Optimization and Control of Advanced Automotive Engines

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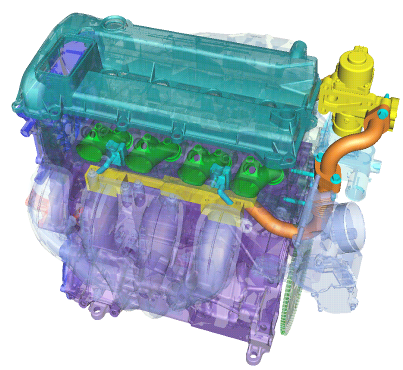
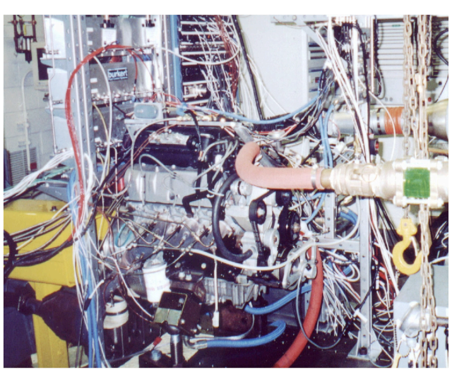
Where, what, how, and why





Modern vehicles are computerized machines …

- Computers control practically everything:
  - **engine**, transmission
  - braking (ABS), traction
  - air-bags, power-windows, …
- Engine computer control enabled
  - very low emissions by accurate of air/fuel control
  - **optimized** performance and **fuel economy** via addition of new devices.
- Optimization task different (more difficult) than set point regulation
  - obtaining accurate models expensive/time-consuming
  - complexity increases exponentially with each additional device.

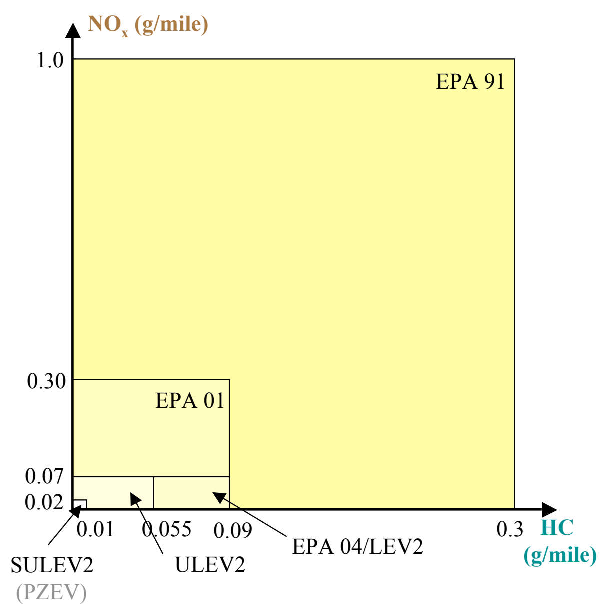
Emissions

Regulated tailpipe emissions (EPA and CARB)

- NMOG (HC)
- NOx
- CO
- particulates

Steps to achieve high standards:

- large/multiple catalytic converters
- control AF ratio at stoichiometry
- special cold start strategies to speed up catalyst light-off.



A sample of emission regulations since 1991 at 100/120 K miles.

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Fuel economy

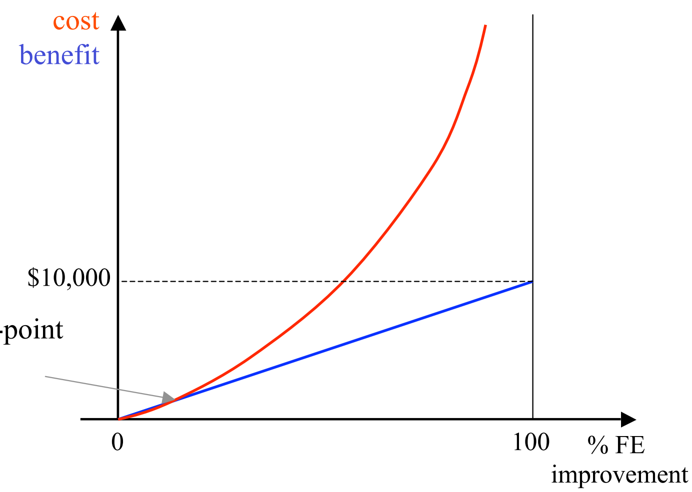
Automakers must satisfy CAFE standard for fleet fuel economy:

- cars – 27.5 mpg
- light trucks – 20.7 mpg increasing to 22.2 mpg (model year 2007)

Customer benefit → average vehicle, driven 120K miles, at $2/gallon gas:

$100 per 1% FE improvement

New technologies slide the base-point along the benefit line.



