Mazda's Approach for Developing Engines from a Perspective of Environmental Improvement

2015 ERC Symposium

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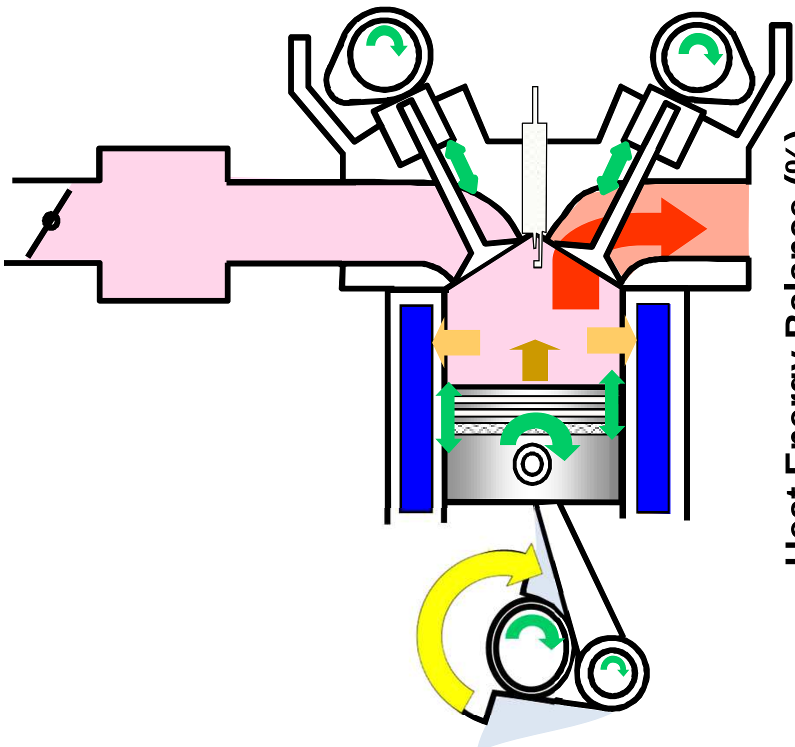
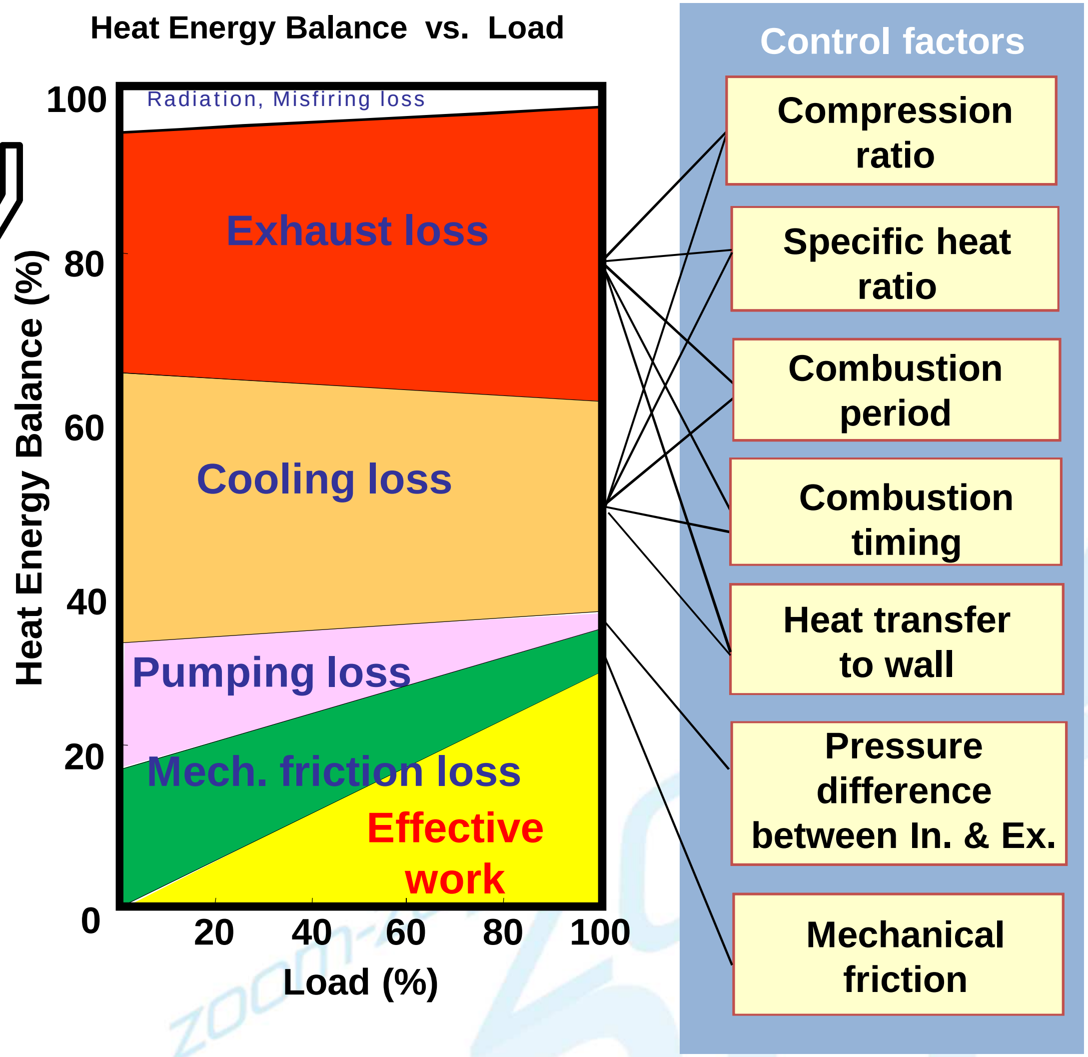
Contents

- **Improving thermal efficiency of ICEs**
- **Goal of SKYACTIV engines**
- **SKYACTIV engines:** 1st step
- **SKYACTIV engines: Next step**
- **Investigation results of boosted downsizing engines and future strategy for engine displacement**

Improving thermal efficiency of ICEs

Energy losses of ICE

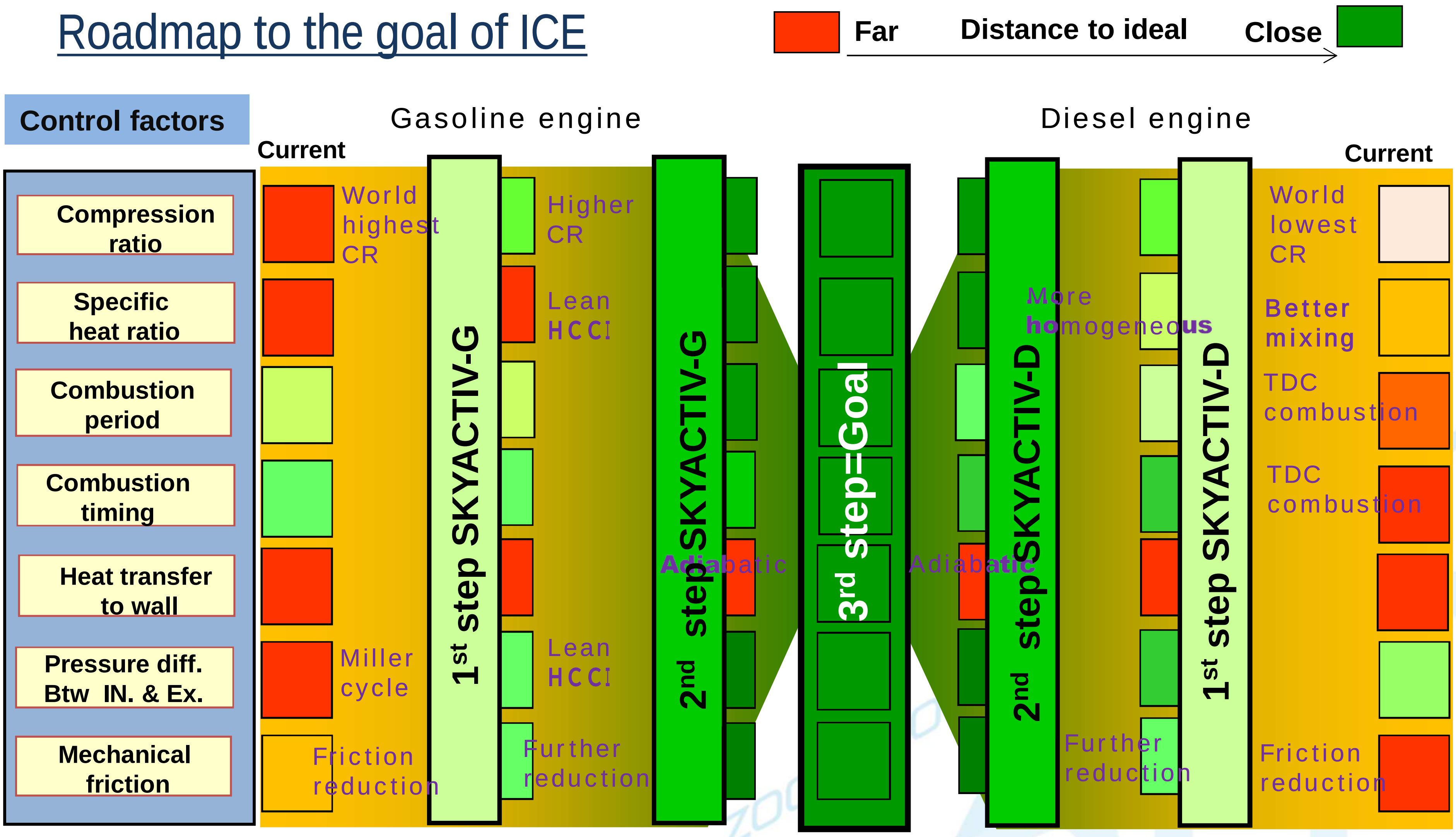




Fuel Economy Improvement = Loss reduction
All technologies for improving fuel economy must overcome these seven controlling factors.

Improving thermal efficiency of ICEs

Roadmap to the goal of ICE



Gasoline engine and diesel engine will look similar in the future.

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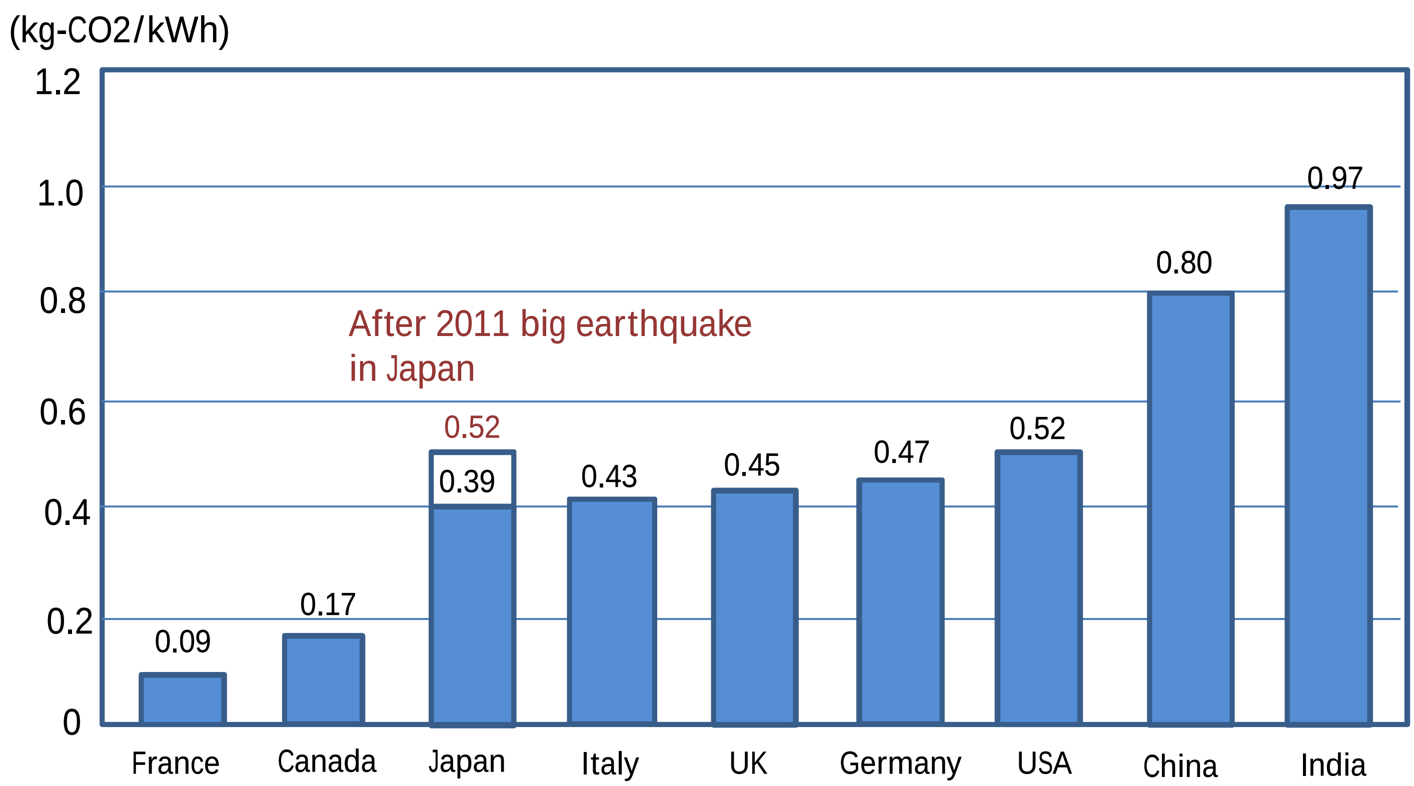
Goal of SKYACTIV engines

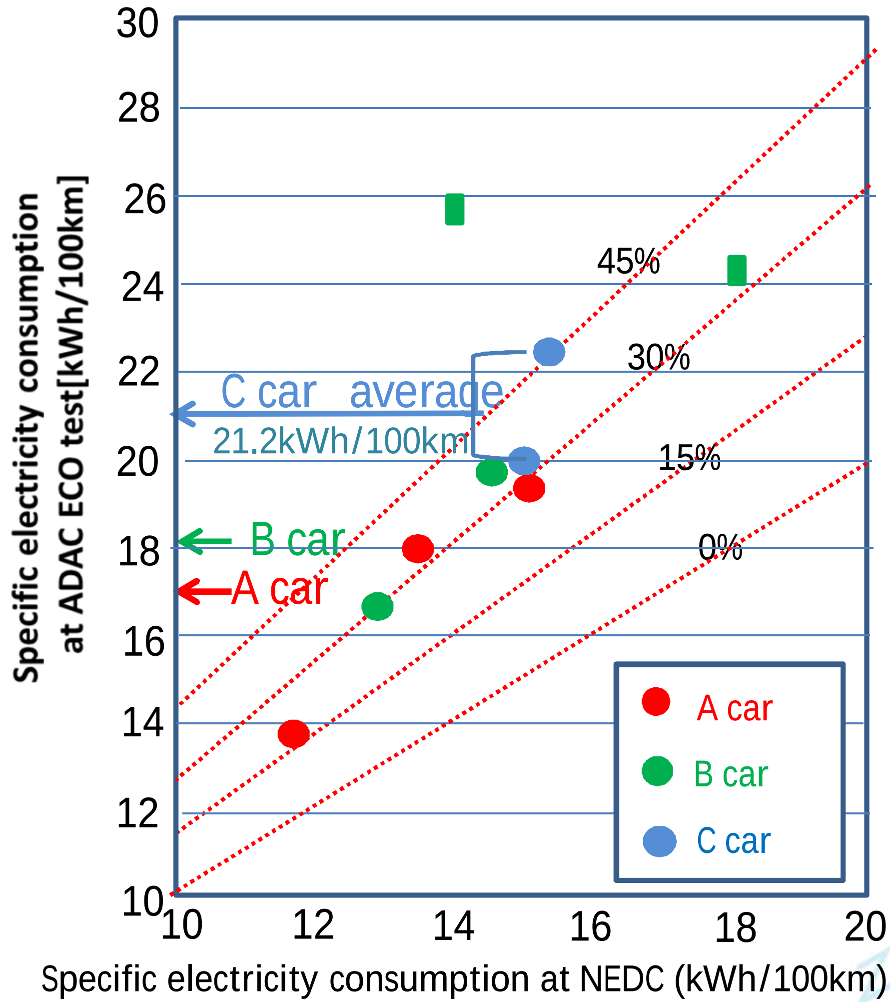
Specific CO2 emissions of electric power generation

