Extended range transmission at low cost and with short time to market

Affordable hybrid drive for delivery truck and city bus

Introduction of a passenger car hybrid concept and it's applicability into delivery trucks and city buses with special focus on feasibility and affordability.

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Extending the extended range transmission
Vicura is developing and designing driveline components covering a vast variety of torque transfer concepts. And therefore initiated the design of an extended range electric vehicle (EREV) powertrain, where low add-on cost (compared to a conventional vehicle) and emission level below 50g CO_2/km have been considered two of the most important design criteria. As Vicura has interest in applications ranging from passenger cars to commercial vehicles also buses, delivery trucks and other applications has been considered and included.
This article is focusing on presenting rationale, layout, functionality and performance for an extended range gearbox installed in a delivery truck. With prerequisites as comparable performance, increased efficiency and low add-on cost the system principals are retrieved from the Vicura passenger car project where rationale, gearbox setup and functional principle have been revised.

Extended range transmission in passenger car
The main goal with the passenger car EREV solution was to design a cost effective driveline to meet emission level legislations and decrease fuel consumption. The starting point of such a setup was a passenger car with an already low certified emission level, hence a fuel efficient engine setup to base the design on. By doing so, the vehicle design and manufacturing may inherit components and processes. Together with a standard electric motor and a straightforward gearbox design there was a strategy to have low add-on costs.
For the EREV vehicle, electric machine, power electronics, shift/clutch actuation system and energy storage will have to be added to the total car cost. The original gearbox is excluded and replaced by the EREV gearbox. The gearbox cost will be

reduced compared to the baseline vehicle with a simplified design and fewer gears. Between a large and a small car, the cost is not that different for the electric machine and power electronics. The component that has a clear dependency to cost is the size of energy storage.
Performance target was to provide a similar vehicle performance but with significantly improved fuel consumption. The performance of the electric motor should be enough to fulfil the original performance without requiring a shifting gearbox in the speed range 0 - 130kph. If the vehicle speed exceeds 130kph, the vehicle had to be driven by the combustion engine which is acceptable since this means that all fuel consumption cycles can be fulfilled fully electric. It also means that the vast majority of real life drive cases also were covered.

How to apply to commercial vehicle
Also for the commercial vehicle it is important that the EREV version is based on an existing baseline vehicle to maximize inheritance on carryover components. The practical driving cycle for a city delivery truck with short distances and many start and stops motivates the extended range concept to work in hybrid mode compared to the passenger car setup. Instead of waiting for low state of charge of the energy storage the vehicle would be setup to combine electric drive with combustion drive at already low vehicle speeds.

The major differences between the passenger car setup and the delivery truck drivetrain will therefore be, to configure the truck drivetrain towards hybrid mode and downsizing the energy storage.

Transmission and drivetrain layout

The most pronounced design features are the electric driven one forward gear, electric driven reverse gear and four forward combustion driven gears. In addition, the shifting is performed automatically by the shift/clutch actuation system. The electric motor would perform torque fill during combustion drive shifts. This further simplifies the mechanical gearbox without decreasing shifting performance.

The gearbox has two input shafts where one is dedicated to the electric motor and the other to the combustion engine. The electrical motor drives the output shafts via one ratio step as a forward gear or reverse gear, and through final drive. The combustion engine drives the output shafts via a four ratio step transmission, and through final drive. The engine torque path is decoupled by a dry clutch system on the input shaft and dog clutches as gear couplers. The electrical torque path is decoupled by a dog clutch. See figure 1.

The available torque paths are therefore:

- Electrical motor driving output shafts.
- Combustion engine driving output shafts.
- Electrical motor driving combustion engine.
- Combustion engine driving electrical motor.
- Electrical motor and combustion engine driving output shafts.

The EREV equipped delivery truck driveline uses the existing inline four cylinder diesel engine and the original gearbox is replaced with the EREV gearbox and components.

