CHANGING THE PARADIGM

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ABSTRACT

The stronghold of the hydraulic industry is the cylinder. Nothing beats a hydraulic cylinder if it comes to compactness, durability, stiffness, or costs. In the field of rotational power however, hydrostatic drives have a strong competition from mechanical and electrical transmissions. Whereas hydrostatic transmissions are favoured for their power density and variable transmission ratios, the lower efficiency (especially at part load and break away conditions), higher noise levels and higher costs offset these strengths. As a result the mobile hydraulic industry is locked in the (albeit large) market niche of excavators, loaders and other off-road machines where hydraulic cylinders are a must.

The floating cup principle for hydrostatic pumps, motors and transformers can change this situation. Its high efficiency and starting torque, the low pressure and torque variations, the high power density and the low cost design enable the realization of a full hydrostatic drive train with in-wheel hydraulic hub units in all wheels. The floating cup principle also allows the realization of the Innas Hydraulic Transformer. Finally, the combination of in-wheel hydrostatic motors and hydraulic transformers creates the opportunity for making a 'hydrid': a hydrostatic hybrid vehicle having all the advantages of hybrid electric vehicles but without the cost increase of these vehicles.

KEYWORDS: Floating cup principle, hydraulic hybrid vehicle

1 THE UGLY DUCKLING

The fluid power industry has a rock-solid reputation. Hydraulic components and systems are able to deliver robust, reliable and compact solutions where mechanical and electromechanical transmissions even can't get close. The diversity of the applications is enormous as is the variety of hydraulic components. However, the fluid power industry also has a rock-solid reputation if it comes to component cost, noise and (lack of) efficiency. The specific production cost (in €/kg) of hydraulic pumps and motors can be up to an order of a magnitude higher than of automotive manual transmissions. The cost increases further if insulation or dampers have to be applied for noise attenuation. Also the poor efficiency causes higher investment and running cost. Although hydraulic systems have the inherent advantage of energy losses being carried away by the oil, a larger installed cooler capacity increases the system cost. Moreover, friction results in higher torque losses. Especially at start-up conditions this can result in a strong reduction of the breakaway torque of hydrostatic motors. As a result, larger and more expensive motors have to be installed, often in combination with an expensive 2-speed option.

On the other hand, the overall efficiency of hydrostatic transmissions is not necessarily worse than of electric motors, automatic gear transmissions or CVT's. Especially if the hypoid and differential gear can be avoided, and with that, the losses of these transmissions, hydrostatic transmissions might have a good chance for application in hybrid vehicles, even in passenger cars. After all, the most efficient and cost effective differential is the hydraulic T-joint. In case of a 4-wheel drive the advantage would even be doubled due to the complex mechanical configuration having three differentials (see figure 1). The limited energy capacity of hydraulic-pneumatic accumulators is not much of a concern either, since the size of the energy storage is largely determined by the power demand at low temperatures, at which conditions especially electrochemical batteries have a poor performance.

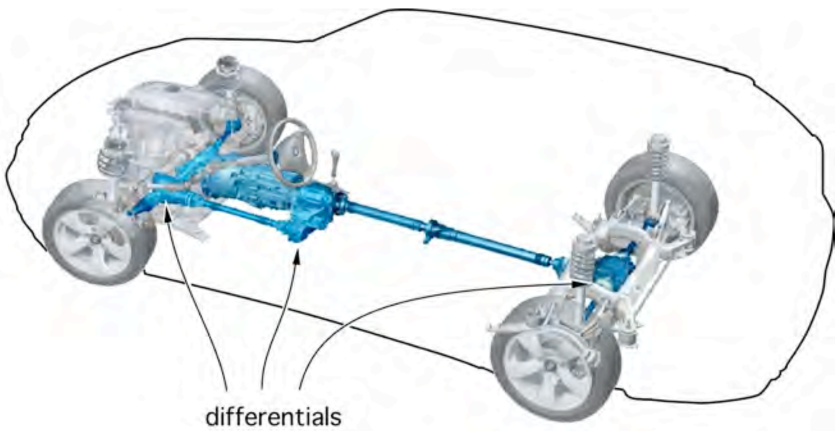


Figure 1: All-wheel-drive vehicle

This raises the question whether there is a chance for full hydrostatic transmissions in the automotive market? And what would be needed to improve the feasibility of these transmissions? This paper attempts to address these questions. The approach taken differs from several previous projects in which the hydrostatic system is considered to be an add-on in a parallel hybrid configuration such as in the system developed by Permo-Drive [1] or the hydraulic launch assist (HLA) from Eaton [2]. It also differs from the recent HHV-development of the Environmental Protection Agency (EPA) in the USA [3] or the latest generation of Cumulo systems developed by Volvo Hydraulics in Sweden [4]. These designs are serial hybrid systems with a hydrostatic unit connected to the differential gear of the rear axle.

