Electric drivetrain components – technology road map for mobile machinery

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Tubridi road map ver. 2015 24.1.2015

Contents

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Introduction

- This version of the road map has been done in early 2015 in Tubridi-project of Electric commercial vehicles (ECV) consortium
  - It is based on experience gathered and work done in various R&D-projects at universities, research institutes and companies.
- This road map is technology-focused
  - All the main components of electric powertrains are examined. Energy storage technologies such as batteries are not in the focus as they are the main topic of another subproject of ECV consortium.
- The reader is asked to reflect our visions on the electrification remembering what happened in the 1950s when the diesel engine and hydraulics revolutionised the working machinery business
- This road map is targeted to people who are assessing the possibilities of electrification in their business. There is a very high number of different non-road mobile machinery (NRMM) on the market and observations discussed here have to be evaluated case by case.

Vision

Vision – short & medium term

Energy efficiency and energy consumption during life cycle become increasingly important issues

- Emission regulations and emission control or after treatment systems enter to all power classes (In Tier V, from 2019, regulated up to 560 kW)
- Consumption of oil increases and production decreases → oil price is likely to increase in the future but is a subject to speculation
- New fuel types and qualities enter to markets, this might favour market area segmentation
- Due to the existing electric powertrains in certain machinery applications (locomotives, forklifts etc.), the development of the electric components is continuous and they become more available
- Changes in energy production and distribution (local vs. global energy production, politics) can favour so-called independent energy sources

Vision – long term

Mobile working machinery will be robotized in long term.

- Automation is a major driving force and has started technology trajectory leading to **autonomous machines.**
- Autonomous machines without human operator may promote **diversity of size / power class of machines** (when driver cost is not significant, machine can work 24/7 → machines can be smaller)
- Demands for energy efficiency and automation are favouring electric drivetrain → **we estimate in year 2040 half of new machines are equipped with electric drivetrain**

→ Options to the companies seem to be a) work at full, b) work with small team or c) wait (may include costs). Development happens in small steps. It is important to follow the field and be one of those taking the small steps towards fully electric working machine.

Exploiting the opportunities and preparing for changes

- There already are machinery applications with electric powertrains that can have economic market success
- For faster introduction and adoption of electric powertrains it is crucial to have strong
  - Understanding about the cost effectiveness of electric powertrains
  - Collaboration between industry, research and legislative bodies
  - Benefit from technology hypes of the consumer market products
- Because of the limited resources of raw materials and energy, relying on only one technology can be risky
- Due to the economy driven world politics, the prices of energy and materials are vulnerable and subject to substantial fluctuation
  - E.g. the changes in crude oil price have been rather significant

Slogans to be challenged

- Hybridisation is a tool for risk management of battery technology
- Electric powertrain is an innovation platform to manage market and customer segmentation and tool for political risk management
- Electric control enhances the user experience that will be even more important selling point in the future
- There will be intermediate solutions on the road of electrification like power take-off (PTO) generators in agriculture within the upcoming 10 years
- New earning and funding models in service and leasing will emerge – public transport and mining may be the ones to follow up
- "Motor vehicles, even when powered by internal combustion engines, contain an ever growing number of electric and electronic parts which is often overlooked" – Vehicles are already electrified, from this on it is a matter of component sizes

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Drivers & trends

EU strategy and policies

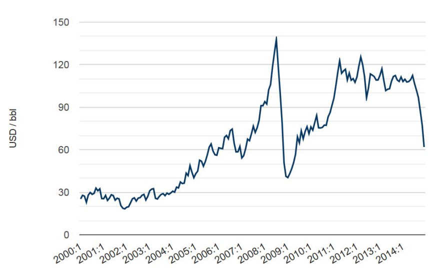
- EU strategy on reduction of CO_2 emissions
  - Objective: reduction of Europe's greenhouse gas emissions by 80–95% compared to the 1990 levels by the year 2050
  - Besides the obvious, the reduction of the CO_2 emissions is beneficial for the following reasons, too
    - Dependence on the oil is reduced that consequently balances the geopolitical power relations
    - The target level cannot be reached simply by savings. Potential for new business in the field of clean technologies
- The CO_2 emission reduction objectives are complemented with other policies or declarations such as with the "Valkoinen kirja" that maps to path to competitive and resource efficient transportation in Europe

