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Hybrid Power-trains for Sustainable Forestry (A Review)

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Introduction

- Presently there are **increasing demands** in terms of **reducing the cost of running forestry machines** along with the **regulatory pressures for lower exhaust emissions** and **reduction of acoustic noise**.
- Manufacturers of forestry equipment are increasingly interested in **electrification (hybridisation) of heavy machinery**.
- **Hybrid power-train offers a favorable solution** for the **propulsion of forestry mechanisation**:
  - Possibility of using a **lower-power diesel engine**,
  - **Additional energy storage system** (e.g. battery) **and driveline power source** (i.e. electric motor) for improved efficiency,
  - Hybrid power-train would also operate with **higher mechanical performance** compared to conventional (diesel engine-based) propulsion system.
- Future development of **electrified forestry vehicles** is also a very important research topic in the field of **sustainable forestry** engineering.
- Having this in mind, this presentation gives **an overview of possible solutions for hybrid forestry vehicle propulsion**.

Forestry Mechanisation

Wheeled tree harvester*

Legged tree harvester*

Wheeled skidder*

Catterpiller-based skidder*

- Different **mechanised systems** are **available to improve the productivity** in forestry operations:
  - **<u>Harvesters</u>**, used for **tree felling** and **cleaning of trunks** (removal of branches),
  - **<u>Grinders</u> for** harvested tree residue and **vegatation mulching,**
  - **<u>Skidders</u>** for **transporting of processed tree trunks to** the open **collection yard**.
  - **<u>Forwarders</u>** for **further** tree **trunk transportation**.

Forwarder (tree trunk transporter)*

- This **study focuses on** the **wheeled-type articulated forestry tractors** (skidders) and their hybridsation.

** Šušnjar, M., et. al., Development of forest machines – new trends, Conference CROJFE 2015: "Current Situation and Future Challenges",18th – 20th March 2015, Zagreb – Zalesina, Croatia*

Forestry Sector and GHG Emissions

Machinery	Used in system[a]	Hourly cost (Can.$/hour)	Fuel consumption (l/hour)	CO_2 emissions (kg/hour)[b]
Grapple loader	S, H, B	104	26	69.4
Trucks	S, H, B	135	40	106.8
Stationary grinder	S, B	300	0	0
Relocation of mobile grinder	H	470	40	106.8
Mobile grinder	H	500	170	453.9
Wheel loader	H	110	20	53.4
Relocation of bundler	B	150	24	64.1
Bundler	B	200	30	80.1

S, slash system; H, hogfuel system; B, bundling system.

Example of machinery cost and fuel rates and CO_2 emissions*

Fuel	Emission factors (g kg^{-1} fuel)		
	CO_2	CO	NO_x
diesel	3188	26.6	38.4
diesel forest machines	3126	19.2	64.7
petrol equipment and vehicles	2450	340	22.8
diesel road vehicles	2836	12.8	37.5
railway diesel	2826	10.4	39.3

Comparative exhaust emissions for different fuels**

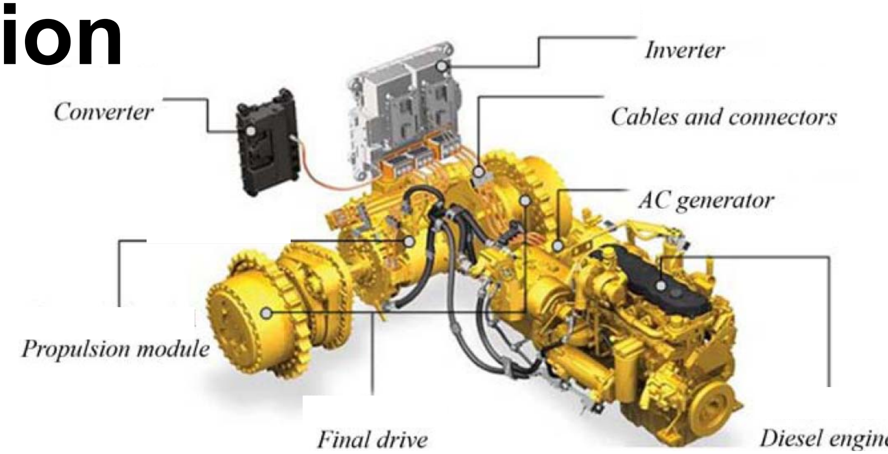
- **Utilisation of forestry machinery requires** petroleum-based fuels (**gasoline/diesel**)
- This **results in** a **significant amount of pollutants** such as **nytrous oxides** (NOx)**, carbon monoxide** (CO) and carbon-dioxide (CO_2).
- Thus, it also **increases** the amount of **greenhouse gases** (GHGs) **in the atmosphere**.
- Thus, **forestry operations using mechanisation** should be **optimised for minimum** exhaust **emissions**.

