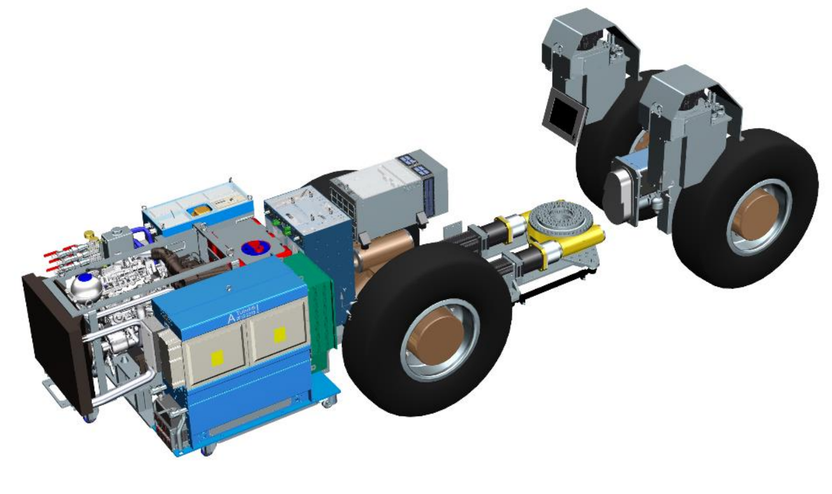
Aalto University
School of Engineering

Hybrid and electric Non-Road Mobile Machines (NRMM)



Kari Tammi, Associate Professor
Panu Sainio, Chief Engineer
Jari Vepsäläinen, Doctoral Student
Aalto University, Finland

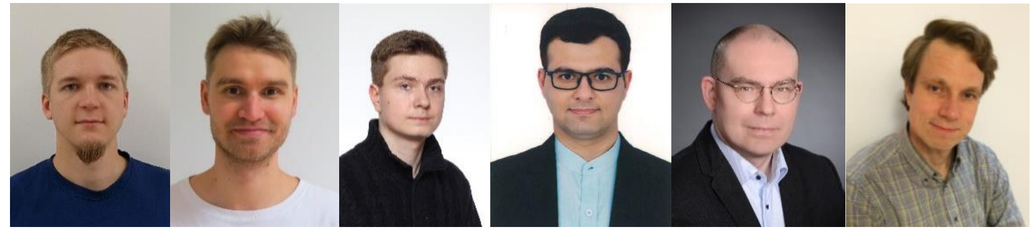
Emission Control Forum for NRMM
September 7-8, 2017 in Frankfurt

For further interest on NRMM roadmap

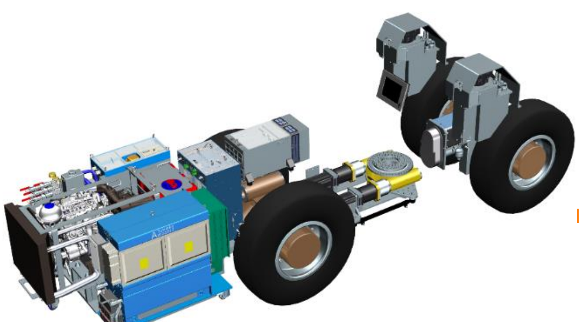
- Note some flavor of national projects & priorities
- Technology roadmap for hybrid and electrical drivetrain of non-road mobile machinery
- *Electric and Hybrid Electric Non-Road Mobile Machinery - Present Situation and Future Trends.* World Electric Vehicle Journal Vol. 8, Issue 1. 2016. pp. 172-183

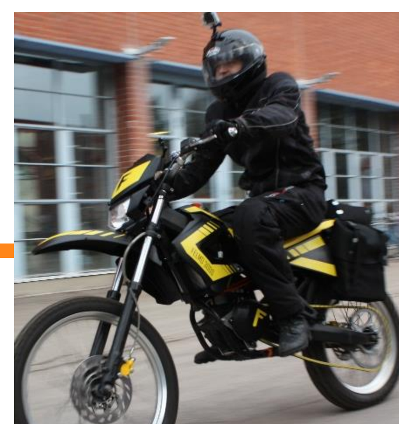
Background & team

- Kari Tammi, Aalto University Aug 2015-
- Earlier Research Professor at VTT: electric machines, energy efficiency, electric vehicles, dynamics & control
- At CERN 1997-2000 (LHC/CMS)
- Teaching: Mechatronic machine design (5 cr), Vehicle mechatronics (5 cr)
- IIT Guwahati, India: Design of electric vehicle systems Nov-Dec 2016