This paper discusses the opportunity to completely eliminate the mechanical transmission, including the differential gear and the driving shafts. In this configuration, wheels are directly driven by means of hydraulic hub motors and all power distribution is achieved by means of hydraulic lines. The recuperation of energy during deceleration of the vehicle is considered to be an option: even without the use of energy storage the hydrostatic transmission has to be competitive with the mechanical driveline.

2. FLOATING CUP PRINCIPLE

The floating cup principle (figure 2, [5-12]) is considered to be a breakthrough technology for such an automotive hydrostatic transmission. The floating cup is a rather new axial piston principle featuring a large number of pistons and a low-friction behaviour. The principle can be applied in hydrostatic pumps and motors, both constant and variable, as well as in hydraulic transformers [5, 15].

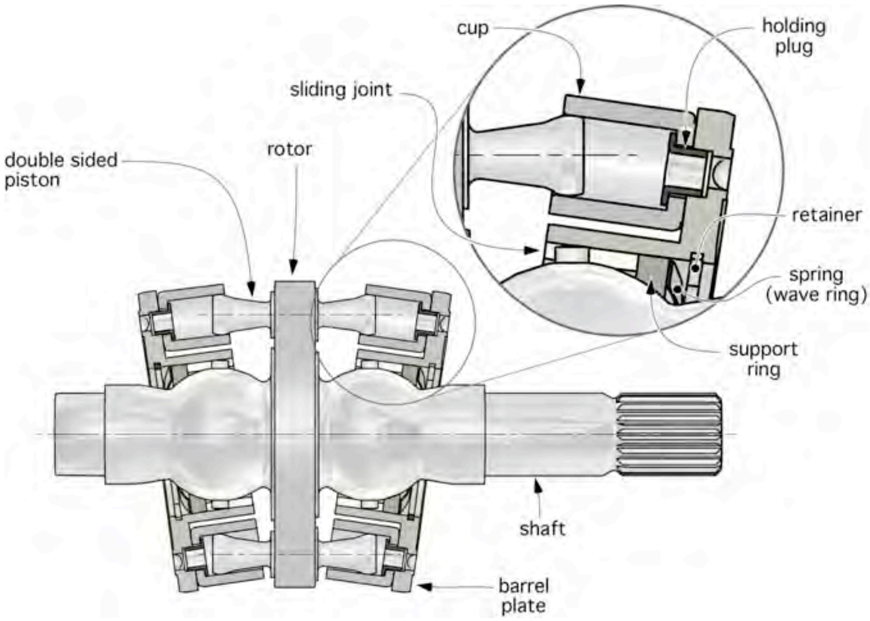


Figure 2: Rotating parts floating cup principle

The high number of pistons (about 3 times as much as in conventional axial piston pumps and motors) strongly reduces the torque variations. Combined with the low-friction behaviour this results in a high start-up torque.

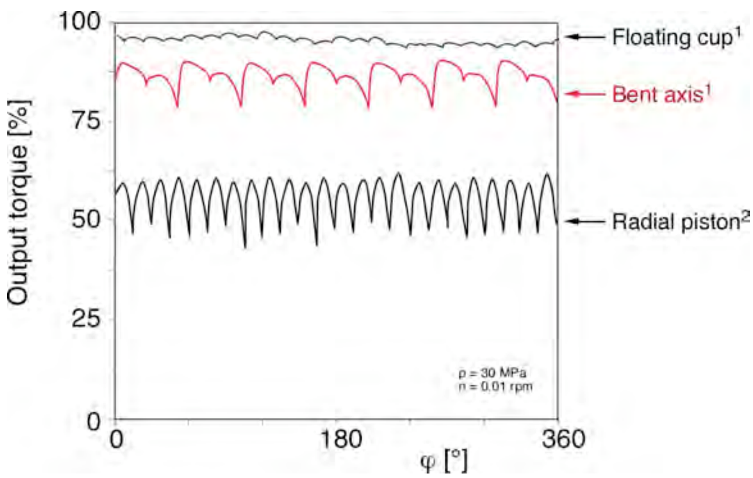


Figure 3: Start-up torque efficiency for 3 different constant displacement motors
[1]measurements IFAS Aachen [11]   [2]measurements Parker

Figure 3 shows a comparison of the breakaway torque efficiency relative to the maximum theoretical torque for a floating cup motor, a bent axis machine and a radial piston motor. The floating cup motor has by far the smallest torque variation and the highest starting torque.

An important characteristic of the floating cup principle is the small tilt angle of the barrel, being around 10°, which is much smaller than the 45° angle of some bent axis units. Despite the small barrel angle the floating cup principle is extremely compact and low-weight. For a range of displacement volumes figure 4 presents the weight of a series of floating cup machines compared to state-of-the-art bent axis and slipper type machines. The comparison has been made for the same rated pressures and speeds and assuming cast iron as the material for the housing. A more extensive analysis of the power density of the floating cup principle can be found in the literature [10].

