4 - Modern Steam Traction and the Protection of the Environment

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After a break of 40 years, Swiss Locomotive and Machine Works (SLM) in Winterthur (Switzerland) resumed building modern steam locomotives. In 1992, three prototype rack tank locomotives were delivered to the Austrian Federal Railways (ÖBB), the Brienz-Rothorn-Railway (BRB) and the Montreux-Glion-Rochers-de-Naye Railway (MGN), the latter two in Switzerland. New steam locomotives should, like any new technical equipment, be optimized for both minimum operating and maintenance costs and lowest possible pollution. The paper describes the design considerations to meet these requirements and presents the results of emission measurements which show that the new oil-firing system specially developed for these modern steam locomotives causes much lower emissions of CO and NO_x than the competing diesel traction. The experience gained in regular service shows that most of the disadvantages of traditional steam locomotives have been eliminated. The overall economy of steam traction has been drastically improved. The good performance, high availability, low maintenance costs and low pollution of the new steam locomotives and their popularity with the travelling public led to orders for five series locomotives that entered service in 1996.

1 What circumstances led to orders for new high-tech steam locomotives?

Tourist railways and railways with a high percentage of tourists among their passengers need steam locomotives because they attract the public more than any other form of motive power. Steam locomotives mean more passengers and thus more revenue. On the other hand, old steam locomotives are rather expensive to run because of high staff and maintenance costs, relatively low thermal efficiency and high stand-by losses. Due to the difference in age and thus in levels of technological development, new diesel locomotives or railcars usually have lower operating costs than old steam locomotives – but they do not attract passengers. Representative opinion polls in Austria revealed that 79 % of tourists prefer steam locomotives, 3 % prefer diesel traction and 18 % have no preference [1]. In fact, drops in ticket sales after dieselization can easily outweigh the lower operating costs achieved, even more so because capital costs entailed by dieselization are not negligible (electrification entails even higher capital costs and does not attract tourists either). Heavy deficits rather than the expected profits are the result. New modern steam locomotives both attract passengers and offer substantial savings in operating and maintenance costs. They are therefore the **only** solution to the problem of long-term profitable commercial tourist railway operation.

The main advantages of modern steam power are:

- one-man operation
- extremely environment-friendly oil-firing system
- fully insulated boiler and cylinders
- high thermal efficiency
- roller bearings and central lubrication
- external electric preheater for unattended steaming-up
- high availability (the same as diesel locomotives)

So far, the Austrian Federal Railways (ÖBB), the Brienz-Rothorn-Railway (BRB) and the Montreux-Glion-Rochers-de-Naye Railway (MGN) have fully realized these advantages of modern steam power for tourist train operation. In 1988, these railways ordered one prototype each of a new H 2/3-type (rack tank 0-4-2) high-tech steam locomotive from Swiss Locomotive and Machine Works (SLM). SLM had built its "last" steam locomotives back in 1952 but had resumed locomotive boiler construction in 1986. Both the railways and the SLM management were convinced that new high-tech steam locomotives were a viable and economically reasonable option for all parties involved.

Table 1: Comparison between old and new steam locomotives of the Brienz-Rothorn-Railway (BRB)

Type	H 2/3	H 2/3	Improvement
Engine No.	6; 7	12; 14, 15	
Year built	1933; 1936	1992; 1996	
Weight in service	20 t	15 t	- 25 %
Power	220 kW_i	300 kW_i	+ 36 %
Power to weight ratio	11 kW/t	20 kW/t	+ 82 %
Fuel consumption per train trip	11550 MJ	6830 MJ	- 41 %
Fuel consumption per passenger trip	145 MJ	57 MJ	- 61 %
Maximum speed 1 in 4-gradient	9 km/h	14 km/h	+ 56 %

2 General concept of the new, modern steam locomotives

Oil-firing was chosen with one-man operation and low day-to-day maintenance costs in mind. Old oil-fired steam locomotives burnt heavy fuel oil (bunker C), but this was ruled out for the new engines. Due to its high sulphur content (≥ 1 % by weight), heavy fuel oil is detrimental to both environment and boiler life (corrosion). Moreover, heavy fuel oil requires heating for both handling and the actual firing which means more dead weight on the locomotive (heating coils) and additional use of energy. As heavy fuel oil is used only by big factories and power stations, it is difficult to obtain in smaller quantities and not readily available in tourist areas, whereas there is a good distribution network for extra-light (EL) oil used in domestic central heating. Due to its low sulphur content (0.10-0.20 % by weight; qualities with an even lower sulphur content are becoming available), its high heat content (lower calorific value ≥ 42.5 MJ/kg) and its cleanness it is one of the least air-polluting locomotive fuels.