- Panu Sainio. Chief Engineer, expertise: vehicle technology, hybridization, electric powertrain
- Shashank Arora. Post-doc, expertise: batteries, mechanical modelling
- Klaus Kivekäs. Electric powertrain optimization with statistical methods
- Jari Vepsäläinen. Multi-objective robust design of electric powertrain
- Juuso Autiosalo. Digital twin for industrial products





Electrification, a new invention?

- Electro-hybrid submarines & cars existed early 1900
- When there will be business case for extensive usage of fully electric and hybrid vehicles?

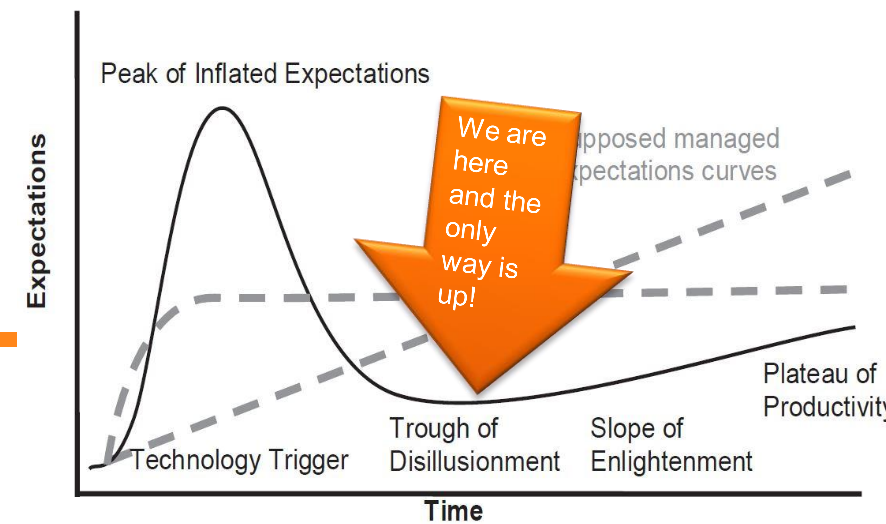
Submarine Vesikko, Crichton-Vulcan CV707 (U-2A). Finnish diesel-hybrid 1933. Diesel, 520kW,elecric 270kW

https://en.wikipedia.org/wiki/Enfield_8000

Where are we now?

- Stage IV, 2014 was somewhat difficult to meet, we still have time before V.
- Price of oil was 120 $/b in the end of 2011, end of 2015 is was 27 $/b and now 46 $/b.
- Battery powered city bus turned out to be a feasible solution beside hybrids – intermediate phase with hybrids might be shorter than believed.
- Role of charging beside “the size of the fuse” is in terms of mechanical and software connection. This is a critical matter.

- Finnish companies are working with electrification and first machines are here, like Linkker and Kalmar “having less noise, reduced maintenance with a smaller number of vehicle components and up to 50% increased energy efficiency compared to diesel/electric drive”,



Desired benefits of electrification (1/2)

Savings case sensitive!

- Improved energy efficiency
  - Energy consumption of an electric machinery can be even 75% lower than that of its diesel engine powered counterpart
  - Cancellation of idle
  - Air consumption, e.g. in mines
- Faster controllability, better maneuverability and drivability
  - Compare, e.g., hydraulically and electrically controlled boom
  - Drive by wire
- Potential for automation

Desired benefits of electrification (2/2)

- Reduced complexity, freedom in design
  - Less gear reductions, elimination of clutch, torque converters
  - Drive shaft vs. electric wire vs. hydraulic line
- Reduced maintenance, both in cost and intensity
- Less noise
- Full-electric machinery is locally emission free

- Discussion focuses on prime mover, but significant also for auxiliaries and e.g. electrically assisted turbo
- New technologies also include new challenges

Training needed!

