SKYACTIV-X
AN INNOVATIVE GASOLINE ENGINE
WITH COMPRESSION IGNITION

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0. INTRODUCTION

1. SKYACTIV ROADMAP
2. CHALLENGES AND SOLUTIONS
3. SKYACTIV-X
4. CUSTOMER BENEFITS
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
MAZDA’S APPROACH TO ISSUES FACING THE EARTH

APPROACH CO₂ REDUCTION FROM A WELL-TO-WHEEL PERSPECTIVE TO REDUCE CO₂ EMISSIONS THROUGHOUT THE VEHICLE’S LIFE CYCLE

WELL-TO-WHEEL (FROM FUEL EXTRACTION TO DRIVING)

OIL WELL → REFINERY

POWER GENERATION → TANK

COMBUSTION ENGINE → WHEEL

MATERIAL MANUFACTURE, ASSEMBLY, DISPOSAL LIFE CYCLE ASSESSMENT
AIM TO REDUCE CORPORATE AVERAGE WELL-TO-WHEEL CO₂ EMISSIONS TO 50% OF 2010 LEVELS BY 2030

CORPORATE AVERAGE WELL-TO-WHEEL CO₂ (G/KM)

- 2010
- 2030: -50%
- 2050: -90%
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.

WHERE MAZDA WILL BE OPERATING BY 2030-2035

INTERNAL COMBUSTION ENGINE (84.4%)

FUEL CELL VEHICLES (4.4%)

ELECTRIC VEHICLES (11.2%)

GASOLINE DIESSEL HYBRIDS

GASOLINE DIESSEL

CNG/LPG

PLUG-IN HYBRID GASOLINE

PLUG-IN HYBRID DIESSEL

ELECTRICITY

FUEL CELL ELECTRIC

SALES OF NEW PASSENGER CARS (MILLIONS)

200

150

100

50

0

2000

2010

2020

2030

2040

2050

WHERE MAZDA WILL BE OPERATING BY 2030-2035

INTERNAL COMBUSTION ENGINE (84.4%)
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## ROAD MAP TO IDEAL COMBUSTION

### Control Factors

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<tr>
<th>Control Factor</th>
<th>MZR</th>
<th>SKYACTIV-G</th>
<th>SKYACTIV-X</th>
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<tbody>
<tr>
<td>Compression Ratio</td>
<td>Red</td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td>Specific Heat Ratio</td>
<td>Red</td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td>Combustion Speed</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Combustion Timing</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Heat Losses</td>
<td>Red</td>
<td>Orange</td>
<td>Green</td>
</tr>
<tr>
<td>Pumping Losses</td>
<td>Red</td>
<td>Red</td>
<td>Green</td>
</tr>
<tr>
<td>Mechanical Friction</td>
<td>Yellow</td>
<td>Friction Reduction</td>
<td>Green</td>
</tr>
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</table>

### Gasoline Engines

#### MZR
- World's highest compression

#### SKYACTIV-G
- Even higher compression

#### SKYACTIV-X
- Lean mixture
- Compression ignition
- Direct pressure measurement
- Thermal management
- Lean mixture
- More friction reduction

### Goal: Ideal Engine

- Better air/fuel mixing
- Even higher compression
- Lean mixture
- Compression ignition
- Direct pressure measurement
- Thermal management
- Lean mixture
- More friction reduction

### Mazda

- SKYACTIV-G
- SKYACTIV-X
- SKYACTIV-D

### Control Factor

- Gasoline engines
- Diesel engines

### Distance to Ideal State

- **Far**: << Distance to Ideal State >>
- **Close**: Close

### Mazda

- Control factor
- Gasoline engines
- Diesel engines

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**Goal:** Ideal engine still secret

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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
GOAL: LEAN COMBUSTION

WHY IS EXTREMELY LEAN GOOD?

EXTREMELY LEAN COMBUSTION IS COOLER

- COOLER COMBUSTION MAKES LESS NOx
- 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

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

**FLAME CANNOT PROPAGATE**

**STOICHIOMETRIC MIXTURE (LAMBDA = 1)**
- CA = -4.3
- CA = -0.7
- CA = -2.9
- CA = -6.5

**SUPER LEAN MIXTURE (LAMBDA = 2)**
- CA = -4.0
- CA = -0.4
- CA = -3.2
- CA = -6.8

CA = CRANK ANGLE

(ACTUAL COMBUSTION AT 750 RPM)
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
1. SKYACTIV ROADMAP
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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
CHALLENGE: HCCI COMBUSTION TIMING IS UNCONTROLLED

SPARK IGNITION IS STILL NEEDED

- Conventional HCCI combustion is limited in its 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
BREAKTHROUGH SOLUTION
SPARK CONTROLLED COMPRESSION IGNITION (SPCCI)
THE BREAKTHROUGH: CONTROL COMPRESSION IGNITION WITH A SPARK!

**VERY LEAN MIXTURE**
**VERY HIGH COMPRESSION**

**START COMBUSTION WITH A SPARK**

**SPARK CONTROLLED COMPRESSION IGNITION (SPCCI)**

- DESIGN THE ENGINE TO RUN JUST BELOW THE THRESHOLD OF COMPRESSION IGNITION
- EXPANDING FIREBALL ADDS MORE HEAT AND PRESSURE
- COMPRESSION IGNITION IS TRIGGERED IN THE REST OF THE CYLINDER

**PUSHING CONDITIONS OVER THE THRESHOLD**
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 \(\rightarrow\) ALLOWS THE FIREBALL TO IGNITE
- THE MAJORITY OF THE MIXTURE INSIDE THE CYLINDER REMAINS VERY LEAN \(\rightarrow\) IT COMBUSTS WITH CI
- SWIRLING THE AIR INSIDE THE CYLINDER AND GENERATING A VORTEX EFFECT \(\rightarrow\) KEEP IT VERY LEAN
CHALLENGE
PREVENTING UNCONTROLLED AUTO-IGNITION
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, it leads to less heat up time.

**INCREASE ATOMIZATION AND MIXING BY UPGRADED FUEL SYSTEM**
CHALLENGE

KEEPING TRACK TO MAINTAIN RELIABILITY
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.
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

SOLUTION: ADAPTIVE SPARK TIMING CONTROL

Adjust ignition timing for different conditions

Compressed stroke
Expansion stroke

1500rpm, 500kPa

Intake air temperature

156.1°C
141.1°C
125°C
120°C

Cylinder pressure vs. crank angle (degree after top dead centre)

Compression ignition threshold pressure

IG = -16
IG = -23
IG = -26
IG = -17
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 usable torque at normal driving conditions
- SPCCI can adapt to different octane gasolines

[Graph showing torque vs. engine speed for SKYACTIV-G and SKYACTIV-X with 91 and 95 octane gasolines compared to previous MZR.]
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
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.
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
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)
THANK YOU!