CO_2 Emissions
from Heavy Duty Vehicles
Overview of VECTO's inputs

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Outline

- Introduction
- Inputs & VECTO
  - Engine module (draft)
  - Transmission module (draft)
- Verification summary
- Conclusions – Follow up

INTRODUCTION

About the JRC / STU

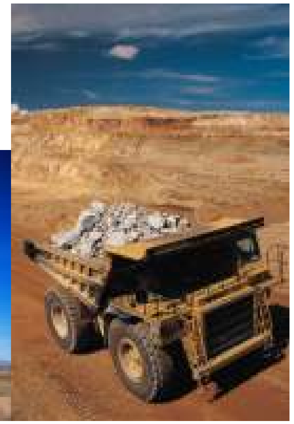
- Joint Research Centre (JRC) research body of the European Commission
- Mission: provide research & innovation oriented to policy support for the European Union
- Sustainable transport unit: Research group working on transport technology & sustainability
- ~60 people, 7 labs, several models and software tools




Monitoring CO_2 from Heavy Duty Vehicles

- Need for an HDV CO_2 monitoring scheme for Europe
- Heavy Duty Vehicles is a complex sector, "*not 2 vehicles identical*"
- European manufacturers are amongst global leaders
- Lack of data to support policy, need for monitoring – data collection
- Tool to be used by EC, TA authorities and possibly by OEMs
- Close collaboration between DG-CLIMA, JRC and ACEA
- Major markets outside Europe already adopted initiatives (mainly simulation based)



Approach Chosen: Simulation

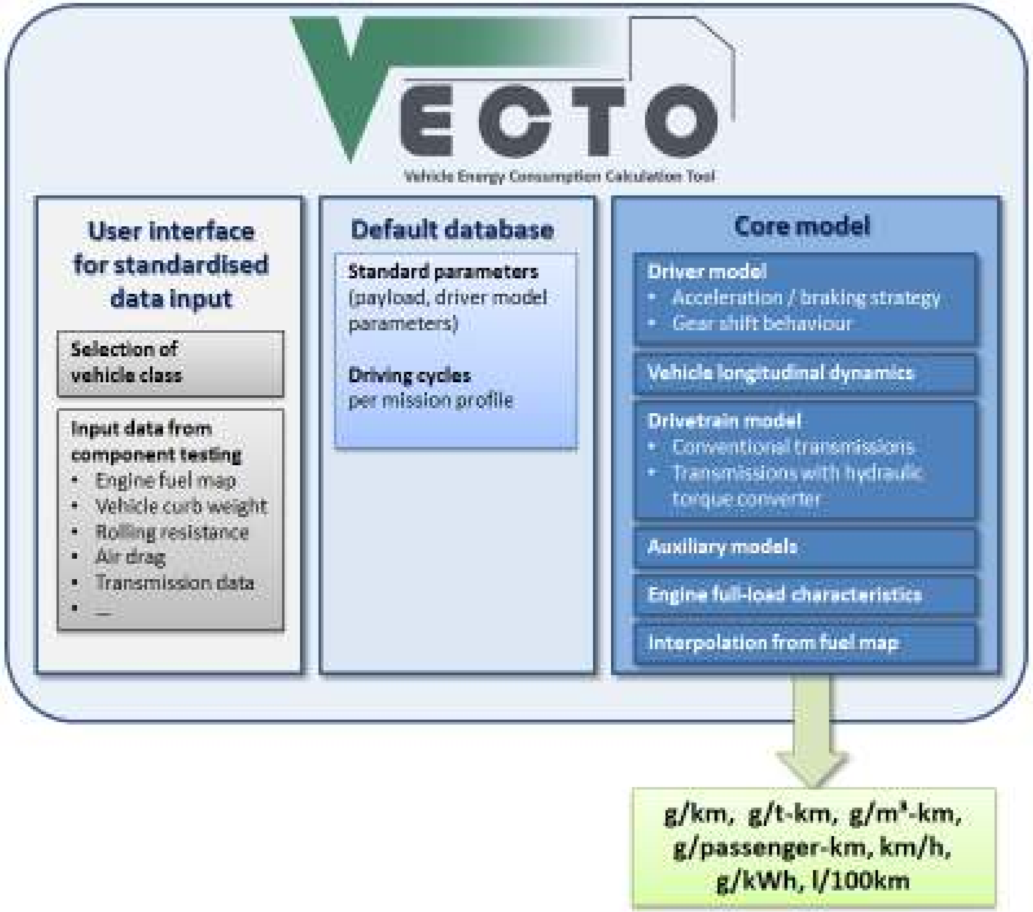
- Approaches explored :
  - ***measurement on chassis dynamometer***
  - ***measurement with PEMS***
  - ***vehicle simulation***
- Selected option:

  - ***Model based simulation for the whole vehicle (truck and trailer) and component testing***

- Methodology considers:
  - ***engine, driving resistances of whole vehicle (rolling, aerodynamic), gearbox, axles, most relevant auxiliaries, driver model, specific mission profiles-cycles***

VECTO: The CO_2 simulation tool for HDVs in Europe

- **V**ehicle **E**nergy **C**onsumption calculation **TO**ol
- Initially to cover:
  - **Delivery trucks (long haul and regional-city)**
  - **Coaches**
  - **Effort to include city buses**
- Effort to standardize:
  - **Measurement protocols for input data generation**
  - **Individual component simulation models**
  - **Mission profiles and cycles**
  - **Evaluation / validation approaches**



VECTO & INPUTS

Overview of simulator

$$Pe = P_{roll.} + P_{air} + P_{acc} + P_{grad} + P_{tr.} + P_{aux} + P_{cons.}$$