References: www.lvm.fi/docs/fi/2497123_DLFE-19513.pdf, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:FI:PDF

Emission standards: Tier V

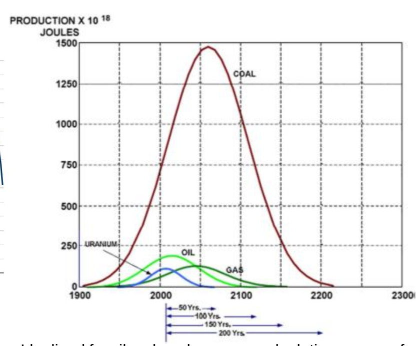
- Upcoming Tier V regulation will impose new limitations on the particle mass and particle number emissions of non-road diesel engines in the power range up to 560 kW
  - Alternative fuels, e.g. biofuels are seen as one solution and are associated with the need for restricting of methane emissions and other non-regulated emissions such as aldehyde emissions
  - Change from Tier IV to Tier V is not cosmetic. Instead, it is almost certain that the particle filters have to be widely applied in working machine engines in the power range of 19–560 kW.
- Regulations of Tier V do not concern the fuel consumption, i.e. no limitations are imposed

Energy prices example: crude oil price development



Crude oil price development (oil.fi, Thomson Reuters).

Crude oil prices react to a variety of geopolitical and economic events



Idealised fossil and nuclear energy depletion curves of the world considering the present availability and the current rate of consumption (Bose 2013).

Market entry is done by steps

	More characteristic	More power to existing machine	Down sized diesel	Pure electric solution	Lower energy consumption
Electric auxiliaries i.e. electric high power components in fans, pumps with voltage over classical 12/24 V, for example 42 or 96 V	✓			✓	✓
Automatically stops/starts diesel engine for waiting times and can sustain for example HVAC for during that	✓		✓		✓
Uses an electric motor to assist a diesel engine and/or can deliver significant electric power to implements		✓	✓		✓
Recharges batteries from a pantograph or a socket for extending or enabling all-electric operation continuously or in periods	✓		✓	✓	✓

Efficiency / performance / readiness for automation

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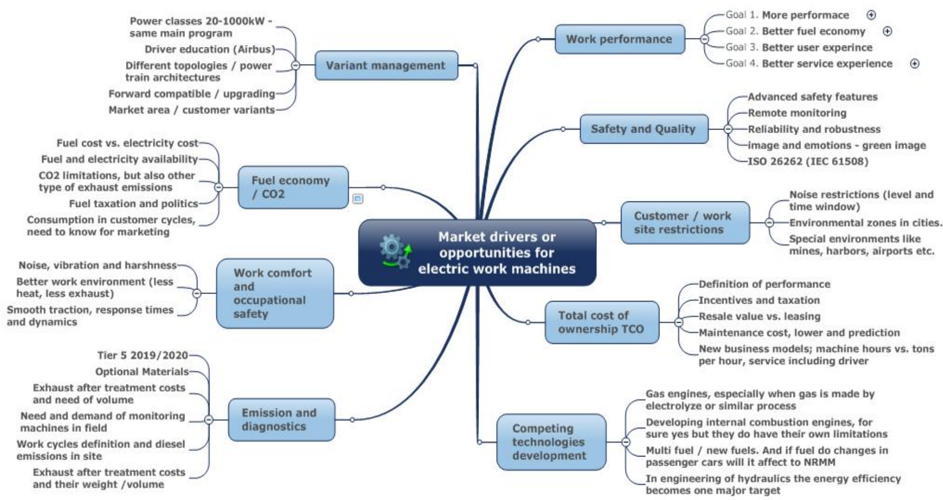
Summary on drivers



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Applied and expanded from article "In search of the optimal future power train", Schmidt-Sante, T., Hammer, J., MTZ 07-08/2012. Original article discussed subject from passenger car point of view.

