A Historical Analysis of the Co-Evolution of Gasoline Octane Number and Spark-Ignition Engines

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CrossMark

A Historical Analysis of the Co-evolution of Gasoline Octane Number and Spark-Ignition Engines

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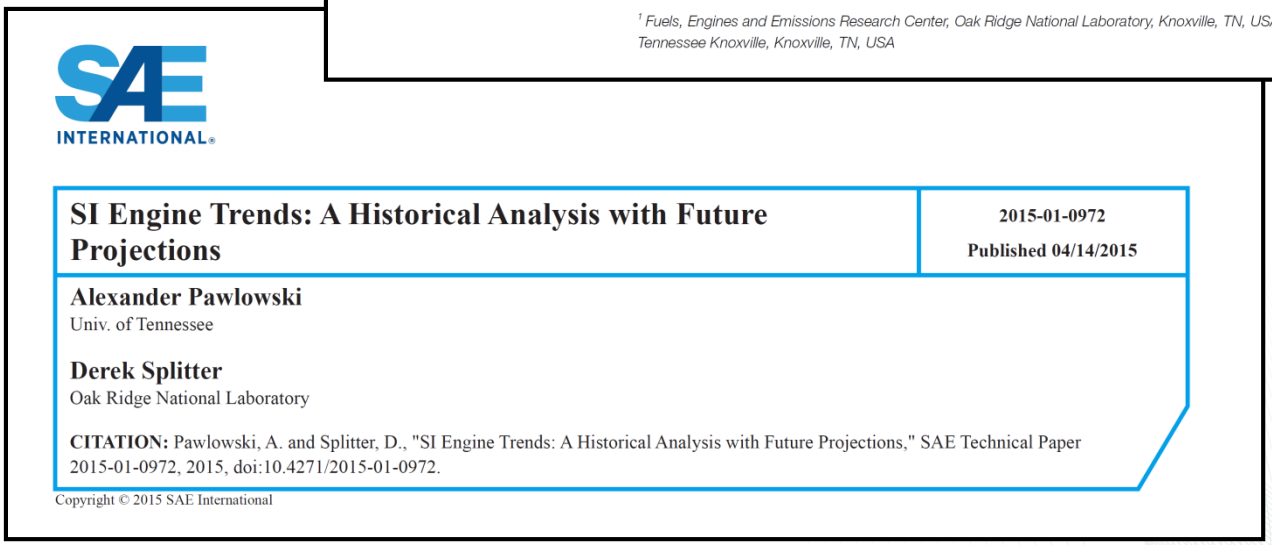
- **2015 SAE paper**



SAE INTERNATIONAL

SI Engine Trends: A Historical Analysis with Future Projections

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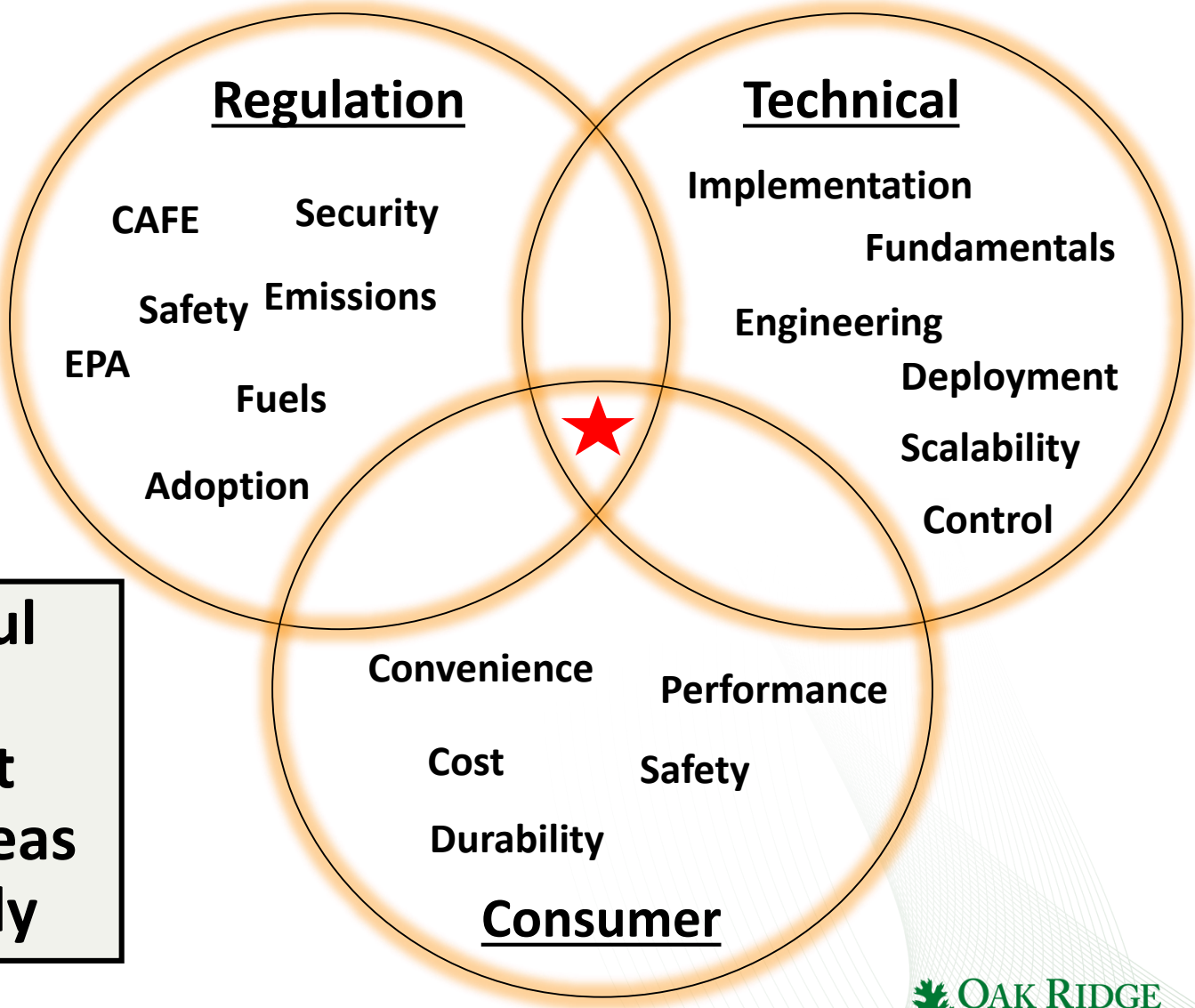
TRANSPORTATION FACES UNIQUE CHALLENGING CRITERIA

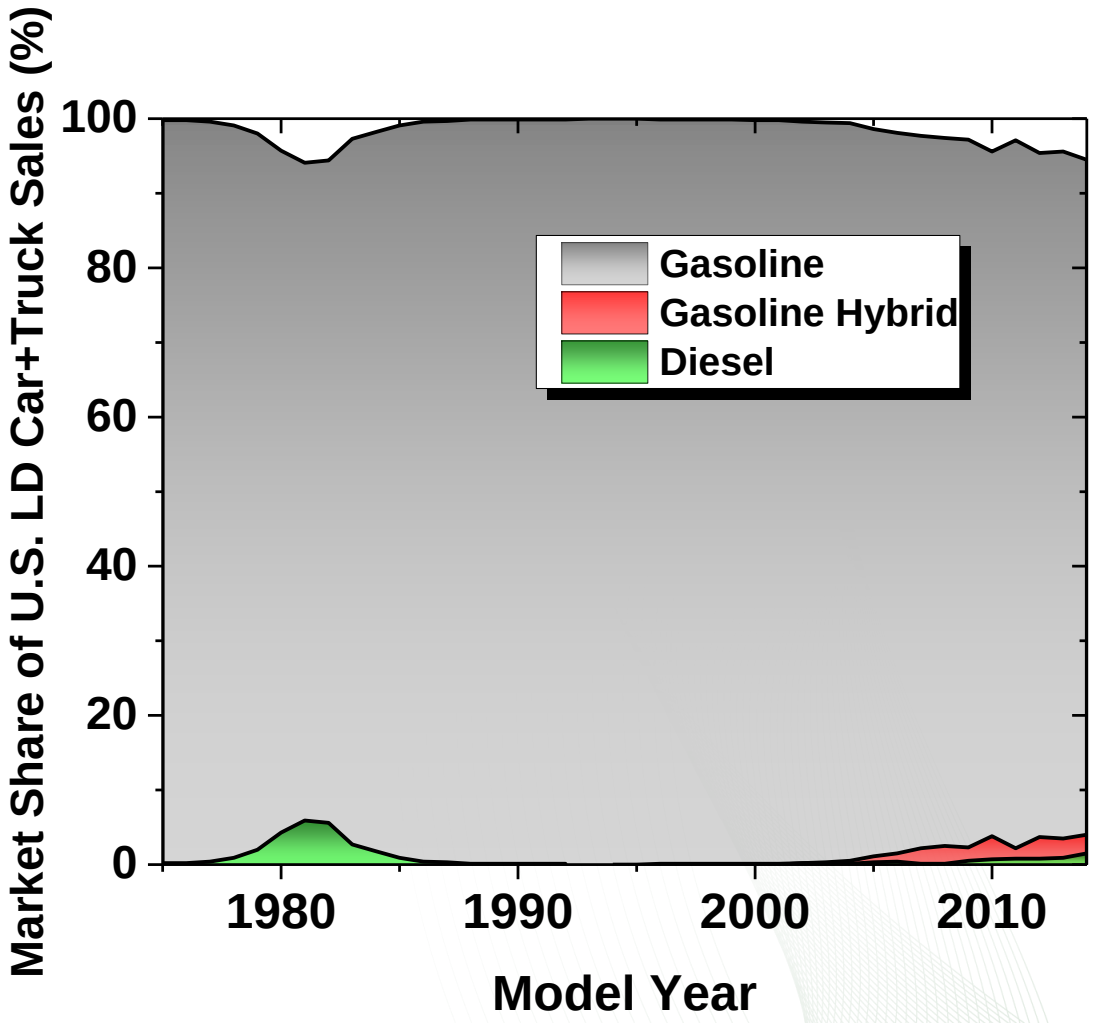
- **3 criteria in light-duty market**



- **Practical useful research and products must address all areas simultaneously**