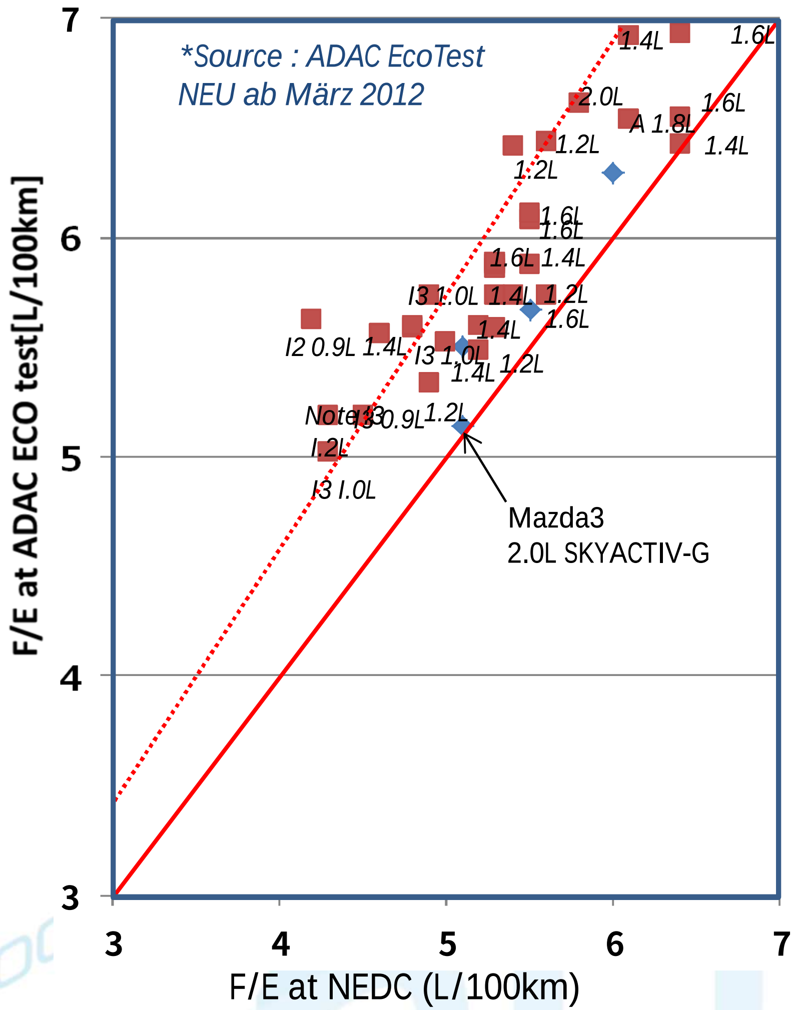


Specific CO2 emission from electric power generation is assumed to be 0.5kg-CO2/kWh.

Goal of SKYACTIV engines

Fuel consumption reduction target for ICE powered vehicle in real world



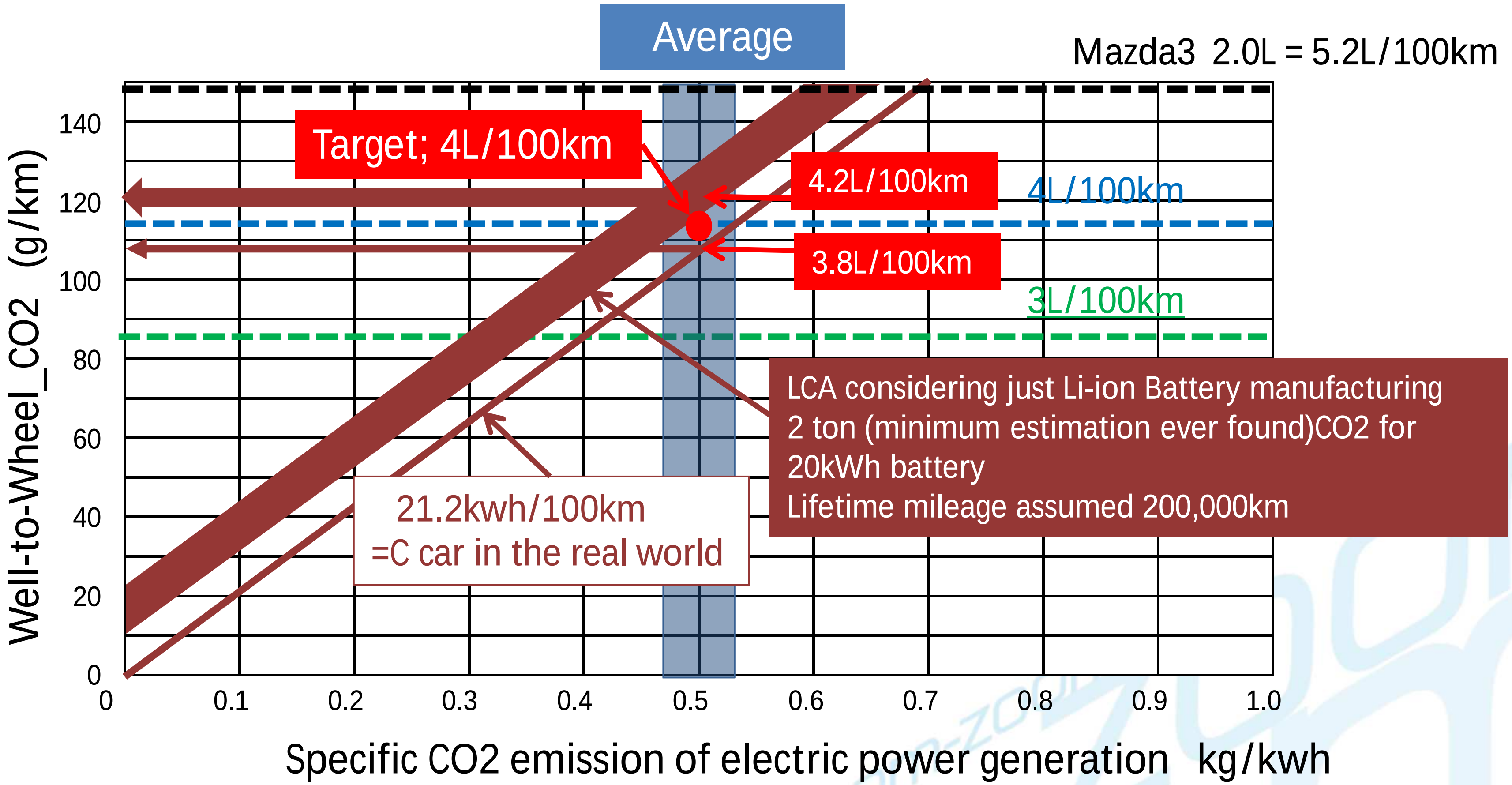


Electric power consumption of C car in the real world: 21.2kWh/100km.

Fuel consumption of Mazda 2L C car in the real world: 5.2L/100km

Goal of SKYACTIV engines

Fuel consumption reduction target for ICE powered vehicle in real world



Target for Mazda 3 5.2L/100km ⟶ 4L (3.8L-4.2L)/100km

Around 25% fuel consumption reduction required

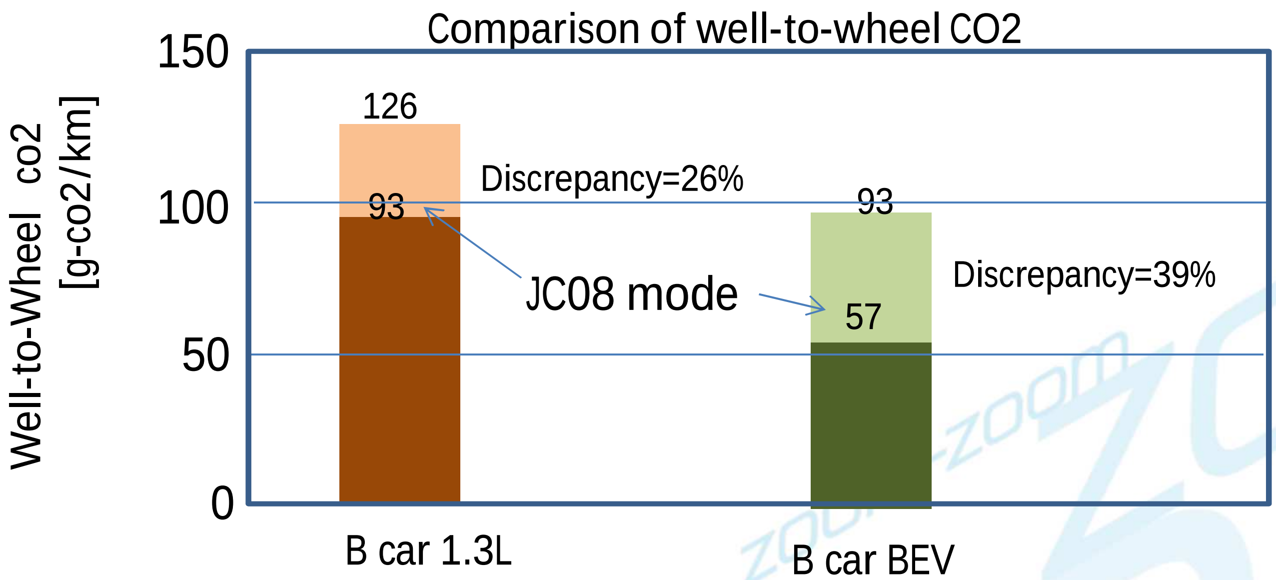
Goal of SKYACTIV engines

Real-world CO2 emissions (In Japan)

Evaluation condition: Weighted average of results of below 3 tests, considering Japanese ambient temperature distribution in a year

1. JC08 Hot ambient temperature 25°C air conditioner 25°C AUTO
2. JC08 Hot ambient temperature 37°C air conditioner 25°C AUTO
3. JC08 Cold ambient temperature -7°C air conditioner 25°C AUTO

Average energy consumption = JC08H 25°C − ((JC08H 25°C − JC08H 37°C) *0.2+ (JC08H 25°C − JC08C -7°C) *0.3) /4



Fuel economy of internal combustion engines needs to be reduced by approx. 26%((126-93)/126=0.26) to attain the EV-level CO2 emissions.

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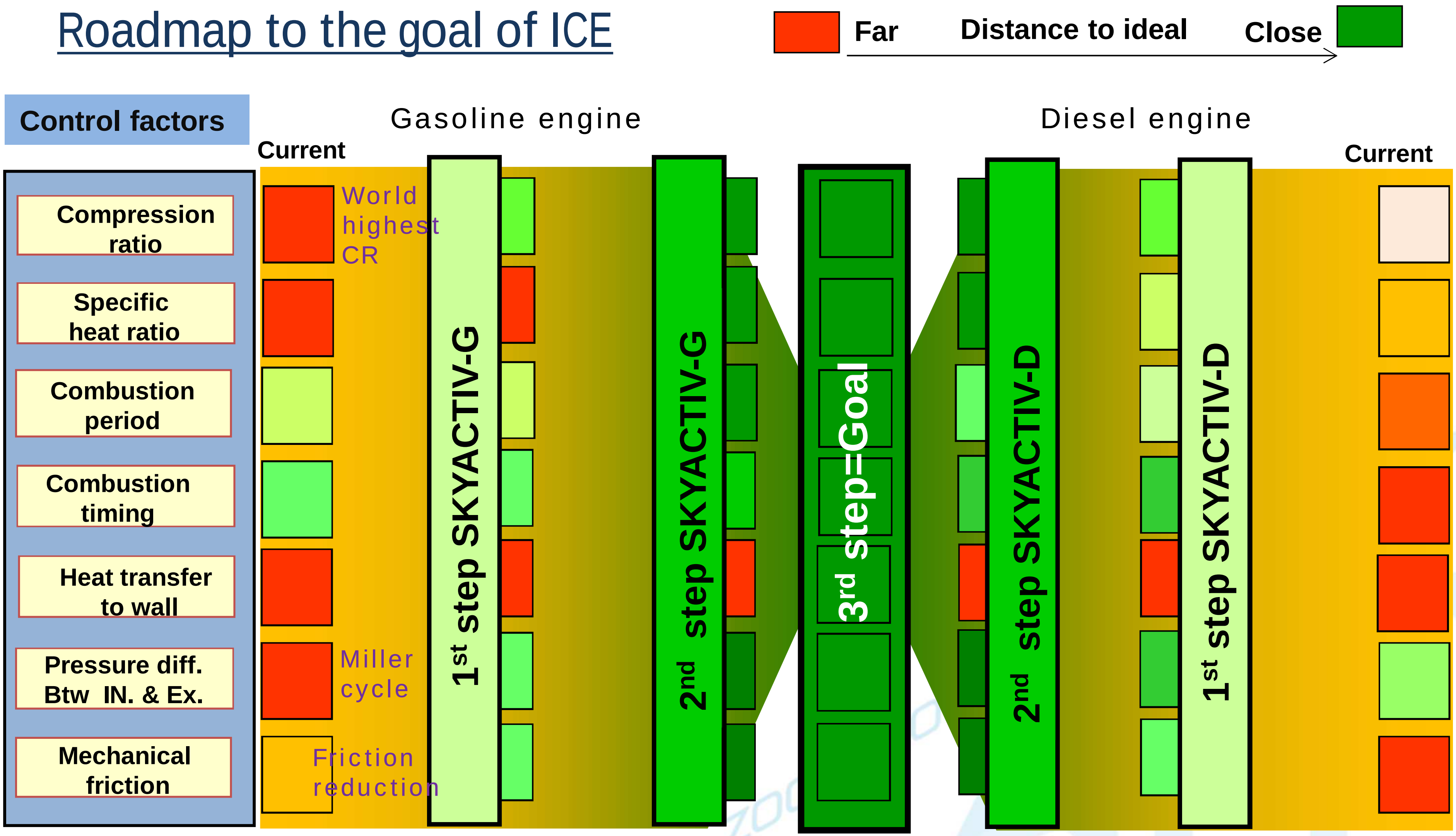
SKYACTIV engines: 1^{st} step

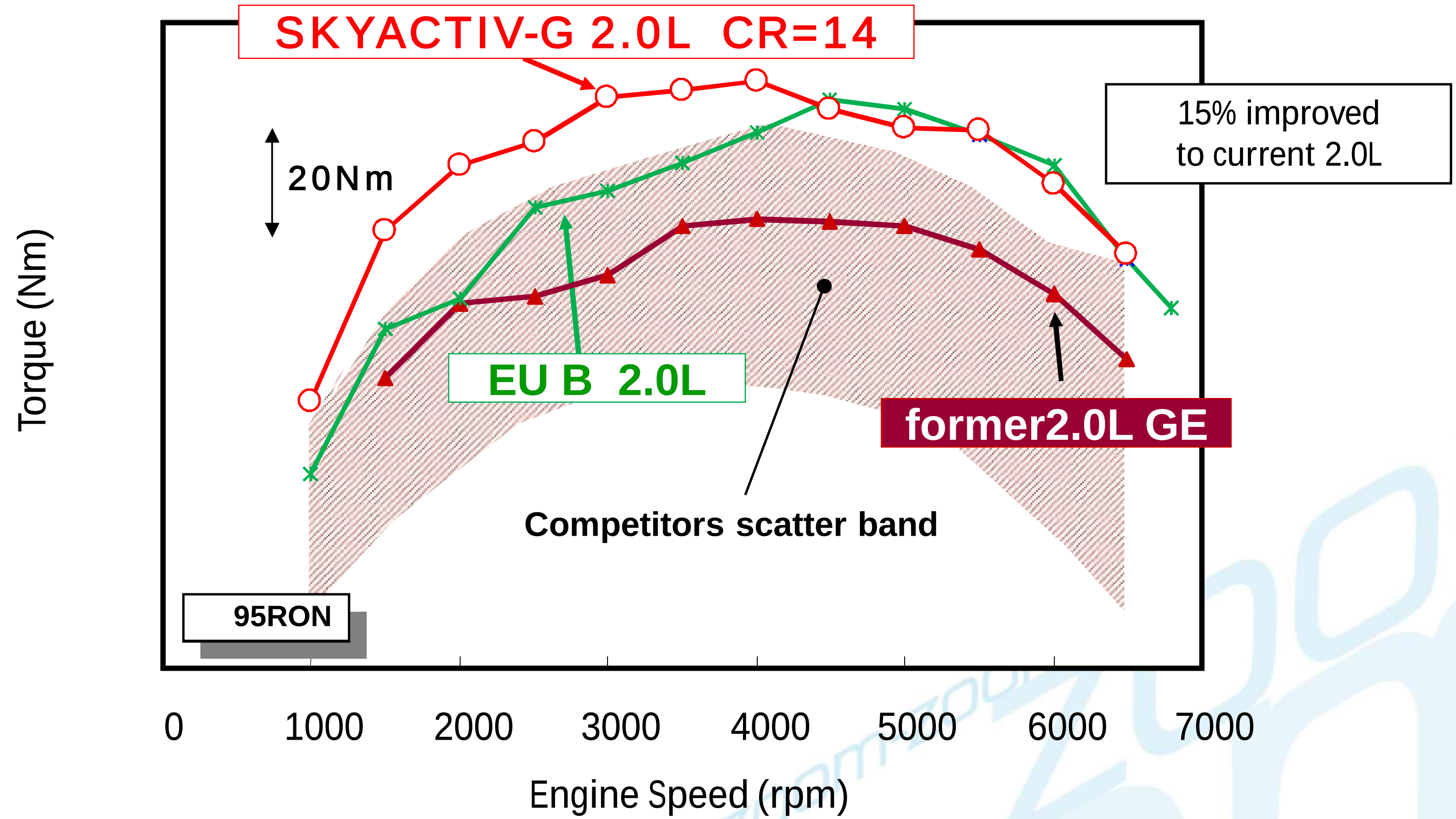
Roadmap to the goal of ICE



The most distinctive feature of 1^{st} step gasoline engine is world highest compression ratio.