**** Lindroos, O., et. al., Costs, CO2 Emissions, and Energy Balances of Applying Nordic Slash Recovery Methods in British Columbia, Western Journal of Applied Forestry, Vol. 26, No. 1, pp. 30-36, 2011.***

***** Berg, S. and Karjalainen, T., Comparison of greenhouse gas emissions from forest operations in Finland and Sweden, Forestry, Vol. 76, No. 3, pp. 271 – 284, 2003.***

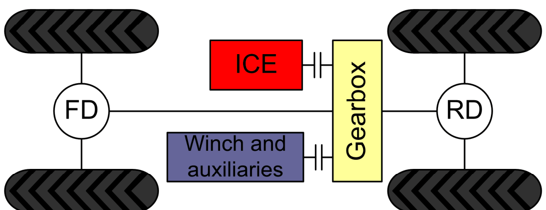
Powertrain Hybridisation

- **Forestry and agricultural machinery powertrain hybridisation** may offer **additional benefits** in terms **of lower fuel consumption and GHG emissions.**

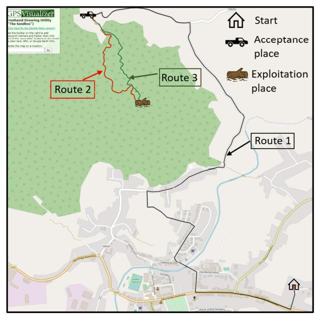


Hybridised powertrain schematic.

Conventional skidder powertrain

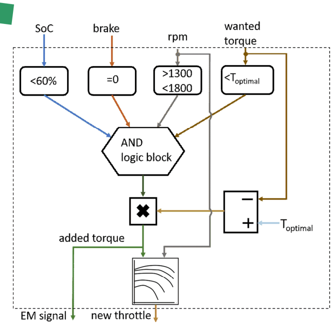


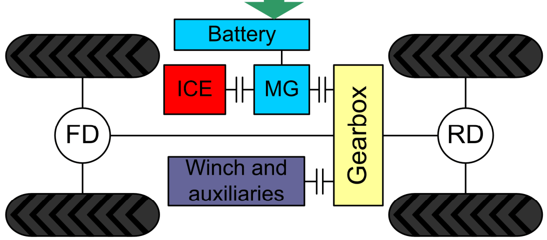
Operating cycle measurements



HiSkid

Optimal: structure selection
component sizing
control





Hybrid skidder powertrain

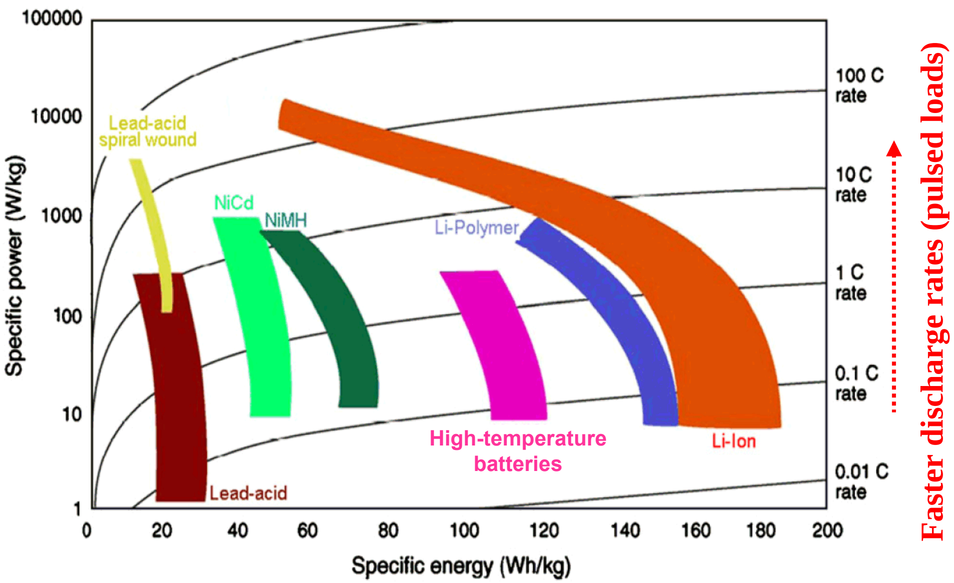
Current project dealing with skidder powertrain hybridisation