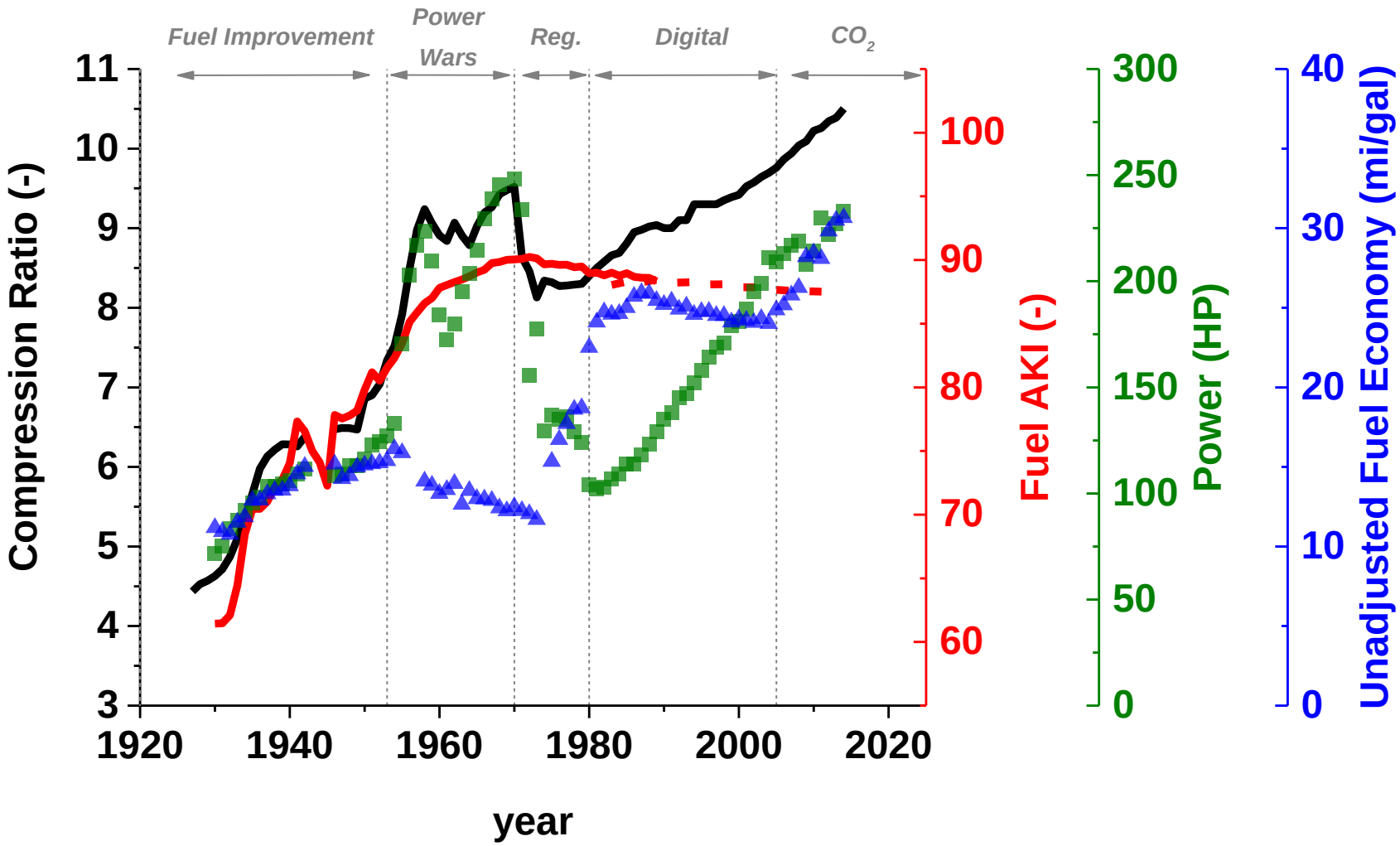
MEETING THE DESIGN CRITERIA HAS BEEN THOUGH GASOLINE ENGINES

- **US LD market is 99% gasoline powered**
- **All 3 rings must address gasoline and gasoline engines**



EPA 2014 LD Trends

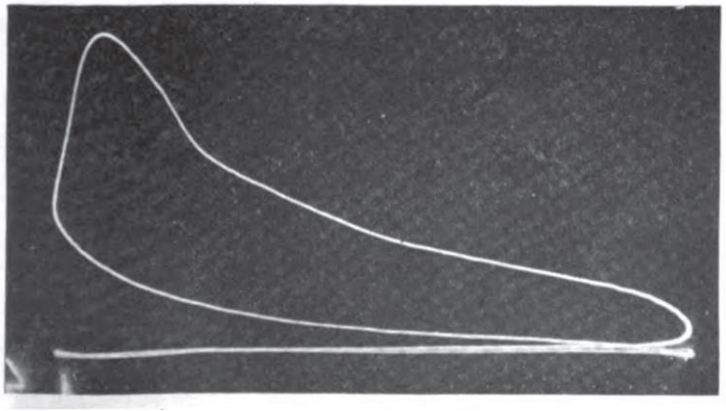
History has shown close coupling between fuel octane, efficiency, and performance, development is time sensitive, 5 defined "ages"

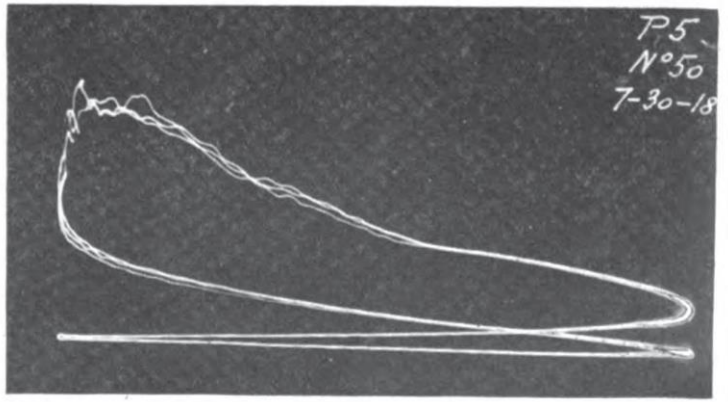


Fuel Improvements

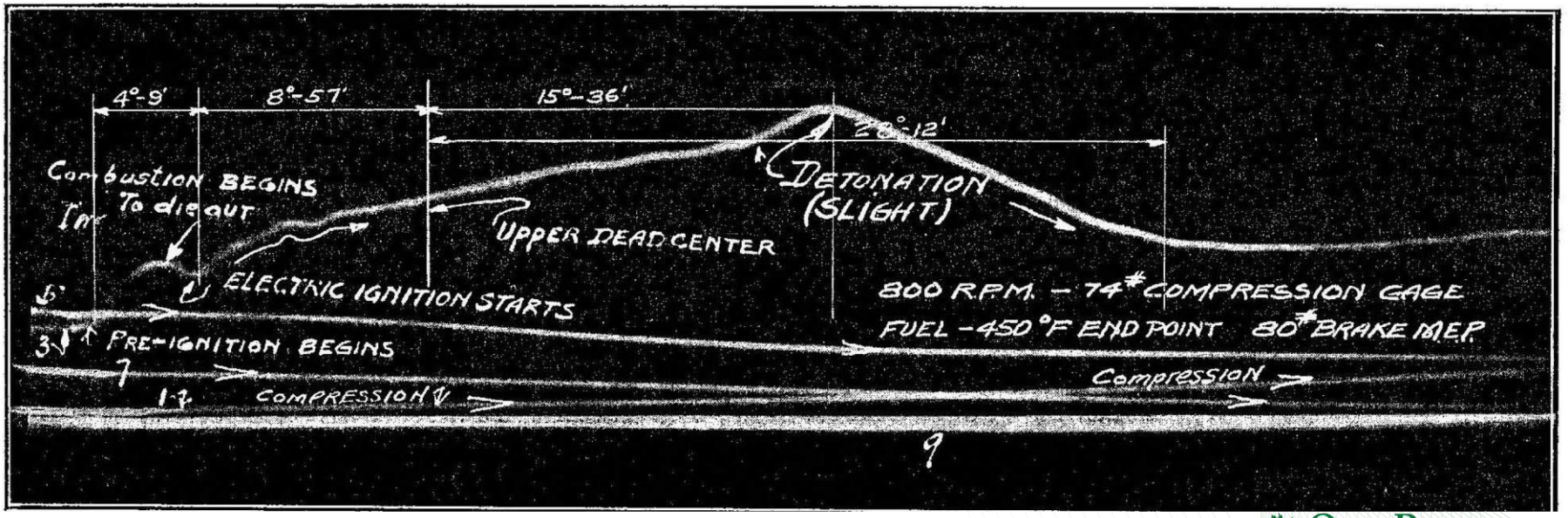
KNOCK FUNDAMENTALLY LIMITS COMPRESSION RATIO, IT HAS BEEN KNOWN AND STUDIED FOR A CENTURY, IT IS STILL AS RELEVANT TODAY AS THEN

***Automotive Industries*, Volume 38, 1918**





SAE 190067



EARLY KNOCK STUDIES WERE ABLE TO CORRELATE KNOCK TO FUEL KINETIC FUNDAMENTALS AND PROPERTIES

- In 1923 Harry Horning summarized the major work of the previous 8 years towards understanding knock and compression ratio ***SAE 230033***

Work indicated an accurate general understanding of fuel chemical kinetics

"1. The reaction coefficient, which is characteristic of a fuel and is related entirely to the force diagram in which the electrons of the fuel are arranged"

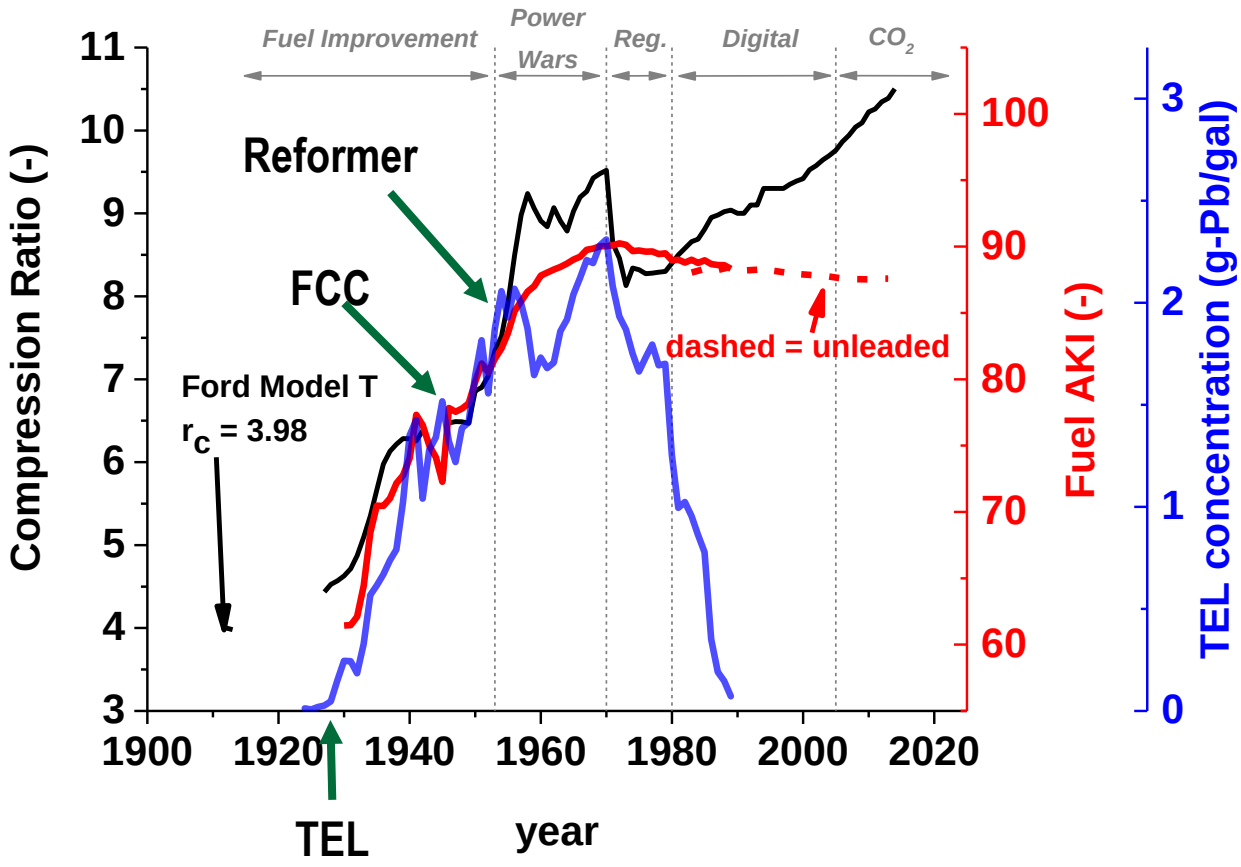
"2. Some power of the density of the fuel in the mixture"

"3. Some power of the absolute temperature"

Fuels "*composed of paraffines, which seem to be the least stable of all our common fuels…large molecules that are also considered less stable than the lighter, simpler ones.*"