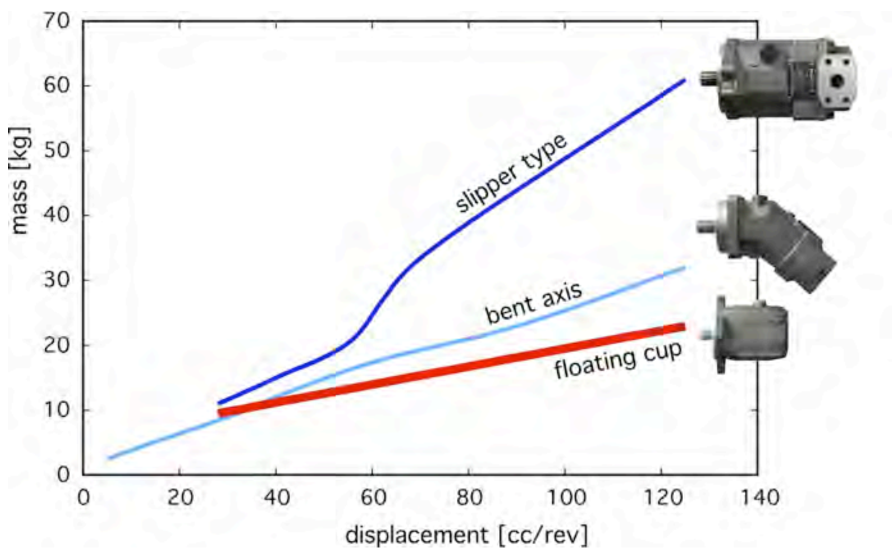


Figure 4: Weight comparison of constant displacement axial piston motors at equal pressure and speed rating

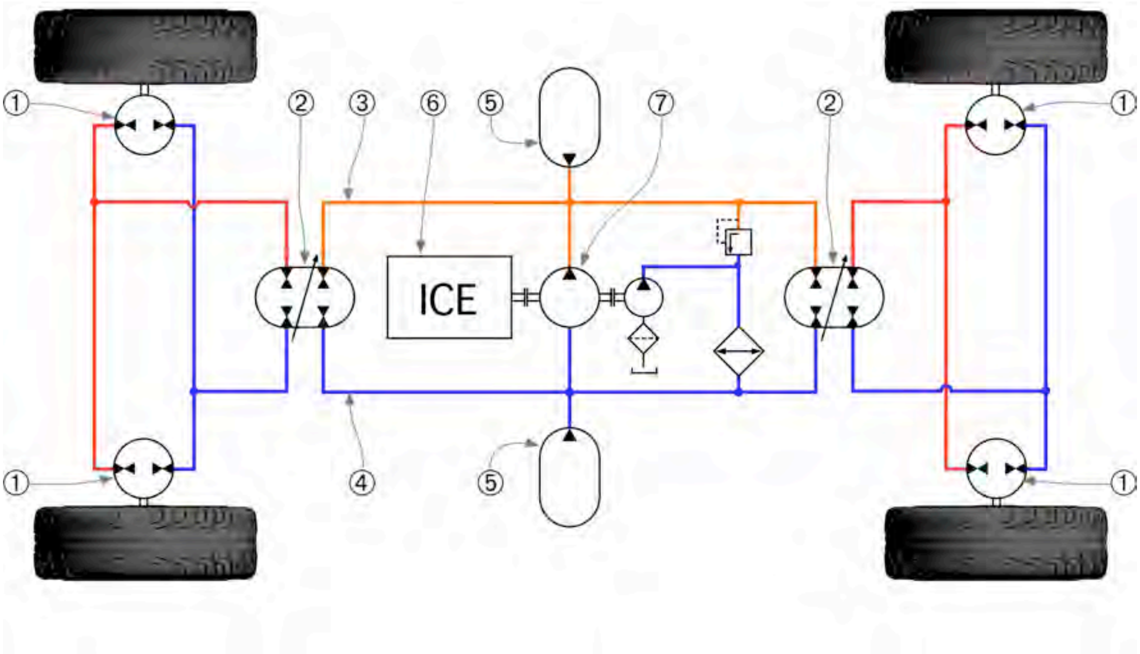
The comparison clearly shows the high power density of the floating cup principle. Furthermore the floating cup machines are shorter than the slipper type and bent axis machines, which is favourable for mounting the unit in the wheel hub.

The higher power density, the high start-up torque and the high efficiency of the floating cup machine all contribute to cost reduction. But above all the design of the floating cup principle is designed for low manufacturing cost. Although the principle is a multi-piston design having many components, the only critical tolerance is between each piston and cup. Because these are separate components, the cups and pistons can be sorted. This has the advantage that the production of the components itself does not need to be precise. Instead the sorting and matching process achieves the required tolerance, similar to the way that bearings, hydraulic lash adjusters and many other (automotive) components are manufactured. Furthermore, the components of the floating cup machines are designed as such that they can be produced by means of modern cost effective production technologies like deep drawing, stamping, fine blanking and sintering. These technologies have been applied for decades in the automotive industry, also for the production of automotive *hydraulic* components like chain tensioners, or variable camshaft driving systems.