Design for fuel economy

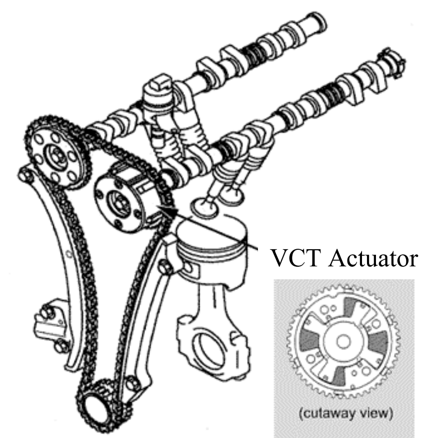
- Conventional **SI** (gasoline) engine
  - throttle controls air (torque)
  - fuel controlled to stoichiometric AF ratio (14.6)
  - spark for best fuel economy (MBT spark) → 1 DoF optimization

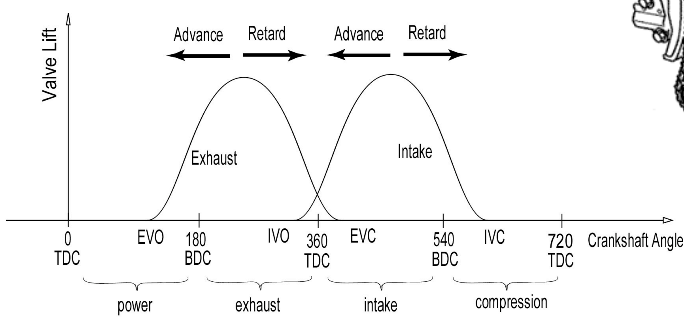
- New devices added/combined to improve FE:
  - **Camless** – 5 DoF:
    - intake and exhaust valve opening and closing times, spark timing.
  - **Lean burn** – 3 DoF:
    - air-fuel ratio, variable cam timing (VCT), spark timing
  - **Dual-independent VCT** – 3 DoF :
    - intake VCT, exhaust VCT, spark timing
    - test platform for this work.

Dual-independent VCT engine

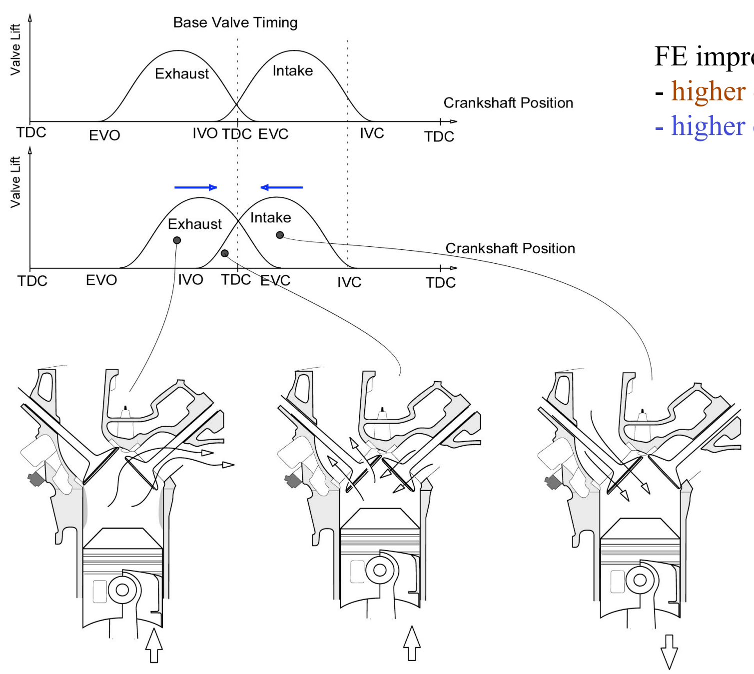
Intake and exhaust cam timing change independently based on operating conditions.

(Leone et al, SAE 960584
Jankovic, Magner, IFAC Congress, 2002)