Technology enablers for electrification (hybridization)

Machinery

- Energy and cost efficient electric powertrain, i.e. electric machines, drives, energy storages, batteries, fuel cells, supercapacitors…
- Sufficient manufacturing **scale & facilities** of components such as electric machines, drives and particularly energy storages and energy buffering
- Solutions independent from rare earth materials, such as Neodymium
- System integration **support & services**, mechanic electrical and control

Environment, infrastructure

- Automatic and easy charging and refuelling
- Vehicle integration with the environment, e.g. tools/technology for fleet management
- Electric power in vehicles is business as usual
  - E.g. 48 V systems are spreading

Fully electric solutions

- Locally exhaust emission free
  - Total CO2 emission depends on electricity pathways
  - Significant amount of renewable or nuclear power needed!
- Nearly noise-free powertrain (work cycle noise is different story)
- Charging?????? (power, connection, automation)
- Power to gas (P2G), gas to power (G2P) technologies may offer new opportunities with fuel cells

Power to gas, gas to power

- P2G converts electric power to a gas fuel
- Electric power to split water into hydrogen and oxygen by electrolysis, three alternative paths to use hydrogen
  1. Inject hydrogen into the natural gas grid or is use in transport or industry as such
  2. Combine hydrogen with CO2 and convert gases to methane
  3. Combine with wood or biogas to upgrade the quality of the biogas
- See Sabatier reaction, G2P ~ inverse P2G
- 6 MW P2G facility by Audi in Wertle, Germany

https://en.wikipedia.org/wiki/Power_to_gas
https://en.wikipedia.org/wiki/Sabatier_reaction
http://www.pv-magazine.com/news/details/beitrag/audi-opens-6-mw-power-to-gas-facility_100011859/#axzz4RPCxKBSo

Electro-hybrid with internal combustion engine (ICE)

- Can be realized in various ways (serial, parallel etc.)
- Shaving the peaks – right sizing of the engine: Downsize is terms of engine power and physical size
  - Allows either smaller after treatment devices or at least more room for them
- More steadily average load for engine and supporting ICE in transients
- Allowing much more peak loads with same or even smaller engine
- Enabling fast load changes in applications like in crushers or drilling machines
- If large battery creates adjustable charging load for idle periods to maintain exhaust temp, to speed up temperature rise, better engine response performance etc.
- Stop-start feature while allowing auxiliary loads with out ICE-idle and immediately work cycle start still while ICE is starting

Challenges

- Economical sustainability (or politically desired)
- Fuel and energy prices, besides environmental issues are very much a political matters
- Electricity generation, emitted CO_2 and production capacity vary from in market areas (see next slide)
- Availability of charging, from grid to energy storages
- Lack of harmonization, for instance, of charging interface and charging communication
- Product lifecycle management
- Practical challenge: insufficient availability of suitable components
- In engineering: aim at good quality but not at perfect…

Energy production pathways: CO2 content in electric power

Pathway	Description	Expended energy (MJ/MJ_{fuel})	GHG emissions ($g\ CO_{2eq}/MJ_{fuel}$)
EMEL1	EU-mix (high voltage)	1.94	135.99
EMEL2	EU-mix (medium voltage)	2.05	141.13
EMEL3	EU-mix (low voltage)	2.24	150.11
KOEL1	Coal (hard), conventional	1.81	292.37
KOEL2	Coal (hard), IGCC[1]	1.54	262.36
KOEL2C	Coal (hard), IGCC + CCS[2]	1.98	71.04
GPEL1a	NG, pipe 7000 km, CCGT[3]	1.35	144.98
GPEL1b	NG, pipe 4000 km, CCGT	1.19	132.43
GPEL1bC	NG, pipe 4000 km, CCGT, CCS	1.71	44.67
GREL1	LNG, CCGT	1.39	141.62
NUEL	Nuclear	2.40	0.39
WDEL	Wind	0.12	0.00
FIMIX	Electricity grid mix in Finland	1.43	32.8

