SOME DEVELOPMENT PROBLEMS OF HIGH-SPECIFIC-OUTPUT RAILWAY DIESEL ENGINES

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Railway traction-generated air pollution

Among service parameters of high-specific-output railway diesel engines, air pollution did not get attention before recently. In fact, most of the transport-generated air pollution is caused by motor vehicles. In the area of large railway stations, of busy urban tracks and of depots, air pollution caused by railway diesel engines affects, however, the environment, the passengers and the engine crew as well. This is why several railway companies surveyed and evaluated the situation and introduced control measures. Moreover, both environmental legislation and public opinion constrain manufacturers and operating companies to consider this problem in merit.

Available investigations show actually railways to be the transport branch the least damaging environment by air pollution. This fact is supported by comparisons between specific energy consumptions of different branches of transport. Obviously, specific energy consumption plays a primordial role in air pollution referred to hauling output of a vehicle or transport branch. Table 1 has been based on references [1, 2] and on author's analyses. Proportions facilitate understanding of orders of magnitude, actual values depending on many circumstances (e.g. transport distance). Specific energy consumption data E_1 and E_2 in the table are rather deviating. In relation to the Hungarian Railways (MÁV) the specific energy consumption of passenger transport (in units kcal/1000 gross ton-kilometers) is about twice that of goods transport, both for diesel and for electric traction. In Hungary the ratio of specific energy consumption of diesel to electric traction was found to be 1,2 to 1,0. Hence, energetically, electric traction is superior to diesel traction. Specific air pollution due to electric traction is lower, besides, power plants are sited at a distance from urban, crowded areas. This advantage is somewhat offset by the regionally significant, concentrated air pollution by power plants, producing higher specific sulfur dioxide and nitrogen oxide pollutions referred to transport performance than does diesel traction.

Table 1

Specific energy consumption rates of various modes of long-distance transport

Transport of goods		Passenger transport	
	Specific energy consumption [E_1/1000 gross-ton-km]	Vehicle of transport Number of passengers in (—)	Specific energy consumption [E_2/1000 passenger-km]
Pipeline	0.66		
On shipboard	0.80		
By rail	1.00	Fast train, electric traction (1095)	1.00
		Fast train, diesel traction (730)	1.00
		TEE-express electric traction (467)	2.11
		Gas turbine mu train (346)	3.06
On road	3.44	Long-distance bus (50)	2.13
		Car (5)	5.00
By air	54.50	Aeroplane, Airbus A 300B (281)	10.74
		Aeroplane, Boeing 727 (148)	11.50

The share of air pollution due to diesel traction in the total transport-generated air pollution can be determined by computations and assessments based on measurements. Conditions in the USA and in the FRG are seen in Table 2 [3, 4]. Data for the US diesel locomotive stock have been determined from emission characteristics of the principal locomotive types, from the mode of operation, from fuel consumption, and from the composition of

Table 2

Air pollution caused by diesel traction in the USA and FRG

Emissions	USA (1970)			FRG (1969)		
	Mobile Sources	Air pollution caused by diesel traction		Mobile Sources	Air pollution caused by diesel traction	
	[10^3t/year]	[10^3t/year]	as percentage of mobile sources [%]	[10^3t/year]	[10^3t/year]	as percentage of mobile sources [%]
Oxides of nitrogen	11300	558	5.2	908.4	36	3.96
Unburned hydrocarbons	18150	150.5	0.83	497.4	8	1.61
Carbon monoxide	108600	206.5	0.19	3712.1	24	0.65
Sulfur dioxide	950	91	9.6	78.4	8	10.20
Smoke	1100	38.5	3.5	59.9	3	5.01
Total	140100	1074.5	0.765	5256.2	79	1.50

the locomotive stock. FRG data are estimations, values seem irreally low. Tables show the percentage of air pollution due to diesel traction to be rather low but its absolute magnitude to be important. High percentages of SO_2, NO_x and smoke are conspicuous. The high value of SO_2 emission comes from a diesel fuel of 0.35% sulfur content.