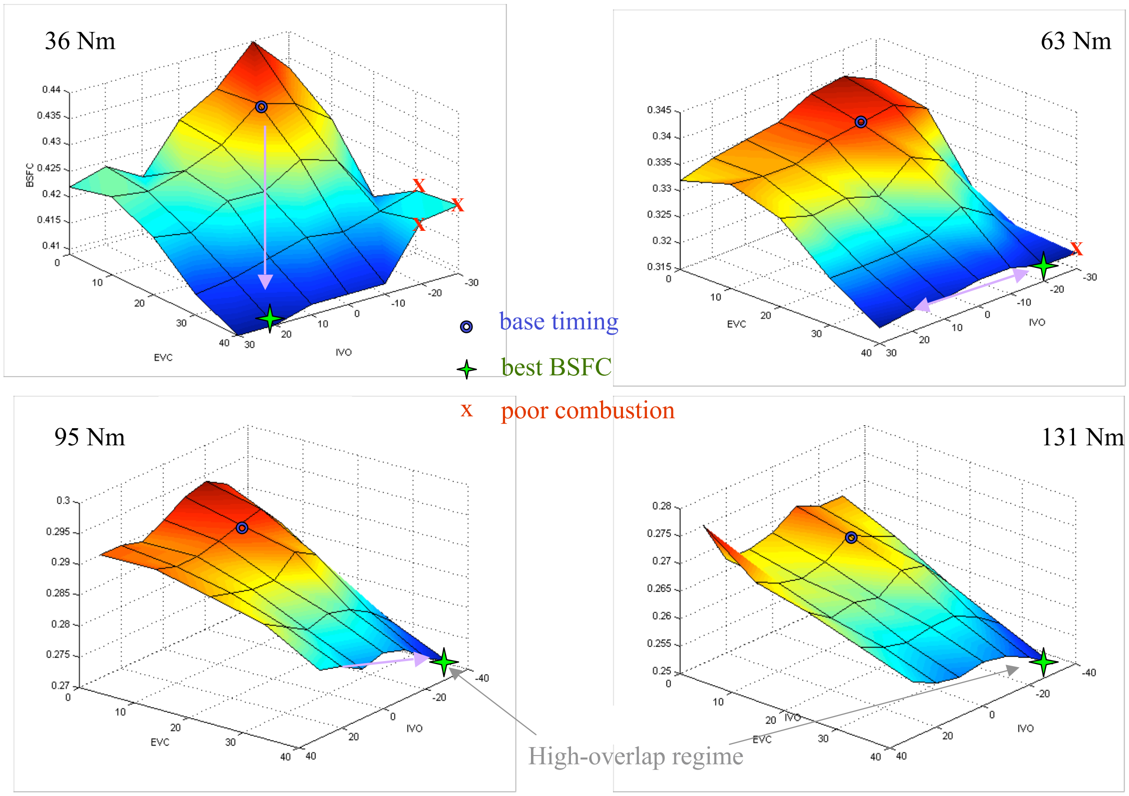


Dual-independent VCT – high overlap regime

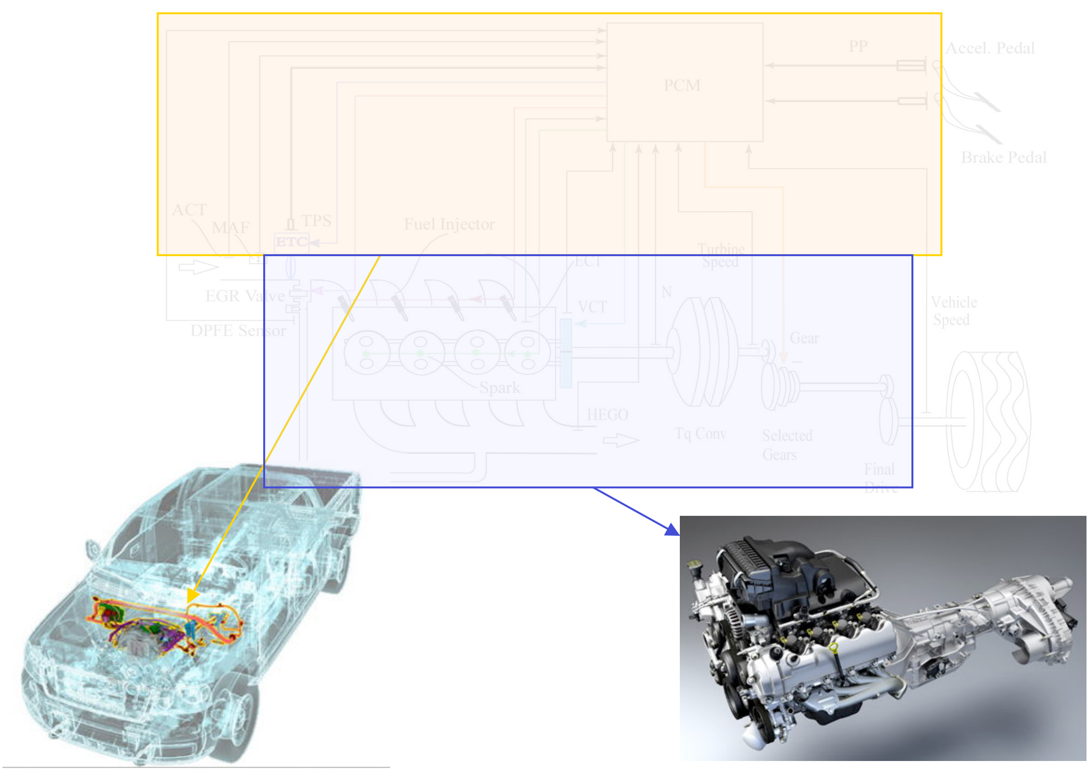


FE improvement through
- higher dilution
- higher compression

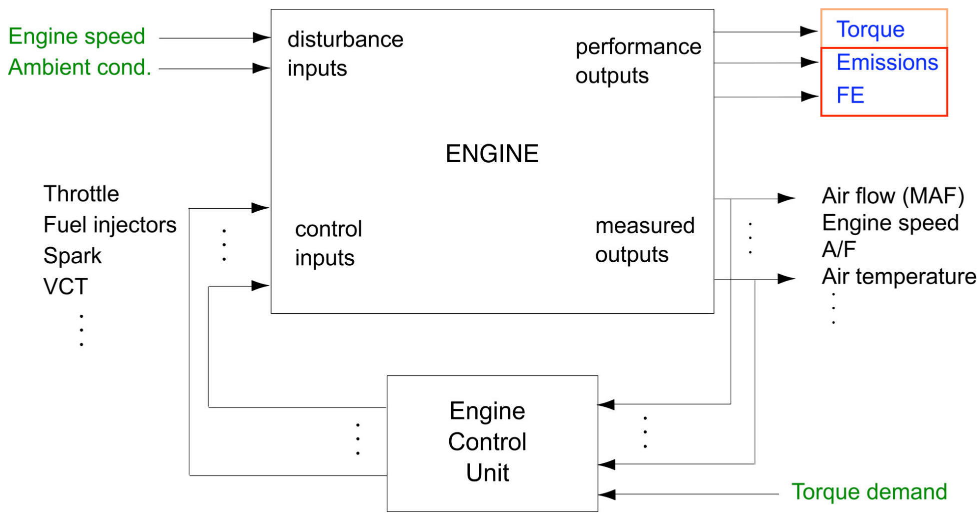
BSFC vs IVO and EVC at MBT spark (1500 RPM)