3. THE 'HYDRID' VEHICLE

There are many reasons for eliminating the mechanical transmission in automobiles (and other road vehicles). Mechanical transmissions are characterized foremost by being inflexible in terms of transmission ratios, energy storage, power management and vehicular design. The design of the car is rather influenced by the position of the mechanical drive train components, especially if all wheels have to be driven. The manual gear transmission offers only a limited number of gear transmission ratios, whereas the continuously variable transmission or CVT suffers from a lower efficiency. New demands, like increased safety or reduced carbon dioxide emissions will put further pressure on the pure mechanical transmission.

To overcome the limitations of the mechanical transmission, in some vehicles the drive train has been expanded with the addition of electro-mechanical transmissions, electrical converters and electro-chemical batteries. All sorts of hybrid transmissions have been designed, ranging from micro-hybrid, like the GM Saturn Aura, to full or strong hybrid solutions like the Toyota Prius. In theory the mechanical transmission could be eliminated completely, thereby avoiding 'double trouble'. The limited power and torque density as well as the high costs of current electric motors, inverters and batteries however does not allow for a direct drive of the wheels. Instead a compromise is made utilizing the electric drive for urban stop-and-go operation and the stronger internal combustion engine for driving on highways and interstates.



① constant displacement hydrostatic pump/motor
② hydraulic transformer
③ common pressure rail: high pressure
④ common pressure rail: low pressure
⑤ hydraulic accumulator
⑥ internal combustion engine
⑦ supply pump

Figure 5: Lay-out of a 'hydrid' vehicle having a full hydrostatic automotive transmission

As an alternative, a full hydrostatic transmission is proposed (figure 5), completely avoiding the clutch, the mechanical transmission, the final gear and the differential gears as well as any shafts and constant velocity universal joints. In this hydraulic hybrid or 'hydrid' concept, each wheel has its own hydrostatic hub unit, having a hydraulic differential for the front and one for the rear 'axis'. The torque delivered by the hub units would be linearly dependent on the pressure level at the high pressure site, which in turn would be controlled by means of a hydraulic transformer.

The hydraulic transformer is coupled to a common pressure rail or CPR, similar to the voltage rail of an electrical grid. Hydraulic-pneumatic accumulators can be connected to the CPR-system creating the possibility for power management of the internal combustion engine and recuperation of the kinetic energy of the vehicle during braking. The CPR is the backbone of the system to which other hydrostatic loads can easily be connected. It also offers the opportunity for a closed centre steering system, thereby eliminating most of the high power and energy consumption of current hydraulic power steering systems. It would even be possible to connect a battery to the CPR by means of a small electro-hydraulic unit, creating the possibility for a larger amount of energy storage.

The application of hydraulic transformers has a number of advantages:

- The engine operation is separated from the load. In the hydrid system the engine has the function of a power station, supplying energy and power to the common pressure rail, whereas the hydraulic transformers control the wheel torque, fulfilling the function of a CVT. With that, the engine can become smaller and can be operated better in or near its optimum or 'sweet' point.

- One transformer can control two or even all four wheel motors. In the latter case the second transformer has to be replaced by a valve, which allows for the coupling or decoupling of the second axis. The hydraulic differential eliminates the need for an active load control for the left and the right wheel. It also offers a simple solution for creating a differential lock between the left and right wheel.

- The wheel motors can be simple constant displacement units. Although the hydraulic transformer creates some extra losses, this is compensated by the higher efficiency of the constant displacement units. The constant displacement units are also much smaller and lighter than secondary controlled variable displacement units. Furthermore, constant displacement units can be better optimized for low noise and pulsation levels than variable displacement machines.

- The transformer can also amplify the pressure [15], creating the ability of having a high break-away torque with relatively small wheel motors.

- The transformers allow for four-quadrant operation, creating the opportunity for recovery of the kinetic energy of the vehicle.

It has already been shown that a transformer can be built on the basis of a constant displacement principle [15]. This Innas Hydraulic Transformer or IHT has the transmission characteristic of a DC motor, being able to deliver high loads at low rotational speeds and high flows at low loads. In order to reduce the pressure pulsations and improve the low speed characteristics the number of pistons has to be maximized. The floating cup principle meets this demand.

The application of hydrostatic units being mounted in the wheel hub sets strict demands for the size, dimensions, weight and costs of these units. As already mentioned, the application of hydraulic transformers creates the opportunity for having simple, small and light constant displacement units. The application of a hydrostatic unit in all wheels further decreases the size and the weight of the units. This creates the opportunity for combining the need for high traction at low speeds, having all four motors in operation, and reduced oil flows at high vehicular speeds, thereby putting one of the hydraulic transformers in the neutral position. The all-wheel-drive (AWD) configuration has a much better traction distribution and traction control than a standard 2-wheel drive, but contrary to a mechanical AWD-configuration the two transformers give the ability of a full variable control of the torque distribution between the front and the rear axis. Different from most hybrid electric vehicles, the hydrostatic AWD-configuration also has the advantage of having energy recovery at all 4 wheels. Finally the elimination of the mechanical axis and constant-velocity joints also eliminates any turning angle restriction created by the mechanical wheel drive and gives the opportunity for a smaller turning angle of the vehicle, eventually allowing steering action on all four wheels.