State of the art

Overview

- Cost per capacity ratio of batteries is decreasing ~2…4% per year. Passenger cars are driving force for entry to mass markets.
- Electric motors and controllers with automotive specifications are available
- Integrated system components (gear motors, diesel generator sets, inverter motors, etc.) are under development
- **Basic theory / technology is ready**; "mobilisation" of the components under work
- Software / model becomes a part of component
- Auxiliary loads development is in the fast lane like controlled fans and pumps (i.e. low power motor drives), lights (= led) and HVAC (heating, ventilation and air conditioning by heat pump)

Batteries

- Despite of their shortcomings, Lithium-Ion batteries have enabled a lot in last 10 years
  - Consider what has happened to hand-held electric tools (batteries) and mobile electronics (electronics and batteries)!
- Electric powertrain has been established in extra large machinery (mining trucks, container handling) and on the rails
  - Applications where electricity can be supplied from net, machines are electric, like cranes, trains, metro; generally vehicles on rails
- There are products in small power class, for instance forklifts, automated guided vehicles (AGVs)
  - Pricing, earning models and trends should be monitored from here?
- Constant demand to have more electric power on board in all vehicles
- Recycle process and costs of batteries?
  - There is need to develop solution for recycling of the different rare materials of the Lithium-Ion batteries

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Electric motors (1/2)

- Asynchronous machines (ASMs), permanent magnet synchronous machines (PMSMs) and synchronous reluctance machines (SRMs) are today's choices, all are "good enough" for most applications; winner is the one that offers decent pricing with mobilisation
- Power & torque or mass & size can always be developed; cooling is the issue
- ASMs /SRMs can be found up to +180 °C, permanent magnet machines typically up to +80 °C
- SRMs are promising: low current, high torque and wide operation area combined with easy manufacturing (recycling) process → might be the surprise champion in the motor game if noise is killed
- Motor with integrated gear and controller might become superior solution; mechanical interfaces standardisation is needed
- Production for mass market with vehicle specs; air cooled ASMs for industry are not the ones for vehicles; SRM is promising

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Electric motors (2/2)

- Motor-gear integration to have output speed < 2000 rpm is mid term (5–10 years) issue
- Motor-gear-inverter integration for mobile applications might be longer term (10+ years), first at low power components, already here in windshield wipers.
- For integration development and technology the follow up area is passenger cars and their motor / transmission / converter development
  - Mitsubishi Electric Develops EV Motor Drive System with Built-in Silicon Carbide Inverter 14.1 l, 60 kW. (2/2014)

- In mobile application, lifetime of electric motor is always enough
  - Other mechanical aspects like bearings and axial seals are the challenge
- SR and permanent magnet motors allow wide geometrical variation in terms of rotor diameter vs. length. Scalability and purchase processes.
- All means to lower costs and increase volumetric efficiency are demanded in vehicles and NRMM, integration of gear and motor are these.
- There are no material improvements seen for magnets into motors, political risks for raw materials can be instead.
  - In long term higher-conductivity wires, such as carbon nanotube (CNT) yarns, for the windings could reduce the motor losses and make it lighter and environmentally friendlier. (10/2014)
- LCA might be an issue in the long term! SRM might win this competition.

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DC-link voltage?

