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Moments of Power: Analysing and Optimising Powertrains and Components under Stochastic Boundary Conditions

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with contributions from
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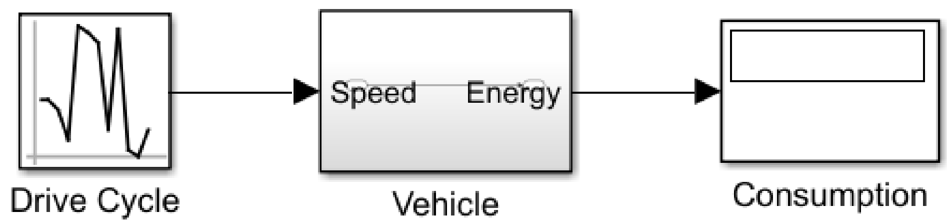
Moments of Power

Drive Cycles

- Why do we have drive cycles?
- How do they differ?
- What are common metrics?

Why Drive Cycles?



Drive cycles define the input boundary condition of a vehicle.

Unlike the driver inputs, a cycle works across different vehicles.

Beginnings: Modal vs Realistic

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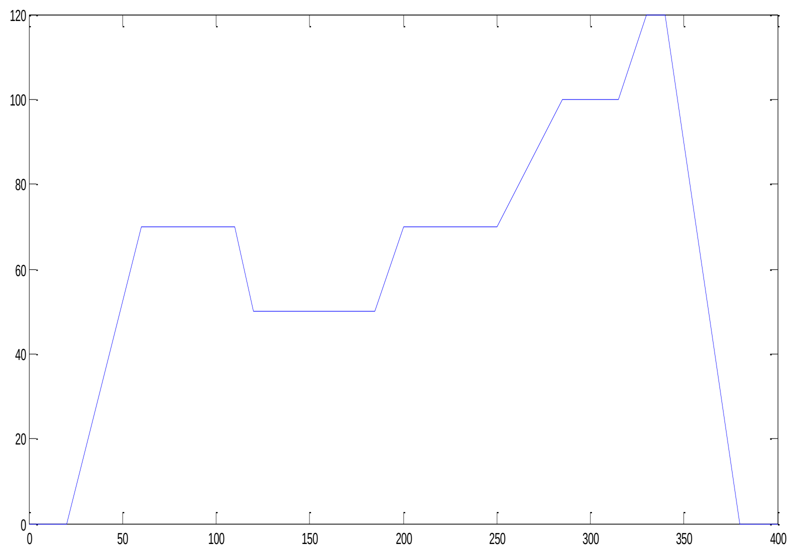
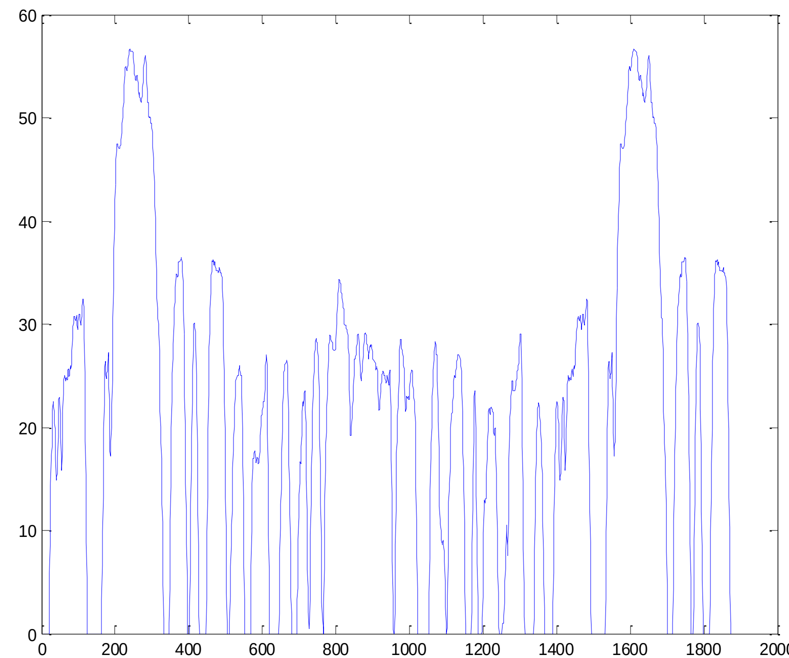
Speed (km/h)



Speed (miles/h)



Time (seconds)

Current: WLTP

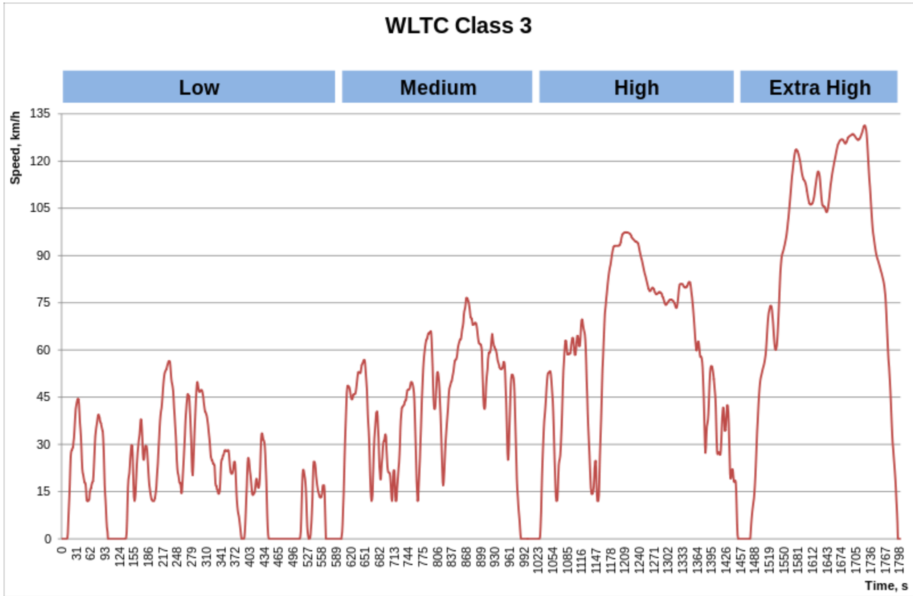
World Harmonised Light Duty Test Protocol (WLTP)

