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Tractor innovations and sustainability

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1. Introduction

The world production for tractors above 18 kW rated engine power is estimated to figure about 1.4 million units per year (2007) [1], representing a value of about 30 billion US $**.** If smaller tractors are included, the figure is again much higher, mainly in units due to high additional numbers produced in Asia. In the highly developed countries such as Europe and the USA rated power of standard tractors peaks to about 250 kW, **Figure 1,** and other concepts even above 400 kW. Main objectives of agricultural mechanization by tractors are

- increased productivity
- decreased production costs
- sustainability (resources, environment, human factors)

Design of tractors for sustainability results in the following scope of duties:

- to save material by lightweight design
- to save material by design for recycling ability
- to save energy by new component technologies
- to save energy by intelligent tractor-implement process management
- to use alternative fuels and liquids for engine, transmission and hydraulics
- to monitor "health condition" of engine, transmission and hydraulics
- to protect the environment
- to secure health and safety for driver and surrounding people

2. Sustainability and tractor first costs

Many farmers worldwide may be interested in more sustainable tractors but only a few may accept additional first costs. This is a problem mainly in those countries in which tractors of lower technology levels are required [2] but sometimes also in developed countries. Some innovations in this field have been initiated therefore by government acts or assurance demands.

Examples for introductions of this kind are

- roll-over protection structures (ROPS) to reduce overturning accident fatalities
- noise isolated cabs to reduce inside noise level and prevent ear damages
- a plurality of measures to reduce exhaust gas pollutions to protect people and environment.

Most regulations have been accepted later by the customers, for example those for the mentioned ROPS and limited noise levels at the driver's ear.

However, the third listed example is still on the way - and is not yet very popular because of again high additional costs. It requires tremendous efforts in development and integration of innovative Diesel engines and their aggregates for agricultural tractors in order to meet the present and future targets – mainly those of Europe and the USA.
This means high development and production costs not only for the engine but also for its integration and often also for a completely new tractor design.

3. Saving material by design and adequate design verification

3.1 Lightweight design

A tractor needs weight for developing pull. But at the same time, a limited weight is required to enable high pay loads such as heavy mounted implements, seeds, chemicals etc. Heavy pull operations can be realized by ballast. A Western Europe tractor should carry a payload equal to about 80% of its net weight. As the maximum weight is usually defined by the load capacity of the tires, light weight design is a strong general demand by the customer. At the same time it is also an upcoming strategy of sustainability. In many cases, it even saves first costs as well.

Engineering challenges of light weight design are stronger than most people think, as the design and verification process must be carried out under strong time pressure. This requires high sophisticated time saving procedures such as

- load-stress analysis for all relevant parts and components
- field measurements and definition of representative load spectra [3]
- random load fatigue analysis using stress analysis and load spectra [4]
- verification of life time simulations by accelerated automatic lab tests [5]
- final field tests under accelerated conditions

Computer programs can support analysis and lab test data handling considerably. Realistic accelerated life time predictions and verifications require outstanding engineering skills. The companies try to reduce the field tests in favor of lab tests if ever possible for two reasons: to limit labor costs, to save time and to secure standardized test conditions. Field tests cannot be eliminated completely, but can be improved. John Deere has, for example, started to run them automatically.

3.2 Recycling

Recycling seems to be an important principle of long term material saving, but is at the same time not driven by customer interests – any extra costs would even more or less be refused. Metallic recycling creates no major problems. But recycling must also be secured, for example, for plastics, electronics, liquids and other more difficult materials by adequate design. The content of these materials is continuously increasing for tractors. Recycling regulations for tractors are not known by the author, but a certain orientation from the car industry can be observed – mainly for recycling of plastics.

4. Saving energy by design

The present world energy balance is by far not sustainable. Consumption is tremendously higher than production as limited resources are used such as crude oil, natural gas, coal or uranium. Mainly crude oil is going to run shorter soon. Its price will again rise until balanced by alternative energy prices – in some cases supported by subsidies. A new low cost type of energy is not to be seen for decades. This means: energy saving will be an issue with increasing importance for both, reasons of economy and sustainability.

4.1 Saving energy by improved tractor components

Regarding energy transfer, the following tractor components are addressed in this chapter: the engine with auxiliary components, the drive transmission, the PTO line, the hydraulic system and the ground drive.

Diesel engines with direct injection are in general use for tractors, even in countries like India and China. Their energy efficiency is defined by their specific fuel consumption, usually expressed in g/kWh and plotted as fuel economy maps versus torque and speed in diagrams [6]. These maps represent the efficiency level clearly. Updated Diesel engines for tractors above about 50 kW should achieve values of about 200 g/kWh in the best point equivalent to best efficiencies around η =42%. This very high level requires engine speeds not much above 2000 rpm which are common in most cases. It is interesting that higher rated engine speeds would reduce the tractor first costs considerably, but fortunately most farmers rate an outstanding fuel economy higher. Further improvements are very limited due to thermodynamics and emission regulations (see chapter 6.1).

Regarding future potentials for energy saving Diesel engines, I see a strong "design for efficiency" borderline at about 190 g/kWh (η = 44%) for the best point within the fuel economy map. At present, even 200 g/kWh are a huge challenge regarding the conflict with the NOx emissions.

Fuel cells may replace the Diesel engine in the far future, see chapter 5.2.

Transmissions are in use with both, stepped and infinitely variable ratios. Efficiency levels for stepped transmissions with and without power shift figure mostly above 85% from flywheel to the rims under full load within the main working range of 4…12 km/h [7]. The main principle for achieving this level is to design for dry sump lubrication with extra pump and intelligent automatic oil level management. Synthetic oils offer further improvements, but are very expensive. Recent research results of TU München indicate a considerable reduction potential for gear wheel losses in case of strongly reduced teeth heights [8]. However, durability would require an increased space.

Infinitely variable drive transmissions (CVTs) had no success over decades because of poor efficiencies [9]. Hydrostatic variators "direct" (without power split) enable full power values from flywheel to the rims of only about 75% in the best point. Proposed "visions" of electric variators "direct" offer almost the same level, which has proved to be not competitive for most agricultural tractors - excepted very small compacts [9]. An efficiency target for tractor CVTs has been developed by the author [10] – **Figure 2** – and has been applied for many CVTs, also for the development of the first mass produced hydrostatic power split transmission Fendt "Vario" (production from 1996). This diagram was at that time a very strong demand, which was commented by some experts to be unattainable, as its level represents almost that one of a stepped full power shift transmission. Fendt was able to meet this target, which required in addition to the power split principle also the basic innovation of 45 degree variable bent axis hydrostatic units, a low energy charging system and a highly sophisticated low energy control system. The target of Figure 2 is still a very strong demand but generally accepted for tractors above about 100 kW. Potential for energy savings with CVTs are outlined more in detail by [9].