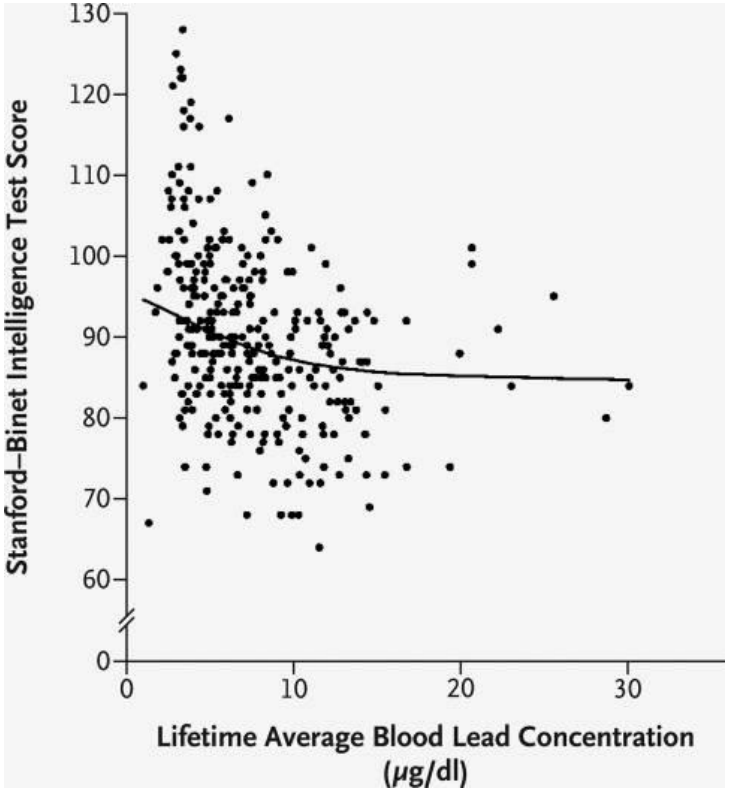
HISTORICALLY AKI INCREASE ENABLED C_R INCREASE, BUT RECENT DIVERGENCE

- Desire to raise r_c
  - Until ~1930 r_c ~4:1
  - FCC invented 1915
    - $ prohibitive pre-WWII
  - Catalytic Reformer invented ~1949
    - HO# from LO# naphtha
    - Deployed at scale in mid 1950's
  - TEL , discovered as AKI additive in 1922
    - Dichloroethane and dibromoethane added in 1928 and deployed at scale
    - lead oxides halogenides



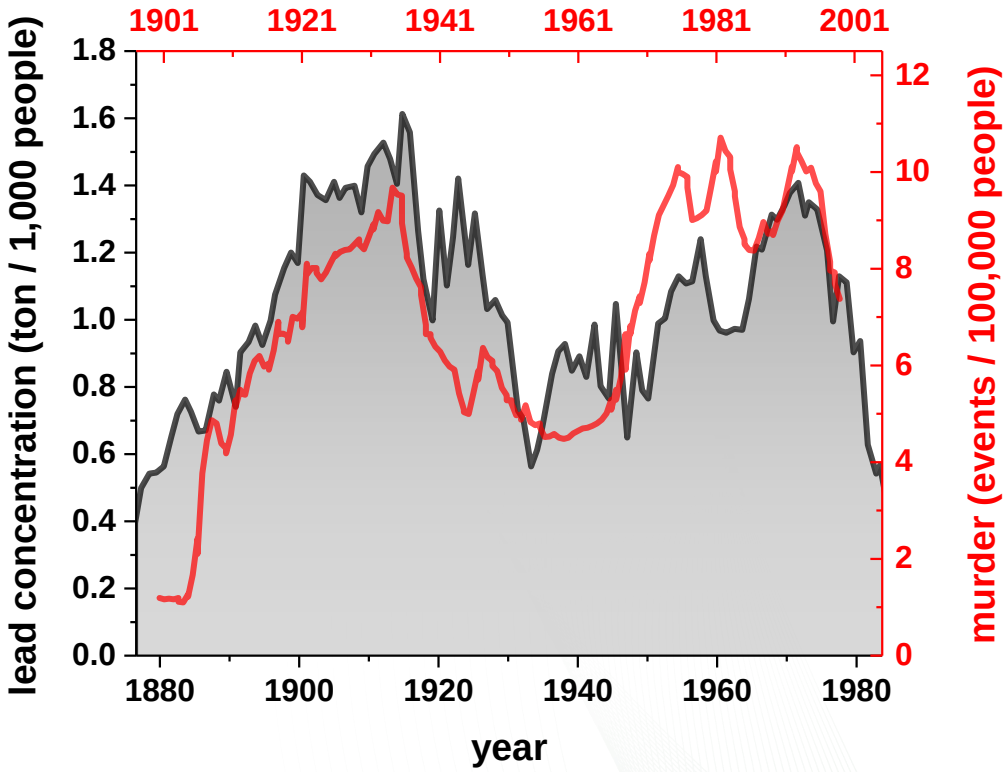
LEAD TOXICITY HAS BEEN KNOWN FOR CENTURIES, LEAD EXPOSURE TO CHILDREN REDUCES IQ, STRONG SOCIETAL IMPACT AS ADULTS

Children's IQ scores



Canfeild et al., N Engl J Med., 2003

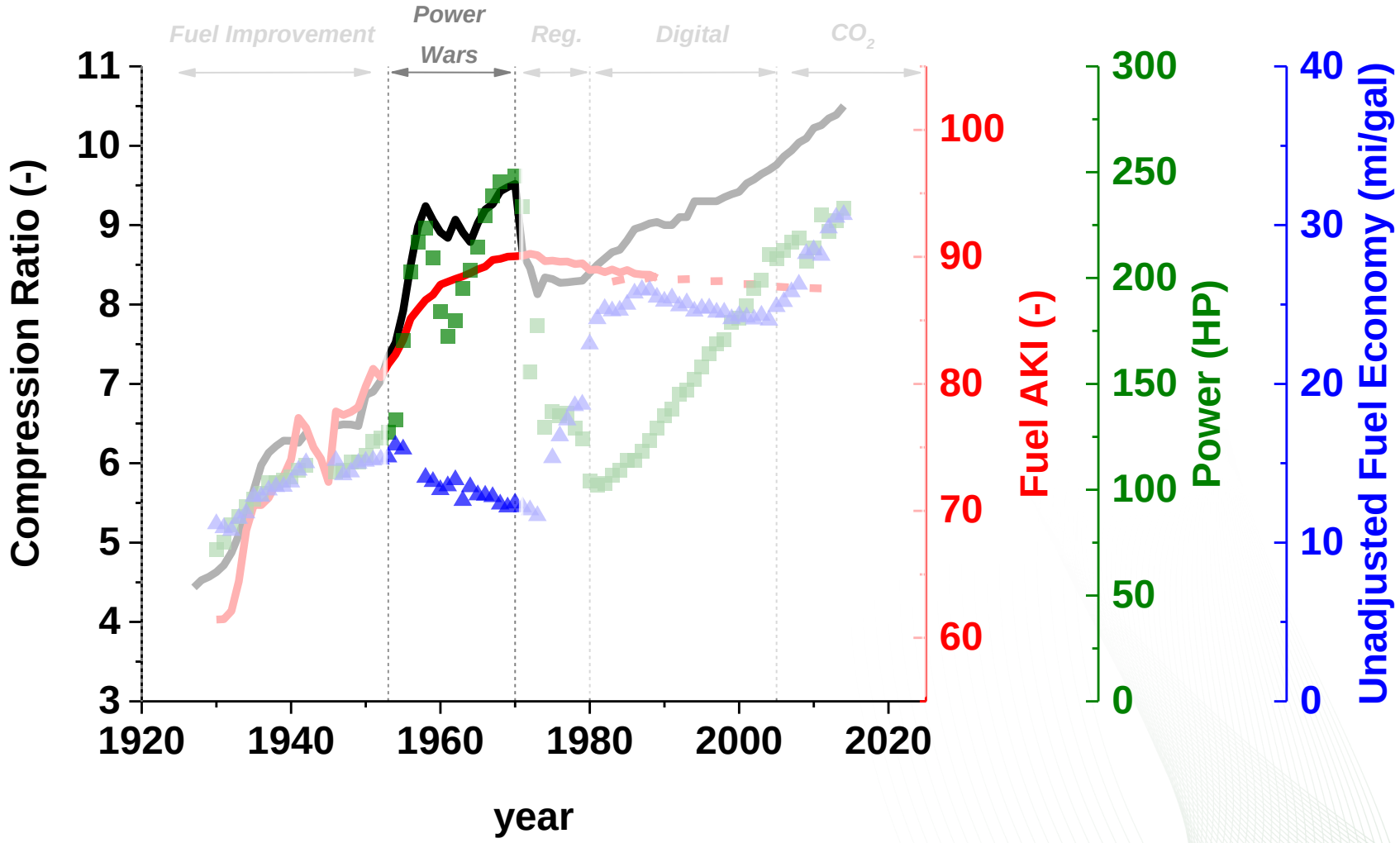
Lead usage & murder rate (21 year lag)



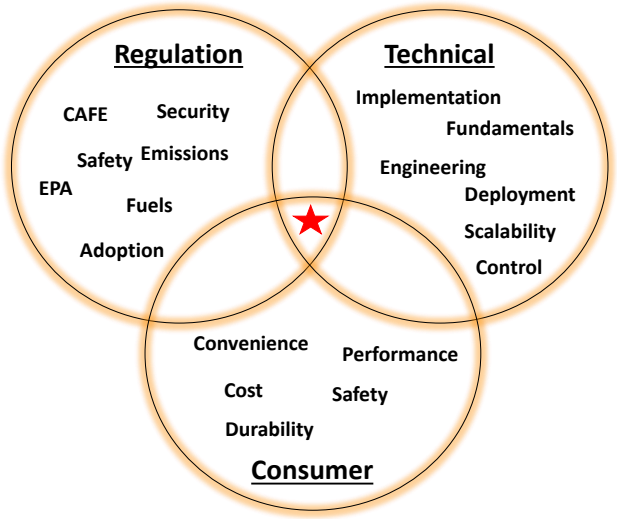
Nevin, Environmental Research, 2000

Power Wars

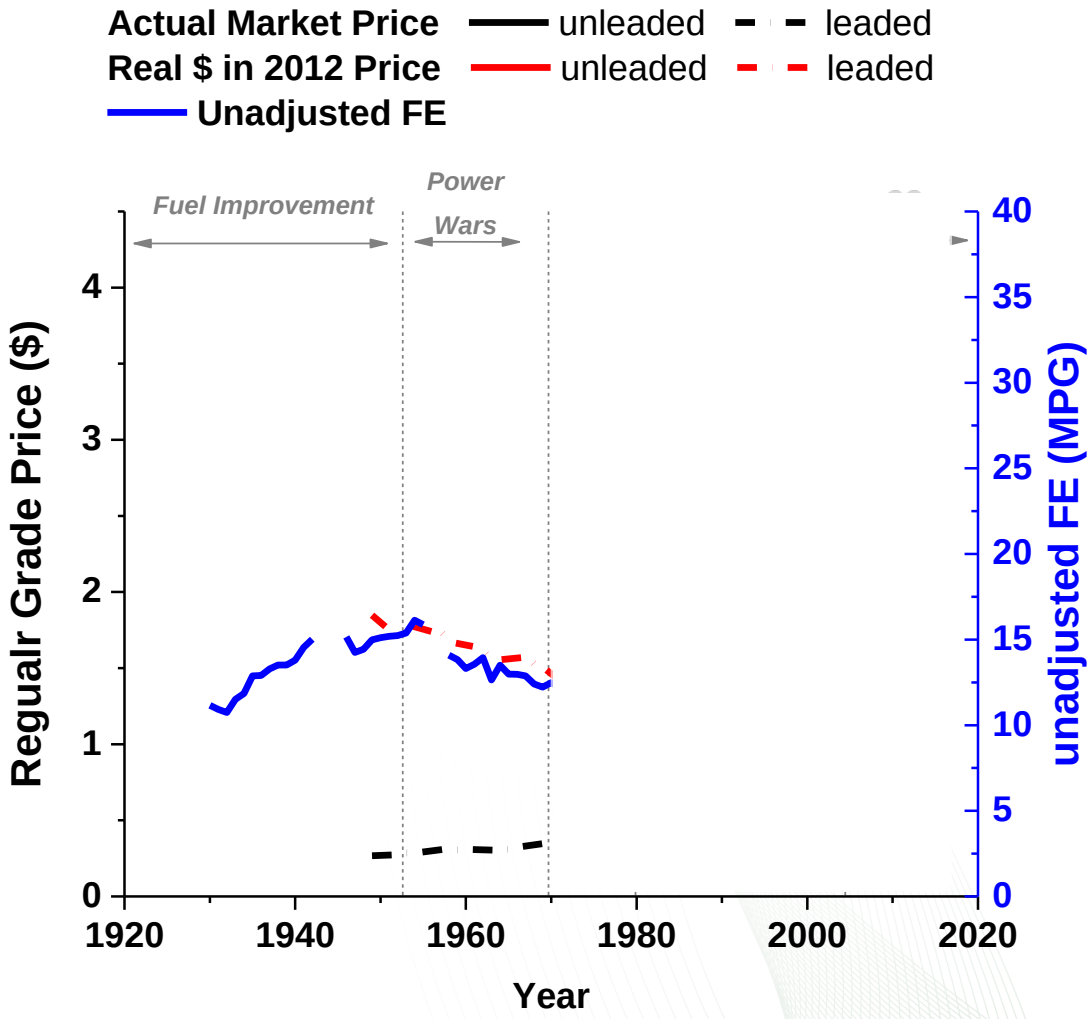
FUEL REFINING IMPROVEMENTS AND TEL ENABLED HIGH OCTANE NUMBER, ENGINES AND SOCIETY ADAPTED