4. HYBRID ELECTRIC VEHICLES

Hybrid vehicles, or better to say, hybrid electric vehicles (HEV's) have become a hype in the past 10 years, especially driven by the US-market. In 2006 more than 250.000 HEV's were sold in the USA, representing 1.5% of all light duty vehicles sold in the US in that year. Toyota is leading the market, having a market share of more than 75%. Many other car manufacturers have followed Toyota and have also introduced or are working on the development of hybrid vehicles. Without any exception these are all hybrid electric vehicles. Also in the heavy-duty truck market, almost all developments point in the direction of electric versions of hybrid drive trains. An exception is the project of the US environmental protection agency (EPA), Eaton and UPC in which a hydraulic hybrid delivery truck has been developed [3].

The driving factor behind the hybrid vehicle is to reduce fuel consumption and exhaust gas emissions, especially carbon dioxide. Most of the time, automotive internal combustion engines are driven in part load conditions. This has a detrimental effect on the efficiency of the internal combustion engine, in particular in the case of gasoline engines. According to German (in [16]) the fuel efficiency can be improved by 5 to 15% by means of engine optimization or downsizing. Furthermore a considerable part of the fuel is burned during idle operation. Some hybrid systems only try to eliminate or reduce the idle fuel consumption, resulting in an efficiency gain of 5 to 8%. Other, larger sized hybrid systems also try to improve the engine efficiency by assisting the engine in delivering extra power and traction at low speed conditions. In these so called strong or full hybrid systems, the engine size is reduced and the engine is operated more near the point of optimum efficiency. In full hybrid electric vehicles (like the Toyota Prius, see figure 7) the battery capacity has to be expanded in order to facilitate sufficient electric power. The larger batteries also have the advantage that part of the kinetic energy can be recuperated during braking. The fuel efficiency of the vehicle could then be increased further by another 5-20%. According to Green et al [17] the fuel economy of passenger cars can be improved up to 40% if a full hybrid system is implemented. Borgmann and Klüting [18] however expect a reduction of the fuel consumption of only 17-20%.

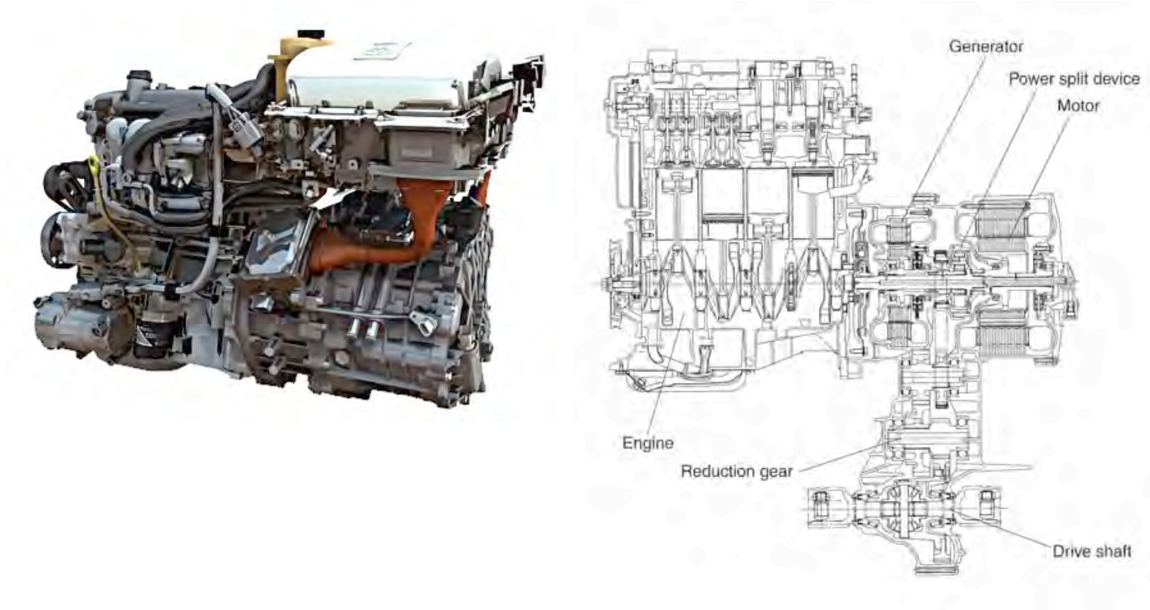


Figure 7: Engine and transmission of the Toyota Prius II. The photo on the left also includes the power control unit on top of the transmission. The batteries are not shown.

