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Introduction to the CO_2MPAS tool

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WORKSHOP NEDC/WLTP CORRELATION PROCEDURE AND USE OF CO2MPAS, 14TH NOVEMBER 2018

European Commission

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Introduction
Why Simulations?

Experimentally testing many vehicles has 2 drawbacks:

1. It doesn't cover all possible configurations of the vehicle and many operating conditions
2. It is expensive and time consuming

Selected Approach: Combine vehicle simulation & measurements → Models of existing vehicles → Calculate CO_2 & emissions over different conditions

Approach extensively used in the industry, while several considerations are of crucial importance:

- Selection of fleet representative vehicle models
- Input data collection
- Accurate simulation of the vehicle's operation
- Validation / quality control of results

Introduction
Simulation of Engine Power & Speed

Simulation of engine power:

Vehicle specific
C_d*A

Vehicle specific
m*g*sinα

Vehicle specific
transmission: **loss maps**

$$P_e = P_{roll.} + P_{air} + P_{acc} + P_{grad} + P_{transm.} + P_{aux.} + P_{cons.}$$

Vehicle + tire specific
$m_{vehicle}$, m_{load},
RRC from drum tests

Vehicle specific
$m_{vehicle}$, m_{load},
I_{wheels}, I_{engine}

Generic
P_{supply} + efficiency

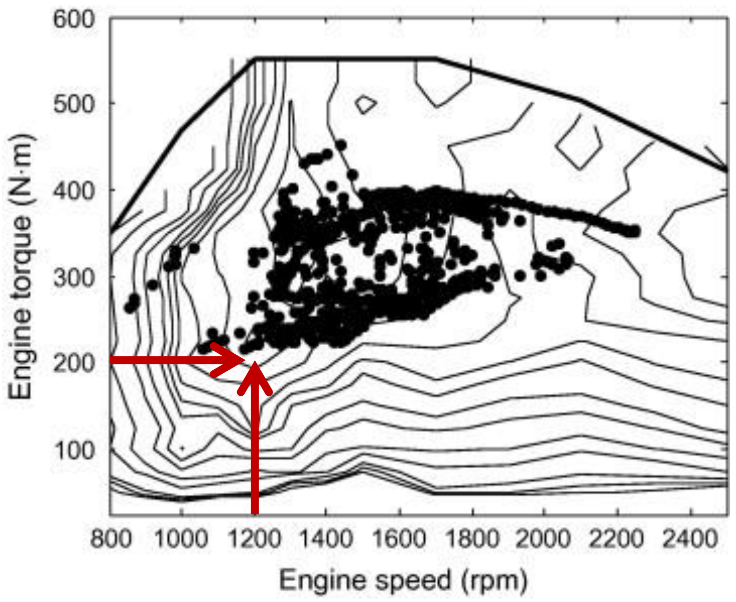
Simulation of engine speed

$$n = (v \times 60 \times I_{axle} \times I_{gear}) / (d_{tire} \times \pi)$$

Vehicle transmission ratios
i_{gear}, i_{axle}

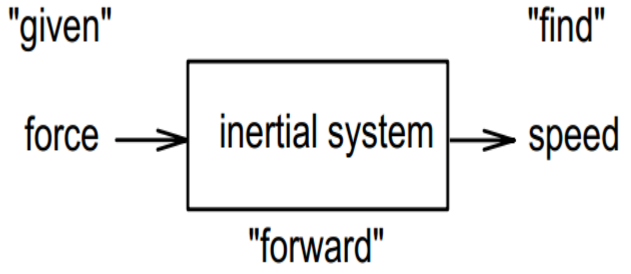
Introduction
Consumption / Efficiency Maps

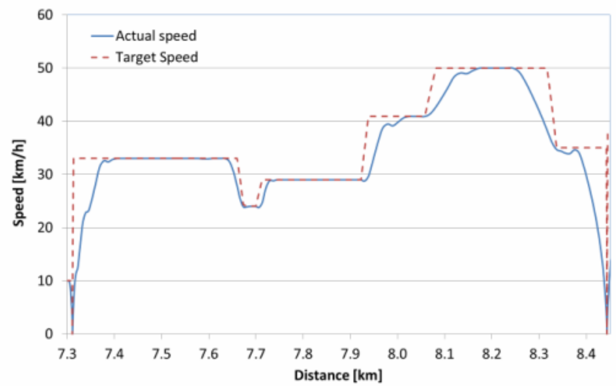
- A map (engine, gearbox, motor, other) is practically a table containing fuel consumption/component efficiency values for pairs of RPM – Torque
- The vehicle model at each calculation step (e.g. each sec), retrieves the fuel consumption/efficiency value depending on calculated RPM, Torque or Power
- There is no physical model of engine/component to react in certain technology changes; new tables need to be provided

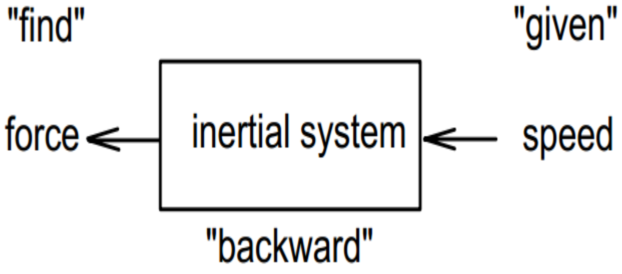


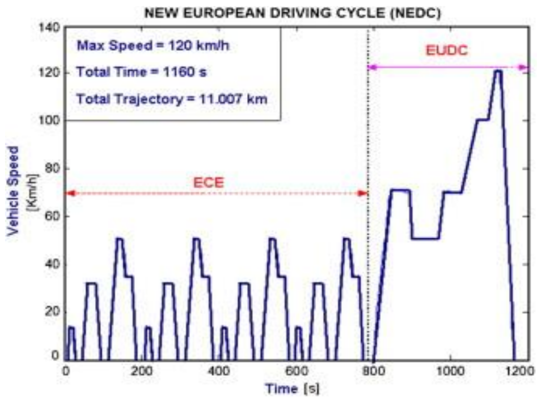
RPM\ Torque	10	50	100	150	200
1000	1	3	4	5	6
1200	2	4	6	8	10
1400	5	7	9	11	13
1600	6	8	10	12	14
1800	8	10	12	14	16

Introduction
Forward vs. Backward Models









Introduction
Simulation Tools used for Regulatory Purposes

Below, a non exhaustive list:

- GEM, US EPA for HDVs
- HILs, UNECE/Japan for Hybrid HD Powertrains
- VECTO, European Commission – HD Vehicles
- KEES, Korea – HD Vehicles
- JSM, NTSEL/Japan – HD Vehicles

And many other commercial brands that may already be in use…

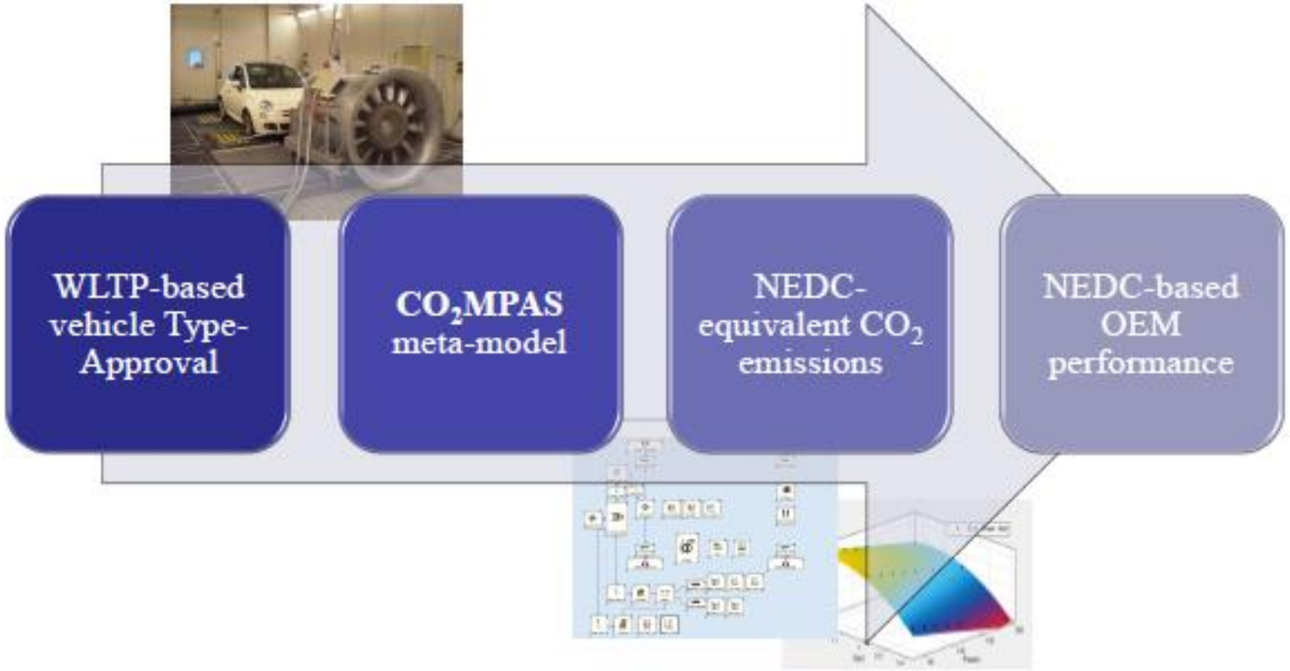
Since Sept. 2017, additionally to the previous:

- CO2MPAS, European Commission – LDV Vehicles

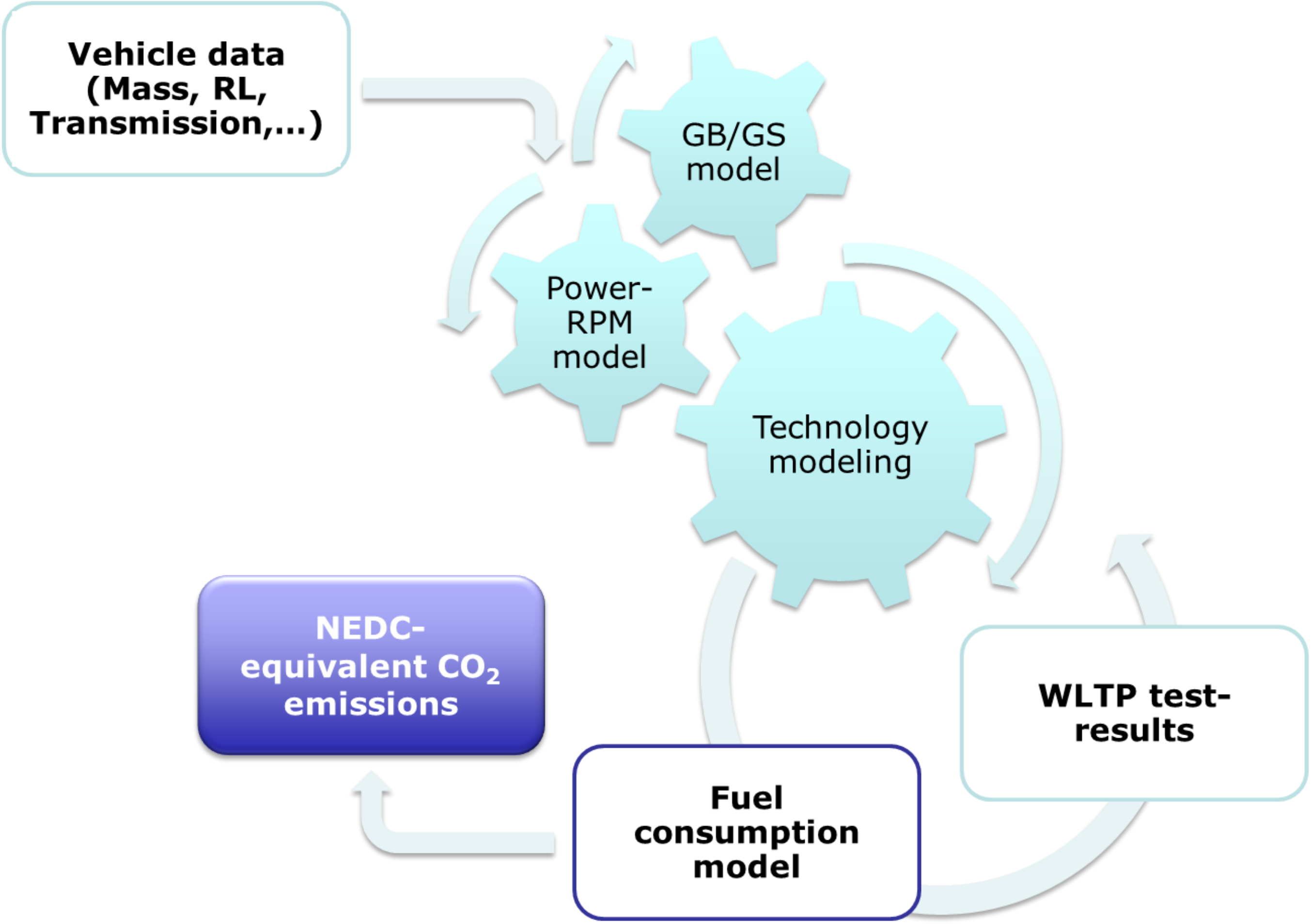
The CO2MPAS Tool
What is it?

WLTP Phasing-in (2017-2020)

WLTP-based CO2 emissions (measured at type-approval) will be translated in the equivalent NEDC-based ones, and then used to assess the compliance towards CO2 emission targets



The CO2MPAS Tool
What is it?



The CO2MPAS Tool
Development Boundaries

Boundary conditions, as set in the beginning of the WLTP/NEDC Correlation:

1. Simple
2. Minimum number of input variables (available in TA)
3. Accuracy of the ΔWLTP-NEDC in the order of 2-2.5g
4. Minimize statistical approaches and calculations
5. Allow for the assessment of as many future technologies as possible

The CO2MPAS Tool
The Modules

The tool comprises of 2 main calculation modules:

Power – RPM module

- Simple longitudinal dynamics (WLTP-GTR)
- Engine power and RPM calc. 1hz
- Inclusion of Mech or Elec. loads where needed
- Generic start-stop logic
- A/T and CVT RPM prediction model
- Alternator logic calibrated over WLTP

Accurate calculation of average / instantaneous power demand

FC module

- Calculation of FC
  Indicative instantaneous approach
- Based on an extended Willans model
- Semi-physical empirical cold start model
- Calibration - Optimization based on WLTP results
- Specific engine technologies included

Very good accuracy when compared with results obtained from the AVL Cruise simulations and real test data

The CO2MPAS Tool
Power – RPM Module Overview

Most important module of any model for accurate ΔCO_2 calculation

- *Calculation of Engine Power demand and RPM (inst. or mean values)*
- ***CO2MPAS: more detailed version of the WLTP-GTR approach***

$$P_{engine} = P_{wheel} / \eta_{dri'train} + P_{elec.} + P_{mech.}$$

$$P_{wheel} = (F_0 + F_1 \times v + F_2 \times v^2 + m \times a) \times v$$

$$P_{elec.} = P_{elec.\ dem.} / (\eta_{alt/or} \times \eta_{batt.})$$

$$P_{mech.} = T_{const} \times RPM$$

RPM is simply calculated from speed and total gear ratio

CO2MPAS

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The CO2MPAS Tool
FC Module Overview

The fuel consumption calculation function:

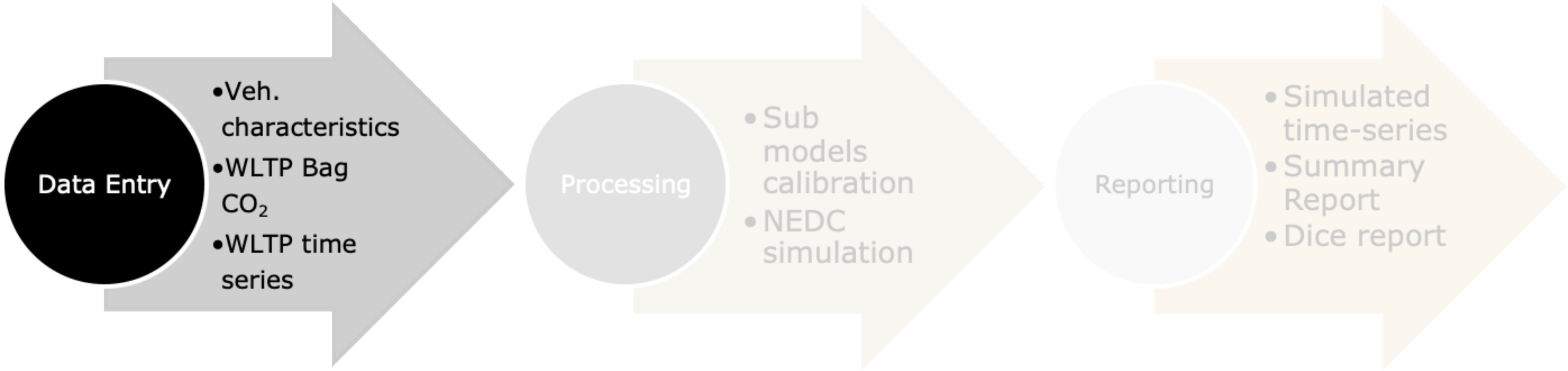
$$\int FMEP(t)\,dt = \int \frac{-(a + b * C_m(t) + c * C_m(t)^2) + \sqrt{(a + b * C_m(t) + c * C_m(t)^2)^2 - 4 * a_2 * \left(\left({T(t)}/{T_{target}}\right)^{-k} * (l + l_2 * C_m(t)^2) - BMEP(t)\right)}}{2 * a_2} dt$$

, where:

- $C_m(t)[m/s] = 2 * {Engine\ Speed\ [rpm]}/{60} * Engine\ Stroke\ [m]$
- $BMEP(t)[Pa] = {2 * Engine\ Power\ [W]}/{\left(Engine\ Capacity\ [m^3] * {Engine\ Speed\ [rpm]}/{60}\right)}$
- $Fuel\ Consumption(t)[g/s] = {FMEP(t)[Pa] * Engine\ Capacity\ [m^3] * {Engine\ Speed\ [rpm]}/{60}}/{2 * Fuel\ Lower\ Heating\ Value\ [{J}/{g}]}$
- *Engine speed, temperature, and engine power are considered as knowns from the measurement / other CO2MPAS modules*

The constant parameters are calculated by "solving" the above equation on the four sub-cycles of WLTP Low & High

The CO2MPAS Tool
Data Flow Overview



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The CO2MPAS Tool
Data Flow Overview – Data Entry

VW_Golf_2.0TDI_ICCT_ESPERIA_wslope.xlsx - Microsoft Excel (Product Activation Failed)

