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PROSPECTS FOR THE REDUCTION OF NOISE FROM HEAVY DUTY DIESEL VEHICLES

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1. Problem statement

Road-traffic noise has come to the fore in recent years as an environmental issue of growing importance. In this respect, according to a recent German study (Fig.1),heavy duty trucks take the third place as an "annoying" source of noise behind aircraft and motorcycles and ahead of construction machinery and cars.

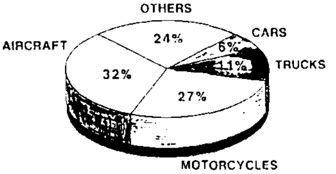

Fig.1 - "Annoying" sources of noise [Infratest, 1987].

Although most of the people who consider traffic noise to be a nuisance are the inhabitants of built-up areas,those who live close to busy highways often find this noise no less disturbing. This has been demonstrated very clearly by the Austrian opposition to night traffic on their highways.

Heavy duty truck noise is therefore a major environmental problem and will be increasingly so in the future.

Before discussing ways and methods to reduce this noise we must however make a very clear statement. Noise being a very elusive subject we must first define what we are aiming at :

- are we trying to lower the " measured" noise level of trucks as defined by current EEC regulations ?

or

- are we trying to reduce the nuisance caused to people by truck traffic ?

As we will see below, the two objectives are not the same. There are clear indications today that methods used to reach the first objective have no influence on truck noise nuisance.What is more serious , there are hints that insisting on reducing "measured" noise may even hamper technical developments directed towards reducing "real" noise as perceived by people.

In any case today's truck noise evaluation standards,which are based on a totally obsolete technique, are leading to a waste of efforts by all truck manufacturers and to an increase in transportation costs with no real

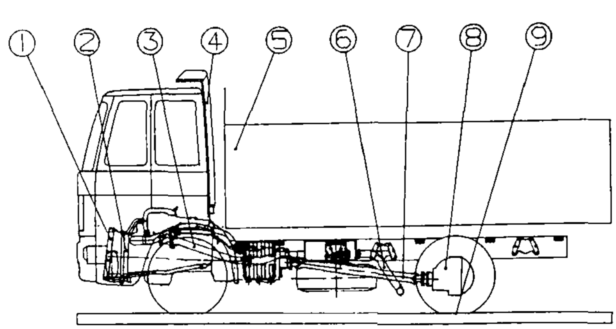

Fig.2 - Main sources of noise in a travelling truck.
1 = radiator ; 2 = fan ; 3 = engine and accessories ;
4 = air intake ; 5 = exhaust ; 6 = transmission ;
7 = superstructure ; 8 = axles ; 9= tyre/road

advantages for the final "customer" : the public.

Sources of noise in a travelling truck are many (Fig.2):

- the engine,
- engine-driven accessories (air compressor, steering gear pump, etc.),
- the engine air intake.
- the engine exhaust,
- the engine cooling airflow and the radiator cooling fan,
- the engine brake valve,
- the exhaust of the pneumatic brake system valves,
- the gearbox,
- the transmission shaft(s),
- the front and rear axles,
- aerodynamic noise from the cab and frame,
- aerodynamic noise from the superstructure,
- noise coming from superstructure installations (refrigeration compressors, etc.),
- the trailer or semitrailer,
- tyre-road interface noise.

Some of these were not important when very little attention was attached to truck noise and the main source of nuisance was the engine exhaust. As soon as better exhaust mufflers began to be installed and the engine noise was reduced by the switch-over from naturally-aspirated to turbocharged engines (a change which was dictated by fuel consumption requirements) the "minor" noise sources become important. Today none of them can be neglected and tyre-road interface noise is clearly coming to the front.
Most of the improvements have occurred in the last 10 years (the acoustic pressure level emitted by today's trucks is 1/10 of that emitted by a truck of the early '80s). This has to be kept in mind when assessing their contribution to truck noise nuisance: today there are many more old "noisy" trucks on the road than "old" cars.
Notwithstanding these improvements, the standard methods for evaluating truck noise basically have not changed for 15 years.We are in the same position as we were,evaluating a Boeing 747 with methods devised to "certify" the Wright machine.

2.- Today's measurement methods and their limitations

The current method for measuring truck noise during European type approval tests is defined by EEC Directive 84/424 in the terms of ISO 362.

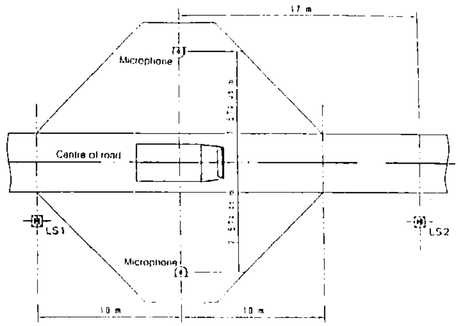

Fig.3 - Schematic of ISO 362 "pass-by" noise test.