HISTORICALLY, WHEN GAS IS CHEAP FUEL ECONOMY REDUCES

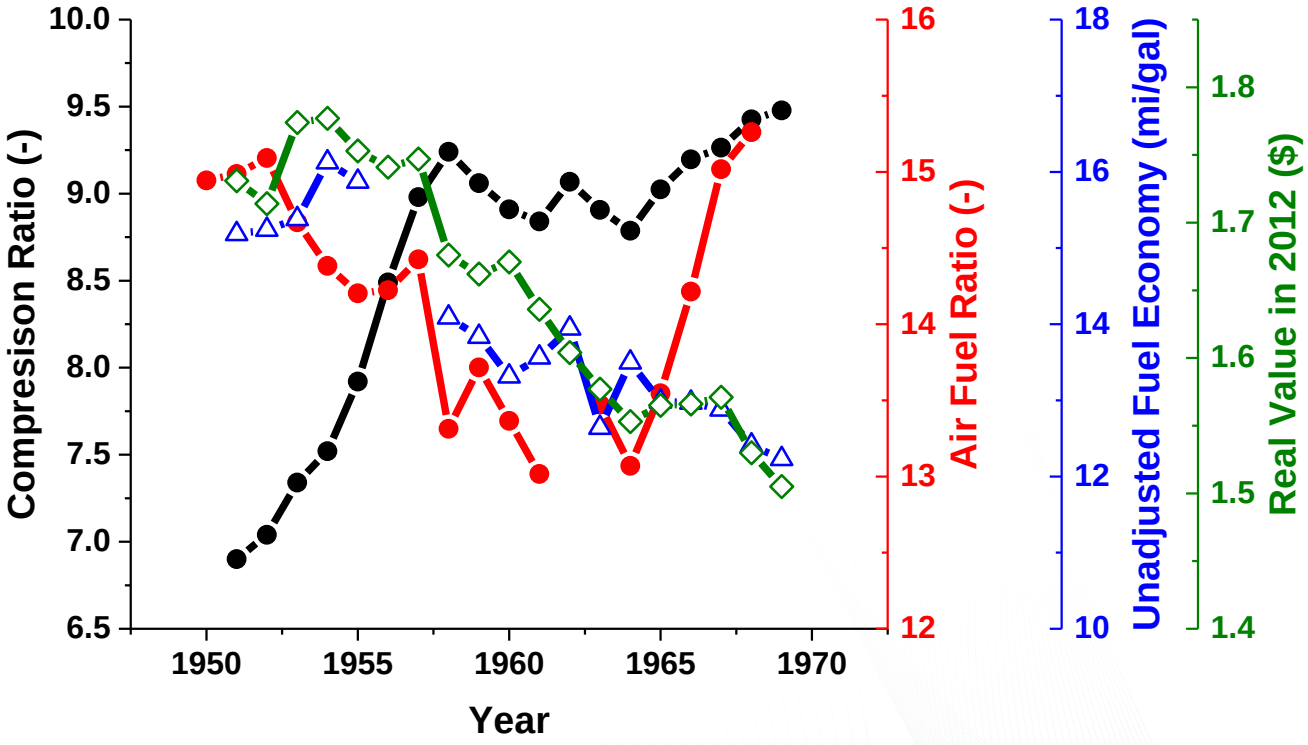


- Historically, when fuel economy reduced, gas was cheap
  - current market volatility illustrates this again



WITH NO REGULATION AND INEXPENSIVE HO FUEL, POWER INCREASED

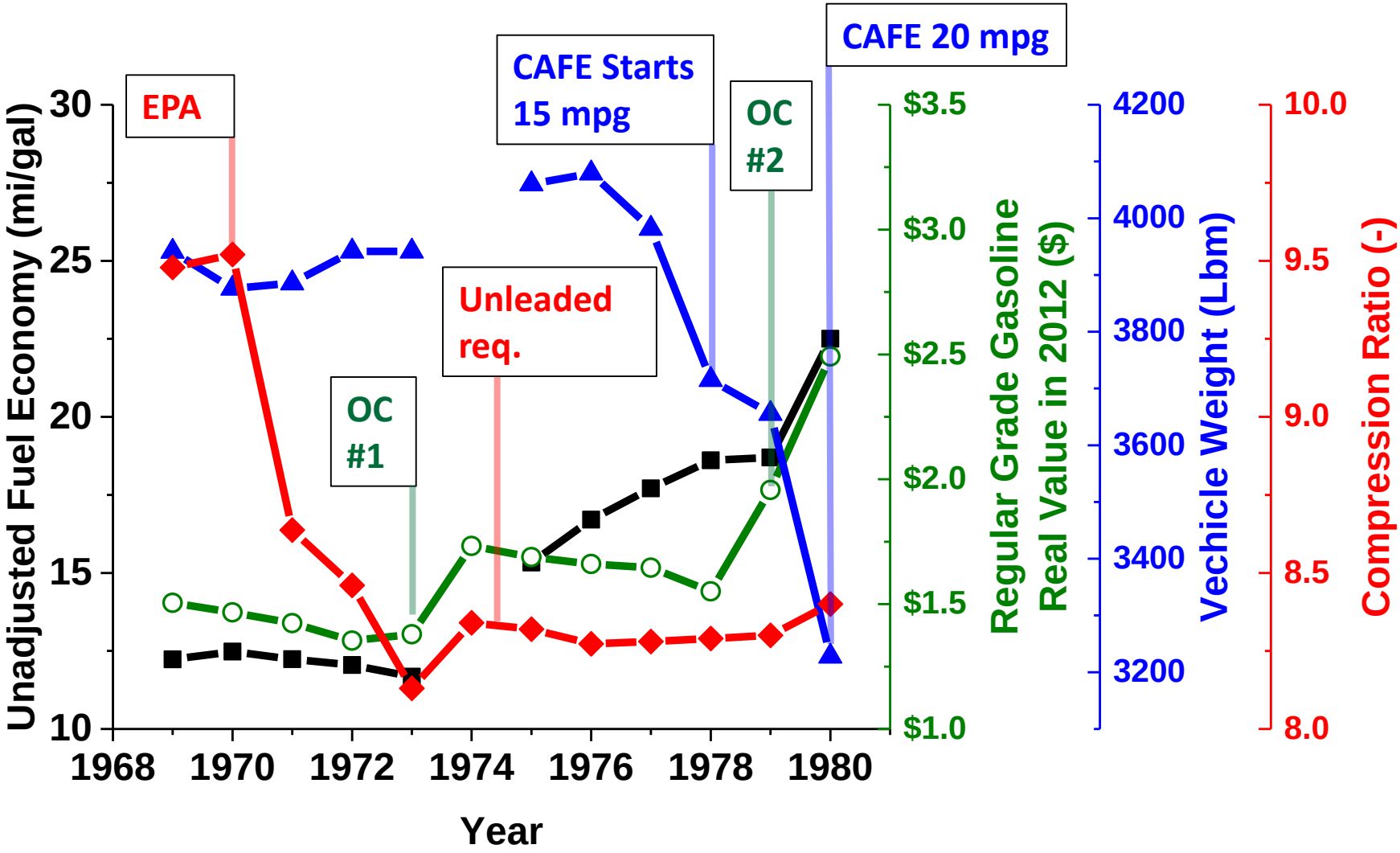
- Without regulation power was king
  - Customers & technology without regulation
  - Power peak in 1960's
  - Poor FE, and emissions
    - Looming reg. in 1969 (CARB) and 1970 EPA



Recovery of C_r and power of 1960's peak took ~30 years

Regulation

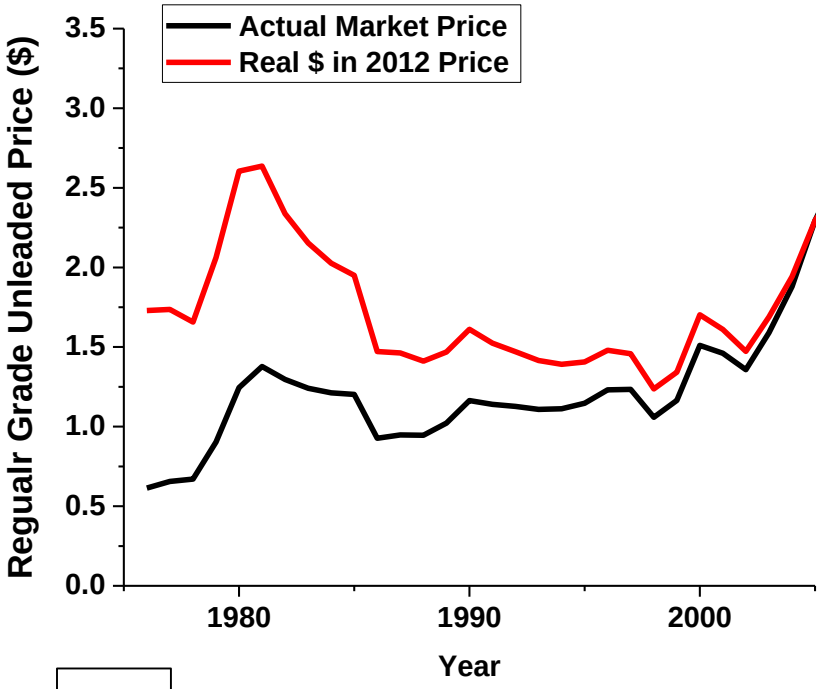
THE 1970'S BROUGHT A DYNAMIC LANDSCAPE AND MANY SIGNIFICANT CHALLENGES TO PERSONAL MOBILITY