Different level of detail

RRC from tyre drum tests, axle loads

Considers $m_{vehicle}$, m_{load}, I_{wheels}, I_{engine}, $I_{drivetrain}$

C_d*A from constant speed tests (new test method developed)
Generic side wind effect added
(in later stage optional vehicle specific)

Simulator (Vehicle Energy consumption Calculation Tool – VECTO):

- Backward simulation; Forward control loops included for target speed cycles, driver model operation, look ahead breaking, eco-roll, over-speeding
- Programming language: Visual Basic .NET
- Simulation of engine power and engine speed
- Interpolation of fuel consumption from engine map

Classification

- Total HDV classes:
  - ***18 truck classes***
  - ***6 bus and coach classes***
- 10 test cycles based on segment (5 for trucks and 5 for busses-coaches)
- Bodies and trailers:
  - ***Standard bodies and trailers***
  - ***Δ(Cd*A) measured for alternatives***
- Simplifications being discussed

Identification of vehicle class					Segmentation (vehicle configuration and cycle allocation)					Norm-body allocation		
Axles	Axle configuration	Chassis configuration	Maximum GVW [t]	<-- vehice class	Long haul	Regional delivery	Urban delivery	Municipal utility	Construction	Standard body	Standard trailer	Standard semitrailer
2	4x2	Rigid	>3.5 - 7.5	0		R	R			B0		
2	4x2	Rigid or Tractor	7.5 - 10	1		R	R			B1		
		Rigid or Tractor	>10 - 12	2	R	R	R			B2		
		Rigid or Tractor	>12 - 16	3		R	R			B3		
		Rigid	>16	4	R+T	R		R		B4	T1	
		Tractor	>16	5	T+S	T+S						S1
	4x4	Rigid	7.5 - 16	6				R	R	B1		
		Rigid	>16	7					R	B5		
		Tractor	>16	8					T+S			W1?
3	6x2/2-4	Rigid	all weights	9	R+T	R		R		B6	T2	
		Tractor	all weights	10	T+S	T+S						S2
	6x4	Rigid	all weights	11					R	B7		
		Tractor	all weights	12					R			S3
	6x6	Rigid	all weights	13					R	W7		
		Tractor	all weights	14					R	W7		
4	8x2	Rigid	all weights	15		R				B8		
	8x4	Rigid	all weights	16					R	B9		
	8x6 & 8x8	Rigid	all weights	17								

R…Rigid,
T…Trailer,
T+S..Tractor+semi-trailer,
W…only weight

Steps:
Vehicle characteristics → Classification → Segmentation → Test cycle selection → vehicle loading and default / specific bodies allocation → simulation

Engine Module: VECTO relevant Input data (draft)

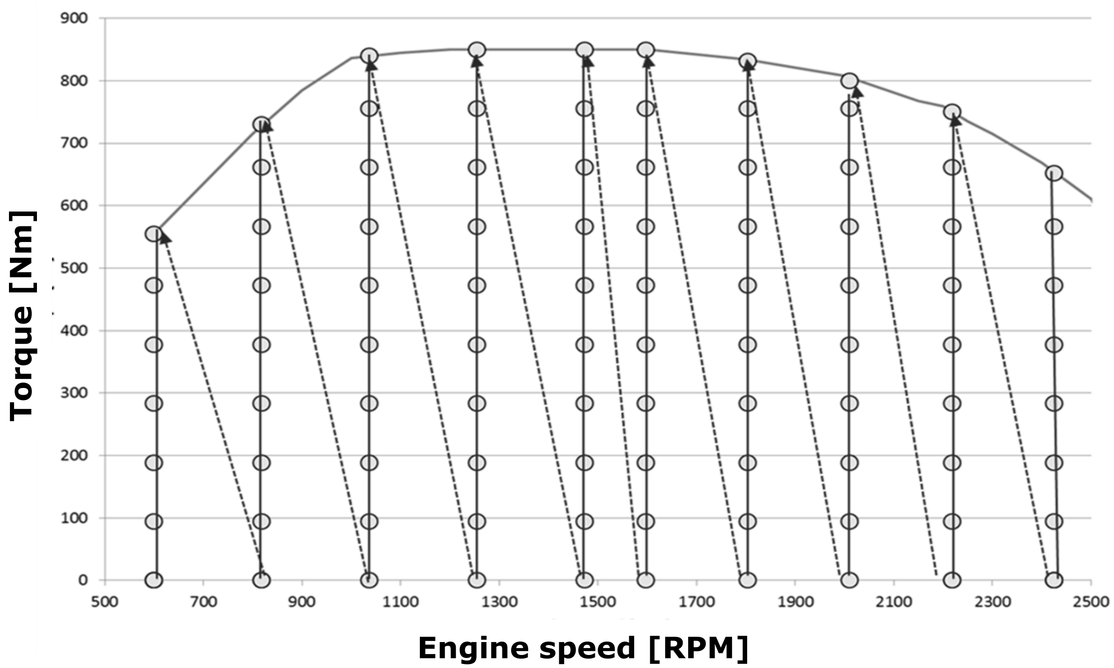
Component	Data	Unit	component specific	Default data	Comments	to be reported to TS	TS to be incorporated	CoP procedure
General	Vehicle class	[-]	X		classification according to HDV CO2 vehicle segmentation matrix			
	Vehicle curb weight	[kg]	X					
	Trailer or body curb weight	[kg]		X	specified for each vehicle class			
	Gross vehicle weight	[kg]	X					
	Axle load distribution	[%]		X	specified for each vehicle class			
	Chassis length	[m]	X		only for busses (→ number of passengers)			
	Chassis width	[m]	X		only for busses (→ number of passengers)			
Engine	Displacement	[ccm]	X					
	Rated power	[kW]	X					
	Idling speed	[rpm]	X					
	Rated speed	[rpm]	X					
	Engine rotational inertia incl. flywheel	[kgm²]		X	calculated from engine displacement			
	Steady state fuel map	...	X		fuel consumption [g/h] = *f* (engine speed [rpm], engine torque [Nm])			
	Full-load curve	...	X		full-load torque = *f* (engine speed [rpm])			
	Drag curve	...	X		drag torque = *f* (engine speed [rpm])			
	Test result WHTC hot	...	X		fuel consumption [g/h] = *f* (engine speed [rpm], engine torque [Nm]) in 10Hz time resolution			