SKYACTIV engines: *1st step*

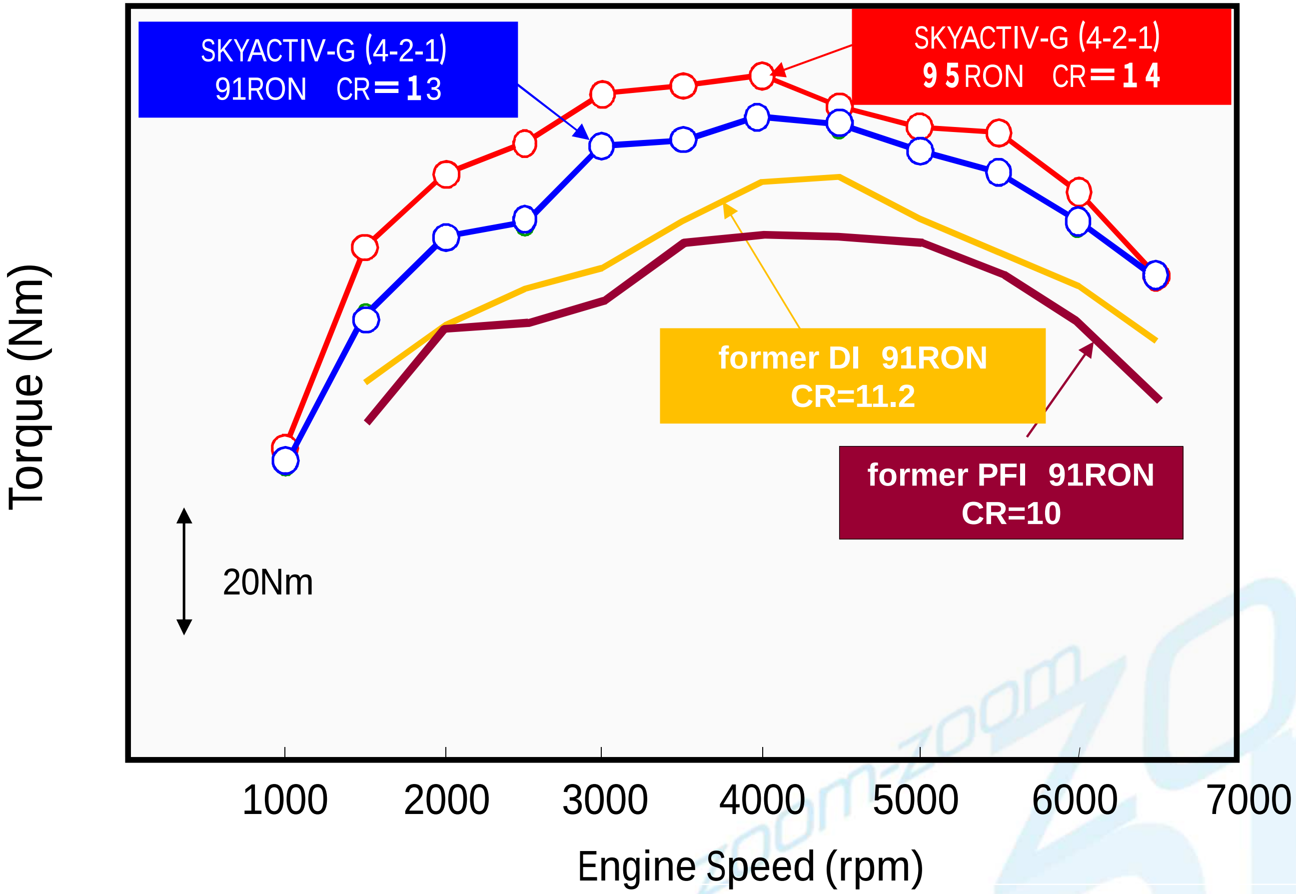
Full load Performance



Improve low- and-mid end torque in spite of a high compression ratio and achieve superior driving

12

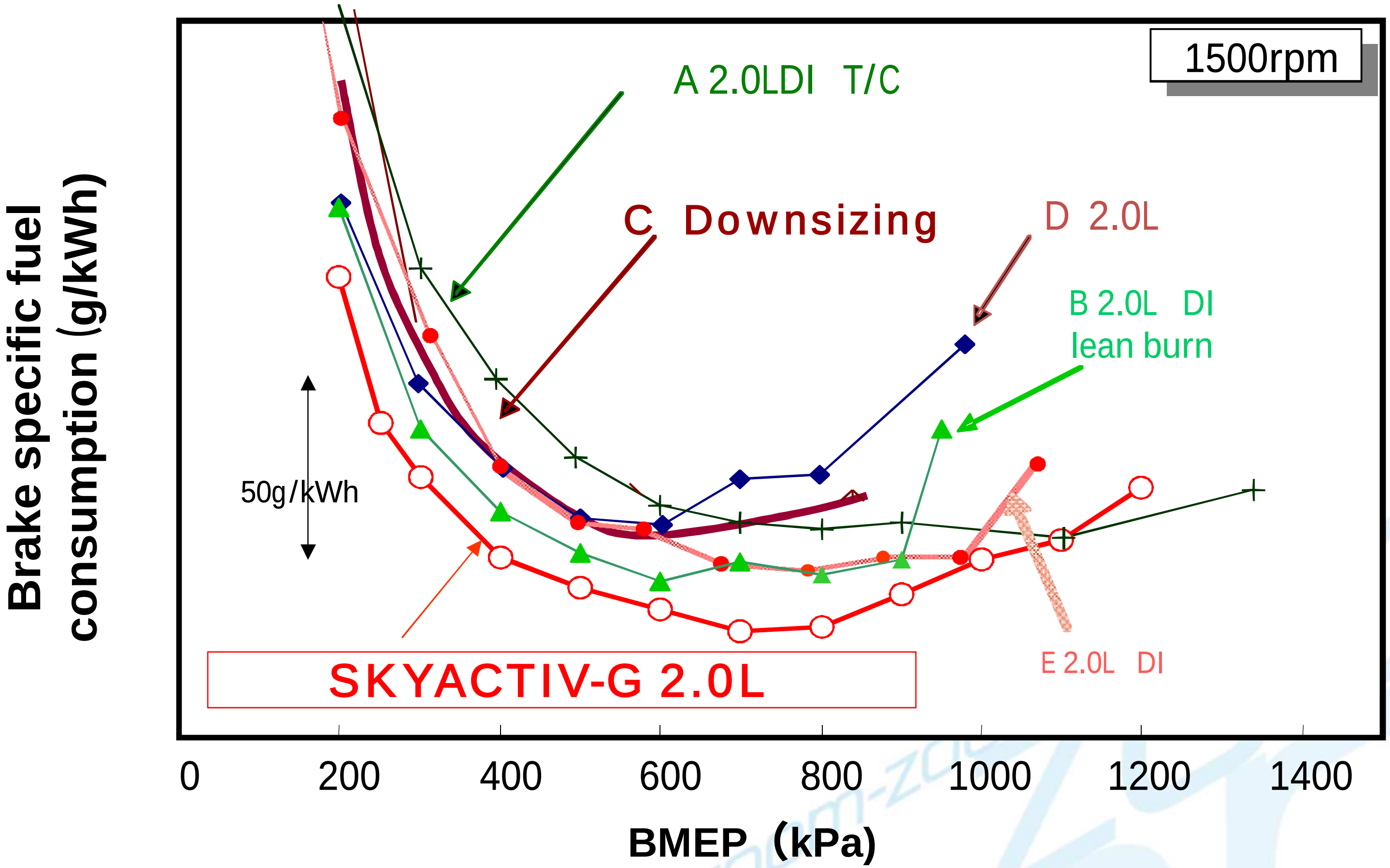
Compression ratio vs. RON



Performance enhanced together with high compression ratio

SKYACTIV engines: 1st step

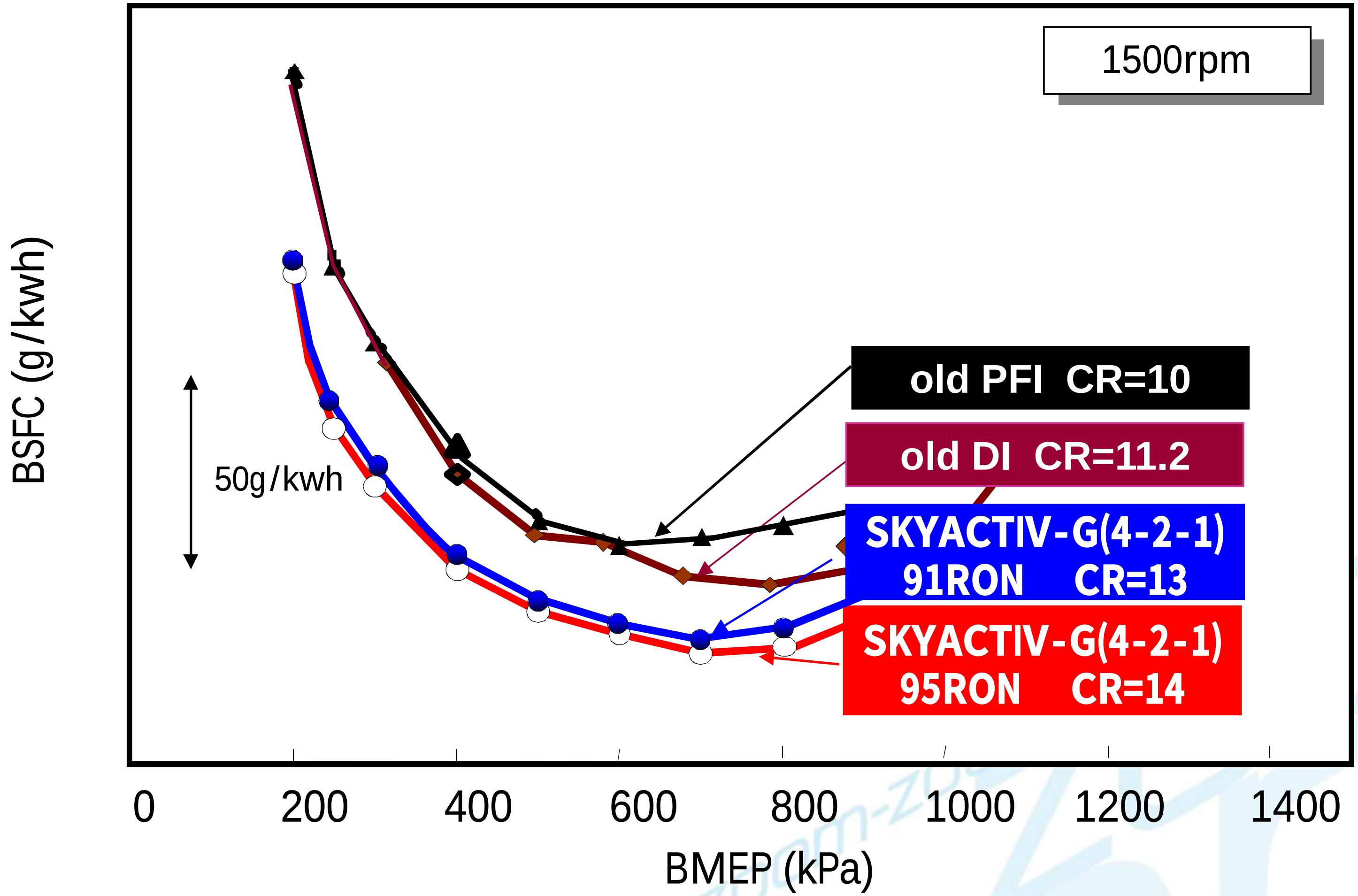
BSFC



SKYACTIV-G surpasses competitors' all new engines including 30% downsized engines in fuel efficiency.

SKYACTIV engines: 1st step

BSFC vs. CR



SKYACTIV-G made a large improvement in performance over conventional engines.