In order to achieve good combustion in the small firebox, a new oil-firing system had to be developed because the maximum possible length of the flame path was not sufficient for a traditional single burner concept with its one big flame guided in the shape of a C or an S. In order to shorten the flame-length, four smaller main burners with a maximum flow rate of 75 l/h each (= approx. 750 kW of heating power per burner) were fitted in the square bottom of the firebox. In their center, there is a so-called pilot-burner (with a maximum flow rate of 8 l/h = approx. 80 kW of heating power) that is used to ignite the main burners and to steam up the locomotive after a night's rest. The total burner power is thus 3.08 MW. All burners are of the specially developed "injection burner" type. Their flames are directed vertically upwards and do not touch the firebox walls. Therefore the traditional brick lining is not necessary, which means better and quicker heat transfer and undisturbed combustion leading to higher boiler efficiency, better response to load changes and much lower air pollution. The injection burners atomize the oil by means of whirling steam that has passed a special superheater coil adjacent to the pilot-burner. Oil flow and thus firing rate are controlled by means of a compound-regulator. This device can be controlled with one hand and ensures the correct atomizing steam pressure for any oil flow rate chosen.

Instead of the fusible plugs used on coal-fired steam locomotives, a low water detector shuts off the main burners automatically via an electromagnetic valve if the water level falls below the safety margin above the firebox crown.

In order to reduce thermal losses drastically, both boiler and cylinders are very well insulated. A roll shutter is fitted to shut off the air flow to the firebox completely when all burners are turned off. When going downhill, the Riggenbach counter-pressure brake is used, all burners are turned off, and the roll shutter is closed – fuel consumption is thus nil.

Due to the excellent boiler insulation and the roll shutter, a locomotive stabled fireless in the evening at almost full boiler pressure will still have a pressure of 800 to 1000 kPa left in the boiler the next morning. It takes the pilot-burner only about 38 minutes to steam up the locomotive from 800 to 1600 kPa, and the natural draught of the chimney is sufficient for low-emission combustion. If the blower and the main burners are used, pressure can be built up much more quickly, of course. The electric preheater is therefore only necessary for unattended steaming-up of a dead engine or if the locomotive is to be kept in steam for continuous stand-by. If electric preheating is not available and the locomotive is dead, the pilot-burner can also work with externally supplied compressed air.

The classical two-cylinder steam engine with Walschaerts valve gear (or Heusinger gear as it is called in Germany and the countries influenced by German locomotive practice) incorporates all known improvements such as

- enlarged steam chest volume
- straight steam ports
- minimum clearance volumes
- efficient exhaust system (a simplified LemPor-exhaust is fitted)
- generous valve travel
- good cylinder insulation

The locomotive has a feedwater heater of the closed type, and the superheater is designed to achieve a steam temperature of 420°C.

3 Environmental protection: modern steam versus modern diesel

As far as air pollution is concerned, is a fair and realistic comparison between modern steam and modern diesel traction possible? On the BRB, the new H 2/3-type steam locomotive No 12 and the Hm 2/2-type hydrostatic diesel locomotives Nos 9-11 are direct competitors (the prototype hydrostatic diesel locomotive No 8 of 1973 is not considered here). Both the diesel locomotives and the new steam locomotive cannot make full use of their rated power because they have to work in the same diagram as the old steam locomotives. To push trains uphill in the present operation, a power of about 179 kW at the driving cogwheels at a speed of approximately 9 km/h is required. In order to produce that tractive power, the new steam locomotive has to be run at a burner load of approximately 52 %, and the diesel locomotives also have to work at 52 % of their rated engine power of 485 kW. A realistic and fair direct comparison is therefore possible and makes good sense.