	A	B	C	D	E	F
1	**Parameter**	*Name*	**Value**	**Unit**	***Format***	***Comments***
2	**Input file version**	**flag.input_version**	**2.2.6**		*str*	*The version of the input-file*
3	**Vehicle family id**	*flag.vehicle_family_id*	RL-10-AAA-2017-0623		*str*	*Individual code for simulated vehicle. Automatically built from items C4:C8*
4	**Type Approval identifier (Section 1)**		10		*int*	*EC type-approval number Section 1 (Member State 2-digit code)*
5	**World Manufacturer identifier**		AAA		*str*	*OEM code as defined in ISO 3780:2009. 2-or-3 alphanumeric chars*
6	**Type Approval year**		2017		*int*	*Type approval year (e.g 2017)*
7	**Family Type ('IP', 'RL', 'RM', 'PR')**		RL		*str*	*Family type code (interpolation, road load, etc.). Enumeration*
8	**Type Approval sequence number**		0623		*int*	*Sequence number corresponding to the type-approved vehicle. 4 digit integer*
9						
10	Fuel type	*fuel_type*	diesel		*str*	*Type of fuel used in the test: diesel, gasoline, LPG, NG or biomethane, ethanol(E85), biodiesel*
11	Fuel lower heating value	*engine_fuel_lower_heating_value*	4261.2	kJ/kg	*float*	*Lower heating value of fuel used in the test*
12	Fuel carbon content	*fuel_carbon_content_percentage*	86	%	*float*	*% of carbon in the fuel by weight. Eg 85.5%*
13	Engine type	*ignition_type*	compression		*str*	*Positive ignition or compression ignition*
14	Engine capacity	*engine_capacity*	1968.0	cc	*float*	*Engine capacity in cubic centimeters*
15	Engine stroke	*engine_stroke*	95.5	mm	*float*	*Engine stroke in mm*
16	Engine idle speed	*idle_engine_speed_median*	780.0	rpm	*float*	*Idle speed - warm conditions*
17	Engine idle fuel consumption	*engine_idle_fuel_consumption*	0.1	g/sec	*float*	*Idle fuel consumption of the vehicle - warm conditions. What is the idling fuel consumption of the vehicle when velocity is 0, Start-stop system is disengaged, and battery SOC is at balance conditions?*
18	Final drive ratios	*final_drive_ratio*	3.04		*float*	*Final drive ratio. If the car has two different final drive ratios please leave it blank and provide the final drive ratios in gear_box_ratios tab*
19		*final_drive_ratios*	"redim", "kwds": {"col": 1, "cell": 1}}		*[float, float, ...]*	*Final drive ratios [ratio 1, ratio 2, ...] see relevant column in sheet (gear_box_ratios)*
20	Tyre dimensions	*tyre_code*	225/40 R18		*str*	*Tyre code (e.g., P195/55R16 85H) of the tyres used in the WLTP test.*
21	Gearbox type	*gear_box_type*	automatic		*str*	*Gearbox type: automatic/manual/CVT*
22	Start-stop activation time	*start_stop_activation_time*		sec	*float*	*Start-stop activation time elapsed from test start, how many seconds after the NEDC test the S/S system is expected to be enabled*
23	Nominal voltage of the alternator	*alternator_nominal_voltage*	14	V	*float*	*Alternator nominal voltage*
24	Alternator maximum power	*alternator_nominal_power*	1.96000	kW	)-/371952387253?fits=C	*Alternator maximum power*
25	Battery capacity	*battery_capacity*	68.0	Ah	*float*	*Battery capacity*
26	Starting ambient temperature WLTP-H	*calibration.initial_temperature WLTP-H*	24.0	°C	*float*	*Initial temperature of the test cell during WLTP-H test. Default value = 23 °C*
27	Starting ambient temperature WLTP-L	*prediction.initial_temperature NEDC-H*		°C	*float*	*Initial temperature of the test cell during WLTP-L test. Default value = 23 °C*

Legend
Yellow **cells** are mar
Orange **cells** are opt
value will be adopte

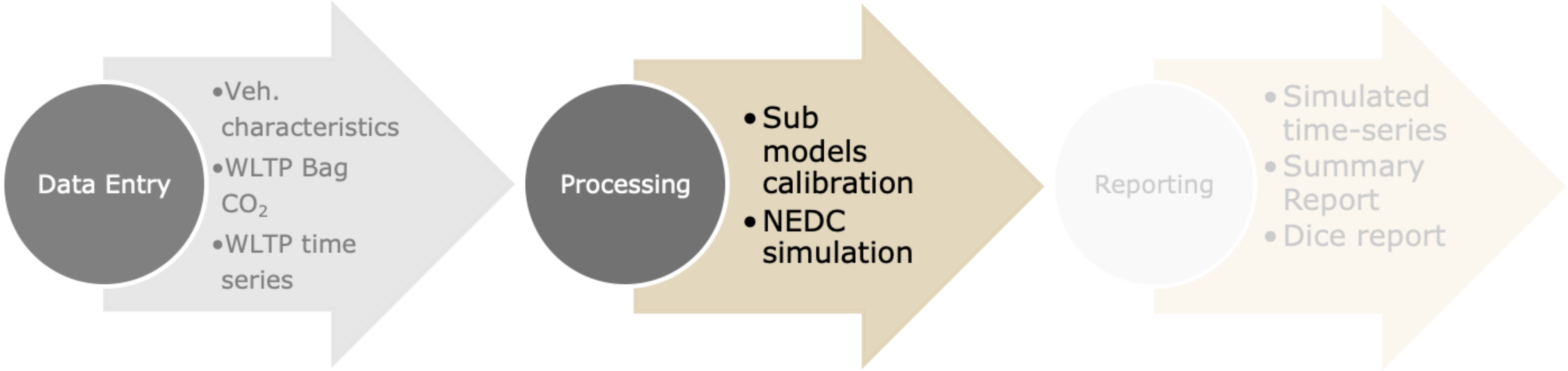
Signals are expected
cycle tabs (NEDC-H,
prediction.WLTP), at
resective resolutions

The model might fai
are time-shifted (> ±
sampling rates. Even
will not be accurate
line tool synchronize
with the theoretical
to be derived from t
other input values.

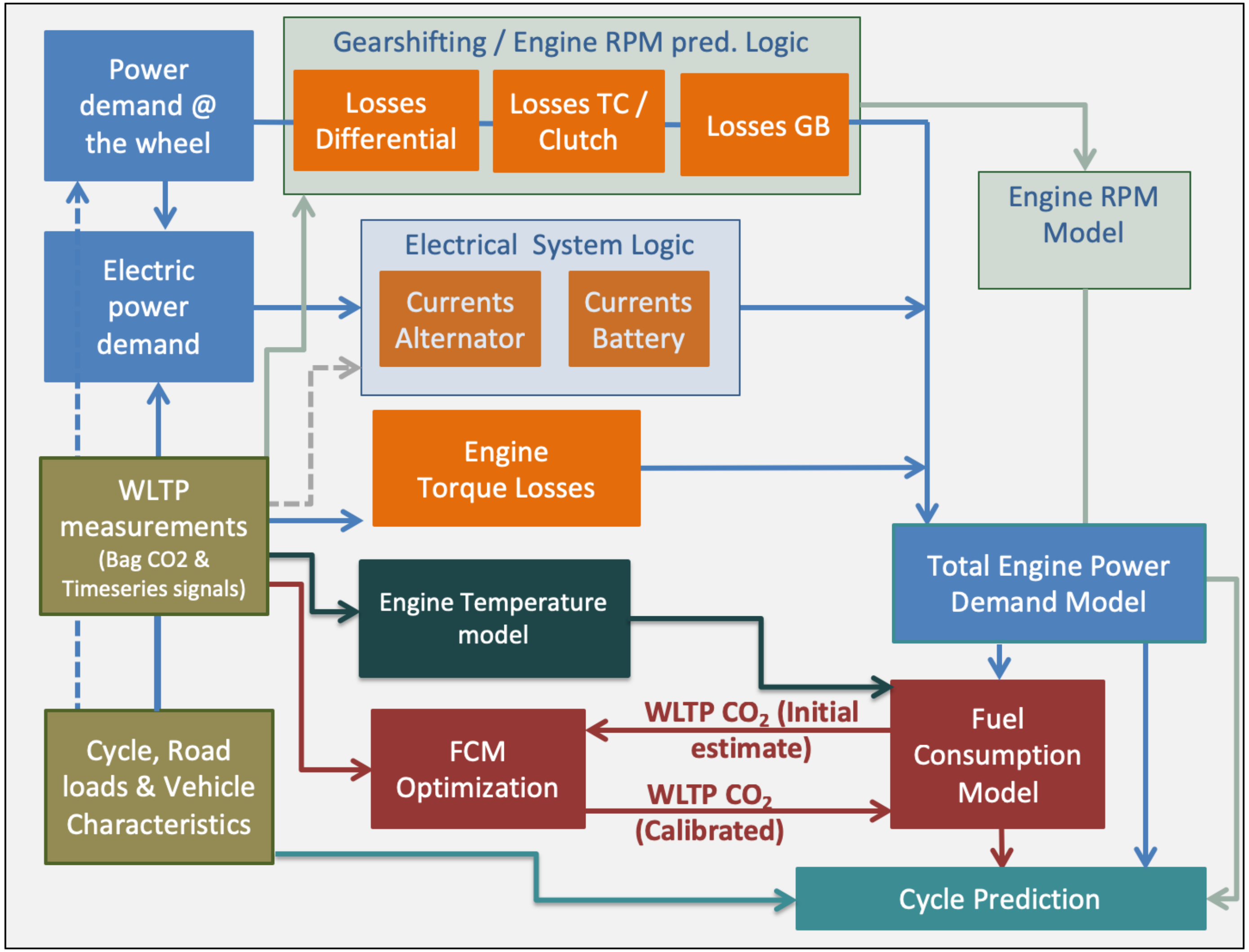
Note:
Engine temperatures
engine oil temperatu

Sheets: About | Inputs | NEDC-H | WLTP-H | NEDC-L | WLTP-L | prediction.WLTP | gear_box_ratios | active_cylinder_ratios | T1_map