The PTO line is usually very well designed regarding losses as there are often only one or three gear wheel engagements. High efficiencies are extremely important as the rated PTO power is the basis for the tractor price in several countries. A CVT-PTO could offer a further important grade of freedom for the tractor-implement management system. It would made it possible to disconnect engine and PTO speeds and thus open new areas of energy savings. This vision is not new – main problems to be solved are the limited space and the required very high efficiency level.

The hydraulic system of agricultural tractors could be improved in energy efficiency by the introduction of "load sensing (LS)" systems, first presented by Allis Chalmers (USA) in 1973 [7] and brought to a breakthrough by Case IH (USA) in 1987 [7] with the new Magnum tractor line.

Regarding losses, the basic idea was and is to enable a stand-by position of the pump, if no hydrostatic power is demanded. This requires variable displacement units with low idling losses, low first costs and closed centre valves. The control value is not the load pressure (as the name may suggest). It is the pressure drop Δp at the operational valve which makes the required oil flow independent from the load pressure and the engine speed.

These LS systems have been introduced for high tech tractors above about 60-80 kW replacing the former gear pump hydraulics. In spite of this progress efficiency of the energy transfer to implements is still not satisfying because of long pipes, the mentioned Δp losses, uneven flow speeds (high number of connections) and high flow speeds (due to poor pipe and hose diameters).

Further innovations for increased efficiencies and improved dynamics seem to be possible, for example by means of the following technologies:

- reduction of the control value Δp (today often 20-30 bar /2-3 MPa) by electronics [11]
- reduction of pipe pressure losses on the way from the pump to the implements
- recuperation of energy, for example during front end loading [12]
- increase of the nominal pressure from 200 to 250 bar (20 to 25 MPa)

The last item could be realised with existing pumps and would be a large step forward, but is unfortunately restricted by a very large number of existing implements and connecting hoses limited to 200 bar (20 MPa). Another progress being widely applied recently is the meanwhile standardized "power beyond" principle. Additional direct working pipes from the tractor pump to the implements bypass the tractor valves - useful in case of operational valves on implements. System configuration and coupling interfaces are standardized by ISO 17567.

An *electric PTO of max. 5 kW* has been presented by John Deere 2008 to replace hydraulic power transfer more efficiently on 7030 tractors, **Figure 3**. This first integrated high voltage electric power grid for tractors incorporates a 20 kW generator. The net reduces also losses of engine aggregates such as generator, cooler fan, air compressor, water pump and AC compressor. The conventional 14V generator, well known for very low efficiencies, is eliminated. Efficiency benefits are not only achieved by electricity but also by intelligent closed loop speed control strategies.

Efficiency of the *ground drive* is of interest mainly in the case of pulling implements off-road. The losses are generated by rolling resistance and travel reduction (slip). They are usually very high, as the following typical example demonstrates. If we assume for a stubble field with average moisture conditions for the rear axle of a rear wheel driven tractor a net traction coefficient of 0.46 at 19% slip and a rolling resistance coefficient of 0.08, we can calculate traction efficiency for the rear axle to be $\eta_T = 0.46/0.54 \cdot (1.00\text{-}0.19) = 0.69$. Considering the amount of push forces for the non driven front axle, efficiency of a complete 2WD tractor declines to about 60% under these conditions. This underlines the efficiency gain of 4WD, which gives for off-road traction in Western Europe for typical soil conditions often a benefit of about 15% over 2WD tractors. Further gains are possible by tire inflation control, see chapter 6.3. Low values reduce rolling resistance and increase net traction in most off-road operations [13, 14]. A vision to increase the traction efficiency level even above that of conventional 4WD tractors has been displayed by the new concept study TRISIX of Fendt (2007), which is based on a co-operation with the authors' department at TU München [15]. All three axles are driven, **Figure 4**. The multi-pass effect [7] of the third axle improves total traction efficiency under the mentioned conditions again by about 7%.

Figure 5 summarizes the traction benefits of 4WD and 6WD over 2WD for typical field conditions. The feared power hop, which can be a serious problem of 4WD [16], was not observed in any situation of the TRISIX test program, which has by now been going on for 2 years.

4.2 Saving energy by intelligent tractor-implement management

The new International Standard ISO 11783 is not only large but also great. It defines for the first time the internal communication between the tractor components linking it with the external tractor-implement communication [17]. This is done by two BUS systems, **Figure 6** [18, 19].

The superior objective is to unburden human control by automatic closed loop control and to improve at the same time the complete process including sustainability aspects. The vision was and is, to create a worldwide standard for the BUS specifications and all important interfaces. The dream is, that one day every high tech tractor can communicate with every high tech implement. The reality is that many tractors and several implement manufacturers already offer this technology. One important step will be presented at Agritechnica ’09: John Deere realizes the “Implement Controls Tractor” principle in co-operation with implement manufacturers. The basic principle was an essential part of a Ph D thesis 6 years earlier [20]. Further progress will take place, concentrated on the upper technology levels as defined by [2].

5. Alternative fuels and working liquids

5.1 Bio-fuels

The Club of Rome states, that the long term energy supply is one of the key questions for the future development of mankind and that renewable fuel will become one important alternative.

The introduction of pure rapeseed oil as Diesel fuel was the subject of broad research and many engineering approaches worldwide. It was not very successful until now. One-tank and two-tank concepts have been in competition. Finally the German Deutz AG was the first company worldwide which was able to offer mass produced engines with full warranty burning rapeseed oil. They have been used in special models by Deutz-Fahr and Fendt since 2007. A two-tank system changes fuelling between conventional Diesel and rapeseed oil automatically according to the engine state. High loads offer good conditions for rapeseed oil burning, while engine starting, idling and low loads do not. The public introduction of “Biodiesel” (also for blends) was promising and booming for some years in Europe, but experienced a strong recession recently because of three reasons:

- introduction of fuel tax on Biodiesel
- decline of crude oil world market prices in 2009
- modified political priorities due to cereal shortages on the world market in 2008.

Political trends now favor a second generation of “Biomass-to-liquid (BtL)” technologies as fore-cast by the Club of Bologna [21]. These fuels can also favor reduced engine emissions as stated by [22]. Production costs are still too high but may become competitive within the next decade.