In order to compare the new H 2/3 steam locomotives with their diesel competitors Hm 2/2 pollutionwise, a special "mountain railway test cycle" that properly represents locomotive operation on the BRB was developed. This test cycle consists of the following three test modes (weighting factors in brackets):

1 **Stand-by** (0.10)
Steam: pilot-burner only
Diesel: engine idling

2 **Uphill train** (0.45)
Steam: 179 kW at driving cogwheels
Diesel: 179 kW at driving cogwheels

3 **Downhill train** (0.45)
Steam: braking with Riggenbach counter-pressure brake, all burners turned off
Diesel: braking with hydrostatic transmission and engine

Table 2: Technical data of the new H 2/3 rack tank steam locomotive

Grate area		0.9	m^2
Tubes, number		62	
Tubes, dimension		38 x 2.9	mm
Flues, number		15	
Flues, dimension		114.3 x 3.6	mm
Total evaporative surface*		30	m^2
Firebox*		5.14	m^2
Tubes*		13.80	m^2
Flues*		10.92	m^2
Superheater surface*		13.23	m^2
Boiler pressure		16/18	bar
Oil firing system		Sonvico/SLM-type	
Fuel		Extra light heating oil (#2 heating oil)	
Cylinders		2	
Diameter		280	mm
Stroke		400	mm
Valve Gear		Heusinger (=Walschaerts)	
Gear ratio		2.3 : 1	
Rigid wheelbase		2070	mm
Total wheelbase		3650	mm
Rack System		Abt (Riggenbach)	
Driving cogwheels		2 x 2 (2 x 1)	
Cogs per driving wheel		15 (18)	
Length over couplers		6260	mm
Maximum width		2200	mm
Service speeds on gradients			
1 in 4		12	km/h
1 in 4.55		13	km/h
1 in 5		14	km/h
Gauge	**800**	**1000**	**mm**
Carrying wheel diameter, worn/new	637/649	693/705	mm
Pony wheel diameter, worn/new	426/440	479/493	mm
Maximum height	3200	3230	mm
Weight, empty	13000	13300	kg
Water in boiler	1200	1200	kg
Water in side tanks	1300	1300	kg
Oil (545 l, 0,86 kg/l)	470	470	kg
Weight in full working order	15970	16270	kg

* fire side

The very low weighting factor for the stand-by mode properly represents the high utilization of the Hm 2/2 diesels on the BRB, and as the new H 2/3 steam locomotives were designed to have the same availability as modern diesels (which they have proved in regular operation ever since they entered service in 1992), the same test cycle as for the diesels applied.

In diesel engine testing, CO, NO_x, HC (hydrocarbons) and particulate emissions are measured in g/kWh over certain test cycles (ECE R 49 for commercial road vehicle diesel engines, ISO F for rail traction diesel engines etc.). The pollutant mass flow rates are measured in g/h in the various test modes; at the same time, the net power obtained on the test bench at the end of the crankshaft (i.e. at the source of tractive power) is measured. The emissions over the whole test cycle are then calculated according to the formulae [2]:

$$CO = \frac{\Sigma\, CO_{\text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (1)$$

$$NO_x = \frac{\Sigma\, NO_{x\ \text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (2)$$

$$HC = \frac{\Sigma\, HC_{\text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (3)$$

$$\text{part.} = \frac{\Sigma\, \text{part.}_{\text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (4)$$

Steam locomotive power is most easily measured as indicated power produced in the cylinders (i.e. also at the source of tractive power). However, the losses for auxiliaries and in power transmission differ vastly between steam and diesel traction. In order to deliver a tractive power of 179.4 kW_d at the driving cogwheels (denoted by the subscript "d" meaning "at **d**riving wheels"), the new steam locomotive must produce 200.5 kW_i (subscript "i" denoting **i**ndicated power) in the cylinders whereas the diesel engine of the Hm 2/2 diesel-hydrostatic locomotive must produce 253.1 kW at the end of its crankshaft. Auxiliaries and power transmission losses add up to 10.5 % on the steam locomotive but to 29.1 % on the diesel. This must be taken into account in a fair comparison because what really counts are the emissions per kWh effectively available for traction, i.e. per kWh at the driving wheels. Therefore, P_d rather than P_i and $P_{crankshaft}$ was used in the above equations (which was applicable only for test mode 2; in test modes 1 and 3 the power output at the driving wheels was zero, of course).