- **Hybridisation** is performed by **adding a suitable energy storage** and **intermediate power conversion systems** (mechanical to electrical or hydraulic)
- **Electrical power** transmission **and energy storage offers a number of advantages** over hydraulics:
  - **Compactness** (electrochemical battery)
  - **High efficiency** (power electronics)
  - **Relatively high power densities** (lithium batteries and electrical machines)

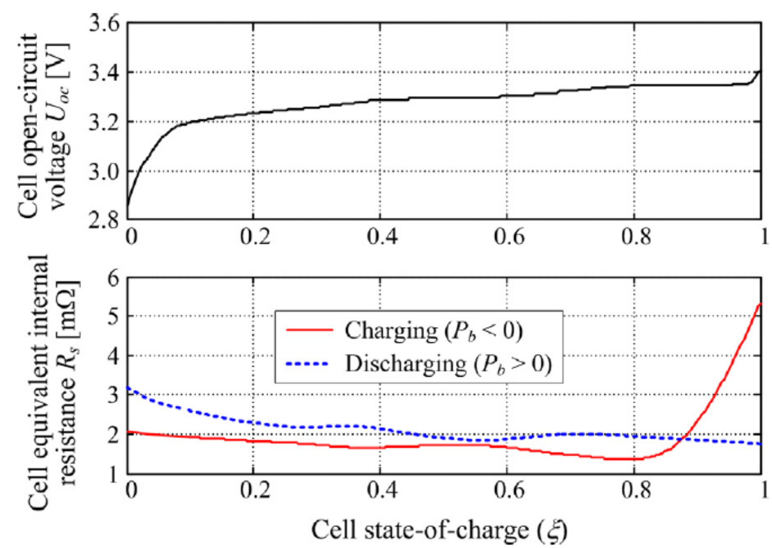
*** Oljača, M.V., et. al., Heavy caterpillar tractors and working machines with alternative power, Agricultural Engineering, Vol. 36, No. 1, pp. 21 – 28, 2011.**

Powertrain Hybridisation

- **Lithium-ion and related battery technologies** are very **versatile**: they can cover **both high energy and high power requirements**.
- **Lithium-iron-phosphate** ($LiFePO_4$) batteries offer some **distinct advantages**:
  - **Low thermal losses** due to small internal resistance values
  - **Flat discharge characteristic** (small variations in battery voltage)