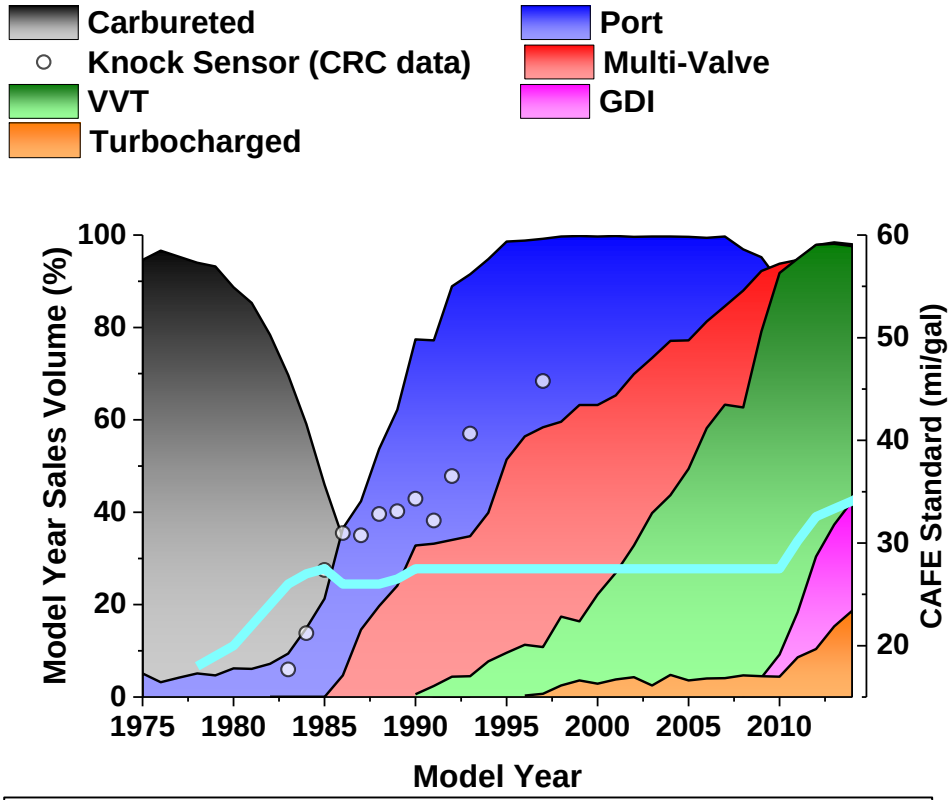
Digital Age

Digital age Technology advancement continued even with constant CAFE regulation, development and performance increase continued

- Technology has improved significantly, driven by emissions regulations (**TWC**)
- Enabled **"do more with less"** for engines, active knock control
- Fuel was cheap



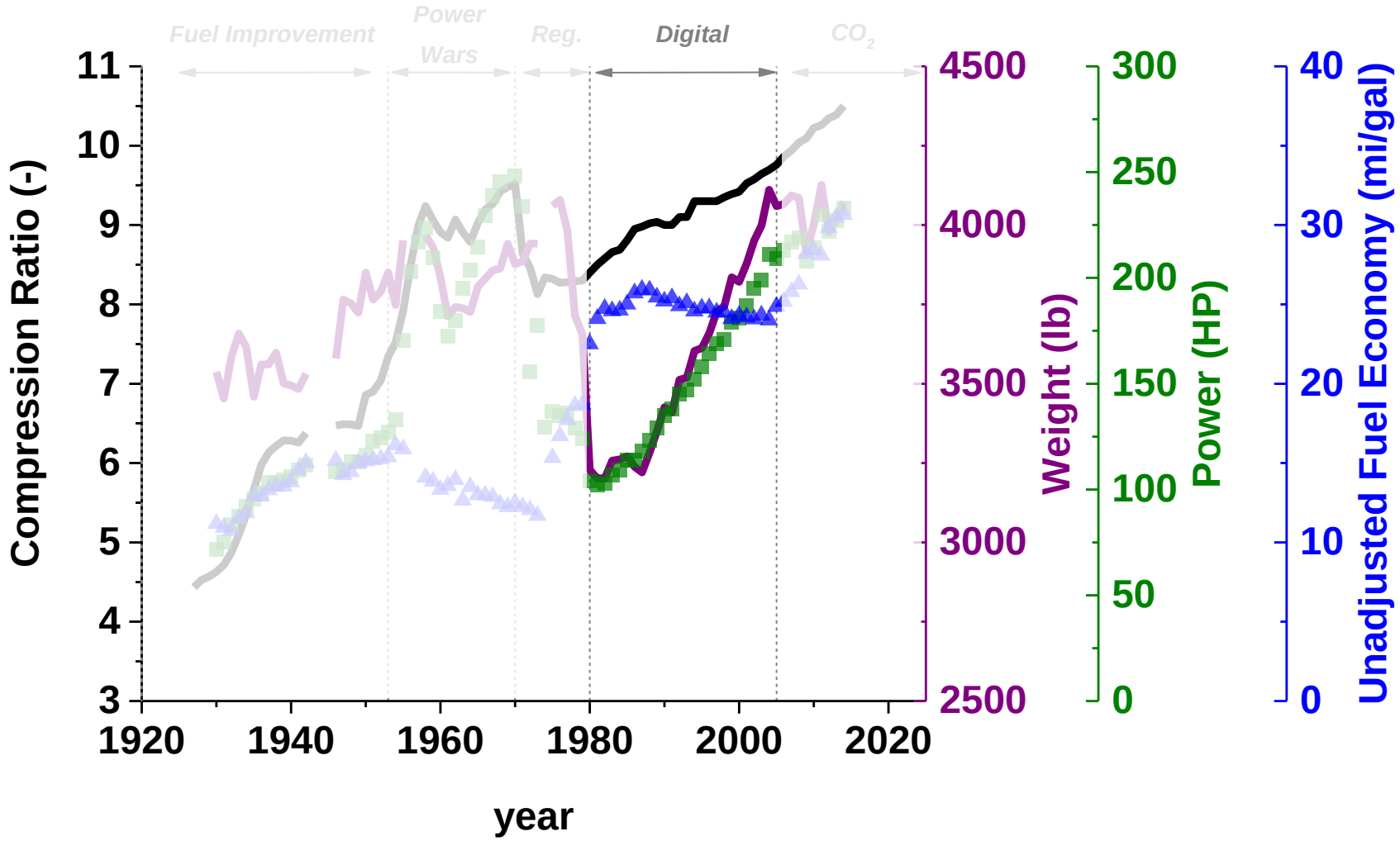
EIA



EPA 2014 LD Trends ; CRC 548, 566, 587, 619

FUEL ECONOMY IS NOT ONLY AN ENGINE FUNCTION, VEHICLE DESIGN ALSO ADAPTS

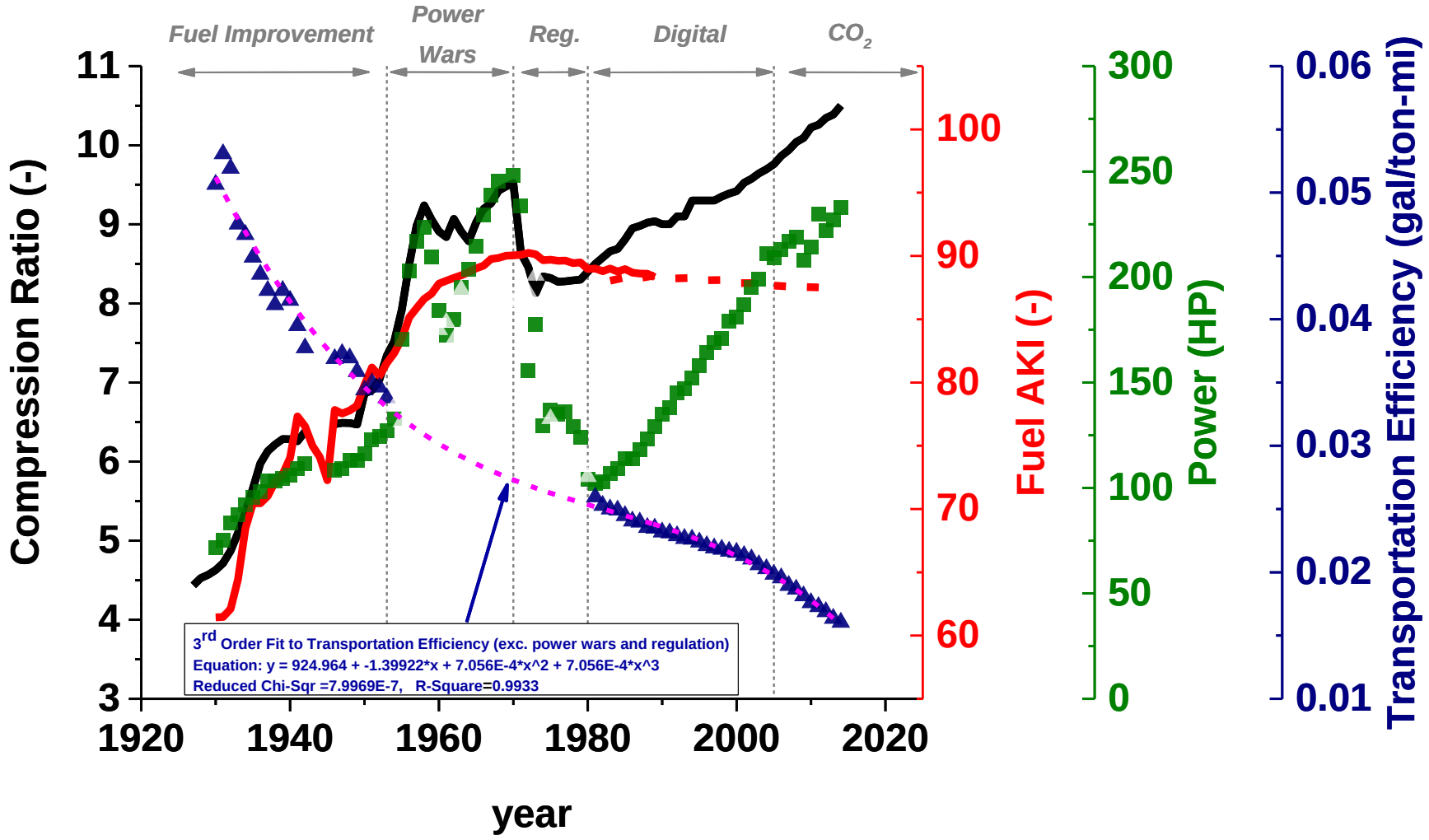
By ~2005, HP Cr and weight returned to their pre-regulation levels, but then compliant



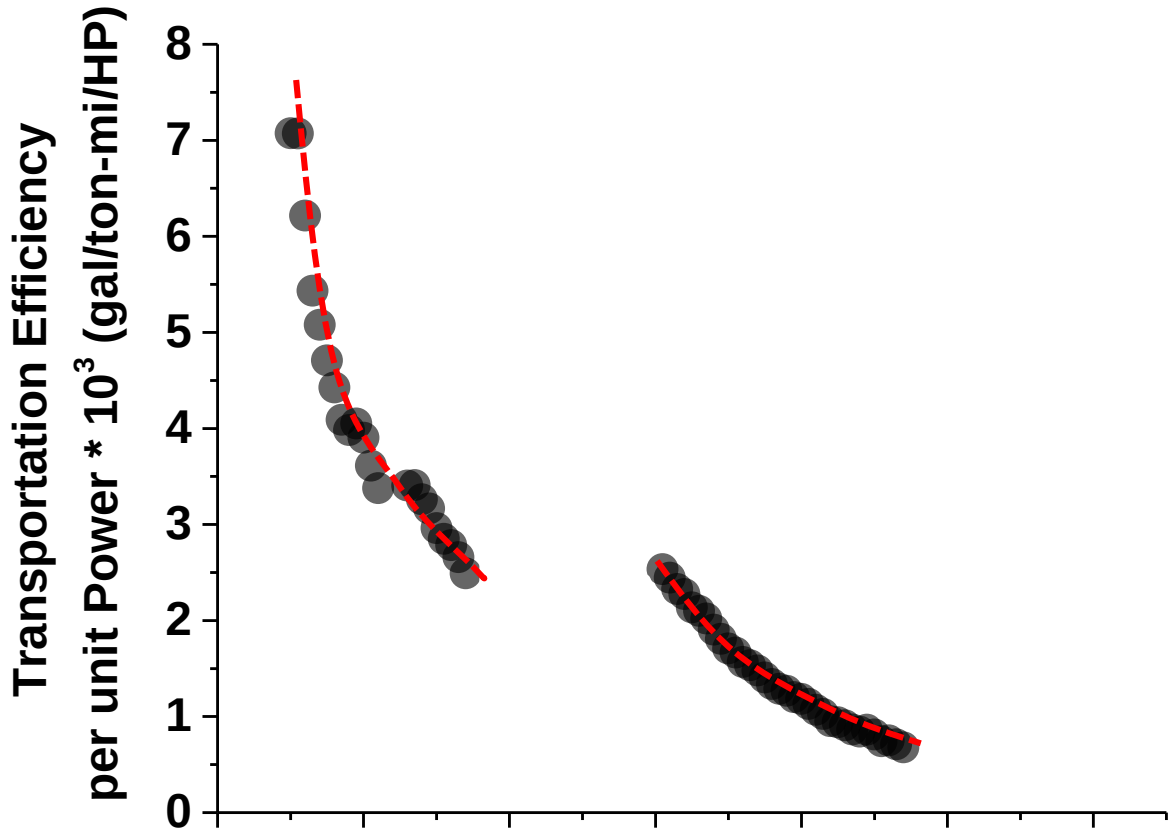
Overarching Historical Trends

TRANSPORTATION EFFICIENCY IS STRONGLY TIME DEPENDENT

Since ~1980 is the only time in history where HP, Cr, and TE improve, while AKI decreases