The test has to be performed by the truck manufacturer. Therefore only light vans or buses are tested in their final form. All other trucks are tested as chassis-cab (without any superstructure) or as isolated tractors.
The test requires that the unladen vehicle be driven up to the start line (Fig.3) with the engine running at 3/4 its nominal speed and vehicle speed < 50 km/h and then be accelerated at maximum engine power over the 20 m long test track.The maximum noise level during acceleration is measured by two microphones located at 7,5 m from the track centerline. The test is repeated with different gears engaged and the truck noise level is the highhest measured during this series of tests.
Normally this occurs with the gear ratio which allows the engine to reach its maximum regulated speed in the second half of the test track.
Maximum values for " ambient" noise and wind velocity are specified.To take into account all other influences (ambient temperature,road surface type,road surface temperature, tyre type, tyre wear, tyre pressure, production tolerances,fuel specification,etc.) EEC 84/424 grants a +1 dB(A) tolerance.That is: noise measured with the same method on a production truck can deviate by + 1dB(A) from the level measured during type approval tests without the truck being rejected.In order to evaluate this "tolerance" it has to be kept in mind that changes in the ambient temperature alone can bring a 2 dB(A)change between the noise levels measured at 0 °C and 33 °C.
A slightly different acceleration test is specified for "silent" vehicles by the German Anlage XXI to para.49 of the StVZO which is also used in other European countries.The main difference consists in testing only with the gear ratios that allow maximum engine speed to be reached within the 20 m length . Additional tests are specified :

-for the truck stationary with engine revving at max. speed (8 microphones at 7 m around the truck),
-for engine brake noise,
-for pneumatic system exhaust noise.

In any case the acceleration test is the strictest one so that the chassis-cab has to be designed acoustically in order to minimize the "pass-by" noise: a condition that is very seldom encountered in real life today since it corresponds to an unladen truck or isolated tractor accelerating at maximum engine speed and engine power.
No truck driver will normally drive like that for the sake of fuel consumption, nor would road congestion allow him to do so except in totally uninhabited areas.
Even if the test is performed at a relatively low speed are its results to be taken as a measure of the "noisiness" of the chassis-cab or tractor or as a measure of the noisiness of the tyre-track surface combination ? In modern trucks, where engine noise has already been reduced to a very low value, tyre noise can be dominant even during low speed acceleration as shown in Fig.4. This figure presents the results obtained during a standard ISO 362 test on two identical high-power IVECO 190.48T tractors fitted with two different makes of tyres. The tests were performed on the same day, on the same track, with the same instrumentation and the same drivers.Admittedly the two "extreme" makes of tyres available on the market were used, but even so the results are so wildly different as to cast some doubt about what one is really measuring during the test.
Of course the rib pattern of the tyre ("traction" or "non-traction") has the most

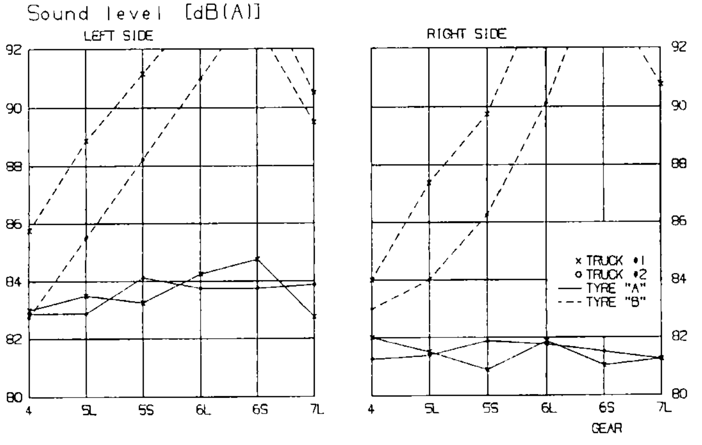

Fig.4-Test results with different tyres. [IVECO]

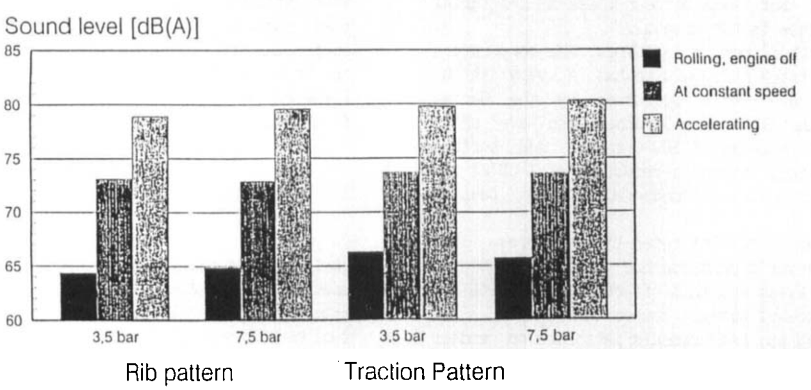

Fig.5 -Influence on tyre-road interface noise of driving mode and tyre inflation pressure.[Continental]
Tyre size 315/80 R 22.5 - ISO 362 (7.5 m).
Tyre load = 9250 N/wheel ; speed = 37 km/h.