Actual testing, however, is much easier if the indicated power of the steam locomotive is measured. Since the same type of diesel engine may find rather different applications, the only emission data available are those based on measurements of pollutant mass flows versus power outputs at the crankshaft. Therefore, the necessary indicated power and power at the end of the crankshaft, respectively, to obtain 179.4 kW_d were calculated from the known power consumptions of auxiliaries and power transmissions. The steam locomotive was then tested at the calculated indicated power of 200.5 kW_i; and the pollutant mass flow rates of the competing diesel engine for the calculated power of 253.1 kW could be obtained from the manufacturer.

To test the new steam locomotive, a test stand was erected at SLM. Two locomotives were placed side by side on sloped pieces of track without rack, and the crankshafts of both engines were connected via a shaft attached to the lower cogwheels of the gearboxes, from which the connecting rods had been removed. Thus the Riggenbach counter-pressure brake on one locomotive could be used to provide the necessary braking power for testing the other one under load conditions. Indicated power was measured electronically.

Two "ECOM-M/CH Smokegas-Analysis-Computers" (Stark STA-Therm, CH-2501 Biel) were used for exhaust gas measurements, one for each side of the smokebox to average out asymmetries in the combustion process introduced by the uncompensated circular whirl of the single pilot-burner. One measurement at a certain point in time then consisted of taking the average values of the readings of the two simultaneously triggered smokegas analysers. The ECOM-M/CH smokegas analyser was developed for (stationary) firing systems that burn extra light heating oil or natural gas. Exhaust gas temperature, ambient temperature, O_2-, CO- and NO-concentrations in the dried exhaust gas are measured and other data relevant for the assessment of firing systems automatically calculated. Of these, the O_2-, CO_2-, CO- and NO_x-concentrations in the exhaust gas and the air excess λ are of interest in the case of oil-fired steam locomotives. Furthermore, the device can be used to determine the "soot number" of the exhaust gas on the Ringelmann-scale (degree of blackening of a filter paper through which a defined exhaust gas volume is drawn) [3]. According to Swiss and German standardization practice, O_2- and CO_2-content of the exhaust gas are printed out in % by volume and CO- and NO_x-concentrations in mg/m^3, in both cases of the dry exhaust gas at the reference temperature and pressure of 0°C and 1013 mbar. NO_x-mass concentrations are based on the mass of NO_2 because after some time all NO is oxidized in air to form NO_2. Moreover, CO- and NO_x-concentrations may automatically be standardized on the dry exhaust gas volume (0°C, 1013 mbar) at the reference O_2-content of 3 % by volume which was done in all our measurements because in Germany and Switzerland this is the standard for comparisons of pollutant concentrations in exhaust gases from firing systems. Unfortunately, a flame ionization detector was not available so that hydrocarbon emissions could not be measured.

In test mode 1, the new steam locomotive was heated up from 800 to 1600 kPa boiler pressure within 38 minutes, using only the pilot-burner and the natural draught of the chimney. Due to the increasing firebox temperature while heating up, NO_x concentrations went up from 116 mg/m^3 at the beginning to 180 mg/m^3 at the end. The relevant average exhaust gas values over the whole 38 minutes and a total of four measurements were:

O_2	:	13.6	% by volume
CO_2	:	5.4	% by volume
CO	:	93	mg/m^3 (at 3 % O_2)
NO_x	:	149	mg/m^3 (at 3 % O_2)
λ	:	2.8	

The soot number on the Ringelmann scale was 0.

In test mode 2, first of all a stationary state had to be reached (cylinders heated up, superheat temperature and indicated power constant). This was the case after 1020 s (= 17 minutes):

Boiler pressure	=	1600	kPa
Superheat temperature	=	389	°C
Cut-off	=	32	%
Speed	=	8.9	km/h
Indicated power	=	200.5	kW_i

The average exhaust gas values over the following 723 s and a total of four measurements were:

O_2	:	9.1	% by volume
CO_2	:	8.6	% by volume
CO	:	22	mg/m^3 (at 3 % O_2)
NO_x	:	200	mg/m^3 (at 3 % O_2)
λ	:	1.8	

The soot number on the Ringelmann scale was 0-1.