To get same tractive force and performance in the delivery truck the electric motor has comparable power to the diesel engine. The ratios are chosen as the electric one step ratio is matching the original first gear ratio. The combustion four gear torque path is matched to the original second to fifth gear ratios. This setup is therefore acting in hybrid mode

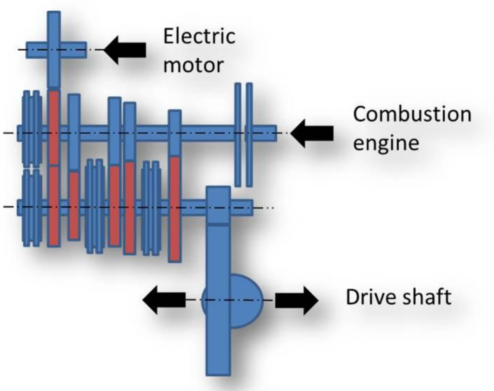

Figure 1. EREV Gearbox layout

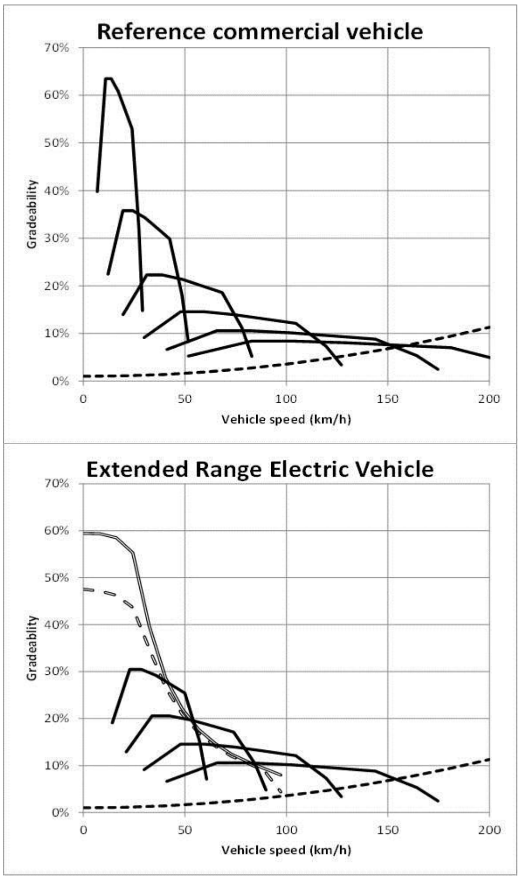

Figure 2. Original and EREV truck tractive force diagrams

as a combined five speed gearbox with a mix of electric and combustion drive. See figure 2.

As the delivery truck is setup for hybrid mode with stop/start, the energy storage is downsized compared to an extended range passenger car. Where extended range vehicles has more than 10kWh and electric vehicles even more, this concept is sufficient with 2-3kWh. At these combinations of power levels, super capacitors should be considered. The downsized energy storage will save money, space and weight compared to the passenger car setup.

Electric drive

All low speed driving within first gear range is performed fully electrical without assistance of the internal combustion engine. In electric mode the regeneration is possible during coast and braking. The braking system could enable active blending between the electric motor (as generator) and the conventional brakes.

The gear ratio for electrical first gear should provide the best possible combination of tractive force at standstill and a suitable top speed. This enables a compromise between the electrical top speed and use of combustion engine drive. The electric motor would be declutched from the driveline to enable vehicle speeds over the electrical drive top speed.

The gearbox is providing the opportunity for the electric motor to be driven by the combustion engine without moving the vehicle to ensure that the battery can be charged at all times.
The delivery truck setup will use the electric drive as emulating the first gear of a conventional drivetrain, with automated shifting.