The CO2MPAS Tool
Data Flow Overview

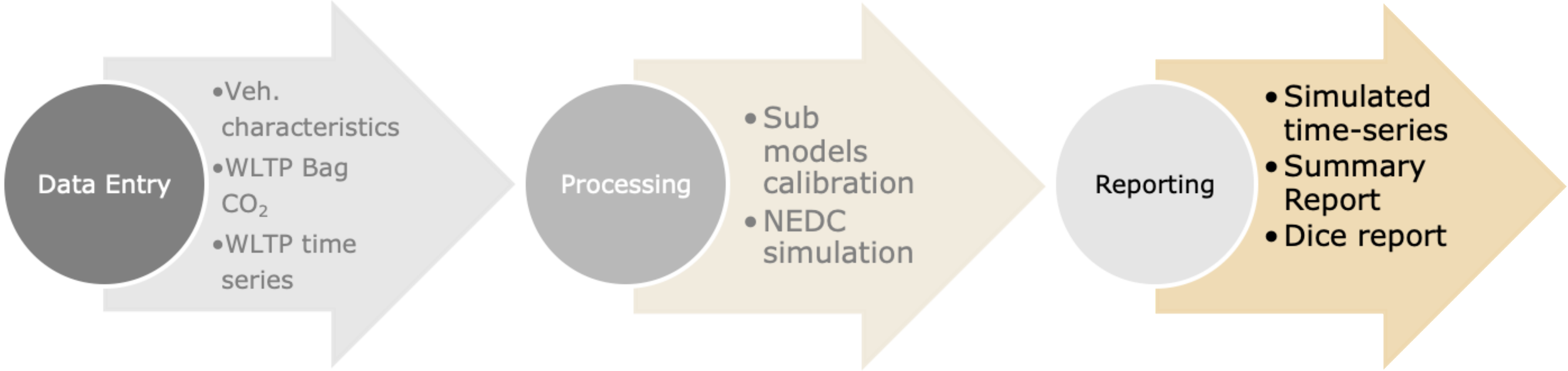


The CO2MPAS Tool
Data Flow Overview – Model



https://co2mpas.io/explanation.html#execution-model

The CO2MPAS Tool
Data Flow Overview



The CO2MPAS Tool
Data Flow Overview – Reporting

20170629_175425-VW_Golf_2.0TDI_ICCT_ESPERIA_wslope.xlsx - Microsoft Excel (Product Activation Failed)

CO_2MPAS SUMMARY OUTPUT REPORT

Vehicle Family ID	*RL-10-AAA-2017-0623*
CO2MPAS version	*1.6.1.dev6_fix_simplan*
Date/Time	*2017/06/29-17:54:28*
Type approval mode	***False***

CO2 Emissions

NEDC Average Specific CO2 Emissions*	Vehicle H	Vehicle L	units
NEDC CO2 declared value	*124.38*		g/km
NEDC CO2MPAS simulated	*125.53*		g/km
CO2MPAS deviation	***0.93***		%

*Ki factor - corrected

NEDC CO2MPAS CO2 Emissions	Vehicle H	Vehicle L	units
CO2MPAS simulated NEDC	*125.53*		g/km
CO2MPAS simulated UDC	*149.45*		g/km
CO2MPAS simulated EUDC	*111.62*		g/km

Vehicle Characteristics

Parameter	Vehicle H	Vehicle L	units
Fuel Type	*diesel*	*diesel*	-
Engine Capacity	*1968.00*	*1968.00*	cc
Gearbox type	*automatic*	*automatic*	-
Turbo engine	*TRUE*	*TRUE*	-

CO_2MPAS SUMMARY OUTPUT REPORT

Vehicle Family ID	*RL-10-AAA-2017-0623*
CO2MPAS version	*1.6.1.dev6_fix_simplan*
Date/Time	*2017/06/29-17:54:28*
Type approval mode	***False***

Model Scores

	Vehicle H		Vehicle L	
Model id	WLTP-H	WLTP-L	WLTP-H	WLTP-L
alternator_model (battery currents)	***9.39***			
alternator_model (alternator currents)	***3.24***			
at_model	***-0.85***			
clutch_torque_converter_model	***65.71***			
co2_params	***0.06***			
engine_cold_start_speed_model	***64.57***			
engine_coolant_temperature_model	***8.54***			
engine_speed_model	***43.66***		***188.36***	
start_stop_model (engine starts)	***-0.99***			
start_stop_model (on engine)	***-0.95***			

output_report | summary | graphs.nedc_h | graphs.nedc_l | graphs.wltp_h | graphs.wltp_l | output.prediction.nedc_h.pa | output.prediction.

Validation & Results
Overview

Essentially, the accuracy of the CO2MPAS tool is analyzed by comparing the NEDC CO_2 emission prediction of the model (predicted CO_2) against the CO_2 emission measured during a NEDC physical test (target CO_2):

$$CO_2MPAS\ deviation = \frac{(Predicted\ CO_2\ - Measured\ CO_2)}{Measured\ CO_2} * 100$$

When CO2MPAS deviation is positive, the model overestimates the target value, while when the deviation is negative, the model underestimates the target value.

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Validation & Results
Datasets

Two complementary datasets have been used throughout the CO2MPAS development and validation phases:

- **Real Cars data:**

  Gathered along time (JRC labs, LAT, mock-up activities, etc.)

  Set of 48 real vehicles

- **Synthetic Cars Data:**

  Derived with AVL Cruise model using OEM-approved input data

  Large set of vehicles with different RLs, masses, available tech configurations

  - *Manual Transmission Vehicles:* ~ 2,150 cases

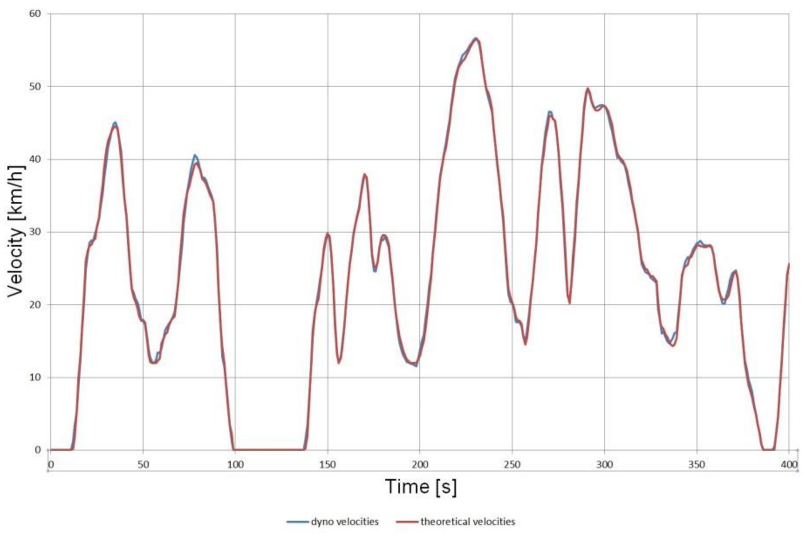
  - *Automatic Transmission Vehicles:* ~ 1,400 cases

The public history of CO2MPAS validation results, along the different versions of the tool, is available here: http://jrcstu.github.io/co2mpas/

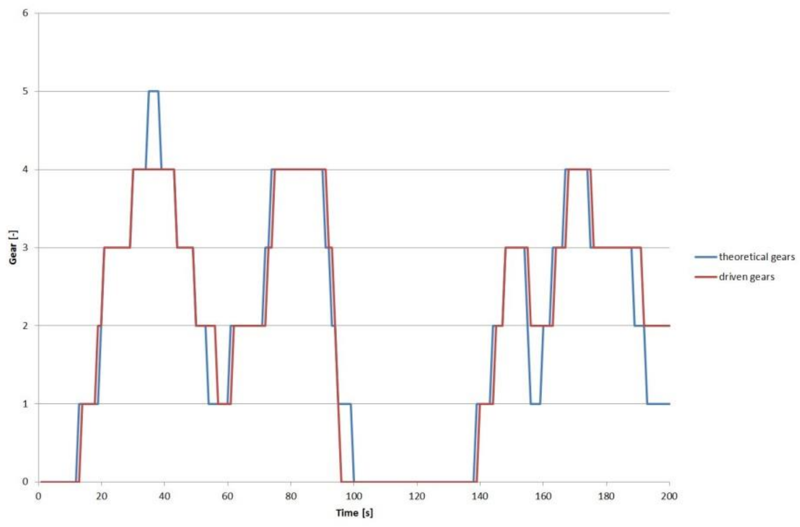
Data are anonymized to ensure confidentiality.