- What will be the windows and de facto -standards
  - DC 12 = 14.3 V, 24 = 28.6 V (there was 36 = 42 V discussion)
  - AC 110/200, 240/400, 1000 V
- Losses are proportional to ~I^2 → voltage up, current down → also less copper and smaller size. This is long term development leading to 400–800 V
- In shorter term low cost, low voltage (24…100 VDC), existing components will be used in low power applications under 30–40 kW
- There might also be several voltages: 12/24 V for accessories, 100–200 V (battery voltage) for pumps and fans and 600–800 V for traction
- This item may be partly solved by some market leaders / machine segments where reasonably priced and commonly available components will be adopted to common mobile use
- 48 V will be the popular trend in hybrid electric cars in the future
- Follow companies like Sevcon, Visedo and John Deere

Remark: Output voltage of batteries and supercapacitors changes as function of the state of charge, and their voltage may be very different from that of DC-link. DC-link voltage may be chosen based on cost, volume and reliability reasons.

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Power converters (1/2)

- The power converter market will be driven by three factors: electrification trends in transportation, the need for power conversion optimisation for CO_2 emission reduction, and the development of clean electricity sources
- Versatile converters; one hardware offers several functionalities;
  - DC/AC, DC/DC, AC/DC with different control
- Substrates, power module packaging and wide band-gap semiconductors are modifying power modules
- Silicon carbide (SiC) was a subject around 2005, and products are now available, e.g. SiC power MOSFETs.
  - Single switch 1200 V, 60 A. Modules 1200 V, 880 A.
  - SiC components increase the efficiency of the whole electric drive.
    - Most car makers agree there is a 10% fuel savings when moving from silicon to SiC in hybrid vehicles
- GaN devices are progressing also, but at smaller power levels (600 V, 10 A)

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Power converters (2/2)

- Temperature control / cooling demands;
  - Allowable temperatures in power electronic components have developed favourably, i.e. increased
- Assembly has to be modular and easy, especially wires and connectors consume too much volume and are too difficult to make →
  - Integration with the motor, rails instead of wires?
- Modular sizing and construction together with easy connections (cooling, high power and signals)
  - Perhaps something like hydraulic valve blocks.

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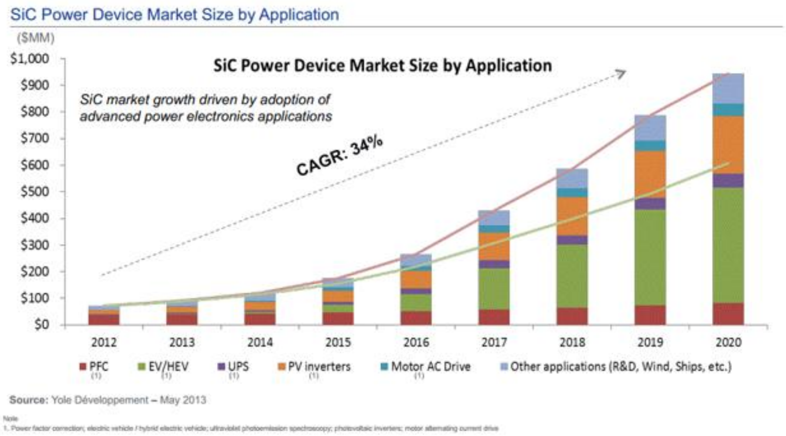
Example of SiC power device markets



Software

- Simulation based software development
  - Modelling and simulation will be increasingly important in the future
  - Virtual simulation enables faster and cheaper product development
- MATLAB/Simulink is for tomorrow's engineers "office software" like today Word and Excel are. Wide educational use supports this strongly.
- Open source development vs. safety & security
  - Development of automation systems requires a lot of work. Possible errors increase with the increased complexity. Therefore it is not foreseen that the customer or operators could access the core of the automation system.
- Service – remote control as part of business model both to machine manufacturer and operators. Could it also be for invoicing?