Fuel efficiency η_i [4] over the whole 1743 s of testing under load in test mode 2 reached 12.7 %, specific fuel consumption was 663 g/kW_ih. Losses for auxiliaries were 1.9 kW for the feedwater pump (at 1600 kPa and 8.9 km/h) and 3.5 kW for the alternator (at 8.9 km/h); according to Giesl [5], losses in the whole steam engine of the locomotive amount to 6 %, and another 2 % are lost in the gearbox. With these values, P_d was (200.5 kW_i x 0.94 – 1.9 kW – 3.5 kW) x 0.98 = 179.4 kW_d, fuel efficiency η_d = 11,4 % [6] and the specific fuel consumption per kWh at the driving wheels 741 g/kW_dh.

In order to calculate the pollutant mass flow rates from the pollutant concentrations in the exhaust gas, the total exhaust gas volume flow rate must be known. A direct measurement on a steam locomotive is not possible, and the simultaneous measurement of fuel flow rate and air intake was impossible in this case because of the design of the air ducts in the burners. Therefore, the exhaust gas flow rate on dry basis for an O_2-content of 3 % by volume was calculated from the measured fuel flow rate and the known elemental composition (C-, H- and S-content) of the fuel derived from chemical analysis.

Table 3 shows the emission values of the new steam locomotive H 2/3 in g/kW$_i$h and g/kW$_d$h for CO, NO_x and SO_2 in the "mountain railway test cycle". The SO_2-emissions were calculated from the measured fuel flow rates and the known sulphur content of the fuel (0.15 % by weight); the values in brackets would have been obtained if the low sulphur fuel only now (1996) available (sulphur content = 0.05 % by weight) had been used.

Table 3: CO-, NO_x- and SO_2-emissions of the new H 2/3 steam locomotive in the "mountain railway test cycle"

Carbon Monoxide (CO)	Nitrogen Oxides (NO_x)	Sulphur Dioxide (SO_2)
0.19 g/kW$_i$h	1.65 g/kW$_i$h	2.01 (0.67) g/kW$_i$h
0.21 g/kW$_d$h	1.84 g/kW$_d$h	2.24 (0.75) g/kW$_d$h

For modern high-tech steam locomotives, both a 13 point emission test cycle and a test cycle corresponding to the ISO F rail traction test cycle for diesel locomotive engines were developed [7]. Unfortunately, further testing of the locomotive beyond the above experiments, which were of immediate relevance for future operation, was not possible because the railways wanted their locomotives to be delivered quickly. Delivery of the new steam locomotives took place in May and July of 1992, in the case of the BRB just in time for the 100th anniversary of the railway.

Since the beginnings of the change-over from steam to diesel traction more than 50 years ago, railways and locomotive manufacturers used to compare their new diesel locomotives with old steam locomotives that had been in service for up to 50 years. In order not to be guilty of the same unfairness the other way round, the new high-tech steam locomotive was not compared with the latest BRB diesel locomotive No 11 of 1987 but with a **fictitious** No 11 locomotive that was assumed to be equipped with a modern diesel engine. A good engine choice for this comparison was the MTU 12V 183 TD12 diesel engine, which has a rated UIC-power of 550 kW but which would be set at a rated power of 485 kW for use on the BRB diesel locomotives with their existing hydrostatic power transmission. A disadvantage even of the newest diesel locomotive No 11 is that it still burns diesel fuel going downhill (in principle, this could be eliminated).

Motoren- und Turbinen-Union Friedrichshafen (MTU) was so kind as to supply the CO and NO_x mass flow rates and fuel consumptions of their 12V 183 TD12 diesel engine for the three test modes of the "mountain railway test cycle". At a power output of 253.1 kW (necessary to obtain 179.4 kW at the driving cogwheels, test mode 2), this engine has a specific fuel consumption of 197 g/kWh which results in a fuel efficiency η_d = 30.3 %.