Engine Module: general provisions (draft phase)

- Fuel consumption map → actual engine fuel consumption measured over different steady state conditions
- For each engine hardware and ECU calibration software combination a fuel map has to be measured
- All measurements performed according to (EC) 595/2009 on type approval of motor vehicles and engines and UN/ECE Regulation No 49.06
- Power consumption of engine auxiliaries (eg oil pump, coolant pump, fuel delivery pump, high pressure pump, alternator) to be covered by the map
- Issues that may arise because of the steady state approach:
  - Possible inconsistencies between engine certified CO_2 (WHTC hot part) and the steady state fuel map
  - transient engine behaviour not considered
- Solution → use of "WHTC correction factor" calculated on the basis of the actual WHTC measurement

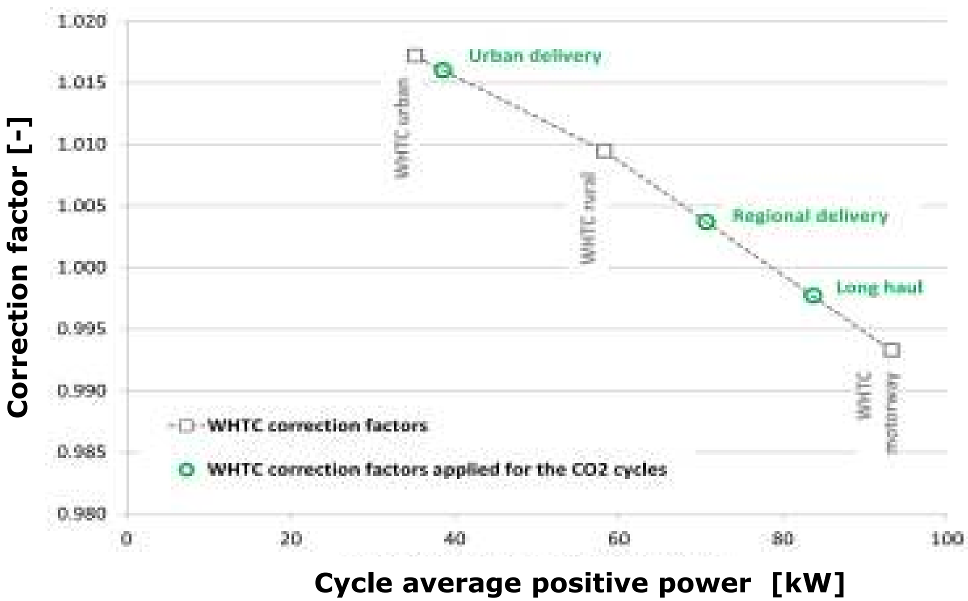
Engine Module: The engine map

- Minimum 10 engine speeds shall be measured. The four base speeds shall be: n_{idle}, n_{pref} - n_{pref} *0.04, n_{pref} + n_{pref} *0.04, n_{95}
- The remaining 6 engine speeds determined by splitting the two ranges (n_{idle} to n_{pref} -4 % and n_{pref} +4 % to n_{95}) into a minimum of 4 equidistant sections
- Torque step width: clustering range 0 - maximum torque into 10 equidistant sections
- Fill up the range below the mapping curve.
- When exceeding mapping curve the full load torque becomes applicable.



Engine Module: WHTC correction factors (draft)

- Engine only operation is simulated over the 3 parts of WHTC
  → fuel consumption calculated from the steady state fuel map (“backward calculation”)
- Measured specific FC per part in [g/kWh] is then divided by the simulated value
  → 3 different correction factors (CFs) calculated
- Total factor (CF_{Tot-i}) weighted average depending on mission profile “i”
  - Produced by VECTO by mission profile specific weighting factors (WFi),
  - $CF_{Tot-i} = CF_{Urb} \times WF_{Urb-i} + CF_{Rur} \times WF_{Rur-i} + CF_{MW} \times W_{FMW-i}$



	WF_{Urb}
1	6%
2	26%
3	77%

Transmission: VECTO relevant Input data (draft)

Component	Data	Unit	component specific	Default data	Comments	to be reported to TS	TS to be incorporated	CoP procedure
	Tyre rotational inertia			X	calculated based on wheel dimension of each axle			
	Tyre RRC (trailer)			X	if applicable			
	Tyre rotational inertia (trailer)			X	if applicable			
Transmission	Transmission type	[-]	X		Manual transmission (MT), Automated manual transmission (AMT) or Automatic Transmission with Torque converter (AT)			
	Torque loss map (mechanical)	…	X	X	for each gear: torque loss [Nm] = *f* (clutch output speed [rpm], clutch output torque [Nm])			
	Gear ratio	[-]	X		for each gear			
	Torque converter (TC) characteristics	…	X	X(?)	if applicable: torque ratio [-] = *f* (TC speed ratio [-]) reference torque at reference speed [Nm] = *f* (TC speed ratio [-])			
	Torque converter reference speed	[rpm]	X		if applicable; (1000 rpm defined as standard?)			
	Gearbox inertia	[kgm²]		X	for transmissions w/o TC set to zero; transmissions with TC: open			
Retarder	Retarder type	[-]	X		none (or transmission internal) / primary / secondary			
	Retarder losses	…	X	X	if applicable: retarder losses [Nm] = *f* (retarder speed [rpm])			