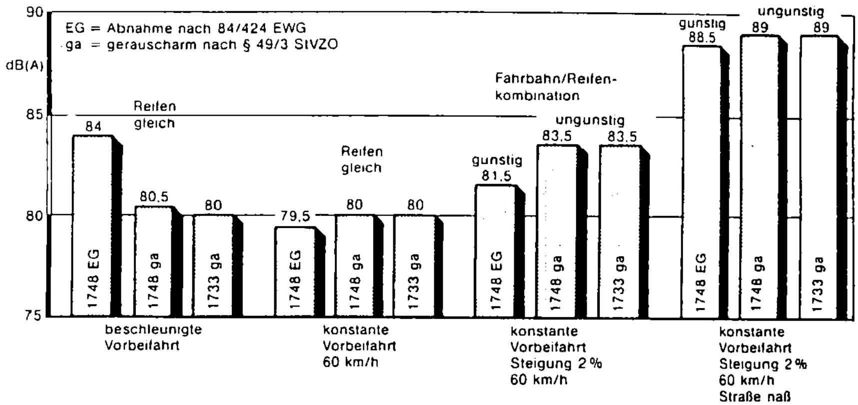

Fig.6 - Tests on the Brenner Autobahn,7.9.1989 [Mercedes-Benz].
1st set : ISO 362 pass-by test
2nd set : same tyres, constant speed = 60 km/h
3rd set : different tyres, 2% climb, constant speed = 60 km/h
4th set : as no. 3 but on wet road.

influence but inflation pressure is also important (Fig.5). The same figure also shows that tyres produce different noise levels when rolling, when driving at constant speed and when accelerating. Incidentally it can be noted that no truck will ever respect an 80 db(A) noise limit if even one of its tyres during the pass-by test produces a noise level of 80 dB(A) which is a common occurrence with today's traction tyres, .

Another influence which has to be combined with tyre influence is that of the track surface.

There are indications that a difference of up to 5 dB(A) can exist between a concrete and a "drained asphalt" surface.The surfaces of tracks used for noise measurement are mostly asphalt but even between these a 2-3 db(A) difference is not unusual.

To further complicate things, the temperature of the track surface also has a very strong influence. Tests performed by the German Bundesanstalt fuer Strassenwesen have shown that an increase of 10 °C in the road surface temperature brings a reduction of 1 dB(A) in the noise levels measured during pass-by tests.

The above results refer to car tyres . An even larger dependence has to be expected with truck tyres and this effect combines with the influence of ambient temperature.

Summing up, measurements performed on modern trucks according to ISO 362 are unreliable, unrepeatable and do not give any indication of the real "noisiness" of the truck even under the one operating condition for which they were devised : full power acceleration of an unladen truck in urban conditions.

It is no wonder then that "silent" trucks designed to pass such a test will in practice prove to be as noisy as "normal" trucks. This point has been very clearly demonstrated by Mercedes - Benz during the summer of 1989 when "silent" and "normal" trucks were compared during actual operation on the very controversial Brenner Autobahn (Fig.6).

The "normal" truck (1748 EG) was "rated" at 84 dB(A) according to the current EEC 84/424; the "silent" trucks (1748 ga and 1733 ga)were "80 db(A)" trucks according to the Austrian requirement. When fitted with the same tyres the "normal" truck was in fact quieter than the "low noise" trucks when traveling at 60 km/h. When the "low noise" trucks were fitted with different tyres (less well adapted to the road surface) they became actually much noisier than the "normal" truck. On a wet road the tyre noise became so dominant that all three trucks registered a noise level of about 89 dB(A).

3.- Methods to reduce noise measured according to ISO 362.

Before discussing the methods which can be used to reduce pass-by noise let us consider a practical case, taking a maxi-code 4x2 tractor designed to meet EEC 84/424 requirements, i.e. 84 db(A). Remembering the uncertainties due to the measurement method, the target design value shall be a maximum of 83 dB(A). Taking into account only the most important noise sources (Fig.7) and the state of the art today

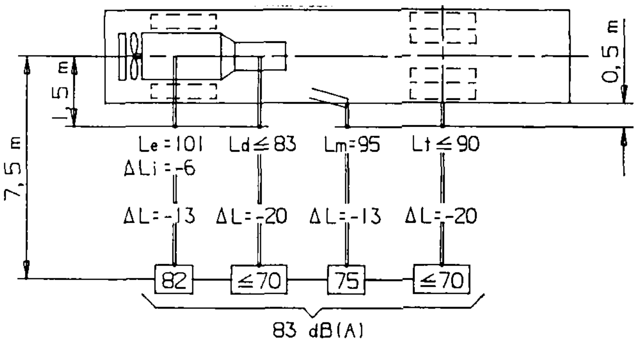

Fig.7 - Noise level of main sources, attenuation and resulting noise level for a truck designed according to EEC 84/424.

we can assume the following situation.