Ragone charts of different battery technologies*

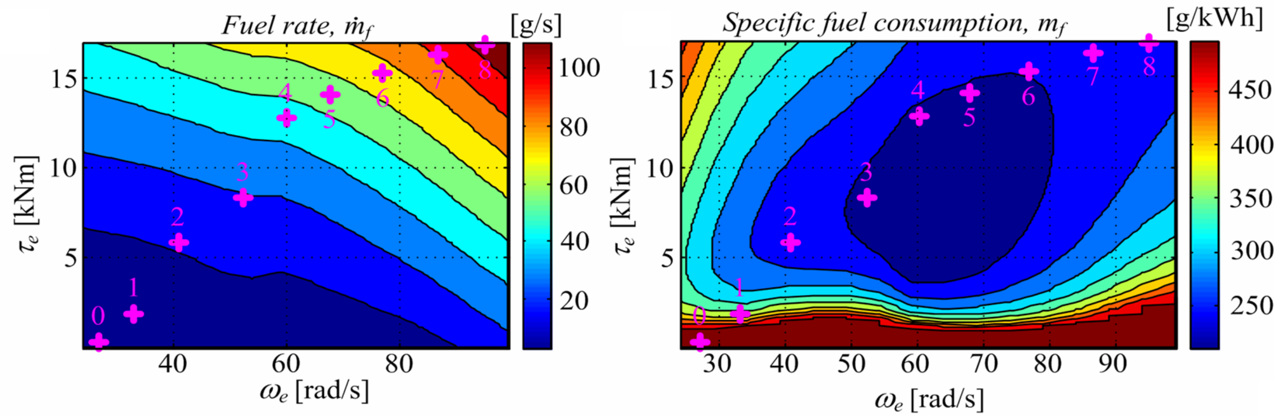


Modern $LiFePO_4$ cell characteristics**

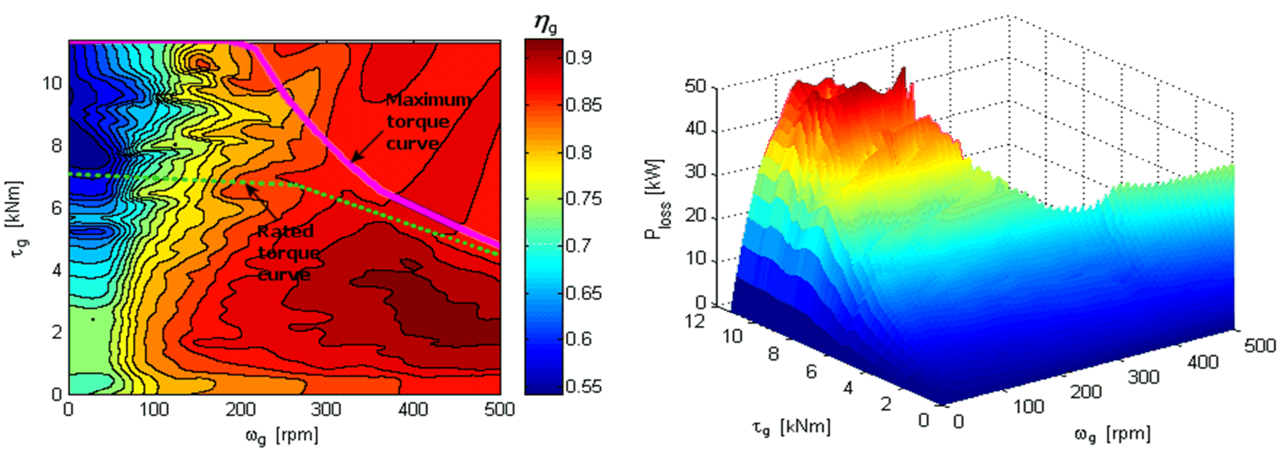
** Van den Bossche, P., at. al., "SUBAT: An Assesment of Sustainable Battery Technology", Journal of Power Sources, Vol. 162, pp. 913-919, 2006.*

*** Pavković, D., et. al., Oil drilling rig diesel power-plant fuel efficiency improvement potentials through rule-based generator scheduling and utilization of battery energy storage system, Energy Conversion and Management, Vol. 121, pp. 194-211, 2016.*

Models and Software Tools



Example of diesel engine torque-speed maps with fuel efficiencies*



Example of electrical drive torque-speed maps and its efficiencies**

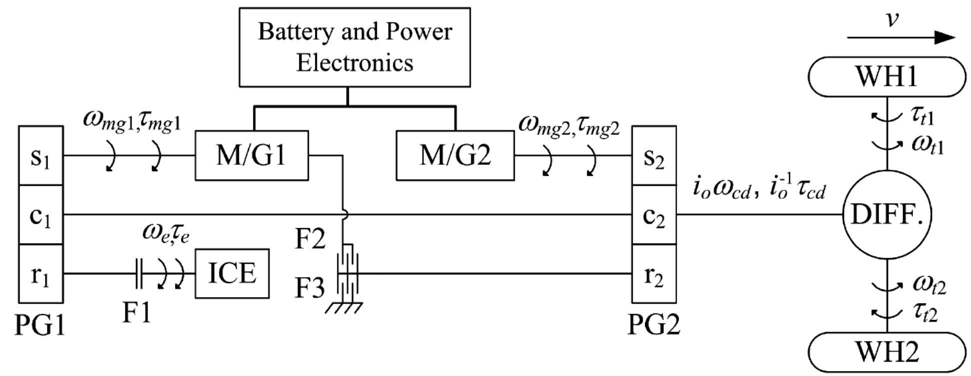
- In order **to determine** the **optimal hybrid powertrain control strategy**, **accurate powertrain** component **models are needed.**
- **Internal combustion engine** is modelled by **torque vs. rotational speed static maps** with **fuel consumption as parameter**.
- **Electrical drive** is **modelled in a simular manner**, with **overall efficiency** (or overall **power losses**) **as parameter**.