Further Applications
Theoretical vs. Real

Velocity

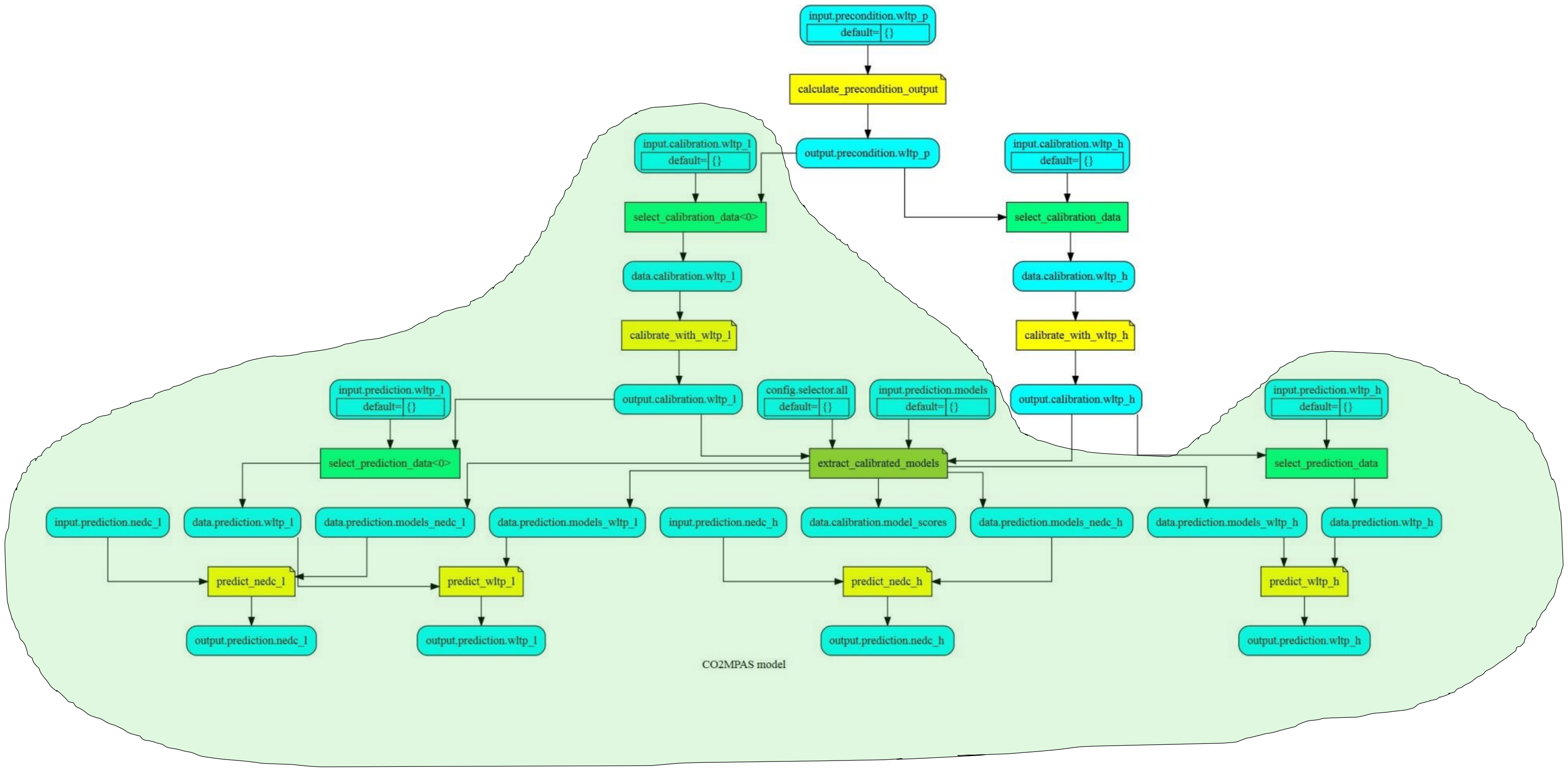


Gears



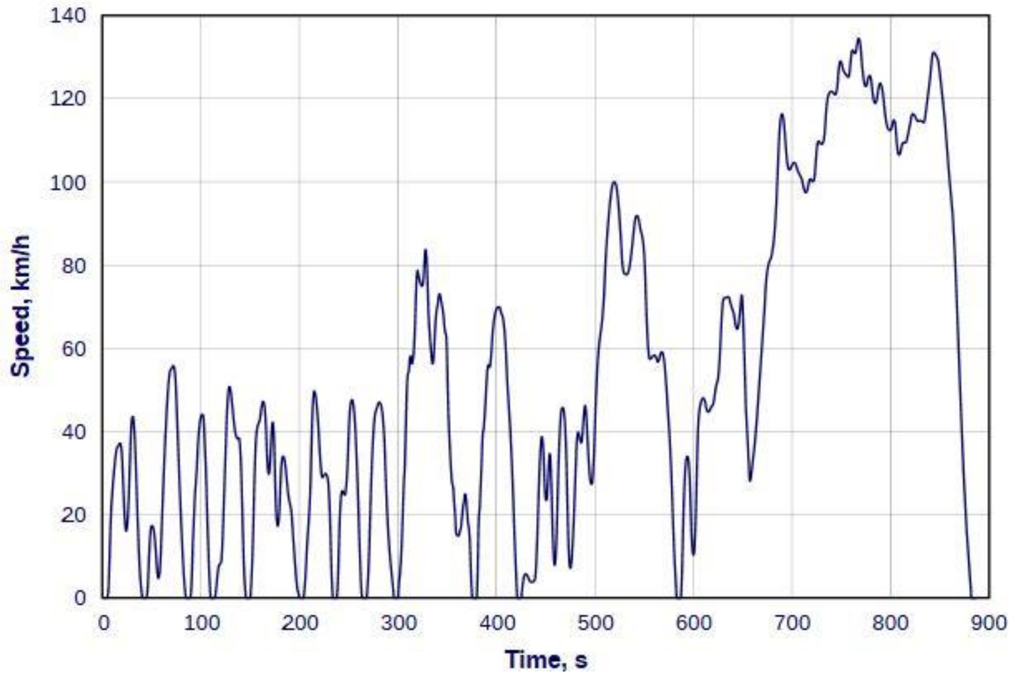
Further Applications
Single test to multiple results

From a single WLTP-X test CO2MPAS can simulate, enabling the model selector, the theoretical NEDC -H & -L and WLTP -H & -L



Further Applications
Simulate any driving cycle

Example: RTS 95 is a chassis dynamometer test cycle representing aggressive driving, including urban, rural and motorway segments. The cycle has been developed based on a subset of the WLTP database.



RTS-H	RTS-L
215.4	199.3

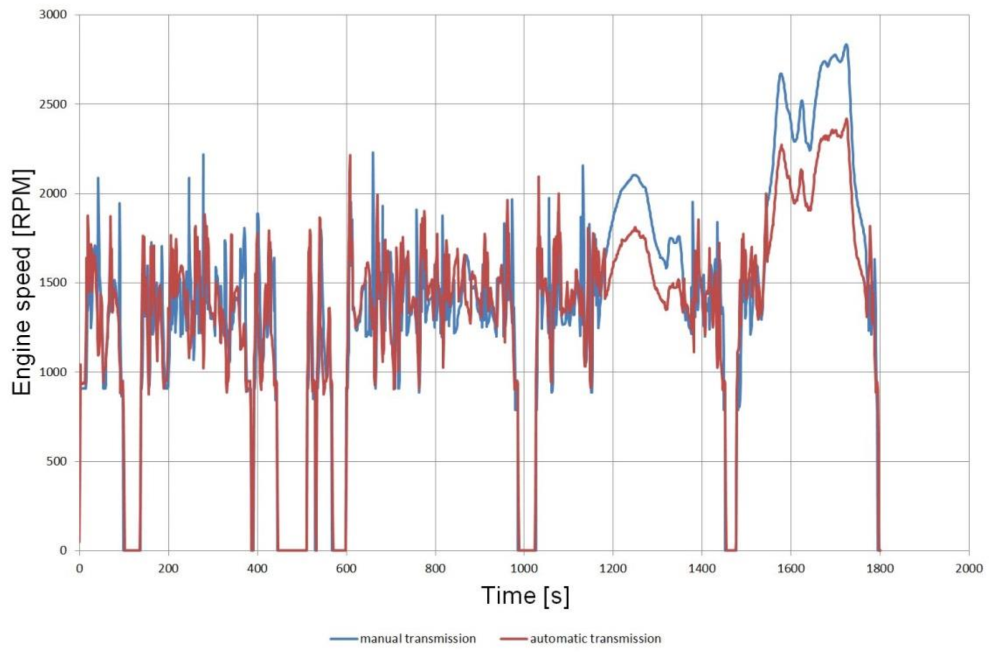
WLTP-H	WLTP-L
169.0	155.6

NEDC-H	NEDC-L
151.0	139.4

Further Applications
From Automatic to Manual Transmission

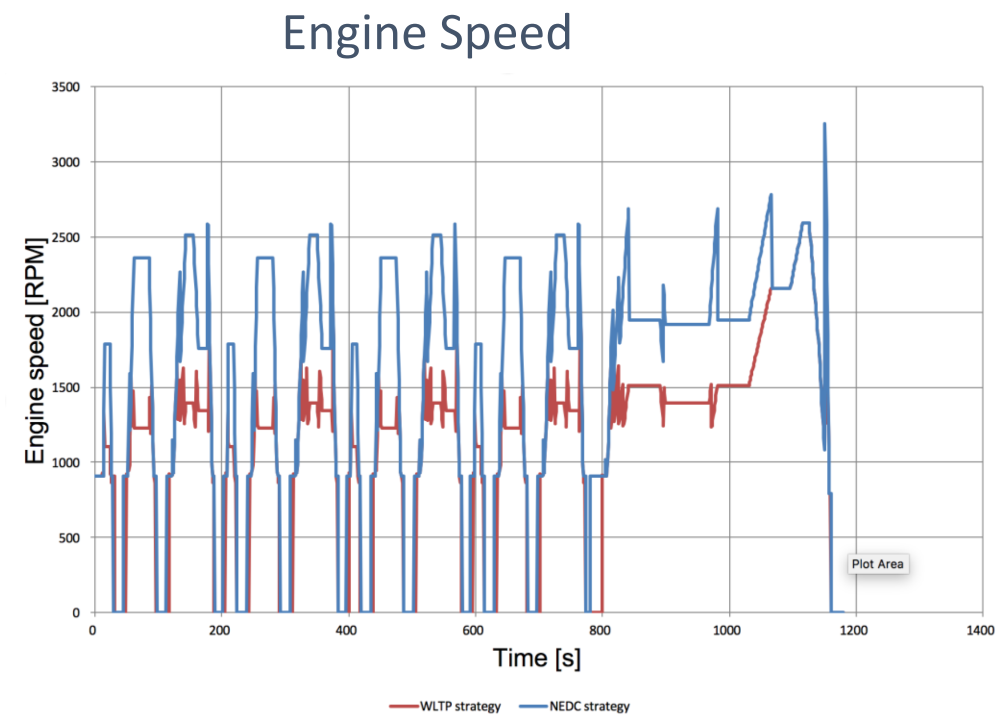
From a test with a vehicle with automatic transmission, you can simulate a manual transmission changing also the gear box ratios.