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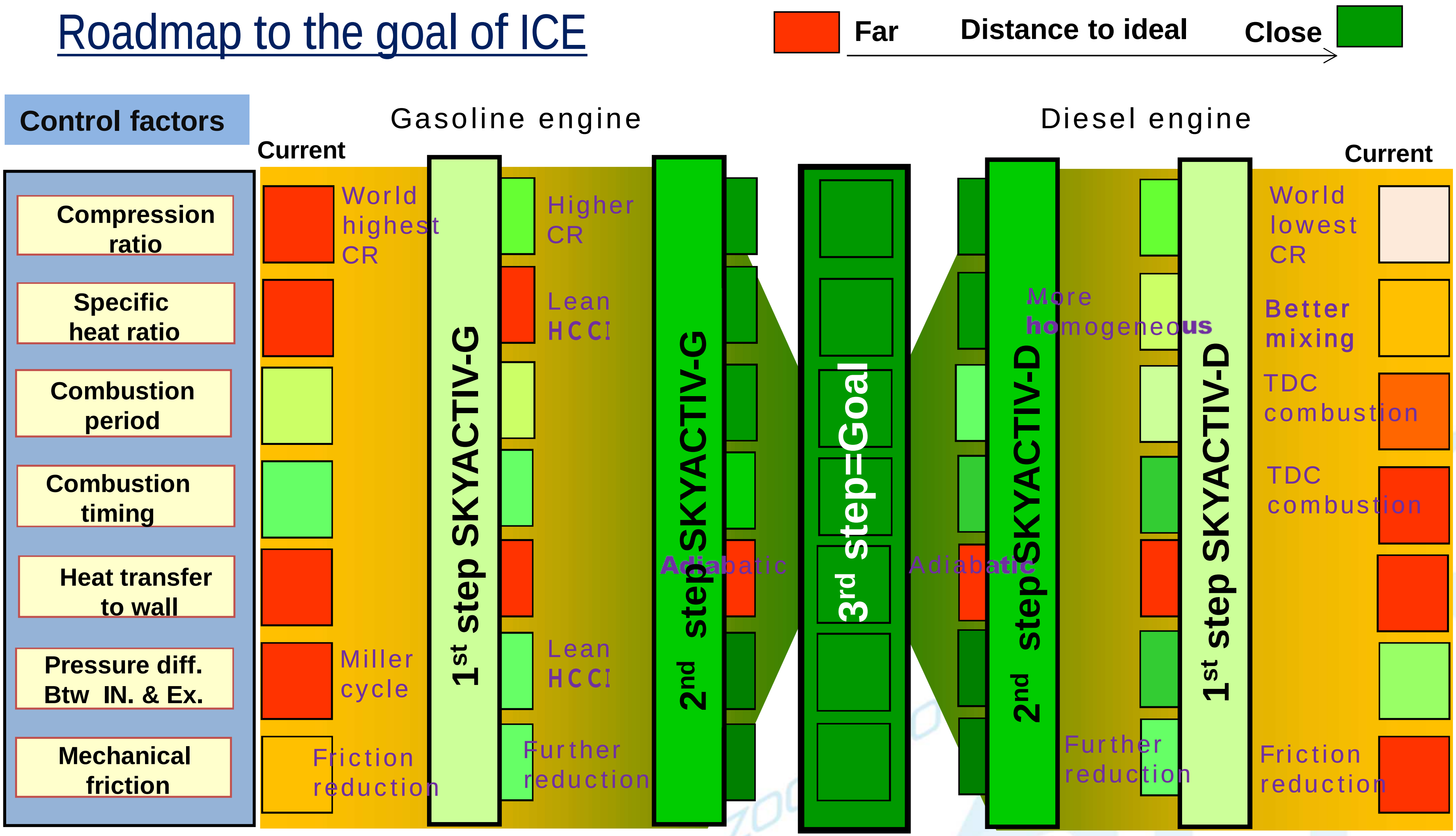
SKYACTIV engines: Next step

Roadmap to the goal of ICE

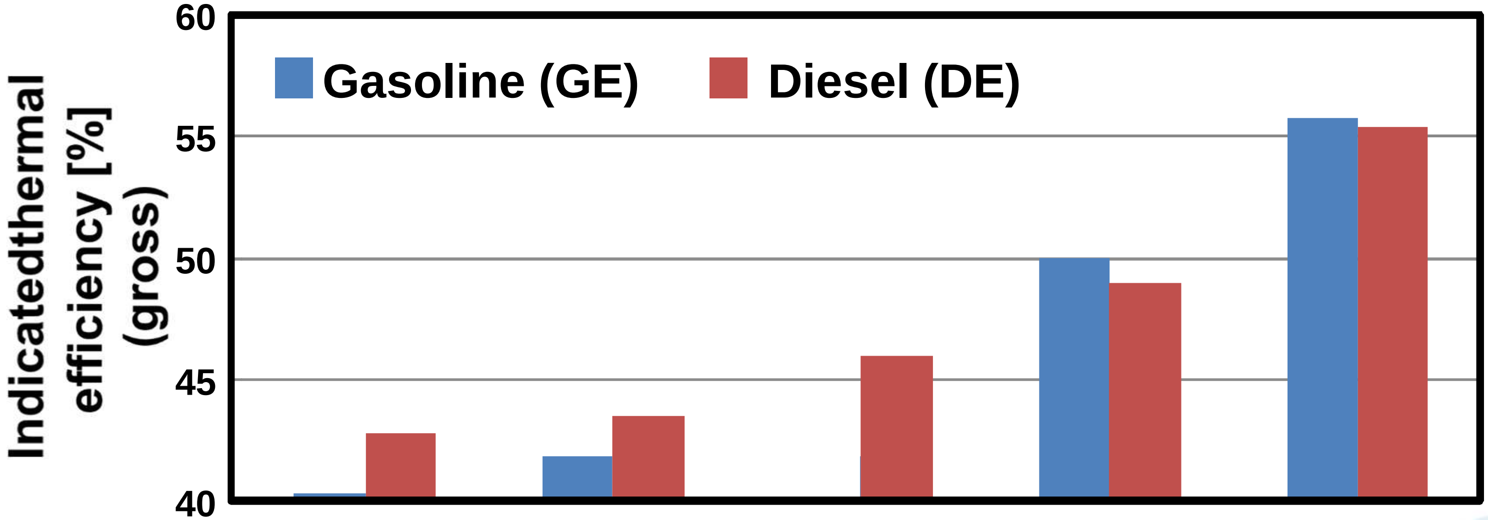


Gasoline engine and diesel engine will look similar in the future.

SKYACTIV engines: Next step

Walk of efficiency improvement

Light load：2000rpm – IMEP290kPa



Combustion period	GE: DE:	75deg 40deg	30deg	- ←	←	←
Specific heat ratio	GE:	λ=1 Homogeneous	←	-	λ=4	←
	DE:	λ=2.8 Stratified	←	λ=2.8 Homogeneous		
Compression raio	GE: DE:	14	←	- ←	20	30
Wall heat transfer	GE: DE:	Base Base	← ←	- ←	← ←	0.5*GE

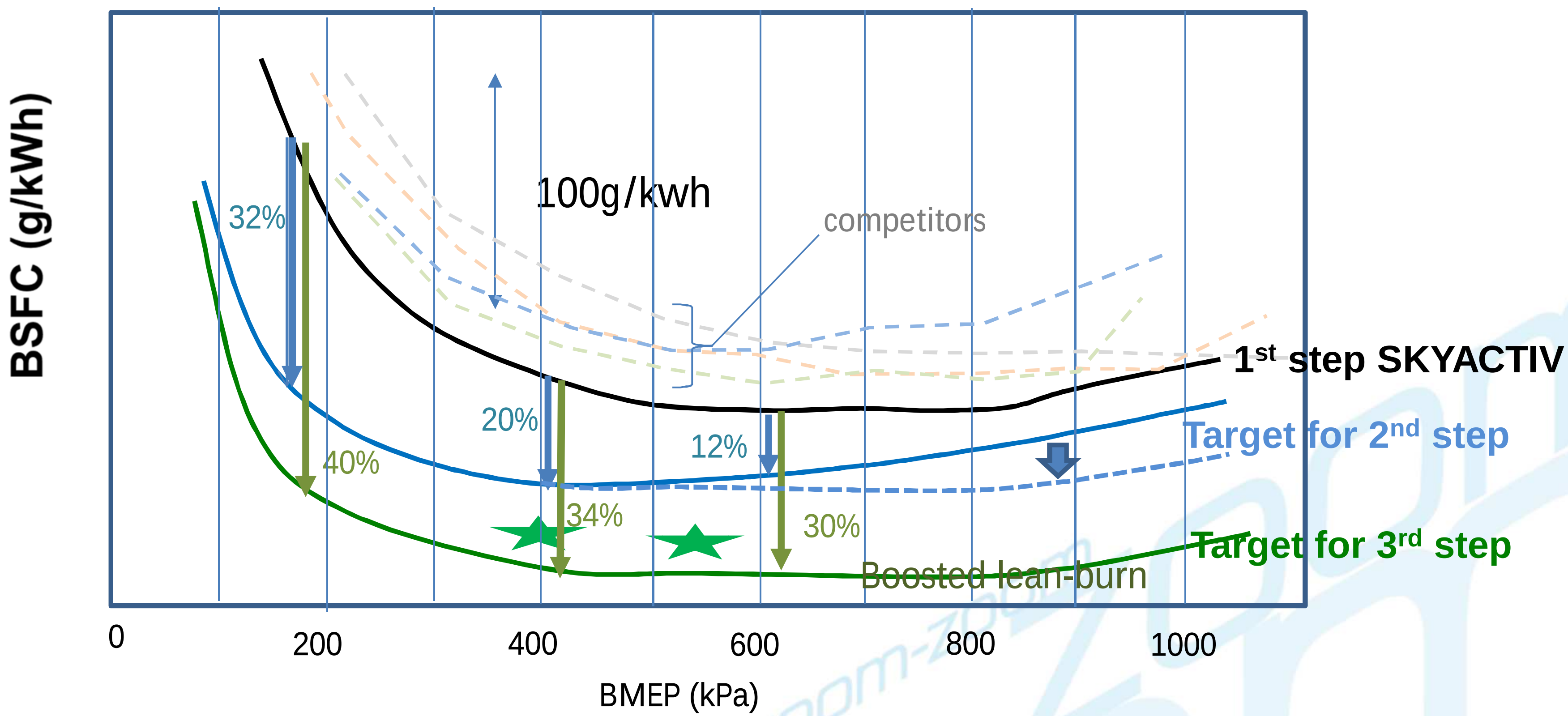
Intake valve close GE: 93deg ABDC DE: 36deg ABDC

There is room for improving thermal efficiency in the light load range:
Approx. 30% for diesel engines Approx. 40% for gasoline engines

SKYACTIV engines: Next step

Brief Specific Fuel Consumption

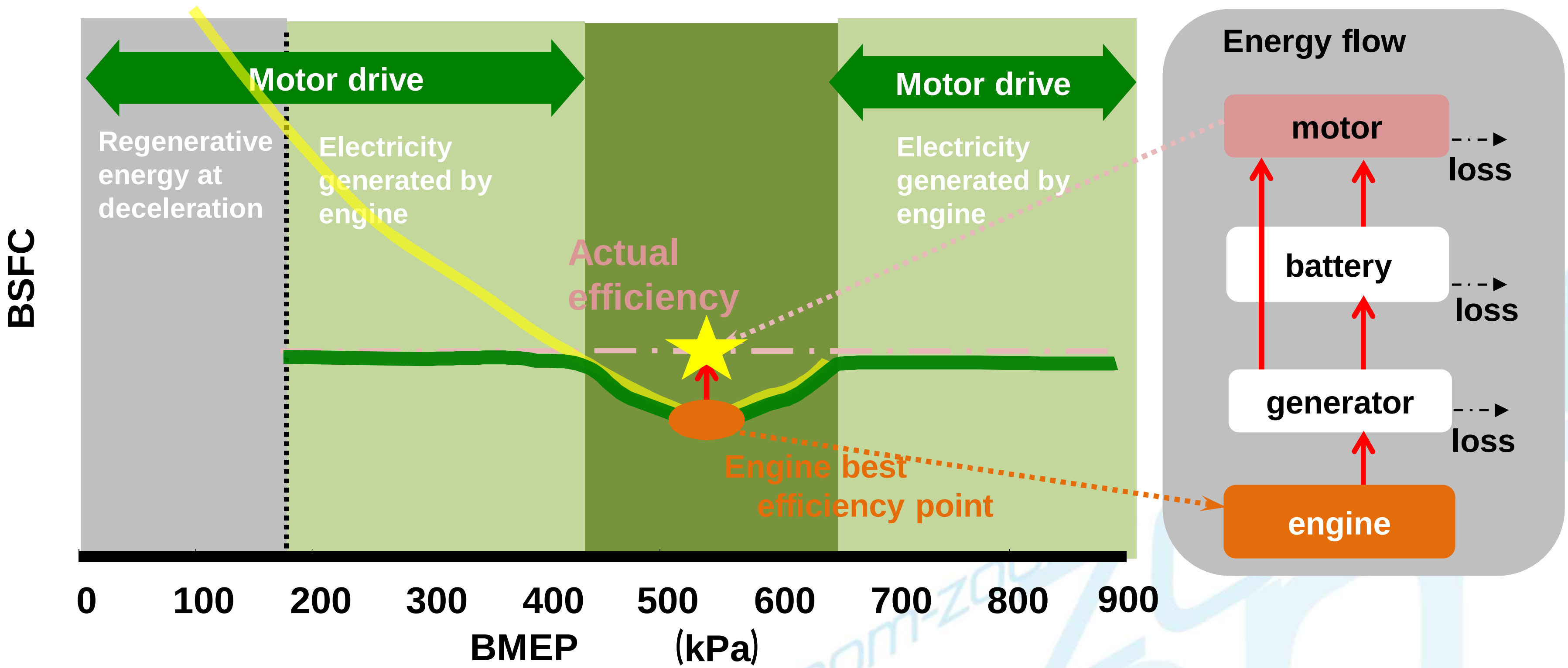
Target for Mazda 3 5.2L/100km → 3.8L-4.2L/100km
around 25% fuel consumption reduction required



It seems possible for ICEs to attain a 25% fuel economy improvement, which is the target to to attain the EV-level CO_2

Hybridization requirement on electric device capacity

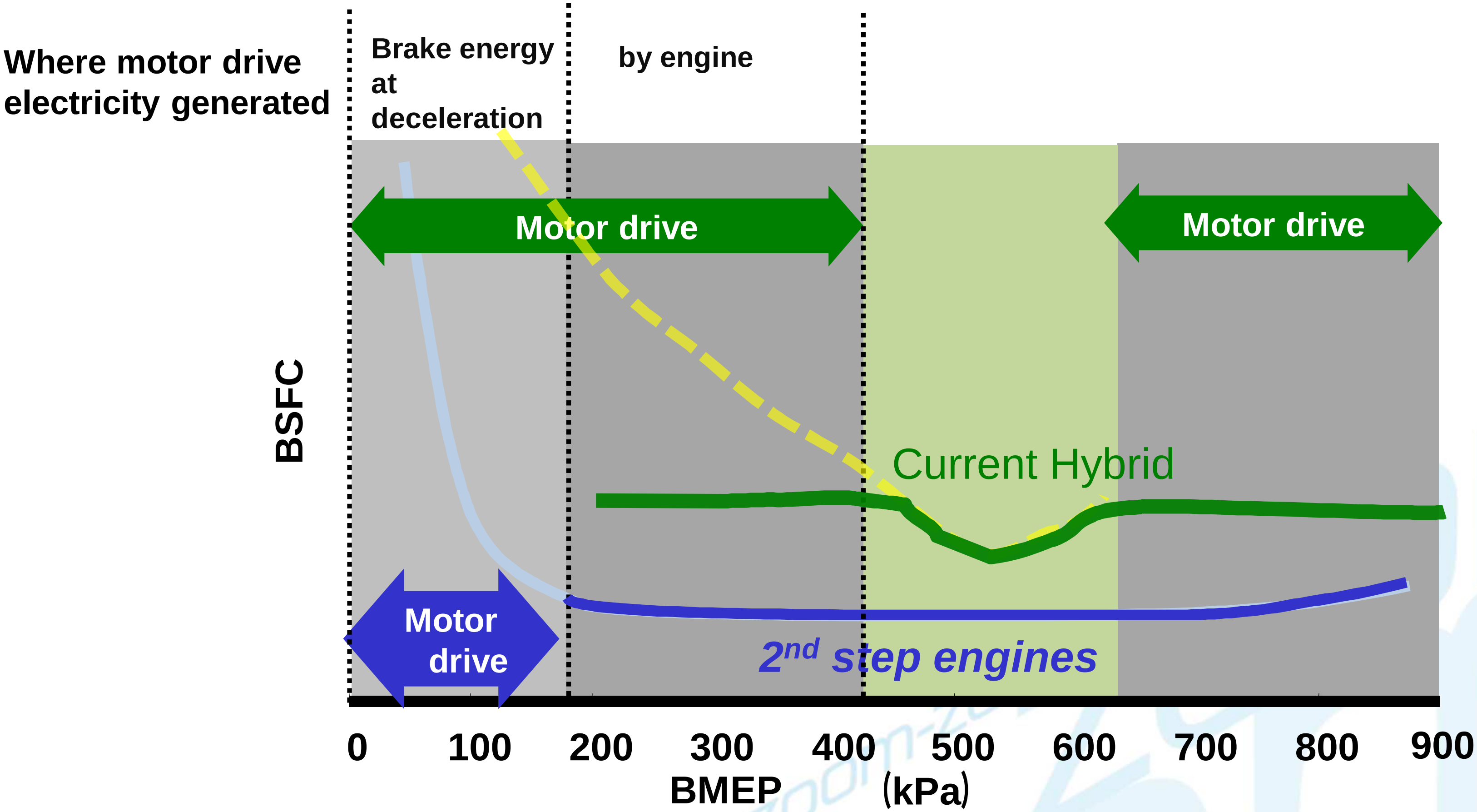
Regenerative energy just delivers10-30% of vehicle driving energy



Motor drive using electricity generated by engine = Large battery and large motor required

SKYACTIV engines: Next step

Hybridization requirement on electric device capacity



When Mazda's next-generation engines are hybridized, small-sized motor and battery are sufficient enough to power engines.

