Hybrid Drive Systems – Performance and Emissions

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Outline

• Why hybrid technology?
• What is a 'hybrid'?
• Different kinds of hybrids
• Why a hybrid is economical?
• Toyota Prius hybrid
  • Personal Experience
• Hybrid buses
  • Volvo
  • Golden Dragon
Why Hybrid Technology?

• Transportation has increased substantially
  • More vehicles on the roads
  • More km's driven
  • More burning of fuel

• Need to reduce CO₂ emissions
  • CO₂ depends on the fossil carbon combusted

• Need to reduce fuel consumption
  • Crude oil will not last forever
  • Reduction in consumption = reduction in CO₂

• Air quality emissions (CO, HC, NOₓ, PM) reduced
Optimistic Market Scenario

Gasoline Hybrid Marketshare Projections:
- Toyota (2006)
- J.D. Power (2005)

Source: Bodek, Heywood, Europe's Evolving Passenger Car Fleet: Fusel Use and GHG Scenarios through 2035

What is a 'hybrid'?

- Literally, the word 'hybrid':
  - 'composite', 'mixture', 'blend'
  - Antonyms: 'homogenous', 'pure'
- Generally not necessarily a positive meaning
- In vehicle technology
  - Meaning is positive
  - Means a vehicle with two sources of power
    - Most commonly a combination of a combustion engine and an electric motor
What is a 'hybrid'?

- Use of the term in auto technology somewhat imprecise
  - Word is used to promote sales
- EU definition:
  - Vehicle that is powered by at least one electric motor
  - and by another power source
  - and which transforms the fuel energy to be stored in electrical form and to be re-used
- UN definition:
  - Vehicle installed with at least two energy delivery and storage systems
- Sub-concepts exist
  - micro-hybrid', 'mild hybrid', 'full hybrid'
Micro hybrid

- Power only 2…4 kW, voltage 12 V
- Start-stop system
- Battery charging during engine braking
  - Generator activation
- Normal starter at flywheel or integrated starter-generator (ISG) with a belt
  - Starter-generator may provide additional power for acceleration
- Fuel savings: 3…6 %
- Drawback: Wear of camshaft due to multiple start-ups
- BMW (normal starter), Smart (ISG)

Source: Diagno Finland (A. Lehtinen)
'Mild hybrid'

- Power 6...15 kW, voltage 42...160 V
- ISG on crankshaft
  - Regenerative braking
- Start-stop system
- Boost power from electric motor for acceleration
- ICE valve shut-off at low constant speeds (Honda)
- Fuel savings: 15%
- Honda, MB, Audi

Source: Diagno Finland (A. Lehtinen)
'Full hybrid'

- Power over 20 kW, voltage 200…600 V
  - Or, "significant" power compared to ICE
- Regenerative braking
- Start-stop system
  - Engine can be stopped during driving
- Mere electric propulsion possible
  - BMW X6 => 60 km/h
  - Toyota Prius => 70 km/h
- Additional power from electric motor for accelerations
- ISG on crankshaft or electric motor and generator integrated in powertrain
- Toyota, Lexus, BMW

Source: Diagno Finland (A. Lehtinen)
Why a Hybrid is Economical?

1. Regenerative braking
   - Gives most benefits in stop-and-go driving
   - At slight decelerations friction brakes not used
   - Motor turns into generator, which is rotated by the vehicle inertia
   - When the motor starts generating, it becomes harder to turn and reduces vehicle speed
   - Generated energy stored in batteries
Why a Hybrid is Economical?

- Measurements at TUAS on Prius II
  - Slight deceleration 40...0 km/h by releasing the accelerator pedal
  - Generator produced 55 % of the kinetic energy of the car at the beginning of the deceleration
  - With charging losses etc. the final amount for re-use would be 40...50 %
  - In practical terms: almost every other acceleration in city is free
  - Is energy conversion efficiency 40...50 % poor or good?
  - Well, it depends...
    - It is good compared to conventional cars with 0 %
    - But if movement is kept as movement, it is 100 %
Calculations: regeneration

1. The mass of Prius II is 1420 kg. Mass of the driver is 75 kg. How many watt-hours (Wh) of electricity can be recaptured during a slow deceleration, if the driving speed is 40 km/h and the overall recapturing efficiency is 45%?