Engine Speed



Transmission	WLTP-H	WLTP-L
Automatic	169.0	155.6
Manual	171.9	158.6

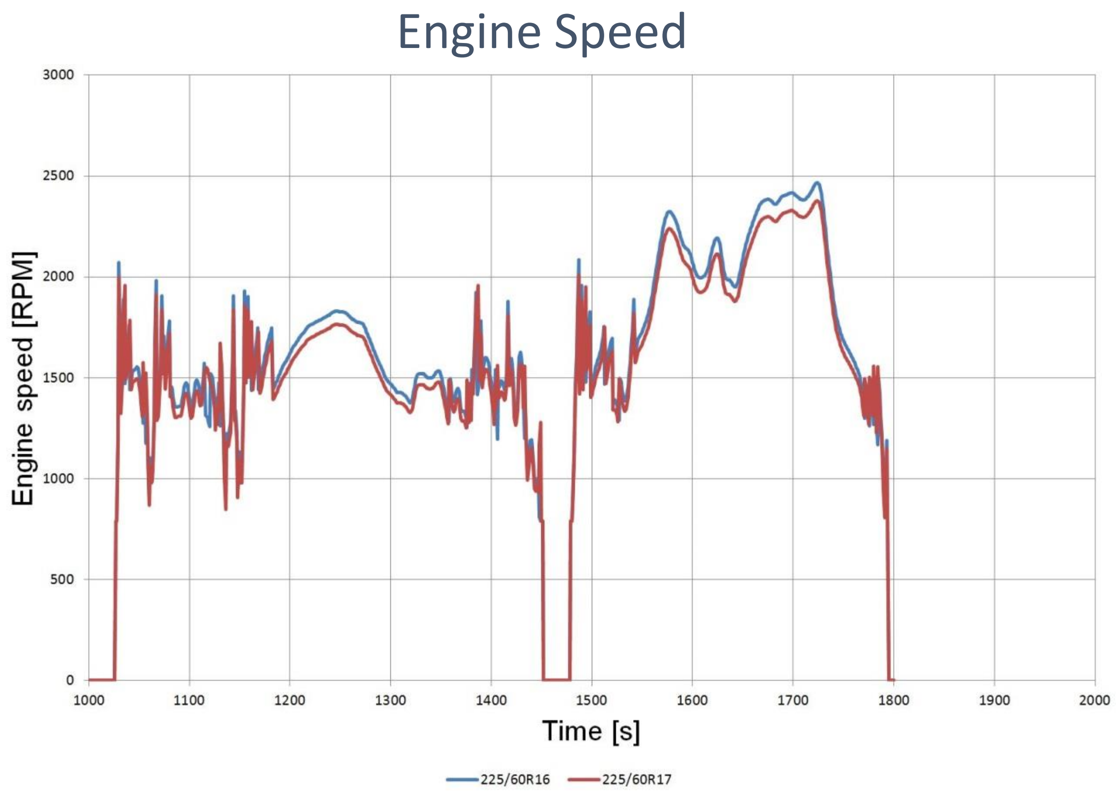
Further Applications
Simulate NEDC with WLTP gear shifting strategy



GS-Strategy	NEDC-H
NEDC	177.5
WLTP	151.0

Further Applications
Change tires

Tires	NEDC-H	NEDC-L	WLTP-H	WLTP-L
225/60R16	150.8	139.2	169.5	156.2
225/60R17	151.0	139.4	169.0	155.6



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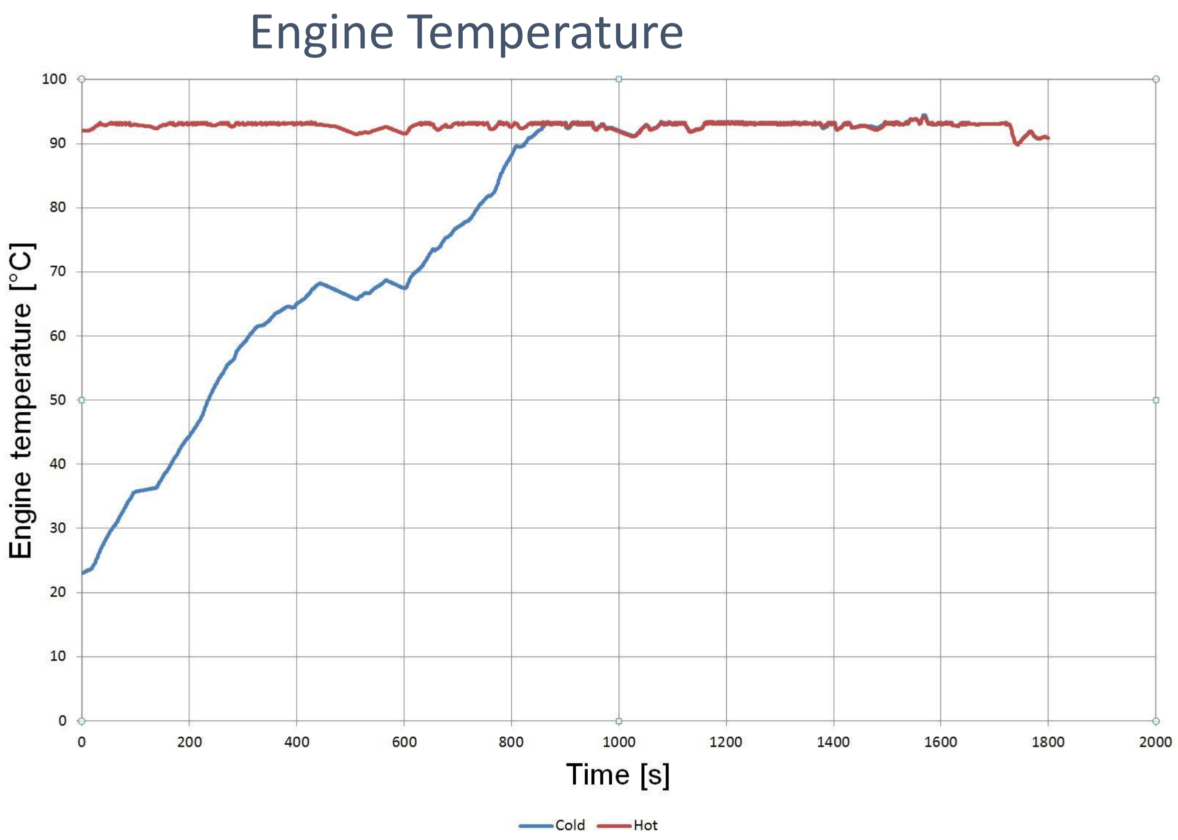
Further Applications
From cold to hot

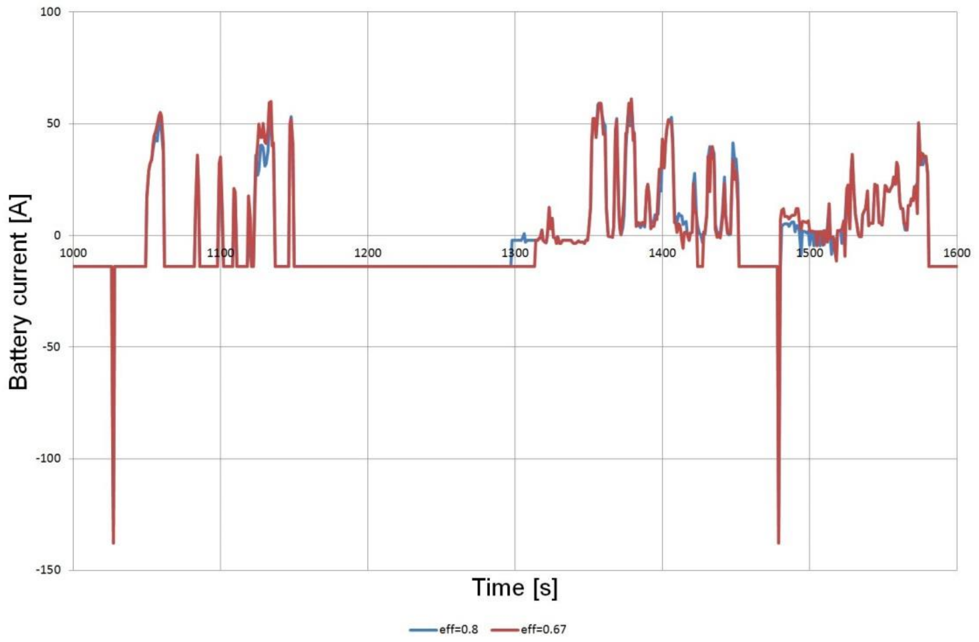
Temperature	WLTP-H	WLTP-L
Cold	169.0	155.6
Hot	165.8	152.5



Further Applications
Improved alternator efficiency

Efficiency	WLTP-H	WLTP-L
0.67	169.0	155.6
0.8	168.8	155.4

Battery Current



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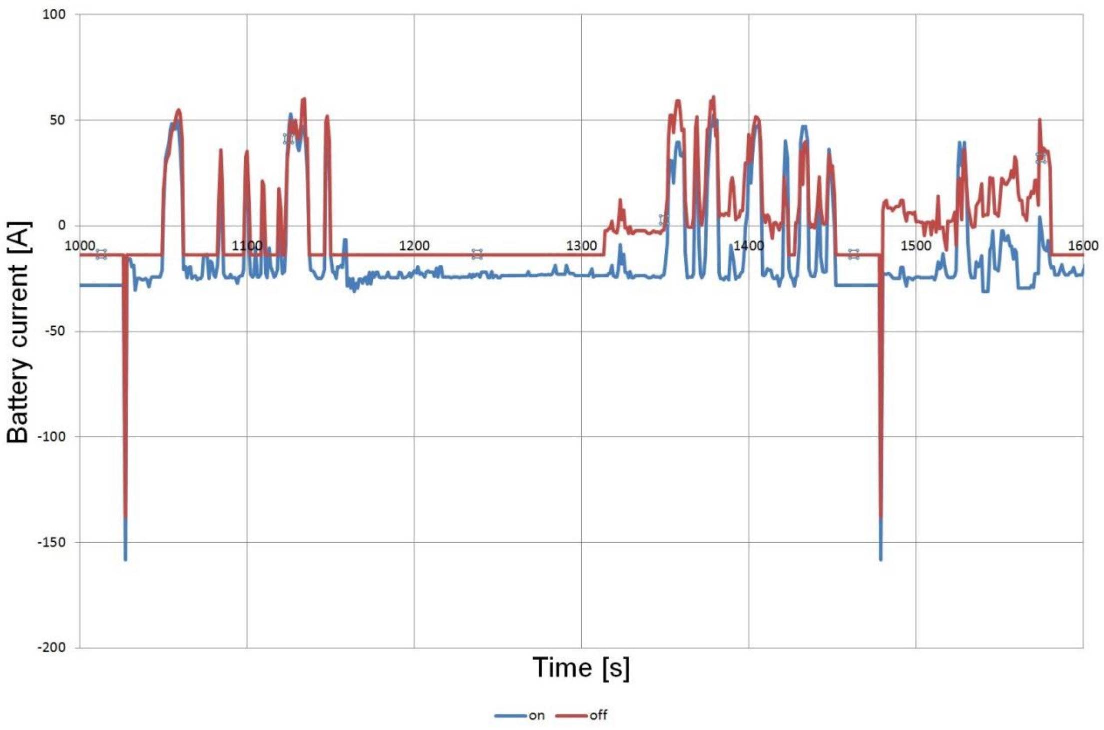
Further Applications
Lights on