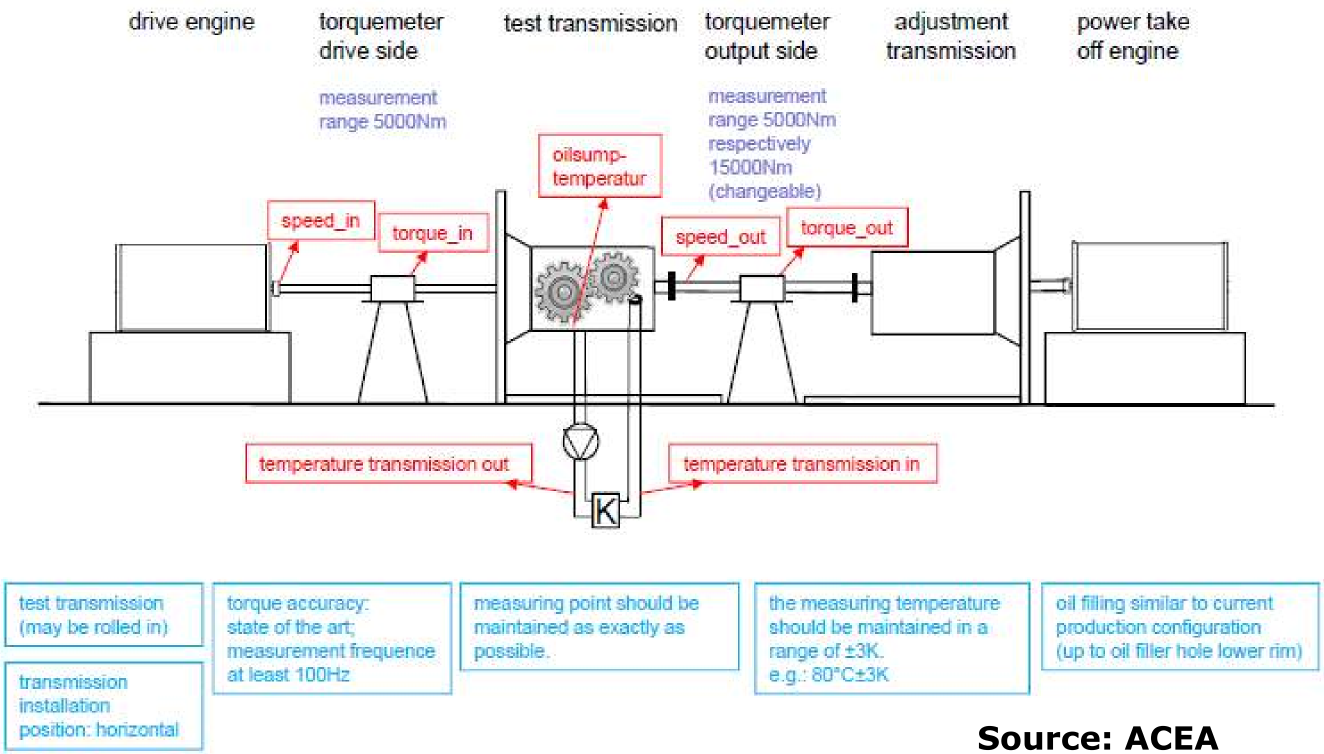
Transmission: general provisions (draft)

- 3 different methods for assessing transmission losses

  Option 1: Fall back values based on the maximum rated torque of the transmission

  Option 2: Torque independent losses (measured), torque dependent losses (calculated). Electric machine & torque sensor before transmission (output shaft free-rotating)

  Option 3: Measurement of total torque loss. Electric machines and torque sensors in front and behind transmission



Source: ACEA

Transmission: Option 1 Fall back values

- Fall back values based on the maximum rated torque of the transmission
- The torque loss $T_{l,in}$ on the input shaft of the transmission is calculated:

$$T_{l,in} = T_{d0} + T_{d1000} \cdot \frac{n_{in}}{1000\ rpm} + f_T \cdot T_{in}$$

Where $T_{l,in}$ torque losses at input shaft

T_{dx} drag torque at x RPM

n_{in} speed of input shaft

f_t equals 1-efficiency (fixed depending on direct / non direct gear)

T_{in} torque at input shaft

→ T_{dx} (T_{max}) = $T_{d0} = T_{d1000} = \mathrm{T}_{const} \cdot \frac{T_{\max\ in}}{2000\ Nm}$

Transmission: Option 2 (mix measured and calculated)

- Torque independent losses (measured),
- Torque dependent losses (calculated)
- Electric machine and torque sensor in front of transmission (output shaft free rotating)
- The torque loss $T_{l,in}$ on the input shaft of the transmission is:

$$T_{l,in}(n_{in}, T_{in}, gear) = T_{idle}(n_{in}, gear) + (1 - \eta_T(gear)) \cdot T_{in}$$

- T_{idle} → Drag torque from testing at 0 load [Nm] (measured component)
- Gear dependent efficiency η_T → calculated for each gear separately (calculated component)

$$\eta_T = \eta_{m,splitter} \cdot \eta_{m,main} \cdot \eta_{lowrange} \cdot \eta_{bearings}$$