5.2 Fuel cells

The long term vision is to use hydrogen fuel cells with the following main benefits:

- very high power plant efficiencies
- zero emissions
- efficient electric CVT drives (no generators)
- low noise levels

The first commercial German passenger cars are announced for "probably 2015" – a forecast for tractors has been formulated as "in series production not before 2022" by [9]. Many innovations are still necessary to overcome the three main problems of high first costs, inadequate durability and hydrogen storage. The last mentioned problem could be solved for a certain period by processing hydrogen on board from liquid fuels. Overall efficiency of such a system suffers but is still little above that of the best Diesel engines. As the power output could be used to drive electric motors and aggregates directly (without generator), additional efficiency benefits can be expected by a simplified drive line.

The final vision is the fuel cell operated by hydrogen. Efficiency could be again improved and exhaust emissions are completely avoided as the output is pure water. This final stage has been addressed by a prototype developed by CNH with support of FIAT as presented at SIMA fair 2009, **Figure 7**. The complete vision is that the farmer produces the hydrogen on-farm by himself.

5.3 Alternative working liquids and condition monitoring for engine, transmission and hydraulics

The main objectives of *alternative working liquids* are

- to become independent of the limited crude oil reserves
- to save the environment by a high grade of biological degradability
- to offer flatter viscosity-temperature characteristics

Regarding the complete specifications of alternative fluids, no functionality should be below conventional liquids. Degradability is mainly important for hydraulic fluids as hydraulic systems have the highest risks of spill – for example during coupling of implements. Broad research activities with public support have taken place over many years [23].

The main objectives of *condition monitoring* are

- to change working fluids only if their functionality has declined below a specified limit
- to use the working fluid as an information carrier for the "state of health" of the system.
- to collect data for future system design

New sensors have been developed to pick up working fluid characteristics [24].

6. Environment protection

The main objectives of environment protection for tractors are to limit or prevent

- exhaust gas emissions, mainly NOx, HC and particles
- CO_2 emissions
- other damaging emissions
- physical damaging of soil

Emissions of Diesel engines and soil loadings by heavy machinery are the most addressed items.

6.1 Emissions

Exhaust gas emissions of Diesel engines for tractors and other mobile machinery have been in the foreground in the developed countries for about one decade now. The pressure on their reduction was clearly initiated by governmental acts – mainly in Europe and North America. The required limits are reduced stepwise and related to performed kW hours – in Europe based on EU regulation 97/68/EG using load cycle C1 of ISO 8178-4, **Figure 8**. The stages I and II could be fulfilled with modifications of existing engines. However, for meeting step III A, highly sophisticated new designs for engine heads, fuel injection systems, cooler packages and other elements had to be introduced – often requiring a completely new design of the entire tractor. Specific engine costs thus increased in the highly developed countries considerably. The further limits are similar to those of the US Tier regulations. Stage IV requires for tractors above 130 kW rated power for example NOx < 0.4 g/kWh, HC < 0.2 g/kWh , CO < 3.5 g/kWh and particles < 0.025 g/kWh – almost clean air. The strong reduction of particle content with the next stage IIIB could be met by particle filters. Adequate technologies are by now available from passenger cars and trucks. But particle content can also be reduced indirectly with SCR systems, **Figure 9** [25].

The following engine technologies are available in order to combine low emissions and low fuel consumptions:

- 4-valve cylinder heads with central injection
- high injections pressures up to 2,000bar by CommonRail systems
- piezo actuators for improved timing of injection
- turbo chargers with VTG (Variable Turbine Geometry)
- "turbo compound" engines feeding back energy from the turbo charger to the crankshaft
- cooled exhaust gas recirculation EGR
- SCR-technologies (Selective Catalytic Reduction of NOx by urea)
- particle filters
- low friction synthetic engine oils
- infinitely variable speeds of fan drive and water pump
- engine oil pumps with infinitely variable flow output
- thermo-electric generation by hot exhaust gas
- infinitely variable electro-hydraulic valve timing

Most of these new technologies have been applied for tractors recently or are in the phase of introduction. Because of high first costs no manufacturer combines at present all these technologies in one engine. **Figure 10** shows a turbo charger with adjustable angle of the turbine guiding vanes. This has not been developed primarily for emission control as the angle control offers improved torque characteristics and lower specific fuel consumption, **Figure 11**. But it can compensate for losses in fuel economy due to other measures such as smooth injection timing (NOx) or particle filters. In addition to all these technical improvements Diesel fuel has been purified to an extremely low sulphur content, in Europe < 0.005 % (in weight) according to European Standard EN 590. The final aim is to introduce hydrogen technologies, see chapter 5.2.

Emissions of fluids for tractor components address mainly engine oils, hydraulic oils, grease, cooling fluids and air conditioning working fluids. A plurality of degradable fluids and greases has been developed. Environmentally friendly air conditioning and cooling fluids are in general use. The highest risk of leakages can be seen for hydraulic working fluids. **Figure 12** shows a small container below the couplers for collecting coupling spill and for preventing soil pollution. In spite of this, bio-degradable oils are required for the tractor hydraulics, if working in declared water protection areas.

Biologically degradable oils are more expensive than conventional ones. Vegetable oil based hydraulic fluids offer excellent physical properties for lubrication but poor chemical properties (limited temperatures, high sensitivity to water contents). Degradable synthetic hydraulic fluids offer a much better chemical stability but are still sensitive to water contents and again more expensive. According to experiences of a large supplier in Germany, importance of bio-oils for tractors remained low. Many farmers in Germany prefer universal oils for engine, transmission and hydraulics in order to simplify storage and oil change - typically STOU 10W-40. Bio-degradable types of this kind are not common.

6.2 Use of heavy metals

Lead, mercury, cadmium and chromium VI are addressed by EU directive 2000/53/EG to be avoided for future passenger cars and light commercial vehicles. Tractors are not included, but consequences are expected as many standardized parts are commonly used also in tractors such as screws (with ChromIV compounds against corrosion) and batteries (with lead).

6.3 Physical soil protection regarding wheel tractors

The soil can be called the most important production factor in agriculture. The soils belong to those resources which are limited on this planet.
The larger the tractor the more striking are the tire dimensions. This has the following mathematical background: the tractor volume and thus the weight increases with the length scale factor λ^3, if the same materials are used while the tire contact areas increase by only λ^2. If the tires are enlarged only by λ, the mean contact pressure would increase by $\lambda^{1.5}$. Rempfer reports in [14], that the weight increase of a higher number of tractors could be described by a regression with the variable $a^{3.11}$ with a as the wheel base. The consequence is, that enlarged tractors need tire dimensions to be increased disproportionately stronger, **Figure 13.**

The first expression of this rule which I found has been given by Galileo Galilei in 1638 [26]. Later on, several basic publications confirmed this coherence.