Engine (and accessories) noise at 1.5 m Le = 101 dB(A) which corresponds to 88 db(A) at 7.5 m (measured value; theoretical attenuation would be - 14 dB(A)). As this value is clearly too high we have two alternatives:

- use an engine having a noise level at max. rpm of 95 db(A);

or :

- encapsulate the engine in order to bring the noise level at 7.5 m to 82 dB(A).

The second alternative is currently the one most used since designing a new heavy duty truck engine from scratch can take anything from 5 to 7 years. An attenuation Li=-6 dB(A) at 7.5 m can be obtained today by fully encapsulating the engine (top, sides, bottom, rear). This poses serious problems for engine and accessories cooling. These problems can be solved but at a certain cost : for instance it is much more difficult to install electronics on the engine in Europe than in the USA. As far as the front engine noise from the cooling fan is concerned, all modern heavy duty engines have a viscostatic or hydraulically driven fan so that the fan itself is rotating at a very low speed during acceleration on a flat road.

Noise from the muffler is not a big problem: a good muffler will give a noise level of Lm= 95 dB(A) at 0.5 m, corresponding to 75 dB(A) at the microphone (again : measured values).

As far as transmission noise is concerned a level at 1.5 m of Ld=83 dB(A) is sufficient to insure a level at 7.5 m of 70 dB(A). In a 4x2 vehicle with a single-reduction rear axle such a transmission noise level does not require encapsulation either with spur gear or with helical gear gearboxes.

In a 6x4 vehicle the situation is a bit more critical but still manageable.

In 4x4, 6x6, 8x8 vehicles the transmission noise is much more important but these vehicles fall under the "off-road" category for which a slightly higher total noise level is allowed.

Finally we can forget the noise of the front tyres since (Fig.5) it is about 65 dB(A) at

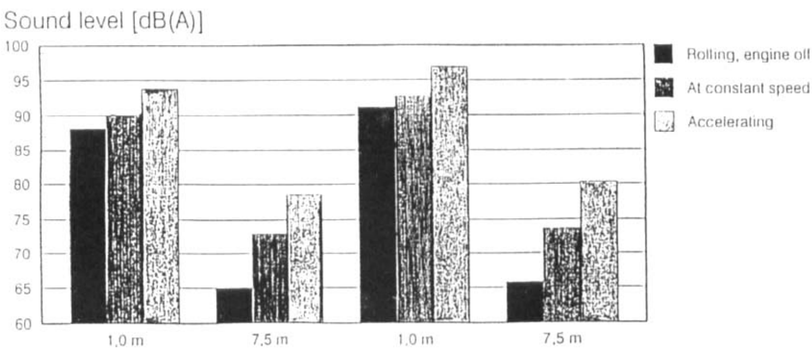

Fig.8 -Influence of tread pattern on tyre/road noise at different distance [Continental].

Tyre size 315/80 R 22.5 - Inflation pressure 7.5 bar - Tyre load = 9250 N/wheel - Speed= 37 km/h

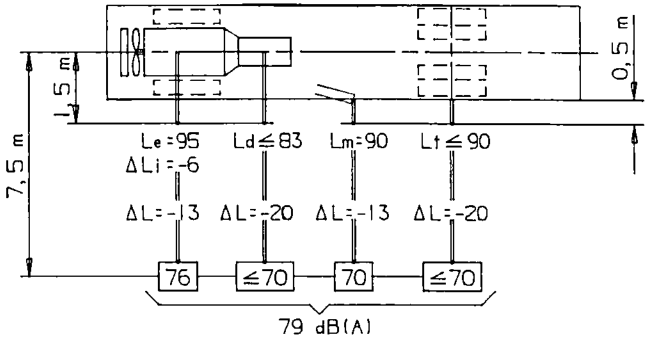

Fig.9 - Noise level of main sources, attenuation and resulting noise level for a truck designed according to an 80 dB(A) requirement.

7.5 m, while we can allow up to 70 db(A) at 7.5 m for the rear tyres, corresponding to a tyre-road interface noise level at 0.5 m of Lt= 90 dB(A) or less. This is clearly incompatible with the current generation of traction tyres or even of straight rib tyres (Fig.8) so that the type approval tests will have to be run with "low noise" tyres.Today "low noise" tyres with fairly good traction performance are available on the market.However it must be borne in mind that, in the case of trucks, the choice of tyres is made by the customer since tyres represent a considerable part of the operating costs. It cannot be guaranteed, therefore, that a truck tested for noise with a specific kind of tyres will be run on the road with the same tyres.

Clearly the situation would become untenable when the number of driven tyres increases and the tyres themselves have to be of the "traction" type (like on "off-road" vehicles 4x4, 6x6, 6x4 etc.) but fortunately so far removed from reality the measurement method is that even these vehicles can be "homologated".

In fact in the unladen vehicle condition the traction load , which is not very different from a 4x2 version, is spread distributed over a larger number of tyres.

So much for the current EEC 84/424 regulations.