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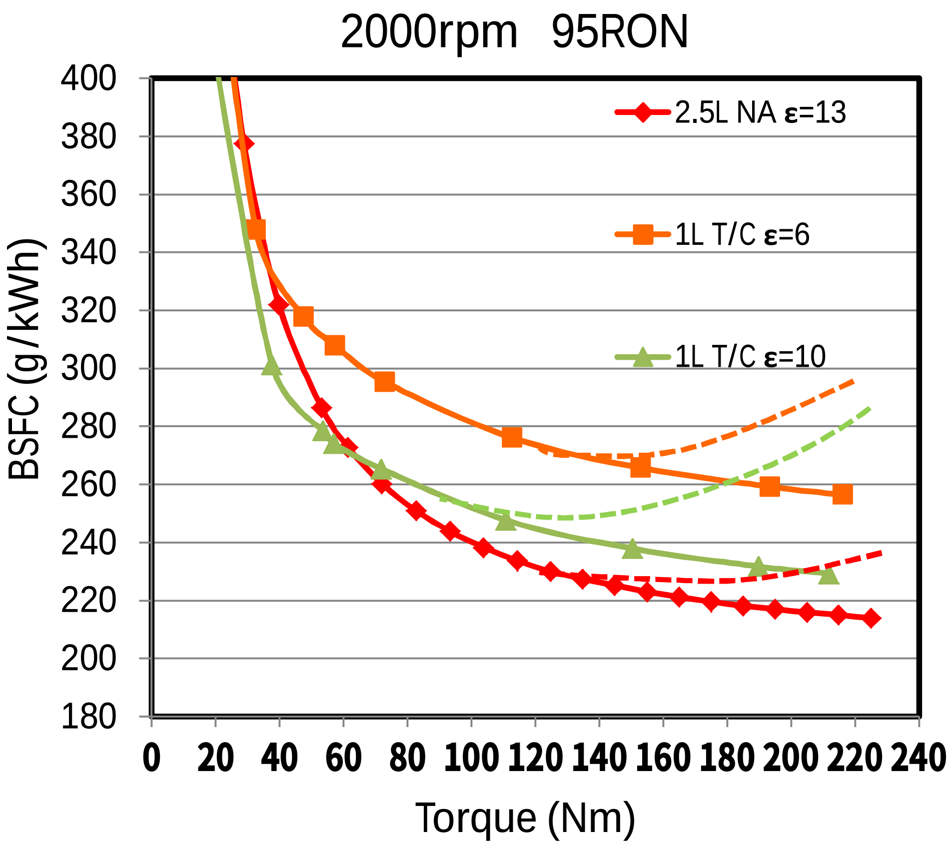
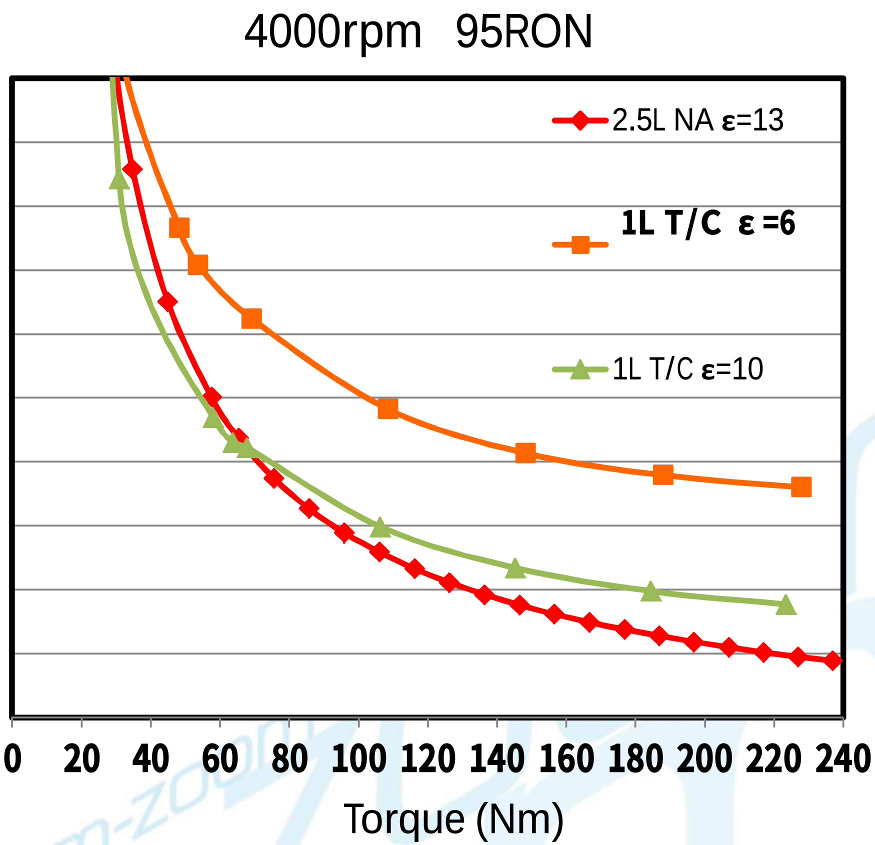
Investigation results of boosted downsizing engines

Prediction of BSFC



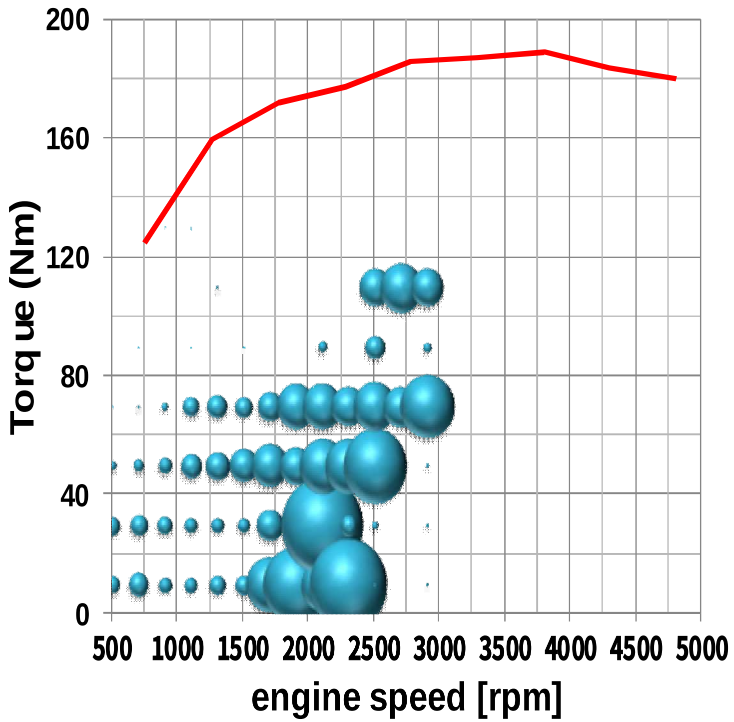


At low load , 1L boosted engine with usual CR=10 shows better BSFC than 2.5L NA, but at mid. and high load, 2.5L engine shows much better BSFC than 1L boosted engine.

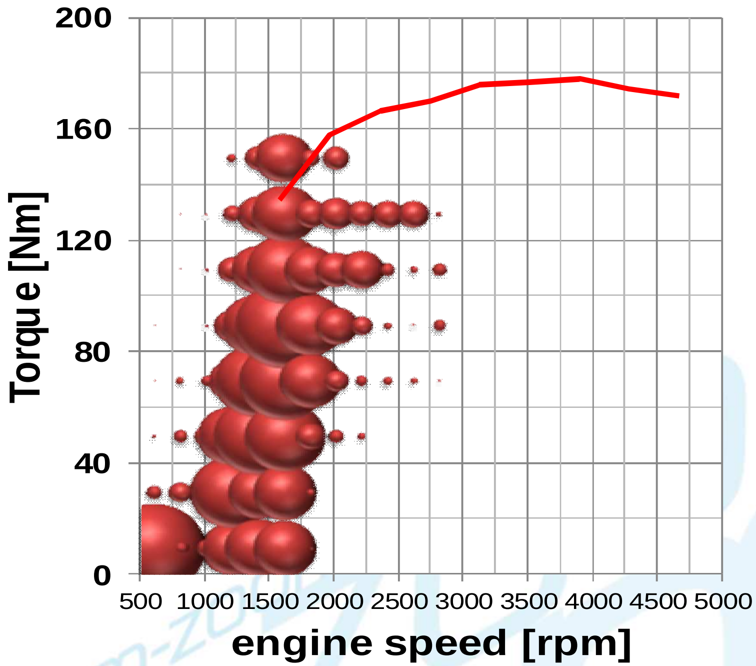
Investigation results of boosted downsizing engines

Mode fuel distribution map

NEDC



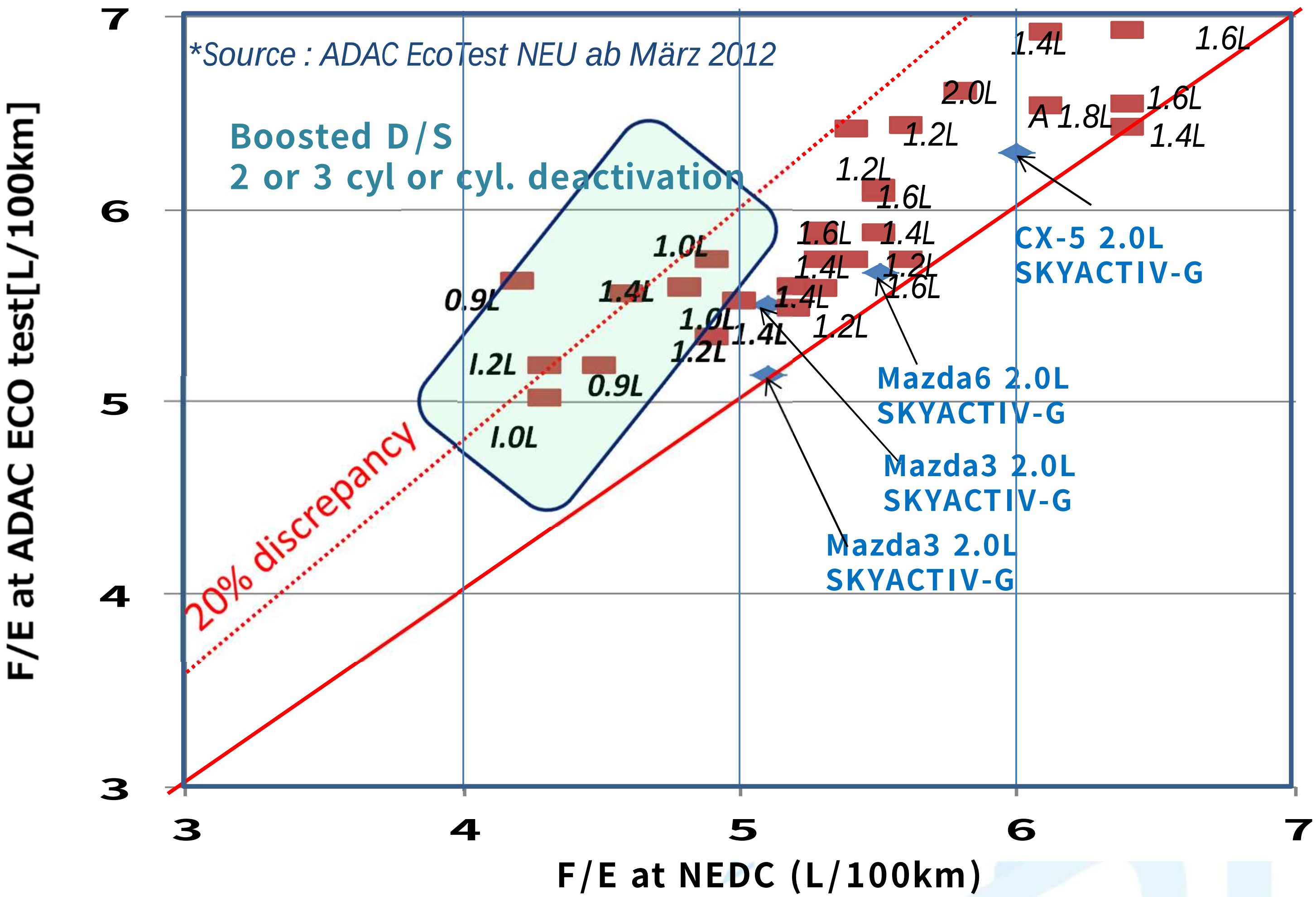
FTP



Downsizing is favorable for NEDC-mode fuel economy

Investigation results of boosted downsizing engines

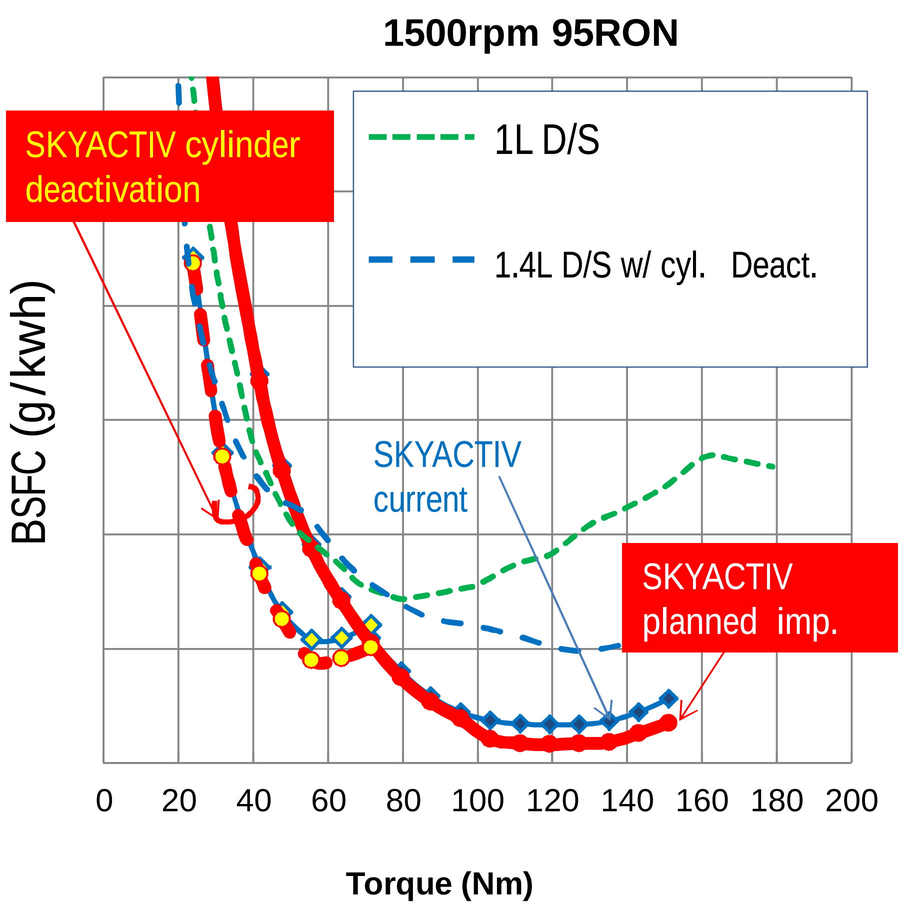
Real world fuel economy

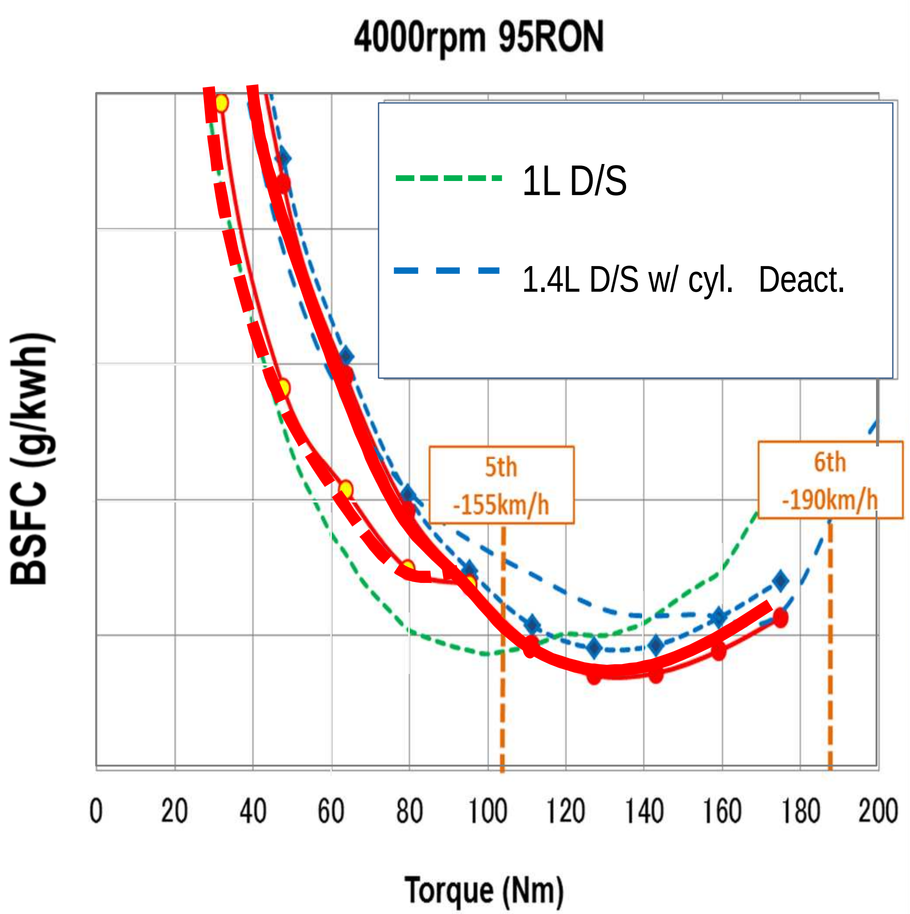


SKYACTIV engines are better than boosted downsizing engines in the real world fuel economy.