1) Integrated Gasification and Combined Cycle, 2) CO_2 Capture and Storage, 3) Combined Cycle Gas Turbine

Lowering the barriers

- Education, common tools and language for e.g. students, company employees across different fields of engineering, electric, mechanical, hydraulics
- Development of tools for engineering and commercial components
- Taxation → based on CO_2 or simply via fuel taxation
- Role of public procurers, such as cities, governments or even military as early adapters
- Establishment of strategic partnerships
- Successful electrification may require or enable new earning models
  - Leasing contracts? Who owns and what?
  - Different means for minimizing the risks related to new technology

Remark: New voltage levels, like 48V in passenger cars i.e. small steps are taken now continuously.

State of the art examples from Finland (1/4)

KESLA C860 Hybrid wood chipper

- Diesel-electric series hybrid
- Engine: Volvo Penta TAD572VE (160 kW / 910 Nm) EU Stage IV / EPA Tier 4 Final
- Energy storage: supercapacitor (by Visedo)

Enables

- Downsizing the diesel engine and its utilisation at optimal speed
- Elimination of traditional drivetrain

Benefits

- Reduced fuel consumption and emissions 20-35%

Kesla

State of the art examples from Finland (2/4)

Konecranes SMV 4531 TB5 HLT hybrid reach stacker

- Diesel-electric series hybrid
- Energy storage: supercapacitor

Enables

- Electric energy recovery
- Peak shaving: boosting the diesel powered electric generator during peak power demand
- Improved control

Benefits

- Estimated fuel consumption reduction 30%

Konecranes

State of the art examples from Finland (3/4)

Kalmar hybrid straddle and shuttle carriers

- Diesel-electric hybrid
- Energy storage: battery
- Automated start-stop system to balance between energy sources

Enables

- Utilisation of the electric braking and spreader lowering energy

Benefits

- Fuel savings up to 40%
- Lower noise
- Less pollution

Kalmar

State of the art examples from Finland (4/4)

Kalmar FastCharge™ solution

- Electric powertrain
- Fast charging concept similar as in large capacity electric buses

Enables

- Utilisation of the electric braking and spreader lowering energy
- Smaller number of vehicle components

Benefits

- Up to 50% increased efficiency in comparison with diesel-electric drive
- Zero local emissions
- Reduced noise and maintenance

Kalmar

Future opportunities

- ✓ Automation and remote control of machines will become more common (electromechanical propulsion and steering as enablers)
- ✓ Electric solutions will bring more intelligence on board. New business models and rent/leasing are hungry for information
- ✓ Hydraulics is also developing – digital hydraulics, direct driven hydraulic (zonal hydraulic)
- ✓ Less waste heat (cooling and exhaust) for under ground & indoor operations, also lower fuel consumption
- ✓ Stage V will come 2019/2020 = downsize (rightsize!) your diesel and improve the performance at the same time by hybridization
- ✓ Auxiliaries!

What’s up in research activities?