What abot the "low noise" Austrian requirements or the forthcoming EEC regulations ? They stipulate that the 84 db(A) total pass-by noise level be brought down to 80 dB(A) which, for politicians, is a 5% reduction while for engineers it represents a 70% reduction in the sound pressure level.

Repeating the same exercise as before (Fig.9) with a target pass-by noise level of 79 dB(A) we see that the engine noise at 1.5 m has to be brought down to Le= 95 db(A) so that, with a -6 db(A) attenuation due to full encapsulation, the noise level at 7.5 m should not exceed 78 dB(A).This, of course,means a totally different engine from the 84 db(A) truck. The muffler also has to be improved since its noise contribution at 7.5 m has to be reduced by 5 db(A).

An alternative could be to reduce transmission and tyre/road interface noise but this looks very difficult since :

- encapsulation of the complete transmission is practically impossible, the transmission shafts and the rear axle(s) being moving parts with respect to the truck frame;
- already the 84 db(A) noise level implies the use of today's "low noise" tyres.

As a consequence : those truck models which already use a "low noise" engine can be brought down to the 80 db(A) level with some modification to the exhaust system. Other models have to undergo a complete engine change which might be or might be not possible. A "low noise" engine at today's state of the art means a low-revving TCA direct injection diesel engine . This corresponds to a large swept volume , heavy and expensive engine while the market request is exactly the opposite.

This explains why all the truck manufacturers are in a position to supply some truck models in respect of the Austrian or Dutch "low noise" requirements but cannot afford to modify all their trucks, in a short time span .

As we have seen, in order to meet the more stringent noise requirements formulated in terms of ISO 362 testing, the truck manufacturer has to concentrate on noise reduction from the engine during full power acceleration.

Up to now this has been accomplished by switch-over from naturally aspirated to turbocharged engines, a move that was also beneficial in terms of fuel consumption and engine size and weight.Turbocharging has also made it possible to reduce maximum engine speed, and therefore engine noise, while increasing the specific maximum power. However, today turbocharging limits have already been reached, with respect to the maximum allowable combustion pressure (mechanical engine limits) and the maximum air supply pressure (aerodynamic and mechanical limitations of the exhaust turbochargers).

The adoption of turbocharged-intercooled engines, which is beneficial in terms of fuel consumption and emissions, has worsened the situation as far as by-pass noise is concerned so that some manufacturers are resorting to intercooler by-pass during acceleration.

Other means of reducing engine noise must therefore be investigated.

The most obvious one : reduction of combustion noise from the direct injection diesel engine does not show much promise. Fig. 10 shows the results of tests performed on an high power IVECO engine. By reducing the combustion noise by 20 dB(A) through the use of a "reformulated", high cetane number, diesel fuel, the engine noise, as measured at a distance of 1 m, was practically unaffected.

Mechanical noise is in fact the dominating factor in modern diesel engines and one that can be controlled only through engine design.

Stiff engine block structures (Fig.11), new piston designs with low clearances, use of damping materials on oil pans and head covers, redesigned timing and accessories drive gear trains, extensive use of torsional dampers, careful design of external engine walls, can all contribute to the reduction of "primary" engine noise. This means however that the engine has to be completely redesigned, which is possible but it will take time before new "noiseless" engines are available.

In the meantime the manufacturer has to re-

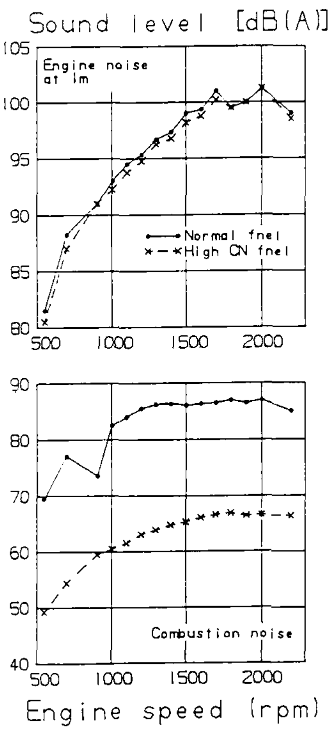

Fig.10 - Influence of combustion noise on the total noise from an high power truck engine. [IVECO]

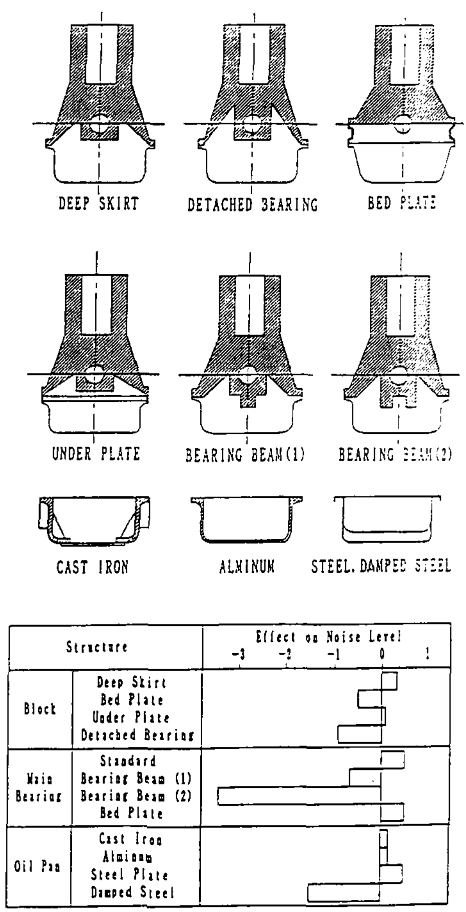

Fig.11 -Influence of engine structure on engine noise [Hino Motors].

sort to "secondary" ways to reduce engine noise, that is: by encapsulating the engine.