Hybrid mode
The state of charge condition on the energy storage is normally used for decide on entering or leaving hybrid mode. However, for the delivery truck the gearbox will be setup and emulate a combined five speed transmission with automated shifting configured for low fuel consumption. The state of charge is still an important parameter to monitor and act on.
Speed matching during shifting is performed by the combustion engine and electric motor. During shifting the electric motor is providing torque fill to ensure continuous tractive force. Shifting is fully automatic with possibility for tap shift.
The combustion engine is preferable declutched and turned off during driving at the electric gear, and coasting or braking at any gear. When reinitiating acceleration the vehicle is initially being driven electrically and the combustion engine is push started through the gearbox via the dry clutch. Regenerative braking is available in all gears.

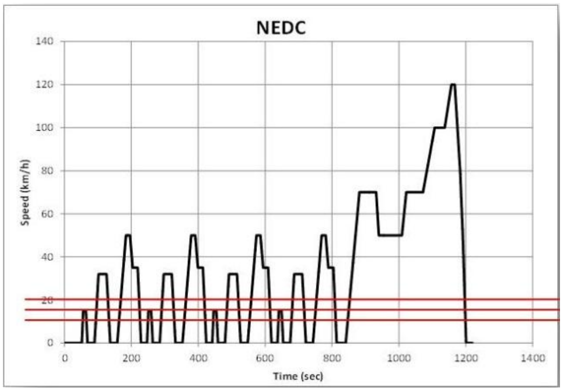

Figure 3. NEDC with three different 1-2 upshift lines

Performance and fuel efficiency
The performance and fuel efficiency figures have been simulated with Vicura proven models.
The delivery truck diesel engine is originating from the reference commercial vehicle and is an inline four cylinder at 120 kW. The electrical motor is suggested to be at 120 kW to get comparable performance to the reference vehicle.
Ratios are selected according to the reference truck gearbox system but could be altered to better fit alternative vehicle weights and performance needs. With above drivetrain setup comparable tractive forces and performance are achieved.
Fuel consumption improvements are significant. A large step is achieved directly with electrical first gear, enabling start/stop and automated shifting.
Further improvements are available if gear selection is state of charge dependent.
The reference delivery truck has certified fuel consumption according to New European Driving Cycle, NEDC, of 7.33l/100 km. See figure 3.
If the extended range concept is applied to the reference vehicle with an electrical first gear to 11kph, rolling start/stop of the combustion engine and optimized automatic shifting, the fuel consumption will be 5.1l/100 km. The shifting from electrical first gear to next gear may be rather freely chosen because of the powershift capability and the matched torque sources. If the upshift speed is increased to 15kph the fuel consumption will be 5.0l/100 km, and with 20kph that will be 4.7l/100 km. See figure 4.
The moving of upshift speeds could be controlled by the state of charge of the energy storage.
If the vehicle is equipped with similar braking system as may be found in electrical vehicles, with a dead-band in the brake pedal travel, which is dedicated to regenerative braking, further improvements will be made. It is possible to manage the complete NEDC cycle with regenerative braking.
A benefit with the integrated extended range concept is that the motor is acting on the front axle of the vehicle, which is a prerequisite to enable full regenerative power and not compromise vehicle stability.

Technology	Fuel consumption [l/100km]	Improvment [%]
Reference vehicle	7.3	0
Start Stop	6.6	9.5
Automated shifting	5.8	20
Electrical first gear (11kph)	5.1	30
1 - 2 gear shift at 15kph	5.0	31
1 - 2 gear shift at 20kph	4.7	35

Figure 4. Truck fuel savings with EREV concept

Conclusions
The transfer of a passenger car extended range concept to a delivery truck has been successful. The vehicle equipped with the extended range concept has comparable performance to the reference vehicle and significant fuel savings. The design uniqueness with electrical first gear and rolling start/stop provides most of the fuel efficiency increase. State of charge dependent shift speeds and regeneration is further adding to the fuel savings. Integrating the concept in a vehicle platform with an already efficient combustion engine by adding an off-the-shelf motor, the straightforward low cost powershift extended range transmission and reasonably sized energy storage ensures a realisable and affordable drivetrain solution with short development time and short time to market.