Powertrain control system – hardware configuration



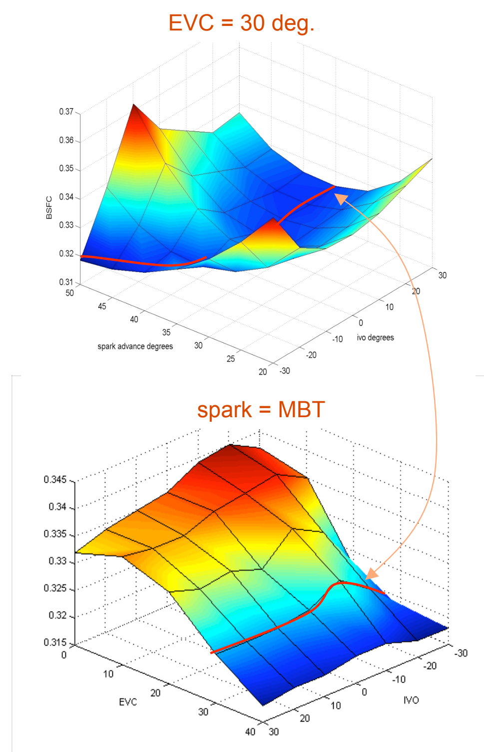
Engine control system – control theoretic viewpoint



- Disturbances are measured/known
- Performance outputs are not measured
- Resulting control system relies on feedforward component

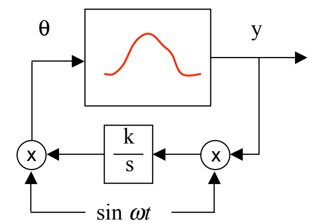
Optimization vs set point regulation (di-VCT)

- performance output (cost) may be unmeasured
- (even if it is measured) set-points not available – the smaller the better.
- At the optimum, gain is 0
  - deviation on either side increases cost
- On an active constraint actuation becomes unidirectional.
- Instead of feedback regulation one can search for the optimum.

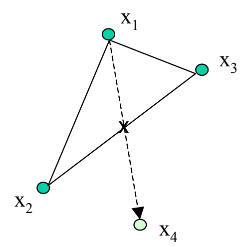


On-line search for the optimum

Several approaches to search for the optimum based on real-time measurements:



- Extremum seeking (sinusoidal perturbation)
  (Ariyur & Krstic, Wiley, 2004)



- Direct search methods (e.g. Nealder-Mead)
  (Wright, *Numerical Analysis* 1995, Addison-Wesley
  Kolda et al, *SIAM Review*, 2003)

- Gradient search / stochastic approximation
  (Spall, *Wiley Encyclopedia of EE*, Volume 20, 1999
  Teel, *CDC 2000*, Sydney)

NEXT

Gradient Search Methods

- Several GS methods experimentally tested on di-VCT engine
  - Modified Box-Wilson method (Box, Wilson, *J. Royal Stat. Soc.*, 1951)
  - Simultaneously Perturbed Stochastic Approximation
  - Persistently Exciting Finite Differences

SPSA/PEFD algorithm

• Iteratively adjust parameters *(ivo, evc, spark)* to minimize a cost $f(\theta)$ (i.e. BSFC):

1. Pick randomly or periodically one direction in R^3 among:

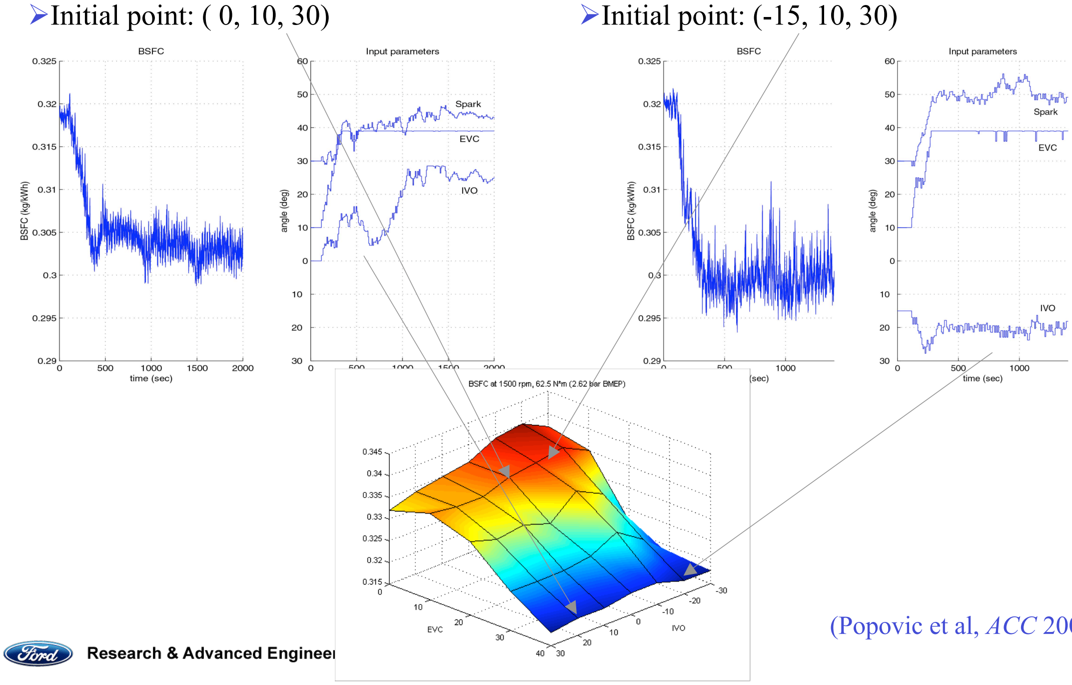
   $v_1 = [1 \quad 1 \quad 1]$, $v_2 = [-1 \quad 1 \; 1]$, $v_3 = [1 \; -1 \; 1]$, $v_4 = [1 \; 1 \; -1]$
2. Assign $\theta = \theta_k + \gamma v_k$, measure $f(\theta_k + \gamma v_k)$
3. Assign $\theta = \theta_k - \gamma v_k$, measure $f(\theta_k - \gamma v_k)$
4. Calculate the *next estimate*:

$$\theta_{k+1} = \theta_k + \alpha \cdot v_k \cdot \frac{f(\theta_k + \gamma v_k) - f(\theta_k - \gamma v_k)}{2\gamma}$$

Experimental results (SPSA algorithm results shown)

Testing at 1500 RPM, 63 Nm torque.

➢Initial point: (0, 10, 30) ➢Initial point: (-15, 10, 30)



(Popovic et al, *ACC* 2003)

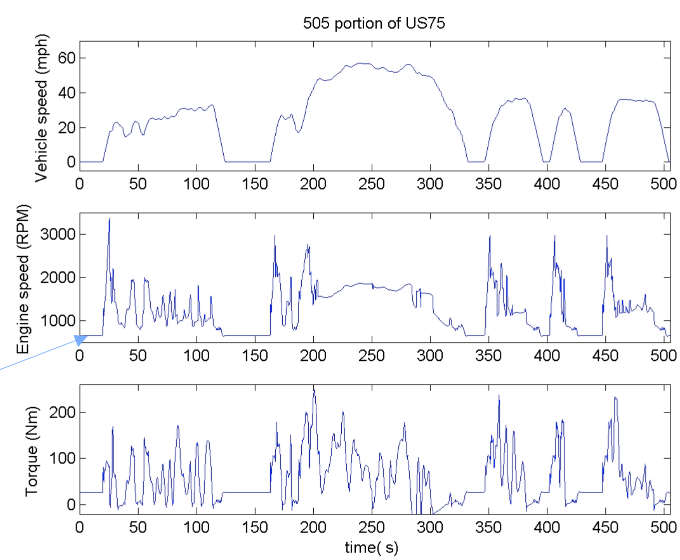
Gradient search optimization – summary

- 15 minutes for GS to find the optimal point with 3 DoF
- 20 seconds just to find MBT spark (Dorey & Stewart, *CCA*, 1994)
- Not fast enough for on-the-road optimization.

Federal drive cycle prescribes the vehicle speed profile.

This constrains engine speed and torque as shown.

Prolonged speed/torque steady state found only in idle.



Cycle optimization (off-line)

- FE optimization subject to emissions (and cycle RPM/torque) constraints

$$\min_{(ivo,evc,spark)} \int_{cycle} \text{fuel consumption}$$

$$\text{subject to} \quad \int_{cycle} \text{emissions}(ivo,evc,spark) \le \text{limit}$$

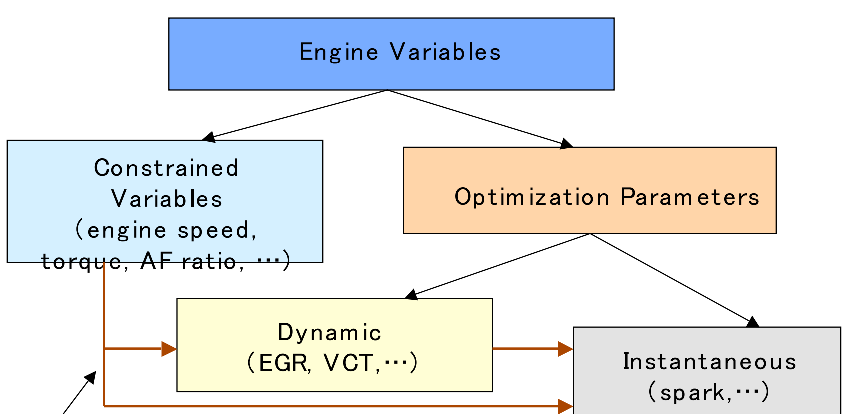
- Dynamic programming → (Auiler et al. SAE 770076 Cohen at al. SAE 840544 Kolmanovsky et al. ACC 2002)
  - Engine and after-treatment models required

- Cycle-gradient optimization (Dohner, SAE 780286)
  - Alternates OL gradient computation & scheduled implementation – *f(N, tq)*

- Point-wise FE optimization
  - if separate emissions (~first 30s) and FE modes are established.