Finally the batteries can also be charged by means of the electricity grid (the plug-in hybrid electric vehicle or PHEV-concept). Although this does not improve the efficiency of the vehicle as such, the target of the PHEV is to reduce oil dependency of vehicles. For that the battery capacity has to be expanded considerably. Plug-in HEV's are therefore much more expensive than non-plug-in vehicles [19].

In recent years detailed studies [20-25] have been performed investigating the pros en cons of HEV's. Many reports show a significant reduction of the specific fuel consumption compared to standard gasoline cars, although in most studies the fuel consumption proved to be considerably higher than what was claimed by the manufacturers. Non-hybrid vehicles driven by an efficient diesel engine can achieve about the same mileage as gasoline HEV's, however with a much smaller cost penalty. The incremental costs of the additional electrical system are considered to be the most limiting factor for hybrid electric vehicles. Currently the Toyota Prius II costs US$ 7.600 more than a comparable conventional Corolla [26]. In Germany and France the cost difference is around €8.750. Even at large scale production the incremental manufacturing cost for a full hybrid electric vehicle are estimated to be between $1800 and $4600, depending on the size of the vehicle [27]:

Table 1: Incremental manufacturing cost for full hybrid vehicles at large scale production (US$ year 2000)

compact	2908
mid-size	1826
large pick-up	4603
mini-van	3492
SUV	4001

For the retail price of the vehicle this means a cost increase of around 20%. Full hybrid electric vehicles are also in the long run expected to be around 85 kg heavier than comparable non-hybrid vehicles [28]. The relatively low weight of the Toyota Prius is mainly achieved by applying lightweight body parts. There is also more energy needed for the production of hybrid electric vehicles. According to Toyota [29] it costs about 45% more energy to manufacture the Prius than a comparable gasoline car. A study performed by Weiss, et al [30] showed a similar result if only virgin materials were to be used.

In order to reduce the cost of hybrid electric vehicles, the manufacturing cost of electric motors, inverters and controllers, and batteries have to be reduced strongly, whereas at the same time the durability, abuse safety and efficiency have to be increased. According a recent industry forecast study [31] mild-hybrid vehicles will predominate the HEV-market in the future, offering launch assist and avoiding engine idling, but having limited or no capacity for energy recuperation during braking. Other studies claim a further reduction of costs for batteries, inverters and electric motors and generators [25, 27, 32]. On the battery site most developments focus on the Lithium-ion (Li-ion) battery, which has a higher power and energy density than NiMH-batteries as well as a higher efficiency. Another development is the development and application of super- or ultracapacitors [33]. The characteristics of these storage devices are very similar to hydraulic accumulators, having a poor energy density but a much higher power density than NiMH, Li-ion or other chemical batteries. Other advantages of the supercapacitors are the high efficiency and good lifetime (> 100.000 cycles).

5. ABANDONING THE MECHANICAL TRANSMISSION

A more radical approach in the design of (hybrid) electric vehicles is visible in some concept cars like the Toyota Fine (figure 7) or the Mitsubishi MIEV in which the mechanical drive train is completely eliminated.

Figure 7: Toyota Fine-X concept car having 4 in-wheel electric hub motors

In these concepts, all 4 wheels are driven by each an electric in-wheel hub motor. Siemens VDO (eCorner) and Michelin (Hy-Light) have announced concepts in which not only an electric wheel motor replaces the mechanical drive but also the suspension and brake functions are made electrical. The advantages of these all wheel drive concepts are obvious [34]:

- increased climbing performance
- increased traction performance
- improved moving-off traction
- more precise handling
- increased pay-load and trailer load
- improved crash resistance due to energy absorption by the whole power train
- identical roll steer effect under different weather conditions

In fact, these are the same advantages as for any other mechanical all-wheel drivetrain. But having a separate motor in each of the wheels would give additional controllability advantages, as well as improved maneuverability.

Current automotive transmissions are however hart to beat. Especially manual transmissions are rather efficient and low-cost. According to Lechner [34] a manual transmission has an average efficiency of 92-97%. Kluger [35] measured an average efficiency of 96.2%. (Locked) automatic transmissions and continuously variable transmissions have a lower efficiency, showing average efficiencies of around 85% [35]. All these values are excluding the final gear, differential and auxiliaries like power steering. Especially bevel gears can introduce substantial extra torque losses, having a maximum efficiency of around 92% [34]. This is especially of importance for four-wheel and all-wheel mechanical drive trains in which three differentials are being used to split the power across the wheels. The efficiency of manual gear transmissions is not much influenced by the gear chosen. According to Kluger [35] the efficiency varies between 92% (second gear) and 97% (forth gear). In automatic transmissions the gear influence is larger, having an efficiency of 89% in the fifth gear and only 70% in the first gear. Summarized, the total average drive-train efficiency between clutch and wheel varies between 78% for an all-wheel driven vehicle with automatic gearshift, to 90% for a simple manual transmission.

Figure 8 shows the influence of the gear on the total efficiency of the vehicle, including the efficiency of the engine. The low efficiency at low gear is especially due to the part load efficiency of the internal combustion engine. By means of adding an extra power source to the vehicle, the engine size can be reduced and the engine can be driven more near the point of highest efficiency.