World Harmonised Light Duty Test Cycle 3a (WLTC)

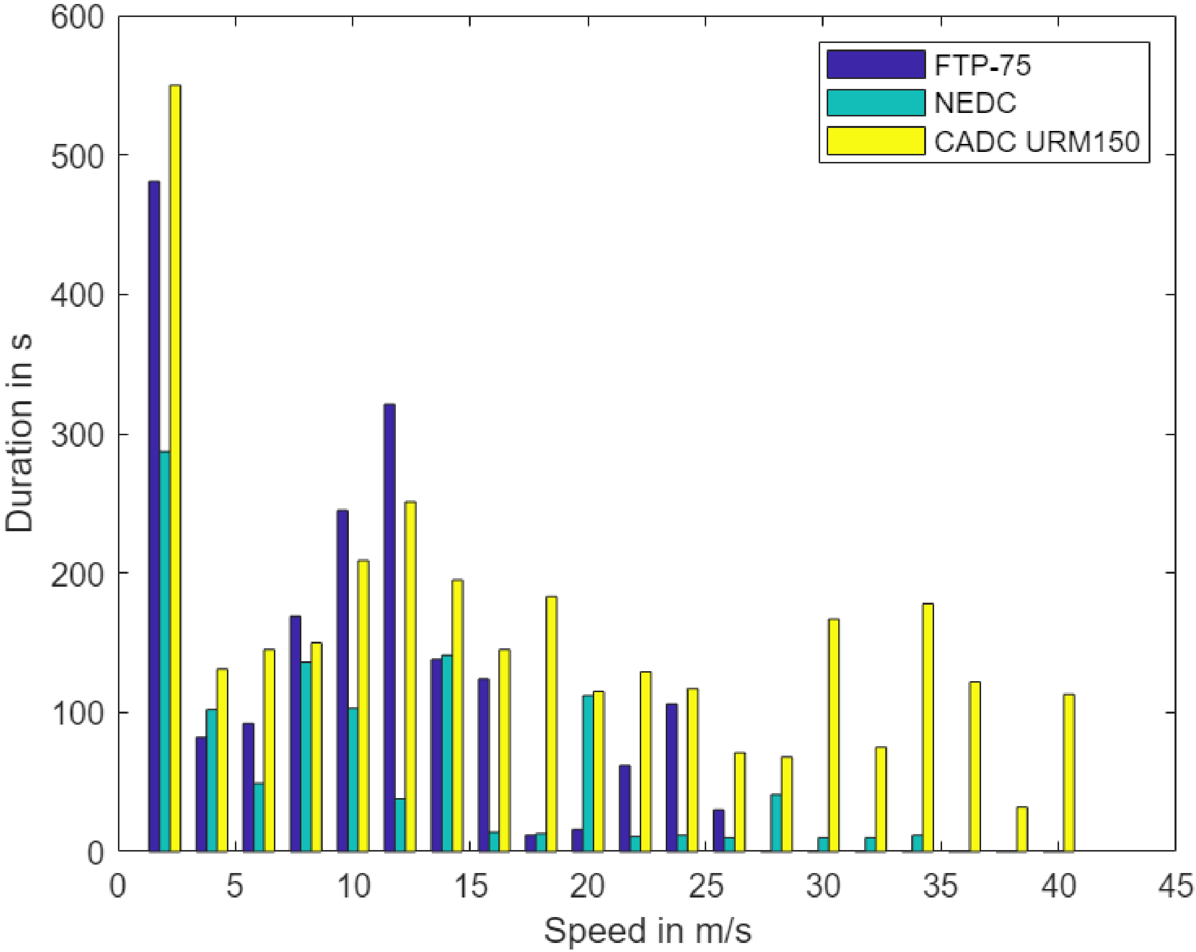
- Better cycle
- Different environments:
  low, medium, high, extra high speed
- Faster, more aggressive
- Global harmonisation

→ Better, but not good enough

→ Adopted in the EU and Japan,
but not the US



Speed Histogram



Common Measures:

- Average
- Standard Deviation
- Maximum
- Time at 0

Moments of Power

Vehicle Model

- Polynomial Model
- Moments

Vehicle Model

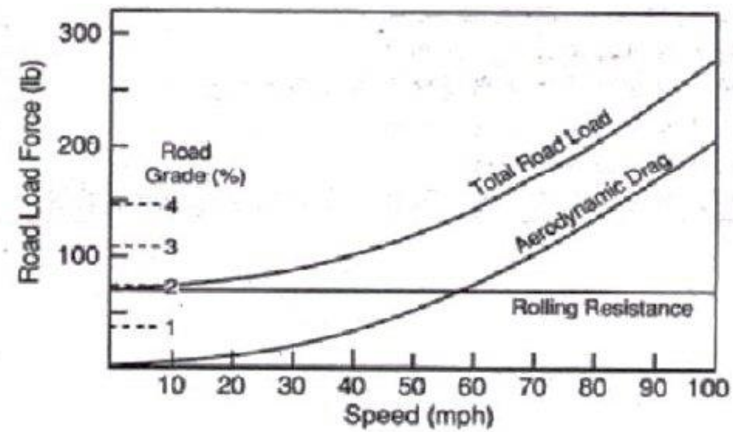
Road Load

$$F(v,a) = c_0 + c_2 v^2$$
$$P = Fv = c_0 v + c_2 v^3$$

Forces

- Tyre Friction
- Aerodynamic Drag
- (kinetic energy can be neglected)