Point-wise optimization

- At each speed/torque find the best combination of the optimization parameters
  - Note that this is not sufficient for transients operation



Scheduling:
dynamic_parameters= f(constrained_variables)
instantaneous_parameters = f(constrained_variables, dynamic_parameters)

Full factorial optimization – cam and spark scheduling

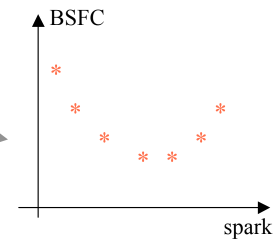
- FE benefit depends on the accuracy of the following ECU schedules

$$ivo = Fn\_ivo(N, tq)$$
$$evc = Fn\_evc(N, tq)$$
$$spark = Fn\_mbt(N, load, ivo, evc)$$

- **Full factorial map**:

N load cam timing (IVO, EVC) in deg. ATDC

$$\begin{array}{c} 650 \\ 1000 \\ 1500 \\ \vdots \\ 4000 \\ 5000 \\ 6000 \end{array} \left\{ \begin{array}{c} 0.1 \\ 0.25 \\ \vdots \\ WOT \end{array} \right. \left\{ \begin{array}{cccc} (-30,40) & (-20,40) & \cdots & (30,40) \\ \vdots & \vdots & \cdots & \vdots \\ (-30,10) & (-20,10) & \cdots & (30,10) \\ (-30,0) & (-20,0) & \cdots & (30,0) \end{array} \right. \{\text{spark sweep}$$



- 35-fold increase over conventional (fixed cam) – would take 15 months to complete.

Engine mapping and optimization – improving efficiency

- Industry standard – Design of Experiments (DOE)

(Montgomery, Wiley NY, 2001
NISIT/SEMATECH e-Handbook of Statistical Methods)

  - (D- or V-) optimal designs
    - use only a fraction of FF points
  - Regressions generate "surfaces"
    - Polynomial
    - Radial basis function
  - The regressed surfaces used to find optimal parameter schedules.
  - "Black-box" approach, accuracy/complexity tradeoff

Box-Behnken Design for Three Factors

4D V-optimal design

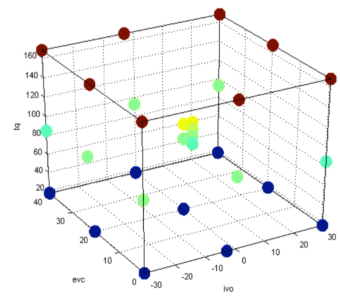
Approach 1

- V-optimal DOE in 4 dimensions (*speed, torque, ivo, evc*)
  - spark sweep at each selected point

- Matlab's Model Based Calibration tool generates mapping matrix
- di-VCT data regressed with a 3rd order polynomials in 4 variables:

$$bsfc\,/\,spark = \sum_{i+j+k+l+m=3} c_n \cdot N^i \cdot tq^j \cdot ivo^k \cdot evc^l \cdot 1^m$$

- Used 100 spark sweeps for 35 coefficients.



A V-optimal design for three factors

2D Quadratic CCD (QCCD)

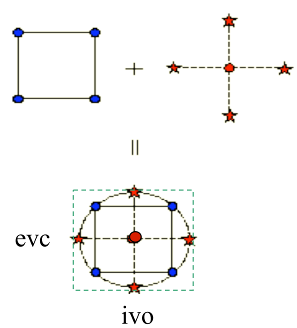
Approach 2

- At each speed/torque the "response surfaces" assumed quadratic in IVO, EVC

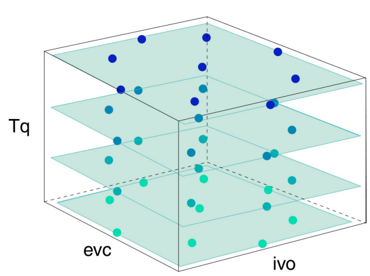
$$bsfc\,/\,spark = a_0 + a_1\,ivo + a_2\,evc + a_3\,ivo\,evc + a_4\,ivo^2 + a_5 evc^2$$

Thus, $a_i = a_i\,(N, load)$ (full factorial in N, load)

- At each speed/load map spark at 9 ivo/evc pairs ("central composite design – CCD")



Box & Wilson CCD



Fuel economy comparisons (our data for di-VCT)

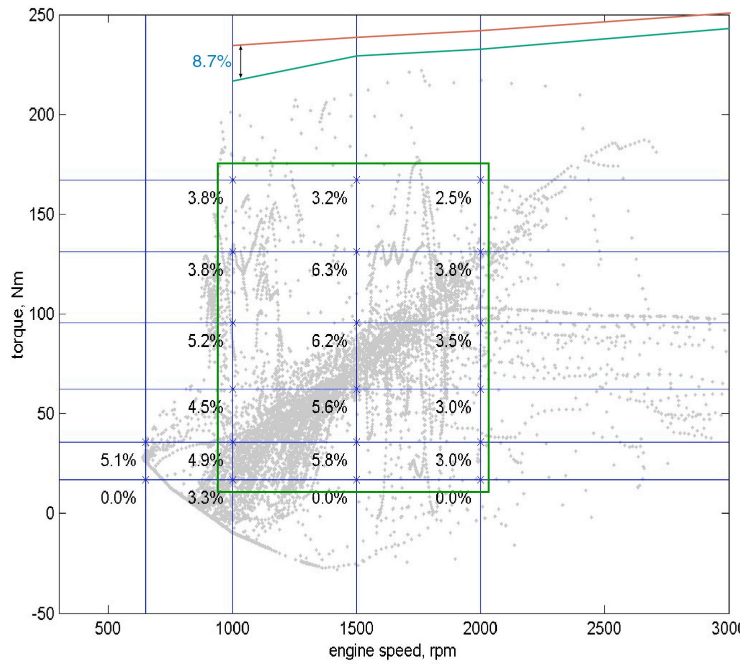
Each gray dot is a 0.1 second operation over the US75 cycle.