To have a picture of the Hungarian situation, the approximate value of overall air pollution due to diesel traction has been calculated. Since the emission characteristics of engine types operated by MÁV have not yet been fully determined, data of foreign engine types of similar characteristics, sizes and uses have been reckoned with. Also the composition and mode of operation of the rolling stock have been considered, but calculations were primarily based on fuel consumption. Determination of the sulfur dioxide quantity assumed a diesel fuel of $S = 1\%$ sulfur content. Computed harmful constituent quantities are seen in Fig. 1. Harmful constituents amount to $22.8 \cdot 10^3$ tons/year. The figure indicates both absolute quantities of the exhaust constituents and their relative noxiousness in terms of air pollution factors L_i. Emissions of NO_x, SO_2 and smoke are seen to lead by noxiousness.

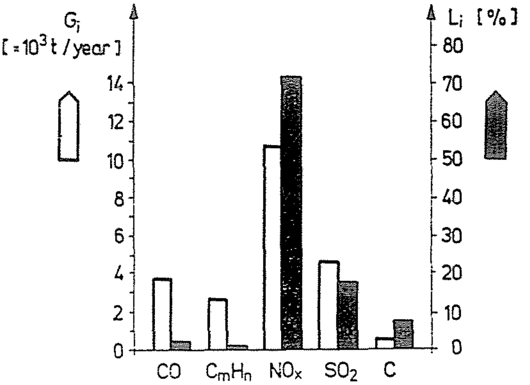

Fig. 1. Diesel railway traction-generated harmful constituent quantities, and their relative noxiousness in terms of air pollution factors L_i [%]

It is rather difficult to decide whether the $22.8 \cdot 10^3$ tons/year of harmful exhaust constituents are much or irrelevant. By proportions, it is rather low related to the air pollution of the power industry. It is by no means irrelevant in absolute value. Fortunately, much of the harmful components transform, decompose after a while.

As a conclusion: the overall picture of air pollution due to diesel traction is rather favourable, low of proportion, and neither high in absolute value. It is interesting to see the worsening or even reverting of the picture by analysing separate engine types involved in the summation.

Emission characteristics of railway diesel engines

Harmful exhaust constituents of railway diesel engines, and their concentration in two operating conditions, i.e. in idle running, and at full load, are seen in Table 3 [5]. These data, referring to no given engine, have been taken from publications, and are correct by order of magnitude.

In listing harmful constituents, it is a question how much they are harmful, how can they be ranked. From hygienic aspects, a correct order is when the unit quantity of the harmful component is related to the respective pollution concentration limit, the immission limit MIK_{Di}, producing ratios $1/\mathrm{MIK}_{Di}$ and ordering them according to magnitude. The previous order of evaluation displays the noxiousness of each constituent of unit quantity present in the atmosphere.

Evaluation of air pollution by diesel engines has to consider both the noxiousness of components, and their actual concentration in the exhaust gas. A method suggested by *J. Sachse* and *E. Hünigen* [6] seems to be adequate. In a given composition of exhaust gas the air pollution factor indicates

Table 3

Harmful exhaust constituents of diesel engines

Constituent	Symbol	Unit	Maximum concentrations	
			Idle	Full load
Oxides of nitrogen Nitrogen monoxide Nitrogen dioxide	N_xO_y NO NO_2	ppm	800	2000
Carbon monoxide	CO	ppm	1800	800
Smoke	C	g/m^3	0.2	0.5
Unburned hydrocarbons Aliphatic hydrocarbons	C_mH_n	ppm	1000	400
Polycyclic hydrocarbons (Benz-a-pyrene)	BaP	μg/m^3	0.5 – 3	0.5 – 3
Aldehydes Formaldehyde Acrolein	R · CHO H · CHO $CH_2 \cdot CH \cdot CHO$	 ppm ppm	 100 10	 100 10
Sulfur dioxide	SO_2	ppm	200	200

the percentage of the noxious effect caused by a given constituent of the exhaust gas:

$$L_i = \frac{\dfrac{E_i}{MIK_{Di}}}{\sum\limits_{i=1}^{n} \dfrac{E_i}{MIK_{Di}}} \cdot 100 \quad [\%]$$

where E_i is the rate of i-th harmful constituent in the exhaust gas [mg/m^3], [g/duty cycle] or [g/HPh],

MIK_{Di} upper limit of the mean immission concentration of the i-th harmful constituent recorded during at least 30 min [mg/m^3].