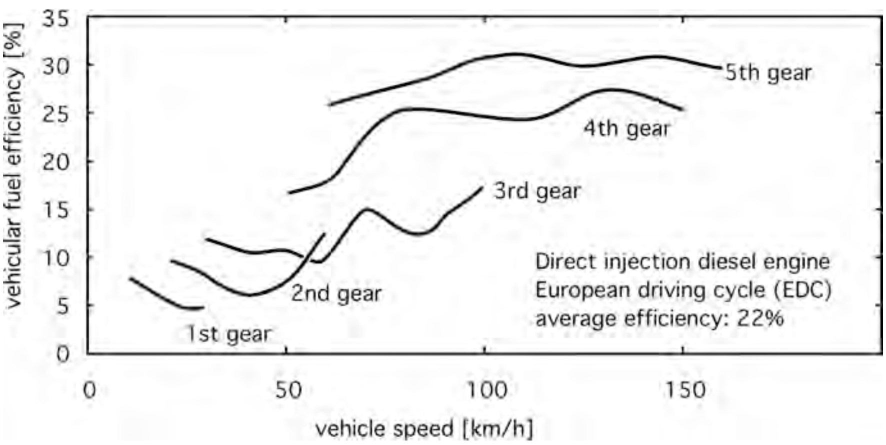
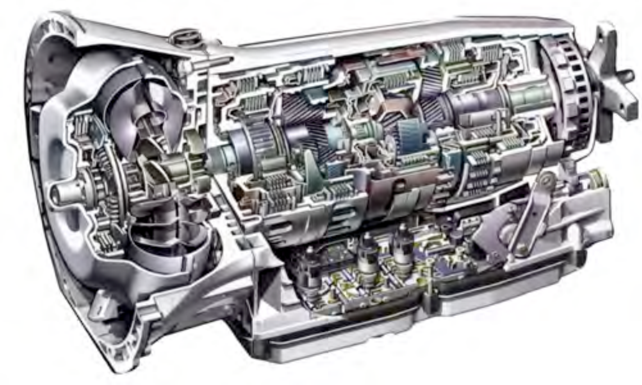
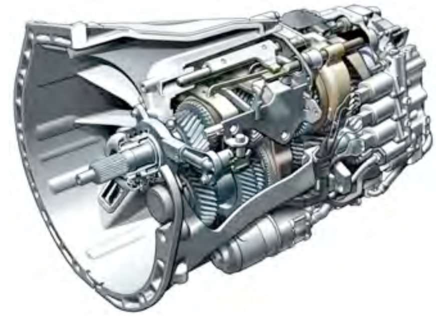


Figure 8: Fuel efficiency of a passenger car (Lenz TU Wien in [36])





automatic gear transmission manual gear transmission

Figure 9: Automotive gear transmission

The costs of transmissions are strongly related to the type of transmission, the maximum torque requirement and the number of gear steps [34]. In a recent study the US Environmental Protection Agency and FEV [3] have given specific manufacturing costs of automotive components. Due to their complexity, automatic transmissions are per unit of weight 21% more expensive than manual transmissions [34]. This than results in the following weight specific manufacturing costs for automotive transmissions:

Table 2: manufacturing cost in US$ (year 2000) per kg

Engine:	9.11 $/kg
Automatic transmission:	10.45 $/kg
Manual transmission:	8.63 $/kg

In another study [37] an average value of 10 €/kg has been used.

In an elaborate study [38] of Porche and the ULSAB (UltraLight Steel Auto Body, a consortium of 35 sheet steel producers from 18 countries) a detailed analysis of the weight structure of a Ford Focus is made. Combining the data from the ULSAB-study with information from the automotive industry results in the following weights and costs of automotive drive train components, assuming a specific cost of 10 €/kg:

Table 3: Drive train component mass and manufacturing cost (at 10 €/kg)

Component	Mass [kg]	manufacturing cost [€]
Gasoline engine (1.4 L, 55 kW)	148	1480
Diesel engine	184	1840
Manual transmission	64	640
Automatic transmission	92	920
All-wheel-drive manual transmission	156	1560
All-wheel-drive automatic transmission	184	1840

Any competitive alternative for the mechanical transmission should stay within the above constraints. The alternative should not weight more than around 60-180 kg, and the average efficiency should be at least 90% if compared to a manual gear transmission.