Different degrees of encapsulation are possible (Fig.12), all of them have an influence on the truck weight and cost. This influence was calculated years ago by CCMC (Fig.13). The values currently available on trucks designed for the Austrian "low noise" limit confirm that forecast.

Some manufacturers have also suggested a full

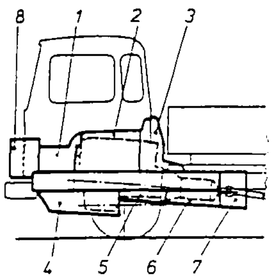

Fig.12- Influence of different encapsulation stages on engine noise from a medium -light truck.[IVECO]

0-NA engine,no encapsulation	90	dB(A)
1-TC engine,cooling air duct	85	dB(A)
2-Top and side noise screens	83.5	dB(A)
3-Full encapsulation above frame	82.5	dB(A)
4-Encapsulation below frame up to front axle	81	dB(A)
5-Full bottom encapsulation	79.5	dB(A)
6-Gearbox encapsulation	78	dB(A)
7-Noise damping cooling air exhaust duct	77	dB(A)
8-Noise damping cooling air inlet duct	77	dB(A)

encapsulation mounted on the engine itself (Fig.14). However this solution poses severe maintenance problems and, again, can only be implemented on new engines ,so that the encapsulation screens are usually fixed to the frame and to the cab.

One point to be mentioned about engine encapsulation is : how long will it stay on the truck during "real life"? Since encapsulation makes service and maintenance more difficult, since it lowers the ATB (air to boil) limit of the engine, since it weighs , it may be convenient for the truck operator to remove it during day-by-day operation and install it again for the official periodical controls.

As we have already mentioned , cooling system noise is not important during ISO 362 tests if the engine has been fitted with a viscostatic fan, which is also improves fuel consumption.

Injection pump noise may be relevant, but its influence can be "mitigated" by installing the injection pump on the opposite side of the engine to the exhaust, provided this does not

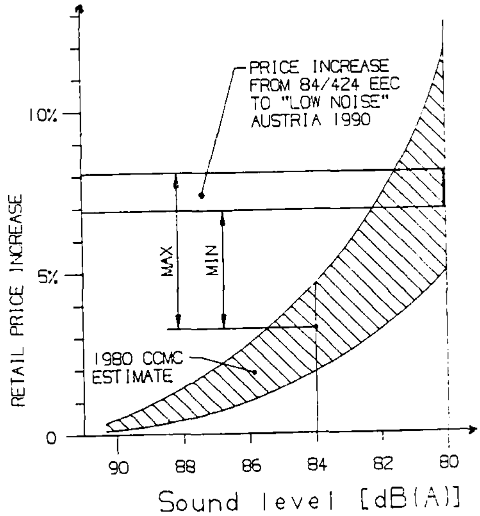

Fig.13-Cost increase for an 80 dB(A) heavy truck as estimated by CCMC in 1980 and actual list price increase by European manufacturers for Austrian "low noise" vehicles in 1990.

means a major engine redesign.

Reduction of noise from exhaust mufflers is not a major problem today, within the limits of Fig.9, provided the corresponding weight and cost penalties are accepted (Fig.15).

4.- Methods to reduce noise nuisance from trucks.

As we have already stated, the methods used to reduce truck noise as measured during the pass-by test are not necessarily those which should be used in order to reduce noise nuisance from trucks.

It is common experience that most noise nuisance comes from traffic travelling at constant medium or high speed on highways. If we repeat the exercise of Figs.7 and 9 for a tractor-semitrailer combination traveling at 80 km/h on a level road we reach totally different conclusions from the preceeding paragraph.

The engine will be running at 3/4 maximum speed and partial load. Even if we assume that combustion noise has no influence on the total engine noise, the engine noise level at 1 m will be of the order of 96 db(A) which gives, at 7.5 m ,78 db(A) <u>even without any encapsulation.</u> With encapsulation the engine noise contribution at 7.5 m goes down to 72 dB(A) which means that the engine is no longer contributing to the overall noise level.