Processing, as an example, data in Table 3, air pollution factors of such an "average" diesel engine in idle and at full load have been plotted in Fig. 2. The overall noxious effect in each operating condition is proportional to the area of circles or to column heights. Although proportions slightly vary with operating conditions, the share of oxides of nitrogen is seen to be decisive, but also effects of smoke, aldehydes, benz-a-pyrene and sulfur dioxide prevail.

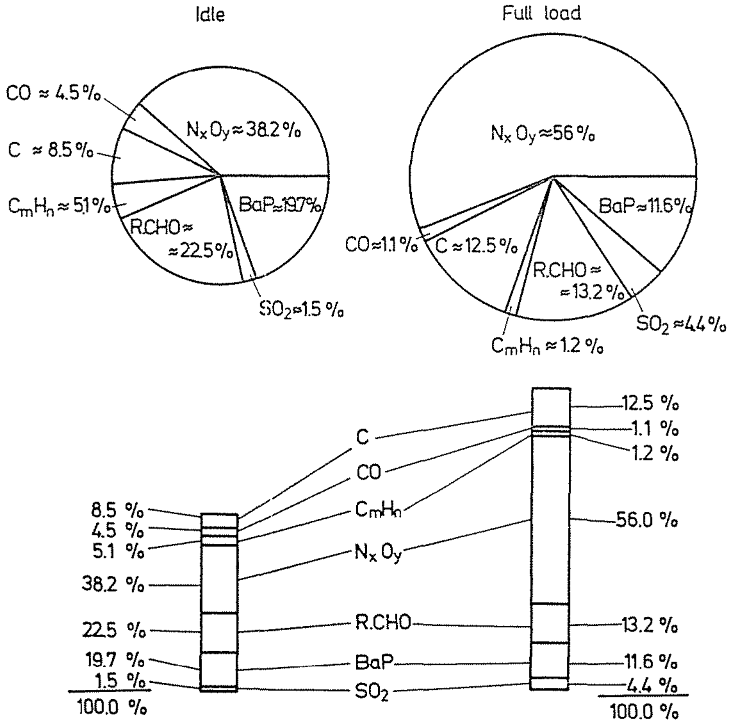

Fig. 2. Air pollution factors L_i [%] of an average railway diesel engine in idle and at full load

A correct evaluation is known to be based on the collection and measurement of noxious constituents throughout the range of operating conditions typical of the average operation of the given diesel engine. Thus, a specified duty cycle has to be established. Electro-Motive Division of General Motors Co. proposed a duty cycle presented in Table 4 for measurement of exhaust emissions of railway diesel engines [7]. Both full load and idle running are equally weighted in the duty cycle. In case of a duty cycle, measured quantities of each harmful constituent permit to deduce specific values in [g/HPh] units.

Table 4

Locomotive duty cycle proposed by GMC—EMD for measurement of exhaust emissions

Throttle position	Engine speed [1/min]	Approximate percentage of rated engine speed [%]	Approximate percentage of rated horsepower [%]	Percentage of total time [%]
8	900	100	100	30
7	815	90	86	3
6	730	81	66	3
5	645	72	51	3
4	560	62	35	3
3	480	53	23	3
2	395	44	12	3
1	315	35	5	3
Idle	315	35	1(2)	41
Dynamic brake	(1)	(1)	3(2)	8

Remarks: (1) Throttle position 5 for Roots blown engines, throttle position 4 for turbocharged engines. (2) No traction horsepower developed, diesel engine drives only auxiliary equipment.