Relationships between tractor and soil parameters are summarized by **Table 1**. Regarding yields the soil porosity is a very important parameter, as sustainable biological activities need values of about 42 to 48 % [7]. If compaction by traffic reduces them, porosity can be recreated by soil cultivation. For subsoil tillage, it has to be considered that the natural soil structure is disturbed for a certain period of time. During this recreation heavy traffic must be avoided.

According to Figure 13, the three most important *tractor* factors affecting soil compaction are

- wheel load
- tire dimensions
- tire inflation pressure

Regarding the *soil*, the by far most important parameter is the moisture content.

Facing the development of large tractors and self-propelled machinery, the German government felt, that sustainability of agricultural soils could be risked. A strong *Federal Soil Protection Act* was released 1998 by the German government challenging mainly the development of the undercarriage of large agricultural machinery [27]. This was the main reason that a group of German experts worked out a new VDI Guideline for traffic ability of soils used for agriculture [28]. Basic recommendations are developed to support “good practice techniques” for soil protection. It was confirmed, that the tractor is mostly not the critical vehicle as its wheel loads, even for very large units, lie mostly below those of heavy large self propelled harvesters.

The VDI Guideline uses among other influences the mean contact pressure and the soil condition to evaluate the soil traffic ability, **Figure 14**.

A very dry soil with a low susceptibility to compaction can carry mean pressures up to 2 bar (200 kPA) while a very humid soil with a high susceptibility to compaction is overloaded with mean contact pressures exceeding 0.5 bar (50 kPA). The lowest mean contact pressure of a tire is usually given with the lowest tire inflation pressure, **Figure 15** [29]. It is at the same time favorable to use the tire load capacity at the given inflation pressure to achieve the minimum contact pressure by the point of “low correct”. The consequence is to reduce the tire inflation off-road to the lowest value as specified by the tire manufacturer. Low values are however not allowed for on-road operation as specified tire loads decrease considerably with the operational speed. It can for example happen, that the optimum inflation for field work is 0.6 bar (60 MPa), but the required inflation pressure for on-road with mounted implements must be 1.5 bar (150 MPa) to meet tractor homologation data.

This conflict, which is demonstrated by **Table 2**, can only be solved well by tire inflation pressure control offering an important potential for sustainable soil protection [13, 14]. On-land ploughing can reduce the depth of the "Söhne" pressure bulbs and thus also compaction, **Figure 16**. It is now easier to implement than in the past due to modern automatic tractor guiding systems.

7. Sustainable health and safety

A high number of regulations exist in the developed countries to protect the driver - mainly in Europe and North America. In order to simplify governmental acts, standards have been developed for the test procedures. The typical trend of the past decades was to move from the national to the international level by ISO standards. A top down introduction of ISO standards to national levels makes much more sense than the opposite procedure and offers also access to the state-of-the-art in this area for less developed countries. ISO 26322-1 contains, for example, a survey on important safety aspects and standards for tractors [30].

Some typical subjects being addressed by sustainable health and safety for the driver are as follows:

- overturning accidents
- sound level at drivers ear
- sound level at bypassing
- access to drivers' seat and exit
- drivers' seat – dimensions, vibrations and seat belts
- dimensions of drivers' operating space, field of vision
- instructional seat or fully integrated passenger seat
- doors, windows, emergency exits
- control elements and related symbols
- brake performance, coupling device, PTO safe guards and clearance zones

Huge progress has been achieved in the highly developed countries within the recent decades. One very positive example is the general introduction of *roll over protection structures (ROPs)* with a drastic reduction of fatalities, **Figure 17**. While their number was about 180 per year in West Germany before 1970, the ROPs (today mostly integrated in the cabs) could finally reduce them by about 96% figuring now in the unified Germany (in spite of a latger tractor fleet) only a few fatalities per year. The standardized test energies, based on broad research results thus meet the practical conditions of overturning with a very high probability. There are even only extremely few technical innovations in modern technical systems resulting in such an outstanding progress. This should be a high motivation for all those countries in which ROPs are not yet in general use.

High *sound levels at the drivers' ear* have damaged the hearing of millions of farmers. The huge problem is that hearing losses cannot be restored. I myself had this experience, I got such a damage during the 1950s on the tractor of our own farm when the full power noise level figured up to 100-105 dB(A) during tillage for hours and days. My doctor identified the hearing losses 50 years later.

The first Nebraska test of a "quiet" cab was carried out in 1972 resulting in 82.5 dB(A) for the cab of a John Deere 4430 under full load – at that time an outstandingly low value. The first mass produced quiet cabs in Europe were launched in 1976 by Fendt and IHC, 1977 by Deutz. An OECD level of about 85-90 dB(A) was typical until about 1980. As these are maximum values, the weighted mean effective noise levels of practical field work have been rather 80-85 dB(A).

However, research results pointed out, that productivity and comfort of the driver could be again improved by lower noise levels. So further reductions became popular, **Figure 18**. Typical values of OECD levels at the drivers' ear stagnate now at about 74 dB(A), one company advertises a value of only 69,5 dB(A). One principle of success is, to prevent any mechanical connections between the cab and the tractor chassis. This is one reason for very early "drive-by-wire" solutions for tractors. Also this important progress of "sustainable health" should be a motivation for all those countries, in which quiet cabs are not yet in general use.

The *bystander noise level* of agricultural tractors is still relatively high as the related traffic regulations are still moderate for tractors. **Figure 19** represents the state of 1998 [31] but the author expects no major improvements for 2009. The meanwhile achieved improvements seem to be compensated by the continuously increased rated engine power. The more power the more noise.

The potential of environmental noise reduction was investigated at TU Munich in the 1980s resulting in the presentation of the Munich Research Tractor Feb. 25, 1988, **Figure 20** [31]**.** Its bystander noise level was like that of a Diesel passenger car and is probably even today the lowest of all commercial tractor models. The vehicle is still ready for operation, now under care of the German Museum of Agriculture at the University of Hohenheim. One of its design messages was that a low environmental noise level requires three typical design measures: a soft suspended engine (interrupting body noise), a well designed engine capsule (interrupting air noise) and a low transmission noise level, which can be achieved, for example, by a very stiff case. A soft engine suspension leads to a replacement of the classical block chassis design by frame concepts as have by now been introduced in many tractor models.

Other examples of improved health and safety for the driver could be listed. Because of limited space of this paper, let me close with one final case. In order to optimise a safe and comfortable operation of control elements, the "arm rest" principle with "control by wire" is going to become a general standard concept for the upper level of comfort demands, **Figure 21** [32].

Regarding future developments in the high tech markets, I see a major potential for improvements of health, safety and comfort issues in the following areas: further improved communication interfaces, increased safety of electronics, increased safety against manipulation, introduction of automatic brake management, further introduction of electronic assistance technologies, further reduction of vibrations, improved implement coupling processes, warning systems for overlooked persons (for example children in the visibility shadow), introduction of seat belts and others.