Even assuming that muffler and transmission

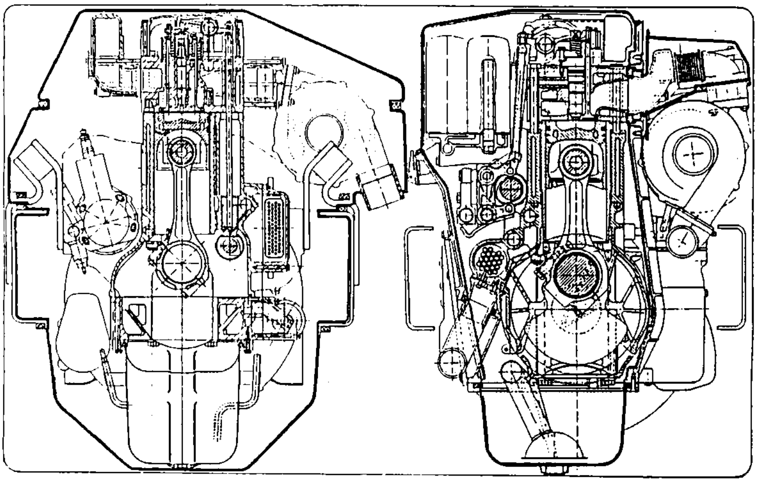

Fig.14-Comparison between a frame mounted "dry" encapsulation and an engine mounted "wet" encapsulation [Steyr].

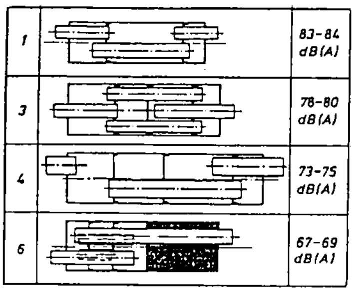

Fig.15-Noise level at 7.5 m of different exhaust mufflers for a medium-light truck.[IVECO]

Model 1 : mass 9.5 kg , volume 22 l ,cost=1
2 : mass 15 kg , volume 37 l ,cost=1.6
3 : mass 18.5kg , volume 48 l ,cost=1.8
4 : mass 18.5kg , volume 48 l ,cost=1.9

noise level remain unchanged with respect to the pass-by test (in fact they will be lower), the total noise level at 7.5 m coming from noise sources that are under the truck manufacturer's control will amount to less than 79 dB(A).

But then tyres/road noise comes into the picture.

The front tyres of the tractor can no longer be ignored as a source of noise sources since their noise level (Fig.16) at 1 m can be as high as 74 dB(A). The same is true for the tridem axle of the semitrailer : using the data of Fig.16 its noise level at 1 m can be assumed to be 102 dB(A).Assuming the tractor to be a 4x2 model , the noise level of the tyres on the driving axle at 1 m will be 99 db(A) (Fig.16).

Altogether the noise level at 7.5 m will be 83.5-84 dB(A),(Fig.17), almost entirely due to tyre/road interface noise and this will be the noise level perceived by the public.

The above calculations are of course approximate especially since they do not differentiate between "unladen" and fully laden tyre noise and do not take into account the semitrailer aerodynamic noise (due to the lack of experimental data). However they demonstrate what is commonly perceived : engine and muffler noise are no longer important in determining "traffic" noise : only tyre/road interface noise is relevant.

Another very important point to be considered is "noise quality".Limit values and measuring standards for truck noise have so far been focused exclusively on engine noise and the part of the exhaust noise which is disturbing outdoors in built-up areas. But due to our knowledge of traffic nuisance today it is important that, when tackling noise problems, we should take into account the nuisance effect of various sound frequencies to all the people who may be affected. In this connection low frequency noise that has the ability to penetrate walls becomes much more important that the overall dB(A) noise level.

It is common experience that people are fully

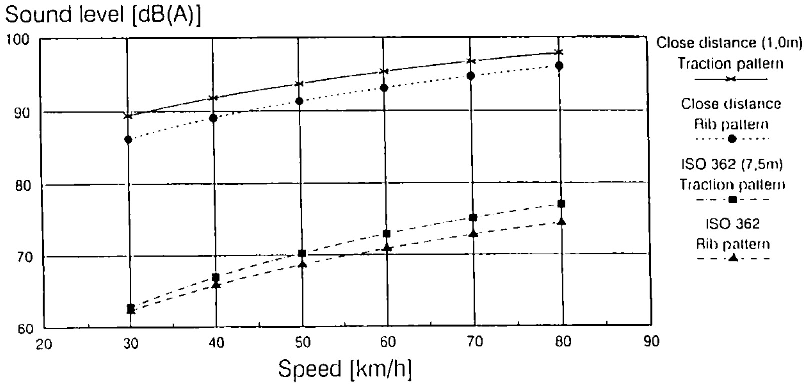

Fig.16 - Influence of speed and tread pattern on tyre noise (engine switched off, constant speed) [Continental].
Tyre size : 315/80 R 22.5
Tyre load = 9250 N/wheel
Inflation pressure = 7.5 bar.