** Cipek, M., et. al., Assessment of battery-hybrid diesel-electric locomotive fuel savings and emission reduction potentials based on a realistic mountainous rail route, Energy, Vol. 173, pp. 1154-1171, 2019.*

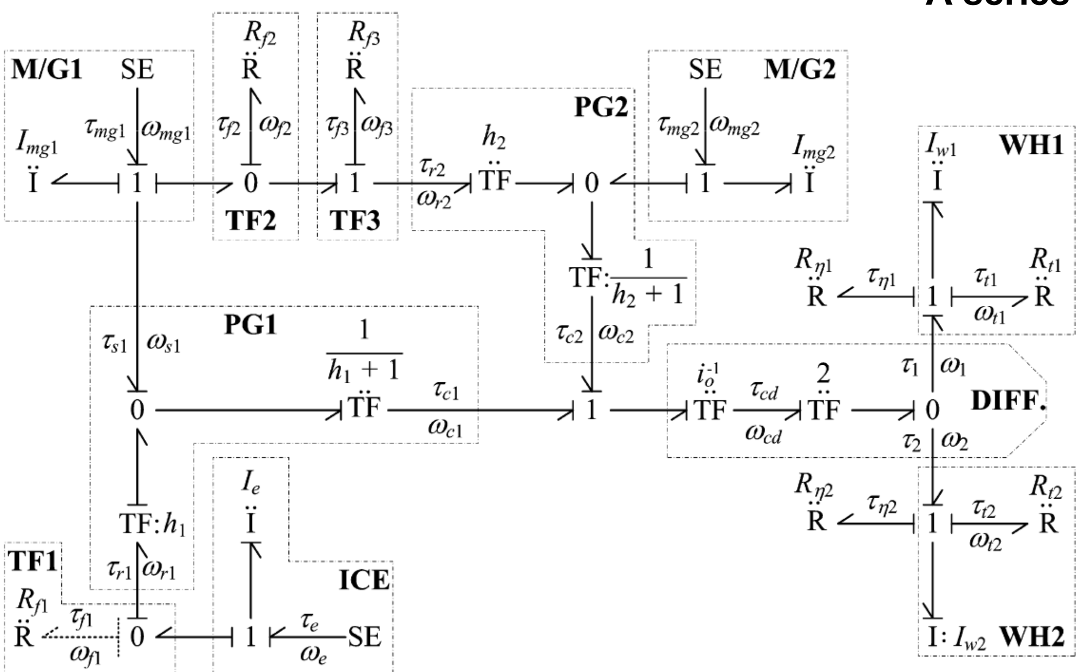
*** Pavković, D., et. al., Modeling, Parameterization and Damping Optimum-based Control System Design for an Airborne Wind Energy Ground Station Power Plant, Energy Conversion and Management, Vol. 164, pp. 262-276, 2018.*

Models and Software Tools

- Individual **component sub-models** are **included within** the particular **hybrid electric powertrain topology**.
- **Power transfer** is **determined by** the **transmission system** configuration.