The numbers show % steady state FE improvement over the fixed base timing.

Drive cycle FE improvement prediction

3.11%

(assuming no FE improvement outside the rectangle)

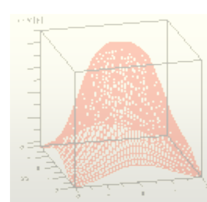


FE penalty compared to full-factorial as a benchmark

	FE penalty	Number of spark sweeps*
Fixed cam at base timing (-10,10) deg ATDC	3.11%	18
4D V-optimal DOE	1.01%	100
Quadratic CCD	0.64%	162
Full-factorial	0%	630

* For optimization over the rectangle (1000 to 2000 RPM x 16 to 167 Nm)

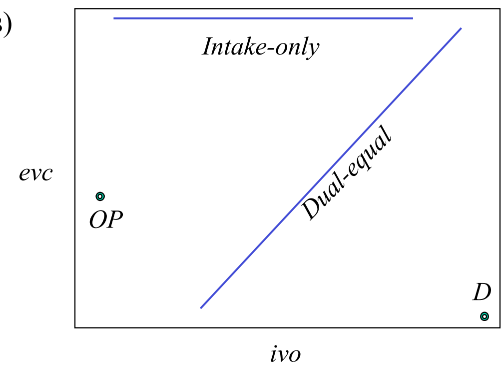
- 20% to 30% FE loss from the benefit potential
  - ➢ lower accuracy at the edges where the optimal points tend to be.
- Difficult to avoid in a DOE approach.



Information function (variance^{-1}) for 2-D QCCD

Feature based guided mapping

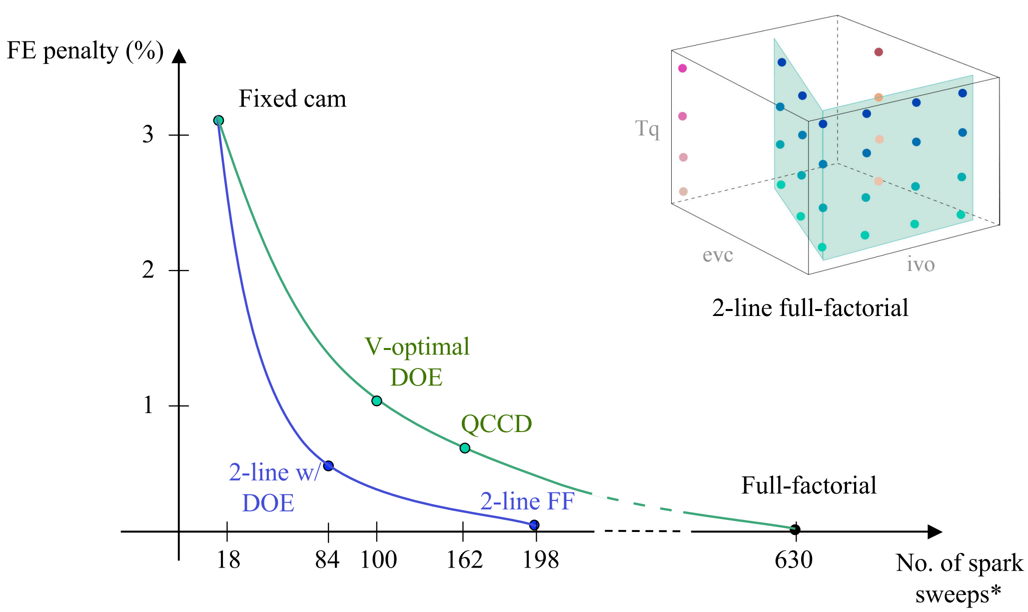
- Basic idea – selectively map region(s) based on
  - a-priori knowledge
  - on-line optimization tests (e.g. gradient search)
- More than 90% of optimal points fall on two lines
  - Dual-equal line
  - Intake-only line
  - + OP and D points (for special conditions)



Advantages
- higher accuracy on mapped features
- compatible with DOE

No point outside these features is mapped
(what happens in transients?)

Steady-state FE penalty and mapping effort



2-line full-factorial

*Mapping/optimization over the rectangle (1000 to 2000 RPM x 16 to 167 Nm)

Inverse distance interpolation for transients

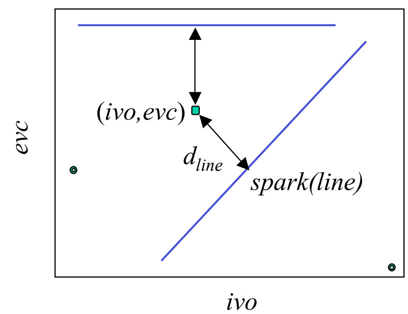
- Nonparametric (kernel) methods (Hardle, Cambridge University Press, 1989)
- Given data $[X_i\ ,\ Y_i]$ and a function $K(u)$ (kernel)

$$\hat{Y}(x) = \frac{\sum_i K(x - X_i) Y_i}{\sum_i K(x - X_i)}$$

  - Less efficient than parametric (e.g. polynomial) methods
  - Predictable in data poor regions
  - Calibration is local