6. THE HYDRAULIC ALTERNATIVE

The hydraulic hybrid transmission shown in figure 5 complies with these requirements. For a mid-size vehicle, having an empty weight of 1300 kg, a maximum vehicle speed of 190 km/h, and a dynamic wheel radius of 0,31 m, the main components have the following dimensions:

Table 4: component size and characteristics of the hydrid drive train:

Component	max. power	size	max. pressure	max. speed
Internal combustion engine	55 kW			6000 rpm
Pump		17 cc/rev	350 bar	6000 rpm
Hydraulic transformers		36 cc/rev[1]	500 bar	3500 rpm
Hydraulic motors		30 cc/rev	500 bar	1620 rpm (@ 190 km/h):

[1] defined in pump equivalents

The size of the internal combustion is chosen to be able to deliver the same maximum power at maximum vehicular speed as for the original mechanical transmission. It is estimated that the engine size can be reduced from 84 kW for the mechanical transmission to 55 kW for the 'hydrid' configuration. In the hydrid transmission, the torque curve of the engine no longer determines the torque delivered at start-up (see figure 10). Instead the hydraulic motors deliver the maximum torque almost independent of the vehicular speed, up to a point where the hydraulic transformer demands the maximum power of the internal combustion engine. The smooth torque delivered by the floating cup motors also allow for smooth vehicle behaviour even at very low vehicular speeds.

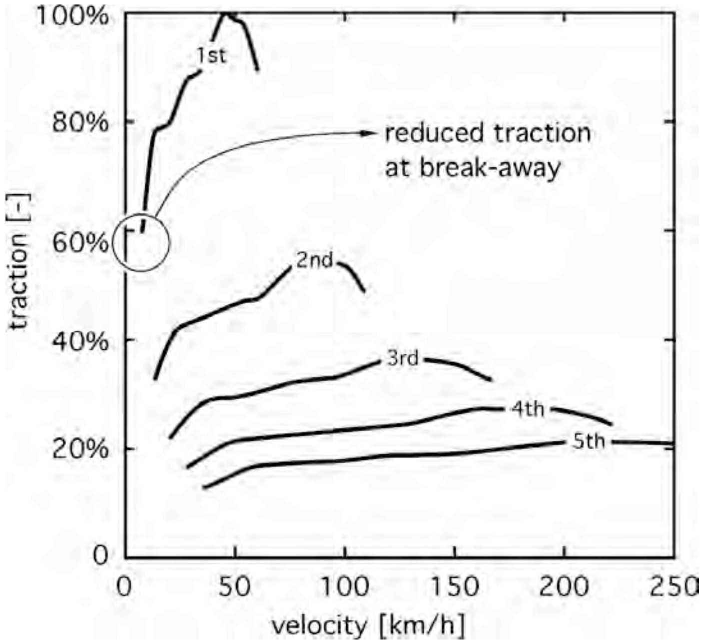


Figure 10: Traction curves of a mid-sized car at different gears, showing the reduced traction at starting or break-away conditions [34]

Each hydraulic in-wheel motor has a mass of about 9 kg. The weight can further be reduced if the hydrostatic units are integrated in the bearing structure of the wheel. Excluding the housing and the bearings, the rotating group of the wheel motor would only weight 3.5 kg. The hydraulic transformers are the heaviest components, having each an estimated weight of about 19 kg. The pump does not need to supply the full flow required by the four in-wheel motors at high vehicular speeds. The reduced torque requirement at high vehicle speeds will be met by the control of the hydraulic transformers, thereby reducing the supply flow to the transformers. If, for instance the motors only require a flow of 100 L/min at a pressure level of 100 bar, the pump only needs to deliver 33 L/min at 300 bar. This strongly reduces the size of the pump, resulting in a maximum displacement of 17 cc/rev, having an estimated weight of only 6 kg.

Constant displacement floating cup machines have a peak efficiency of 98%, hydraulic transformers of 96%. Idle losses will be avoided completely since the internal combustion engine only runs if needed for maintaining the pressure level in the high-pressure accumulator. As an option the accumulators could be enlarged to allow (at least for a part) for recuperation of the kinetic energy of the vehicle during deceleration. Accumulators can have an efficiency of 98% [39], much higher than the NiMH-batteries of current hybrid electric vehicles having an efficiency of 70-85% [25]. Like super-capacitors, the hydraulic accumulators are excellent devices for handling high power levels and have an almost unlimited cycle life-time.

7 BRINGING TWO WORLDS TOGETHER

The total weight of the full hydraulic transmission for a mid-size vehicle will be around 150 kg. Taking into account the lower weight of the smaller internal combustion engine and the weight of the replaced mechanical transmission, the net weight increase will be on par with current mechanical 2-wheel drive trains. For that the vehicle will obtain:

- an all wheel drive
- in-wheel motors in all 4 wheels
- high starting torque at break away conditions
- separate continuously variable transmissions for the front and the rear axes
- hybrid vehicle fuel economy benefits, without the high costs of electric systems
- including an option for energy recuperation on all 4 wheels
- full integration of other hydraulic actuators, like (close centre) power steering and active suspension systems

Unlike many electric components, hydraulic components and systems have an outstanding reputation if it comes to reliability, being able to resist high loads, large G-forces, humidity and dirt. Moreover they can operate in a wide operating temperature range. On the other hand the hydraulic industry has to learn from the automotive industry how to lower manufacturing cost by means of introducing mass production technologies into the design of hydrostatic components. Up till now the mobile machinery market has been separated from the automotive market. It is time to bring the two together.

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