- Fixed values or specific formulas for subcomponents

Transmission: Option 3 (full measurement)

- Measurement of total torque loss
- Electric machines and torque sensors at both sides of transmission
- General model as in option 2

$$T_{l,in}(n_{in}, T_{in}, gear) = T_{idle}(n_{in}, gear) + (1 - \eta_T(gear)) \cdot T_{in}$$

- The torque loss measured for (speed of the input shaft):
  - 600, 800, 1000, 1200, 1400, 1700, 2000, 2400, 2800, 3200, … rpm up to the maximum speed according to the specifications of the transmission (or higher).
- At each speed, torque measured for (input torques):
  - 0 , 200, 400, 600, 800, 1000, 1200, 1400, 1700, 2000, 2400, 2800, 3200, 3600, 4000, … Nm up to the maximum input torque according to the specifications of the transmission (or higher

Retarder: general provisions (draft phase)

- 2 different methods for assessing retarder losses
  - Option 1: standard technology specific table value for drag torque losses
  - Option 2: measurement of drag torque in deactivated mode

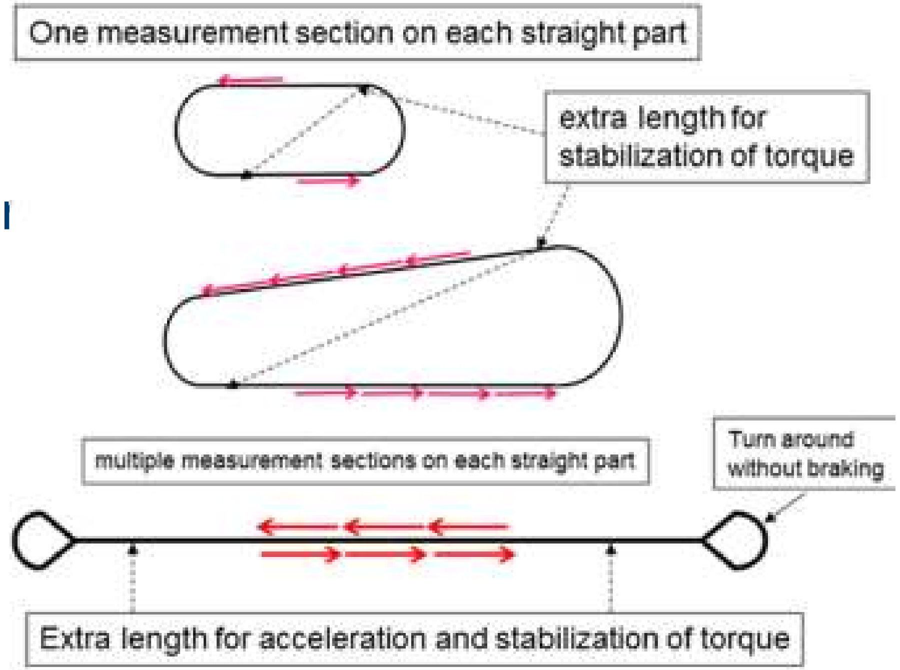
- Option 1:

$$T_{l,Ret,\,input/prop} = 10 + 2 \cdot \left(\frac{n_{input/prop}}{1000}\right)^2$$

- Option 2:
- Retarder losses measured in combination with transmission testing
  →The transmission losses already include the retarder losses.
- If retarder individual component, retarder losses determined by subtracting gearbox losses measured with and without the retarder over one gear ratio

Input: Aerodynamic drag - rrc

- Constant speed test (at 2 velocities)
  - torque meter rim
  - anemometer
  - correction for gradient and for vehicle speed variations
  - correction for ambient p,T
  - $F = F0 + Cd * A * v^2 * \rho/2$



Important tire and vehicle conditioning for accurate Cd*A results.

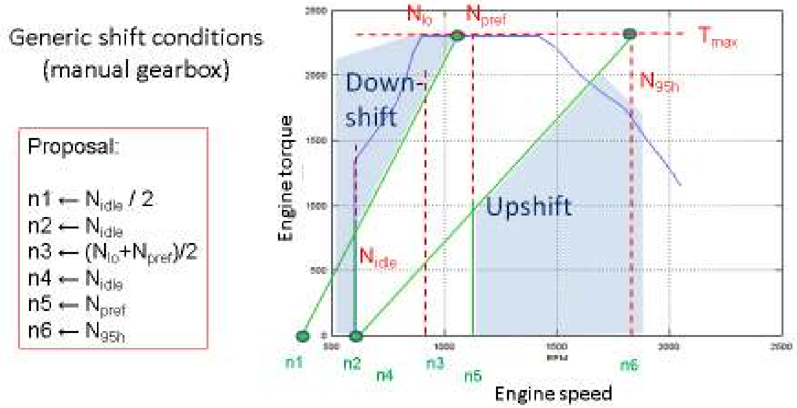
RRC calculated in these tests not to be used. Official value to be used for monitoring purposes

Gearshift model

- Implementation of gear shift strategy proposed by ACEA for manual and automated manual transmissions

Up- and down-shift polygons

Torque [Nm]	Downshift [rpm]	Upshift [rpm]
-500	650	900
0	650	900
500	700	950
...	...	...