Fig. 1: CO-, NO_x- and SO_2-emissions, "mountain railway test cycle"

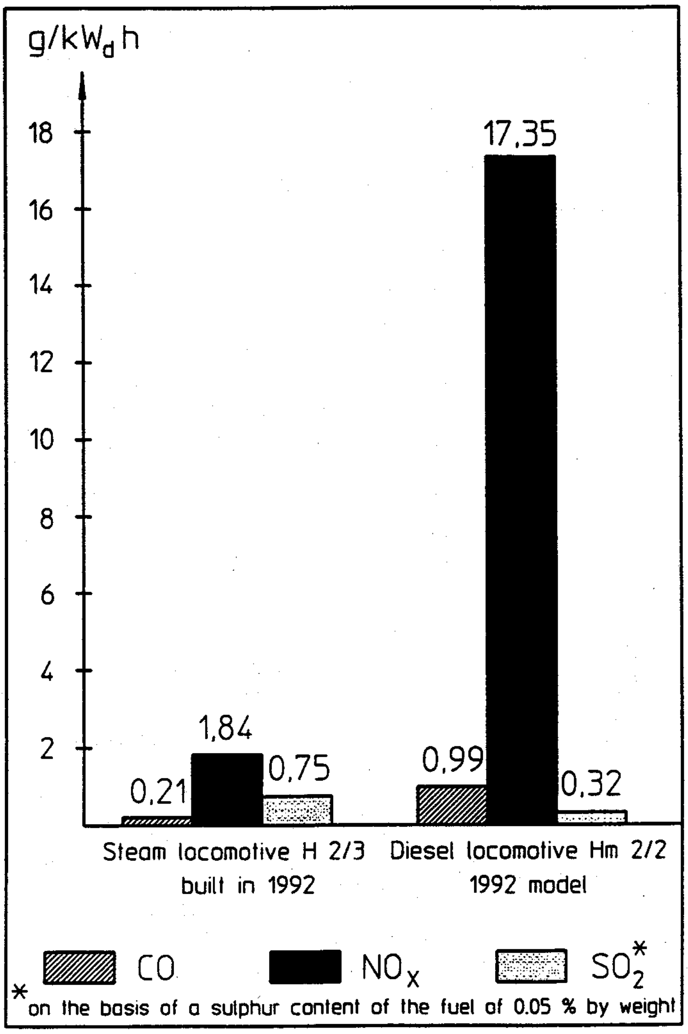

Fig. 1 directly compares the CO-, NO_x- and SO_2-emissions of the new steam locomotive H 2/3 of 1992 with those of the Hm 2/2 hydrostatic diesel locomotive No 11 if it were equipped with a modern MTU 12V 183 TD12 diesel engine also of 1992. SO_2-emissions in this graph are based on the fuels with the lowest sulphur content available in Switzerland in 1996.

Besides the noxious exhaust gases, CO_2-emissions also have to be considered. Although CO_2 is not toxic, an increase of this natural constituent of the atmosphere may lead to changes in the world climate (glasshouse effect). The CO_2-emissions of the two competing forms of motive power can be calculated from the known average carbon content of extra light heating oil (86.68 % by weight) and diesel fuel (85.92 % by weight), respectively, and the known specific fuel consumptions in the different test modes. Table 4 lists the CO_2-emissions per kW_dh in the "mountain railway test cycle" of the new high-tech steam locomotive No 12, the latest diesel locomotive No 11 as it is in service now, and the No 11 diesel if it were equipped with the modern MTU 12V 183 TD12 diesel engine.

Table 4: CO_2-emissions of the new H 2/3 steam locomotive and the BRB Hm 2/2 diesel locomotive No 11 in the "mountain railway test cycle"

Locomotive	Carbon Dioxide (CO_2)
Steam Locomotive H 2/3 No. 12 of 1992	647 g/kW$_d$h
Diesel Locomotive Hm 2/2 No. 11 MTU 8V 331 TC10	302 g/kW$_d$h
Diesel Locomotive Hm 2/2 No. 11 MTU 12V 183 TD12 of 1992	271 g/kW$_d$h

4 Conclusion

From the environmental protection point of view, it is interesting to note that – at least as far as CO and NO_x emissions are concerned – the new high-tech steam locomotive easily outclasses the competing diesel traction. Yet, the new H 2/3 is still a truly Stephensonian steam locomotive. The use of zero or extremely low sulphur heating oil poses no problem at all and would mean the elimination or drastic reduction of SO_2-emissions. In principle, LNG (liquefied natural gas) operation is also possible on new steam locomotives, which would lead to even lower overall pollution and – in contrast to the use of LNG on diesel locomotives – not lower the fuel efficiency.