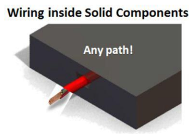
New products

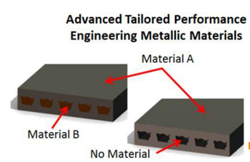
- Very large vs. very small machines = new power classes in different product segments, e.g. tractors
- Developing countries where human labour is available and cost effective – will there be need for simple, cheaper machines?
- Repair and additional construction sites inside dense cities and underground – external skeleton type machines
- Indoor and underground operational demand to be more common

Production tools

- 3D printing is coming – but what are material strength, costs and production time issues. Perhaps prototypes and very small series at this stage. Creating shapes, design and customising?
- Multi material joints e.g. aluminium-copper becoming more common for low cost / weight power cables, cooling plates and corrosion protection.
- There can also be single new machining method to create function with reasonable costs like a predetermined friction stirred (FS) channel pattern that is produced in an aluminium work piece. Target is to obtain a component with specific mechanical and metallurgical properties. FS channels can be filled with other materials or be used only to reduce the component structural weight, optimise its stiffness or as cooling channels. This technology is in research phase.

Linear Friction Based Processing Technologies for Aluminium Alloys: Surfacing, Stir Welding and Stir Channelling, http://dx.doi.org/10.5772/52026





Charging – EV and PHEV systems (1/4)

- When having electric NRMM or public transportation like electric buses – it is a purchase of a system – not a single vehicle. I.e. customer needs to acquire vehicles and charging infrastructure. It may also be the case for plug-in hybrids.
- Charging EV or PHEV type NRMM, different charging system options are available
  - Conductive chargers (plug or pantograph / current collector) either On-Board type or Off-Board type (DC-charger)
  - Inductive chargers (wireless energy transfer via magnetic field)
- On-board chargers are supplied with normal AC grid voltage or DC-voltage. They have the benefit of very simple infrastructure but are usually relatively low power. If high power increased weight and volume.

Charging – EV and PHEV systems (2/4)

- Off-board chargers may be quick-charging units installed at the infrastructure and often are of high power (up to 90 kW with CCS plug and 500 kW with pantographs). The unit communicates, supplies the power and is responsible for the charging process.
- Inductive chargers require equipment both at vehicle and infrastructure and are expensive. Benefits include no contacts and the ability to camouflage the chargers. Power ranges from couple of kW’s to 200 kW.
- Standards are essential for interoperability and flexibility in choosing suppliers. Investments into infra may be expected to last longer than those of vehicles.

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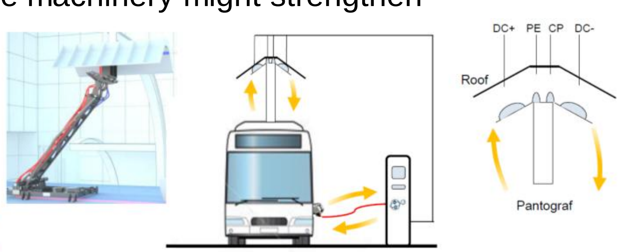
Charging – EV and PHEV systems (3/4)

- Off-board charging standards are available: Japanese originated CHAdeMO and Europe/USA CCS
- CCS standard set is considered to be extended to include high-power pantograph based charging systems utilising CCS technologies, this should work with busses and might offer interesting opportunities for example machines operating in city area maintenance
- Low power on-board charging plugs and standards are available today for electric cars
- On-board systems are often liquid cooled while off-board systems are air cooled. Air cooled solutions in dusty environment may need regular maintenance.

Charging – EV and PHEV systems (4/4)

- Inductive charging is yet to be standardised
- Battery swapping used in forklifts, difficult to automatize and quite laborious, high investments especially in case of big batteries, layout of vehicle should support this.
- Same supplier of the energy for the industrial process and for the mobile machinery might strengthen partnerships



- CCS provides energy from 20 to 200 kW according IEC 61851. Additionally e.g. a pantograf system is possible that could transfer energy up to 500 kW.