8. Summary and conclusions

Sustainability is an important aspect of tractor development, mainly in the more highly developed countries. As a higher grade of sustainability mostly increases the first costs, innovations are sometimes initiated by regulations but later on often accepted by the customers. The author defines the main objectives of sustainability for tractors as follows: to save material by intelligent design with adequate design verifications, to save energy by efficiency-improved tractor components and intelligent tractor-implement management, to look for renewable fuels, to protect the environment by degradable working fluids, reduced emissions and soil protecting tire contacts and to protect the driver by a long list of technical measures regarding his health and safety. Typical developments and experiences of the high tech markets are described – also as a motivation for less developed countries. However, also in countries like Europe or the USA there is a further potential of sustainable tractor design – recent innovations have been on display at EIMA 2008, SIMA 2009, and are now also presented at Agritechnica '09 and awarded by the DLG.

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Tables and Figures

Figure 1 - Large standard tractors, left Fendt 900 and right John Deere 8000 line. *Source: Courtesy AGCO-Fendt and John Deere.*

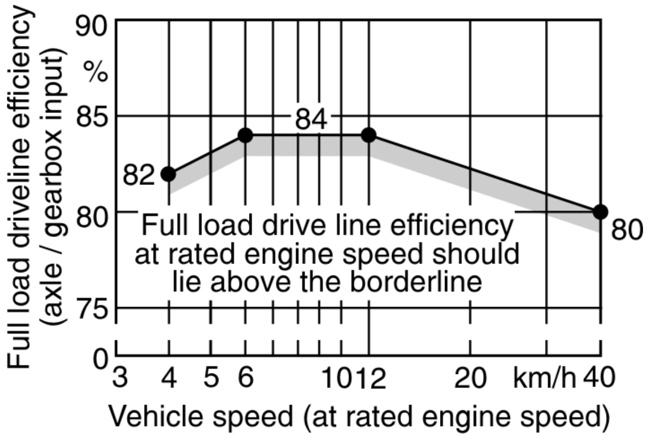


Figure 2 - Efficiency target for CVTs of larger tractors above about 100 kW. *Source:[10].*

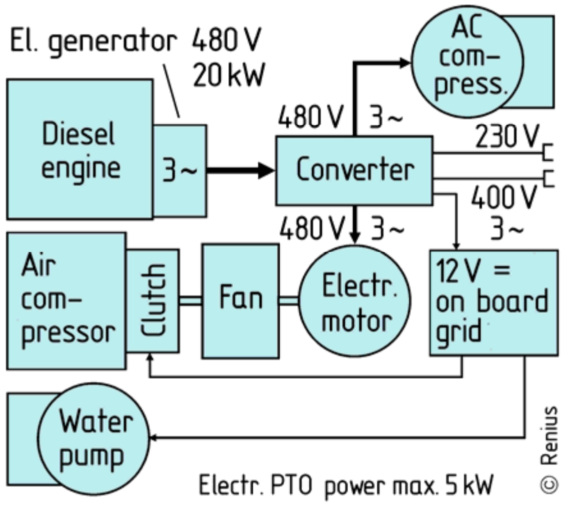
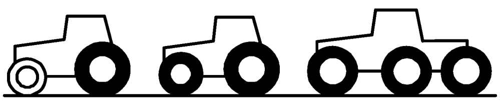


Figure 3 - Integrated high voltage power grid of John Deere E-Premium tractors 7430 and 7530 (2008).
Information source: John Deere.

Figure 4 - Fendt concept study TRISIX, presented at Agritechnica 2007. *Source: AGCO-Fendt.*



	2WD	4WD	6WD
Tractive Efficiency	60%	69%	73%
Gain	0%	**15%**	**22%**

Figure 5 - Comparison of total traction efficiencies for three tractor concepts under typical field conditions in Mid Europe.
Source: author.

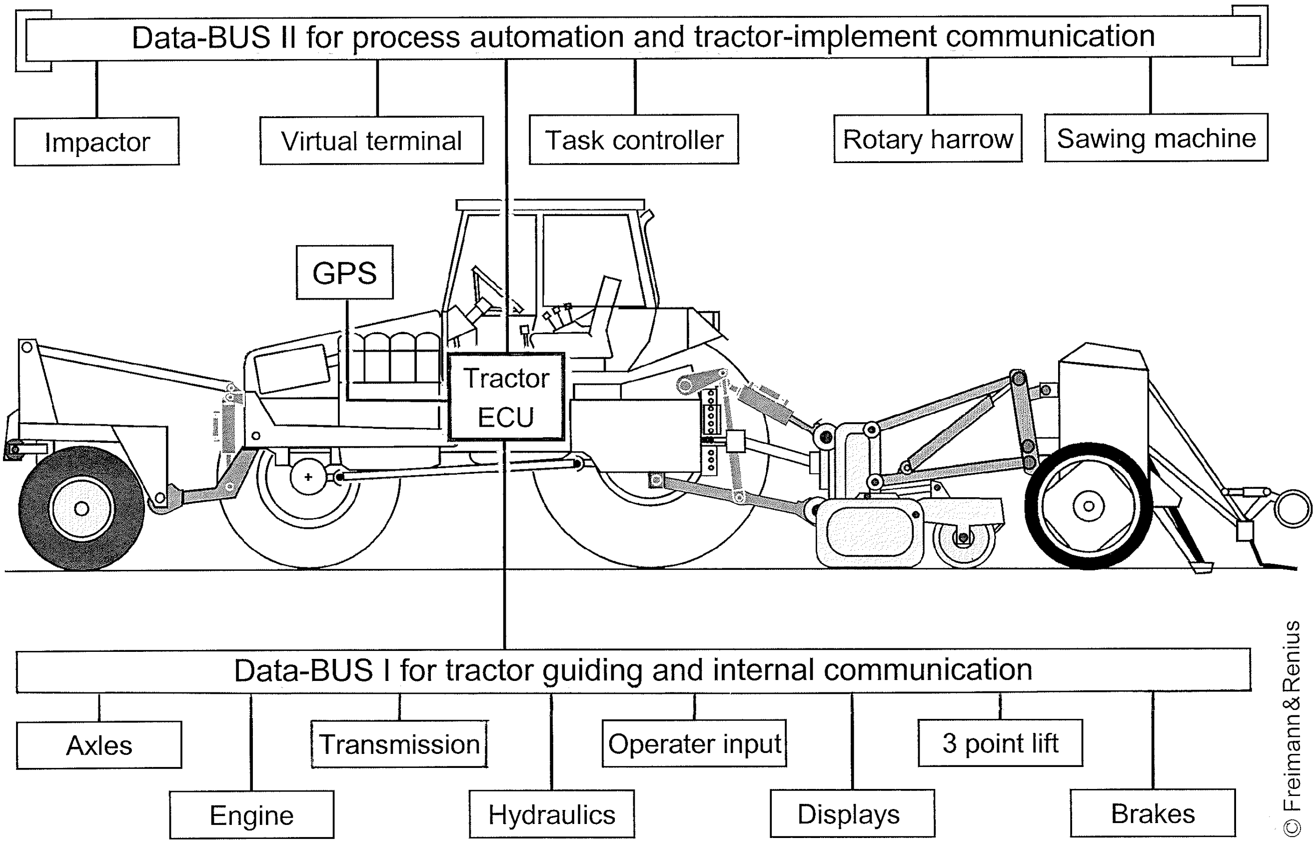
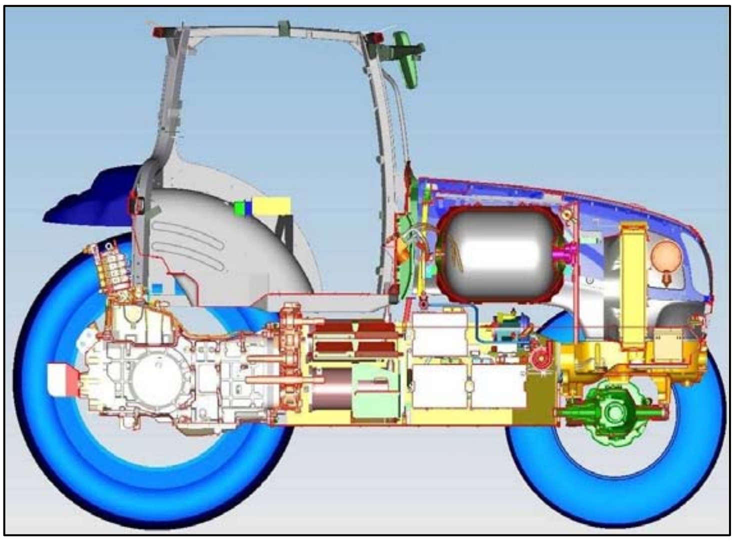