Other duty cycles similar to the GMC-EMD one have been applied by American railway companies [8], differentiated according to the traction service (seen in Table 5). Former tables lead to the conclusion that in lack of a duty cycle, useful information and correct evaluation may result from the analysis of full load and idle running.

Emission characteristics of railway diesel engines based on published data [7, 8, 9, 10] are seen in Fig. 3. Except the Pielstick engine type PA4—200, the specific pollutant quantities have been determined according to the GMC-EMD duty cycle. Data of engine type PA4-200 refer to full load. Analysis of the test results shows NO_x and $NO_x + C_mH_n$ emissions of the engines to be high, exceeding the limits specified in the USA and in California for diesel trucks. Aldehyde emissions, lacking from Fig. 3, have been determined for 2-stroke Roots blown and turbocharged, as well as for 4-stroke turbocharged engines. Values range from 0.03 to 0.12 g/HPh, except idle running

Table 5

Locomotive duty cycles proposed for measurement of exhaust emissions

Throttle position	Percentage of total time [%]			
	GMC—EMD	ATSF Railway		
	Heavy road service	Heavy road service	Medium road service	Yard switch engines
8	30	24	20	0
7	3	2	1	0
6	3	3	2	1
5	3	2	2	1
4	3	3	2	2
3	3	3	3	4
2	3	3	4	5
1	3	5	5	10
Idle	41	46	59	77
Dynamic brake	8	9	2	0
Total	100%	100%	100%	100%

of the 2-stroke turbocharged engine, with a specific emission as high as 0.35 g/HPh [8].

Most types seen in Fig. 3 are 2- and 4-stroke turbocharged, and some are 2-stroke Roots blown engines, invariably with high specific outputs and brake mean effective pressures. Emission characteristics are known to be affected primarily by the temperature of the working cycle, resp. the temperature in certain parts of the combustion chamber and by the air-fuel ratio. NO_x emission values may be attributed to the high pressure and temperature levels unfortunately more or less concomitant to the high brake mean effective pressure.

Different exhaust gas compositions between normally aspirated, mechanically supercharged and turbocharged engines are essentially due to air-fuel ratio differences. Under partial load conditions mechanically supercharged engines have a higher air excess than have normally aspirated engines; for higher loads air-fuel ratios converge. Turbocharged engines behave contrarily. Air-fuel ratios little differ in the range of low partial load, upon increasing loads the air excess decreases rapidly for normally aspirated engines, and but slowly for turbocharged engines. Unfortunately, there are few publications to report on the exhaust gas composition of one and the same engine built in normally aspirated and in turbocharged version.

Diesel engine smoke is definitely limited by the minimum permissible air-fuel ratio depending, in turn, on the process of mixture formation and on the cylinder size. In general, performance of both the normally aspirated and the mechanically supercharged engine is controlled by this limit, that is, fuel injected during the cycle is adjusted to this limit. Exceeding this