A series-parallel hybrid-electric powertrain topology*



Example of bond graph modeling of hybrid-electric powertrain*

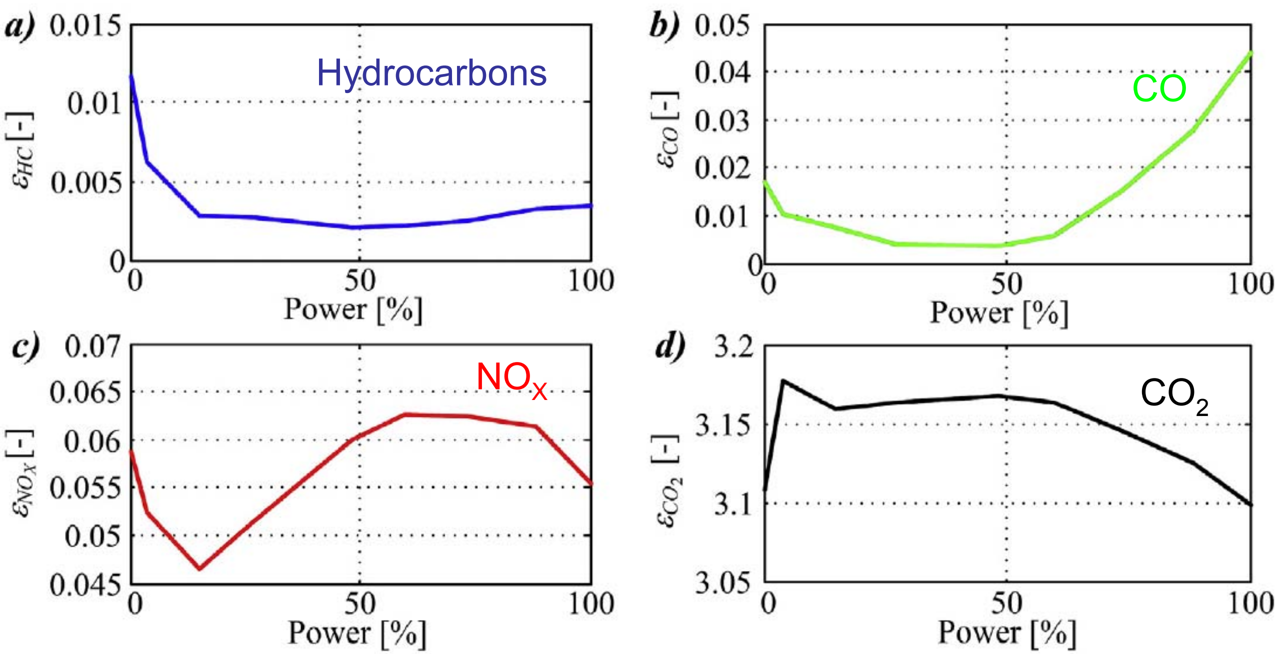
- For **each transmission system** configuration (**gear ratio**) the **corresponding power flow model** is **established**.
- **Power-flow based modeling** can be **achieved by using specialised modeling tools** such as **bond graphs**.
- A **relatively straightforward methodology** for quasi-stationary model derivation.

*** Cipek, M., et. al., A Control-Oriented Simulation Model of a Power-Split Hybrid Electric Vehicle, Applied Energy, Vol. 101, pp. 121-133, 2013.***

Models and Software Tools

- **Internal combustion engine** (diesel or gasoline engine) **exhaust emissions are expressed as a function of power percentage** and **normalized by the fuel rate** (also related to the output power percentage):

$$\varepsilon_{HC,CO,NO_X,CO_2}(\%P) = \frac{\dot{m}_{HC,CO,NO_X,CO_2}(\%P)}{\dot{m}_f(\%P)}$$