Figure 6 - Automation of the tractor-implement system according to ISO 11783. Combination of a closed internal data BUS for component management with an open external data BUS.for communication between tractor and implements.
Source: [18] and [19] based on ISO 11783 [17].



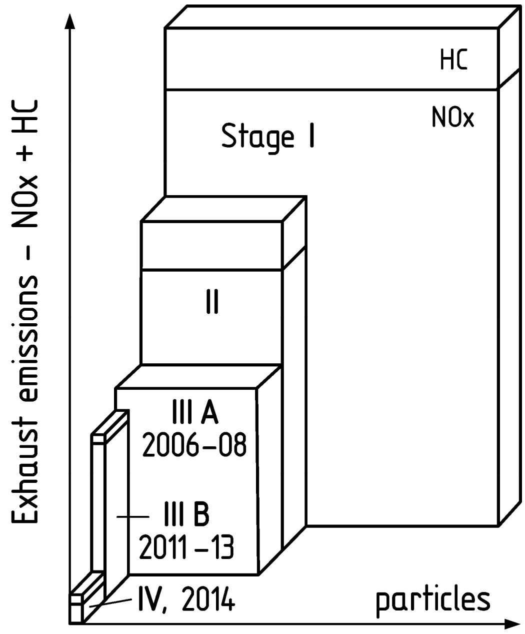


Figure 7 - NH prototype "NH^2" with hydrogen tank, fuel cells and 2 electric motors. Rated power 75 kW, tank capacity for 1,5 hours of operation. SIMA 2009. *Source: CNH Germany.*

Figure 8 - Exhaust gas emission limits for Europe by act 97/68/EG. Additional CO limits around 5 g/kWh with only slight reductions. *Source: VDMA.*

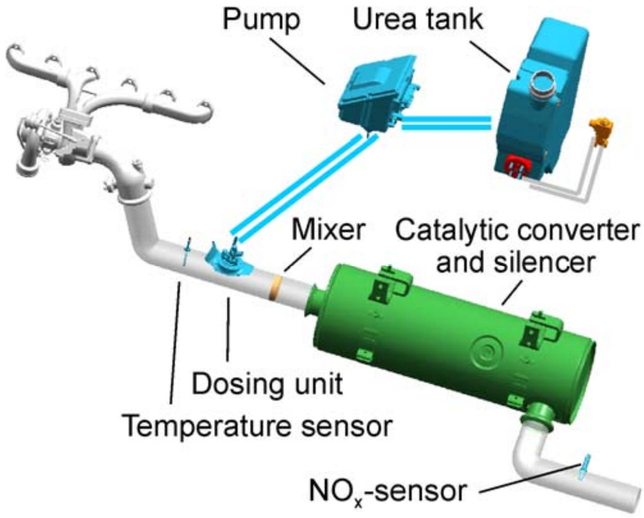
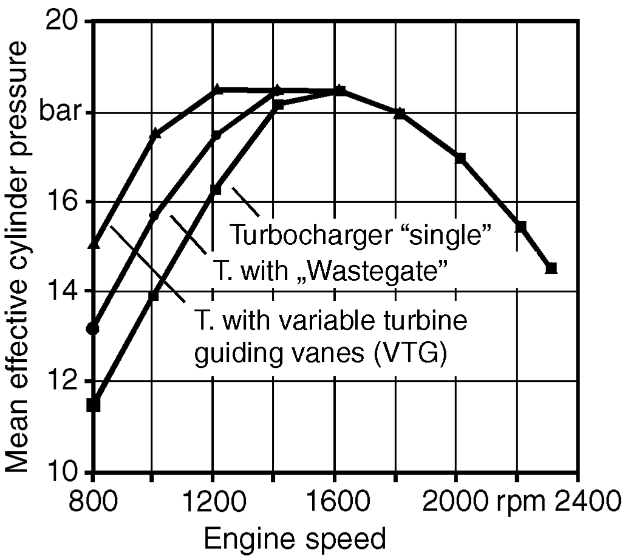


Figure 9 - SCR technology: Catalytic reduction of NOx by urea (add blue). *Source: [25]*