NORMALIZE WEIGHT BY FUEL ECONOMY, TRANSPORTATION EFFICIENCY

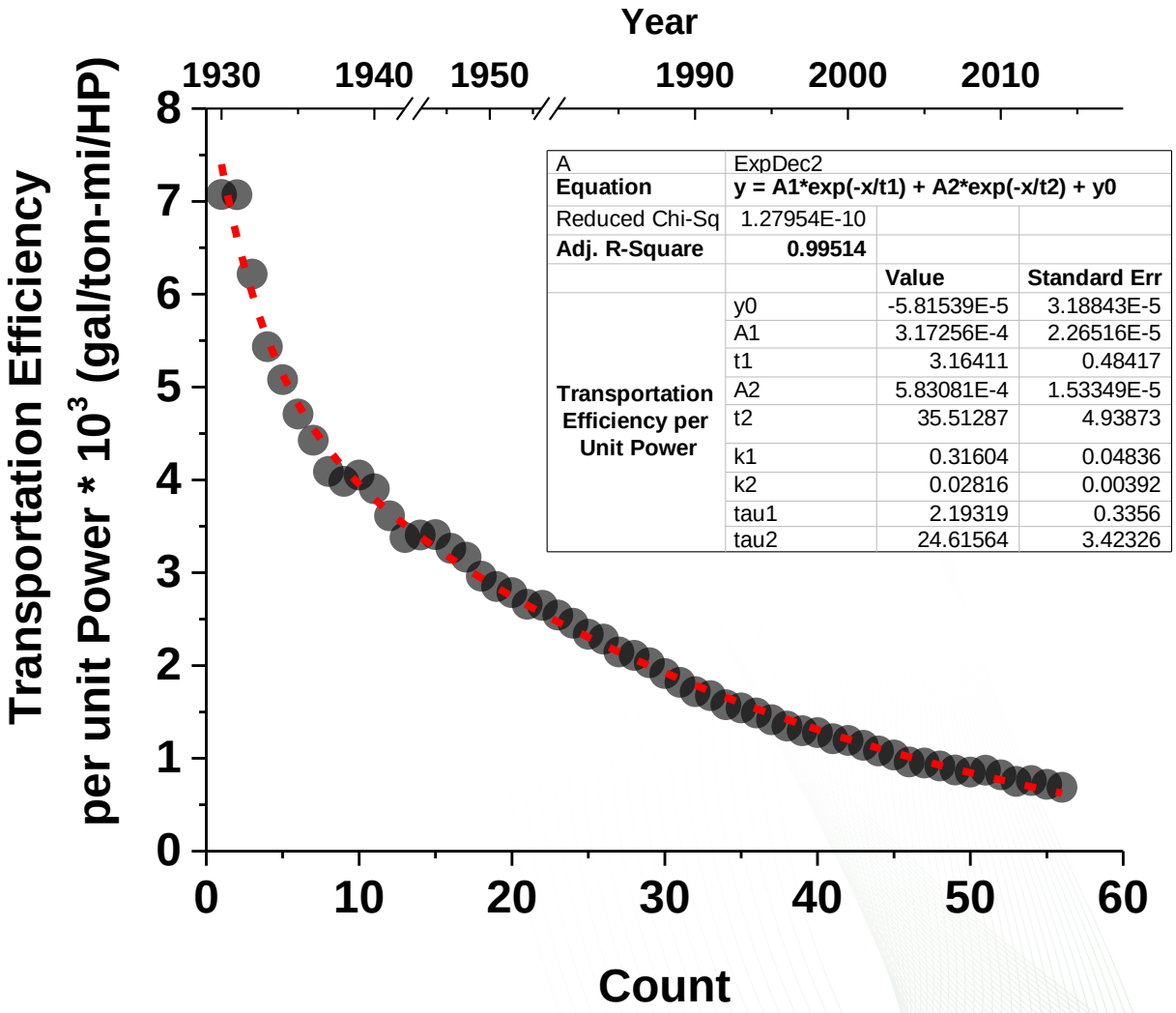


Physically cannot go negative

TE not fully capturing governing market trend

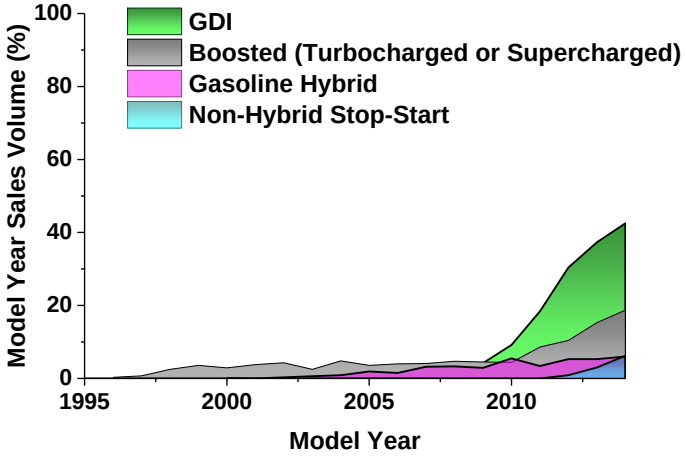
EXCELLENT EVOLUTIONARY TREND CAN BE ACHIEVED IF SELECT DATA ARE REMOVED FROM THE ANALYSIS

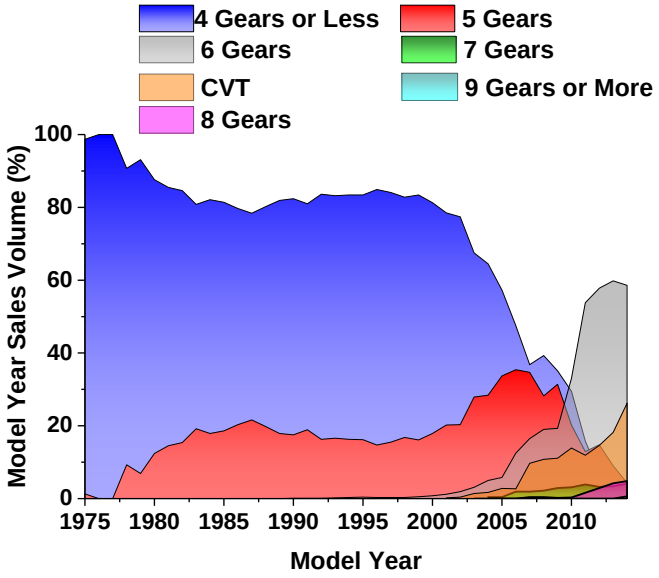
- Cut WWII (no production) & 1952-1980 “power wars” & “reg.”
  - Flat trend in TE/HP ignored
- Exponential decay is an excellent fit!
- Completely non-physical in time
  - Shows imbalanced development hinders progress



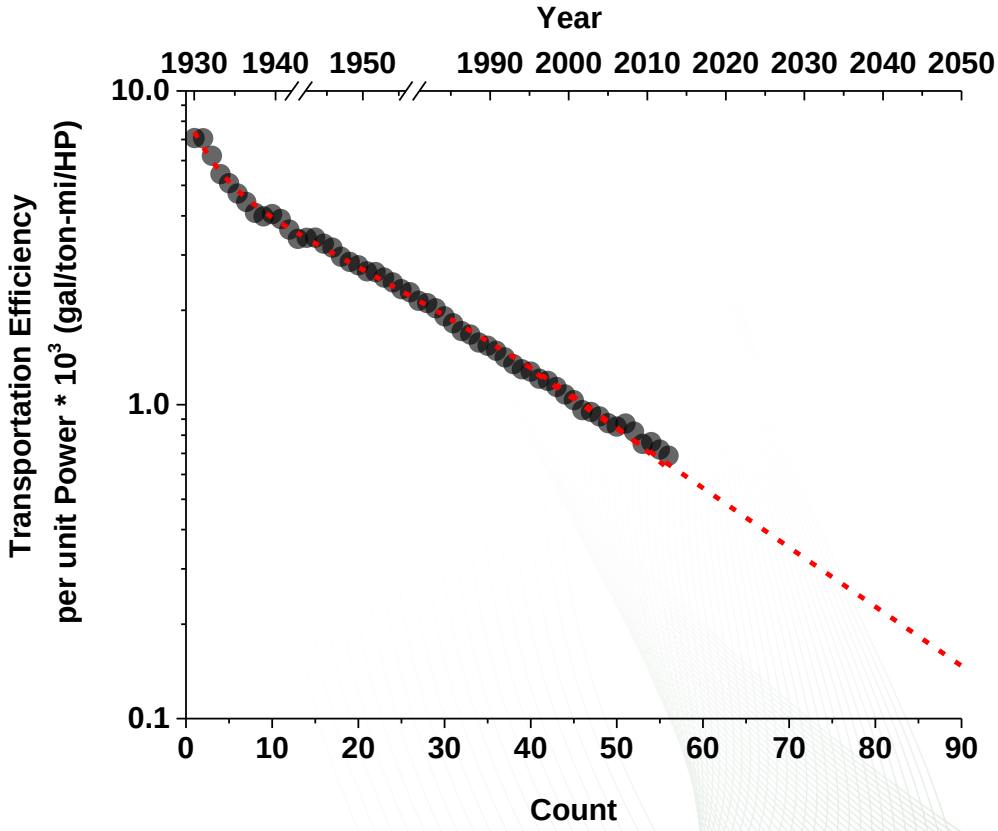
CO2 age
(Forward projections)