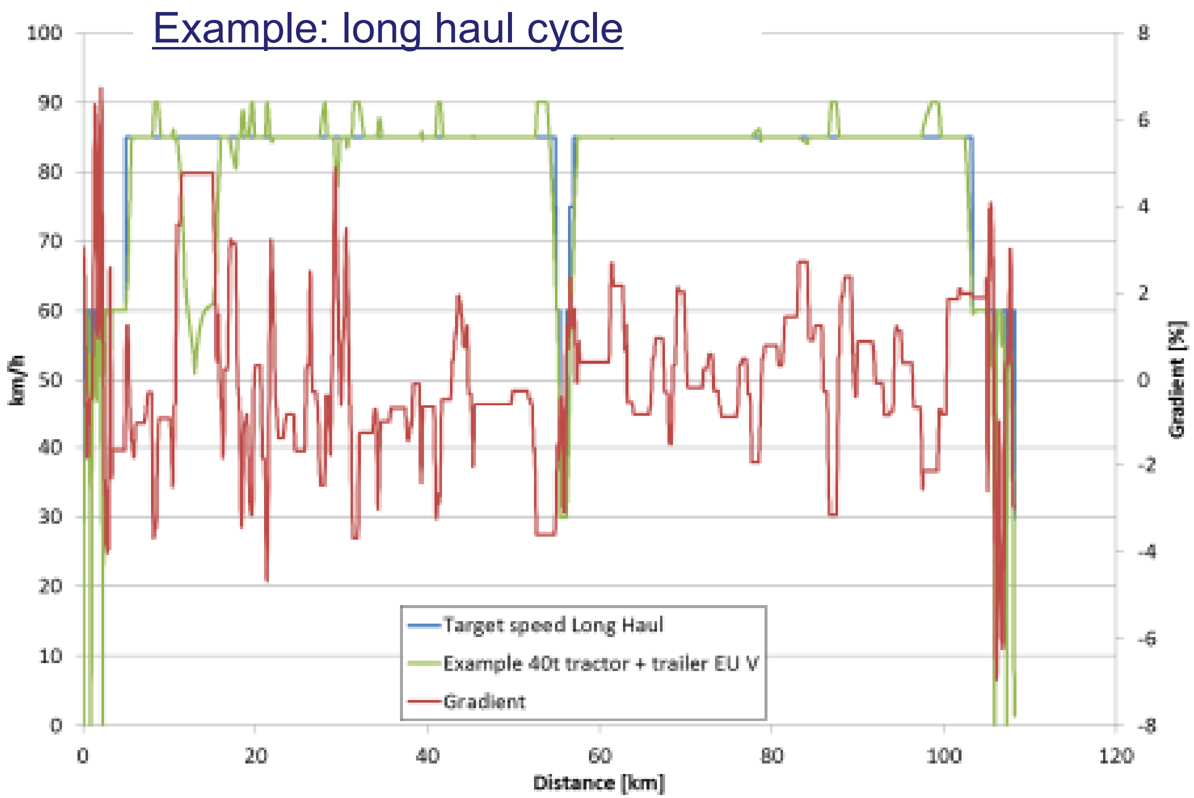


Default-Option: skipping of gears: Criteria:
1) rpm is still over DownShift-rpm and
2) torque reserve is above a user-defined value (e.g. 20%)
Additional parameter for avoidance of ocillating shifts:
minimum time between two gear shifts (e.g. 3s)

- AMT = MT with different polygons and early upshifting
- Skipping gears possible based on torque reserve criteria, starting from gear >1
- Automatic GB model under development based on input received from OEMs and GB manufacturers

Input: Test cycles - driver model

→ Different representative cycles per vehicle category and mission profile including target speed phases and road gradients



Driver model:

Acceleration: limited by full load and max. driver demand

Gear selection with torque interruption

Overspeed function optional eco-roll or none

"Look ahead" braking

<u>Cycles</u>: *Trucks*: Long haul, Regional delivery, urban delivery, Municipal utility, Construction
***Busses*: Urban bus (heavy urban, urban, suburban), Interurban bus, Coach**

General structure of auxiliary models

Additional load to ICE from auxiliary operation „$P_{mech,ICE}$“ calculated in VECTO in 1Hz

$$P_{mech,ICE} = \frac{1}{\eta_{trans}} \cdot f\left(n_{ice} \cdot i_{aux}, \frac{P_{sup}}{\eta_{sup}}\right)$$

„performance map“

Auxiliary speed	Supply power	Mechanical power
[rpm]	[kW]	[kW]
1415	0	0.07
1415	0.53	0.87
1415	0.64	1.03
1415	0.75	1.17
1416	0.84	1.36
1416	1.4	2.4
1887	0	0.07
...	...	...

Alternator ……..... Average electric power demand

Compressor ……. Average compressor supply power (Integral volume-flow

Steering pump …. Steering power course over distance (M_{wheel} * ω) [kW]

Air conditioning .... e.g. cooling capacity (mass flow * (h_{out} – h_{in})) [kW]

Engine cooling system: special case

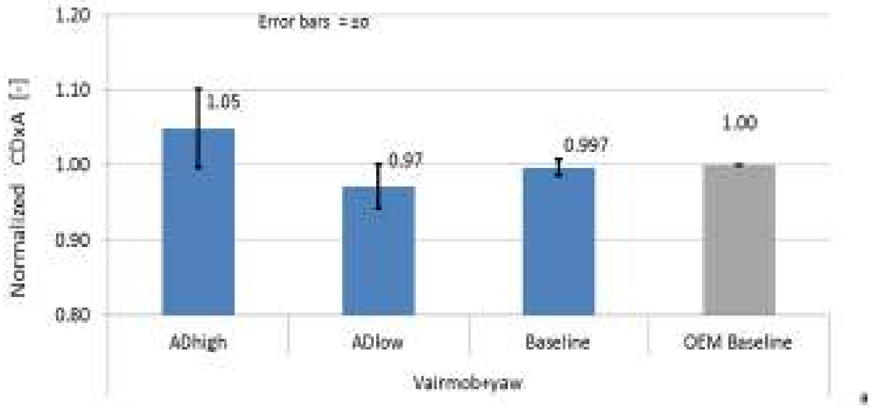
Detailed air-conditioning and air pump sub-models to developed by ACEA