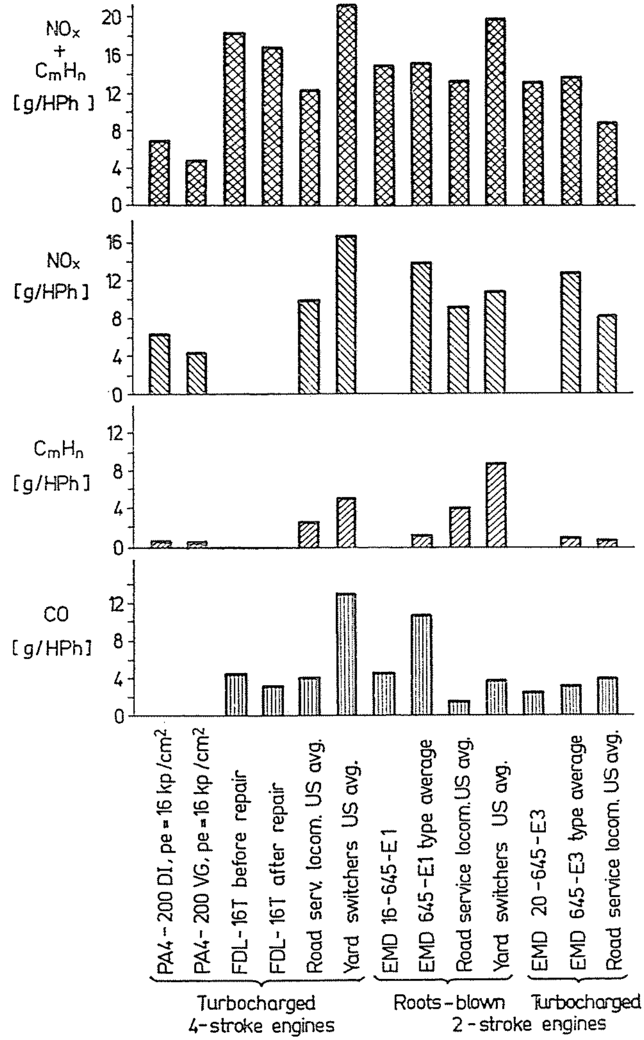

Fig. 3. Emission characteristics of railway diesel engines

limit upon outside effects e.g. higher suction temperature or lower atmospheric pressure (at high altitudes), or upon inside effects such as choked, worn out fuel injectors or injection pumps, disturbing mixture formation results in heavy smoking. In fact, this can only be counteracted by a safe distance from the smoke limit kept in adjusting the maximum dosage.

In general, turbocharged diesel engines do not operate at the smoke limit but other limits are set by the thermal and mechanical load of certain parts. The smoke to output ratio is anyhow lower because of the higher air-fuel ratio. The reduced ambient air density results in a higher exhaust gas temperature, responded by the turbocharger with a higher rpm, hence increase of the charging pressure. Minor disturbances in the injection are partly offset by the higher exhaust gas temperature because of increased fuel consumption, hence the higher rpm of the turbocharger. In the acceleration period the engine emits smoke due to air shortage. In railway diesel engines subject to load variation, rise of the charging pressure created by the turbocharger lags by 3 to 15 seconds behind the fuel dosage increase. During this time the air-fuel ratio significantly decreases, the temperature of the working cycle increases, rather increasing noxious emission. This inconvenience may largely be avoided by using the charging pressure in the suction pipe to control fuel dosage rating. Thereby boosting of turbocharged engines will somewhat be protracted, the new, higher output level will require further 2 to 6 seconds to develop.

The CO, C_mH_n and NO_x emissions of turbocharged engines referred to output will be lower; the latter mostly only if the effect of higher air-fuel ratio due to charging air recooling is not compensated or is overcompensated by higher cycle temperatures.

Let us outline now some further conclusions drawn from measuring or estimating air pollution.

Unburned carbon and hydrocarbons leaving with exhaust gases refer to incomplete utilization of the fuel, to a poorer efficiency. Hence, to reduce air pollution is an important environmental but also energetic problem.

The composition of combustion products is function of the process of mixture formation and combustion. Therefore periodical observation of certain components in service permits to conclude on the mixture formation-combustion mechanism, hence on the correct operation or the damage of certain parts in the injection system. Some engine-diagnostic purposes are best met by smoke measurement, performed by rather simple instruments. Evaluation of smoking characteristics indicated by instruments with different operation principles raises problems of conversion in the order of railway diesel engines requiring utmost care. At the same time remind that smoke reduction may be accompanied by an increased concentration in other components, hence by a higher noxiousness of combustion products, necessitating a complex evaluation of exhaust gases and control measures.

Summary

From energetic and environmental aspects, railway traction can be stated to be superior to other transport branches. Emission characteristics of the high-specific-output railway diesel engines are, however, relatively unfavourable. There are significant reserves in this field, environmental, energetic and diagnostic possibilities are by far not exhausted. Research achievements may contribute to make railways the environmentally optimum transport branch.

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