- Inverse-distance kernel $K(u)=1/(||u||^2+\varepsilon)$
- Replaced points (X,Y) with (line) features

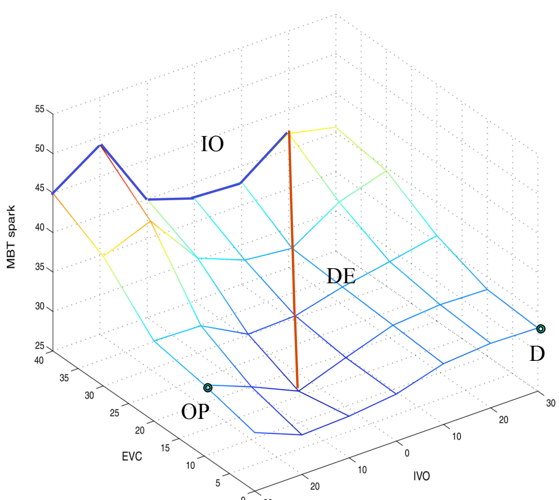
$$spark(ivo, evc) = \frac{\sum_j \frac{1}{(d_{line\_j}^2 + \varepsilon)} \times spark(line_j)}{\sum_j \frac{1}{(d_{line\_j}^2 + \varepsilon)}}$$



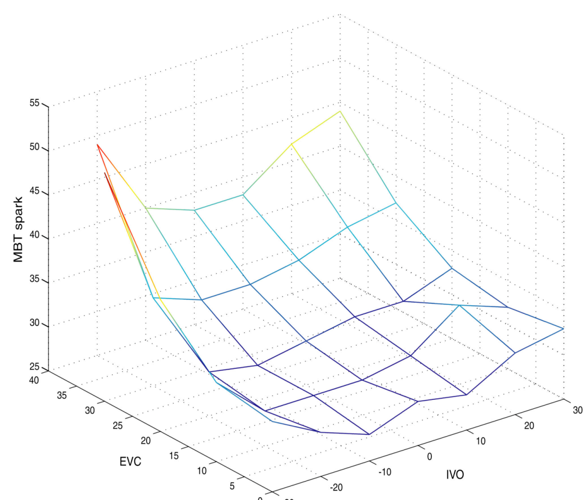
(Jankovic & Magner, ACC 2004)

Comparison of MBT spark response surfaces

Surface generated by inv-dist from values at mapped features



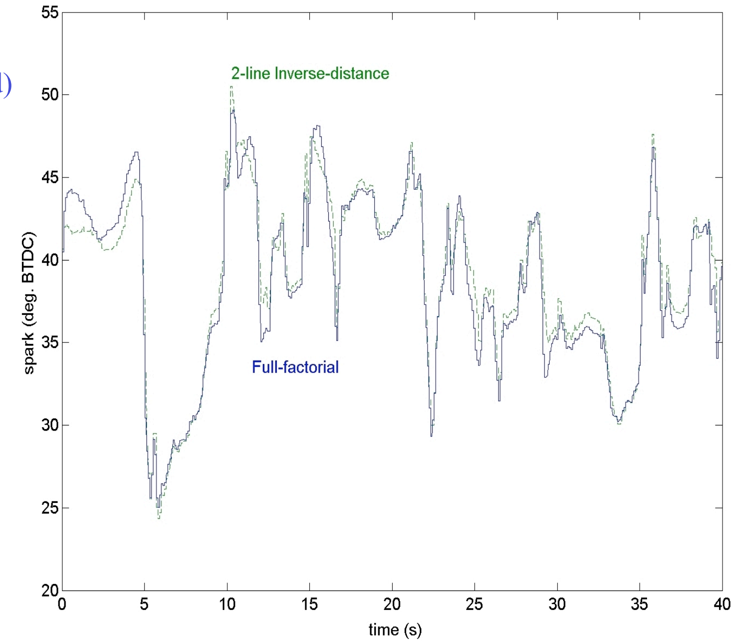
Full factorial surface



Transient spark scheduling accuracy (40 sec. of the drive cycle)

Vehicle data:
Full factorial (post-processed)
2-line inverse-distance
(vehicle ECU)

FE penalty (transient)
for 2-line ID → 0.04%



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Vehicle tests

To test the approach in the vehicle we implemented 2-line + inv. dist.

Fuel economy comparison (di-VCT versus fixed base cam timing)

- Drive cycle simulation prediction → **3.11%**
- Vehicle tests (4+4 back to back tests) → **2.97%**

If you are not convinced yet …

Before

After

Conclusion

- "It is difficult to specify and impossible to implement a general multivariable function even if the function is known" – Ho
  - For modeling/mapping, curse of dimensionality strikes early.
  - ES, direct, or gradient search too slow for on-the-road application.

- "All models are wrong, but some are useful," – Box
  - full-factorial approach costly to map
  - explored mapping with reduced measurement set
    - DOE and guided (2-line) mapping compared.

- "The minimum is the result of the omission of the inessentials" – Powson
  - inverse-distance interpolation implemented, tested in-vehicle.