Investigation results of boosted downsizing engines

Comparison between 2L SKYACTIV and 1L and 1.4L boosted D/S

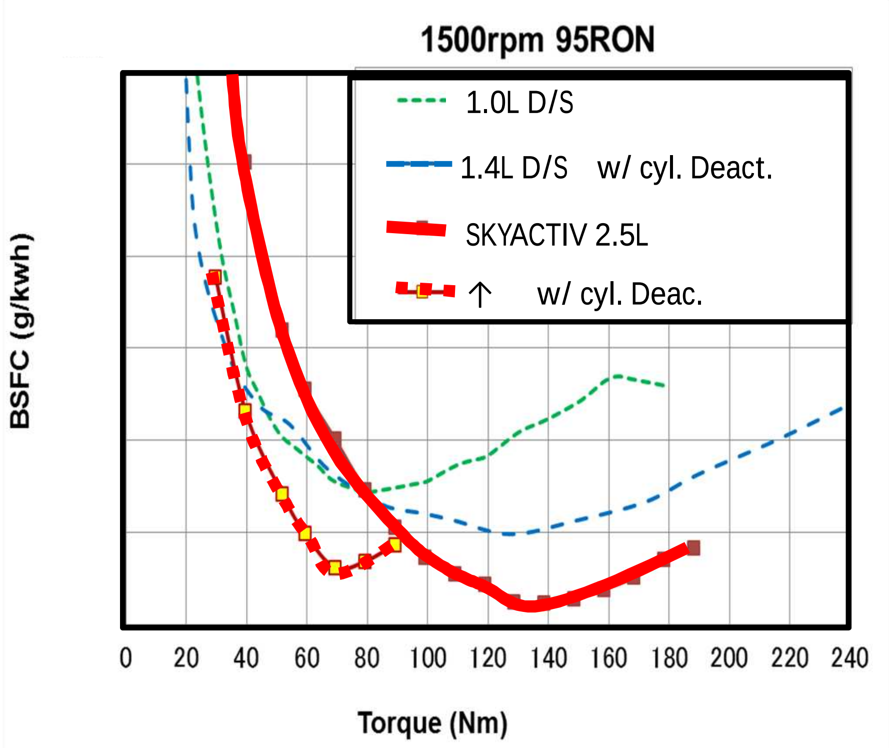


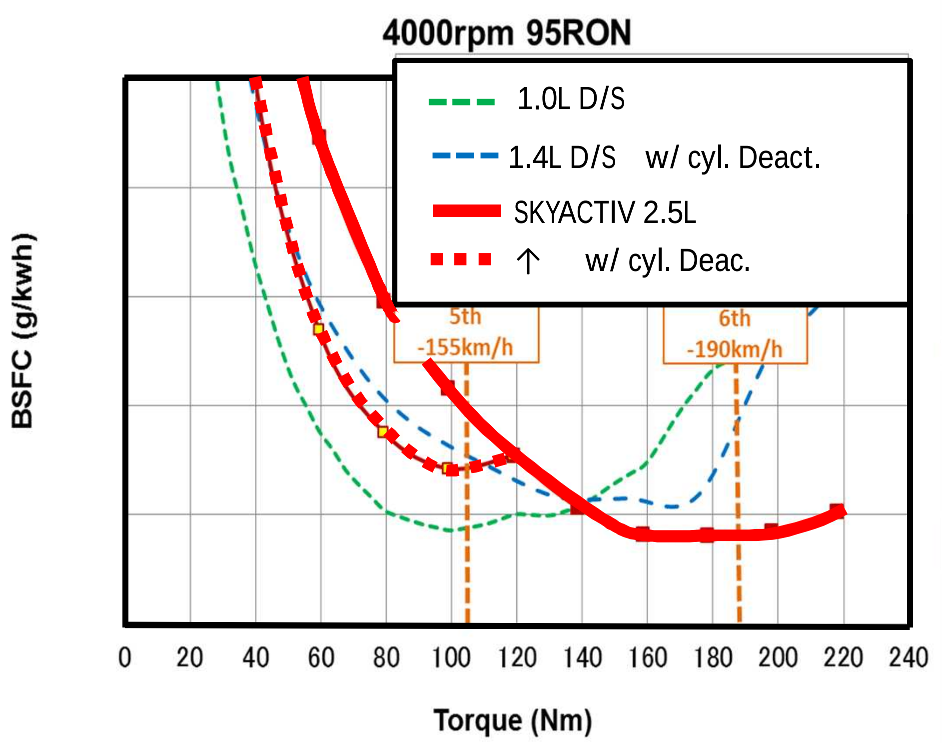


2L SKYACTIV engine can be superior to 1.4L boosted D/S engine with a cylinder deactivation system, and 1L 3 cylinder boosted D/S engine in all operational ranges.

Investigation results of boosted downsizing engines

Comparison between 2.5L SKYACTIV and 1L and 1.4L boosted D/S





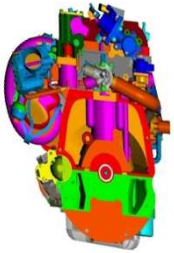
Even 2.5L SKYACTIV engine can be superior to 1.4L 4-cylinder boosted D/S engine with a cylinder deactivation system, and 1L 3 cylinder boosted D/S engine in all operational ranges.

Investigation results of boosted downsizing engines

Cost

Base engine (Direct Injection)

Boosted D/S

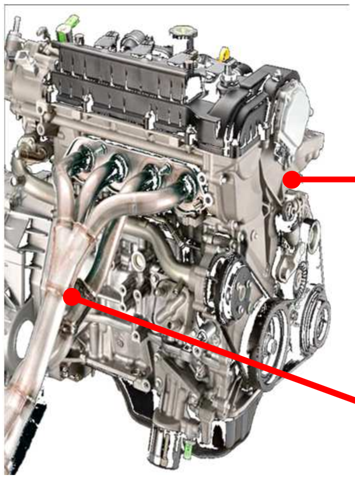


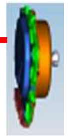
Turbocharger

Intercooler & piping

Strengthened piston ,con-rod, crankshaft, block, head

SKYACTIV-G





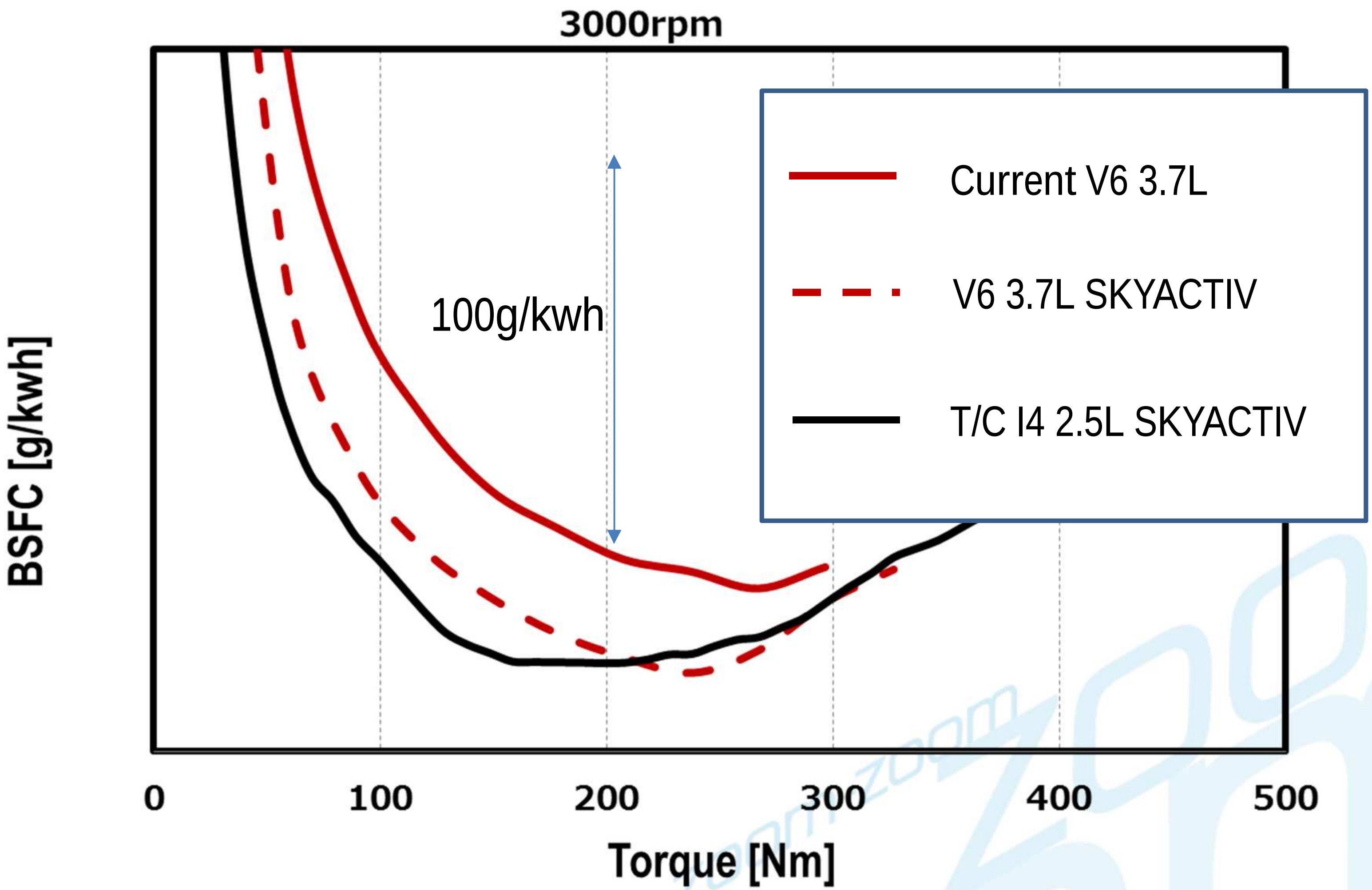
Electric VCT

4-2-1 exhaust

Boosted downsizing engines require extra expensive devices.

Investigation results of boosted downsizing engines

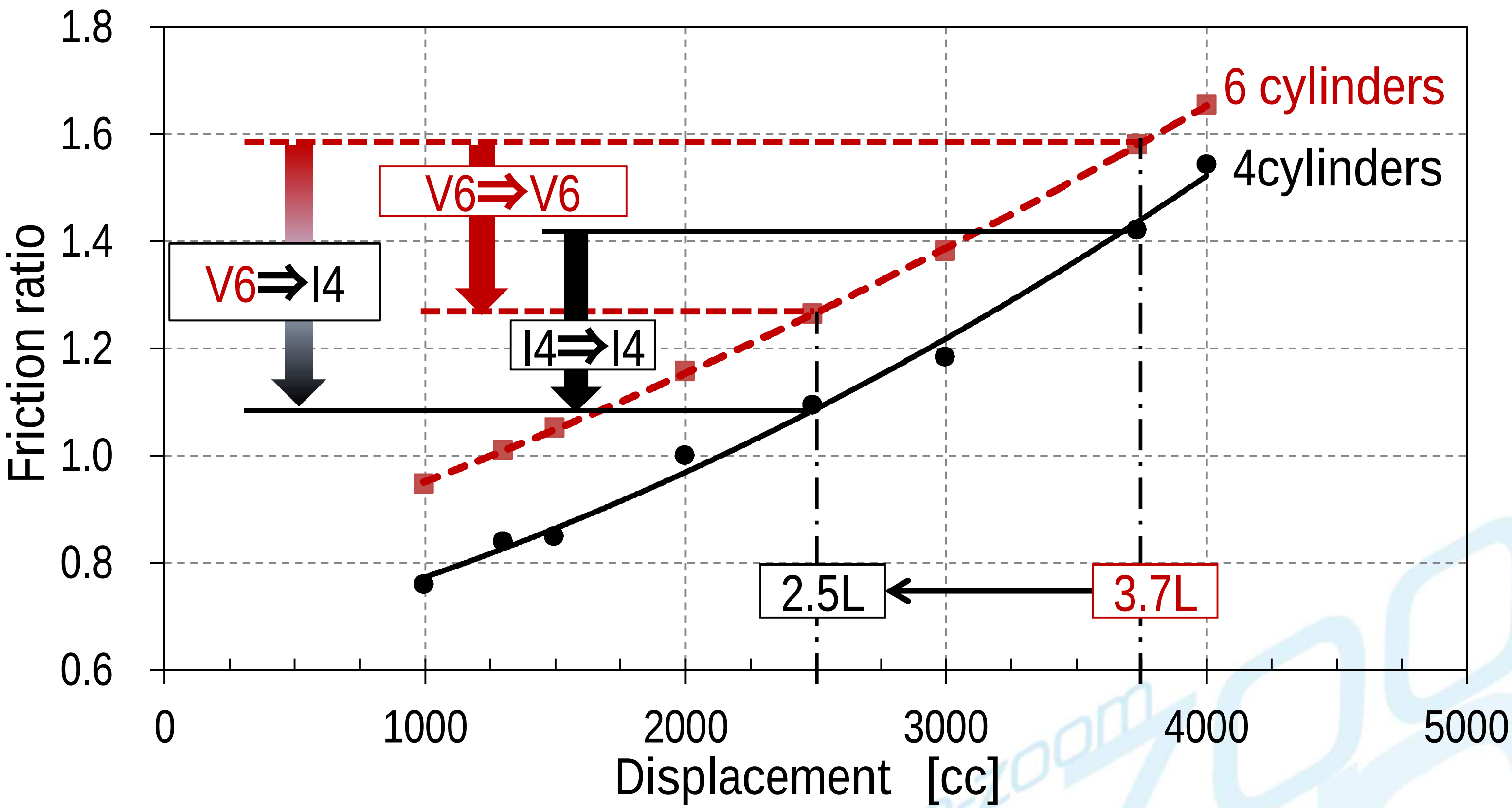
Turbocharged I4 SKYACTIV vs. NA V6 SKYACTIV



The most efficient way to downsize engines is to convert V engines to inline engines and downsize, while controlling knocking in the high load range with specific technologies to boosted engines.