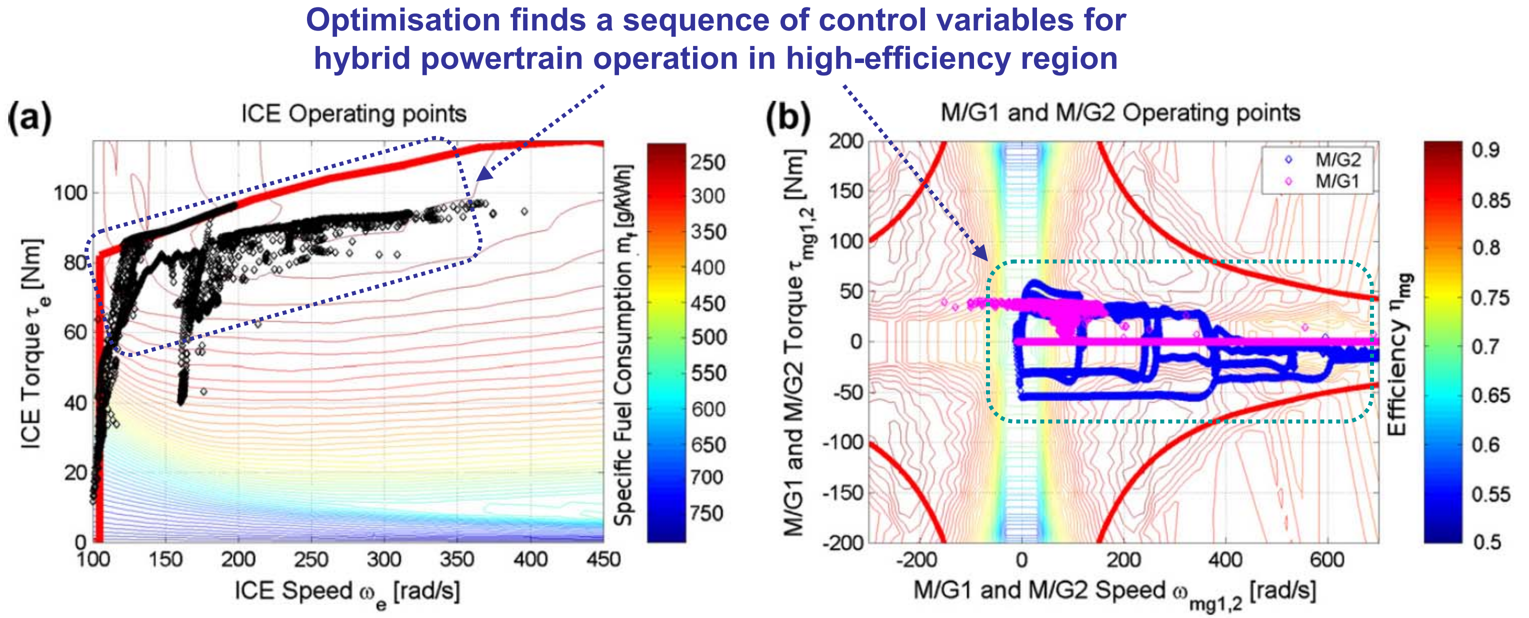
Example of pollutant emissions maps for a diesel engine: hydrocarbons (a), carbon-monoxide (b), nytrous oxides (c) and carbon-dioxide (d)*

- For the **particular power demand**, required **fuel rate is determined using engine and electrical drive maps**.
- Based on these data, **exhaust emissions can be estimated** and **used as an additional criterion in** hybrid powertrain **evaluation**.

*** *Cipek, M., et. al., Assessment of battery-hybrid diesel-electric locomotive fuel savings and emission reduction potentials based on a realistic mountainous rail route, Energy, Vol. 173, pp. 1154-1171, 2019.***

Energy Consumption Optimisation

- **Optimisation tools** that can be **used to find the optimal operating regime of** the **hybrid powerplant** (powertrain):
  - **Dynamic programming** (slow convergence, requires time and magnitude discretisation)*
  - **Gradient-based methods** (fast convergence, cannot guarantee global optimum)*
  - **Cascade optimisation** combining **dynamic programming with gradient optimisation****



Example of hybrid-electric powertrain optimisation results: engine operating points (a) and electrical machines' operating points (b)*

*** Cipek, M., et. al., A Control-Oriented Simulation Model of a Power-Split Hybrid Electric Vehicle, Applied Energy, Vol.101, pp. 121-133, 2013.***

***** Cipek, M., et. al., Cascade Optimization of Control Variables for a Series-Parallel Hybrid Electric Vehicle Power-train, Proceedings of 2019 SDEWES Conference, Dubrovnik, Croatia, 2019.***

Conclusion

- **Increased level of mechanisation** in the **forestry sector** results in **increased operational costs** (in terms of machinery fuel consumption and maintenance), as well as **increased pollutant** (GHG) **emissions**.
- Hence, it is **worthwhile to introduce measures to increase energy efficiency** (and reduce fuel consumption) through **hybridisation of forest machinery powertrains.**
- **Hybridisation of heavy forestry machinery** poses **a challenge** in **selecting the suitable powertrain configuration**, with **electrified powertrains having distinct advantages** over hydraulic-based ones.
- **Tools needed for sucessful hybridisation** of forestry vehicles include:
  - **Suitable battery** energy storage system **models**,
  - **Power flow-based models of** the **internal combustion engine and electrical drive** with **fuel rate and overall efficiency as parameters**,
  - **Pollutant emissions model** related to power demand and fuel consumption,
  - **Optimisation tools**, preferably those that can guarantee **fast convergence rate and near-global optimality**.

Thank You for Your Attention!

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