Projects

Past

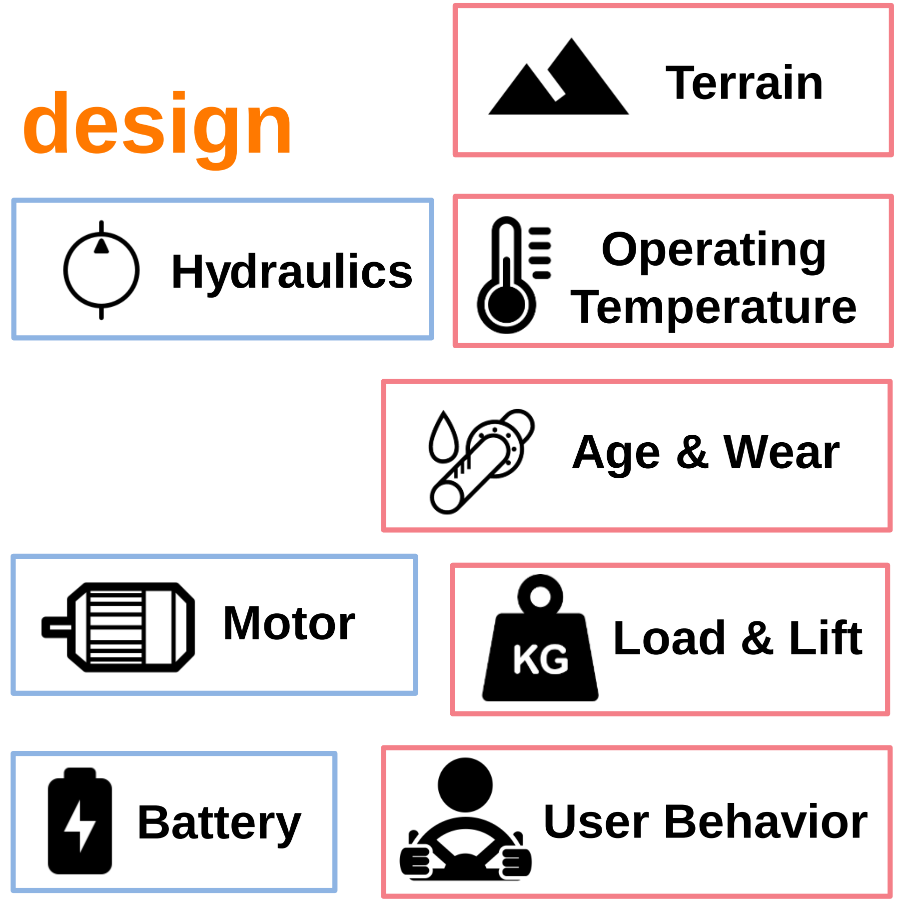
- Since 1996 in eight EU-projects on tire road noise, dangerous driving situations, intelligent tire, and rolling resistance
- Electric commercial vehicles (www.ecv.fi)

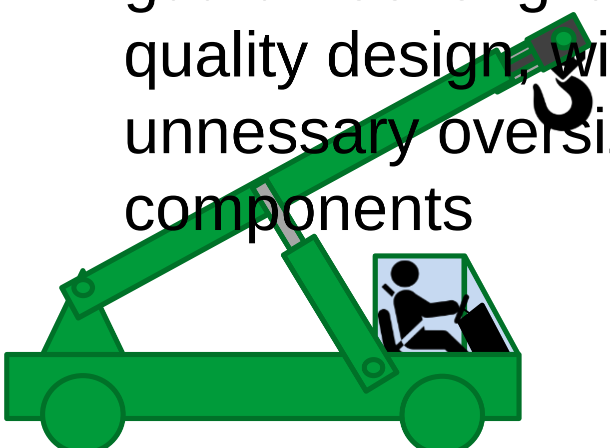
On-going

- Batteries: life-time estimation, safety (Tekes, in collaboration with VTT)
- Inductive charging (EU/EMPIR)
- Smart mobility (Henry Ford Foundation, Finland)

Implementing robust design

- **Identify** ***noise factors*** and their range
- **Study** ***control factors*** that reduce the effect of noise factor variations
- **Adjust** ***control factors*** to guarantee long lasting quality design, with no unnessary oversizing of components





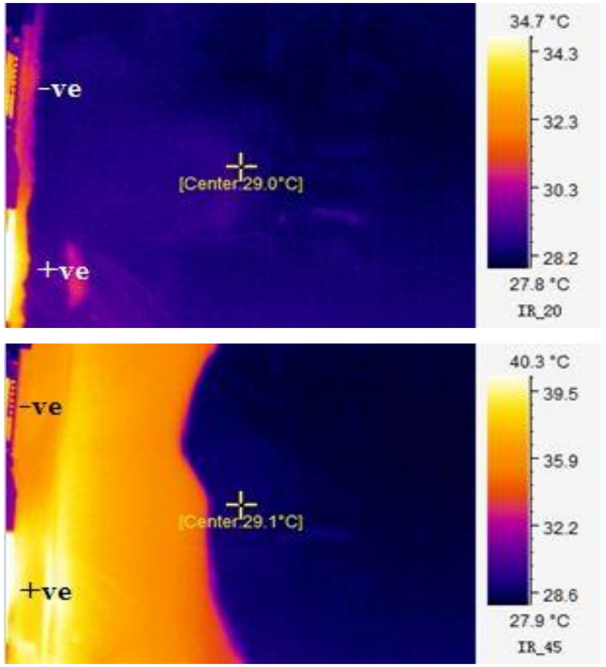
Battery modelling and thermal characterization

