADING GASOLINE ENGINE FUEL ECONOMY

- SKYACTIV-X TARGETS A 20% IMPROVEMENT IN FUEL CONSUMPTION OVER OUR CURRENT CLASS-LEADING SKYACTIV-G ENGINE

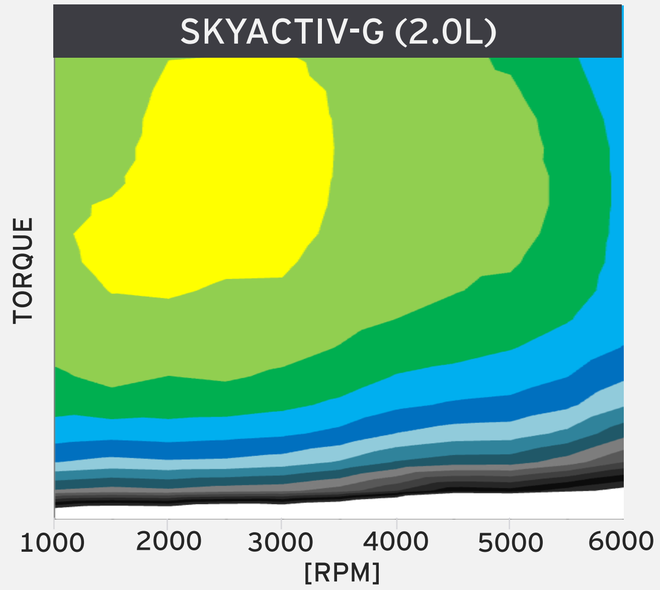
- THE BROAD, FLAT FUEL CONSUMPTION CURVE MEANS THAT FUEL USE IS LOW OVER A WIDE RANGE OF DRIVING CONDITIONS

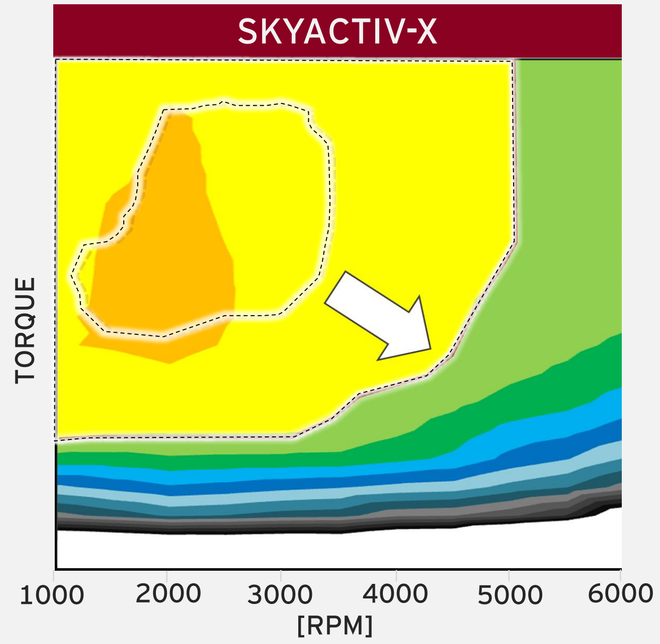


REAL WORLD FUEL ECONOMY

A WIDER RANGE OF FUEL ECONOMY FOR A REAL WORLD IMPACT

- CURRENT ENGINE TECHNOLOGY TRENDS LEAN TOWARD DOWNSIZED TURBOCHARGING AND CVT DRIVETRAINS TO IMPROVE FUEL ECONOMY
- THESE TECHNOLOGIES FOCUS ON A NARROW REGION OF OPTIMAL FUEL ECONOMY BUT FALLS OFF QUICKLY OUTSIDE OF THIS REGION
- MAZDA PRIORITIZES LOW FUEL CONSUMPTION OVER A BROAD RANGE OF DRIVING OPERATIONS AND STYLES
- SKYACTIV-X HAS A WIDER BREADTH OF FUEL EFFICIENT OPERATION MAKING REAL WORLD FC BETTER