2. How many this kind of decelerations would generate enough energy to charge the hybrid battery (201.6 V, 6.5 Ah) from 30% to 100% state of charge, when the usable storage capacity is 10% of the nominal value?

3. How many liters of gasoline would correspond the amount of energy recoverable from 10 such decelerations? Gasoline energy content is 42.5 MJ/kg and density is 0.745 kg/l.
Why a Hybrid is Economical?

2. Smaller and more economical ICE can be selected

- Atkinson cycle commonly used
- Electric motor assists => sufficient performance
- Reduces consumption also on motorways (higher load => higher efficiency)
- Full power need very seldom: why select the ICE size based on this?
- Full acceleration need: max 10–15 s (otherwise the police catch you) => no need for a huge battery
- Principle of "Downsizing"
- Gives consumption benefits also on highways
Why a Hybrid is Economical

3. The power of the ICE can be separated from the road load power needed to move the vehicle
   - Low load: No use to run the ICE, let's use only the electric motor and cut down idling
   - Medium load: ICE load and efficiency increased by charging the batteries
   - High load: Electric motor assists the ICE
Engine Map of the Prius

Min BSFC: 200 g/km

Source: Miller, Comparative Assessment of Hybrid Vehicle Power Split Transmissions

BSFC = Brake Specific Fuel Consumption
Low load (below 8 kW): BSFC over 290 g/kWh

Source: Miller, Comparative Assessment of Hybrid Vehicle Power Split Transmissions

BSFC = Brake Specific Fuel Consumption
Engine Map of the Prius

Medium load (15 kW): BSFC 240 g/kWh

BSFC = Brake Specific Fuel Consumption

Source: Miller, Comparative Assessment of Hybrid Vehicle Power Split Transmissions
Engine Map of the Prius

15 kW of traction power + 5 kW of battery charging:
BSFC 220 g/kWh

Source: Miller, Comparative Assessment of Hybrid Vehicle Power Split Transmissions

BSFC = Brake Specific Fuel Consumption
Hybrid Info from Toyota

1. **Energy Supply to Make Up for Shortage during Acceleration, etc.**
   - When the vehicle is stationary, the engine turns off.
   - Engine output energy with high efficiency.

2. **Braking Energy**
   - Braking energy is recovered and stored.

3. **Secondary Battery**
   - At steady speeds, surplus energy is stored.

4. **Figures**
   - Acceleration
   - Cruising
   - Deceleration

Source: Toyota
Official CO$_2$ value vs. Weight

Source: VTT Technical Research Center of Finland (J. Laurikko)
Toyota Prius Principle

- MG1 (Generator)
- Engine
- Power split device (planetary gear unit)
- Differential Gear Unit
- HV Battery
- Inverter
- MG2 (Motor)

Source: Toyota
Hybrids Popular in Taxi Use

Paris, France

Valencia, Spain

Helsinki, Finland

Turku, Finland

Barcelona, Spain
Personal Experience

- Toyota Prius in the family since 9/2006
  - No technical problems
  - Quiet, smooth, reliable
  - Very economical
  - 99 000 km, 4 906 liters
    => 4.97 l/100 km
  - Trip computer/refilling comparison: - 1.8 %
Personal Experience

- Toyota Prius data since 9/2006
Personal Experience

Distance driven, tankful by tankful

Distance per tankful, [km]

Gasoline price

Toyota Prius - Annual average fuel consumption

Date

Price (€/l)

Energy Efficiency
Hybrid Bus Situation

• Most manufacturers have activity
  • Volvo, Solaris, Golden Dragon commercial
  • Scania, MAN, Mercedes, Iveco; Kabus, concepts