→ Polynomial Power



A. Bhave. H. Taherian: Aerodynamics of Intercity Bus and its Impact on CO2 Reductions, UAB - ECTC 2014.

Road Energy

Energy Over a Cycle

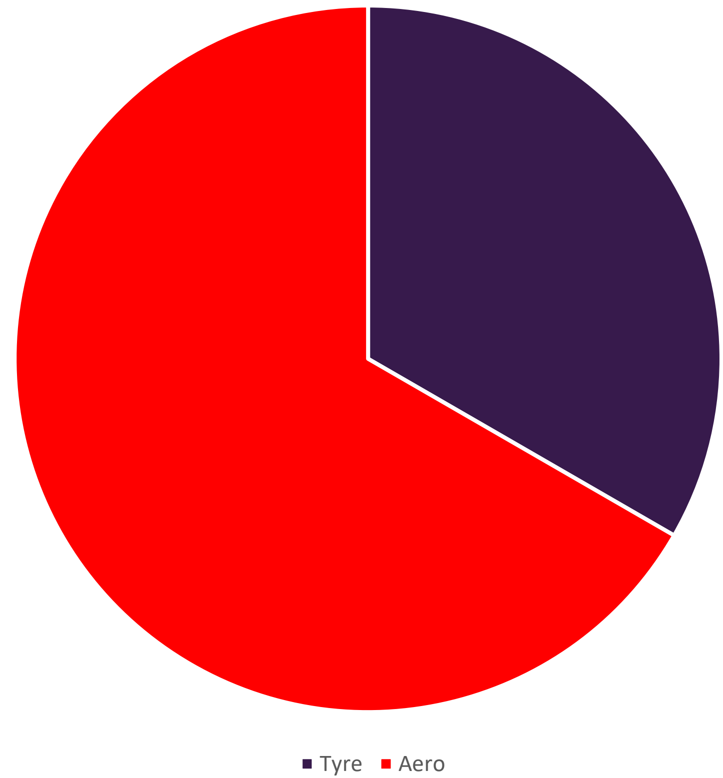
$$E = \int P(t)\,dt$$

$$= \int c_0 v(t) + c_2 v(t)^3 dt$$

$$= c_0 \int v(t)\,dt$$

$$+ c_2 \int v(t)^3 dt$$

$$= c_0 l + c_2 T v_{RMC}^3$$



Road Energy

heúrēka!

$$E = c_0 l + c_2 T v_{RMC}^3$$

2 Terms

- Tyre loss depends on distance (of course)
- Aero loss depends on the **Root Mean Cube Speed** (!)

$$v_{RMC} = \sqrt[3]{\frac{1}{T}\int v(t)^3 \, dt}$$

Related to the third moment (skewness):

$$\mu_3' = v_{RMC}^3$$

Simulation vs Analysis

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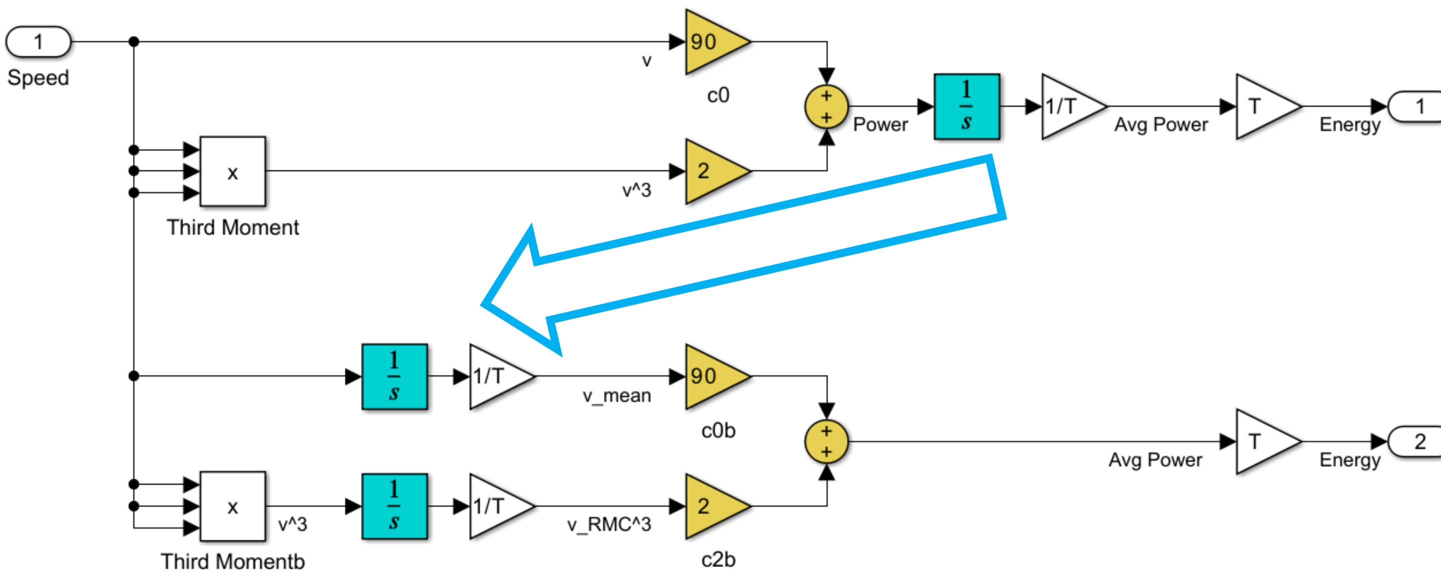
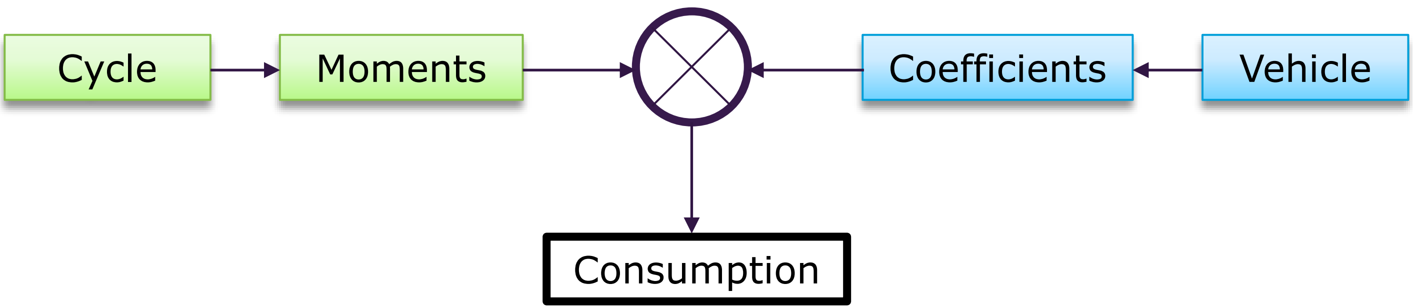