Synchronous belt drives for NRMMs (1/3)

- Rotating speeds in NRMMs are traditionally based on diesel engine speed (up to 2500 rpm). Higher speeds can exists in implement and auxiliary drives (up to 4000 rpm)
- Electric motors are often capable 2–4 times higher speeds than diesel engine. This brings new challenges and also opportunities to design drivelines for NRMMs.
- Dimensioning electric driveline has two approaches:
  - High torque low speed (0–4000 rpm) electric motor which fits directly or with some small (about 1:2) reduction in to the existing driveline (expensive, bulky and needs high current capable controller)
  - High power and high speed motor (0–10000 rpm or higher) which needs always some reduction between motor and existing driveline (cost efficient, compact, flexible design and works with almost any controller)

Synchronous belt drives for NRMMs (2/3)

- Transmissions with higher input speed (6000 rpm continuously) may need pressure lubrication what is used in passenger car conventional automatic transmissions and HGV's but only rarely used is NRMMs transmissions
- To adapt high speed motor to low speed transmission needs additional reduction and one answer for that can be lubrication free synchronous belt transmission.
- Synchronous belts are developed to level where it's capable to transfer high power with high speed and still fulfilling NRMM level lifetime and environmental requirements.
- Timing belts are often seen in passenger car size engine cam shaft drives – those cases have crated bad mouth over the years but also boosted development of belt drivers

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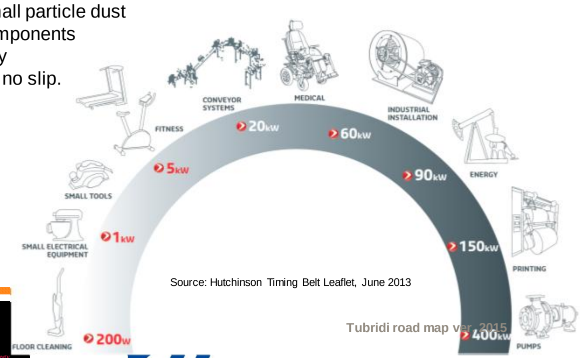
Synchronous belt drives for NRMMs (3/3)

1. Wide speed range (up to 10000 rpm or even 20000 rpm in low power applications) and wide power range (up to 500 kW)
2. Long enough lifetime for most NRMM applications 10000 h or more
3. Wide temperature range (with some materials −54–+140 °C)
4. Depending of chosen material a belt can be conductive or nonconductive.
    - Nonconductive belt blocks possible rotor current going through bearings in secondary axle
    - Conductive belts can be used in ATEX-environments
5. Non sensitive for humidity and small particle dust
6. Good selection in off-the-shelf components
7. Generally good chemical durability
8. High accuracy, minimal backlash, no slip.
9. Allows small misalignments
10. High efficiency (up to 98%)
11. No need for lubrication
12. Maintenance free

The International Energy Agency's paper on "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems" advises to use synchronous belts as an improvement possibility for energy savings. The US Department of Energy also encourages the use of synchronous belts in all motor installations to maintain an overall efficiency rating of 98% across a wide load range.

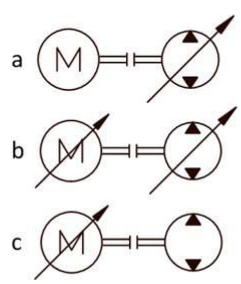


Source: Hutchinson Timing Belt Leaflet, June 2013

Hydraulic driven by electric motors

Displacement control
(method: changing pump output flow)

a) variable displacement pump + constants speed motor
b) variable displacement pump + variable speed motor
c) fixed displacement pump + variable speed motor



Electro-hydrostatic actuators (EHA)
(compact pack of actuator, pump, electric motor)

Moving from mechanical and hydro-mechanical control systems to electronic solutions in following concepts

- **Fly-by-wire** and **Drive-by-wire** concepts
- **More Electric Aircrafts** (MEA) concept
- **Steer-by-wire**, power steering