Figure 10 - VTG turbo charger. *Source: courtesy John Deere.*



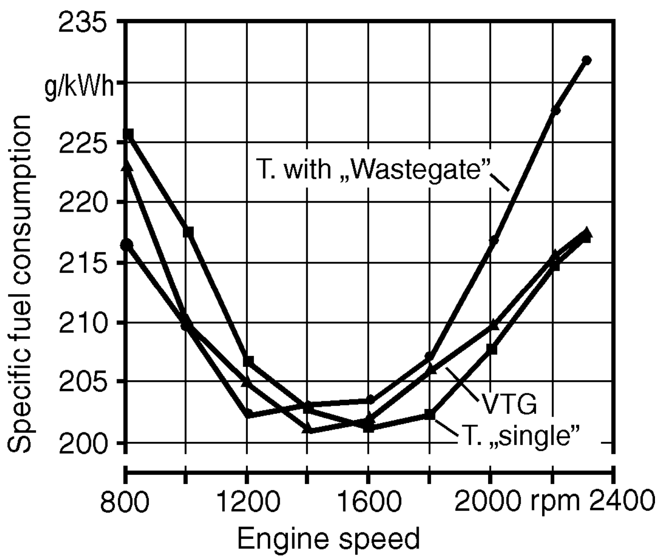
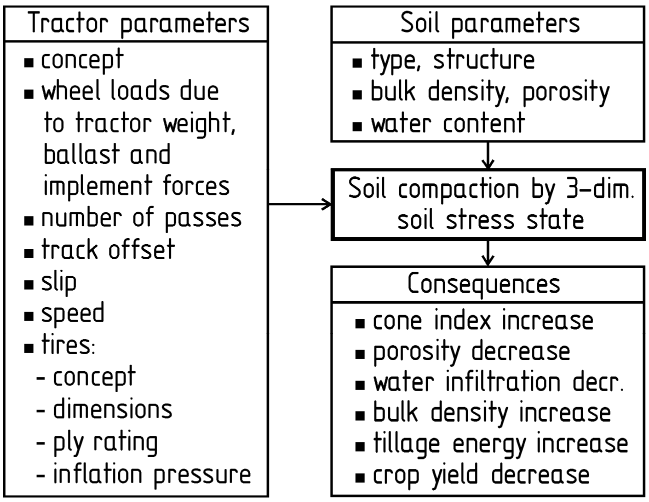


Figure 11 (above) - Influence of turbo charger control on torque and efficiency characteristics of Deutz Diesel engine BF 6 M 1013 FC, 200 kW @ 2300 rpm. Level of NOx about 6 g/kWh..
Source: Deutz AG.

Figure 12 (left) - Container for coupling spill.
Source: Courtesy AGCO-Fendt.

Figure 13 - Sustainable tractor-implement operation: Low contact pressure and rut depth by large duals and reduced tire inflation pressures. *Source: Courtesy Deutz-Fahr.*

Table 1 - Tractor and soil parameters as far as influencing soil compaction and the resulting consequences. *Source: [7].*



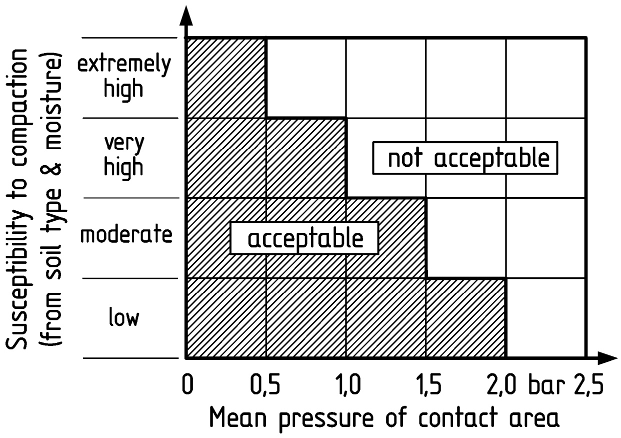


Figure 14 - Guideline for traffic ability of soils being used for agricultural production. *Source: [28].*

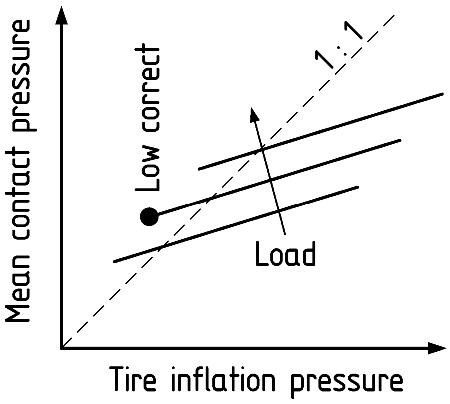


Figure 15 - Influence of tire inflation pressure and tire load on the mean soil contact pressure. *Source: [29].*

Table 2 - Favorable tire inflation pressures. *Source: [7].*

Criteria	Inflation pressure high	Inflation pressure low
First costs per unit load capacity	X	
Required space p. unit load capacity	X	
Tire weight per unit load capacity	X	
Rolling resistance on the road	X	
Soil contact pressure		X
Offroad performance		X
Riding comfort		X

X indicates „favorable"

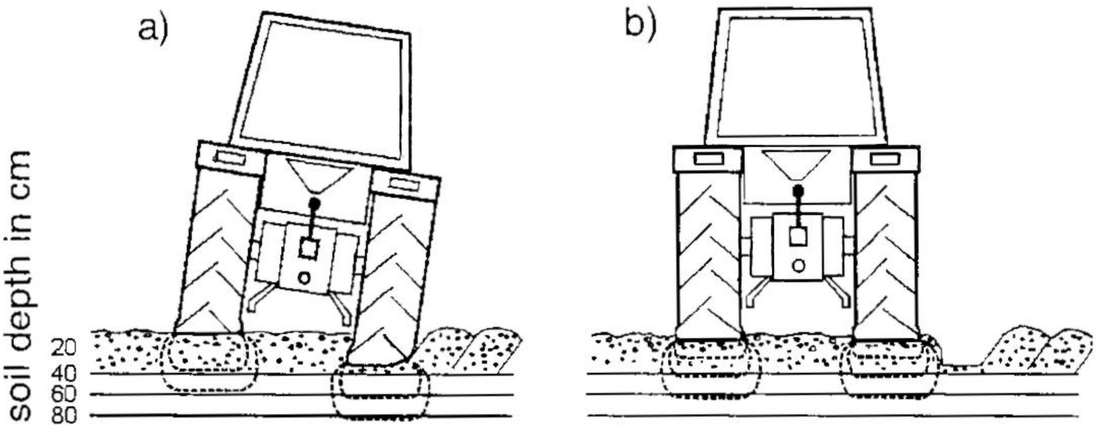


Figure 16 - Schematic "Söhne" pressure bulbs of conventional (a) and on-land ploughing (b). On-land ploughing reduces compaction of deeper layers. *Source: [28].*