GOING FORWARD THE TREND BECOMES INCREASINGLY DIFFICULT/EXPENSIVE TO MAINTAIN

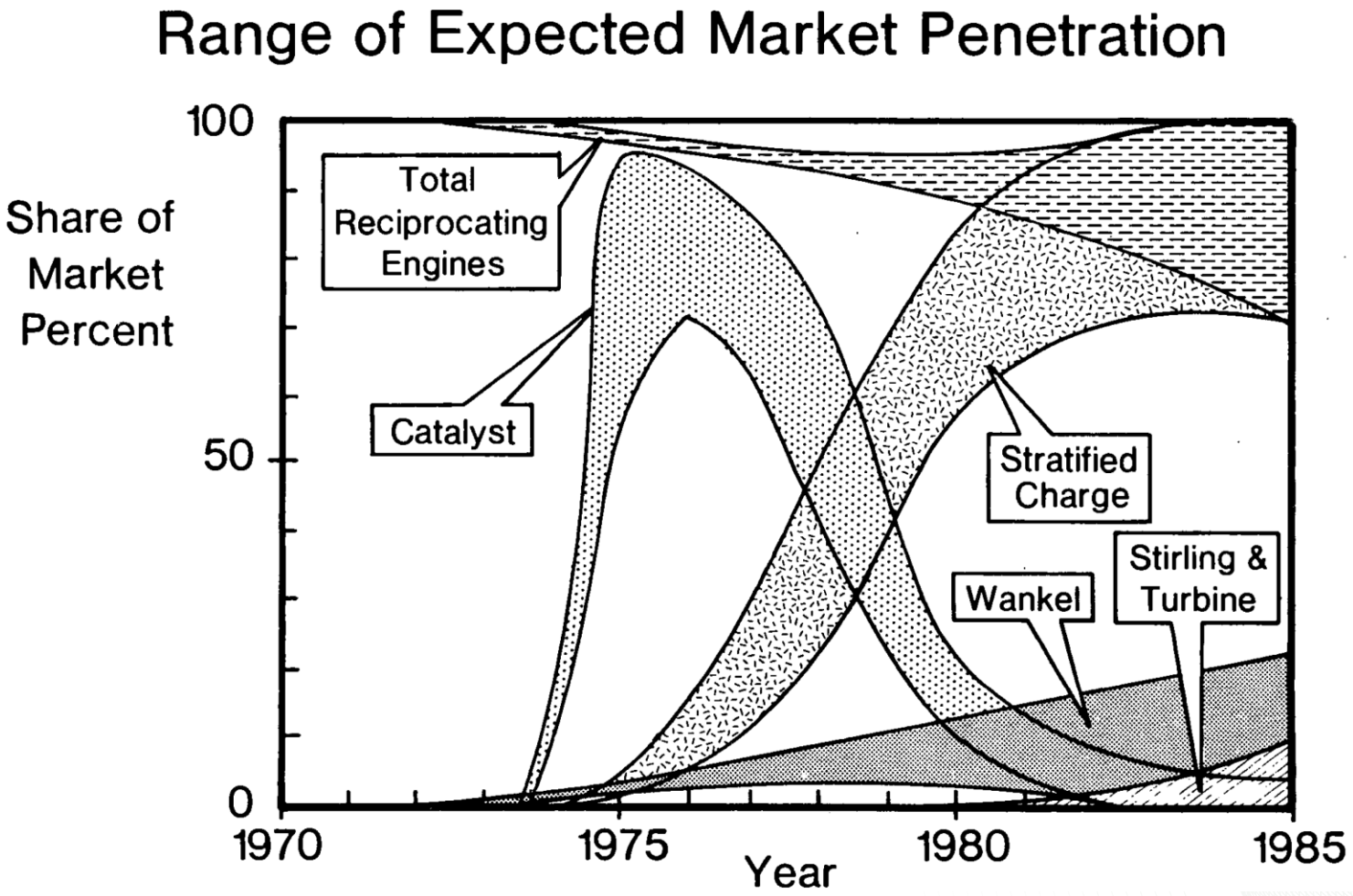




- Increasingly difficult to maintain trajectory
- Currently downsize & downspeed



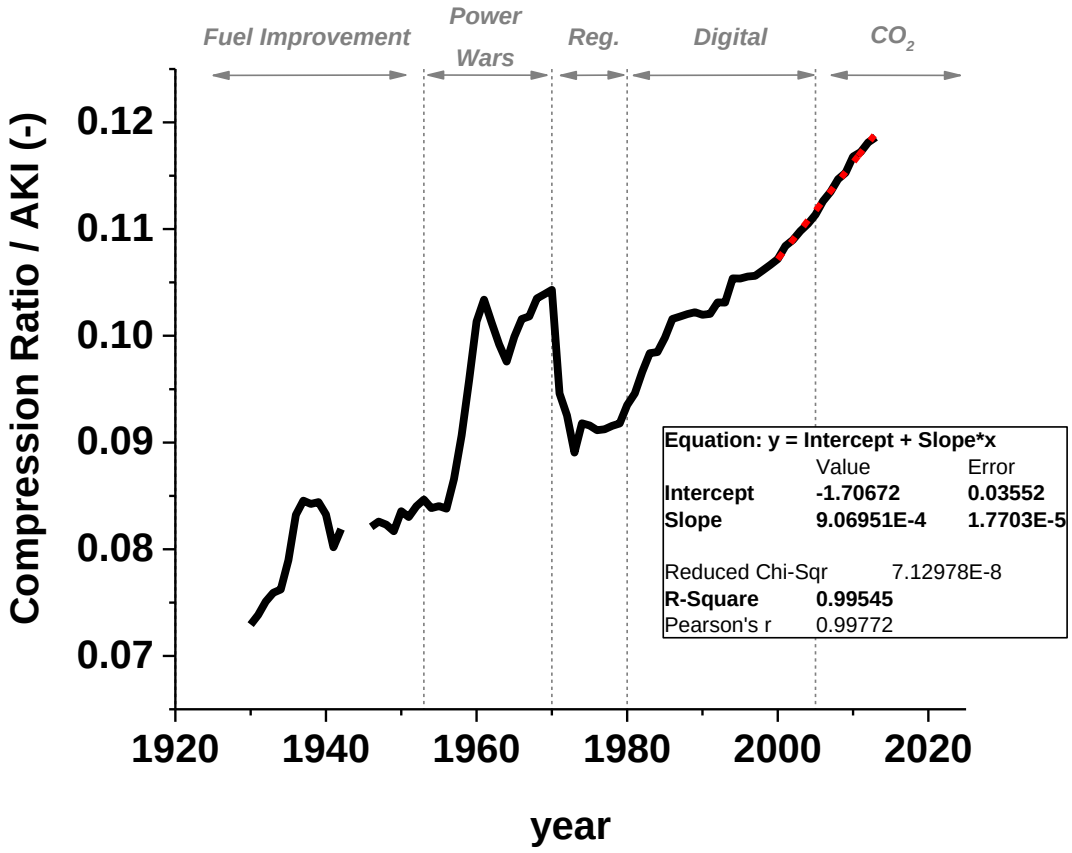
PROJECTIONS ARE JUST THAT PROJECTIONS, TRANSFORMATIVE TECHNOLOGIES ARE NOT ALWAYS ADOPTED AS PROJECTED



Richardson, Robert W. "Automotive Engines for the 1980's." Eaton's Worldwide Analysis of Future Automotive Power Plants, Eaton Corporation (1973)

WHAT IS A PROJECTED RESULTS OF OUR CURRENT TRAJECTORY?

- Fuel caused a step change before, can it occur again, what is required?
- Assume that previous 14 year trend is steady as technology progresses
- Determine when will compression ratio reach a maximum?



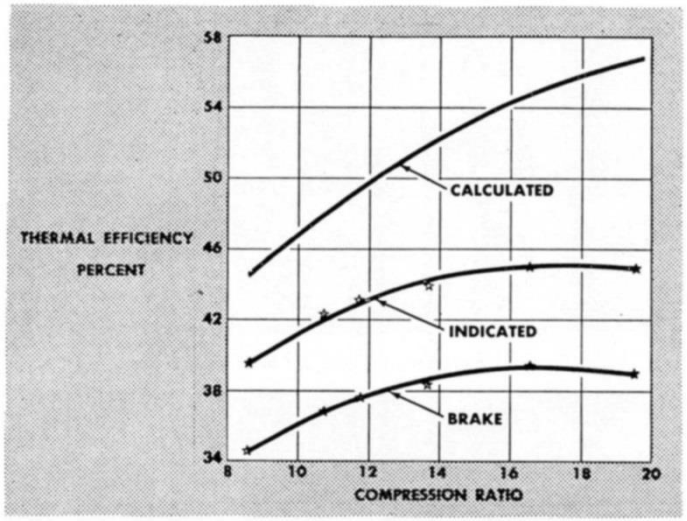
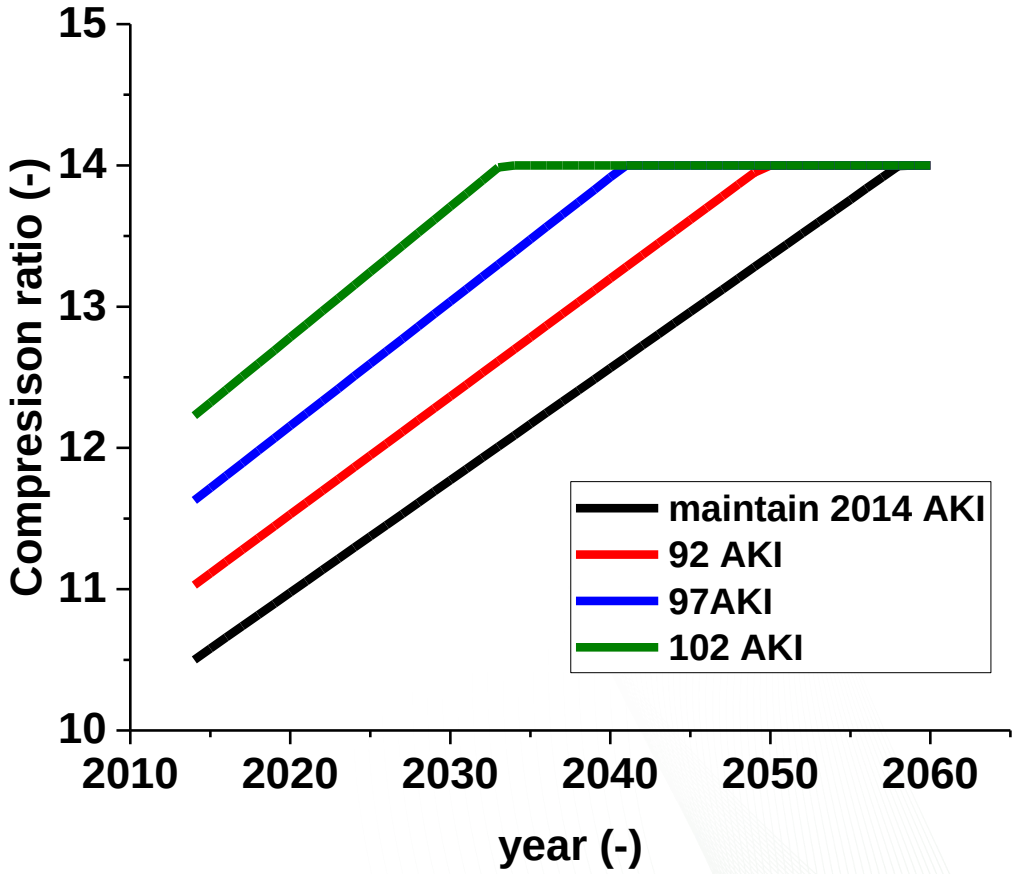


Fig. 5 — Full-throttle thermal efficiency at maximum economy settings and 2000 rpm