Lights	WLTP-H	WLTP-L
off	169.0	155.6
on	170.3	156.8

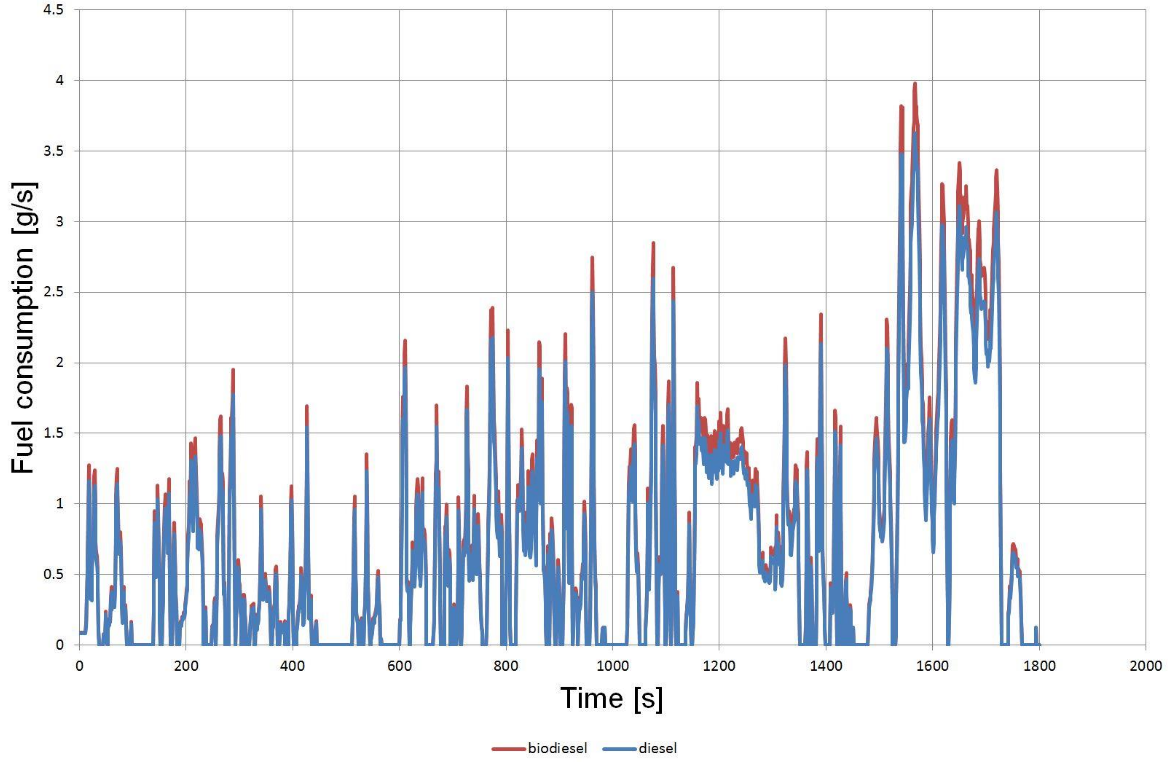
Battery Current



Further Applications
Fuel properties

Fuel	WLTP-H	WLTP-L
diesel	169.0	155.6
biodiesel	164.5	151.5

Fuel consumption



Same engine efficiency assumed

Possibility to calibrate with alternative fuel

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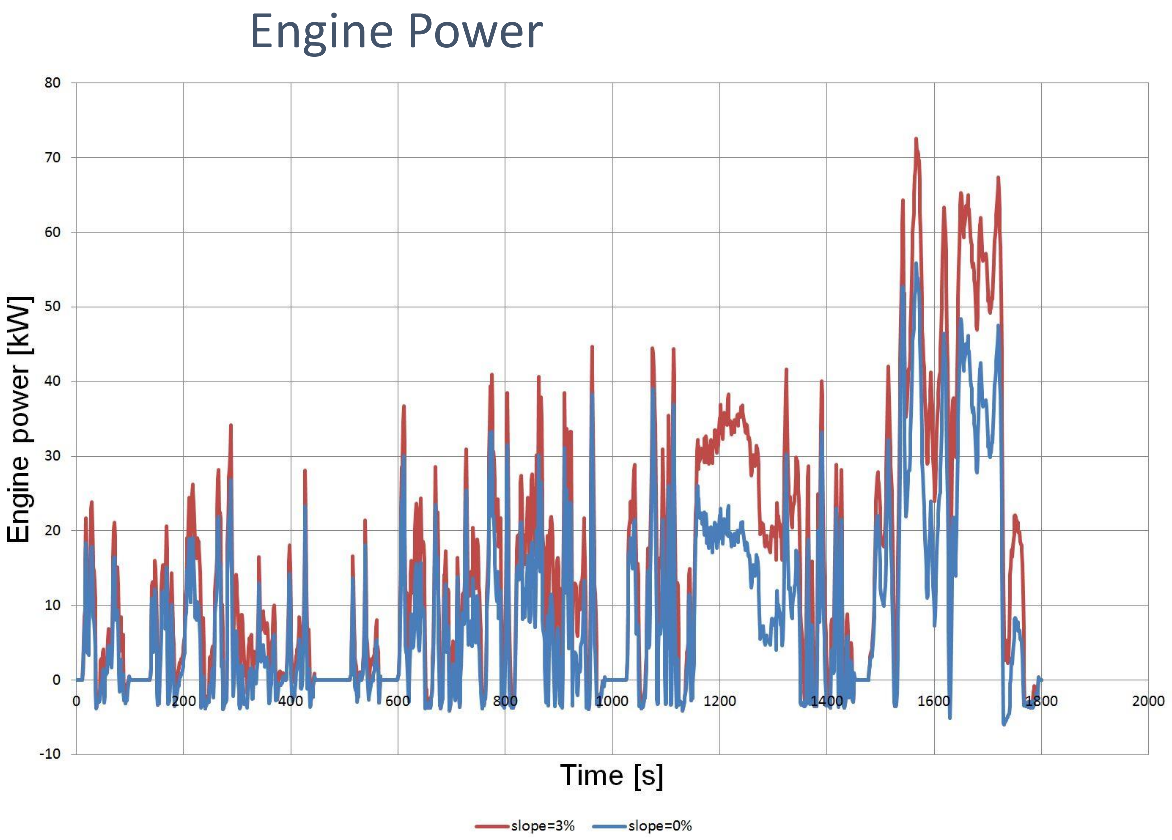
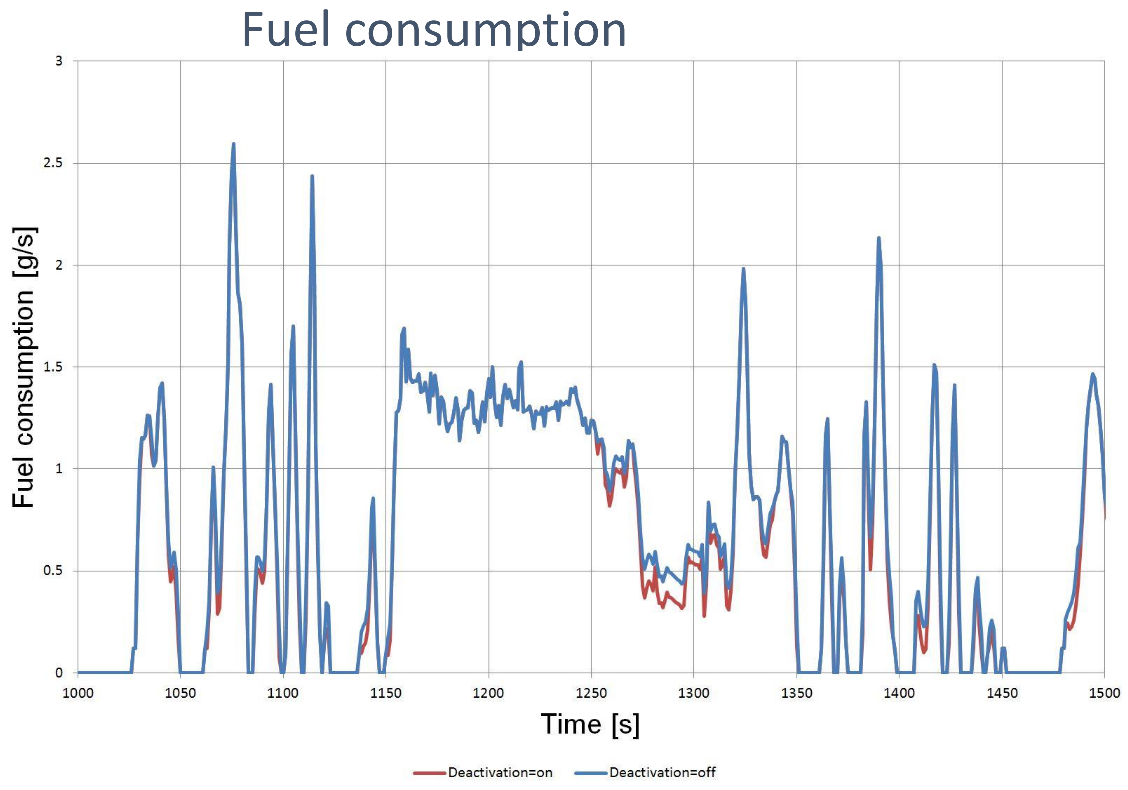
Further Applications
Change slope