Investigation results of boosted downsizing engines

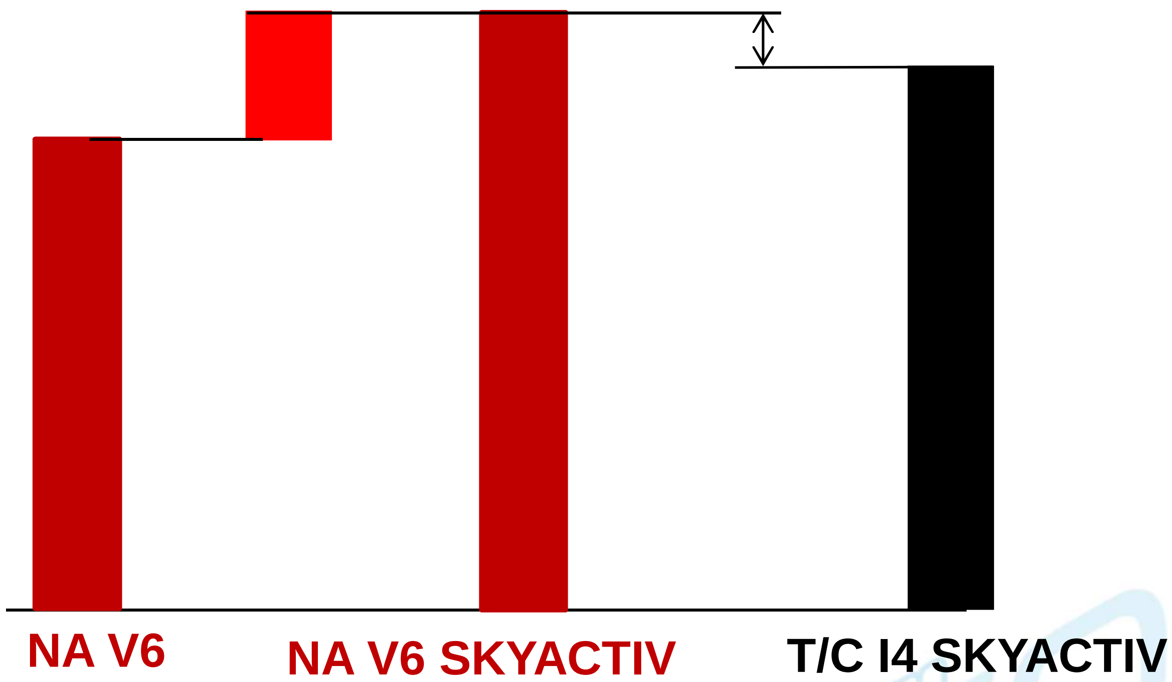
Effect of friction reduction by downsizing and cylinder number reduction



Mechanical friction reduction due to downsizing 3.7 L V6 to 2.5 L I4 is 1.6-times greater than downsizing 3.7 L V6 to 2.5 L V6 or 3.7 L I4 to 2.5 L I4. As a result, fuel economy is significantly improved.

Investigation results of boosted downsizing engines

Cost comparison between NA V6 SKYACTIV and Turbocharged I4 SKYACTIV

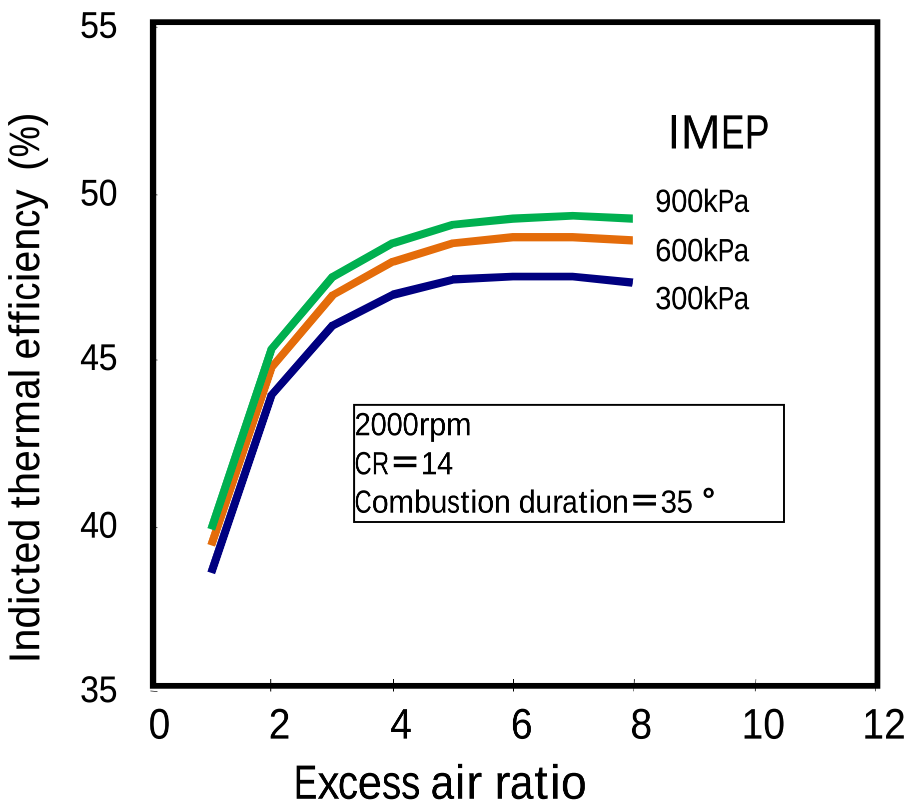


- To convert a NA V6 engine to a T/C I4 SKYACTIV engine with 4 cylinders, costs of some devices, such as an electric VVT, a high-pressure fuel rail and others will be halved than to convert a V6 engine to a V6 SKYACTIV engine.
- The cost of an injector and coils will be reduced to two-thirds.
- When an inlet 4-cylinder engine is converted to a inlet 4-cylinder SKYACTIV engine, the cost of additional devices are unchanged. The cost is raised due to a turbocharger.
- In the case of a 3-cylinder engine, only costs of parts for one cylinder are saved.

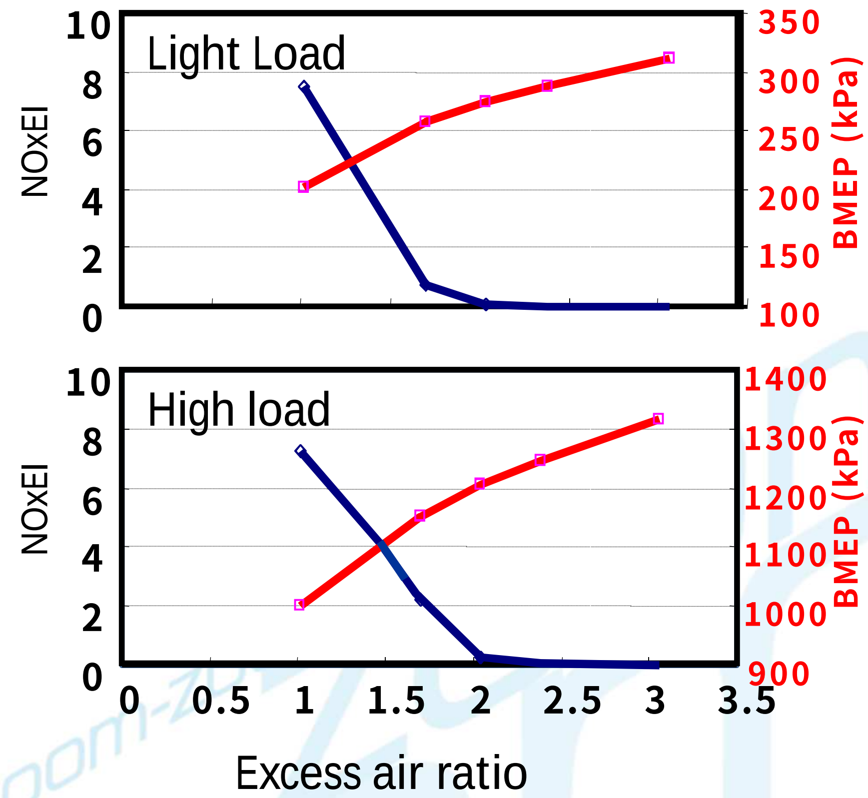
Future strategy for engine displacement

Target of lean burn

Excess air ratio vs. thermal efficiency



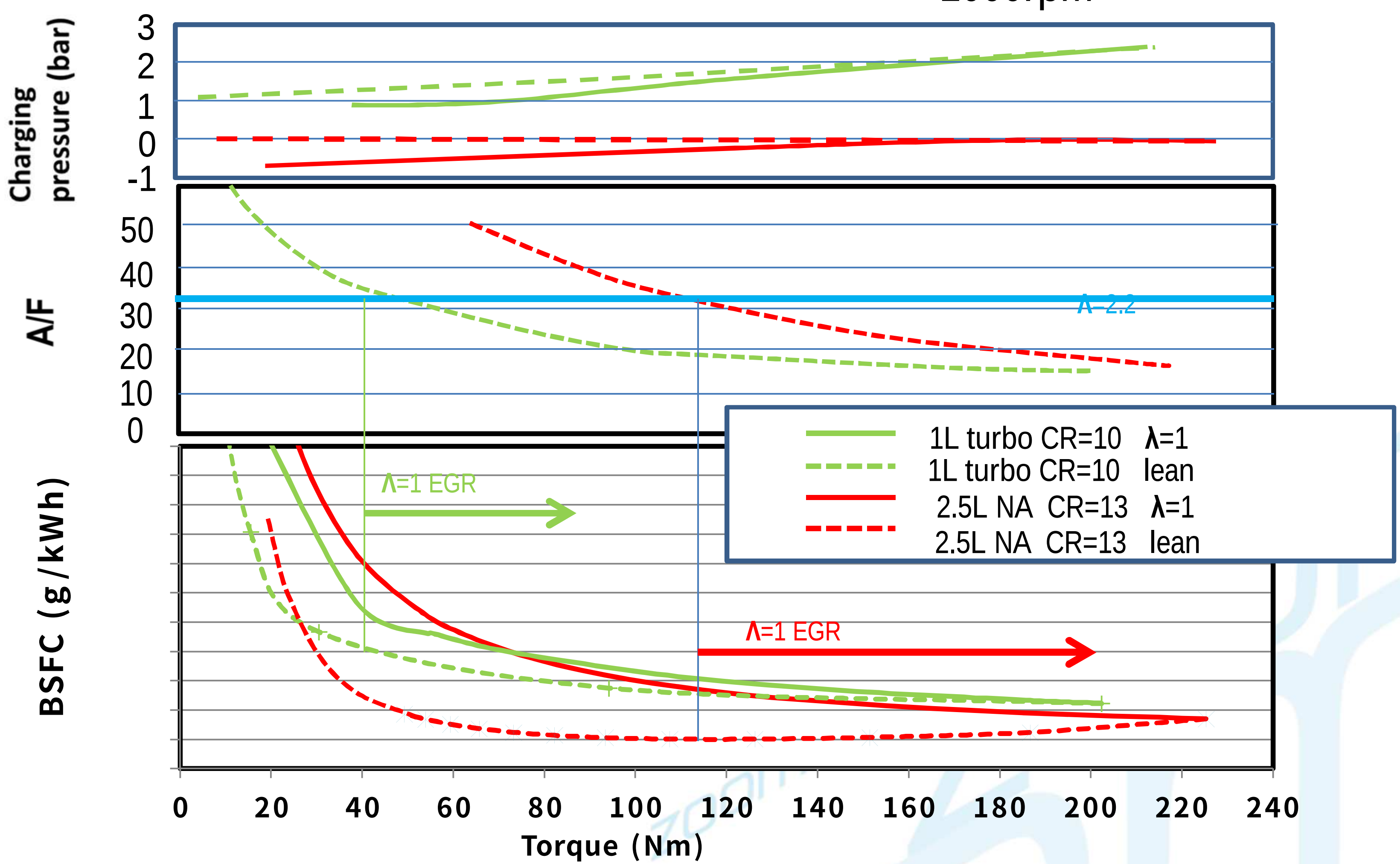
NOx vs. excess air ratio



Expanding Λ>2.2 is required for the compatibility of both efficiency and no NOX after-treatment

Future strategy for engine displacement

Lean burn capable area against displacement



Large Disp. NA can enlarge lean-burn area wider than boosted downsizing.
Boosted Upsizing for wide lean-burn area is recommendable

Examination of fuel economy

Examination of fuel economy

Average mileage /year

Country	Mileage/year (km)	Vehicle age（years）
Japan	9,896	5,84
United States	18,870	8,30
England	14,720	6,20
Germany	12,600	6,75
France	14,100	7,50

Ref.） report from investigative commission on c lean diesel passenger car growth・future prospect July 2008

Averaged mileage/year is somewhere between 10,000 and 15,000 km. (US excluded.)

Examination of fuel economy

Real world fuel economy (US)

Consumer report 2013

Midsized cars

Fuel economy (mpg)		COMBI	CITY	HWY
1	Ford Fusion SE Hybrid	39	35	41
2	Toyota Camry Hybrid XLE	38	32	43
3	Volkswagen Passat TDI SE	37	26	51
4	Hyundai Sonata Hybrid	33	24	40
5	Mazda6 Sport	32	22	44
6	Nissan Altima 2.5 S (4-cyl.)	31	21	44
7	Honda Accord LX (4-cyl.)	30	21	40
8	Chevrolet Malibu Eco	29	20	41
9	Toyota Camry LE (4-cyl.)	27	19	41
10	Hyundai Sonata GLS	27	18	39
11	Subaru Legacy 2.5i Premium	26	18	35
12	Chevrolet Malibu 1LT	26	17	38
13	Toyota Camry XLE (V6)	26	17	37
14	Honda Accord EX-L (V6)	26	16	39