Required technology enablers

Innovating actors, enactors, and selectors

- Genuine race vs. waiting game
  - Patience is acceptable especially in system innovations, where multiple actors need to cooperate and develop technology simultaneously
- Innovation journey include meeting new partners such as electric utility companies → Open mind has an important impact on innovation
- Technological hype is a necessity to draw attention and get funding
  - E.g. investors may benefit from hype by higher returns
- Hype is typically followed by a disappointment, or at least, the progress is only done by incremental innovations
- After hype there is “down time”, then begins real growth and work
  - Experienced and networked engineers are valuable for long-term development

Applied from the article "Technological hype and disappointment: lessons from hydrogen and fuel cell case", Bakker, S., Budde, B., EVS 26, 2012

Identified missing links – what to look at fairs

- Battery capacity and lifetime – gets better every year
- Usability/applicability of supercapacitors is approaching that of batteries
  - However the work cycle counts and decision on the energy storage depends on that
- Electric connectors with reasonable costs and easy assembly
- Components with mobile specs at low cost and high number
- Missing subsystems: ultra compact diesel-generators and e-motor + gears for traction
- Manufacturing cost of electric motor (in these power classes)
- Standards and regulations – either they are missing or taken from totally different industry. Every industry has their own way of working and standards can not be copied between techno-economical domains.
- Education – where to find talented people with multidisciplinary skills

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Other opportunities for productivity, energy efficiency and environmental acceptance

- In hydraulics, when engineers will face demands for low energy consumption, hydraulic systems will be engineered to achieve remarkably better efficiency than today. Consider what happed with passenger cars. Prius set benchmark level at 100 g CO_2/km. However, "conventional" powertrains with down sized diesel and gasoline engines reached this same level within 5 years due to the demand.
- New means to control hydraulics like digital hydraulics will enter to mass markets and boost energy efficiency and level of control
- Cost efficiency and energy efficiency may be improved through logistics
- New fuel grades and sources are considered more environmentally friendly than convectional fossil fuels

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Visions of other areas may be real eye-openers…

Following "More Electric Aircraft" -theme

- Reducing size and number of engine driven pumps
- Increase capacity of on board generators
- Secondary controls realised with electric actuators instead of hydraulic
- Reduce extend of hydraulic network in airplane, use of power packs locally, no need connection to central hydraulic network
- In primary control usage of EHA as more electric solution
- Reduce the extent of hydraulic piping
- Green taxing
- Potentially reduced system weight, easy maintenance and advanced diagnostics and prognostics
- http://m.hydraulicspneumatics.com/200/TechZone/HydraulicPumpsM/Article/False/83396/TechZone-HydraulicPumpsM
- http://www.nottingham.ac.uk/aerospace/documents/moreelectricaircarftresearch.pdf

Actions

What to do if we want to meet the vision of this road map (1/2)

- Let's not follow what others are doing, but create the future by ourselves!
- Means for the road map realisation
  - Tekes program? New Tekes program on mobile working machines, first the modern mobile working machine then automatized versions
  - FIMECC program?
  - EU related, e.g. Horizon 2020?
  - FIMA project with Tekes?
- What do we see as interesting research topics in road map?
  - Scope of the further activities, i.e. for instance development of components or development of integrated powertrain solutions in accordance with upcoming regulations?
  - What is missing?

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What to do if we want to meet the vision of this road map (2/2)

- Possible topics
  - Challenges in implementation of a hybrid drive system in total in a NRMM
    - System automation, making the whole system to work
  - Taking steps towards full robotization
    - Electric powertrain is an innovation platform for intelligent control; making every driver intelligent, energy efficient, productive and capable to operate in difficult environment
    - Remote control and remote drive
  - Development of standards and regulations
    - Taking actively part in process
  - Create needs for customers (as well as understanding on the State of the art solutions)

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Follow up

- This work has been carried out in Tubridi project of Electric commercial vehicles (ECV) networked project. ECV is active 2012–2015.
- This presentation has been updated in early Q1/2015. It is the third revision of the road map.
- Feedback, comments and particularly, challenging of our views and estimates are welcomed

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