Slope	WLTP-H	WLTP-L
0%	169.0	155.6
3%	267.6	244.8



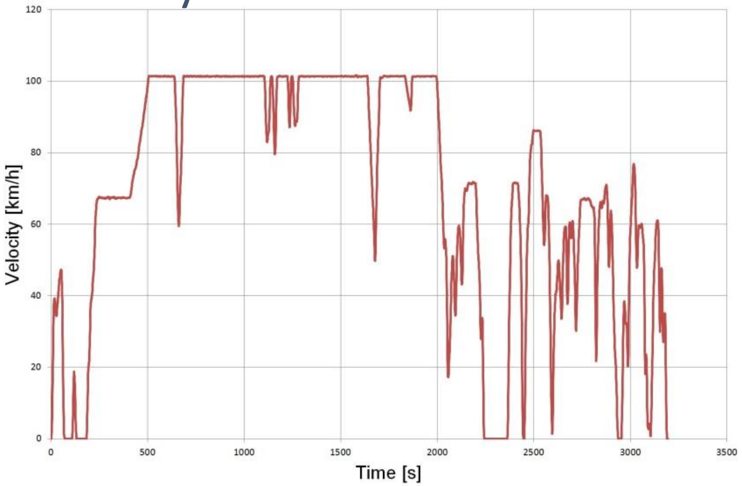
Further Applications
Cylinder deactivation strategy

Deactivation	WLTP-H	WLTP-L
No	169.0	155.6
Yes	165.1	151.2

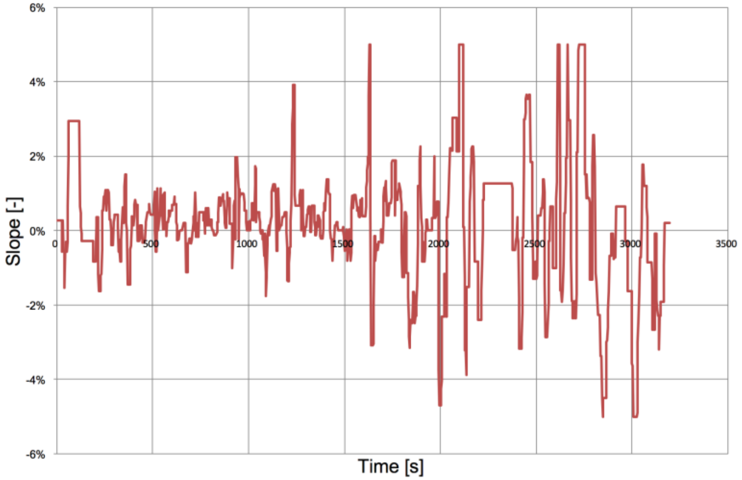


Further Applications
Real profile

Velocity



Slope



Fuel consumption
5.8 L/km

Further Applications
What else?

Building on the work performed for the development of the CO2MPAS tool, two additional tools have already been developed:

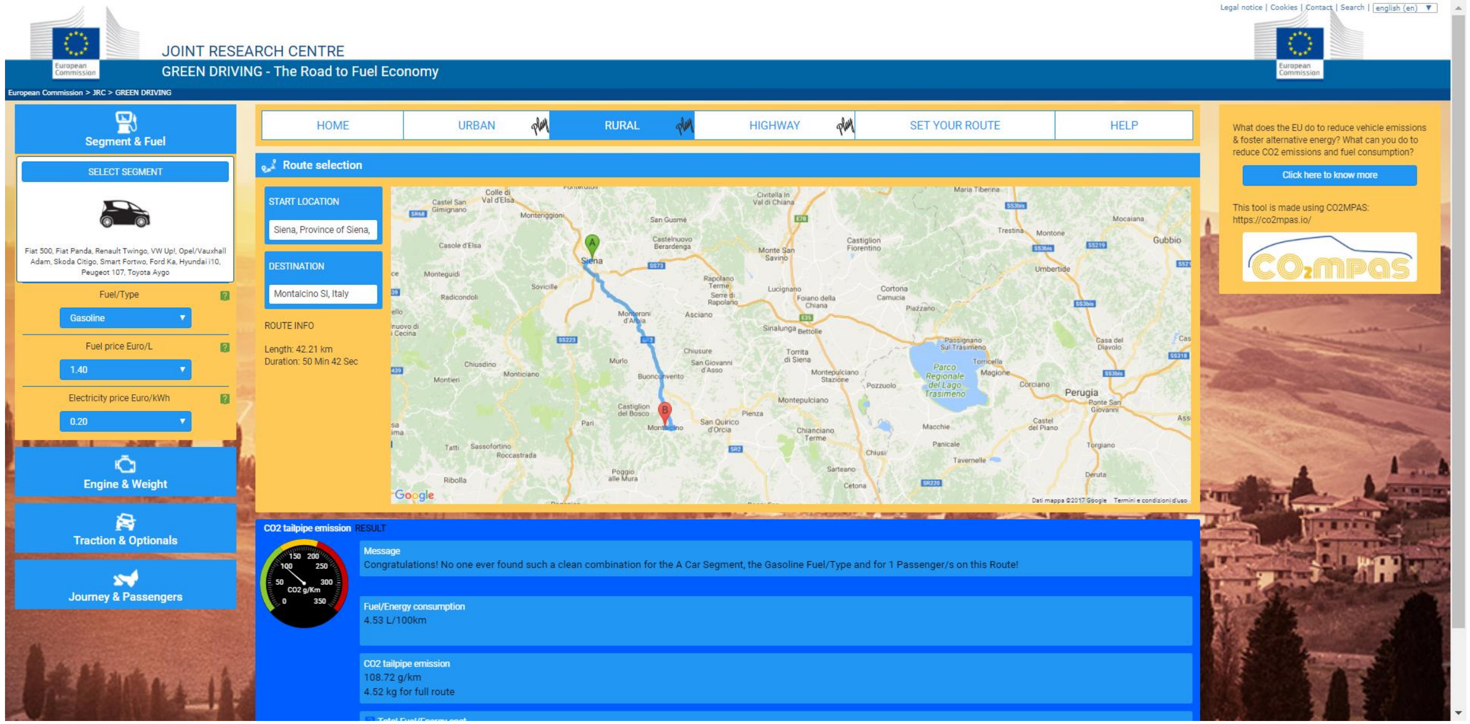
✓ **The Green Driving Tool** (https://green-driving.jrc.ec.europa.eu/)

An interactive tool for evaluating CO_2 emissions and costs for different types of vehicles, users selected in-use options and routes

✓ **The PyCSIS Tool**

A simulation-based quantification methodology for the detailed calculation of passenger cars fleet test-based & real-life CO_2 emissions

Further Applications
The Green Driving Tool



Metric	Milano-Ispra			Ispra-Milano		
	Real (Uconnect)	Geen driving	viamichelin	Real (Uconnect)	Geen driving	viamichelin
	Fiat 500X	Class - C	Hatchback	Fiat 500X	Class - C	Hatchback
Time		1h 12m	1h 20m		1h 11m	1h 22m
Distance	68.7km	70.9km	70km	67.9km	71.7km	70km
Fuel used	3.54L	3.66L	4.47L	3.27L	3.48L	4.54L
Liter/100km	5.15L/100km	5.16L/100km	6.39L/100km	4.82L/100km	4.86L/100km	6.49L/100km

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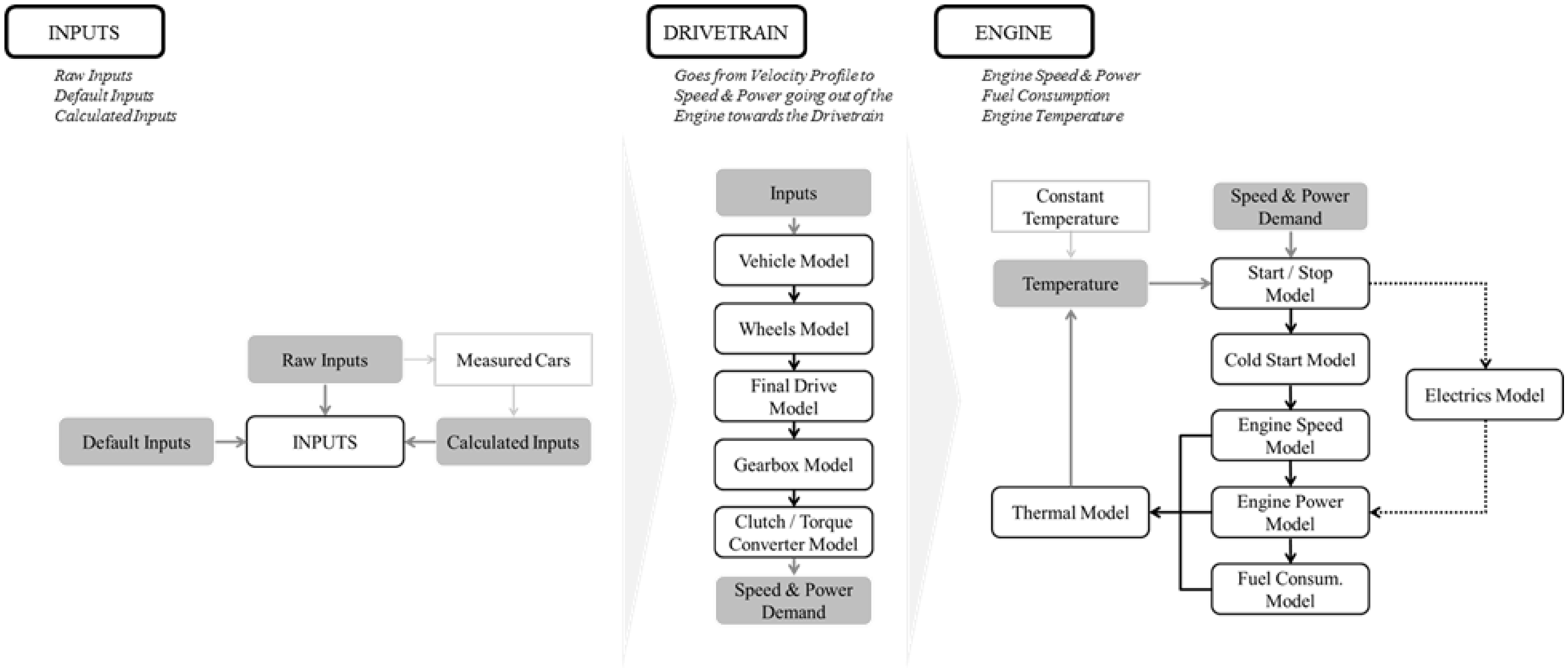
Further Applications
The PyCSIS Tool



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Thank you for attention!

Any questions?