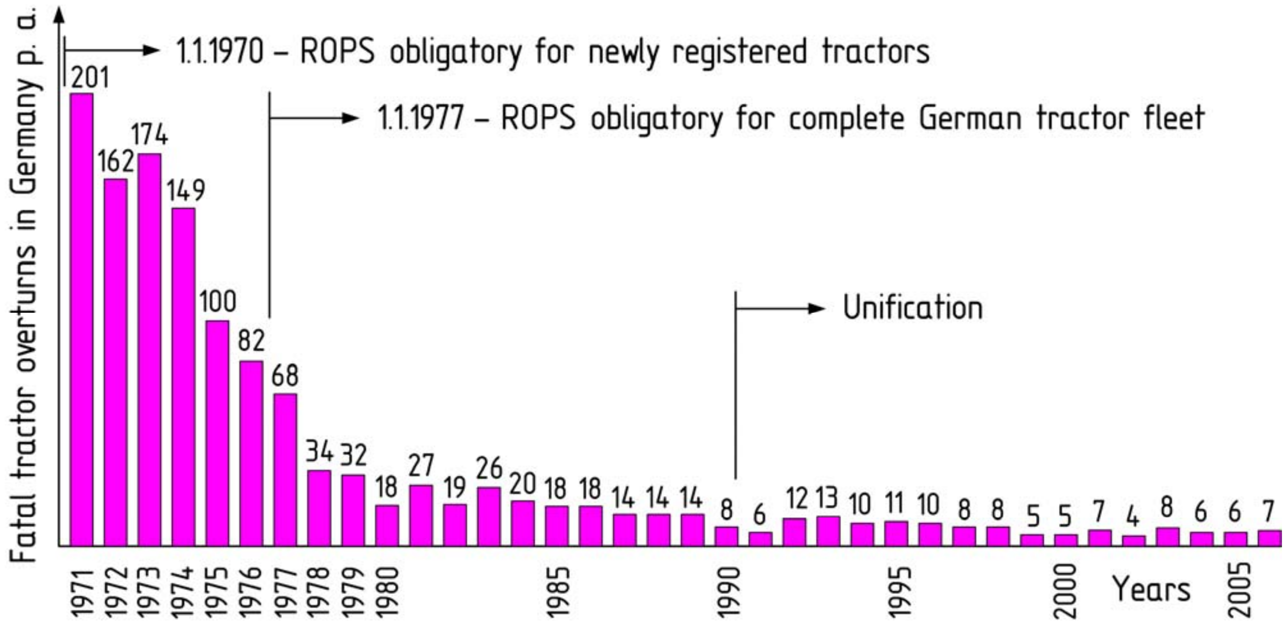


Figure 17 .- Fatal tractor overturns in Germany – sustainable reduction by roll over protection structures (ROPs). *Source: German Agency of Farmer Assurances (BLB).*

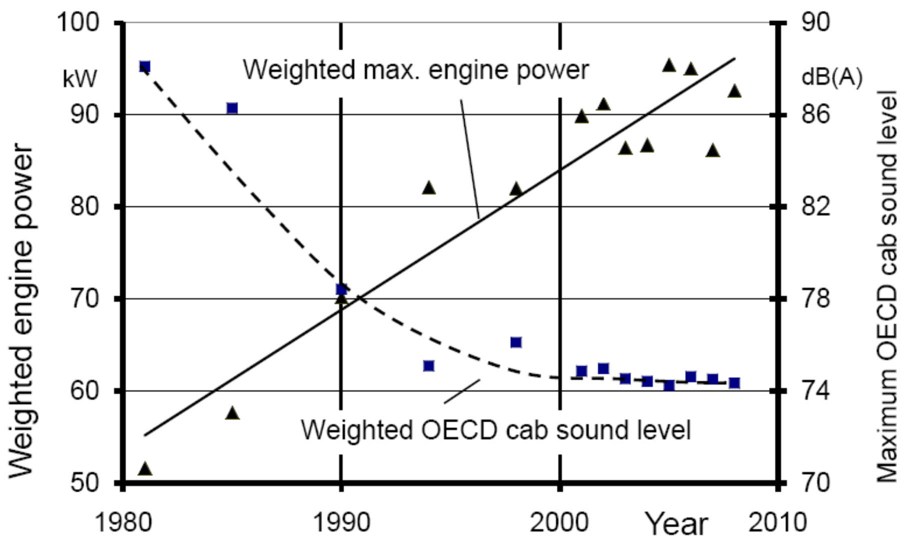


Figure 18 - Maximum OECD noise level at drivers ear. Each point represents a mean value of a group of the most popular tractors of that year in Germany. The mean value is weighted by their sales in units. Mean maximum engine power is calculated in the same way. *Source: [32].*

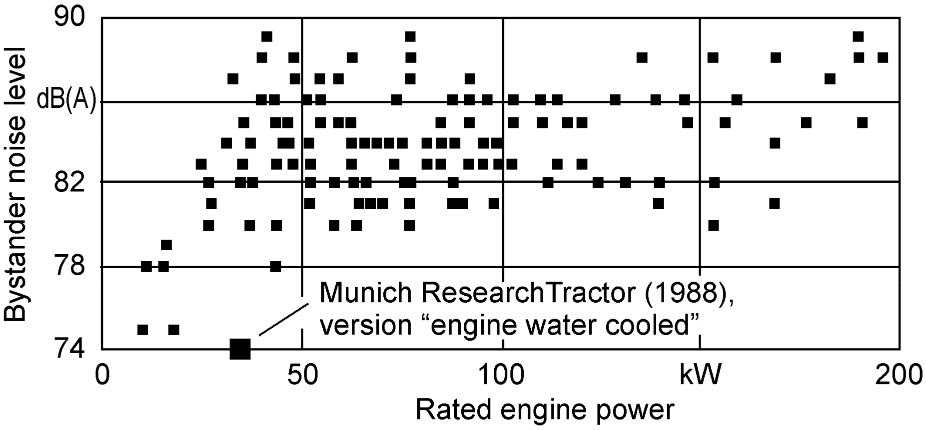


Figure 19 - Statistics of tractor bystander noise emissions. Levels for accelerated passing according to the traffic regulations.
Munich Research Tractor 1988 compared with commercial tractors offered in Europe 1998.
Source: [31].

Figure 20 - The Munich Research Tractor (1988), concept study for low noise levels and other advanced technologies.
Noise measurements on the runway of an airport near Munich.
Source: Institute of Agricultural Machinery at Technische Universität München (Garching). See also [31].

Figure 21 - Typical seat locations, instrumentation and comfortable arm rest control of a modern high tech cab.

Tractor New Holland
T 7000 Auto Command.
Source: Courtesy CNH.