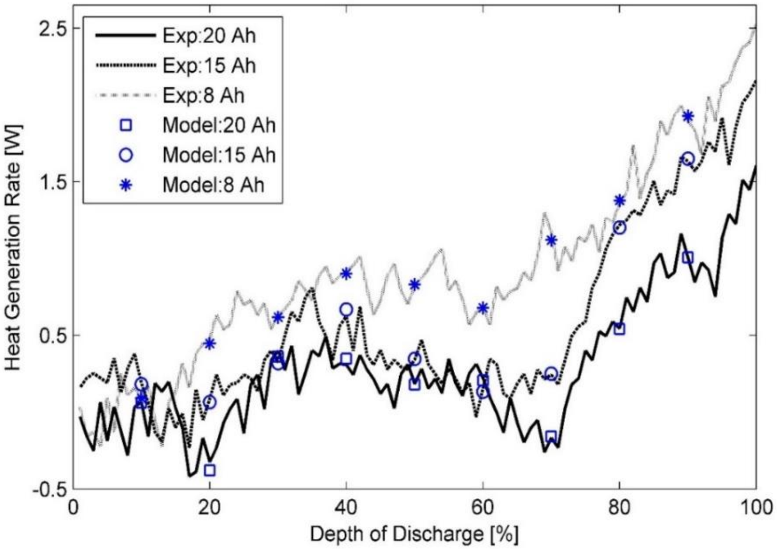
Improved estimation accuracy of polarization models (Newman, Tiedemann and Gu)

A novel, cost-effective, and versatile technique for estimation of SEI film resistance

Easy to implement and simple computational model for estimating heat generation for Li-ion cells with different nominal capacities

Identification most promising new technologies for mobile and stationary applications. And to establish a reliable end-of-life estimation criteria for battery systems





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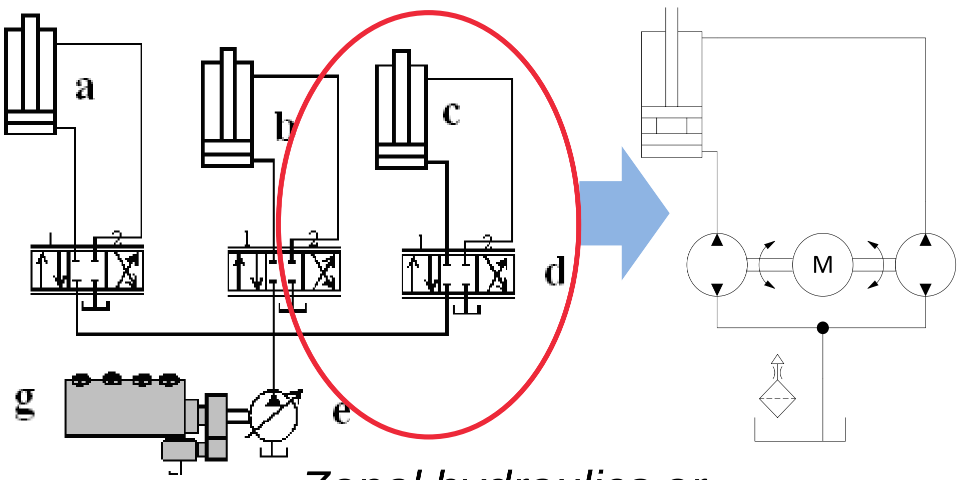
Electric zonal hydraulics

Inspired by aircraft industry: electric motor running hydraulic pump on-demand

NO connection to engine, NO valves

- Power-on-demand
- Independent control of actuators
- Efficiency improvement 21% → 50 %
- Potential energy recovery
- Reduced hydraulic tubing
- Reduced number of leakage points



Zonal hydraulics or direct driven hydraulics

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