HIGH FUEL CONSUMPTION

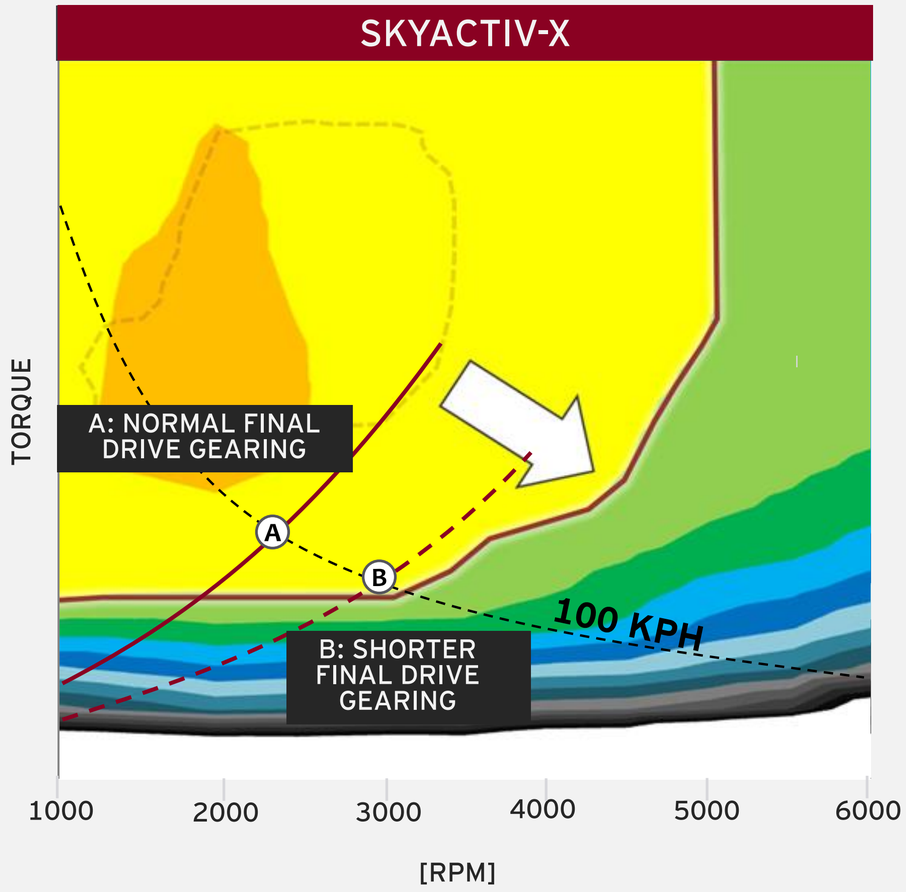
BSFC

LOW FUEL CONSUMPTION

BETTER EFFICIENCY AND BETTER PERFORMANCE

LESS PENALTY FOR HIGHER RPM

- A WIDER BREADTH OF FUEL EFFICIENT OPERATION MEANS WE'RE NO LONGER LIMITED TO LOWER ENGINE SPEEDS TO SAVE FUEL
- HIGHER RPM MEANS BETTER RESPONSE AND HIGHER POWER
- SKYACTIV-X ALLOWS THE VEHICLE TO BE GEARED LOWER FOR FASTER ACCELERATION AND MORE DIRECT RESPONSE TO THE DRIVER'S INPUTS

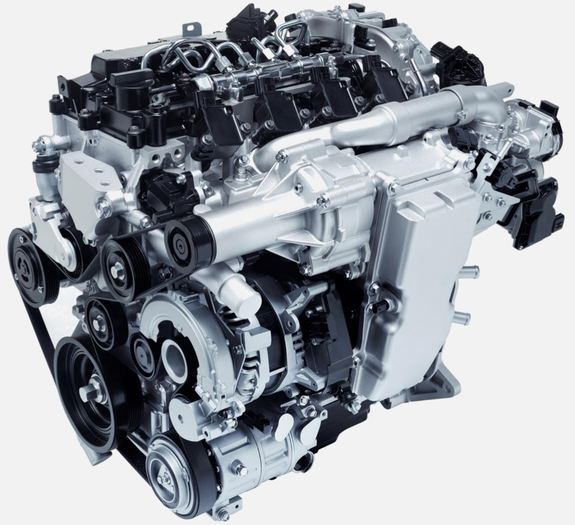


HIGH FUEL CONSUMPTION — BSFC — LOW FUEL CONSUMPTION

PERFORMANCE FROM EFFICIENCY

SKYACTIV-X SUMMARY

- NEW MEMBER OF SKYACTIV FAMILY
- REVOLUTIONARY METHOD OF BURNING GASOLINE IN A INTERNAL COMBUSTION ENGINE
- GLOBAL FIRST FOR COMMERCIAL USE
- PART OF MAZDA'S GOAL OF THE IDEAL INTERNAL COMBUSTION ENGINE
- BETTER PERFORMANCE AND ECONOMY: SUSTAINABLE ZOOM-ZOOM 2030
- COMPLETELY CONTROLLED COMPRESSION IGNITION THROUGH SPCCI
- AWARD WINNING TECHNOLOGY
  - "QUATTRORUOTE GLOBAL TECH AWARD" (ITALY)
  - "FUTURAUTO 2018 TROPHY FOR AUTOMOTIVE INNOVATION" (BELGIUM)
  - "2017 BEST TECHNOLOGY" (PORTUGAL)



KIYOSHI FUJIWARA

DIRECTOR, SENIOR MANAGING EXECUTIVE OFFICER,
OVERSIGHT OF R&D, MDI & COST INNOVATION
MAZDA MOTOR CORPORATION

THANK YOU!