- Same vehicle model → more efficient
- But the model comes after integration → clear sensitivity (both to cycle & model)

Simplified Analysis

Not Simulation (what?), but analysis (why?)



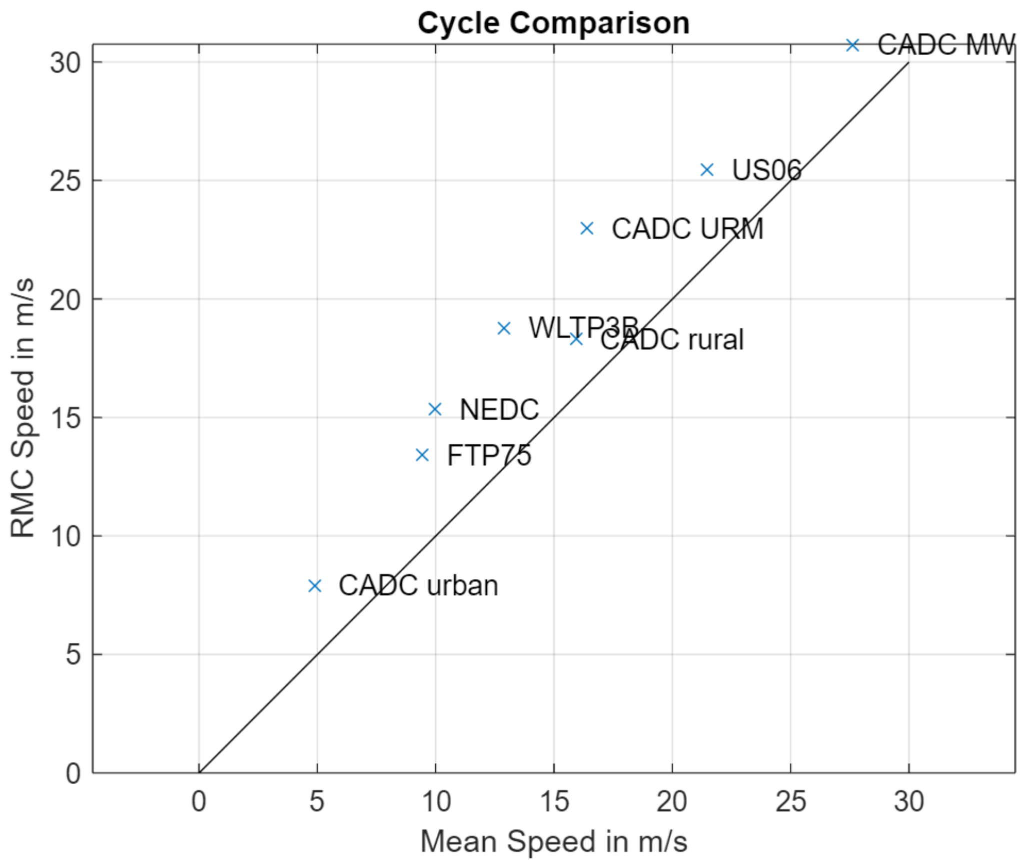
Cycle:

- Mean Speed / Length
- **RMC Speed** v_{RMC}

Vehicle:

- Rolling Friction
- Drag Coefficient

Moments of Cycles



Moments of Power

Powertrain Model

- Polynomial Model
- Moments

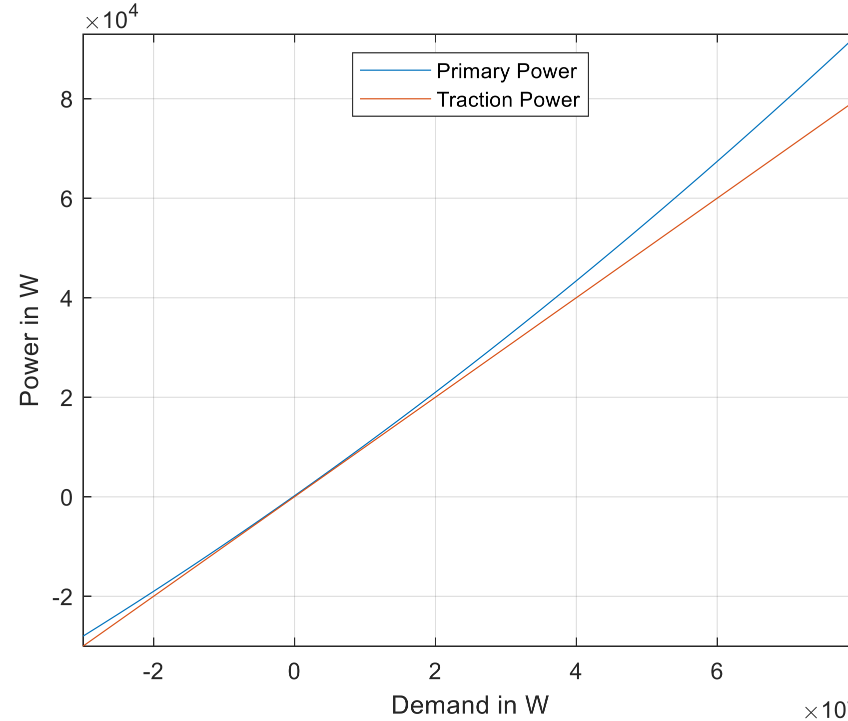
Powertrain Model

Primary Power

$$Y(P) = y_0 + y_1 P + y_2 P^2$$

Polynomial model:

- Idle drain y_0
- Raw efficiency y_1
- Overproportional / quadratic losses (e.g. resistive losses) y_2



Example: Nissan LEAF motor

Powertrain Energy

Primary Energy

$$E = \int Y(t)\, dt$$

$$= y_0 T$$

$$+c_0' l + c_2' T v_{RMC}^3$$

$$+ y_2' \int v^2 a^2\, dt$$

Two New Terms:

- Idle losses $y_0 T$
- Aggressiveness

$$\int v^2 a^2\, dt$$

This is also a new term not seen before.

Aggressiveness

Conventional Measure: Positive Kinetic Energy

$$PKE = \frac{1}{2}\int va^{+}\, dt$$

measures braking losses and potential energy.

But it does not change if a cycle is sped up, causing harsher accelerations.

New Term:

$$\int v^2 a^2\, dt$$

If the cycle is sped up, this terms grows proportionally. The faster an acceleration, the more it counts.

4 Drive Cycle Metrics

Based on standard models, the consumption has four key components. It predicts consumption and range using only parameters and statistics.

Idle Losses - Duration

$$P_{idle}\ (const)$$

Tyre Losses - Distance

$$\overline{P}_{tyre} = k_t \overline{v}$$

Aero Losses - Aerodynamics

$$\overline{P}_{aero} = k_a v_{RMC}^3$$

Regen Losses - Aggressiveness

$$\overline{P}_{power} = k_p \mathbb{E}[v^2 a^2]$$

With

Root mean cube:

$$v_{RMC}^3 = \mathbb{E}[v^3] = \mu_3'$$

Average: $\overline{v} = \mathbb{E}[v] = \mu$

Mixed moment: $\mathbb{E}[v^2 a^2]$

$$\mathbb{E}[v(t)] = \frac{1}{T}\int_{t=0}^{T} v(t)\ dt$$

$$k_a = \frac{A\sigma c_d}{2\eta}$$

$$k_t = \frac{mgC_{rr}}{\eta}$$

$$k_p = \frac{R_{phase}}{V_{DC}}$$

Moments of Power

Heavy Duty Application

- Engine Model
- Moment Model

Example Engine: Achates 10.6L

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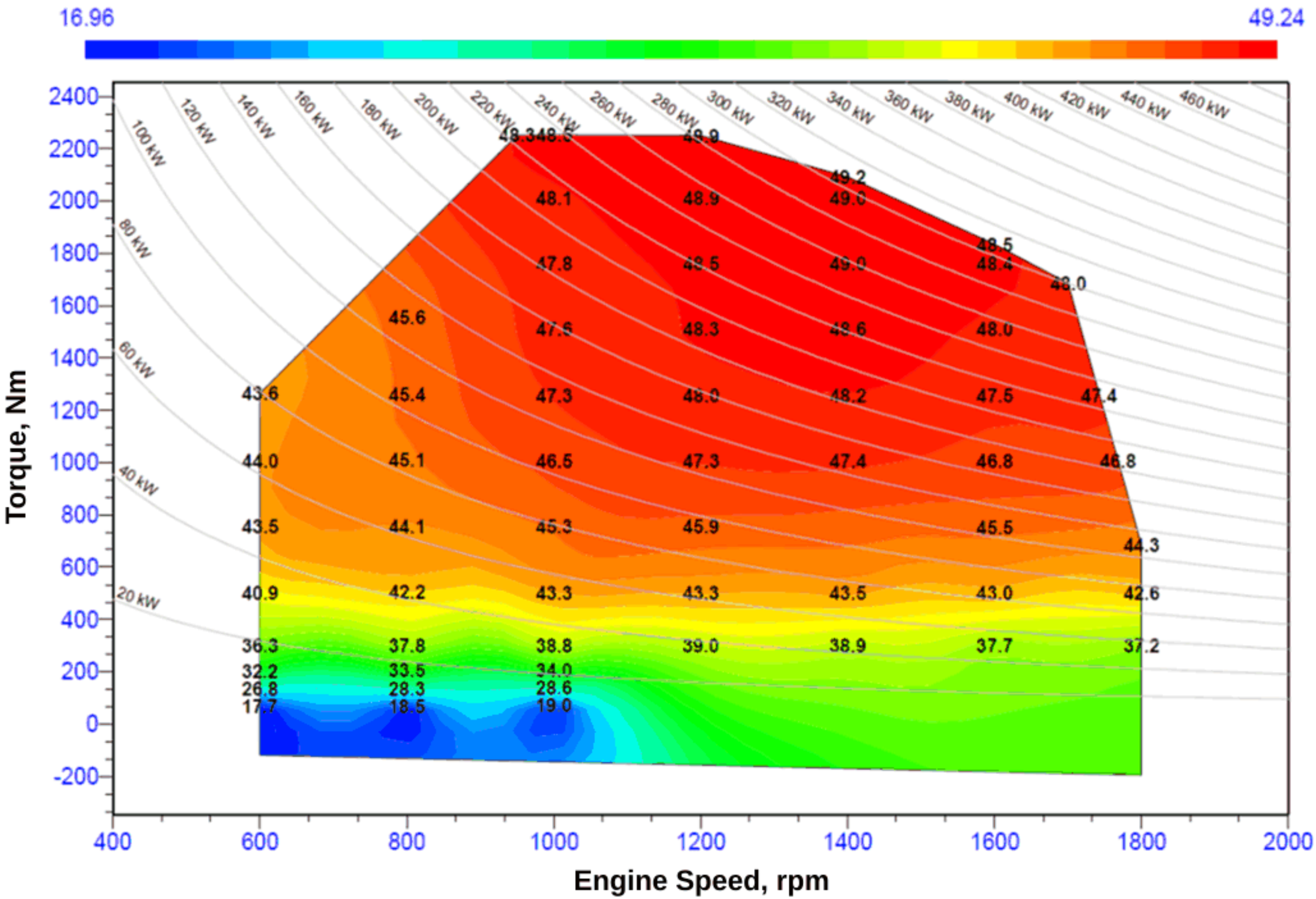
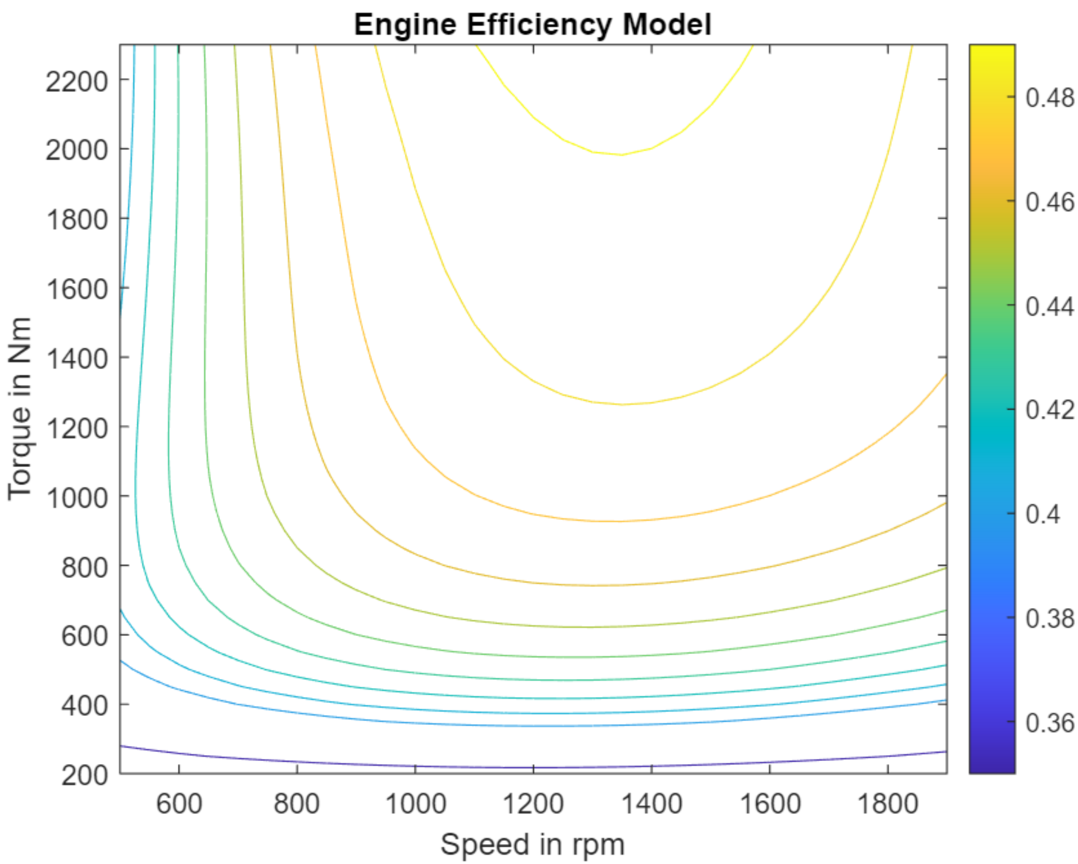