SAE 590015

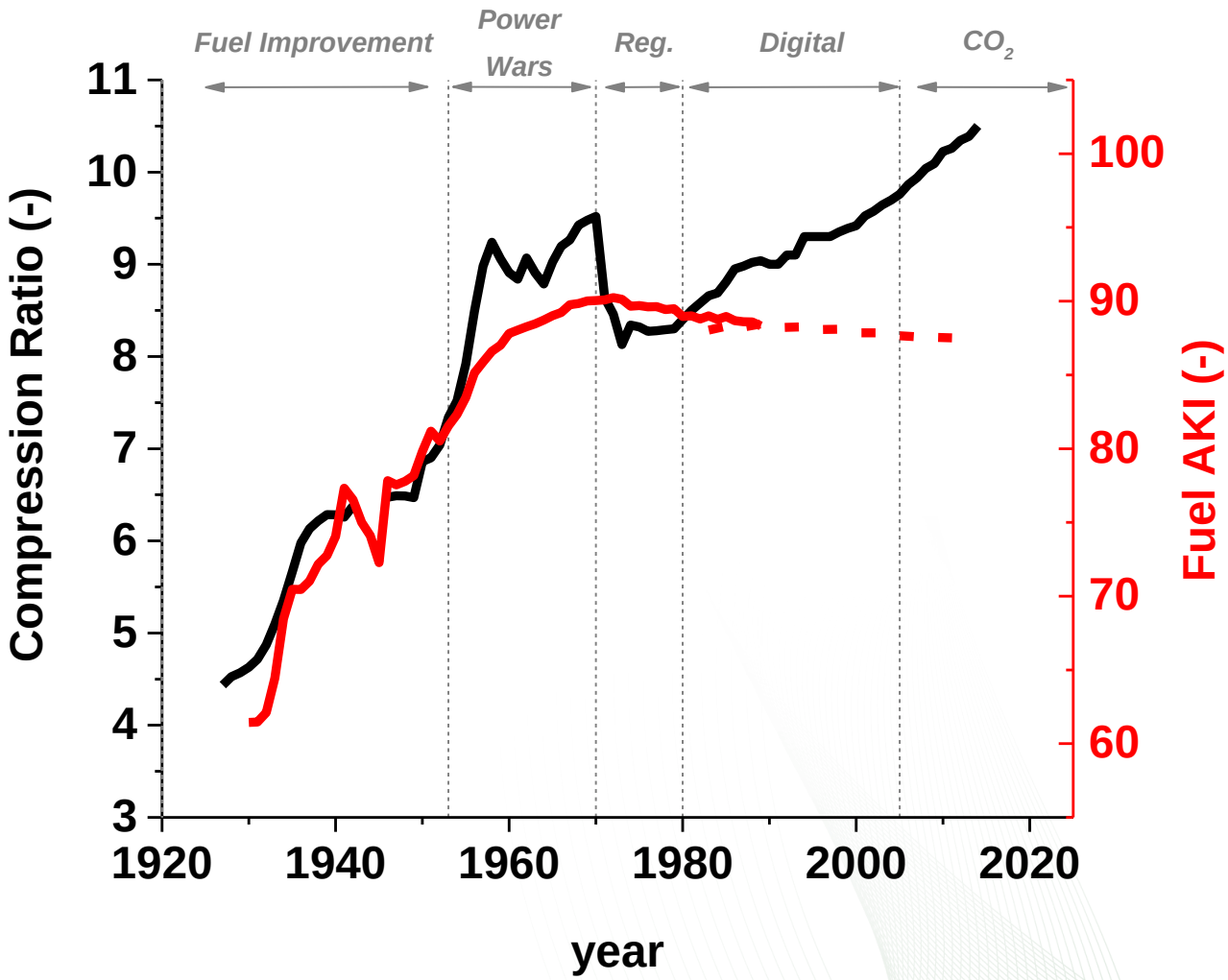
Leveraging fuel properties can decrease time to pragmatic maximum engine efficiency

- Assume 14:1 compression ratio is the practical compression ratio limit (thermal and friction effects)
  - Some Literature suggests 14:1
- What can changes to AKI provide to change the time to maximum compression ratio?
- Business as usual ~40 years to maximum
- 102 AKI ~15 years to maximum
- Minimum time is applying a step change today



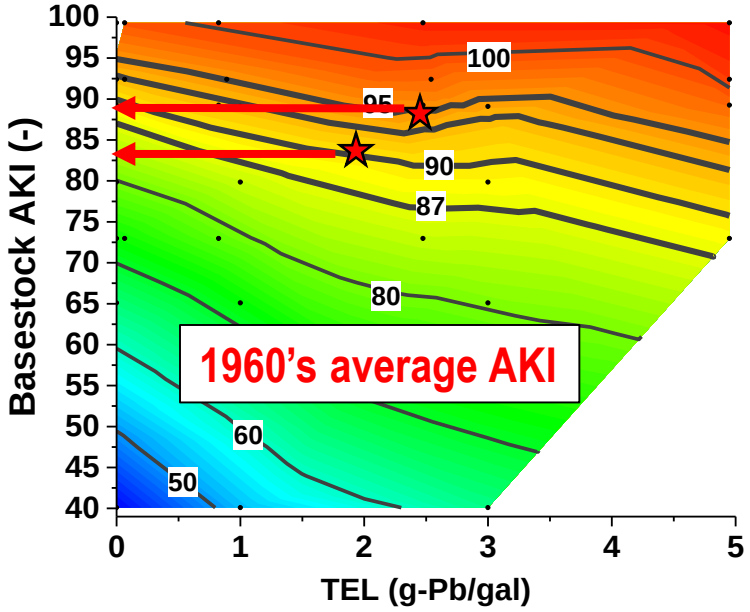
HISTORICAL STEP CHANGES TO COMPRESSION RATIO WERE ENABLED BY AKI STEP CHANGES

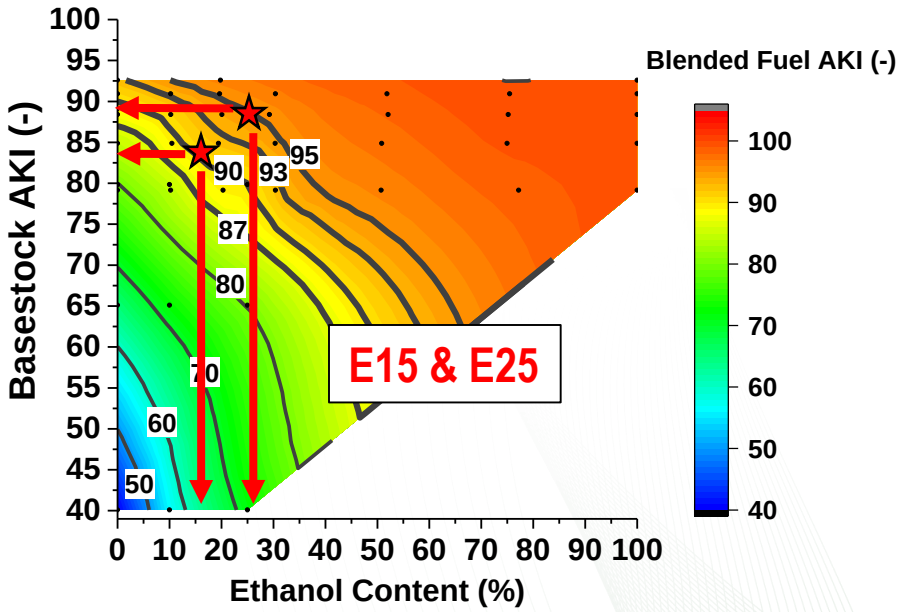
- Two major Cr increasing step changes observed
  - TEL in 1930's
  - catalytic reformer in 1950's-1960's
- One major Cr step change down
  - 1970's emissions
- If a step upward change is desired or needed, what is a deployable option today?



WHAT IF ETHANOL HAD BEEN USED INSTEAD OF TEL, WHAT ETHANOL BLEND WOULD HAVE MATCHED HISTORICAL LEADED GASOLINE AKI?

- For a step change today with EtOH what AKI would be needed?
- Develop response surface AKI increase from TEL and ethanol
  - Maps are a guide for reverse engineering historical basestock AKI
  - Using same basestock from 1960's today yields
    - 87AKI with E10, 90 AKI with ~E15 (1960's regular) or 95AKI with ~E25 (1960's premium)



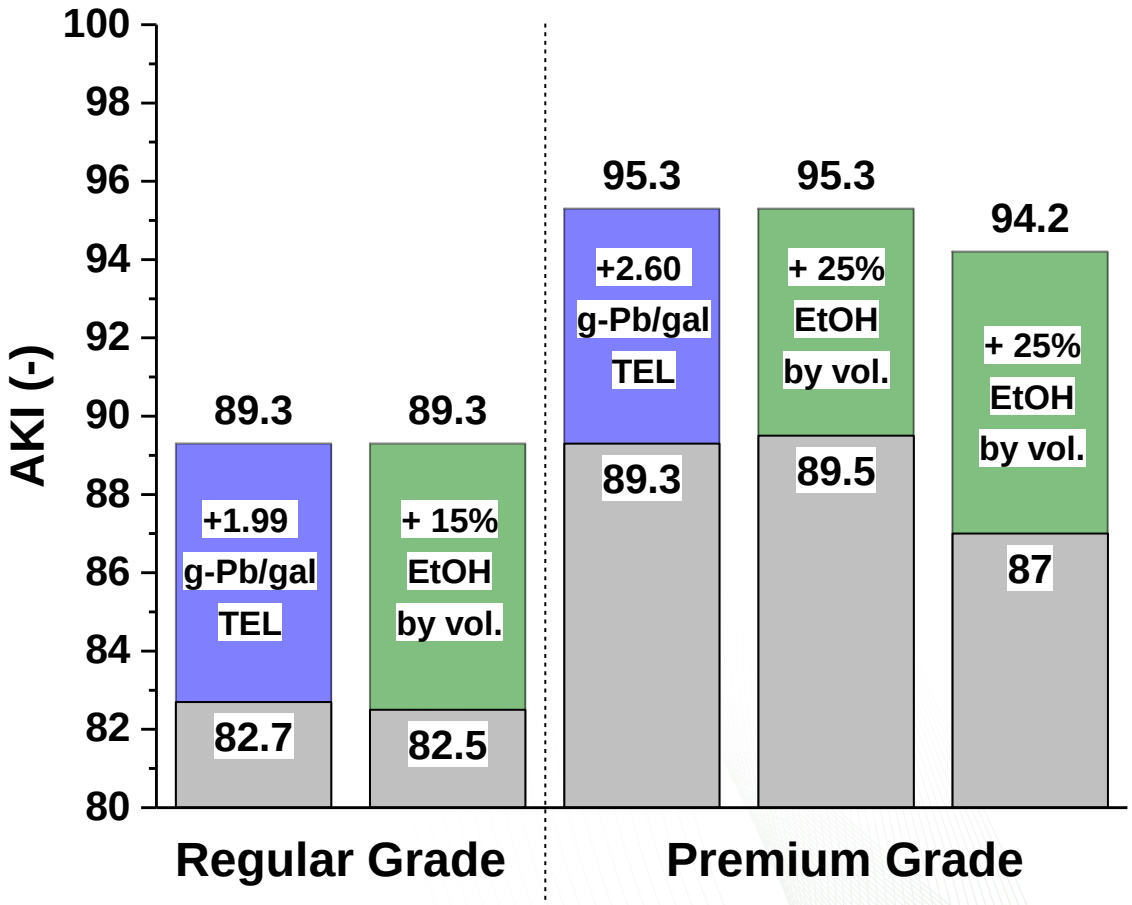


Forster and Klein SAE 620043, Porter and Wiebe 1952

Stein et al., SAE 2012-01-1277, Porter and Wiebe 1952

MID-LEVEL ETHANOL ENABLES MATCHED FINISHED PRODUCT AND BASESTOCK AKI TO HIGHEST HISTORICAL OCTANE NUMBER FUELS (TEL)

- Matched finished product AKI to 1960's averages (maximum ever)
- Back solved for basestock required using
  - TEL (actual, historical)
  - Ethanol (theoretical, today)
- E15 regular
  - existing vehicle compatibility
- E25 premium
  - UL pump compatibility
- 87AKI E0 with E25 splash for reference



Summary and Lessons learned

- There is a fundamental connection between engine efficiency and fuels AKI
- History illustrates that the co-evolution of engine efficiency and fuel anti-knock has been very strong, recent trend is fuel AKI stagnation
- The co-evolutionary trajectory of fuel economy, engines, and vehicles displays exponential behavior
- History has also showed that there must be the proper balance between technology and regulation to with consumer preference to maintain trajectory
  - improper balance causes the overall developmental progress to stagnate
- Today CAFE regulation presents a need to rapidly change fuel economy
- Step changes to improve fuel anti-knock historically enabled disturbances to the evolutionary trajectory, this can be replicated today
  - Employing proven fuels, there is the possibility of creating positive modern disturbances to the co-evolutionary trajectory

QUESTIONS?

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