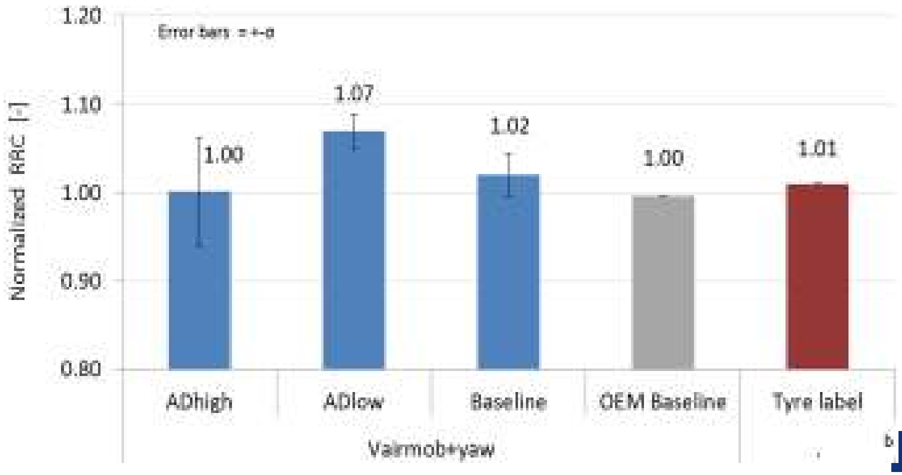
Operation profiles and/or generic default values for auxiliaries-vehicle-mission profile combinations are under investigations

VALIDATION SUMMARY

Results Air Drag With Yaw correction

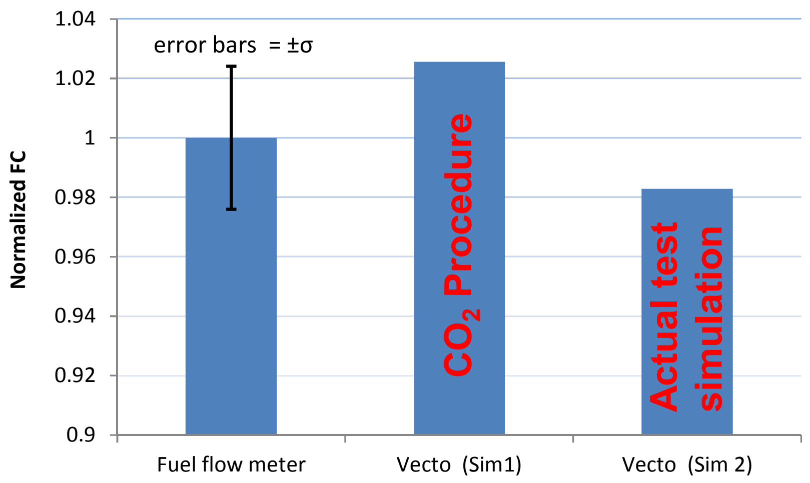
- Application of generic yaw correction curve improves accuracy (>99%)
- Very good reproducibility in a different proving ground

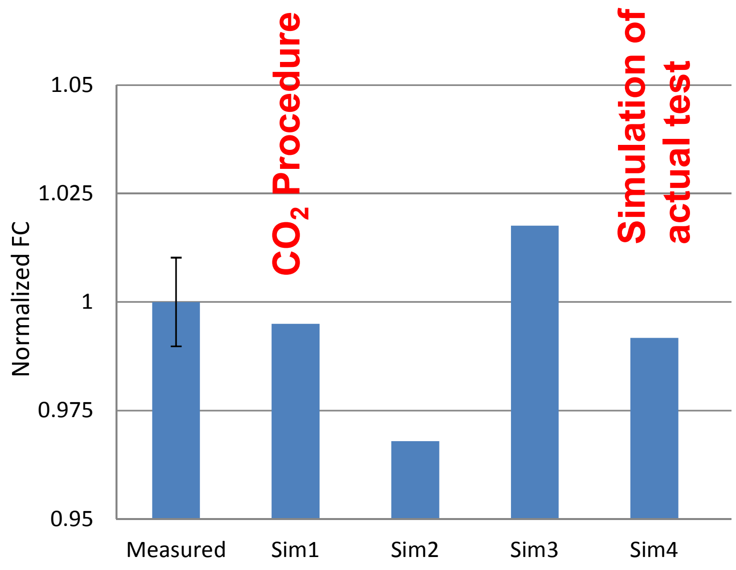




Difference from OEM measurement for $C_d \bullet A_{cr}$ [%]	- 0.3 %
Standard deviation of $C_d \bullet A_{cr}$ measurement [%]	1.1 %
Difference from OEM value for RRC [%]	2.0 %
Standard deviation of RRC measurement [%]	2.3 %