The good performance, high availability, low maintenance costs and low pollution of the new high-tech steam locomotives – in addition to their popularity with passengers – led to orders for five series locomotives: in 1994, the Brienz-Rothorn-Railway ordered another two and the Austrian Federal Railways another three. These engines entered regular service during the 1996 season. The ÖBB locomotives – numbered 999.202/3/4 – are for use on the Schafberg Railway from St. Wolfgang along with their prototype sister engine 999.201.

The initial goal of the endeavours described above was to design and build an economically and ecologically competitive steam locomotive for tourist train operation. Clearly, this has been fully achieved. But even if the new steam locomotives were slightly more expensive to run than comparable diesel or electric motive power, their use would be justified because of the additional income generated by their attractiveness. The results show, however, that modern steam locomotives are fully competitive on purely economic terms.

Operating experience with new high-tech steam locomotives since 1992 has proved that modern steam traction is a serious alternative to diesel and electric motive power, not only from the ecological but also from the economic point of view. As far as economy is concerned, steam locomotives can use a wide variety of fuels, ranging from wood, peat, lignite and coal to oil, liquefied natural gas (LNG) and various new biomass fuels, whichever may be cheapest under the operating conditions in question. In Western Europe and North America oil is still the overall cheapest fuel (taking high labour costs into account), whereas coal is most economical in countries like South Africa and Zimbabwe with ample indigenous coal supplies at low prices and relatively low wages. Bearing in mind the carbon dioxide-problem (due to increasing use of fossil fuels, the CO_2-content of the atmosphere has increased which may give rise to dangerous changes in the earth's climate – greenhouse effect), regenerative, carbon dioxide-neutral biomass fuels will become important in the 21st century, and **waste** biomass fuel can play an important role in the economical operation of railways, using modern high-tech steam locomotives.

Many old diesel locomotives and diesel railcars that are approaching the end of their useful lives will have to be replaced soon, and environmental considerations call for less polluting motive power. In some cases, no doubt, electrification will be the solution but electrification requires really big investments that are justifiable only on lines with high traffic densities. Modern steam locomotives offer a low-investment solution and economical, clean and attractive service. It would be wise to consider this in future motive power decisions.

The author wishes to thank Motoren- und Turbinen-Union Friedrichshafen GmbH for supplying the MTU 12V 183 TD12 emission data.

References and Notes

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2. Agreement Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts. Regulation No 49, Revision 1. Uniform provisions concerning the approval of compression ignition (c.i.) engines and vehicles equipped with c.i. engines with regard to the emissions of gaseous pollutants by the engine. Anlageband zum Bundesgesetzblatt Teil II Nr. 11, issued the 9th of April, 1992.

3. The German regulation containing the Ringelmann-scale is: Verordnung zur Neufassung der Ersten und Änderung der Vierten Verordnung zur Durchführung des Bundes-Immissionsschutz-gesetzes. Vom 15. Juli 1988. Anlage I. Bundesgesetzblatt, Jahrgang 1988, Teil I, Nr. 34 – Issued: Bonn, 26th of July, 1988.

4. On the European continent, η_i = (indicated power over flow rate of **lower calorific value of fuel**) x 100 %. The lower calorific value of the fuel is defined as its heat content **minus the condensation heat of the water vapour formed in the combustion process**.

5. Giesl-Gieslingen: Lokomotiv-Athleten. Josef Otto Slezak Publishing House, Vienna 1976, on p. 215.

6. On the European continent, η_d = (power output at the driving wheels over flow rate of **lower calorific value of fuel**) x 100 %.

7. Renhard W. Serchinger: Dampftraktion und Umweltschutz – ein Emissions-Meßzyklus für neue Dampflokomotiven. ZEV+DET Glasers Annalen 117 (1993) No 4, pp. 122-129.