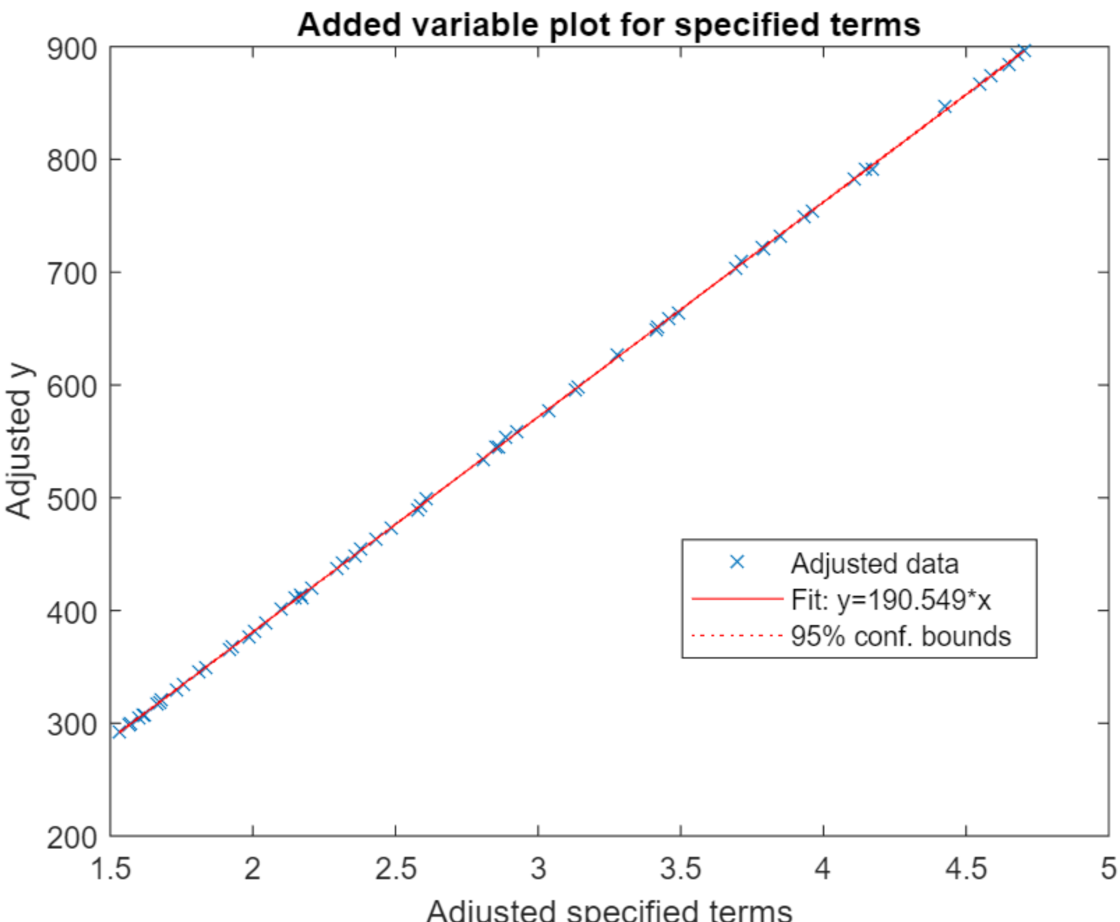
Polynomial Model



Linear regression model:

$$y \sim 1 + n + n^2 + n^3 + M^2 + M^3 + nM + (nM)^2 + n^2M$$

Polynomial Model



Within 0.2%
for most points

Better over
a cycle

Needs 8 moments:

$$\bar{n}, n_{RMS}, n_{RMC}$$
$$\bar{M}, M_{RMS}$$
$$\bar{P}, P_{RMS}$$
$$\mathbb{E}[nP]$$