COMPACT CARS Overall mpg = 29 or higher

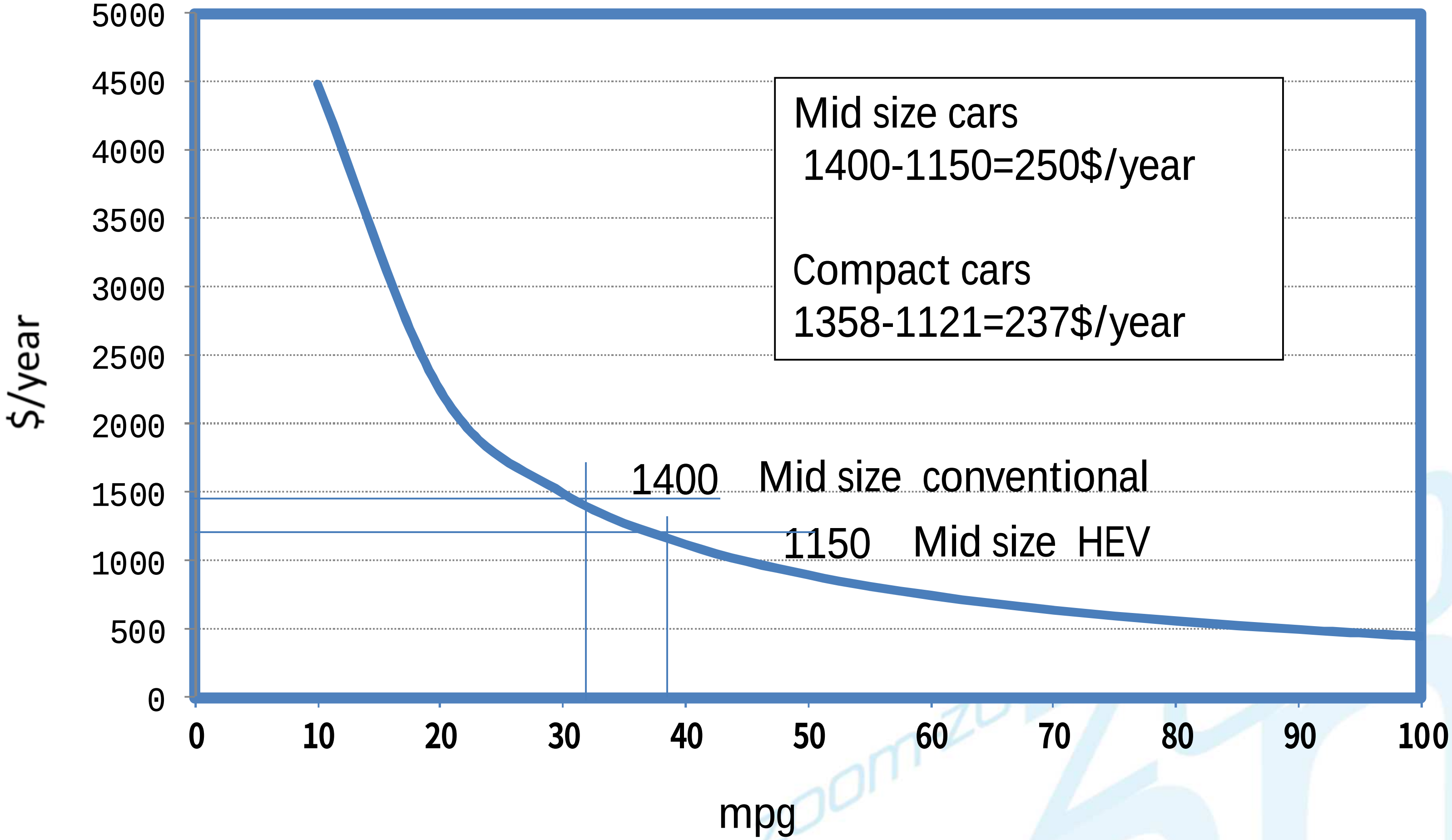
Fuel economy (mpg)		COMBI	CITY	HWY
1	Honda Civic Hybrid	40	28	50
2	Volkswagen Jetta Hybrid SE	37	29	45
3	Volkswagen Jetta TDI	34	25	45
4	Mazda3 i Touring sedan	33	23	45
5	Chevrolet Cruze Turbo Diesel	33	22	49
6	Mazda3 i Grand Touring hatchback	32	24	41
7	Toyota Corolla LE Plus	32	23	43
8	Ford Focus SE SFE	31	21	43
9	Volkswagen Jetta SE (1.8T)	30	21	39
10	Nissan Sentra SV	29	21	38
11	Honda Civic EX	29	20	40
12	Hyundai Elantra GLS	29	20	39
13	Dodge Dart Rallye	29	19	41

Fuel economy of HEV is superior , however,…

Examination of fuel economy

Fuel cost / year

assuming 19,000km /year   gasoline price; 3.8$/gallon



Average drive cannot payoff the price increase by HEV by superior fuel economy

Summary

- We created roadmaps toward the ideal ICE and are steadily advancing developments accordingly.
- We introduced the world's highest compression ratio into the gasoline engines at the first step.
- We believe that our approach is more reasonable than the boosted downsizing approach from a perspective of real-world fuel economy and cost.
- We believe that hybrid-level fuel economy is achievable with just improving ICE technologies and that EV-level CO2 emissions is also achievable with improved ICE and simple hybrid technologies.
- We believe that the EV-level of well-to-wheel CO2 emissions is achievable with approx. 25% improvements from that of the current SKYACTIV. Once EVs have held a large share of the market, tremendous amount of electricity will have to be generated. As a result, EVs will be unable to obtain benefits from the current electric price due to the electric price increase.
- We regard large engine displacement as a cost free turbocharger, and plan to maximize its advantage and increase engine displacement.
- If expensive technologies which only improve fuel economy are offered to our customers, they cannot pay off high vehicle prices. Therefore, we continuously offer technologies together with additional values, such as driving pleasure.

Thank you for your attention!

Conclusion

1. Boosted downsizing engines show better BSFC at a light load. However, large displacement NA engines (SKYACTIV) show the better BSFC at a mid-and-high load due to higher compression ratios.

2. With introduction of cylinder deactivation systems into large-displacement NA engines, NA engines show better BSFC in all the operational ranges. The 2.5L NA engines beat the 1 liter turbo engines in both F/E and power performance.

3. Large-displacement NA engines have demonstrated their advantages in the real world fuel economy over boosted D/S engines.

4. It is clear that NA engines cost less than boosted D/S engines.

5. Further drastic improvements in thermal efficiency is possible with introduction of lean-burn technologies. It is easer to expand the lean burn area of large displacement engines.

<u>The best direction is upsizing.</u>

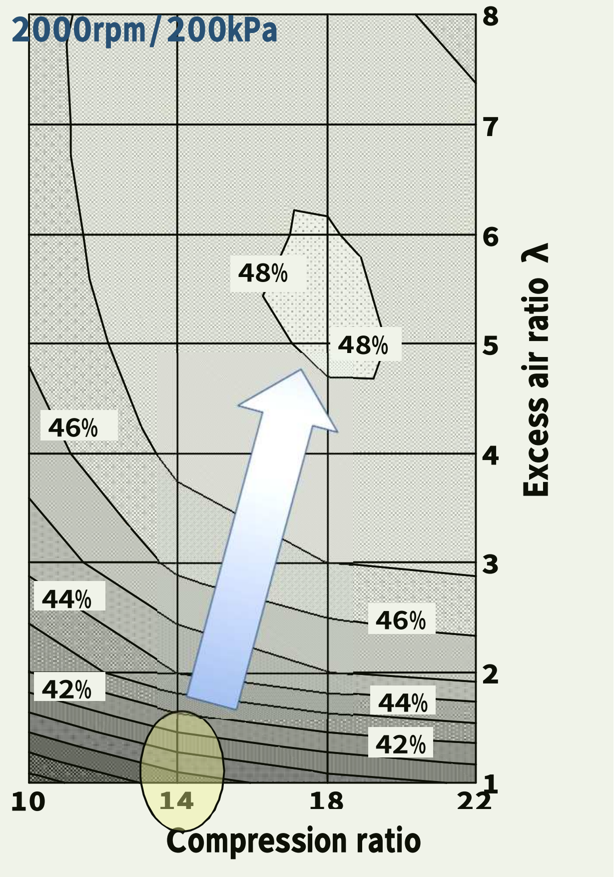
Additional message

- Fossil fuel reserve production said to be more than 170 years. (Source: World energy outlook 2011)
- Please assess CO2 on the well-to-wheel basis.
- Please bear in mind that establishing low CO2 electric power generation must come first before giving much incentives and prepare many electric chargers to expand EV use. This is the same for FCVs (fuel cell vehicles)
- It is possible to improve ICEs to achieve the well-to-wheel CO2 equal to that of EVs.

Drastic improvements of ICE efficiency are the most realistic way to improve the environment until a sustainable new energy source is developed.

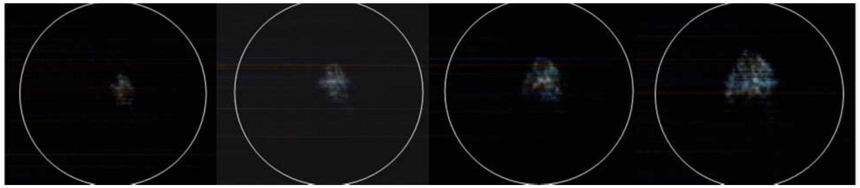
SKYACTIV engines: Next step

Further thermal efficiency improvement



SI

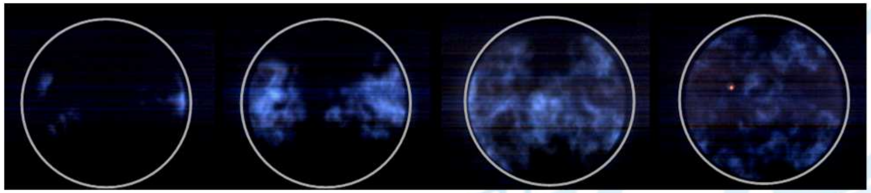
λ=2.0



SI lean-burn is not feasible at λ>2

CAI

λ=2.5



NOx=0 λ>2.2

The 2nd step engine targets higher CR & leaner CAI.

Goal of SKYACTIV engines

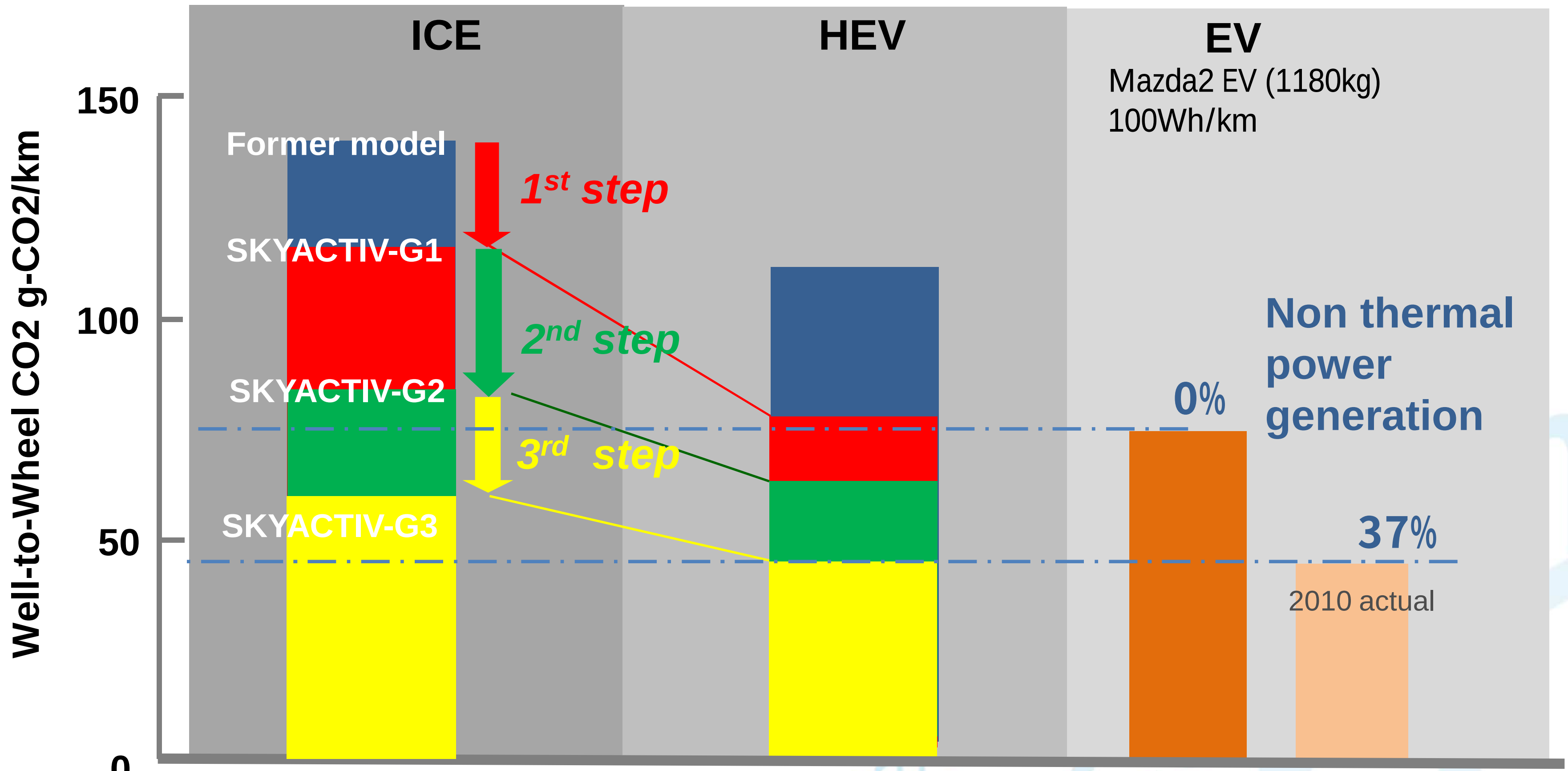
Comparison of thermal efficiency improvement

ICE vehicles will be able to attain the CO_2 level of EVs based on mode simulation.
Efficiency improvement for EVs is nearing its limit.

Goal of SKYACTIV engines

Targeted CO2 reduction level by ICE improvement

Case study Mazda2 JC08
(including vehicle improvement)

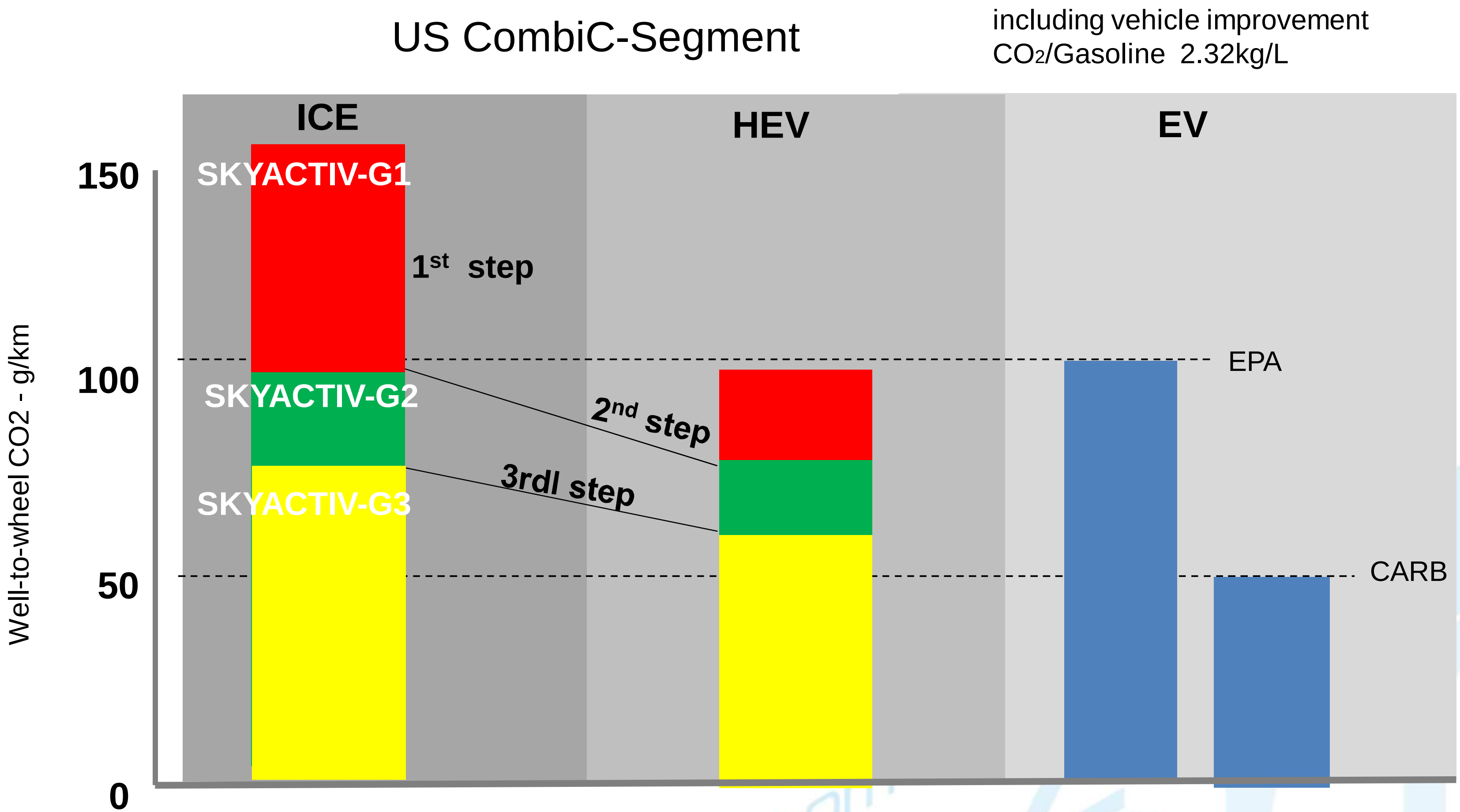


※Calculated based on Electric generation life cycle by Central Research Institute of Electric Power Industry(2010)

Aiming at CO2 level of EVs by ICE improvement

Goal of SKYACTIV engines

Targeted CO2 reduction level by ICE improvement



US average level of CO2 is achievable.