On road testing: summary of results

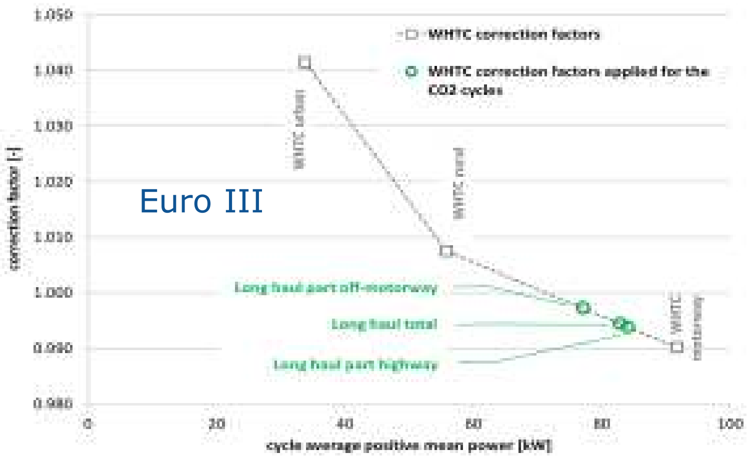


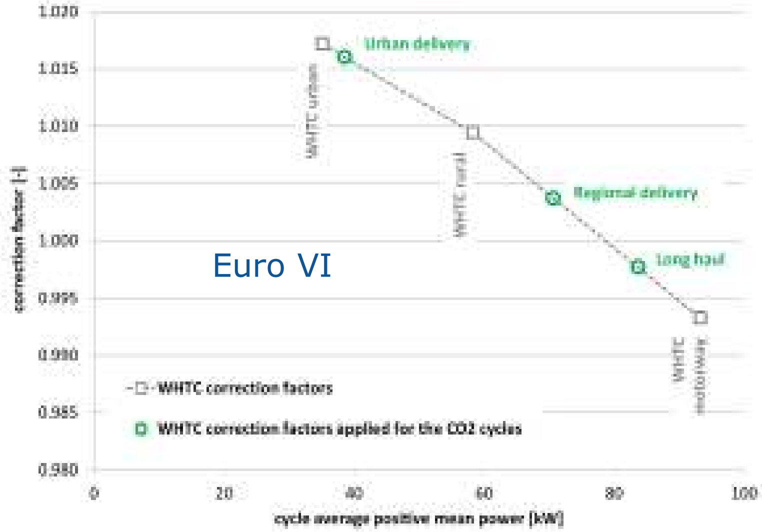


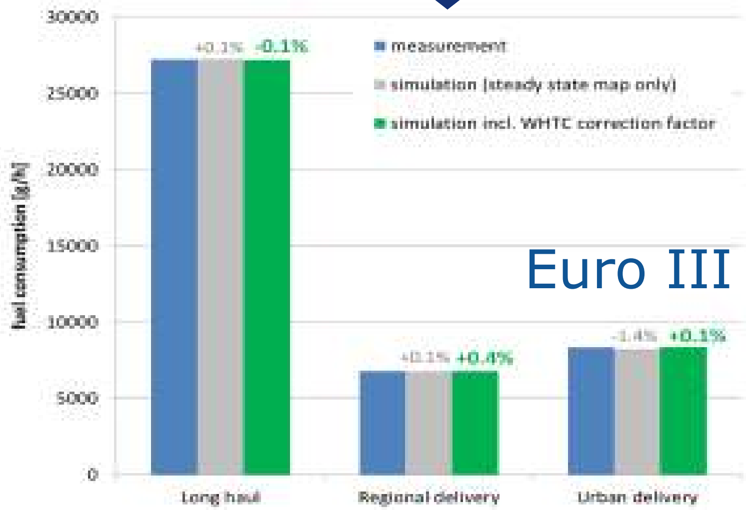
Method seems to be quite accurate, even before full development (results are even better than expected but this may be by chance)

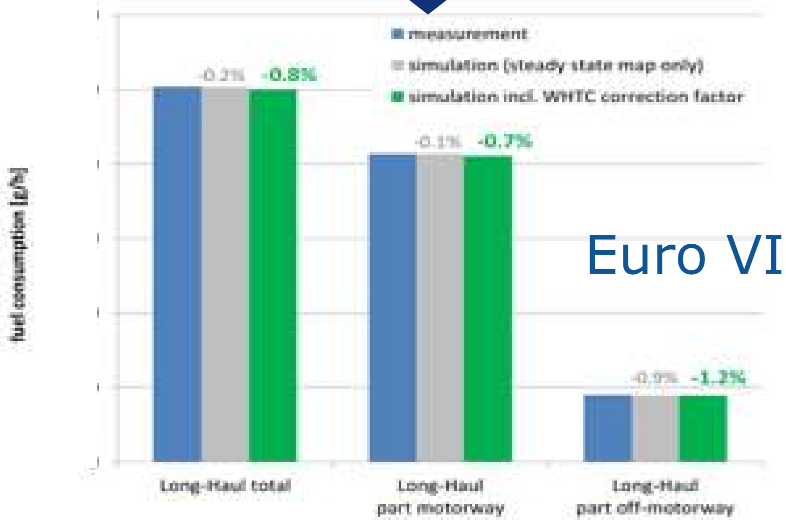
On-going: Extensive experimental campaign to verify overall performance with several different kinds of vehicles.

Engine mapping









CONCLUSIONS & FOLLOW UP

Conclusions

- The declaration method (DM) proposed can provide results representative of the real world performance
- Accurate input data essential, positive feedback regarding the quality of developing measurement methods
- Simulator presents satisfactory accuracy within a +-~3% from measurements
- Good results from engine mapping approach & other modeling concepts introduced

Follow up

- Finalize & validate topics remaining open *(gearbox and driveline efficiency quantification, auxiliary units power consumption, automatic gear shifting strategies, mobile air conditioning simulation for city buses)*
- Accurate quantification of uncertainties for different vehicle types
- Apply the method to additional vehicle types / components, generate data. Lay down the foundations for a full scale application on different vehicles (pilot phase)
- Shift to forward simulation tool, attempt to merge with HILs simulator used for Hybrid HD powertrains

Thank you for your attention

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