• Already in use in many cities
  • London: 56 since 2010, 2011 target 300 units
  • Other cities in the UK: Manchester and Bath
  • Gent, Belgium: 20 hybrids replace trolley-buses
  • Turku; Finalnd: plans for 4 buses
  • Tampere, Finland: 1...2 coming in 2011

• Expected benefits (research data still missing):
  • Fuel consumption - 25...35 %
  • Air quality emissions decrease

Source: Volvo
Hybrid Bus Expectations in Finland

Expectations of different powertrains in city buses in 2016, selected cities in Finland  
Source: Tampere University of Technology, H. Llimatainen
Volvo Hybrid Bus

- Expected fuel savings (Volvo):

  - City bus: 20...30%
  - Long-haul: 0...5%
  - Garbage collection: 20%
  - Bulldozer: 20...50%
Volvo Hybrid Bus

ENGINE:
Downsized, Volvo Powertrain
MD5 (EU5 / EEV)
4-cyl, 5-litre, 235 kW

Source: Volvo Finland (T. Rönnberg)
Volvo Hybrid Bus

TRANSMISSION:
I-SHIFT (AMT-D)
(Automated Mechanical Transmission)
Fuel savings 4% compared to traditional automatic

Source: Volvo Finland (T. Rönnberg)
Volvo Parallel Hybrid System

ELECTRIC MOTOR / GENERATOR (ISAM)
- 120 kW peak
- 70 kW nominal
- 600 V, 800 Nm, 135 kg

ENGINE

TRANSMISSION

ENERGY STORAGE: Li-ion
- 600 V DC, 1.2 kWh, 120 kW
- 200 kg, recyclable

POWER ELECTRONICS
- DC/AC, DC/DC

Source: Volvo Finland (T. Rönnberg)
Volvo Hybrid Bus, Torque

- Combined Torque Diagram

Source: Volvo Finland (T. Rönnberg)
Environmental properties

**Fuel consumption [%]**

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<th>Euro III</th>
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*Source: Volvo Finland (T. Rönnberg)*
Volvo Hybrid Bus

Source: Volvo Finland (T. Rönnberg)
Golden Dragon Hybrid Bus

- No gearbox, one fixed gear ratio and clutch
  - Very simple structure
- Engine running always, driving a generator
- Below 22 km/h: only electric propulsion
- At 22 km/h: clutch kicks in
  - Engine 700 1/min
- Over 22 km/h: both motor and engine drive the vehicle
- Vehicle price + 30 % to diesel

Source: GD Bus
Golden Dragon Hybrid Bus

- 6.7 l Cummins engine, very little modifications
  - (Usually 9…10 l)
- Ultracapacitors, holding 70 % of energy overnight
- Top speed 70 km/h
- A developed version with a 2-speed automatic considered
Golden Dragon Hybrid Bus

System structure

- Engine
- Electromotor
- Axle
- Generator
- Inverter
- Controller
- Ultra-capacitors

Source: GD Bus
Golden Dragon Hybrid Bus

Speed under 22 km/h

Working Principle

- Clutch disengaged
- The bus is driven by electromotor, power is supplied by Ultra-capacitors.

Source: GD Bus
Golden Dragon Hybrid Bus

Speed over 22 km/h

Working Principle

- Clutch engaged
- The bus is driven by engine and electromotor.
- Electromotor is working for accelerated motion.

Source: GD Bus
Golden Dragon Hybrid Bus

Deceleration

Working Principle

- Electromotor is driven by axle, Ultra-capacitors are charged (energy recovery)

Source: GD Bus
Conclusions

• Hybrid technology will provide
  • Fuel savings of 25...35 %
  • Reductions in air quality emissions

• Factors behind the fuel efficiency of hybrids
  • Regenerative braking
  • Possibility to choose a smaller and more economical ICE
    • Provides savings also on highways
  • Possibility to separate the engine power output from the road load power needed
    • Engine can either be shut off or used at higher (economical) loads

• Hybrid city buses are entering the market
  • At least Volvo and Golden Dragon commercially available
  • Other manufacturers have at least concept vehicles