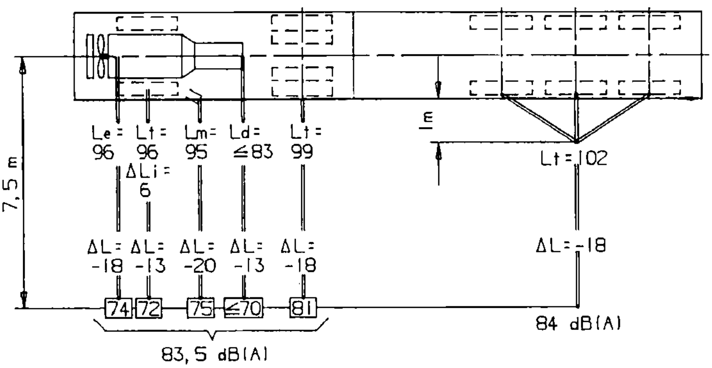

Fig.17 - Noise level of main sources, attenuation and resulting noise level for a tractor-semitrailer combination traveling at 80 km/h.

prepared for the high level of noise that will occur when they sight an accelerating truck. They will therefore tolerate an expected temporary noise peak without much nuisance. Noise which encroaches on the individual without a visible reason is much more irritating and disturbing even if its level is much lower than that of a "visible" noise source. Indoor noise which awakens a sleeping person is a particularly serious nuisance especially if it is of a continuous nature.

As a consequence today's efforts by all the truck manufacturers toward noise reduction are misdirected if we judge them from the point of view of the actual nuisance to people:

- engine noise at maximum rpm and maximum power is not as important ; on the contrary low frequency components at intermediate speed are to be reduced ;
- low frequency muffler noise is important : means to reduce it at constant speed are to be sought, like active noise reduction (which is now neglected since it has no effect on acceleration noise);
- low frequency air intake noise might be important: again no attention is today given to this problem;

But, above all, the utmost effort should be directed towards reducing tyre/road interface noise in all the frequency spectrum.

Today what little research effort goes into tyre noise reduction is mainly concerned with low speed, low load, acceleration conditions. Nobody knows if the results of such research will also be applicable to constant high speed and high load operations, especially as low frequency noise is concerned.

Research on tyres has to go together with research on "low noise" road surfacing. It is well known that, besides the use of curtain walls, the nature of the road surface considerably affects the traffic noise disturbance (Fig.18).

Little attention is paid today to this point since nobody has apparently evaluated the cost/return ratio between the improvement of road surfaces (which affects all running vehicles) and the reduction of source noise level (which affects new vehicles only).

Tyre/road interface noise is also affected by the truck suspension system. Again no research has been performed on this subject since truck suspension does not have any influence during ISO 362 tests.

Little research is done on noise from truck superstructures, semitrailers or trailers. On the contrary we find "low noise" chassis-cabs for municipal trucks which are fitted with extremely noisy garbage compactor systems. People will still be awakened in the early morning and they will be happy knowing that their municipality has paid for the increased cost of the "low noise" trucks. That, as we have seen, is what is happening to people living alongside the Brenner Autobahn.

Methods to further reduce noise nuisance by trucks are, and will be, available. However nobody will use them since they are expensive, both in terms of basic research and in production, and they will not influence the "noise level" of the truck as defined under the current measurement methods.

5.- Conclusion.

In the history of motor vehicles there is no greater example of efforts wasted and misdirected by obsolete regulations and bureaucratic inertia than the case of the reduction of truck noise nuisance.

In Europe many millions of ECU are spent in research and in product cost increases just to obtain a "political" noise reduction which will not be perceived by the people for whom truck noise is a real nuisance.

Today to increase our knowledge of heavy vehicle noise research efforts should be directed mainly toward the tyre/road interface problem. However this is prevented by EEC insistence that the ISO 362 method is the only one used to regulate truck noise. It would not be difficult to devise other, more realistic, methods to measure truck noise. For instance a method similar to the one used for evaluating truck engine emissions could be used. The use of such a method, which envisages "weighting" factors for different operating conditions, would redirect research toward more realistic objectives and, what is more important, would establish a much closer collaboration between truck, tyre and road designers.

We hope that this paper, admittedly provocative, will be of some help in convincing concerned people to rethink the global approach to the truck noise problem.

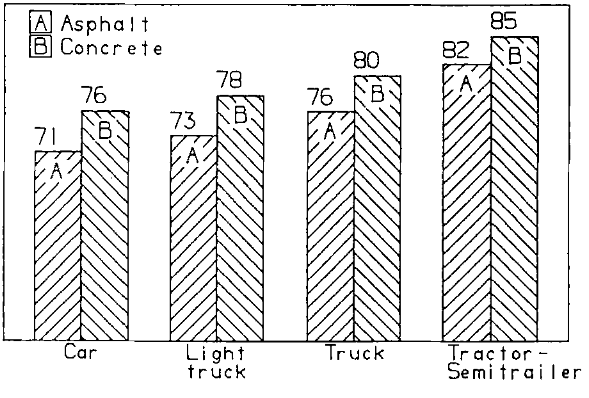

Fig.18 - Measured noise levels at 80 km/h on different road surfaces. [IVECO]

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