5 highly significant

Polynomial Model

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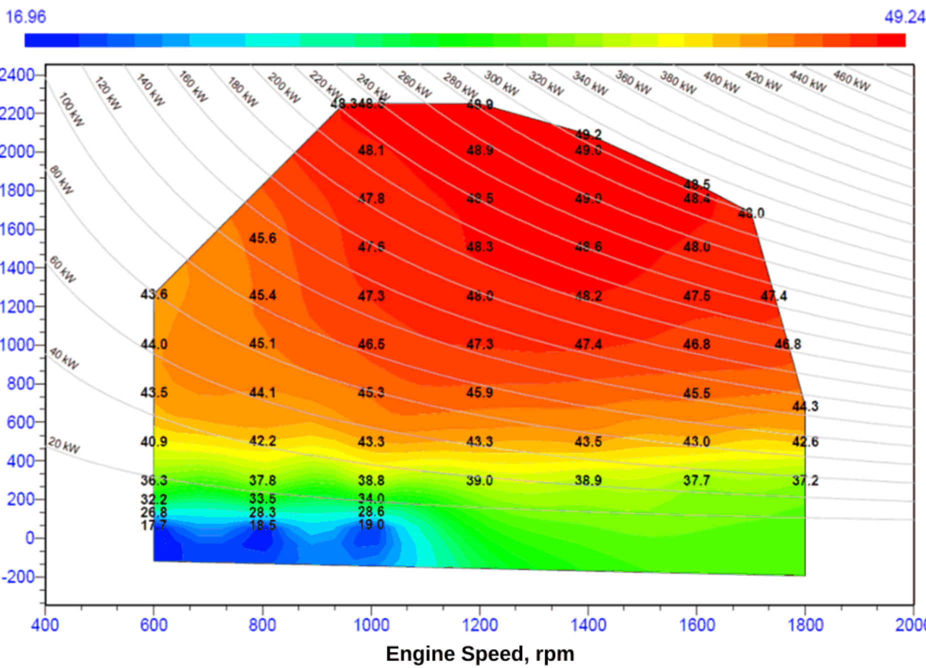
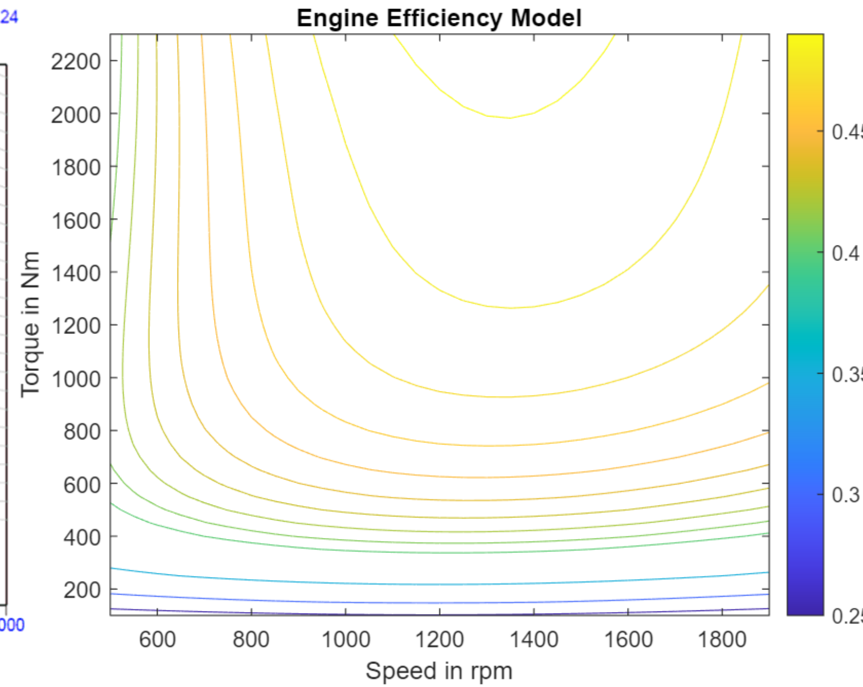
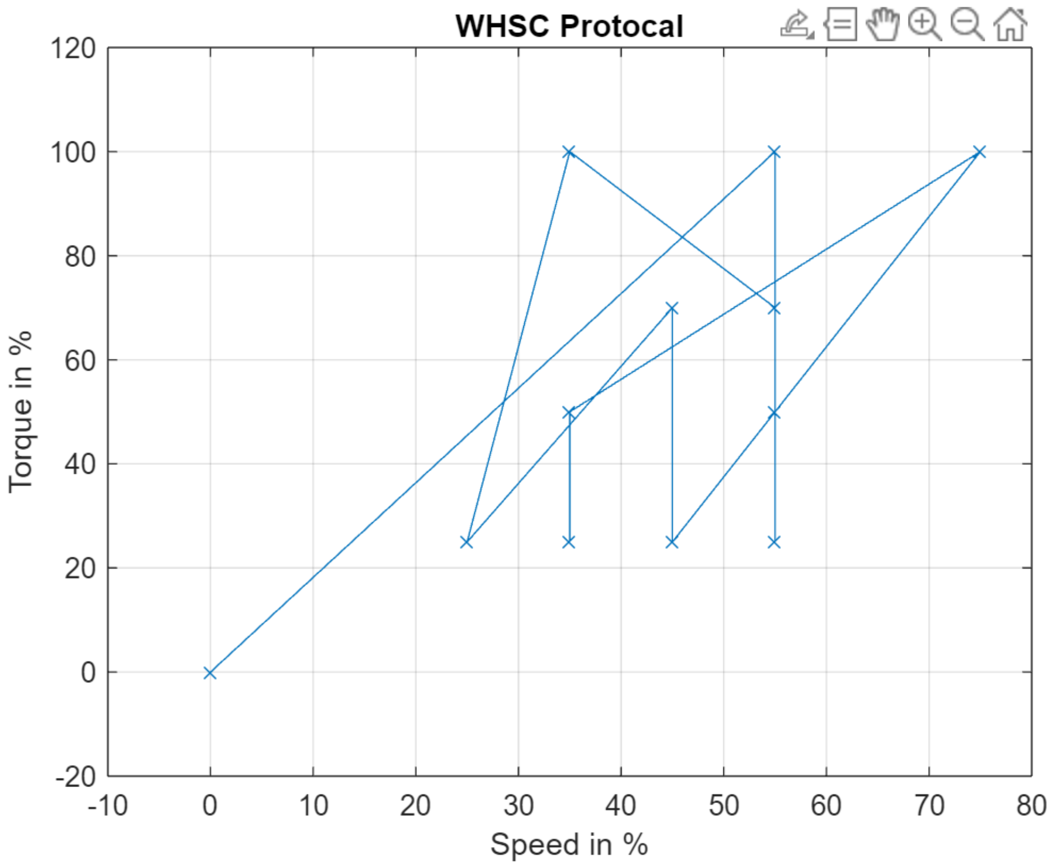




Compare: UNECE WHSC



12 point "average cycle"
But there is no such thing.

The data is sufficient to create a polynomial model.

	—	*RMS*	*RMC*
n	28%	34%	37%
M	17%	30%	39%
P	7%	14%	19%

Future Research

More (easy)

- Fast dynamics ($\frac{d}{dt}a$)
- Hybrids & scheduling
- Component models
  - Motors
  - Engines
  - Gearboxes
- Wear & Degradation
  - Bearings
  - Batteries
- Simulink Library

Different

1. Include limits & discrete modes
   (gears, regen limit etc)
2. Include slow dynamics (thermal)
3. Include dynamic/adaptive control

Conclusion

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- The use of moments in combination with polynomial models offers an **analytical** solution for energy consumption
- The applications are many and profound:
  - Analysis
  - Consumption Prediction
  - Operator Categorisation
  - Planning
  - Component Selection
  - Calibration

For questions, please contact Thomas Steffen
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You can find a video of a 2023 SAE (LDV) presentation on youtube: